PETROLEUM SYSTEMS OF SUBANDEAN BASINS BASED ON GEOCHEMICAL CHARACTERIZATION OF OILS

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ABSTRACT

In most areas of the Subandean megatrend exploration is far from being mature, although geochemical data show that Upper Cretaceous source rocks account for more than 90% of the oil in place discovered to date. Geochemical investigations of some of the most productive Subandean sedimentary basins have been conducted using a wide selection reservoired oils. The objectives were to identify and characterize the oil types, and to assess the depositional paleoenvironments and the age of their source rocks, in order to establish and predict the petroleum systems in the basins.

The integration of geochemical and geological data allowed the differentiation and characterization of five major age related oil types in the Subandean basins studied: Upper Devonian marine epicontinental; Upper Jurassic marine anoxic; Triassic lacustrine freshwater; Upper Cretaceous marine anoxic, varying from carbonate to siliciclastic; and Tertiary marine deltaic, ranging from distal to paralic.

Thermal evolution levels ranging from early mature to overmature and post-generation alteration processes such as biodegradation can explain most of the compositional differences within each oil type. Basin modelling suggests that the Subandean paroxysm had played a major role in the establishment and preservation of the petroleum systems of the area (generation, migration pathways, reservoir leaking, biodegradation, secondary cracking of oil and gas, oil mixing etc.). Two major pulses of generation and expulsion occurred, one before (Eocene-Oligocene), and the most important after the andean paroxism during Late Miocene.

Although this study confirms the Upper Cretaceous marine anoxic oil type as the most important in the Subandean megatrend, the Tertiary type presents a promising oil-prone potential for future exploration.

INTRODUCTION

A geochemical study of the most productive Subandean sedimentary basins was carried out using a wide selection of oils ranging from Late Devonian to Miocene in age (Fig. 1). The objectives were to identify the oil types and to assess the depositional paleoenvironments, age and thermal evolution of their putative source rocks in order to characterize their petroleum systems. This approach was based mainly on the distributions and concentrations of biological markers following the petroleum system concept (Moldowan et al., 1985; Mello et al., 1988, Mello and Maxwell, 1991, Magoon and Dow, 1994).

The petroleum system concept requires a shift in emphasis from sedimentary rocks and traps to discovered petroleum occurrences. Petroleum system investigations require, first, identification of the hydrocarbon fluid system, then investigation only of those sedimentary rocks that relate to this fluid system (Magoon and Dow, 1994).

Representative oil samples for each sedimentary basin studied were recovered from carbonate and siliciclastic reservoirs, ranging in age from Late Devonian to Miocene. They were analyzed for API gravity, carbon isotopic composition, sulphur content and biomarker distributions, using gas chromatography and gas chromatography-mass spectrometry and GC-MS/MS techniques (Penteado, 1996).

RESULTS AND DISCUSSION

The integration of geochemical and geological data of selected oil samples from the Subandean sedimentary basins studied in Venezuela, Colombia, Peru, Ecuador, Bolivia and Argentina, in a geologic context, allowed the differentiation and characterization of five major age related oil systems (Table 1, Figs 2-6), discussed separately below.

1. Upper Devonian marine epicontinental oil system

Although the Upper Devonian marine epicontinental oil system is widespread around the Subandean basins (Figs 1-2), its oil reserves and potential have been considered insignificant. Up to now this system accounts for no more than 2% of the oil in place discovered to date along the entire Subandean megatrend, and has been detected in the Marañon, Ucayali (Peru), Madre de Dios (Peru and Bolivia), Santa Cruz (Bolivia) and Noroeste (Argentina) basins; Mello., and Trindade, 1995; Peters et al., 1997).

Thermal modelling based on burial history and vitrinite reflectance suggest for the Upper Devonian source rocks, in the Subandean megatrend, a gas-condensate-prone character, with peak oil generation and expulsion ranging from Juro-Triassic to Miocene times, when most of gas and condensate generation and expulsion occurred. The latter pulse was caused by the deposition of a thick molasse sequence during the Tertiary (Eisner et al., 1996). Regarding hydrocarbon preservation, the Subandean orogeny, followed by uplift and erosion**,** caused biodegradation, reservoir leaking, oil remobilization and destruction of preexisting oil acummulations. Subsequent overthrusting caused secondary oil and gas cracking in most areas of the Upper Devonian petroleum systems, enhancing their gas-condensate hydrocarbon potential.

The diagnostic geochemical features that differentiate and characterize the Upper Devonian light oil-condensate type are: saturates > 60%, whole oil ? ^{13}C values lower than -28 ‰, very low sulfur content, pristane/phytane ratios (< 1.5), low relative proportions of extended homohopanes, hopane/ sterane ratio < 5, Ts > Tm, dominance of C_{29} steranes over C_{27} and C_{28} counterparts, low relative proportions of tricyclic terpanes and diahopanes (Table 1; Mello et al., 1994).

Integration of geological and geochemical data suggests that the most common reservoirs associated with the Upper Devonian petroleum system consist of marine sandstone sequences ranging in age from Devonian to Permian.

2. Triassic lacustrine freshwater oil system

Oils from this system have been only identified in the Cuyo Basin, Argentina, which are derived from an overcharged lacustrine petroleum system (Figs 1 and 2).

Thermal modelling based on burial history and vitrinite reflectance suggest for the Triassic lacustrine freshwater system of the Cuyo basin a waxy oil-prone system, with peak oil generation and expulsion occurring from Paleocene to Recent times. Good source rocks are also present in the upper portion of the Triassic Potrerillos formation, although no considerable volumes of oil and gas, derived from it, have not been discovered yet.

Up to now, only one genetic oil family derived from lacustrine source rocks of the Triassic Cacheuta formation has been identified in the Cuyo basin. All the oil**s** analyzed exhibit identical biomarker and carbon isotopic compositions, and all are correlated to the Gautier source rock extracts that present minor vertical and lateral organic facies variability. Variations in some oil compositional features are attributable mostly to varying degree**s** of thermal evolution.

Oils from this group have unique compositional features when compared with all the other Subandean oil types. The most important features are: very high wax content (saturates > 70%), with dominance of odd high molecular weight *n*-alkanes, ? ^{13}C of the whole oil ranging from -28.5 to -30 ‰, sulfur contents < 0.08 %, pristane/phytane > 2, predominance of C_{29} steranes over their C_{27} and C_{28} counterparts, absence of C_{30} steranes and dinosteranes and hopane / sterane index > 15 (Table 1e.g. Mello and Trindade 1995; 1996).

Integration of geological and geochemical data suggests that the most productive reservoirs associated with the Triassic lacustrine oil system consist of alluvial and fluvial sandstone sequences from the Triassic Rio Mendoza formation.

3. Upper Jurassic marine anoxic oil system

The Upper Jurassic marine anoxic oil system was only identified in the Neuquen basin, Argentina (Figs 1 and 2). Although this basin is one of most prolific, oldest and most well explored oil province in the **s**outhern part of the Subandean megatrend, its petroleum system is not well understood, because detailed geochemical and basin compositional modelling studies have not been performed yet.

Thermal modelling based on burial history and vitrinite reflectance of the Jurassic Vaca Muerta Fm. data suggest an oil/gas-condensate-prone area, with the peak of oil generation and expulsion occurring from Paleocene to Late Miocene (e.g. Urien and Zambrano, 1994). The Upper Miocene Andean paroxysm caused significant secondary cracking of the reservoired oils and gas in the basin.

Diagnostic carbon isotopic and biomarker features that differentiate and characterize the Upper Jurassic oil type are: whole oil ? ^{13}C values lower than -27.5 ‰, slight even carbon preference, very low sulfur content and tricyclic terpanes; pristane/phytane > 1, hopane/ sterane ratio < 3, Ts > Tm, dominance of C_{29} steranes, and the presence of dinosteranes and C_{30} steranes (Table 1; Mello et al., 1994).

Integration of geological and geochemical data suggests that the most productive reservoirs associated with the Upper Jurassic petroleum system are alluvial, coastal plain and eolian sandstone sequences from the Tordillo-Sierras Blancas formation, ranging in age from Kimmeridgian to Tithonian (Hogg, 1993; Urien and Zambrano, 1994).

4. The Upper Cretaceous marine anoxic oil system

The Upper Cretaceous marine anoxic oil type, ranging from carbonatic to siliciclastic, has long been considered the most prolific petroleum system in South America, with more than 1.5 trillion barrels of oil in-place (Fig. 3; e.g. Talukdar et al., 1994; James et al., 1990; Mello and Trindade, 1995; 1996).

Thermal modelling based in burial history and vitrinite reflectance data suggest an overcharged, mainly oil-prone, laterally/ vertically drained, high impedance entrapment style system, associated with at least, two major generation and expulsion events. Such data suggest a complex generation-migration history, in which the oils that originated from the first pulse of generation-migration (Eocene to Middle Miocene) underwent partial destruction by biodegradation after the Sub-Andean uplift. With subsequent burial, biodegradation ceased and a following generation-migration pulse (Upper Miocene to Recent) resulted in the mixture of non-biodegraded and biodegraded oils into the reservoir. The final composition of the oils depends on the degree to which biodegraded and non-biodegraded oils are mixed. It is important to mention that the Subandean paroxysm caused tremendous damage, regarding preservation, to most of the Eocene to Middle Miocene petroleum systems of the Subandean megatrend (e.g. biodegradation, remobilization, leaking, secondary cracking of oil and gas, oil mixing etc). The most important migration event occurred from Eocene to Middle Miocene times (most laterally drained migration pathway) and was responsible for most of the oil in-place discovered up to now. On the other hand, the last migration pulse, appears to have occurred in the last 4 Ma (Upper Miocene to Recent; predominant vertically drained), played a pivotal part in determining petroleum quality, since it mixed non-biodegraded oils to the biodegraded ones from the previous pulse.

The diagnostic geochemical features that characterize the Upper Cretaceous marine anoxic oil type, and distinguish it from all the other oils studied, are: whole oil ? ^{13}C higher than -28 ‰, sulfur content higher than 0.35%, pristane/phytane ratio <1, very low relative abundance of oleanane, high abundance of extended tricyclic terpanes, C_{30} steranes, 28,30-bisnorhopane, extended homohopanes and C_{28} steranes (Table 1). Thermal evolution levels ranging from early-mature to mature and post-generation alteration processes (e.g. biodegradation) can account for most of the compositional differences within the oil family.

This oil type, derived from the Upper Cretaceous marls and calcareous shales, comprises more than 90% of all oil in-place in the Sub Andean basins. Also, in detail, it can be sub-divided into several sub-families, ranging from marine carbonate to marine siliciclastic, reflecting the vertical and lateral organic facies variability of the Upper Cretaceous source rocks.

Integration of geological and geochemical data indicate that the most productive reservoirs associated with the Upper Cretaceous petroleum system in the Subandean basins are marine and fluvio-deltaic sandstone sequences ranging in age from Eocene to Miocene (James, 1990; Dashwood and Abbotts, 1990; Butriago, 1994; Talukdar and Marcano, 1994).

5. Tertiary marine deltaic oil system ranging from distal to paralic

The Tertiary marine deltaic oil system, in the past, has been recognized as a non-important petroleum system in South America's sedimentary basins, with no more than 300 MM barrels of oil in-place (Fig. 4; Mello and Trindade, 1995).

In the last years, extensive investigations of biological markers in oils from Venezuela and Colombia have shown that Tertiary oils do represent a new subandean pearl for future exploration (e.g. Drozd and Piggot, 1994; Hernandez et al., 1996; Luna et al., 1996; Ramon and Dzou, 1996; Mello et al., 1993). Although good source rock is quite rare in the Tertiary section of the Subandean sedimentary basins, considerable volumes of tertiary oil and gas reserves have been discovered in some basins, such as: Falcon and Eastern Venezuela basins in Venezuela, and Llanos and Lower Magdalena basins in Colombia (Table 1 and Figs 1 and 4; e.g. Luna, 1994; Drozd and Piggot, 1994; Mello et al., 1994; Hernandez et al., 1996; Luna et al., 1996; Ramon and Dzou, 1996; Trindade et al., 1997; Tegelaar et al., 1996).

The integration of geochemical and biostratigraphic data of selected oil and rock samples from Venezuela (Falcon and Eastern Venezuela basins) and Colombia (Llanos and Lower Magdalena basins), in a geologic context, allowed the differentiation and characterization of two major Tertiary oil types (Fig. 4). One is related to marine deltaic depositional settings derived from an anoxic clay-rich marine deltaic, distal, environment associated with a deep basin (Paleocene/Eocene age); the other reflects a suboxic marine deltaic proximal to paralic setting associated with a large input of terrestrial plants (Miocene age).

Thermal modelling based on burial history simulation and vitrinite reflectance data for the Subandean Tertiary System suggest**s** that source rocks reached the peak of oil generation and maximum hydrocarbon expulsion during the last 3.5 Ma (Upper Miocene to Recent; Luna et al., 1994; Tegelaar et al., 1996, and this study). The integration of geological and geochemical data suggests a light oil-prone, charged, high impedance entrapment style and laterally drained petroleum system. It is important to mention the occurrence of a complex generation-migration history, involving this oil system and the Upper Cretaceous one described above. In several basins, there are mixtures of Upper Cretaceous oils, originated before and after the Andean paroxysm, with Tertiary oils related to the post Sub-Andean migration pulse (e.g. Ramón and Dzou, 1996; Tegelaar et al., 1996; Luna et al., 1996; Schiefelbein et al., 1996). The final composition of the oils reflects the degree of mixture of Upper Cretaceous (biodegraded) and Tertiary (non-biodegraded) oils.

The diagnostic geochemical features of the Tertiary derived oils are: whole oil ? ^{13}C higher than -26 ‰, high to very high pristane/phytane ratio, very low sulphur and aromatic contents, low concentrations of extended tricyclic terpanes and hopanes; and high concentrations and relative abundances of biomarkers diagnostic of Tertiary higher plants such as oleanane, C_{30} terpenoids, des-A and des-E tetracyclic terpanes, lupanes and C_{29} steranes (Table 1).

This oil type comprises around 5% of all oil in-place in the subandean basins. Also, in detail, it can be subdivided into several sub-families, ranging from marine distal to marine proximal and paralic, which are related to the vertical and lateral organic facies variability of the Tertiary source rocks (Fig. 4).

CONCLUSIONS

The integration of geochemical data together with geological information, in this study, allows the assessment and characterization of major oil systems in the Subandean sedimentary basins. The following conclusions and recommendations can be made:

1 - Geochemical and biomarker data of selected oils identified five major age-depositional-source related oil systems in the Subandean basins (Figs 2-3): Upper Devonain marine epicontinental system in the Marañon, Ucayali, Madre de Dios, Santa Cruz and Noroeste basins; Triassic lacustrine freshwater system in the Cuyamas basin; Upper Jurassic marine anoxic system in the Neuquen basin; Upper Cretaceous marine anoxic system varying from carbonate to siliciclastic in the Eastern Venezuela, Barinas-Apure, Lake Maracaibo, Lower, Middle and Upper Magdalena, Putumayo, Llanos, Oriente, Marañon, Ucayali and Noroeste basins; and Tertiary marine deltaic system, ranging from distal to paralic, in the Falcon, Eastern Venezuela, Lower Magdalena and Llanos basins.

2 -Thermal evolution stages ranging from early mature to overmature, and post-generation processes, such as biodegradation, can explain most of the compositional differences within each oil family.

3 - Basin modelling suggests that most of the oil generation and expulsion in the Subandean sedimentary basins occurred prior to the Subandean paroxysm during the Eocene-Oligocene.

4 - The Subandean paroxysm played a major role in the destruction of most of the pre-existing hydrocarbon accumulations enhancing processes such as: seal leaking, biodegradation, oil remobilization, oil mixing and secondary cracking of oil and gas.

5 - The final composition of the oils, in most of the petroleum systems studied, reflects oil mixing from several pulses of oil generation, migration, and events of biodegradation.

6 - Although this study confirms the Upper Cretaceous marine anoxic oil system as the most important in the Subandean megatrend, the Tertiary marine deltaic system has a promising oil-prone potential for future exploration.

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PETROLEUM SYSTEM	Pristane /Phytane	Oleanane Index	$d^{13}C$‰ aromatics	C_{27}/ C_{27} steranes	Hopanes/ Steranes
Tertiary (marine deltaic)	**2.5 to 7.5**	**>0.3**	**-28 to -29.5**	**1.0 to 1.5**	**>7**
Upper Cretaceous (marine anoxic)	**0.8 to 1.2**	**<0.3**	**-27 to -28**	**0.1 to 0.8**	**<2**
Upper Jurassic (marine anoxic)	**< 1**	**n.d.**	**-27 to -29**	**1.1 to 1.4**	**2 to 5**
Triassic (lacustr. freshwater)	**>2.5**	**n.d.**	**-24.5 to -31**	**0.7 to 0.9**	**>15**
Upper Devonian (marine epicontin.)	**1.2 to 1.8**	**n.d.**	**-24 to -26.5**	**0.3 to 0.5**	**2 to 4**

Table 1 - Geochemical features of oils present in the Subandean Petroleum Systems

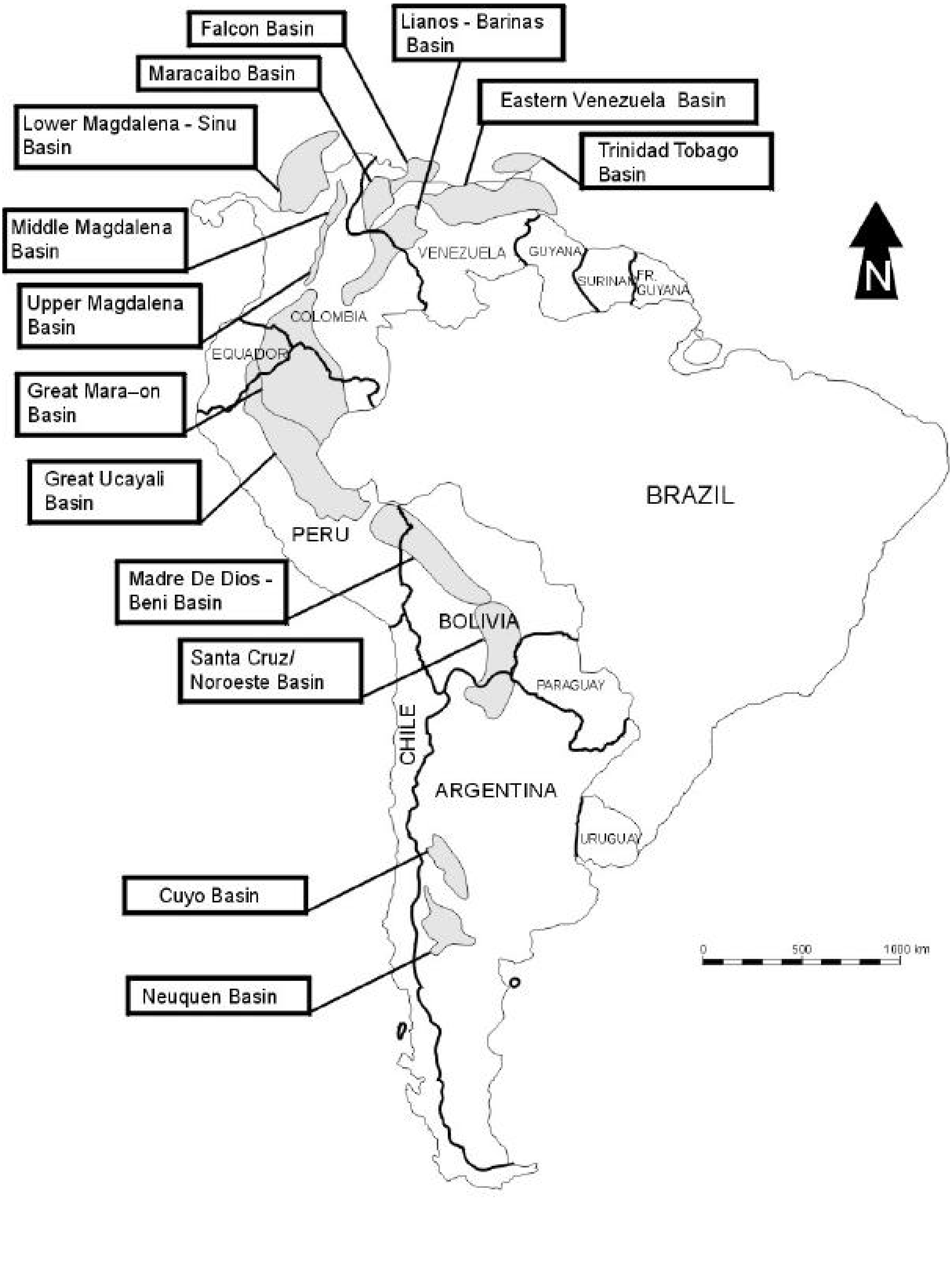

Fig.1 - Studied basins, showing the Subandean Megatrend

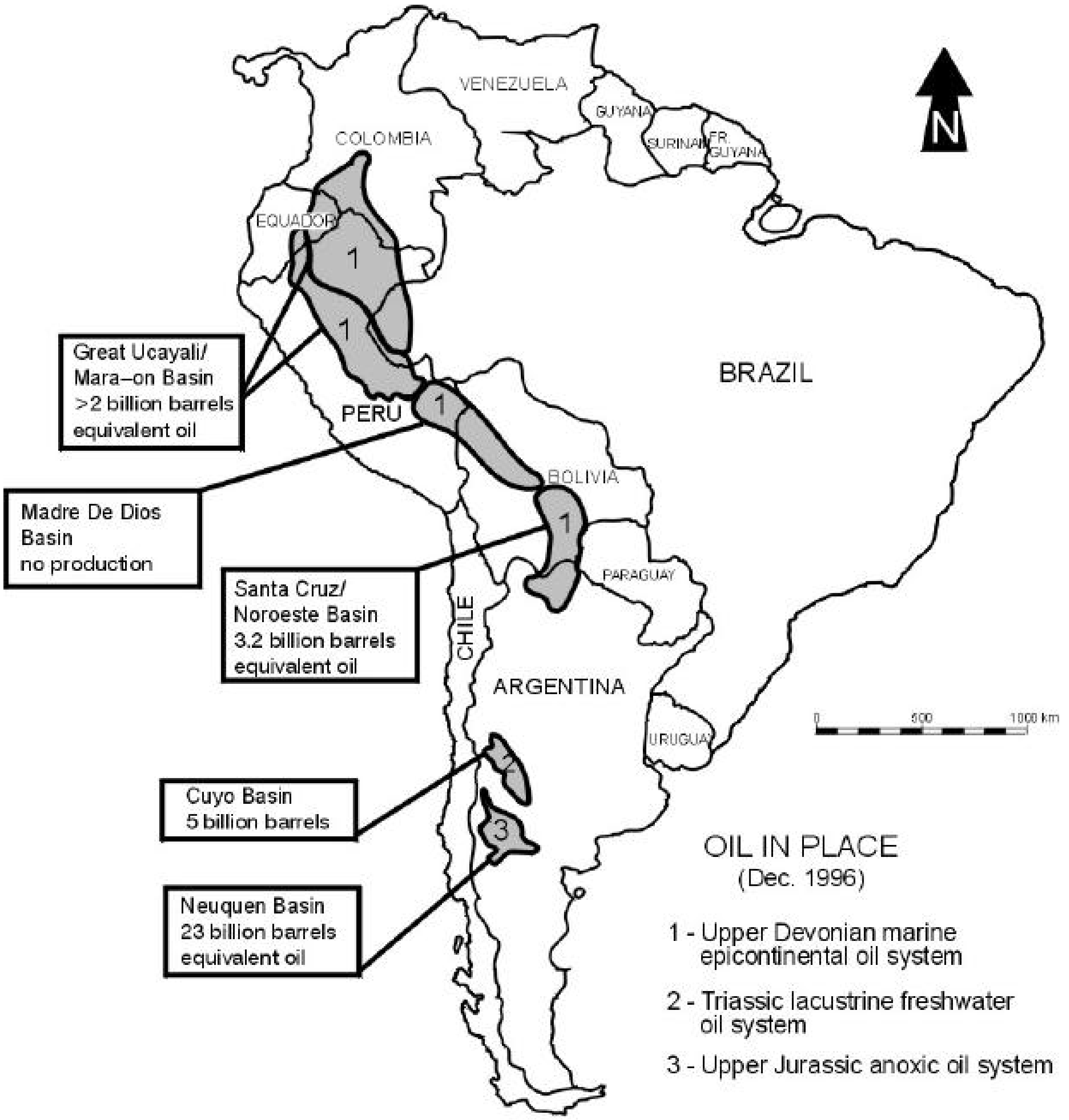

Fig. 2 - Oil types related to the depositional environment ranging from Upper Devonian to Upper Jurassic of the Subandean Megatrend

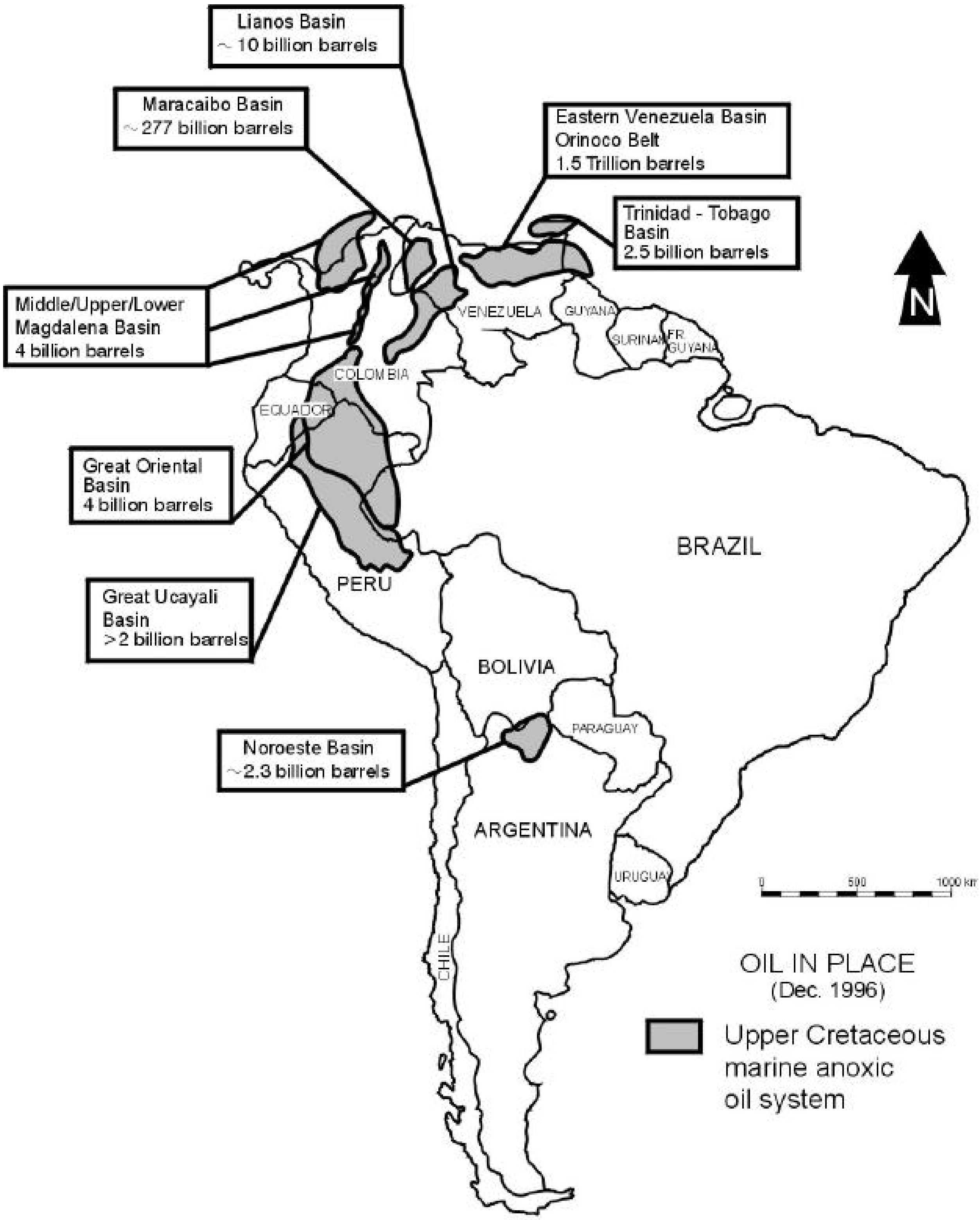

Fig. 3 - Oil types related to the Upper Cretaceous Petroleum system of the Subandean Basins

Fig. 4 - Oil types related to the Tertiary petroleum system of the Subandean Basins