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1.0 INTRODUCTION

1.1 Objectives

Oil generation and migration in the Oriente and Marañon Basin occurred in two main phases each accompanied by a hydrodynamic phase which impacted migration, affected oil quality and caused tilted oil/water contacts. The objective of this study is to model oil migration patterns for the major Marañon Basin reservoirs during both phases.

The presence of a dynamic water flow field in the Oriente Basin in Ecuador has been documented in a recent hydrodynamic evaluation by Rakhit Petroleum Consulting Ltd. (RPCL), and in a number of studies published in the literature. Our investigation shows that hydrodynamic gradients and water flow commenced during Late Andean uplift post-dating peak oil expulsion. Present day hydrodynamic influence has been documented at a number of Cretaceous oil fields. Many major pools in Ecuador (Sacha) are shifted from the structural crests and oil/water contacts are tilted in the direction of water flow (Canfield, 1991).

1.2 Methodology

Petroleum migration modelling and the analysis of potential tilted oil/water contacts is conducted using RPCL’s proprietary “Dynamic Migration Modelling” and “Trap Map” software. The theoretical methodology is based on defining the driving forces behind a particle of water and oil as a series of vectors which resolve hydraulic head, buoyancy and elevation drives. A discussion of the methodology is provided in Appendix A.

1.3 Exploration Applications

There are a number of specific applications of an integrated petroleum hydrogeology study for exploration and production:
Create a coherent hydrogeologic framework for the basin. This provides a three-dimensional picture of flow patterns, recharge and discharge areas and both lateral and vertical pressure profiles.

- Analyse reservoir continuity, which when integrated with geology helps to refine geologic trends, define play fairways and new areas with potential trapping capacity.

- Hydrochemical mapping, maps of formation water salinity and oil quality have applications for analysing areas of recharge, flushing and biodegradation as well as maturity. Formation water data also helps constrain petrophysical parameters for water saturation calculations.

- Petroleum migration modelling provides a means to investigate the pathway that links source areas with known accumulations, by doing which, new unexplored/underexplored fairways may be identified.

- Tilted oil/water contacts, which can result from a dynamic flow system can impact reserves and productivity. An understanding of their occurrence and trend may breathe new life into existing pools or marginally economic pools.

### 2.0 GEOLOGY

The Marañon Basin of northern Peru is classified as a continental cratonic margin polycyclic basin with good to excellent hydrocarbon potential. Current production is exclusively from Cretaceous sandstone reservoirs, which are the focus of this study.

#### 2.1 Regional Setting

The Marañon Basin is one of a chain of sub-Andean basins that extend along the eastern flank of the Andes from Venezuela in the north to the southernmost tip of South America. The Marañon basin forms the southern end of the largest basin complex of the sub-Andean trend. The basin extends north into Ecuador and Colombia, where it is named the Oriente Basin and the Putumayo Basin, respectively. Different names across political boundaries are given to these different parts a single Tertiary basinal feature that is completely contiguous between the three countries.
Marañon Basin is flanked by the Santiago and Huallaga basins to the west and by the Ucayali Basin to the south. To the east, the Marañon wedges out against pre-Cambrian Guyana basement shield.

### 2.2 Stratigraphy

The Marañon Basin preserves a long history of deposition and deformation as shown in the stratigraphic column Figure 1. The pre-Cambrian crystalline basement was formed by accretion of continental terrains to the margin of the Brazilian/Guiana shield. The Marañon contains a Paleozoic passive margin succession comprised of marine carbonates and fluviodeltaic clastics. Late Permian/Triassic extension created grabens in which thick Triassic and Jurassic evaporites, marine shales and continental red beds were deposited unconformably on the rifted Paleozoic surface. The Pucara shale, a major source rock that has charged Cretaceous reservoirs in the southern Marañon, was deposited during this time. Following a break in sedimentation due to regional uplift, in early Cretaceous time a major influx of sand eroded from the Guyana shield entered the basin from the east. The basal Cretaceous transgression flooded a surface of peneplaned, block faulted Jurassic rocks and crystalline pre-Cambrian basement. Cretaceous sediments form a westward thickening wedge of fluvial and shallow marine clastics comprising two shale-prone formations sandwiched between three sandstone sequences. The shales include major source rocks and the sandstones form the main hydrocarbon reservoirs. The Cretaceous is overlain by more than 4 km of Tertiary molasse shed from the Cordillera to the west.

### 2.3 Structural Framework

As mentioned previously, the Peruvian Marañon Basin is part of a much larger basin complex (including the Ecuadorian Oriente and the Colombian Putumayo) that is a fairly typical sub-Andean basin. Located at the southern periphery of the overall basin, the Marañon is a 400 km wide westerly dipping frontal monocline, bounded to the east by the Guyana Shield which is onlapped by Tertiary and Cretaceous sediments. The deformed western margin of the basin terminates at the foldbelt bordering the transpressional Santiago and Huallaga basins which contain partially inverted, highly folded and faulted Mesozoic sediments. North of the Santiago Basin in southern Ecuador is the Cutucu Uplift, a fully inverted, fault-bounded Jurassic depocentre which has been uplifted over 4,500 m in places and deeply eroded. Figure 2 is a structural cross-section oriented southwest to northeast through the northern Marañon and Santiago Basins.
Enclosure 1 shows the land surface topography. The land surface over most of the basin slopes gently towards Amazon River with an elevation less than 200 m. The fold belts along the western and southern margins rise abruptly to elevations up to 1,000 m. Cretaceous strata outcrop in the foldbelts and the outcrops are continuous into the basin except immediately west of the Shanusi well where a portion of the outcrop belt is isolated by a backthrust.

The gross form of the whole basin and its margins dates from late Miocene to recent tectonism, although this episode has often been strongly influenced by an inherited grain from as far back as the Paleozoic. Dating of pre-Cretaceous faulting is generally problematic but it seems that much of the pre-Cretaceous sediment was deposited in basins which appear to have persisted until Jurassic times, albeit with intermittent deposition.

Figure 3 shows the location of three sub-basins on the west flank of the Oriente-Marañon that formed oil kitchens in Eocene time. The Napo and Cutucu Basins were fully inverted during Quecha tectonism. The Santiago Basin still exists as a partially inverted “piggy-back” basin on the western flank of the Marañon (see Figure 2).

The structural analysis of Peru including the Marañon basin has been described in detail by A. Tankard (2001) in a proprietary report titled: “Tectonic Framework of Basin Evolution in Peru.” Fluid flow can be modified by fault systems and whether fault systems are open or closed to fluid flow depends on the prevailing stress field. Reconstruction by Tankard (2001) shows a right lateral (dextral) stress regime for the Marañon Basin in late Cretaceous-Tertiary time with compression oriented north-northwest to south-southeast and extension oriented almost east to west. Shear Riedel orientations are northwest to southeast (antithetic Riedel) and northeast-east to southwest-west (synthetic Riedel).

Most of the hydrocarbons in the Marañon basin are trapped in northwest to southeast trending structures. These structures are aligned with the antithetic Riedel shear orientation which will allow fluid flow in left-stepping fault transfers and will stop fluid flow in right stepping fault transfers. Some traps in the Dorado area are aligned with north-northwest to south-southeast compression and faults associated with these traps will be sealing. Another important structural area in Block 64 contains the Situche grabens which have undergone a complex deformation history. During Pozo time these extensional grabens were open and allowed fluid flow but current inversion along the
right stepping fault transfers has closed most of these faults. Hence the Situche fault systems may have functioned as conduits at Pozo time, allowing light oils from deep pre-Cretaceous source rocks (possibly the Permian Ene Formation) to migrate up into Cretaceous reservoirs. This could explain the presence of mixed Ene and Chonta oils at Shiviyacu and Capahuiri (GeoMark, 1997), directly updip from the Situche fault systems.

3.0 PETROLEUM GEOLOGY

Oils in the northern Marañon are sourced from the upper Cretaceous, whereas oils in the southern Marañon are from a pre-Cretaceous source (the Jurassic-Triassic Pucara Formation). There have been two phases of generation-migration, a paleo-event that ended in the middle Eocene (Pozo time) and the Quecha event that began in the late Pliocene and continues today. During the paleo-event, oil charged the northern basin from mature source rocks located outside (west of) the present basin margin. Oil also charged the southern basin from the Pucara. Since the late Pliocene, oil has been generated within the northwest Marañon, while gas is being generated from the Pucara in the southern part of the basin. The petroleum systems will be discussed in greater detail in the following sections.

3.1 Hydrocarbon Occurrence

Figure 4 shows the recoverable reserves assigned to the main Marañon Basin oil fields with their discovery dates. The total reserves (Mathalone and Montoya, 1995) are 734 MMBO of which 62% is in the Vivian and 37% in the Chonta. The discovery of heavy oil in Block 67 by Barret in 1998 has added another 150 MMBO recoverable to bring the total to around 900 MMBO. The oil fields and oil shows for each reservoir are shown on Enclosures 4, 5 and 6 discussed below. Oil quality is discussed in Section 5.3 and the oil gravity distribution is mapped on Enclosures 11-13.

3.2 Reservoirs and Seals (Enclosures 2 to 6)

Virtually all the producible oil discovered to date in the Marañon Basin of Peru of Ecuador is trapped in the Vivian and Chonta sandstones. Minor reserves have been discovered in the
Cushabatay at Tambo Sur (4.2 MMBO) and in a basal Tertiary reservoir at the Corrientes field (1.4 MMBO).

The main Cretaceous reservoirs and seals are shown in three maps and two schematic cross-sections on Enclosure 2. As discussed previously, the Cretaceous interval comprises two shale dominated formations, the Raya and the Chonta, sandwiched between three sandstones - the Cushabatay, the Agua Calinete-Chonta and the Vivian. The shales are thickest in the west, thinning and ultimately pinching-out to the east. On the eastern flank of the basin, the entire Cretaceous interval is composed of stacked sandstones that form an effective “sand chimney.” Enclosure 2 illustrates the “charge potential” for different areas of each formation based on carrier bed continuity to the relevant oil kitchen and the presence or absence of seals that effect oil entry into or spillage out of the reservoir. The schematic cross-sections on Enclosure 2 show the potential ‘staircase’ oil migration pathways that occur as oil migrates out from the western kitchens and spills upwards at the seal edges. These schematic cross-sections are included in the report as Figures 5 and 6. Figure 5 shows the northern Marañon where Cretaceous source rocks have provided the main charge. Figure 6 shows the southern basin being charged with oil by pre-Cretaceous source rocks at Pozo time. Cretaceous shales in the southern Marañon seal most of the western basin and fault conduits are required in this region to by-pass the seals. Enclosure 3 shows four west-to-east stratigraphic cross-sections of the Cretaceous section supplied by PeruPetro. Oil shows and reserves have been noted and possible oil migration pathways have been added. Structural dip was down to the west for both the paleo and the present day. Cross-section B-B’ (Enclosure 3a) is in the northern Marañon and cross-sections E, G and H are in the southern part of the basin. Note on Enclosure 3d, that a fault conduit is required somewhere west of the Santa Lucia 2X and the La Fronterra 3X wells to explain the presence of tar staining (evidence of oil migration) in the Vivian sandstone bottom-sealed by thick Chonta shale in these wells.

3.2.1 Cushabatay Formation

Present day structure on the Cushabatay is shown on Enclosure 4. The Cushabatay outcrops along the west and south basin margins. In the northeast the reservoir is 2,000 m deep, and reaches over 5,000 m depth adjacent to the Santiago Basin. The Cushabatay has not been mapped in the northwest, in Block 64 possibly because the sand is thin/non-existent. The Cushabatay basal transgressive sandstones have a variable thickness, being about 200 m thick.
in the northwest Marañon (Chapuli 1X), and thinning to zero over Pre-Cambrian highs in the northeast (e.g., Dorado-1X) but exceeding 500 m in outcrop in the south at the Cushabatay Hills. Porosity varies between 10 and 22% and permeability is moderate to good. High gas flow rates have been obtained in the Uyacyali Basin and the Cushabatay equivalent (Hollin Formation) in the Ecuadorian Oriente Basin is a major reservoir with excellent water drive and permeability in the 1-10 Darcy range. The Cushabatay is top sealed by the Raya Formation which thickens in the west. Raya shales are effective seals despite being locally interbedded with siltstones and sandstones. The extent of the Raya Formation seal edge is shown on Enclosure 2a.

3.2.2 Agua Caliente Formation

The Agua Caliente Formation sandstones are commonly thickly bedded with porosities up to 25% and variable but locally high permeability. Agua Caliente sandstones are top-sealed by lower Chonta shales. No significant oil reserves have been found in the Agua Caliente in the Marañon Basin and this formation has not been analysed in this report. It is possible that the top seals are weak and that oil migrating through the Agua Caliente has generally spilled upwards into the overlying Chonta sandstones.

3.2.3 Chonta Formation

Present day structure on the top Chonta sandstone is shown on Enclosure 5. The shale-prone Chonta Formation was deposited during the greatest marine transgression of the Cretaceous. The base of the formation contains multiple sandstones, generally less than 100 m thick, which thin to the west. Unlike the Cushabatay and Vivian, the Chonta sandstones pinch-out within the basin and are not exposed in the western margin foldbelt. These shallow marine sandstones are sealed by thick and organic-rich Chonta shales (e.g., the Corrientes field with over 140 MMBO recoverable) and/or the tight Chonta limestone (e.g., Dorissa field) which is present only in the northwest Marañon. The lowest sandstone (Cetico member) extends further west than the upper sand and its limit is shown on Enclosure 2b. In the southwest, Marañon the Chonta comprises over 450 m of shale (Shanusi 2X). The Corrientes field hosts over 140 MMBO of recoverable oil reservoired in the upper and lower Chonta sands (the Pona and Cetico members) where porosities are about 22% and lateral permeability up to 1,000 md. Chonta sandstones host over 30% of the oil reserves.
discovered to date in the Marañon (270 MMBO recoverable). The eastern edge of the Chonta seal (thick shale and/or Chonta limestone) is shown on Enclosure 2b.

3.2.4 Vivian Formation

Present day structure on the top Vivian sandstone is shown on Enclosure 6. The Vivian Formation is a widespread reservoir interval in the Marañon with both shorezone and fluvial depositional environments recognised. Fluvial sandstones dominate in the northeast passing into marginal marine deposits in the west. The sands were deposited during a major regression following the Chonta highstand at which time the Marañon region was an arid alluvial plain. Over most of the Marañon Basin, the Vivian comprises two sandstones separated by a shale up to 25 m thick. The shale thins and pinches out in the eastern sand chimney. The upper and lower Vivian sandstones each range in thickness between 20 m and 100 m and are generally homogeneous with excellent reservoir quality and high recovery factors. Permeability is generally very high, commonly over 1,000 md, and the sandstones form a continuous aquifer over the basin. The Vivian sandstones are sealed by Cretaceous or Tertiary shales and are thus the highest sealed reservoir in the Cretaceous. The Vivian sandstones consequently host over 60% of the reserves discovered to date (459 MMBO). The largest oil field is Capahuari Sur in Block 1-AB with recoverable reserves of 141 MMBO.

3.3 Source Rocks

There are two main oil families in the Marañon Basin related to distinct source rocks. Oils in the northern Marañon are typed to upper Cretaceous source rocks, whereas oils in the southern Marañon were generated by a pre-Cretaceous source rock. In the literature, opinions differ as to whether the pre-Cretaceous source is the Jurassic-Triassic aged Pucara, or the Permian Ene Formation. A recent reassessment of the basin geochemistry performed for PeruPetro (Chem Terra, 2000) favours the Pucara. The two families are geographically separate. No Cretaceous sourced oil is known to the south of the Pavayacu field and no pre-Cretaceous sourced oil is found north of Pavayacu (Gary Wine pers. comm.). With the possible exception of a group of oils in Block 1-AB that exhibit mixing with a local pre-Cretaceous (Ene?) source (GeoMark, 1997).
Upper Cretaceous shales, rich in oil-prone Type II kerogen, were deposited in a restricted seaway that extended from the Caribbean coast to the Ecuador-Peru border. In the Marañon Basin, the Raya and Chonta Formations (equivalent of the Napo Formation of Ecuador and the Villeta Formation of Colombia) contain the main oil prone shales with up to 2-4% TOC in the northwestern corner of the basin only (including the present-day Santiago Basin). To the east and south the kerogen changes to Type III and the organic content falls off rapidly since the shelf setting in which these formations were deposited shoals and a terrestrial character develops.

Fortunately, in the southern Marañon, where the Cretaceous source rocks are absent, the Pucara source rock is well developed. The Pucara Formation in Peru contains organic-rich shale and limestone intervals interbedded with non-source platform facies. Individual organic-rich units thicker than 50 m are exposed in the Cushabatay Mountains where the Pucara Formation is over 1,000 m thick (Mathelone and Montoya, 1995). Source rock samples from outcrops between the Santiago and Huallaga Basins have been extensively analysed and TOCs over 8% have been measured. The Pucara has been penetrated by three wells in the southwest Marañon. Barren evaporite-red beds and tight carbonates were encountered in the Orellana and Loreto wells. The Shanusi-2X well, further west, intercepted gas-charged porous intratidal carbonates. Kerogen samples from this well yielded 6% TOC (PeruPetro). Three oil seeps in this area have been typed to a Pucara source. Extrapolating the results from these three wells, the Pucara source rock is inferred to occupy a narrow band parallel to the fold belt along the western margin of the basin. The source rocks and kitchen outlines are shown on Enclosure 7.

Other intervals in the Marañon Basin with source potential are discussed by Aleman et al. (1999) and Mathelone and Montoya (1995), but are not considered here.

3.4 Oil Generation, Migration and Entrapment

Dashwood and Abbots (1990) presented structural and geochemical data to support the major phase of oil charge to the Oriente Basin at early Andean time (Paleocene to Oligocene). They argued that since the oil in Ecuador is typed exclusively to Cretaceous source rocks which are largely immature or marginally mature within the present confines of the basin, that the main phase oil kitchen was located west of the present basin (see Figure 3). The western paleo-oil kitchen was uplifted and eroded during Quechua tectonism. Aleman et al. (1999) confirm the existence of a
paleo-western oil kitchen and present evidence that charge to the Marañón-Oriente Basin from this kitchen ended in the middle Eocene. Apatite fission track data indicate that the initial phase of uplift of the Cutucu and Napo highs was during the Incaic inversion in the middle Eocene at around 40 Ma (see their Figure 10). Since these initial uplifts created a barrier between the Marañón-Oriente Basin and the western oil kitchen, this date fixes the effective end of main phase paleo-charge at approximately 40 Ma. This corresponds to the age of the Top Pozo Sand which is the marker used for our paleo-reconstruction. Basin modelling (PeruPetro, 2002) indicates that the Pucara source rock in the southwest Marañón was thermally mature at Top Pozo time and was charging the southern part of the basin with light oil. Figure 7 (PeruPetro, 2002) shows a burial history curve for the Piuntza 1X well in the Santiago Basin. The Chonta enters the oil window at 40 Ma and provided charge to the Marañón at this time.

During Quecha tectonism as the western paleo-kitchen was inverted and destroyed, deep burial occurred in the subsiding Marañón Foreland. This burial brought the Raya-Chonta source rocks in the northwest depocentre into the oil window and the Pucara source rock in the south into main gas generation.

In summary then as indicated by basin modelling (PeruPetro, 2002) the petroleum kitchens that have charged the Marañón Basin are:

At Pozo Time:

- In the northwest Marañón, Raya-Chonta source rocks only attained marginal maturity (c. 0.5 % Ro). Main phase oil charge originated from the “Quito paleo-kitchen” to the west.

- In the southwest Marañón, Pucara source rocks were in the late-mature oil window (1.0 to 1.3% Ro).

At Present Day:

- In the northwest Marañón, Raya-Chonta source rocks are in the mid-mature oil window (0.7 to 1.0% Ro).
• In the southwest Marañón, Pucara source rocks are in the Main Stage Gas Generation window (1.3 to 2.6% Ro).

The charge events are summarised on Figure 8. The second phase indicated on Figure 8 relates to the Oriente and Putamayo Basins and is not considered significant for the Marañón. Thus our paleo modelling focusses on the first phase of Pozo time and the third phase (late Miocene to present-day).

4.0 HYDRODYNAMICS

The Marañón Basin of Peru contains significant volumes of oil trapped in the Cretaceous Chonta and Vivian sandstones. Much of this oil migrated from western mature source rocks prior to the late Andean tectonic events. The late Andean tectonic episode has severely altered the structural and hydraulic regimes for the Cretaceous reservoirs, resulting in the remigration of trapped oil, the generation of tilted oil/water contacts and the degradation of shallow oil.

4.1 Hydraulic Continuity

Figure 9 is a pressure versus elevation graph for all pressures from Cushabatay, Agua Caliente, Chonta and Vivian sandstones demonstrating their regional hydraulic continuity throughout the basin. To subsea depths exceeding 4,800 m (16,000 ft), formation pressures cluster near a regional water gradient. This indicates good regional scale permeability in the sandstones and confirms their capacity to function as long-distance carrier beds for oil migration. Figure 10 shows pressure versus elevation graphs for the Cushabatay and Agua Caliente individually against the background of all data. Figure 11 shows Chonta and Vivian pressures in the same fashion.

Closer inspection of the Vivian pressures reveals subtly distinct gradients at different depths (Figure 12) for various groups of wells in the basin. The deepest at 4,100 m subsea (13,500 ft) is slightly overpressured relative to the regional gradient and is defined by the Huasaga, Sungachi, Ungumayo and Pauyacu wells located near the western basin margin. These high pressures at great depth reflect the high elevation of the water table in the adjacent elevated Vivian outcrop belt. The high pressure is transmitted into the basin via active freshwater influx through the Vivian...
aquifer. A second distinct gradient is defined at subsea depths between 1,200 m and 1,500 m (4,000 to 5,000 ft) by the Arabela well located in the extreme northeast of the basin. This gradient is slightly high relative to the regional trend indicating weak water flow into the basin from the east. There is a significant pressure drop between the Arabela and the Paiche well continuing to decrease to Bartra and Tigre. These pressure differences when converted to hydraulic head and mapped as a potentiometric surface for the Vivian Formation, reveal an extensive linear trough of low pressures along the eastern flank of the basin. Water flow converges into this trough from both the west and the east. Since there are currently no elevated uplands east of the basin to provide a drive for flow, we interpret the Arabela-Paiche high as a relict (paleo) flow system. Recharge probably dates from the period immediately after the Incaic tectonic phase of compressional deformation in early to middle Eocene time (see Figure 1). During Incaic compression the entire Marañon-Oriente-Putamayo region was uplifted and a swathe of lower Eocene and Paleocene clastics were eroded. When sedimentation resumed, the Pozo Formation was deposited. A sandstone and tuff interval was deposited which is capped by thin marine Pozo shales. This final marine incursion was caused by accelerated erosion of the rising Cordillera and consequent depression of the basin due to the applied orogenic load (Mathelone and Montoya, 1995). At Pozo shale time (late Eocene to Oligocene) then, the Vivian was probably locally outcropping or at very shallow depth below the land surface in moderately elevated uplands on the eastern basin margin with a marine basin to the west and the as-yet low relief mountains of the emerging Cordillera beyond the western horizon. Being at or close to an elevated land surface, the sandstone was recharged with freshwater. Subsequently, the entire Marañon Basin was blanketeted with a thick package of red bed shales and evaporites of the Oligocene to Upper Miocene aged Chambira and Pebas Formations. These tight, fine grained sediments represent molasse shed from the west during the period of relative quiescence prior to the convulsive Quecha inversion in the late Miocene to Pliocene. The shales and evaporites top sealed the whole basin and the high pressures in the Cretaceous sands related to the recharge event were preserved. The maintenance of this relict flow system over the succeeding 40 million years attests to the competence of the Chambira-Pebas seals.

Figure 13 is another pressure versus elevation plot which in this case shows Vivian and Cushabatay data from the Arabela 1X and the Yurimaguas 2-1 wells only. Arabela near the northeastern basin margin is in the region of the Cretaceous “sand chimney” where no substantial shales are present. Here, the pressures at the top and base of the section line up on a single water
gradient indicating vertical pressure continuity. The Yurimaguas well near the western margin, shows a 2,400 kPa (350 psi) break between the Vivian and the Cushabatay sandstones reflecting the presence of thick intervening Raya and Chonta shales.

4.2 Potentiometric Surfaces (Enclosures 8 to 10)

Cretaceous sandstones outcrop at high elevation in the foldbelts along the western and southern basin margins (see Enclosure 1). The Vivian sandstone outcrops in an almost continuous band from the Ecuadorian border in the northwest to the Brazilian border in the southeast, at elevations ranging from 600 m to 200 m. The Chonta sandstone outcrops only in the southern uplands, east of the Rio Ucayali at 200 m and the Cushabatay outcrops at 1,000 m in the Cushabatay Hills and at lower elevations further north. The high elevation of the water table in these outcropping sandstones provides the drive for active recharge (water intake), which penetrates deep into the basin. Enclosure 8 shows the potentiometric surface for the Cushabatay. The contours indicate strong flow in the Cushabatay aquifer into the Marañon Basin from the western and southern outcrops. This is fully consistent with the flow pattern of the Hollin in the Ecuadorian Foothills where recharging freshwater and consequent hydrodynamic tilting of oil/water contacts have been documented at Sacha and Bermejo Sur. Pressure data in the east is sparse but seems to indicate a flow reversal related to weak recharge from the east. This weak easterly flow creates linear zone of flow convergence parallel to the eastern flank of the Marañon Basin.

The Chonta sandstone (Enclosure 9) shows a similar flow pattern but lacks the strong drive from the west since the Chonta sands pinch-out into thick shale at least 100 km east of the western foldbelt. Only Chonta shales outcrop in the west. Hence, flow in the Chonta is funnelled north from the southern outcrop region.

The hydraulic head regime for the Vivian (Enclosure 10) is very similar to the Cushabatay and confirms the regional flow pattern with more abundant pressure data. As discussed in the previous section, the weak flow from the east is interpreted to be paleo-flow dating from Eocene exposure of the Cretaceous sandstones associated with the Incaic tectonic event.

It is important to note that RPCL uses Dynamic Water Migration Modelling to determine water flow directions. This process uses hydraulic head in combination with water density and structural dip
of the carrier bed to determine a valid potential for water flow in a formation with variable water salinity. Freshwater hydraulic head maps do not account for differences in water density, thus they may not accurately depict water movement. The density of the water is important because more energy is required to drive a heavy brine updip than freshwater. High density brine can actually flow downdip against a weak updip hydraulic head gradient. (See Appendix A for a further description of water flow modelling). The water force vectors for the Cushabatay, Chonta and Vivian Formations are shown on the tilted oil/water contact maps.

4.3 Formation Water Salinity and Oil Gravity (Enclosures 11 to 13)

Salinity distribution in the Cushabatay, Chonta and Vivian sandstones clearly reflects the dynamic mixing of fresh meteoric water with older brines. Cushabatay formation water (Enclosure 11) changes systematically from a dense brine with 200,000 ppm total dissolved solids in the central basin (Chambira region) to freshwater with less than 10,000 ppm at the southern and western basin margins. There is also a freshening trend to the east. Recharging freshwater has diluted the original brine and the present day flow prevents the residual heavy brine from moving downdip down to the depocentre in the west. The brine probably originated from dissolution of Triassic salt, which is present today only in the Huallaga Basin. The brine was driven into the overlying Cretaceous aquifers presumably along faults by a combination of compaction and tectonic squeeze, and then updip laterally into the northern Marañon and the southern Oriente in Ecuador. Oil gravity in the Cushabatay (also shown on Enclosure 11) ranges from 45 to 34 API. The contours are based on samples from the only five wells in the basin which have tested oil in the Cushabatay. The lightest oils are in the west (Tambo Sur, Huasaga and Pauyacu) and are associated with relatively high salinity formation water.

Chonta formation water (Enclosure 12) shows a similar trend to the Cushabatay with 200,000 ppm brine located in the basin centre, freshening to the north, the south and the east. The dilution is less marked than in the Cushabatay probably due to the lower permeability and the more heterogeneous character of the Chonta sandstones. Oil gravity in the Chonta (also shown on Enclosure 12) ranges from 10 to 44 API. The heaviest oils are in Block 64 in the northeast (Dorado, Paiche and Pirana) where they are associated with the freshest water. The lightest oils extend in a narrow linear trend from Valencia and Nueva Esperanta to Dorissa and are associated with relatively saline formation water.
Vivian formation water (Enclosure 13) shows a very similar trend to the Cushabatay with 200,000 ppm brine located in an updip location near the basin centre, freshening in all directions, particularly towards the western and southern foldbelts. The most saline water is located further south than in the Cushabatay, probably reflecting the slightly weaker head gradient in the Vivian (the Cushabatay outcrop is higher than the Vivian outcrop, hence the head drive in the Cushabatay is stronger). Oil gravity in the Chonta (also shown on Enclosure 13) ranges from 10 to 44 API. The heaviest oils overlie the heavy Chonta oils in Block 64 (Dorado, Paiche and Pirana). In the Vivian reservoir, the heavy oil trend extends further downdip to include Forestal, Shiviyacu and Jibarito in Block 1-AB (maximum 20 API). South and west of Jibarito there is a very abrupt jump from less than 20 API to 30 API and higher. For example, Jibarito (14 API) and Ceci (42 API) are only 20 km apart and Hauyuri Norte (18 API) and Hauyuri Sur (29+ API) are just 6 km apart. Assuming there is no obvious geological cause for this transition, it may reflect a biodegradation front; perhaps a temperature control.

Figure 14 shows the average oil gravity for oil in Chonta and Vivian reservoirs at all oil fields that have pay in both reservoirs. Usually the Vivian oil is heavier. This presumably reflects the shallower burial depth of the Vivian (especially at Pozo time) as well as the higher permeability and lateral continuity of the Vivian reservoir which allowed more efficient invasion of the reservoir by freshwater and hence a greater degree of biodegradation. Figure 15 shows a gas chromatograph for Vivian oil from the Jibaro field (Higley, 2001). This sample indicates that an early oil trapped at Jibaro was biodegraded and a later pulse of oil remains unaltered.

4.4 Observed Tilted Oil/Water Contacts

Numerous oil fields in the Marañon Basin, have been mapped with tilted oil/water contacts in both Chonta and Vivian reservoirs (PlusPetrol). Corrientes, the largest Chonta oil field in the basin (142 MMBO recoverable) has an oil/water contact tilted at 8.8 m/km (47 ft/mile) southwest in the Cetico based on virgin oil/water contact elevations observed in early exploration wells (Figure 16). The main Shiviyacu field (the second largest Vivian oil field in the basin) has a mapped oil/water contact slope of 3.9 m/km (20 ft/mile) to the southeast (Figure 17).

Other Chonta fields with documented tilted oil/water contacts include:
The Dorissa field is shown to have a basal Chonta sand oil/water contact in the south that is 9 m (29 ft) deeper than in the north. This may indicate the presence of two separate pools or it could reflect a hydrodynamic tilt of a continuous oil column.

In Vivian reservoirs, documented tilted contacts occur at:

- Shiviyacu
- Forestal
- Jibaro-Jibarito
- San Jacinto
- Valencia/Neuva Esperanza
- Capahuari Norte

The mapped tilt directions and slopes will be compared with our modelling results.

### 5.0 DYNAMIC MIGRATION MODELLING

#### 5.1 Theory

Dynamic oil migration modelling is a technique used by RPCL to predict potential migration routes of oil (see Appendix A for details). Oil migration forces are controlled primarily by the buoyancy force of the oil and the direction and strength of hydrodynamic flow. For example, in the absence of any hydrodynamic forces, oil would simply migrate up structure (updip). The presence of flowing water can aid, hinder or deflect this updip buoyancy force and hence can greatly impact the migration routes of oil. Water flowing updip assists the buoyancy-driven migration of oil, since both forces are parallel. This can have a negative effect on oil in structural traps, because a strong
hydrodynamic force can flush them out. Downdip flow is working in the opposite direction to the oil buoyancy and therefore can be beneficial. Hydrodynamic forces that are sufficiently strong can impede the updip migration enough to create traps (hydrodynamic trapping). Water flow occurring at angles to the buoyancy force can divert the oil migration route. When flow and/or structural focussing are favourably combined, this creates focussed zones of oil migration and accumulation.

The RPCL methodology, by mapping structure, hydraulic head, water density and oil density in the reservoir, together with knowledge of the locations of mature, oil-prone source rock regions, calculates the migration routes for expelled oil. The resulting maps use vector arrows to depict the force (calculated from above mentioned parameters) acting on oil of a specified density at that node point. By following these force vectors, pathways of potential oil migration can then be traced out as migration lines. These lines simply represent the total migration pathway for the oil constrained by the series of force vectors encountered.

Migration modelling accuracy is strongly dependant on a detailed understanding of the timing of source rock maturation, structural evolution and the evolution of water flow patterns. The Marañon-Oriente-Putumayo Basin experienced main phase oil generation during the late Cretaceous to middle Eocene, long before the late Andean structures formed in the Miocene-Pliocene. Much of the early oil remigrated, and by studying both the past and the present migration patterns, new exploration leads may be developed.

It should be noted that permeability variations in the carrier bed/s were not available for this study and hence the possible impact of permeability on oil migration patterns has not been addressed.

5.2 Paleo-Migration Modelling (Enclosures 14 to 16)

As previously discussed, it is generally agreed that much of the oil in the Marañon-Oriente Basin was generated in pre-Quecha time (pre-Miocene). Since the present structural form of the basin dates from Quecha time, paleo-migration pathways were controlled by a very different structural configuration and a different hydrodynamic regime than at present. By mapping paleo-structure and reconstructing the paleo-water flow pattern, the present study attempts to model the paleo-oil migration pathways in the Marañon Basin. Potential oil traps at paleo-time may be identified and
the remigration of oil from those paleo-traps can be analysed for present-day conditions. In this way, we may identify oil migration fairways that are otherwise undetectable.

RPCL’s analysis of paleo-oil migration at top Pozo time is presented as a montage of maps for each reservoir: structure, salinity, hydraulic head and the resulting paleo-dynamic oil migration map.

We have modelled 40 API oil to represent the light oil expelled from both the Pucara paleo-kitchen in the south and the western Chonta/Napo paleo-kitchen that charged the northern basin. Modelling work done for PeruPetro (Chem Terra, 2000) indicates that the Pucara was in main stage oil generation at Pozo time with Ro close to 1.0% and a similar level of maturity is assumed for the Cretaceous source rock west of the northern basin.

Paleostructure maps for the three Cretaceous reservoirs were created for this study by PeruPetro using two structure maps, based on seismic mapping tied to well control: the top Pozo Sand and the base Cretaceous. Isopach maps were also generated for the intervals from base Cretaceous to the three reservoir tops based on well control. Pozo structure was subtracted from the base Cretaceous (effectively pulling the base Cretaceous up, by flattening the Pozo) and then adding each requisite isopach to generate paleostructure on each reservoir top. Paleo salinity was very high as indicated by the residual brine that presently occurs in all three reservoirs (see Enclosures 11-13). The brine originated by dissolution of evaporites in the Huallaga and Santiago Basins, which must have been displaced into the Marañon at Pozo time.

The paleo-hydraulic head maps were created by maintaining the head gradient on the eastern basin flank and calculating the head gradient required to drive brine up the paleo-dip from the west. Tectonic compression and shale compaction are the presumed driving forces for this updip head gradient.

5.2.1 Cushabatay Formation (Enclosure 14)

Enclosure 14 is a montage showing paleo-structure, paleo-hydraulic head, paleo-salinity and paleo-oil migration for the Cushabatay. Enclosure 14a shows the paleo-structure sloping down to the southwest with the deepest area north of Yuramaguas at -2,750 m subsea. The eastern shelf area
was relatively flat and very shallow at only 750 to 500 m below sea level. Paleo-dip steepened to the west, continuing to deepen west of the study area. The paleo-hydraulic head map (Enclosure 14b) shows water influx from the southwest driven by compaction and tectonic compression of the thick Cretaceous shales to the west. As discussed previously, considerable tectonic shortening occurred during the Incaic tectonic phase as well as major sediment loading of the basin west of the present margin, which was the cause of the Pozo transgression. Weak paleo-recharge occurs in the east related to paleo outcrop of the Cretaceous sandstones in this direction. The paleo-salinity map (Enclosure 14c) shows high salinity brine in the southwest with freshwater in the northeast.

Enclosure 14d shows that paleo-oil migration in the Cushabatay was directed generally toward the northeast from both the Pucara and the Chonta paleo-kitchens. Our analysis of the migration pattern ends at zero edge of the Raya shale which is the Cushabatay top seal. Updip of this edge, oil from the Cushabatay spills upward into the overlying Agua Caliente-Chonta sandstones.

In the southern Marañón, Pucara oil potentially accumulated in the zones of oil flow vector convergence (inward-pointing arrows) adjacent to the Orellana, Santa Catalina and especially the Loreto wells. The paleostructure at Loreto focusses the oil flow from a large area downdip into a potential accumulation. Further north Pucara sourced oil converges toward a paleo-high at Santa Martha. However, because this structure is east of the Raya edge the oil probably spilled up into the Chonta.

In the northern Marañón, oil from Cretaceous sources in the western oil kitchen (the Cushabatay, Raya and Agua Caliente, as well as the Chonta all have potential source intervals) formed several potentially large accumulations. The convergence zones north of Huasaga and northeast of Sungachi are the largest. The richest accumulation site with a substantial downdip drainage area is centred on the Ceci and Dorissa wells.

Since the Cushabatay was at shallow burial depth there is a risk of biodegradation at Pozo time especially in the east toward the region of paleo-recharge. Dashwood and Abbots (1990) estimated the maximum depth of bacterial degradation in the southern Oriente Basin as approximately 1,500 m. This depth is identified on our paleo migration maps and there is a risk of biodegradation updip of this line.
5.2.2 Chonta Formation (Enclosure 15)

Chonta paleo-structure (Enclosure 15a) shows a regional southwesterly dip similar to the Cushabatay. There was a potential paleo-outcrop in the extreme northeast (Block 67). Paleo-hydraulic head (Enclosure 15b) shows a paleo-convergence zone caused by downdip freshwater recharge from the northeast and updip compression/compaction drive from the southwest. The updip head drive is weaker than for the Cushabatay since the Chonta sandstones pinch-out within the basin, so would have had less capacity to gather water in the west. Paleo-salinity (Enclosure 15c) in the Chonta shows brine freshening updpip to the northeast.

As shown on Enclosure 15d, in the southern Marañón the basal Chonta sandstone pinches out 25 to 100 km updpip of the Pucara source rock, and the Raya shale functions a bottom seal over the entire western basin. These factors present an obstacle for Pucara oil to access the Chonta in the southern Marañón. East of the Raya shale edge, Pucara sourced oil could spill from the Cushabatay into the Chonta (via the Agua Caliente). The potential entry points for oil spilling into the Chonta from the Cushabatay are indicated on Enclosure 15d. Overlying the basal Chonta reservoir sands, the Chonta Limestone and the “Thick” Chonta Shale provide obvious top seals. The limits of these seals are shown on Enclosure 15b. Immediately updpip of these edges, the Chonta section is a complex mix of interbedded sandstones and thin discontinuous shales. Clearly, these discontinuous shales can form locally competent seals since Corrientes (the largest Chonta oil field yet discovered in the basin) is within this zone, but the possibility of spillage up into the Vivian also exists in this belt. The combination of subdued paleo-dip and downdip water flow along the eastern shelf area retarded updpip migration and our analysis suggests that oil did not migrate much further east than the thick Chonta shale edge.

Potential paleo-traps in the southwest Marañón occur near Santa Lucia, Pastacocha, Santa Martha, Samiria Sur and La Frontera. These paleo-traps are all located east of the Raya edge and may have been charged via spill from the Cushabatay carrier bed. The potential accumulation at Ungomayo further west overlies the Raya shale so there is a risk of no charge.

In the northern Marañón, there was also a charge issue at Pozo time, since the Chonta sandstone pinches-out 50 km updpip of the present basin margin, hence a considerable distance from the paleo-oil kitchen. The Chonta reservoir was only 500 m deep in the northwest Marañón at Pozo
time so local Cretaceous source rock was immature. The Situche fault system may have functioned as a conduit for deeper, fully mature pre-Cretaceous source rocks. Some geochemical studies have suggested that Shiviyaçu and Capahuari Sur oils (Vivian reservoir) are derived from a mix Chonta and Ene sources. Migration mapping indicates that one potential paleo-trap for mixed oil occurred in the area between Yanez and Capahuari. Another paleo-trap occurred at the end of a narrow migration fairway at Ceci. Additional traps formed at Sanguchi and just west of the Tancheplaya well. Very little oil migrated east of the thick Chonta shale edge, so minor spillage from the Chonta into the Vivian occurred at Pozo time. Notably, apart from the fairway charging Ceci, no oil migrated into Block 1-AB.

5.2.3 Vivian Formation (Enclosure 16)

Enclosure 16a shows that at Pozo time the Vivian, like the deeper reservoirs, was essentially flat-bedded on the shallow eastern basin flank, with steeper dips to the west culminating in a depocentre north of Yurimaguas. The Vivian reservoir outcropped in the northeast and the southeast where paleo-recharge occurred. The paleo-head map (Enclosure 16b) and paleo-salinity map (Enclosure 16c) show patterns very similar to the Cushabatay.

Paleo-oil migration patterns are shown on Enclosure 16d. Regarding charge potential in the southern basin, both the Raya and the thick Chonta shale exist as vertical seals between the Vivian and the Pucara oil kitchen. Vivian sandstones extend to the western basin margin though and may have been charged from the Pucara by early faults in the west. As discussed in the previous section, little oil spilled from the Chonta into the Vivian.

Regarding paleo-traps in the southern basin, as for the Chonta reservoir, the largest paleo-prospect in the Vivian is at Santa Martha. Further south, a paleo-oil fairway focussed by the paleo-structure at Loreto ends in a trap near the Samiria Sur and Zapota wells.

In the northern Marañon, the Vivian probably extended far enough west to be charged directly by the underlying Chonta shale in the western paleo-kitchen. A large potential paleo-accumulation site occurs in the Dorissa-Ceci region at the southwest corner of Block 1-AB. A smaller accumulation lies west of Tuncheplaya. A prospective fairway with potentially mixed Chonta and Pucara sourced oil runs from Limonyacu to a potential accumulation site near the Intuto well in the
east between blocks 25 and 26. Finally, again the Situche graben faults potentially allowed pre-Cretaceous (Ene?) sourced oil to charge the Vivian in Block 64, and this oil mixed with Chonta oil, potentially accumulated in the region southwest of Capahuari just west of Block 1-AB.

5.3 Present-Day Migration Modelling (Enclosures 17 to 28)

Our analysis of current oil migration patterns is presented as a series of migration maps and tilted oil/water contact maps for the Cushabatay, the Chonta and the Vivian. For each reservoir, the present-day structure, salinity and hydraulic head maps were used to generate dynamic oil migration maps as discussed in Appendix A. Two simulations were run for each reservoir using a 40 API oil to simulate light oil and a 15 API heavy oil. The Pucara source rock in the southern Marañon is currently expelling gas and the Cretaceous source rocks in the north are expelling light oil.

5.3.1 Cushabatay Formation (Enclosures 17 to 20)

Enclosures 17 and 18 show the present-day migration pattern and tilted oil/water contacts for the Cushabatay for 40 API oil. This is the correct map to use, given the observed high gravity of Cushabatay oil shows to date. Enclosures 19 and 20 show the potential migration pathways and tilts for heavy (15 API) oil. Since there is no evidence of heavy oil in the Cushabatay, Enclosures 19 and 20 will not be discussed further. The light green flowlines shown are Enclosure 17 are for “young” oil generated in the present-day oil kitchen and the dark green flowlines are for “old” oil remigrating from the Pozo time paleo-accumulation sites.

In the southern Marañon the paleo-accumulations in the Orellana region were lost to outcrop as the southern foldbelt formed. The strong buoyancy of the oil drives it up the very steep updip tilts to outcrop overcoming the down dip water flow. However, the paleo-accumulation further north at Loreto potentially remains trapped within the much larger dome that formed during the Quecha inversion. The small capacity of the paleo-structure means that the Loreto Dome is currently underfilled in the Cushabatay reservoir and the current hydrodynamic flow has shifted the “old” oil onto the northeastern flank. Enclosure 18 shows tilt magnitudes of 6-8 m/km down to the east in this area. Figure 24 shows how this oil could now be located offset from the structural crest penetrated by the Loreto 1X well. This could explain the lack of oil shows in the Loreto 1X well.
since it did not penetrate the oil column which is located in hydrodynamic equilibrium on the northeastern flank.

In the northern Marañón, the “old” oil trapped at Pozo time in the three paleo-accumulation sites described in the previous section, potentially migrates updip mixing with new oil generated from the present Chonta oil kitchen. All of this oil migrates across Block 1-AB to the Raya shale edge southwest of the Arabela well. A major oil fairway is indicated here focussed into a narrow spill point providing charge to the overlying Chonta Reservoir.

5.3.2 Chonta Formation (Enclosures 21 to 24)

Enclosures 21 and 22 show the present-day migration pattern and tilted oil/water contacts for 40 API oil in the Chonta. Enclosure 21 includes analysis of the remigration of oil trapped at Pozo time.

In the southern Marañón there is a potential trap due south of La Fronterra where the oil trapped at Pozo time north of Santa Lucia has remigrated to. Present-day recharge from the southern fold belt creates downdip tilts of c. 2 m/km that have a constructive impact in this region. This potential accumulation site is shallow and there is a risk of biodegradation. Other paleo-accumulations, at Pastacocha, Ungomayo and Santa Martha, remigrate updip to the east. Notably, the Santa Martha remigrated oil is driven in a fairway that includes Corrientes. Other potential present-day traps occur at Otorango, south of Arabela and at Cunamba on the Ecuadorian border in Block 39. Enclosures 23 and 24 show migration patterns and oil/water contact tilt magnitudes and directions that are relevant to the heavy oils in the northeast.

5.3.3 Vivian Formation (Enclosures 24 to 28)

Enclosures 25 and 26 show present-day migration patterns and oil/water contact tilts for the Vivian. Potential traps occur in some of the same locations as for the Chonta: south of La Frontera, at Otorano and south of Arabela. The first two locations have little oil charge in the Vivian, but the structure near Arabela receives focussed charge from a fairway that gathers oil from virtually the entire present-day oil kitchen in the northwest. the Loreto dome has possible oil potential (charge risk) and should presently be receiving gas from the adjacent Pucara gas kitchen. Enclosures 27 and 28 are relevant to the heavy oils in the northeast basin.
6.0  CONCLUSIONS (Enclosures 29 to 32)

The three summary maps clearly illustrate that the northern basin has received more oil charge than the south. In the north, there were two phases of direct oil charge from source rocks at the same stratigraphic level as the reservoirs. The present oil kitchen occupies the northwestern depocentre. In addition, the Situche grabens potentially provided extra vertical light oil charge from a pre-Cretaceous source at Pozo time. Migration pathways are generally direct and relatively short. Although some of the Pozo-time oil was biodegraded, the present day oil kitchen has charged reservoirs that are deep and hot which has probably protected the “young” oil from biodegradation.

In the south on the other hand oil charge occurred only at Pozo time and from a source rock that is isolated from the Chonta and Vivian reservoirs by thick Cretaceous shales. Long-distance migration pathways are needed in the Cushabatay as a carrier bed, to bypass the overlying seals and spill up to the Chonta and Vivian. The basin was shallow at Pozo time so there is a risk of biodegradation. There has been no recent oil charge, since the Pucara source rock is now in the gas window. The location of the narrow Pucara gas kitchen close to the western margin probably means that this gas has largely been lost to outcrop which would explain the paucity of gas recoveries from wells in the southern basin. On the other hand, there may be large, as-yet undiscovered gas reserves.

Figures 18 and 19 are schematic cross-sections that summarize the petroleum hydrogeology of the basin at Pozo time (Figure 18) and at present-day (Figure 19). Figure 18 shows freshwater recharge in the east through the paleo “Vivian Uplands” and brine flow being driven out of the Santiago Basin in the west by sediment compaction and tectonic compression. Oil expelled out of the western oil kitchen (in the northern Marañon) migrates through carrier beds and via faults to charge the Chonta, which does not extend far enough west to be charged by the oil kitchen directly. The extensive zone of potential biodegradation is shown in the east. Figure 19 shows the basin configuration after the Quecha Inversion of the Santiago Basin and formation of the high elevation outcrop belt in the west. Now the basin hydrodynamics change with strong recharge in the west.

Figure 20 shows regional horizontal gradient maps of the base Cretaceous structure at Pozo time and at present-day. The structural hinge line of the basin has sifted northeast since Pozo time.
Figure 21 shows the paleo and present-day hydraulic head maps for the Vivian, superimposed on the same horizontal gradient maps. Interestingly, the flow convergence zone both at paleo time and present-day is east of the hinge line. The structural flexure may represent a barrier on a regional scale that has helped preserve the low pressure convergence zone and may play a role in trapping oil moving updip from the west.

Figures 22 to 24 are cross-sections illustrating the potential for oil accumulation in the southwest Marañón, in the Marañón 1X area of Block 27, at Yurimaguas and Loreto. The former areas have a negative prognosis.

The structural dip of the huge Quecha structures is extreme, resulting in very strong buoyancy drives for updip migration along the basin margin.

Figure 22 shows the steep dip of the Cretaceous Reservoirs at the southwest basin margin. Calculated tilts are too small to trap oil in this region, given the extreme inclination of the beds at the basin margin.

Figure 23 shows the Yurimaguas structure. The 1X well confirms that the structural crest is wet. Dip magnitudes for light oil are too small to generate prospects on the north flank in either the Vivian or the Cushabatay.

Figure 24 shows the Loreto structure. Assuming any oil in this area will be light oil (Enclosure 14d indicated potential paleo-charge of 40 API oil in the Cushabatay) the oil/water contact will slope at 7 m/km to the east. From the cross-section it is clear that even though the Loreto well proves the crest of the structure is wet, there is scope for a substantial accumulation on the flank. Quick calculation indicates “space” for a pool 8 km long that could contain around a billion bbls of oil.

Table 1 shows observed versus predicted tilts for all Chonta and Vivian oil fields with mapped oil water contacts that were supplied to us by PeruPetro. The agreement is excellent for Corrientes in the Chonta) and good for Shiviyacu in the Vivian. Five fields have reasonable agreement, e.g., the Chonta oil/water contact at Carmen is flat according to Plus Petrol where we predict generally small tilts (c. 2 m/km) and variable tilt directions. Five fields have poor agreement, e.g., the
oil/water contact in the Vivian at Capahuari Norte is mapped tilting at 10 m/km to the southeast and northeast, where we predict only 2 m/km to the northeast.

It must be stressed that the present study is regional in scope and that any individual field must be analysed at the local scale to fully evaluate the hydrodynamic impact.

6.1 Cushabatay Formation

The main migration fairways are identified on Enclosure 29.

6.2 Chonta Formation

The main migration fairways are identified on Enclosure 30.

6.3 Vivian Formation

The main migration fairways are identified on Enclosure 31.
7.0 REFERENCES


GENERALIZED STRATIGRAPHIC COLUMN

MARAÑON/UCAYALI MADRE deUCAYALI TectonicSANTIAGO DIOS Events

Tertiary
Olig
Eoc
Pal

Upper

Upper

Jurassic

Triassic

Permian
Carboniferous

Devonian
Silurian
OrdoVICIAN

Cretaceous

Pre-Cambrian

Corrientes / Marañon
Ipururo
Chambira
Pebas

Pozol
Yahuarango

Vivian
Chonta

Agua Caliente

Chonta

Cushabatay

Grupo Oriente

Sarayaquillo Group

Pucara Group

Mitu Group

Copacabana / Tarma

Ambo
Cabanillas

Ananea / San Gaban

Contaya

Basement

Quechua III
Quechua II
Quechua I

Tectonic Events

Incaic
Peruvian

Nevadian
Triassic Event
Late Hercinian

Chanic
Taconian Uplift

Salt

From Mathalone and Montoya, 1995

OIL
GAS
SOURCE ROCK
Marañon Basin - Santiago Basin
Present Day Structural Cross-Section

Cross-Section supplied by: PERUPEtro
Late Jurassic- Early Cretaceous

"Paleo" Kitchens

Napo Basin
Cutucu Basin
Santiago Basin

ECUADOR
COLOMBIA
PERU

Iquitos
Marañon
R = Recharge

Oriente
Huallaga
Ucayali

R = Recharge

Paleo Oil Kitchens Location Map
(After Tankard, 2001)
Total 734 MMBO: 50% in 3 fields, 62% in Vivian, 37% in Chonta (data from Mathalone and Montoya, 1995)
Northern Marañon Basin

**Kitchens**

1) **Pozo Time**
   The "Quito" Kitchen located west of the northern Marañon expelled oil from Cretaceous reservoirs.

   Possible oil expulsion from pre-Cretaceous source rocks (Ene Shale?). Access to reservoirs via Situche graben faults?

2) **Present Day**
   Cretaceous source rocks expel oil in NW Marañon. Pre-Cretaceous source rocks expel gas but Situche graben faults now closed?
Southern Marañón Basin

Kitchens

No Cretaceous source rocks present.

1) Pozo Time
Pucara shale expels oil in SW Marañón. Older source rocks (eg. Ene Shale?) also effective?

2) Present Day
Pucara shale in main stage gas window. Older sources probably over-mature.

Southern Marañón Basin
Kitchens and Pozo Time Migration

SOURCE / SEALS
Yahuarango Shale

RESERVOIRS
Vivian Sandstone
Upper Chonta Ss (Pona)
Lower Chonta Ss (Cetico)
Agua Caliente Sandstone
Cushabatay Sandstone

Requires Fault Charge

Non-Source Facies
Burial History Graph for the Chonta Paleo Kitchen (After PeruPetro, 2002)

Location of Modelled Wells and Pseudo Wells

Chonta Entering Paleo Kitchens

Santiago Basin

Maturity versus Time Graph in Piuntza IX in the Central Santiago-Nieva Tectonic Depression
Summary
Petroleum Systems
Marañon Basin
Pressure versus Elevation Graph

Regional Water Gradient
Maraño Basin
Pressure versus Elevation Graphs
1. "Paleo" Recharge
2. Flow Convergence
3. Present Day Recharge

Regional Water Gradient

Pressure versus Elevation Graph

-18,000
-16,000
-14,000
-12,000
-10,000
-8,000
-6,000
-4,000
-2,000
0
2,000 4,000 6,000 8,000 10,000

Pressure (psi)

Elevation (ft)
Marañón Basin
Pressure versus Elevation Graph

Different Pressure Gradients Because: Cretaceous Includes Tight Shale and Limestone

Yurimaguas 2-1 Western Margin Well

Arabela 1X Eastern Margin Well

Single Pressure Gradient Because: Cretaceous = Sand Chimney

350 psi Pressure Break
Most Often Vivian Oil is Heavier than Chonta - Due to Higher Permeability (Water Washing) and Shallower Depth (Biodegradation) Exceptions: Neuva Esperanza, pavayacu, and Tigre.
Whole crude gas chromatograph of oil from the Cretaceous Vivian Formation in the Jibaro Field, Marañon Basin (GeoMark, 1997). The hydrocarbon fraction to the right of C$_{15}$ is highly biodegraded. A later phase of migration is indicated by presence of nonbiodegraded C$_1$ to C$_{15}$ hydrocarbons.
Original Oil/Water Contact
-2878 mbls Well 1X

Original Oil/Water Contact
-2886 mbls Wells 5XC and 33XC

Cross-Section supplied by: Perupetro

Tilted Oil/Water Contact
Corrientes Field
Basal Chonta Sand
Cross-Section supplied by: Pero Petro

Tilted Oil/Water Contact
Shiviyacu Field
Vivian A Sand

FIGURE 17
Petroleum Hydrogeology of the Marañon Basin at Pozo Time (40 Ma)

- **Pliocene (PLIO)**
- **Miocene (MIO)**
- **Paleocene (PAL)**
- **Cretaceous (K)**
- **Vivian Ss (VIV)**
- **Chonta (CHON)**

- **Cushabatay (CUSH)**
- **Jurassic (JU)**
- **Triassic (TR)**
- **Paleozoic (PZ)**
- **Precambrian (PE)**

- **Freshwater Flow**
- **Brine Flow**
- **Oil Migration**
- **Fault Conduit**
- **Source Rock (S)**

**Driving Forces** for Brine Flow in the West

- Freshwater Recharge

**Western Oil Kitchen**

- **Salt Dissolution**

**Tectonic Compression**

**Sediment Load Compaction**

**Before Quecha Inversion = Western Oil Kitchen**

**Sea Level**

**Extensive Paleo Biodegradation c. 65°C**

**Paleocene (PAL)**

**Cretaceous (K)**

**Triassic (TR)**

**Paleozoic (PZ)**

**Precambrian (PE)**

**Vivian Ss (VIV)**

**Chonta (CHON)**

**SEA LEVEL**

**Before Quecha Inversion = Western Oil Kitchen**

**W**

**E**

**Western Oil Kitchen**

**Pozo Sea**

**Vivian Uplands**

**Proto Anean Uplift**

**Proto Cutucu Uplift**

**Driving Forces** for Brine Flow in the West

**Freshwater Recharge**

**Salt Dissolution**

**Sediment Load Compaction**

**Tectonic Compression**

**Before Quecha Inversion = Western Oil Kitchen**

**Sea Level**

**Extensive Paleo Biodegradation c. 65°C**
Petroleum Hydrogeology of the Marañón Basin at Present Day

- **Driving Forces** for Brine Flow in the West
- **Freshwater Flow**
- **Brine Flow**
- **Oil Migration**
- **Oil Migration**
- **F** Source Rock

**Strong Freshwater Recharge**

**Weak 'Paleo' Water Flow**

**No Present Day Biodegradation (Reservoirs Too Hot)**

**SANTIAGO BASIN**

- **PLIO** Pliocene
- **MIO** Miocene
- **PAL** Paleocene
- **K** Cretaceous
- **VIV** Vivian Ss
- **CHON** Chonta

**CUSH** Cushabata

- **JU** Jurassic
- **TR** Triassic
- **PZ** Paleozoic
- **PE** Precambrian

**CORDILLERA REAL**

**CUTUCU UPLIFT**

- **Sea Level**
- **C. 65°C**

**PETROLEUM HYDROGEOLOGY OF THE MARANÓN BASIN AT PRESENT DAY**
Horizontal Gradient
Paleo Structure Base Cretaceous

Paleo Structural Hinge Line

Horizontal Gradient
Present Day Structure Base Cretaceous

Structural Hinge Line

Hotter Colours = Steep Gradients
Cooler Colours = Flatter Regions

Regional Structural Dip Gradient Map
Marañon Basin
Horizontal Gradient
Paleo Structure Base Cretaceous (Pozo Time) and Paleo Head Vivian

Horizontal Gradient
Present Day Structure Base Cretaceous and Head Vivian

Paleo Structural Hinge Line

Structural Hinge Line

Hotter Colours = Steep Gradients
Cooler Colours = Flatter Regions

Regional Structural Dip Gradient Map
with Vivian Water Flow
Marañon Basin
Structural Cross-Section with Predicted Tilted Oil/Water Contacts Near Marañón 1X, Marañón Basin

Y Axis: 20X's Exaggeration

-5000 -4000 -3000 -2000 -1000 0 1000 2000 3000 4000 5000

Distance (km)

Structure Elevation (m)

Vivian, 7 m/km (40ºAPI)
Vivian / Top Cretaceous
Cushabatay Formation
Chonta Limestone

A A'

Y Axis: 20X's Exaggeration
Structural Cross-Section with Predicted Tilted Oil/Water Contacts
Yurimaguas, Marañon Basin

Y Axis: 20X’s Exaggeration