GANDOLPH

PALEOGEOGRAPHIC AND PALEOCLIMATIC CONTROLS ON HYDROCARBON SOURCE ROCK DEPOSITION

A PROPOSAL OFFERED BY

GEOMARK RESEARCH, LTD.

&

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(The PALEOMAP Project)

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INTRODUCTION

GeoMark Research, Ltd. and Dr. Christopher R. Scotese (The PALEOMAP Project) are collaborating to produce a digital map database from which the occurrence of hydrocarbon source facies can be predicted at basin or subbasin scale -- GANDOLPH (Geologically AND Oceanographically Linked Programming Heuristics.)

Exploration groups employ a range of tools in identification and evaluation of new opportunities. Characterization of the distribution and composition of sediments with the potential to be hydrocarbon source units is central to predicting the existence of petroleum systems.

In the GANDOLPH Project, predictions will be based on geographic, environmental, and geochemical criteria obtained by combining the PALEOMAP Project's paleogeographic reconstructions with paleoclimatic modeling. Results of the reconstructions and modeling will be supported and constrained using oil, rock, and gas geochemical data from GeoMark Research's global geochemical databases.

PROJECT GOALS

The project will produce a digital paleogeographic-paleoclimatic map archive for eight geologic time intervals listed (nominated) below and discussed in **Appendix A**.

50 Ma, Middle-Late Eocene
90 Ma, Late Cretaceous, Cenomanian-Turonian boundary
150 Ma, Late Jurassic, Tithonian-Kimmeridgian
280 Ma, Early Permian, Sakmarian-Artinskian
20 Ma, Early-Middle Miocene
140 Ma, Early Cretaceous, Valanginian
360 Ma, Late Devonian, Frasnian-Famennian
430 Ma, Early Silurian, Llandovery

Climatically modeled reconstructions will be presented in global and regional maps that will be used to predict hydrocarbon source bed occurrence in the selected geologic time intervals. Project goals include:

- provision of plate tectonic and paleogeographic reconstructions for explorationists interested in, or working, specific geological time intervals;

- provision of paleoclimatic and paleo-oceanographic simulations for specific time intervals for explorationists interested in environmental conditions associated with the formation of hydrocarbon source rocks;
- evolution of source rock prediction criteria from the paleogeographic reconstructions and paleoclimatic modeling.

Predictions regarding the distribution of hydrocarbon source sediments will be framed in context of the paleogeographic, -oceanographic, and -climatic settings for the selected time interval. Successful confirmation of the predictions using oil, rock, and gas data serves to elevate paleogeographic-paleoclimate modeling to a more routinely usable status. These issues directly effect the evaluation of exploration risk.

GANDOLPH COMPONENTS

GANDOLPH will combine plate reconstruction and paleoclimate modeling with geochemical data to create a unique set of petroleum system evaluation tools. These new tools are *SourceRocker* and *SourceFinder*, and they will provide participating companies a novel approach for evaluating undrilled or under-drilled sedimentary basins.

PLATE RECONSTRUCTIONS AND PALEOCLIMATOLOGY COMPONENTS

The GANDOLPH Project will use ArcGIS Geodatabase (ESRI) as a mapping system. Plate tectonic and paleogeographic maps used in this study will be updated versions of the digital maps that comprise the Earth System History – Geographic Information System (ESH – GIS) assembled by the PALEOMAP Project. Paleoclimate simulations will be performed on a contract basis using the Fast Ocean and Atmospheric Model (FOAM).

PALEOMAP - Earth System History GIS

- Plate Tectonic Reconstructions
- Paleogeology
- Clastic / Carbonate lithofacies
- Paleo-Digital Elevation Model (DEM)
- Lithologic Indicators of Climate
- Depositional Environments

During the past 3 years the PALEOMAP ESH-GIS has become the industry standard for GIS-based plate tectonic and palegeographic reconstructions. High-resolution, digital elevation models (DEM) illustrating both paleobathymetry and paleotopography will provide the framework for the paleoclimatic simulation of ocean and atmospheric dynamics during the eight time intervals.

In addition, the ArcGIS geodatabase for each time interval will include additional map layers illustrating the active plate boundaries, paleogeography, paleogeology, environments of deposition, clastic/carbonate lithofacies, as well as lithologic indicators of climate such as evaporites, coals, calcretes, bauxites, and tillites. **Appendix B** lists ESH-GIS map layers provided by the PALEOMAP Project that will be incorporated in the GANDOLPH Project Geodatabase.

FOAM - Fast Ocean & Atmosphere Model

Paleoclimatic simulations of atmospheric and oceanographic dynamics will be run using the Fast Ocean - Atmospheric Model (FOAM), a new coupled climate model that utilizes parallel computing to more efficiently model the Earth's climate system.

Figure 1 is an example simulation obtained from the Fast Ocean and Atmospheric Model (FOAM). The figure shows observed mean annual surface temperature distributions and surface temperature predicted by the FOAM simulation. **Figure 2** presents estimates of paleosalinity from FOAM simulations for the Cretaceous (100Ma) and Triassic (216 Ma) using four times the modern level of carbon dioxide.

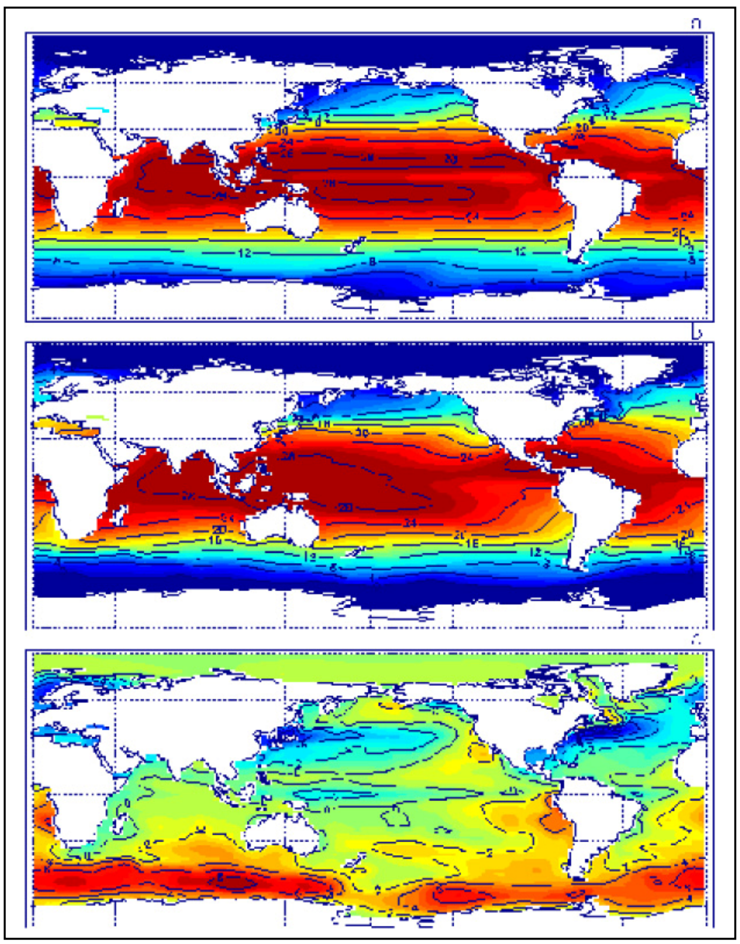

Figure 1. Example FOAM simulation contrasting observed mean annual surface temperature (upper panel) with surface temperature from simulation (middle panel). The bottom panel represents a map of the difference between the observed and the simulated temperatures.

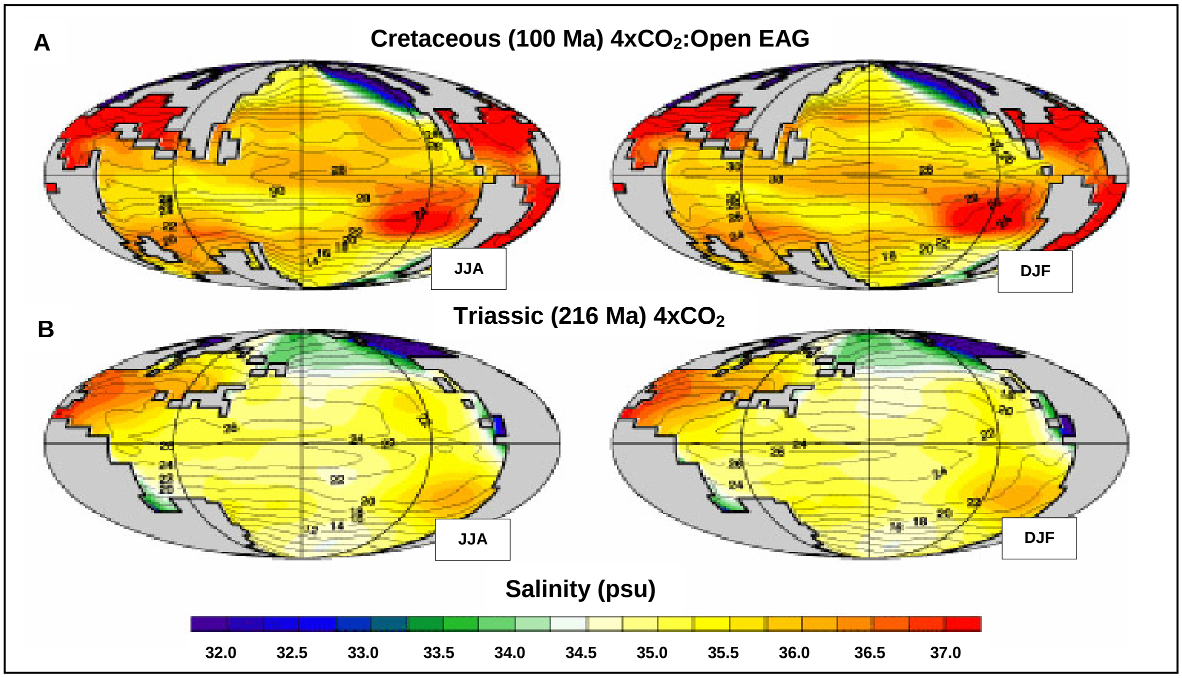

Figure 2. FOAM paleosalinty simulations for the Cretaceous (100 Ma) and Triassic (216Ma).

The GANDOLPH ArcGIS geodatabase will contain the paleogeographic and geologic map layers described in the previous section, as well as the output from the FOAM paleoclimatic simulations. These paleoclimatic map layers will include information about:

- atmospheric pressure
- temperature
- wetness (precipitation and evaporation)
- surface winds
- surface ocean currents
- deep ocean circulation
- salinity
- wind stress
- depth of mixed layer
- areas of upwelling

Additional map layers showing environmental characteristics important to prediction of the occurrence of regions of high organic productivity, organic preservation, and rates of sediment influx will be provided as they are identified. **Appendix B** lists principle products provided by the PALEOMAP Project to GANDOLPH.

General modeling specifications for the project are summarized in **Table 1**. Paleoclimate modeling will be performed at a global scale, but model cells are sufficiently small to permit consideration of major regions and basins contained in the regions.

Resolution of Paleogeographic Maps
Horizontal Resolution = 0.1 degree of latitude (10 km) x 0.1 degree of longitude (10 km); Vertical Resolution = 40 meters
Temporal Resolution of Data
Paleogeographic Interpretations - nearest Sequence Boundary or Maximum Flooding Interval; Lithological Data - stratigraphic stage Plate Tectonic Reconstructions - nearest isochron or magnetic anomaly age Source Rock Data – Stage to substage; Oil Data – Stage to substage
Resolution of Climate Model
Temporal Resolution - Seasonal Maximum & Minimum, Annual Averages Grid Resolution - ~ 2 degrees x 2 degrees (Ocean), and ~ 4 degrees by 4 degrees (Atmosphere), with 18 “.

Table 1. GANDOLPH modeling specifications

Criteria contributing to the identification of conditions conducive to deposition of hydrocarbon source rocks obtained from the modeling will be reported and critically discussed in the report. The success of these criteria in the prediction of source rock occurrences will be evaluated using statistical tests, and a scoring system will be presented indicating the confidence of the predictions.

GEOCHEMISTRY COMPONENTS

Depositional systems for source rocks within selected time slices will be identified and characterized using the World Class Petroleum Systems Database. Source rock data in the World Class Petroleum Systems Database will be refined using data and interpretations in GeoMark’s RFDbase.

WORLD CLASS PETROLEUM SYSTEMS DATABASE

The World Class Petroleum System Database is a petroleum system database developed by Texaco; it has been acquired and expanded by GeoMark. The database contains information necessary for defining petroleum systems at the basin level. Information on source, seal, and reservoir is presented along with exploration and production history.

Currently, over 100 petroleum systems have been evaluated, and data from these system will be used where appropriate to the modeled time slices. A GIS (ArcView™) application provides flexibility in manipulation and query operations. All data is spatially collated to reservoir and generative kitchen areas for the modeled time slices.

RFDbase - Reservoir Fluid Database

RFDbase contains more than 10,000 oils from most important international basins (**Figure 3**). In addition, GeoMark's rock extract and gas databases will support the paleoclimate interpretations of source rock distribution. These data will be used to define, characterize, and constrain source rock environments in specific time slices.

Data in the RFDbase were mainly complied from detailed geochemical evaluations of important producing and potentially productive basins globally. Knowledge accrued in the execution of these studies is an important asset available to GANDOLPH.

Data from additional rock and oil geochemical sources will be used where available or contributed to the project by participants; however, no data or sample contributions are required of project participants.

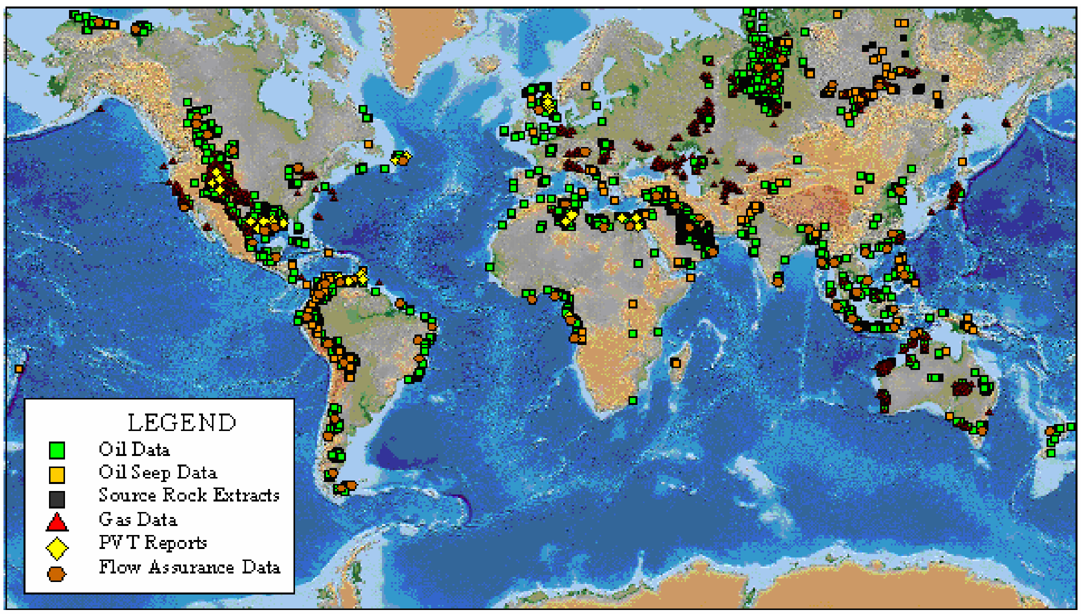

Figure 3. Map distribution of oils in GeoMark Research's RFDbase.

Table 2 presents example data for a number of well documented petroleum systems taken from GeoMark's regional studies, and data contained in GeoMark's RFDbase. In the table, two Cretaceous petroleum systems are shown for the Napo Formation in the Oriente Basin of Ecuador. Oils from these systems are compositionally distinct.

Distribution of compositionally distinct oils from the two Napo source intervals is shown in **Figure 4**. The two sources undergo major organic facies shifts in a north-south direction, and each contributes to the occurrence of an addition mixed oil family.

System ID	Basin/System	Country	General Age	SR Type	Example Oil
C1	***Azua Basin***	Dominican Republic	Miocene	carbonate	DR002
DS14	***GOM/Wilcox***	USA	Eocene	shale	LA471
DS15	***Angola MAN2***	Angola	UK Maastrichtian	shale	AN064
M3	***Maturin/Querecual***	Venezuela	UK Turonian/Cenomanian OAE2	marl	VA073
C5	***Maracaibo/La Luna***	Venezuela	UK Turonian/Cenomanian OAE2	carbonate	VA052
M4	***Oriente/Napo***	Ecuador	UK Turonian/Cenomanian OAE2	marl	EC084
DS20	***Maranon/L Chonta***	Peru	UK Turonian/Cenomanian OAE2	shale	PR055
DS21	***Upper Magdalena/Villeta***	Colombia	UK Turonian/Cenomanian OAE2	shale	CO124
DS22	***Putumayo/Villeta***	Colombia	UK Turonian/Cenomanian OAE2	shale	CO031
DS23	***Cote d'Ivoire ICM1***	Cote d'Ivoire	UK Turonian/Cenomanian OAE2	shale	IC023
DS24	***Espirito/Cacao***	Brazil	UK Turonian/Cenomanian OAE2	shale	BR030
DS25	***Gabon MG1***	Gabon	UK Turonian/Cenomanian OAE2	shale	AF079
DS26	***Alberta Basin***	Canada	UK Turonian/Cenomanian OAE2	shale	CN001
DS27	***GOM/Eagle Ford D***	USA	UK Turonian/Cenomanian OAE2	shale	TX129
C6	***S. Gulf/Shilaif***	UAE	UK Cenomanian	carbonate	UE009
DS34	***Big Horn/Mowry-Cody***	USA	LK/UK	shale	WY870
DSa	***Oriente/Napo***	Ecuador	Upper Albian-Cenomanian	shale	EC040
DS35	***Cote d'Ivoire ICM2***	Cote d'Ivoire	LK Late Albian OAE1	shale	IC033
DS36	***Gabon MG2***	Gabon	LK Albian/Cenomanian OAE1	shale	AF100
C7	***Maverick Co/McKnight***	USA	UK Cenomanian	carbonate	TX302
DS37	***Angola MAN1***	Angola	LK Aptian/Cenomanian	shale	AN062
C8	***Dezful Embayment/Kazhdumi***	Iran	LK Albian	carbonate	IN006
DS38	***Offshore GOM C1***	USA	LK Albian	shale	LA327
DS39	***Mackenzie Delta/Shale B***	USA	LK Aptian/Albian	shale	AS084
DS40	***North Slope/Hue***	USA	LK Aptian/Albian	shale	AS007
DS41	***Onshore GOM/C1***	USA	LK Albian	shale	TX120
DS42	***Sergipe Basin***	Brazil	LK	shale	BR015
DS43	***Cauvery Basin***	India	LK	shale	IA010
C9	***S. Florida/Sunniland***	USA	LK Albian	carbonate	FL002

Table 2. Sample of petroleum systems well defined in GeoMark regional studies and in the geological literature. Systems are arranged by increasing "average" age. Two chronostratigraphically separate Napo Formation systems are show in the table.

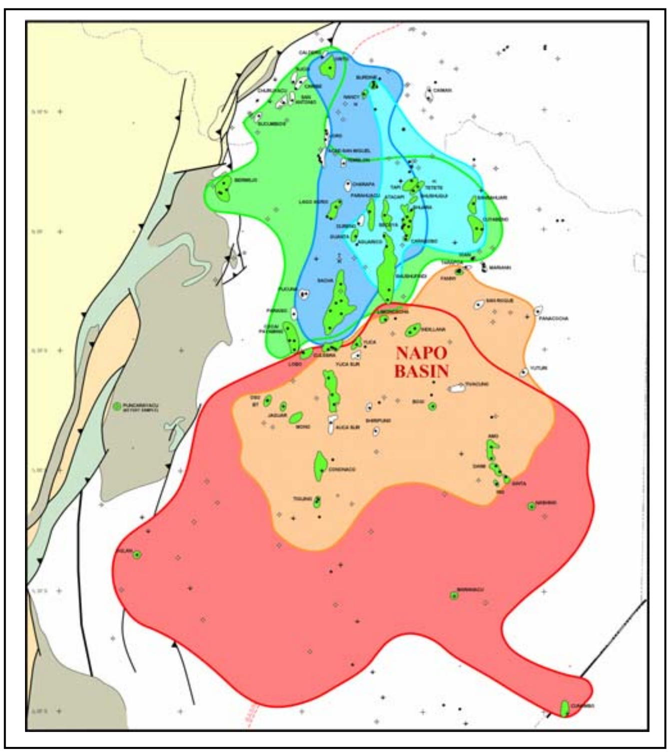

Figure 4. Map of the observed distribution (reservoir distribution) of compositionally distinct oil families in Oriente Basin, Ecuador. The map is based on study of 180+ oils.

Table 3 reconciles source rock data from the World Class Petroleum System Database, regional data from the geochemical literature, and GeoMark's RFDbase oil collection for the "Lower Napo Shale" petroleum system. In this table, source rock geochemistry is reviewed in context of oils taken from the Oriente Basin oil study. Definition of hydrocarbon source facies supported and constrained by well characterized oil collections is essential if the source intervals are to be correctly identified for use in the GANDOLPH Project.

General	**Lower Napo Shale Petroleum System**	
	Basin	Oriente Basin (synonymous with Napo Basin)
	Country	Ecuador, but extends into Colombia (Putumayo Basin)
	Tectonic Setting	Compressional, Klemme Type 2 or Type 2a (Klemme, 1980)
	Source Rock	Lower Napo Shale (Albian-Cenomanian) and stratigraphic equivalents in Putumayo
	Traps	Hanging wall anticlines (thrust front) and large low amplitude closure over basement blocks (basin center)
	Reservoir Rocks	Hollin (Aptian-Albian) and Napo "T" (Cenomanian)
	Seals	Napo B Limestone (Cenomanian) and Middle Napo Shale (Turonian)
Constraining Oil	**Representative oil**	**EC0040** -- Family 4 GM Oriente Study
	Number of oils	Family 4 (29)
	Depositional Characteristics	Distal marine shale to marl, characteristics of an upwelling environment
	Rationale for Source Rock ID	stratigraphic dispersion of Family 4 plus literature describing organic character of Napo
Source Rock (SR)	**SR "Name"**	Lower Napo Shale (locally containing "C" Limestone and calcareous shales)
	SR Age Base/Top	Upper Albian and Lower Cenomanian 100 Ma/94 Ma
	SR Lithology	Marine shale, calcareous shale (marls), and argillaceous limestones (Dashwood and Abbotts, 1990; White et al., 1995; and Mello et al., 1995)
	SR Depositional Environment	Stable marine shelf (Dashwood and Abbotts, 1990). Mello et al., (1995) suggest that the source units may have been deposited in a salinity stratified water column based on the presence of specific biomarkers.
	SR TOC Content	1% to 10% but typically 3%-4% in western part of basin (Dashwood and Abbotts,1990; Mello et al., 1995). Highest TOC at Cenomanian-Turonian boundary 93.5 Ma (Mello et al., 1995).
	SR Kerogen Types	Type II (Mello et al., 1995)
	SR Thickness	The Napo formation attains a thickness greater than 2000 feet A significant fraction of this section is shale and limestone having the potential to be organic-rich (Dashwood and Abbotts, 1990).
	SR Maximum Burial Depth	~16,000 feet in Bobonaza well southern part of basin.
	Typical SR Burial Depth	<10,000 feet (estimated from Dashwood and Abbotts, 1990).
	SR Maturity	Typically, <0.6 % Ro (Dashwood and Abbotts, 1990 and Mello et al., 1995). Higher maturities apparently occur in deep trough in southern Oriente Basin (Bobonaza Trough) where Ro's approach 0.80%.
	SR Hydrocarbon "Kitchens"	West of current thrust front, possibly in northwest Oriente (Dashwood and Abbotts, 1990 and Mello et al., 1995).
	Oil Migration Time	Burial history models by Dashwood and Abbotts (1990) indicate generation is no earlier than 15-10 Ma (Miocene) -- Quechua III orogenic event (Mathalone and Montoya, 1995)
	Migration Mode	Extensive lateral oil migration west (thrust front) to east (craton), subordinate cross stratigraphic migration
Main Reservoirs	**Reservoir Name**	**1) Hollin**
	Lithogy	Fluvial to marine sandstones
	Age Base/Top	114-100 Ma, Upper Aptian to Upper Albian
	Seal	Overlying Lower Napo Shales (100-94 Ma)
	Reservoir Name	**2) Napo "T"**
	Lithology	Stacked fluvial and deltaic sandstone (White et al., 1995)
	Age Base/Top	Cenomanian (94-93 Ma)
	Seal	Overlying "B" limestone and Middle Napo Shale Upper Cenomanian to Upper Turonian (93-89 Ma)
Comments	**1)** The Lower Napo Shale is the oldest of two sources in the Napo that can be distinguished and defined using oil geochemistry	
	2) Burial history (TTI) diagrams provided by Dashwood and Abbotts (1990) on page 98 and page 99 of their paper	
	3) Shales in the upper part of Hollin may contribute hydrocarbons to the oils derived from the overlying Lower Napo shales	
Constraining Oil General Data		
	EC0040	**Field**: Shushufindi **Reservoir:** Napo"T" **Depth**: 9328 feet **API**: 28.4 **%S**: 0.52% **Family:** GM 4
References		
Dashwood, M. F. and I. L. Abbotts, 1990, Aspects of the petroleum geology of the Oriente Basin, Ecuador; in, Classic Petroleum Provinces (Brooks, editor), Geological Society of Great Britain, Special Publication No. 50, p. 89-117.		
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Mathalone, J. M. P. and M. Montoya, 1995, Petroleum geology of the subandean basins of Peru; in, Petroleum Basins of South America (Tankard, Soruco, and Welsink, editors), American Association of Petroleum Geologists, Memoir 62, p. 423-444.		
Mello, M. R. , E. A. M. Koutsoukos, and W. Z. Erazo, 1995, The Napo Formation, Oriente Basin, Ecuador: Hydrocarbon source potential and paleoenvironment assessment; in, Petroleum Source Rocks (Katz, editor), p. 167-181.		
White, H. J., R. A. Skopec, F. A. Ramirez, J. Rodas, and G. Bonilla, 1995, Reservoir characterization of the Hollin and Napo formations, western Oriente Basin, Ecuador; in, Petroleum Basins of South America (Tankard, Soruco, and Welsink, editors), American Association of Petroleum Geologists, Memoir 62, p. 573-596.		

Table 3. Oil and source rock data for "Lower Napo Shale" petroleum system.

Data for ***type*** oils used to characterize source facies in basins in the selected time slices will be provided in the form of Geochemical Summary Sheets. Average data for oil "families" represented by ***type*** oils additionally will be provided. Average oil data provide an additional way to compositionally compare oils from different basinal areas in the same time slice, or from different time slices.

Data for each petroleum system used to characterize and constrain the modeling will be presented in the reconciled format illustrated in **Table 3**.