GEOLOGICAL AND GEOCHEMICAL MODELING OF THE FOLD AND THRUST BELT OF SOUTHEASTERN PERU

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ABSTRACT

This paper addresses the tectonic processes that have occurred in the Southern Peruvian Andes since the Eohercynian orogeny in the latest Permian time. These tectonic processes shaped the depositional patterns of Upper Permian through Tertiary units and are discussed in a sub-regional context. The structural/stratigraphic relationships of Southern Peru have been important to the exploration efforts of Mobil and partners beginning in the mid 1990's. The Southern Peruvian Sub-Andean foothills belt is composed of complexly deformed thin-skinned thrusts and detached folds. Variable decollement levels include the Upper Paleozoic and the basal Tertiary. The decollements appear to be controlled by pre-existing Late Permian-Cretaceous(?) paleo arches, as are the strike trends of individual thrust sheets. The paleo arches created important subcrop relations with the Paleozoic section below a Late Permian unconformity and likely owe their origin to the Eohercynian orogeny. The first units deposited onto this Late Permian unconformity surface belong to the "Mitu Group." Beds of Late Permian through Jurassic age were drilled in the Candamo 78-53-1X wildcat, beds that previously were assigned to the Early Cretaceous Oriente Group.

Four potential source intervals include the Devonian, Mississippian, Early Permian, and Cretaceous. Devonian and Mississippian beds are at high maturity levels in the thrustbelt and are capable of generating only gas in their present structural setting. The Early Permian Ene Formation and Cretaceous Chonta Formation exhibit oil generative potential. Basin modeling results indicate that footwall kitchens are capable of gas phase generation and that proximal kitchens are capable of gas generation from Devonian and Mississippian source rocks, while Early Permian and Cretaceous source rocks are capable of oil generation. Burial by synorogenic Tertiary deposits is recognized as the mechanism responsible for creating active hydrocarbon generation in the previously described kitchens. The Candamo 78-53-1X/ST wildcat improved the understanding of the petroleum system, regional structural, and stratigraphic relations.

STRATIGRAPHY

As documented by Mathalone and Montoya (1995) the Ucayali and Madre de Dios basins contain predominantly Miocene beds. In the southern Madre de Dios Basin (Fig. 1) between 3,000 to 5,000 meters of Late Oligocene to Recent Upper Tertiary Red Beds were deposited synchronously with thrusting and belong to Stage 2 of the Corocoro Supersequence (Fig. 2). The dominant age of beds contained in the sequence is between 5 to 8 million years. It is in this sequence that the Candamo 78-53-1X/ST spud in late 1998. One sample from this sequence cut by the well exhibited a bathysiphon known elsewhere in Peru as an indicator of a Late Miocene marine incursion, originating in Bolivia to the southeast. Evidence for such a marine incursion has been reported previously (Sempere, 1995). An underlying sequence of Paleocene to Eocene/early Oligocene Lower Tertiary beds (between 700 to 800 meters thick) were identified by charophyte picks made during drilling of the well (Fig. 3) and correlates to Stage 1 of the Corocoro Supersequence. These units belong to a pre-orogenic sequence composed of highly compacted, dominantly clay, silt, and sand which are underlain by Late Cretaceous fluvial/deltaic/shallow marine, Jurassic-Late Permian continental clastics, Early Permian shale and limestone, Carboniferous continental and marine, Devonian marine, and Siluro-Ordovician marine sediments (Fig. 2). The Carboniferous through Cambrian units, will only be mentioned briefly herein. Stratigraphic interpretations of Southern Peru have been related to the Supersequence classification of Sempere (1995) for the Bolivian Andean/Sub-Andean region (Fig. 2).

Upper Cretaceous units at Candamo 78-53-1X have been correlated by biostratigraphic age control to units in the Ucayali Basin, including the uppermost Casa Blanca Sandstone, Huchpayacu Formation, Vivian Sandstone, and at the base, the marine shales of the Chonta Formation, all belonging to the Puca C Supersequence. Four or five marine incursions can be interpreted from flooding surfaces in the Chonta and Huchpayacu marine sequences and by fluvial/deltaic progradations of the Vivian and Casa Blanca Sandstones. An influx of clean sand from the east of Campanian-Maastrichtian age has been attributed to reactivation of thrusting in the Bolivian orogen with an accompanying uplift of a forebulge in the Sub-Andean foreland basin. It is probable that deposition of the Casa Blanca fluvial/deltaic wedge in the Madre de Dios Basin is evidence of a major transgression from the north in the early Maastrichtian.

In Bolivia, this and other incursions from the north are also recorded for the Cenomanina-Turonian, early Santonian, middle Campanian, and Danian (Sempere, 1995).

Lower Cretaceous units have not been successfully documented in the block and, in fact, are believed non-existent in the Madre de Dios Basin. Units formerly assigned to the Lower Cretaceous Oriente Group are now assigned to the Upper Permian-Jurassic Mitu Group based on biostratigraphy, Apatite fission track age (AFTA) determinations, potassium-argon dating of Early Jurassic intrusives cutting these sedimentary deposits, and stratigraphic correlations to the Beu Sandstone of Bolivia and Upper Permian units at Camisea. The Mitu Group clastics are composed of at least four formations (Upper Nia/Beu, Lower Nia, Shinai, and Noipatsite). The Noipatsite and Shinai formations are believed to be contained in the Cuevo Supergroup, while the Lower Nia Formation is believed to be contained in the Serere Supergroup, and the Upper Nia/Beu Sandstone is contained in the Puca A&B Supergroup. In the Southern Ucayali Basin, a similar understanding of the stratigraphy was recently revised by correlations from the stratigraphy at Pongo de Mainique to the Camisea gas fields (Bennett, et al., 1997). Bennett et al (1997) describe Cretaceous and Permian (formerly assigned to the Oriente Group) clastic reservoirs and a low-angle unconformity within the subsurface reservoir systems. The Candamo well identified subsurface reservoirs belonging to the Mitu Group in Block 78. At Candamo, the Permian sequence exhibits fluvial sandstone at the base grading up into a Jurassic "coastal" dune sequence similar to eolian deposits of the Beu and Upper Nia Sandstones. Recent well log interpretations illustrate the traditional view of the Oriente Group correlating into the Madre de Dios Basin from the Southern Ucayali Basin via the Camisea area (in Mathalone and Montoya [1995] Fig. 10, p. 431). The new Mitu interpretation proposed here is supported by extensive data, which contradict the prior interpretation in favor of Upper Permian-Jurassic Mitu Group picks. Jurassic eolian beds of the Beu Sandstone occur at the Peru/Bolivia country boundary, and are believed to correlate to the Jurassic Upper Nia Sandstone.

In the Tambopata Block, the Mitu units are contained in the hanging wall of the Candamo thrust system, and are faulted over a footwall sequence composed of Upper Cretaceous clastic rocks by a roof thrust. The Cretaceous footwall units form part of a footwall ramp collapse feature which is itself thrust over a hypothesized Lower Tertiary through Paleozoic footwall sequence. Such structural relations readily demonstrate the geologic complexities documented in the petroleum systems of Block 78. However, on the thrust belt trend, the giant fields at Camisea attribute the hydrocarbon potential contained within Upper Cretaceous and Upper Permian clastic units. It was these reservoir objectives that the Mobil operated Candamo 78-53-1X tested in Block 78.

TECTONIC ELEMENTS

The petroleum systems of the sub-Andean fold and thrust belt in southern Peru were modeled from a geologic kinematic and geochemical standpoint. These petroleum systems are contained within the Sub-Andean mega trend as illustrated in Figure 4. The area recently experienced periods of contractional deformation beginning in the Oligocene with deformation continuing into Late Miocene/Pliocene. This tectonic activity and coeval synorogenic Tertiary basin deposition created the mechanism responsible for hydrocarbon generation in most of the previously marginally mature Middle and Upper Paleozoic, and Mesozoic source beds. However, other significant tectonic events had already imparted geothermal, structural, and stratigraphic changes to the sequences contained in the Madre de Dios Basin and must be understood to adequately model the source rock distribution, quality, and thermal maturity in the basin. These same factors also affected the lateral distribution of reservoir rock facies and the reservoir quality.

Paleozoic Arches

Significant tectonic elements within the Peruvian portion of the Madre de Dios Basin are the Late Permian-Cretaceous(?) aged paleo arches called the Madidi, Manu, and farther west the Fitzcarrold Arches. These arches created important subcrop relations with the Paleozoic section below the regional Late Permian unconformity and in places acted to control the spatial distribution, decollement levels, and temporal sequence of thrusting in the Sub-Andean region (Fig. 5 and 6). These arches seem to evidence an earlier period of Middle Triassic tectonic activity known locally as the Jurua orogeny and mentioned by Mathalone and Montoya (1995). Sempere (1995) describes a similar period of intense compressional or transpressional deformation, which occurred between middle Permian through Early Triassic and is ascribed to the Eohercynian deformation, followed by a Middle Triassic to Middle Jurassic rifting period. At first glance, the arches appear to be contractional features, which in fact control the entire basin architecture of the Madre de Dios Basin and would be ascribed to the Eohercynian deformation. For example, the Madre synclinorium is bounded on the west by the approximately north-south trending Manu arch and on the south by the approximately east-west trending Madidi arch.

However, upon close inspection of seismic lines, even though sub-regional truncations of somewhat asymmetrical geometry can be observed, in the case of the Madidi arch, it is very difficult to determine if the truncated units on the north reappear on the south side of the bald high. Thus, it is possible that the Madidi "Arch" is some type of tectonic platform (tilted horst block) developed during back arc rifting. Herein the entire Mitu sequence between Late Permian through Jurassic is interpreted to be associated with back arc type volcanism, and to a large extent be bounded by horst and graben type basinal accommodation areas. However, any direct control regarding the Late Permian to Early Triassic age for such deformation is highly speculative. Mathalone and Montoya (1995) mention that clastic and volcaniclastic units of the Mitu Group are noted to thicken into faults, thus appearing to have been deposited in extensional basins. There is also a well-documented series of Early to Late Triassic plutons (Abancay and Zongo-Yani, 1995) occurring in the Southern Peru vicinity. In Block 78 at least two intrusive units have been dated as early Jurassic. Regardless of the "exact" timing, the Middle Triassic to Middle Jurassic back arc extension period appears to have been a prelude to the actual breakup of the Pangae supercontinent.

Early/Late Permian unconformity

The Early/Late Permian unconformity itself warrants great interest. It separates a Lower Paleozoic through Upper Paleozoic passive margin sequence from the overlying Upper Permian through Upper Cretaceous/Tertiary subduction-collision sequences. This unconformity is interpreted to correlate with the onset of back-arc extension where oceanic crust was subducted beneath continental crust. Back-arc extension is created in foreland/back-arc settings when the rate of convergence is less than the rate of subduction. Although back-arc extension is widely recognized in the Andean outcrops of the Upper Permian through Jurassic Mitu Group as discussed above, this paper presents the first tie of such back-arc related extension into the foreland basin sequence. Based on seismic interpretation, and ties to Jurassic through Upper Permian clastic rocks at the Candamo wildcat, a thin "Mitu Group" is interpreted as being distributed above the angular unconformity, well into the Madre de Dios Basin sequence (Fig. 5).

Major Thrust Trends

Major thrust trends, which propagated from the hinterland into the foreland Madre de Dios and Ucayali basins, occurred in response to the placement of such pre-existing arches. The local thrust systems in Block 78 include the frontal Tambopata thrust, a series of back thrusts, the intermediate Candamo triangle zone, and two major thrust sheets on the south, the Iñambari and Azulmayo (Fig. 6 and 7). Deformation generally occurred between about 30 to 2 Ma, with decreasing offset and higher stratigraphic levels of deformation occurring in the more frontal thrust sheets. The Azulmayo thrust to the south (hinterland) appears to be an out of sequence event based on AFTA data, which show very recent displacement. Decollement levels are variable across block 78 with the northwestern portion exhibiting a decollement below Upper Paleozoic level. On strike to the southeast and east, a decollement occupies a level very close to the basal Tertiary claystones. The progression of the thrust events was determined by AFTA which was used to determine the timing of uplift and cooling on the thrust sheets as well as the cutting relations between Tertiary red beds and faults. These data and fault cutting relations support the age range suggested above. Postulation of earlier thrusting (>30 Ma) is based on extrapolation of maximum displacement and recorded uplift and cooling age.

GEOCHEMISTRY/BASIN MODELING

Four potential source intervals have been documented, three in the Paleozoic (Devonian, Carboniferous, and Early Permian) and one in the Cretaceous. The Devonian and Carboniferous beds are locally at high maturity levels, with excellent total organic carbon levels, but believed capable of generating only gas in their present structural setting. Recent studies in the Madre de Dios Basin of Bolivia and Peru have documented generation of medium gravity, low-sulfur oil which migrated updip towards the Brazilian shield and was generated from world class Upper Devonian shales (Carpenter, 1997; Peters, et. al., 1997a, 1997b, and 1997c). These and other studies have demonstrated the highly marine character of the Type I/II Upper Devonian shales, including a possible link to glacial related deposition environments (Isaacson,, et. al., 1995). It has been hypothesized that glacial conditions permitted algal abundance blooms (tasmanites) in near surface fresh waters that were density and salinity stratified above nutrient rich marginal marine waters of the Amazon/Madre de Dios troughs. The algal blooms deposited with the highly stratified black shales and formed an excellent source rock with source potential indices recorded between 15 to 18 tons of hydrocarbon per square meter of source rock column (Carpenter, 1997; Peters, et. al., 1997). Gas and condensate at the nearby Camisea fields were sourced from Lower Paleozoic source rocks (Geuns, et al., 1997). In outcrop samples, the Early Permian Ene Formation and Cretaceous Chonta shale beds exhibit moderate to high levels of total organic carbon, hydrogen indices, and S2 yields at immature to marginally mature levels of maturity. In the Candamo well, the Cretaceous Chonta shales exhibited very lean organic content. The Permian Ene shales were not penetrated before entering the Upper Cretaceous footwall sequence.

Basin modeling incorporated "Rock-Eval" data and balanced cross sections. Results suggested that footwall kitchens are capable of full maturation of all source rocks into gas phase generation. Proximal hanging wall kitchens are capable of full maturation (through gas) of Devonian and Carboniferous source rocks, while early to peak phase oil generation is possible for Early Permian and Cretaceous source rocks. The source rock generation history seems to be controlled by thrust related burial of prospective kitchens, culminating with the latest displacement on the southeast-northwest trending Azulmayo thrust sheet. This compressional pulse was an important contributor to late stage hydrocarbon generation and migration into pre-existing up-dip structures.

ACKNOWLEDGEMENTS

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CONTRIBUTIONS TO GEOLOGICAL KNOWLEDGE

- Newly identified Jurassic-Late Permian continental clastics were drilled in the hangingwall sequence of Candamo. These beds are assigned to the Mitu Group. They were previously assigned to the Early Cretaceous Oriente Group sandstones.

- Late Permian-Cretaceous(?)paleo arches such as the Madidi, Manu, and farther west the Fitzcarrold, created important subcrop relations with the Paleozoic section below the regional Late Permian unconformity and in places controlled the spatial distribution, decollement levels, and temporal sequence of thrusting in the Sub-Andean region.

- An Early/Late Permian unconformity separates a Lower Paleozoic through Upper Paleozoic passive margin sequence from overlying Upper Permian through Upper Cretacaeous/Tertiary subduction-collision sequences.

- A thin wedge of the "Mitu Group" is interpreted as being deposited across the southern portion of the Madre de Dios Basin, above the angular unconformity.

- Decollement levels are variable across the block with the northwestern portion of Block 78 exhibiting a decollement below Upper Paleozoic level and on strike to the southeast and east, the decollement occupies a level very close to the basal Tertiary claystones.

- Devonian and Carboniferous source rocks are locally at high maturity levels in the thrustbelts, with excellent total organic carbon levels, but are believed capable of generating only gas in their present structural setting. In the foreland basin, generation of medium gravity, low-sulfur oil from the world class Upper Devonian shales has occurred.

- In outcrop samples, the Early Permian Ene Formation and Cretaceous Chonta shale beds exhibit moderate to high levels of total organic carbon, hydrogen indices, and S2 yields at immature to marginally mature levels of maturity.

- Basin modeling results suggest that footwall kitchens are capable of full maturation of all source rocks into gas phase generation. Proximal hanging wall kitchens are capable of full maturation (through gas) of Devonian and Carboniferous source rocks, while early to peak phase oil generation occurs for Early Permian and Cretaceous source rocks.

- Burial by synorogenic Tertiary deposits in response to tectonic activity is recognized as the mechanism responsible for creating active hydrocarbon generation in the previously described kitchens.

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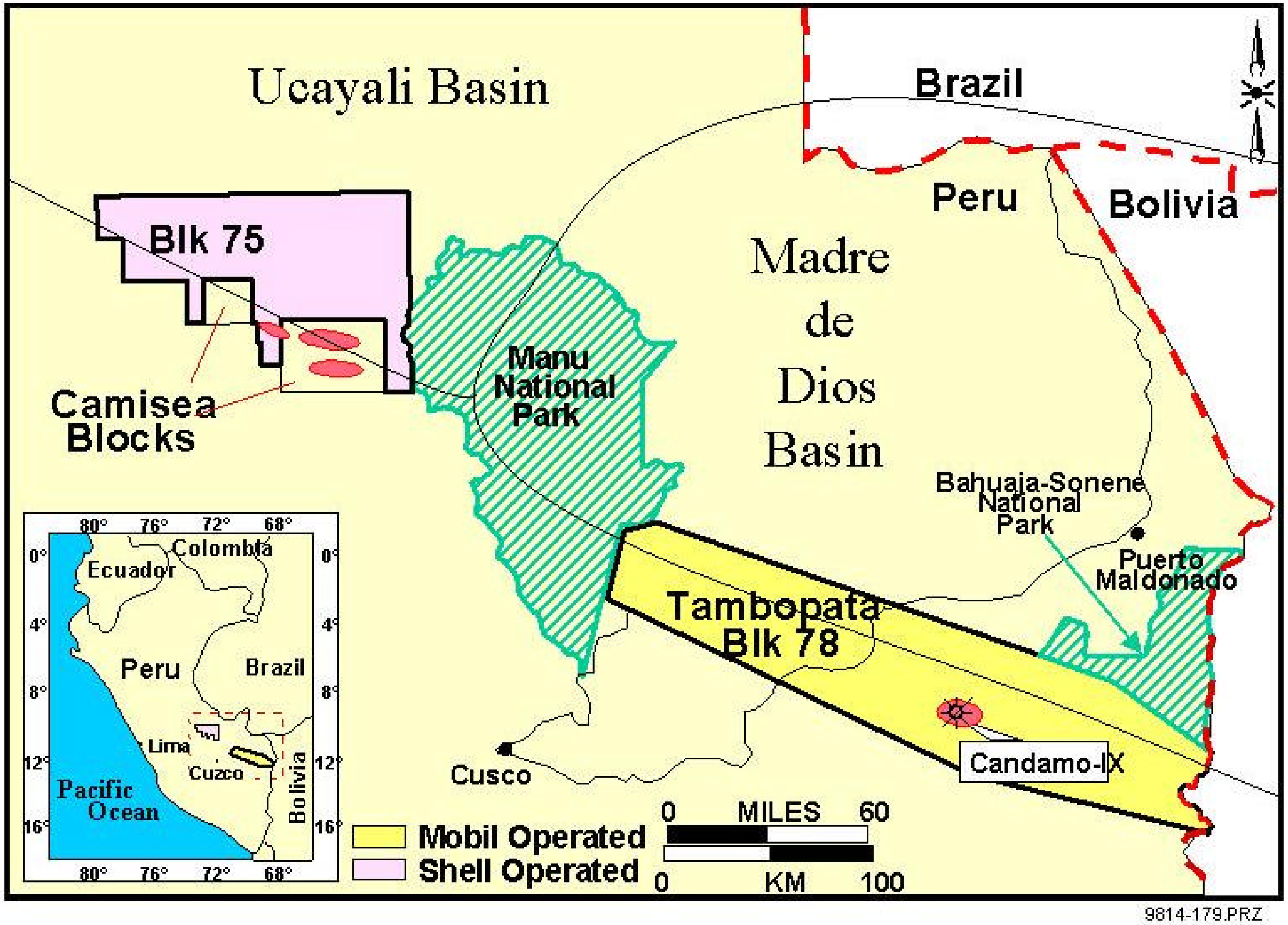
Figure 1: Tambopata Block 78 Base Map



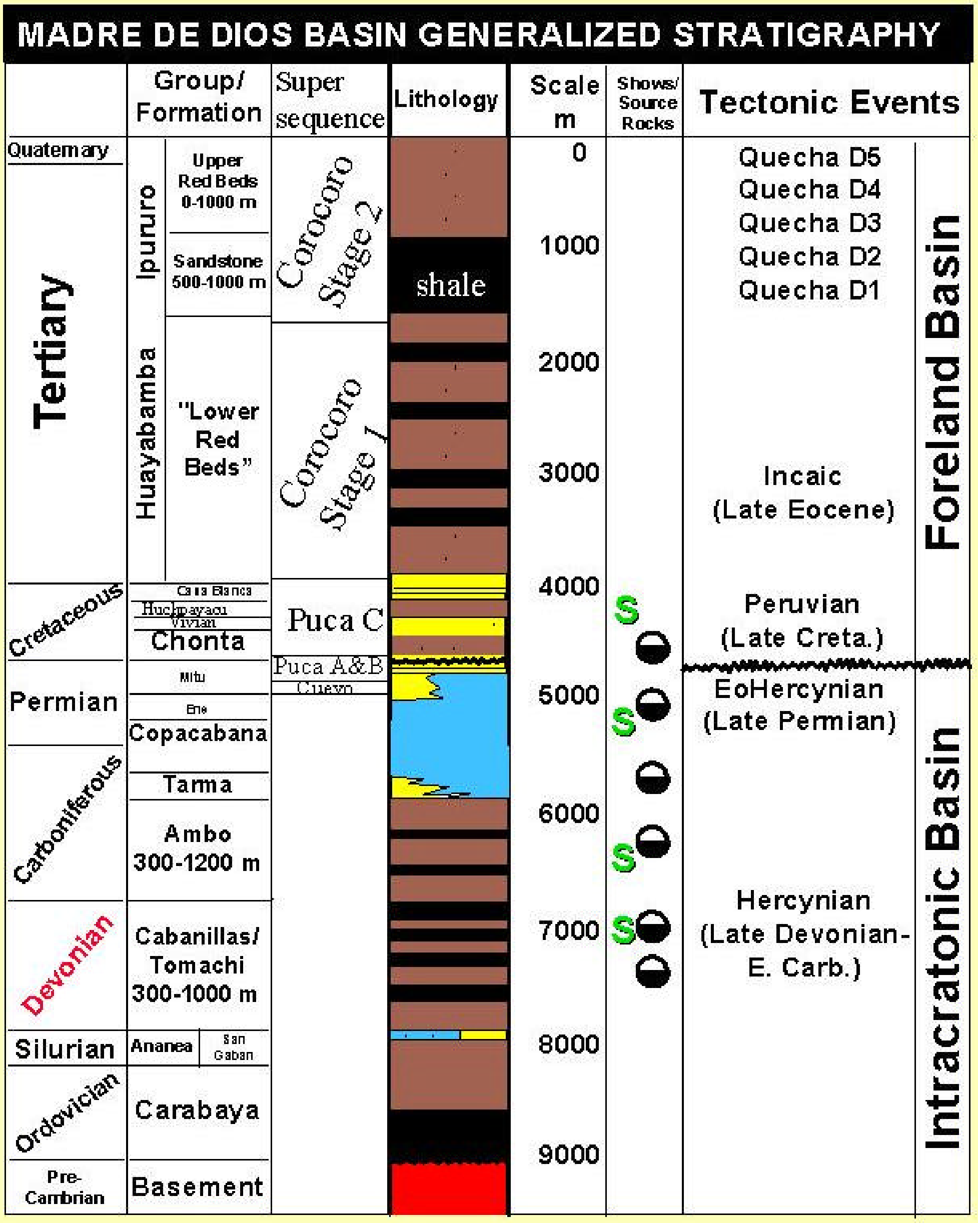

MADRE DE DIOS BASIN GENERALIZED STRATIGRAPHY
Group/ Formation
Super sequence
Lithology
Scale m
Shows/ Source Rocks
Tectonic Events
Quaternary
Tertiary
Cretaceous
Permian
Carboniferous
Devonian
Silurian
Ordovician
Pre-Cambrian
Ipururo
Huayabamba
Upper Red Beds 0-1000 m
Sandstone 500-1000 m
"Lower Red Beds"
Casa Blanca
Huchpayacu
Vivian
Chonta
Mitu
Ene
Copacabana
Tarma
Ambo 300-1200 m
Cabanillas/ Tomachi 300-1000 m
Ananea
San Gaban
Carabaya
Basement
Corocoro Stage 2
Corocoro Stage 1
Puca C
Puca A&B
Cuevo
shale
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
S
Quecha D5
Quecha D4
Quecha D3
Quecha D2
Quecha D1
Incaic (Late Eocene)
Peruvian (Late Creta.)
EoHercynian (Late Permian)
Hercynian (Late Devonian-E. Carb.)
Foreland Basin
Intracratonic Basin

Figure 2

Figure 3: Candamo 78-53-1X Charophyte Results

Formation	Age	Top (depth below KB)	Base (depth below KB)	Diagnostic Charophytes
Upper Tertiary Red Beds	Late Miocene or younger	0 m	650 m	Barren
Upper Tertiary Red Beds	Indeterminate (barren)	650 m	1,855 m	Barren
Upper Lower Tertiary Red Beds	Indeterminate (barren)	1,855 m	1,970 m	Ostracods
Upper Lower Tertiary Red Beds	Indeterminate (barren)	1,970 m	2,135 m	Barren
Upper Lower Tertiary Red Beds	Miocene-Oligocene	2,135 m	2,160 m	*Tectochara ucayaliensis coronata* *Bathysiphon* Microgastropods
Upper Lower Tertiary Red Beds	Indeterminate (barren)	2,160 m	2,340 m	Barren
Lower Lower Tertiary Red Beds	Eocene	2,340 m	2,415 m	*Kosmogyra monolifera* Microgastropods Reworked fusilinid (Copacabana?)
Lower Lower Tertiary Red Beds	Paleocene	2,445 m	2,515 m	*Porochara gildemesteri costata* *Porochara gildemeisteri solensis* *Spaerocharas huaroensis*
Createaceous	Cretaceous Undifferentiated	2,515 m	2,780 m	*Porochara gildemeisteri* *Chara cylindrata* *Saportanella riverae* *Brevichara* and *Brevichara 4* *Tolypella biacuta* *Saportanella riverae globosa* *Saportanella riverae cilindrata* Microgastropod
Mitu Group	Jurassic? through Upper Permian	2,885 m	3,080 m	Barren
Casa Blanca/ Huchpayacu/ Vivian	Upper Cretaceous	3,080 m	3,890 m	Barren

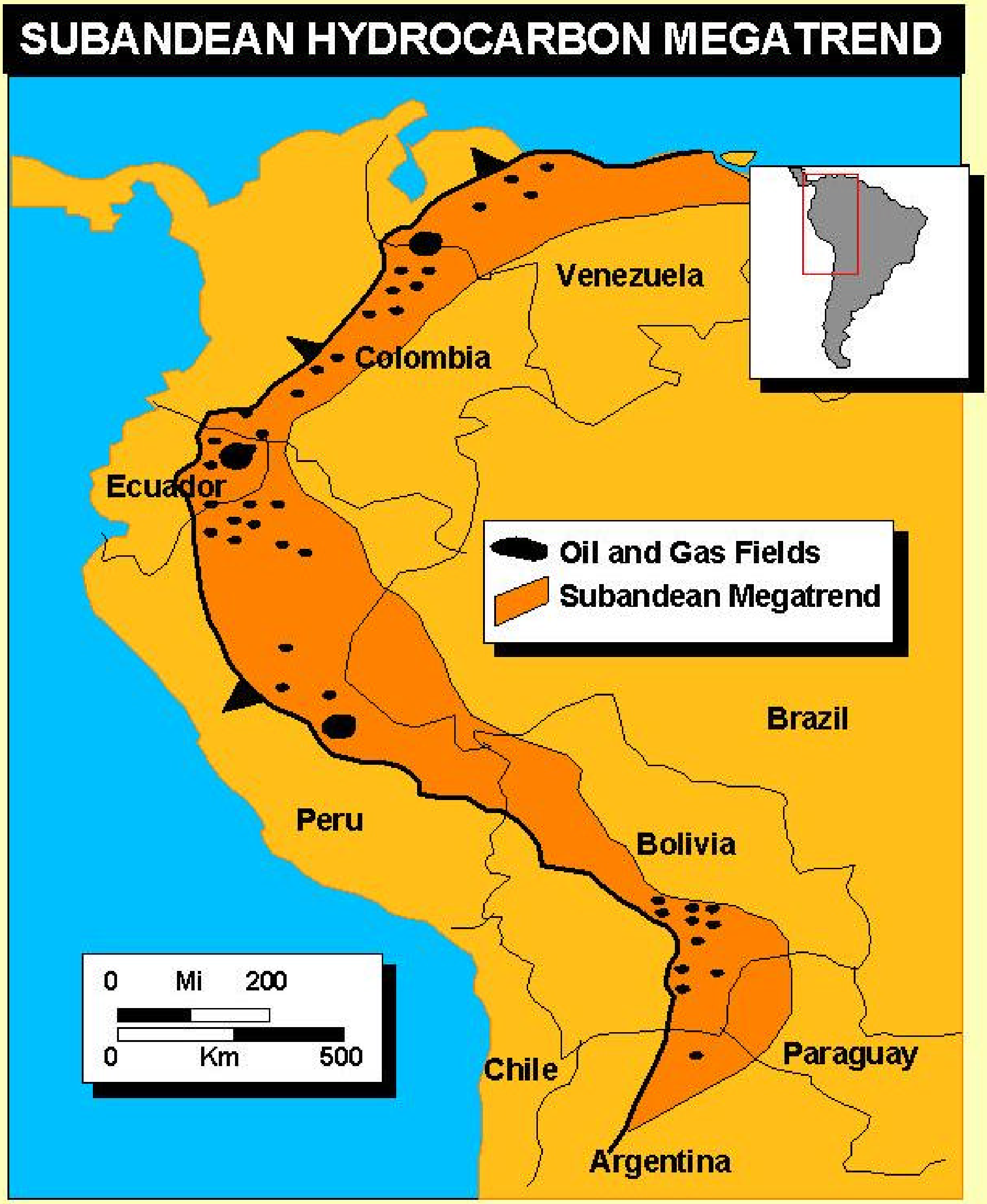

SUBANDEAN HYDROCARBON MEGATREND
Venezuela
Colombia
Ecuador
Oil and Gas Fields
Subandean Megatrend
Brazil
Peru
Bolivia
0 Mi 200
0 Km 500
Chile
Paraguay
Argentina

Figure 4

Figure 5: Madre de Dios Basin Subcrop Map

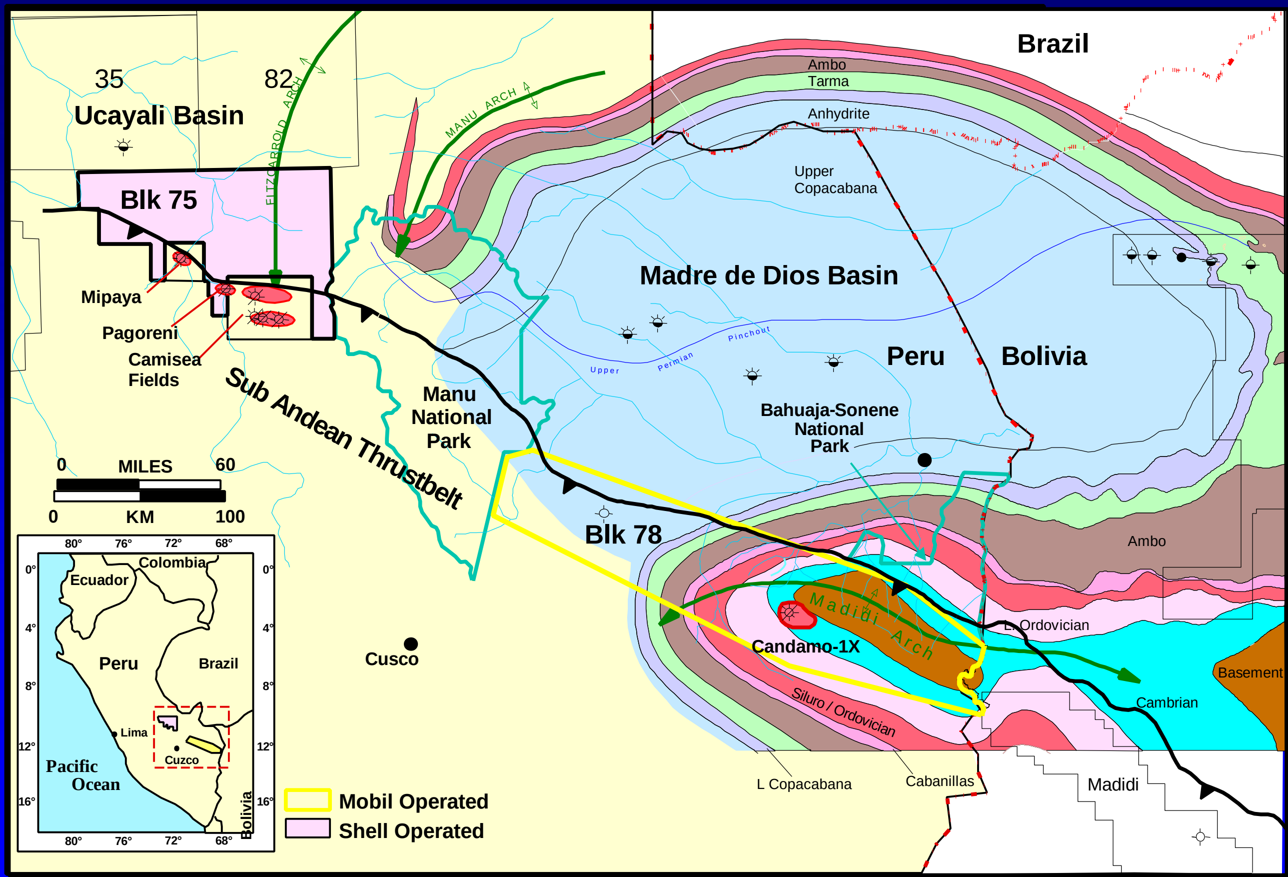
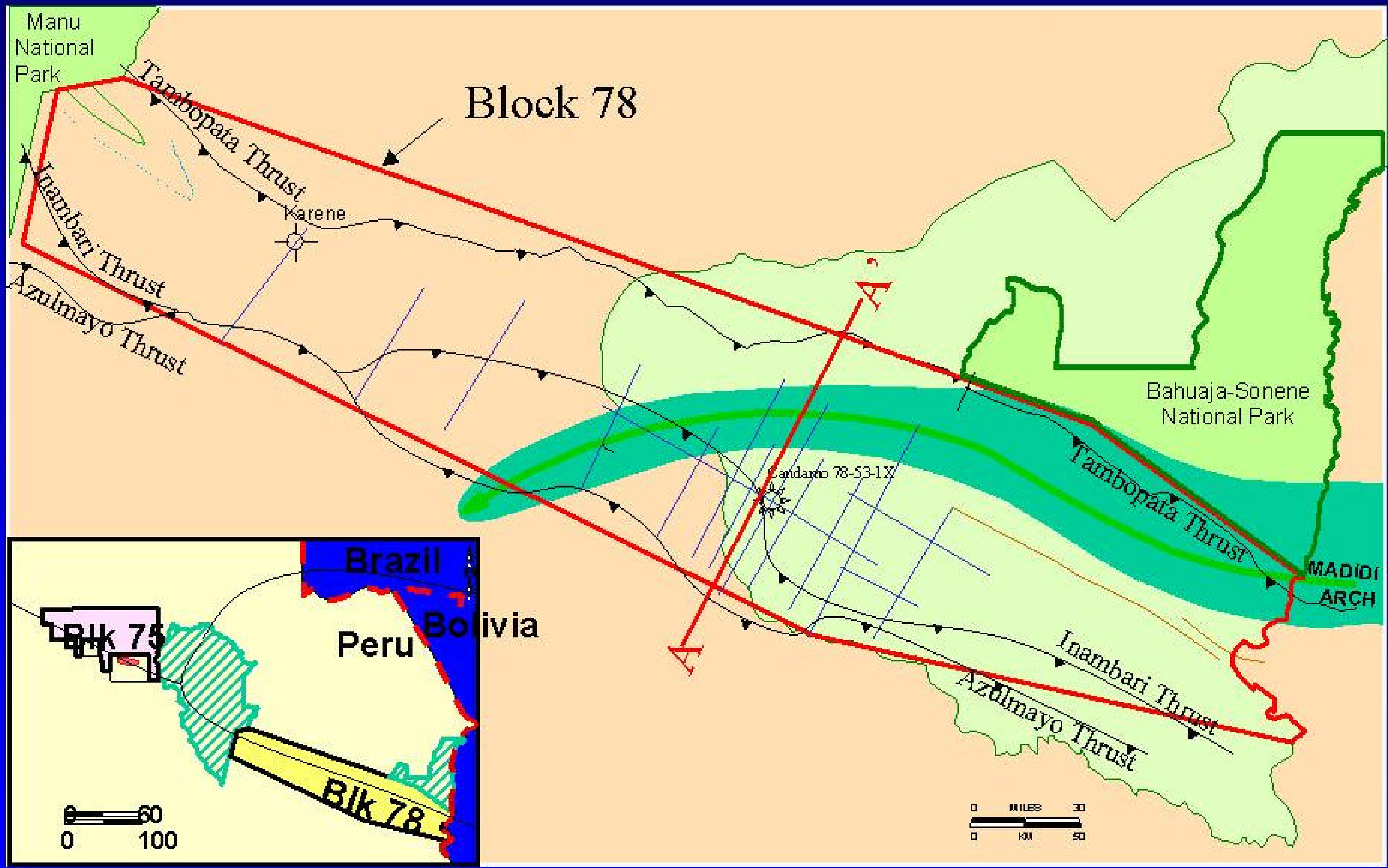


Figure 6: Tectonic Elements Map: Block 78



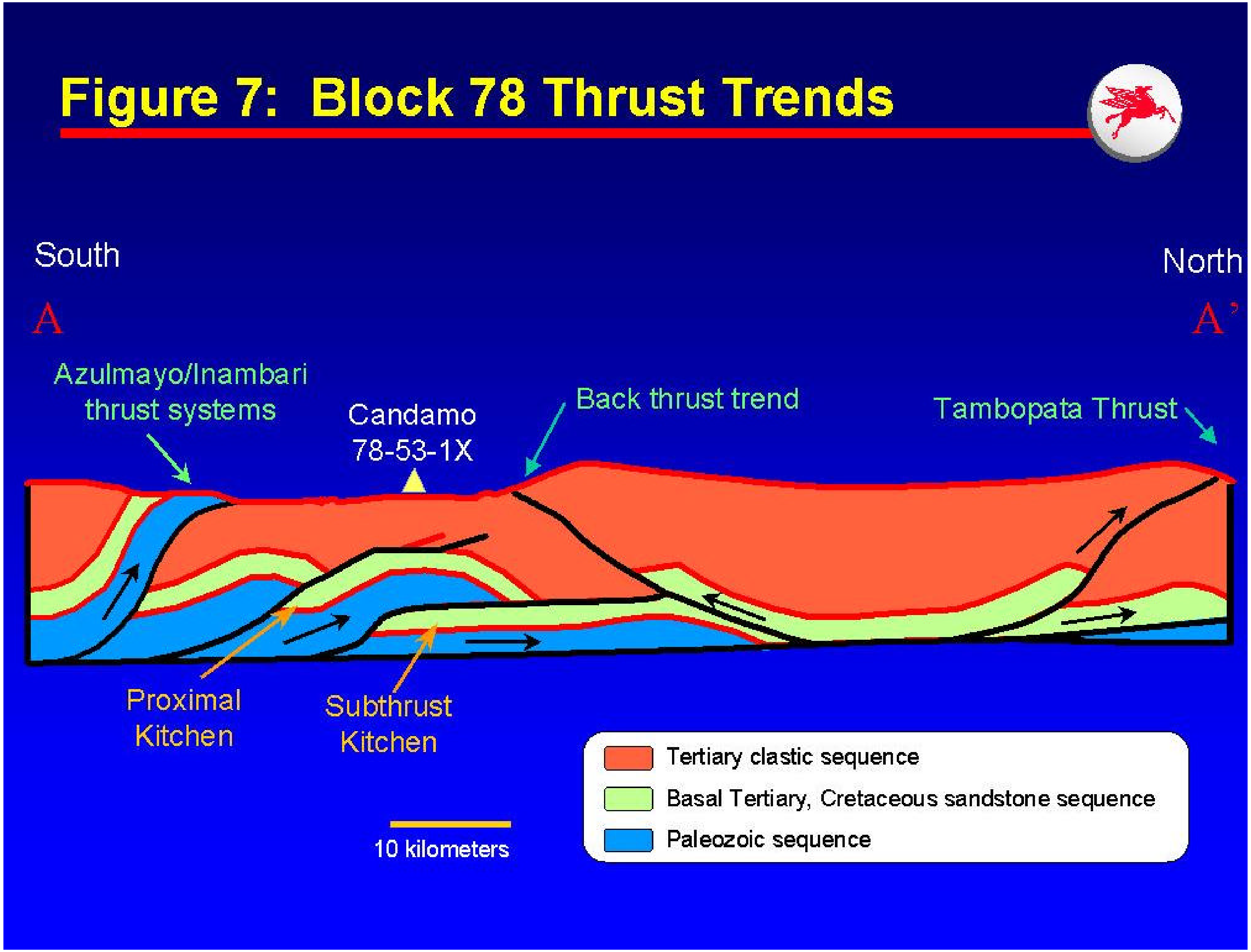


Figure 7: Block 78 Thrust Trends
South
North
A
A'
Azulmayo/Inambari thrust systems
Candamo 78-53-1X
Back thrust trend
Tambopata Thrust
Proximal Kitchen
Subthrust Kitchen
10 kilometers
Tertiary clastic sequence
Basal Tertiary, Cretaceous sandstone sequence
Paleozoic sequence