

REGIONAL GEOLOGY & PETROLEUM SYSTEM

CHOCO BASIN Atrato - San Juan

**TECHNICAL VICE PRESIDENCY
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1 Contents

1	REGINAL GEOLOGY	6
1.1	Introduction.....	6
1.2	Exploration history.....	7
2	GEOLOGICAL FRAMEWORK	11
2.1	Surface geological mapping	11
2.2	The istmina-condoto high	12
2.3	El paso complex	12
2.4	Viravira complex.....	12
2.5	Alto condoto ultramafic complex	13
2.6	Tectonic setting.....	13
2.7	Surface structural expression	17
3	STRATIGRAPHY	18
3.1	ATRATO BASIN.....	18
3.1.1	Introduction.....	18
3.1.2	Exploratory wells in the atrato basin	22
3.2	SAN JUAN BASIN.....	23
3.1.3	Introduction.....	23
3.1.4	Exploratory wells in the san juan basin	25
3.1.5	The san juan delta. a geological model for the cenozoic san juan basin	25
4	PETROLEUM SYSTEM	26
4.1	ATRATO BASIN.....	26
4.1.1	Elements and processes	26
4.1.2	Events chart.....	28
4.1.3	Source rock properties	28
4.1.4	Petroleum system models	31
4.1.5	Definition of the petroleum system	31
4.2	SAN JUAN BASIN.....	34
4.2.1	Elements and processes	34

4.2.2	Events chart	36
4.2.3	Source rock properties	36
4.2.4	Petroleum systems modeling	42
4.2.5	Definition of the petroleum system	43

LIST OF ILLUSTRATIONS

Figure 1.	Geological situation of the Atrato and San Juan Basins. Modified after Cediel et al., (2003).	7
Figure 2.	Location of source data used in this study.	8
Figure 3.	Geological Map Chocó Arc: Atrato, San Juan and Urabá Basins. Modified from these sources: IGAC (2006), Schmidt-Thomé et al, (1992), Minera Utah de Colombia (1980).	10
Figure 4.	The Istmina-Condoto High (geological map). Source: Utah Minerals, 1980.	14
Figure 5.	Sequence of major tectonic events in the Chocó Arc.	15
Figure 6.	Surface structural map of the study area.	16
Figure 7.	General lithostratigraphic sequence in the Atrato and San Juan Basins.	19
Figure 8.	Chronostratigraphic chart and depositional environment of the Atrato Basin.	20
Figure 9.	Lithostratigraphic correlation chart of the Atrato Basin	21
Figure 10.	Schematic profile along parallel 6.0°N.	21
Figure 11.	Chronostratigraphic chart and deposit environment of the San Juan Basin.	24
Figure 12.	Schematic cross-section along the San Juan Basin. Modified after Escobar, 1993.	24
Figure 13.	Geochemical source data available for the evaluation and modeling of the Atrato and San Juan Basins.	27
Figure 14.	Event Chart of the Atrato Basin petroleum system. The red line corresponds to the burial curve of the Clavo Formation.	29
Figure 15.	Modified Van Krevelen Diagram (HI Vs OI), kerogen type III and IV	30
Figure 16.	Hydrogen index and thermal maturity of the organic matter. Samples located at the beginning of the generation window.	30
Figure 17.	Diagram %TOC Vs GP (S1 + S2), showing the generating potential of the rock.	32
Figure 18.	Synthesis of the geochemical evaluation using the data that is available for the Atrato Basin. The generating potential considered for these units could be depreciated due to low availability of information, taking into account the lithofacies similarities with the Iró Formation.	32
Figure 19.	Location of the Atrato well on the seismic line QA-1982-20.	32
Figure 20.	Burial curve in the area. Middle Eocene reached the maximum burial in the Pleistocene.	33
Figure 21.	Rock maturity Profile through time. The top of the Clavo Formation reached the delayed maturity phase of oil generation.	33
Figure 22.	Hydrocarbon expulsion process at the end of the Pliocene in the Clavo Formation. The dotted blue line represents the burial curve; the continuous pink line shows the hydrocarbon expulsion.	34
Figure 23.	Map of the proposed hypothetical petroleum system. The map shows the depocenter at the upper limit of the plinth, the oil seeps reported in the Basin and the hypothetical area of system influence in this system.	35
Figure 24.	The Events Chart shows the elements and processes of the Iró petroleum system (.). The red line corresponds to the burial curve.	37

Figure 25. Modified Van Krevelen Diagram (OI Vs HI). The Iró Formation contains values corresponding to kerogen type II with oil generation potential.	38
Figure 26. Diagram Tmax Vs HI. The analyzed samples of the Iró Formation are at the beginning of the generation window.	38
Figure 27. Diagram % TOC Vs GP (S1+S2). The Iró Formation registers the most favorable values. Illustrates a synthesis of the most important geochemical characteristics that identify the Iró Formation as a very good source rock	39
Figure 28. Summary of the geochemical evaluation to rocks in the San Juan Basin. This chart is obtained from the average values of the studied geochemical parameters	40
Figure 29. Ternary diagram showing the proportions of saturates, aromatics and resins plus asphaltenes. The last mentioned predominating over the analyzed extracts.	40
Figure 30. Pristano/fitano Diagram Vs C35/C34 Hopanes in which the suboxic marine character of deposition is observed. (Modified by Garcia et al. 2001).	41
Figure 31. Fitano Diagram Vs Pristano. Suboxic environment. The analyzed samples show intermediate biodegradation.	41
Figure 32. Diagram % C29 Steranes Vs C27 Steranes, indicating a high correlation in the organic matter type (marine algal), for the rock extracts and the oil seep crude	42
Figure 33. Location profile of the San Juan well on seismic line TB-91-1130.	43
Figure 34. Curve of maximum burial occurred during the Miocene.	44
Figure 35. Profile of %Ro through the time, Lower Iró reached the peak of oil generation.	44
Figure 36. The expulsion process was reached only for Interval C	45
Figure 37. Location of the Urabá Basin, municipalities and wells based on the seismic line L1979-18-5.	46

TABLE LIST TABLE LIST

Table 1. Tops of the lithostratigraphic units as defined in the Buchadó-1	22
Table 2. Tops of lithostratigraphic units as defined in the Urodó-1 and Opogadó-1	22
Table 3. Tops of lithostratigraphic units as defined in the Pacurita-1 and Nécora-1	23
Table 4. Table 5. Lithostratigraphic units as defined in the Tambora-1	25
Table 6. Summarizes some of the main properties obtained from the geochemical data that is available for the rock extracts in the Iró Formation and the crude in the oil seep of the basin.	42



1 REGIONAL GEOLOGY

1.1 Introduction

The Panamá Arc is composed by two physiographically distinct portions: the Chorotega (Panamá) Arc to the west and the Chocó (Panamá) Arc to the east - south-east. The regional interpretation of this segment of the Panamá Arc (Chocó – Panamá Arc), is still in process, subject to the integration of new geological and geophysical information. Regardless, the concepts applied herein (*Figure 1*) already suggest the need to revise existing interpretations, especially within the zone of influence of the Chocó – Panamá Arc, from both an onshore and offshore perspective. The three basins studied (Atrato, San Juan, and Urabá) present individual characteristics which reflect differing geotectonic origins. Kinematic time-space evolution is linked to differing geological episodes affecting the Chocó –Panamá Arc, as reflected in the basin analysis:

Atrato (Forearc) Basin: a marine sedimentary sequence attaining a maximum thickness of 10 km, deposited since the Eocene (?).

San Juan (Continental – marine delta basin): more than 10 km of continental deltaic facies and marine sediments, in the process of subsidence since the Paleocene (?).

Urabá (Pull-apart) Basin: Up to 4 km of predominantly marine deltaic sediments deposited since Miocene time (?), in a transtensional regime, marked by the influence of transcurrent faults

The basement of the three basins (ATB, SJAB, URB) is comprised of allochthonous fragments of late Cretaceous oceanic crust and/or island arcs, accreted via subduction-related processes and by tangential collision(s) which led to the progressive counter-clockwise (NE to NW) rotation of structural trends, as recorded by the measurement of fold axes and fault and fracture patterns (see figure 6).

The sutures generated during these events have been partially exhumed. One of them, the IsthminaCondoto High (San Juan Fault System) contains Cretaceous komatiite. The scarcity of petrologic and geochronologic data for the Serranía de Baudó, as well as the absence of seismic data for the western flank of the Atrato Basin, impede understanding of the role the Baudó morfotectonic unit plays in the most recent phases of geo-tectonic development of the Panamá-Chocó Arc. The Atrato and San Juan Basins were historically referred to as the Chocó Basin. They are physiographically bound to the west by the Baudó Range, to the east by the Western Cordillera Mande – Acandi Batholith.

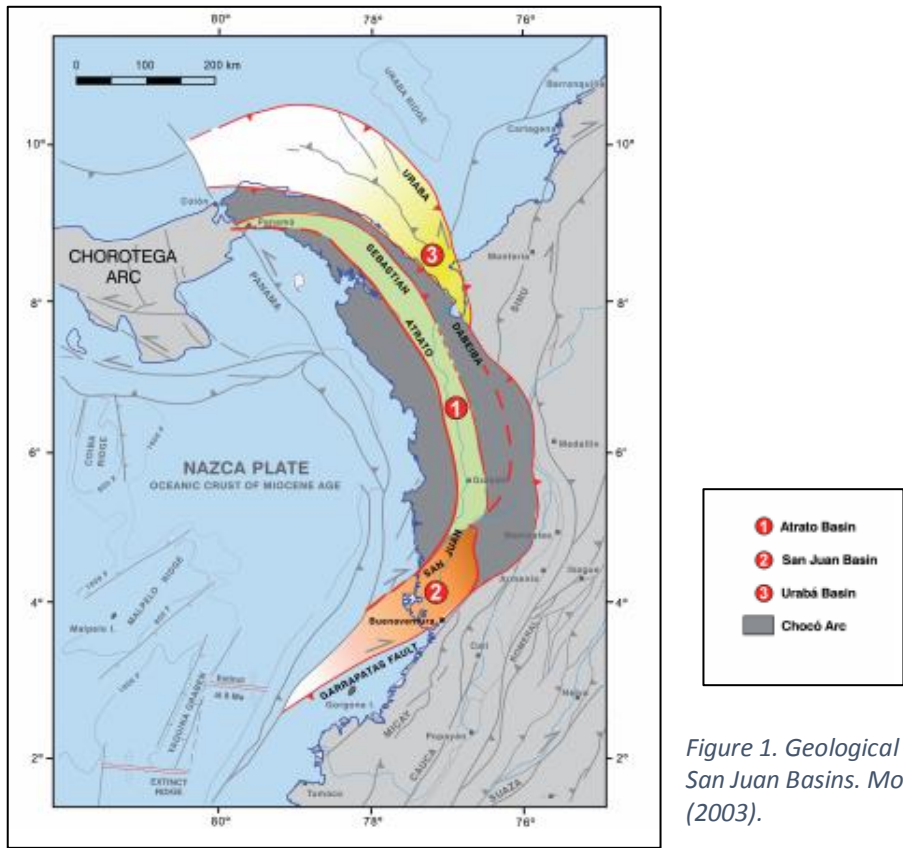


Figure 1. Geological situation of the Atrato and San Juan Basins. Modified after Cediel et al., (2003).

The Atrato Basin to the north, and the San Juan Basin to the south, are separated by the San Juan Fault System. The San Juan Basin continues to the south-south west into the Pacific Ocean. To the north the Atrato Basin continues geographically in the Republic of Panamá. The Atrato Basin covers approximately 25,000 km² whilst the San Juan Basin covers approximately 10,500 km². The Urabá Basin lies in the eastern flank of the Choco-Panama Arc, facing the Caribbean Sea; to the south it is covered by Holocene deltaic deposits

1.2 Exploration history

This balance of the geological exploration of the Atrato, San Juan and Urabá basins is the result of the systematic compilation of data generated by early-phase exploration undertaken by various petroleum and mineral exploration companies since the 1940's (Figure 2). Many of the documents produced during these programs are lost, and only a fraction of them are preserved and sometimes in poor physical condition. Regardless, we feel that efforts to recover the most relevant information and results have been successful, and that these data augment and support the conclusions presented herein.

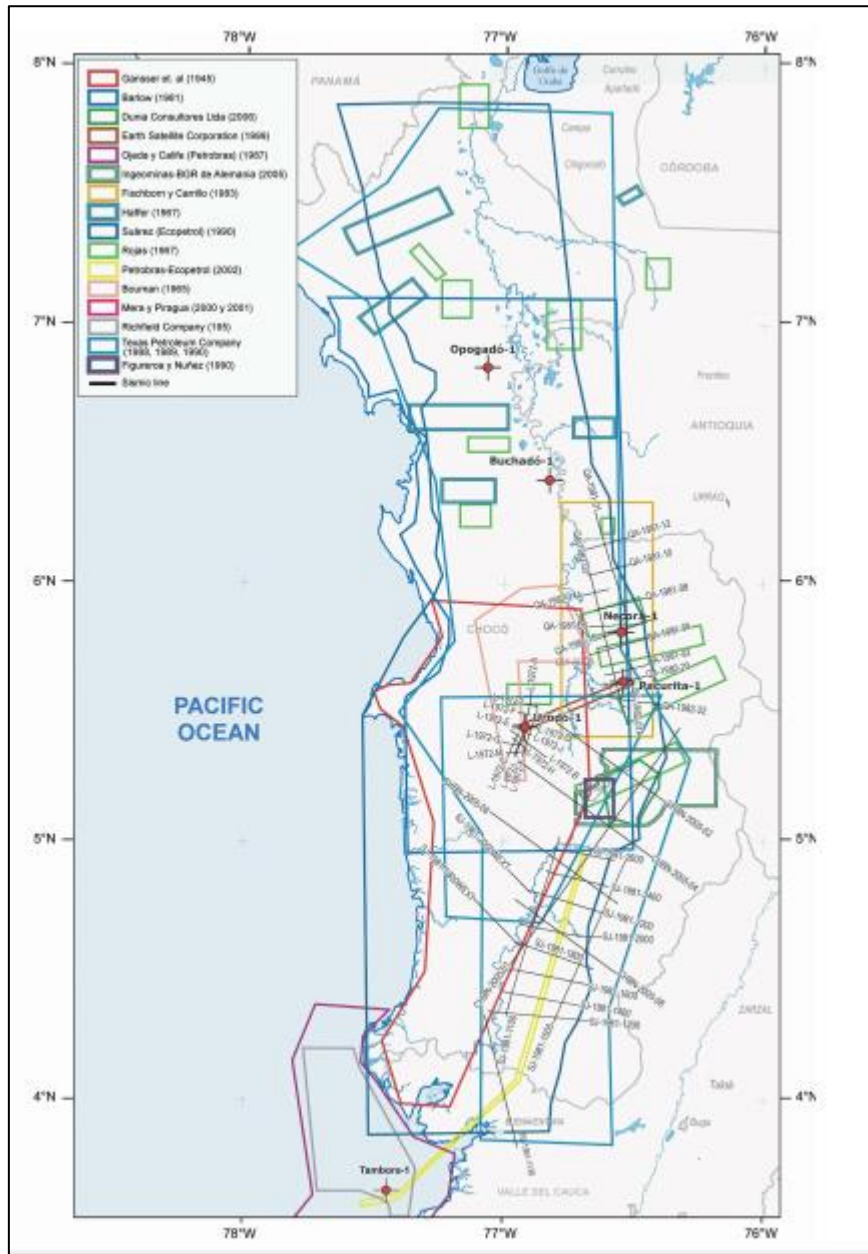


Figure 2. Location of source data used in this study.

The evaluation and interpretation of available information were completed using modern techniques, within the context of present scientific knowledge for the region. We were particularly careful to review geological concepts and interpretations elaborated on the bases of punctual data, in order attain an adequate regional evaluation according to the (very low) density of available information for the three basins. It can now be asserted that these basins are sub-explored.

However, this does not mean that their rating is negative. On the contrary, the balance is positive; we have identified important exploration opportunities which deserve further investigation.

The presence of hydrocarbon-generative rock in the San Juan basin is deduced upon the basis of the geochemical characterization of the Iró Formation in the Istmina-Condoto High. Furthermore, on the basis of results obtained from hydrocarbon generation model 1D, we conclude that units, which have not been studied from a geochemical standpoint, such as time-stratigraphic equivalents of Iró Formation, including the Salaquí and Clavo Formations in the Atrato Basin, were subjected to important hydrocarbon generation and expulsion processes during late Miocene-Pliocene. The presence of oil seepages at surface attests to bedrock permeability, which permits the migration of hydrocarbons.

Principle field exploration to date, including seismic programs and wildcats wells are shown in *Figure 3* Taking into account the surface extension of each of the basins, the results obtained in the present study, and the identified exploratory potential, it can be concluded that both basins are in an incipient exploration stage or, in other words, are sub-explored. For instance, only five wildcat wells have been drilled in the Atrato Basin.

- Buchadó-1, Richmond 1953, T.D. 15.539'
- Opogadó-1, Continental 1973, T.D. 11.372'
- Urodó-1, Superior 1973, T.D. 15.000'
- Pacurita-1, Asamera 1981, T.D. 9.489'
- Nécora-1, Asamera 1983, T.D. 6503'

Amongst the mentioned wells, Opogadó - 1 and Urodó - 1 were drilled, at least partially, into “structural highs” now identified as mud diapirs.

Pacurita-1 and Nécora-1 stopped near the top of the Oligocene, and did not reach their exploration objective which included higher potential rock units, at lower stratigraphic levels.

Buchadó-1 totaled 15,539 feet in depth, reaching the top of the Upper Eocene. These rocks are chronostratigraphic equivalents to the Iró Formation, recorded in the Istmina-Condoto High, known for its capacity to generate hydrocarbons. Buchadó-1 seems to have been drilled out-of-structure. Regardless, it presented important hydrocarbon showings between 5,800' (gas) and 11,500' (oil). In the San Juan Basin, only one well, Tambora-1, was drilled. It is located off-shore and partially crossed a mud diapir

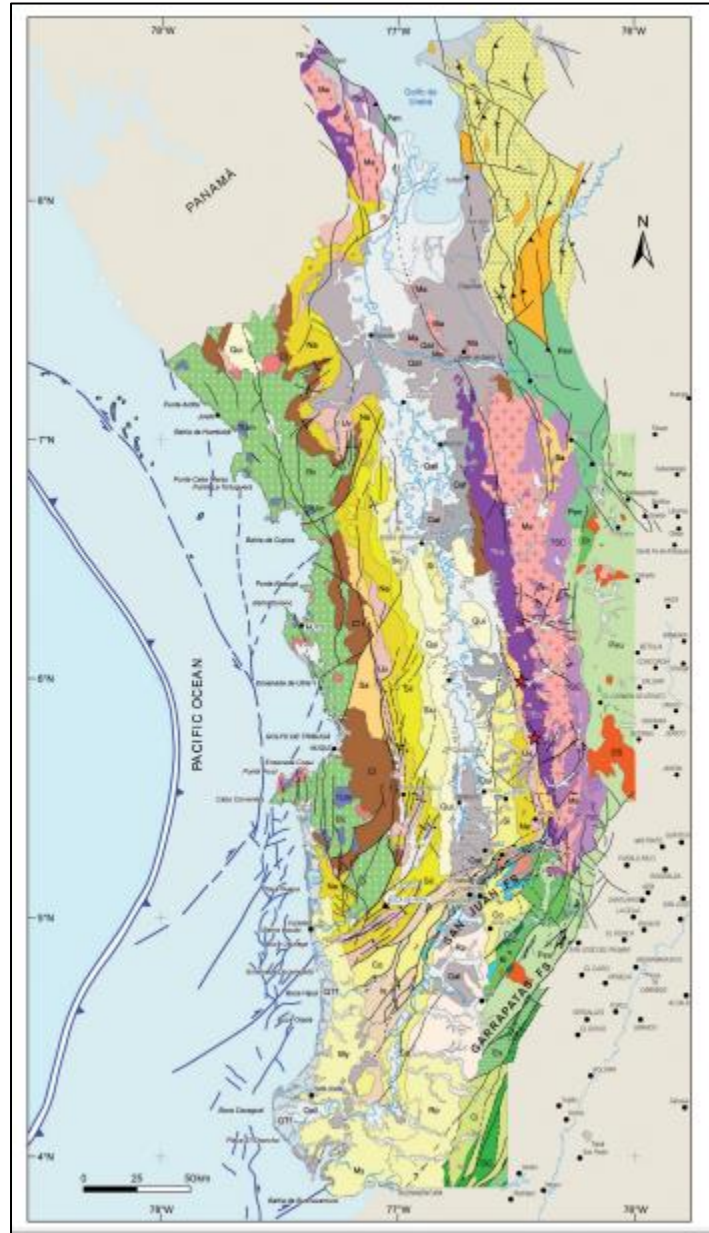


Figure 3. Geological Map Chocó Arc: Atrato, San Juan and Urabá Basins. Modified from these sources: IGAC (2006), Schmidt-Thomé et al, (1992), Minera Utah de Colombia (1980).

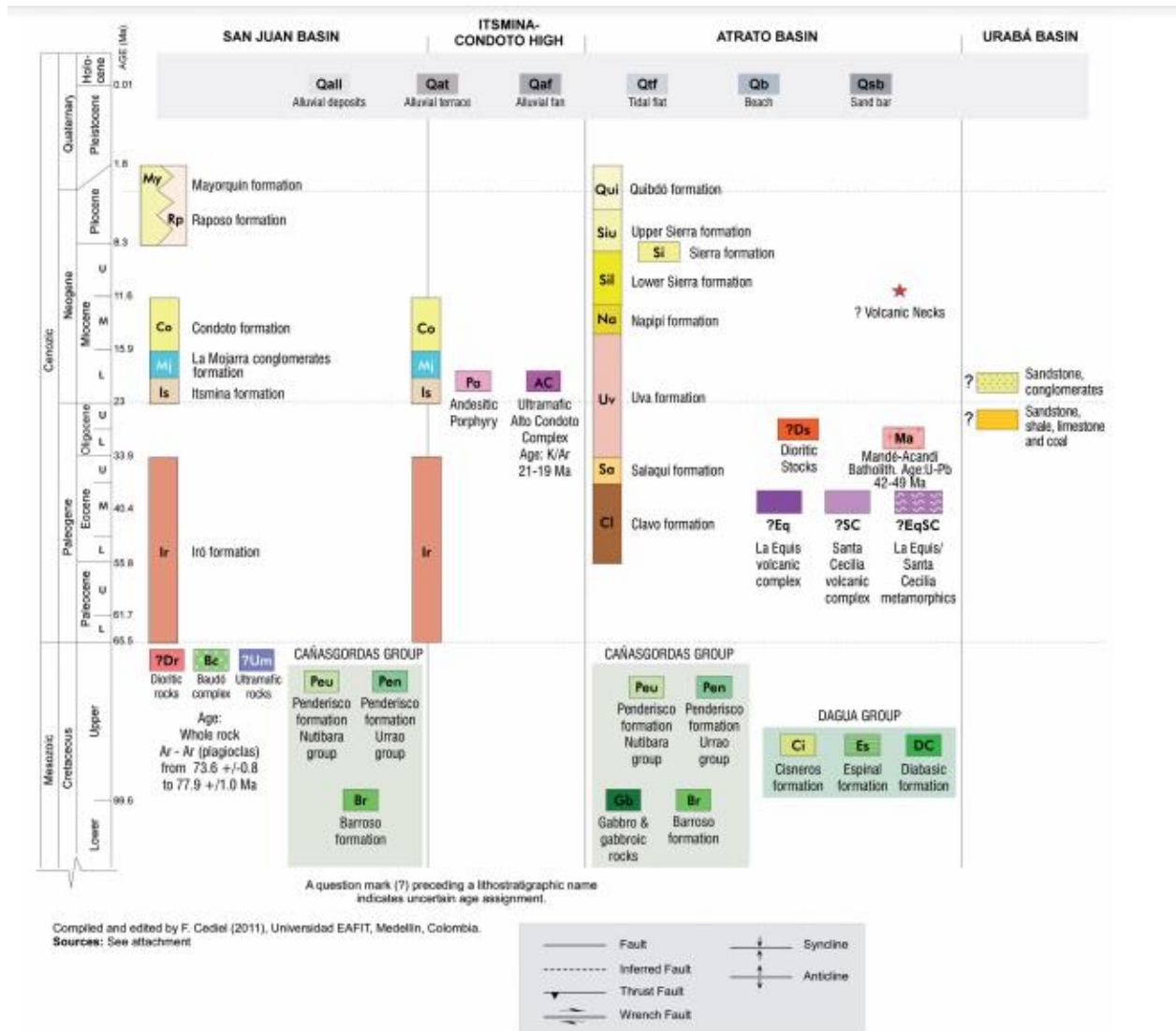


Figure 3a

2 GEOLOGICAL FRAMEWORK

2.1 Surface geological mapping

Surface geological mapping is a very difficult task in the Chocó-Panamá Arc because the dense, rain tropical forest that covers the whole area and the lack of access infrastructure. Nevertheless, field work along rivers and creeks started in the late 40's, in several field campaigns conducted by Shell Oil Co. A significant amount of stratigraphic data collected at that time is still the support and basis for our regional understanding of the Atrato basin in particular. Sporadic and local field surveys were carried out in the second half of the last century by mining companies.

The attached geological map (*Figure 3*) is the result of a systematic compilation of field studies and and new structural interpretation of radar images, satellite images, digital elevation models and aerial photographs.

2.2 The istmina-condoto high

The BGR-INGEOMINAS (Muñoz et al., 1990) study provides the most comprehensive geological knowledge of this area. The (ICH) (*Figure 4*) is a SW-NE elongate composite structure, approximately 130 km long and up to 30 km wide, which plunges to the SW beneath a thick cover of Cenozoic sediments and into the Pacific Ocean. This structural assemblage contains thrust, high-angle reverse, and normal faults and associated folds, all of which define a transpressive shear zone with right lateral displacement. With the exception of the Pleistocene deposits, all rock units present angular base-and-top unconformities and a high degree of deformation. Based upon a close association with typical upper mantle ultramafic rocks, it is inferred that the composite IstminaCondoto structure evolved within an intra- oceanic suture, beginning in the late Cretaceous followed by exhumation in the Cenozoic.

The last phase of uplift took place along SW- NE striking faults, causing flow reversal of the regional drainage system into the present San Juan basin, especially along the Mondo, Bochoroma and Iró rivers. The following is a brief description of the most significant igneous rocks associated with the Istmina-Condoto High

2.3 El paso complex

El Paso Complex is the oldest lithological unit in the Chocó Arc. It is a strongly fractured sequence of high Mg-tholeiitic basalts and ophitic diabases with interbeds of chert, claystone and mudstone. Cr/Y and Ti/ Zr ratios suggest an oceanic (MORB) origin. No radiometric dates are available, however regional geologic analysis indicates that the El Paso Complex is likely late Cretaceous to Paleocene in age.

2.4 Viravira complex

This complex includes a sequence of basalt, basaltic breccia, peridotite, harzburgite and serpentinized dunite, along with mudstone, black claystone, fine grained sandstone, some calcareous sediments and chert. The marine deposits attain 500 m to 1,000 m in thickness. Radiolaria and globorotaloid fossils represent the Upper Eocene to Lower Miocene. Ultramafic rocks (Alto Condoto) dated at 17.8 and 21.5 Ma are known to intrude sedimentary interbeds which belong to the Viravira Complex, producing a metamorphic contact zone up to 1.5 km wide.

Geochemical data from basalt and serpentinite samples suggest magmas originated in the upper mantle, generating the komatiitic facies and high Mg contents.

2.5 Alto condoto ultramafic complex

The mapped out crops of this complex occupy an area of approximately 3 km² by 6 km². It appears to be a zoned intrusive with a dunite core, grading in composition outwards to wherlite and clinopyroxenite. In the outer rim small out crops of hornblendite, diorite and dioritic dykes are observed. Potassium-Argon radiometric dates range from 21.5 Ma, to 17.8 (Lower to Middle Miocene). Ultramafic intrusive assemblages of similar age and/or composition have not been documented elsewhere in northwestern South America.

2.6 Tectonic setting

The formation and development of the Atrato, San Juan and Uraba Basins took place within a sequence of events, which are schematically outlined in *Figure 5* The geological characterization of these events remains incomplete due to scarcity of geological and geophysical data. Regardless, evaluation of the available information within a regional context, permits recognition of the principle tectonic elements and tectono-stratigraphic events for the region. These include:

- a. The Garrapatas-Dabeiba Suture (Late Cretaceous) The youngest age recorded in the Cañasgordas Group (the principle component of the Cañasgordas Terrane), is Late Cretaceous (Maastrichtian). Accretion of the Cañasgordas Terrane to the continental margin took place along the Garrapatas-Dabeiba Suture during the Maastrichtian and possibly continued into the Paleocene. This event generated discrete (calc- alkaline subduction-related) magmatism which is not yet fully understood.
- b. The San Juan-Sebastián Suture (Eocene) The second tectonic event of regional importance involves the collision and accretion of the El Paso Terrane along the San Juan-Sebastian Suture. The Mandé Magmatic Arc, dated between 54 and 49 Ma, was generated via Chilean-type subduction processes. At the same time as the San Juan- Sebastián Suture was formed, the Atrato Forearc Basin developed, open to a western sea, the Pacific Ocean.
- c. Baudó is without doubt an assemblage of allochthonous oceanic rocks emplaced along the continental margin by the continuous interaction of an oceanic plate with the NW corner of the South American continent.

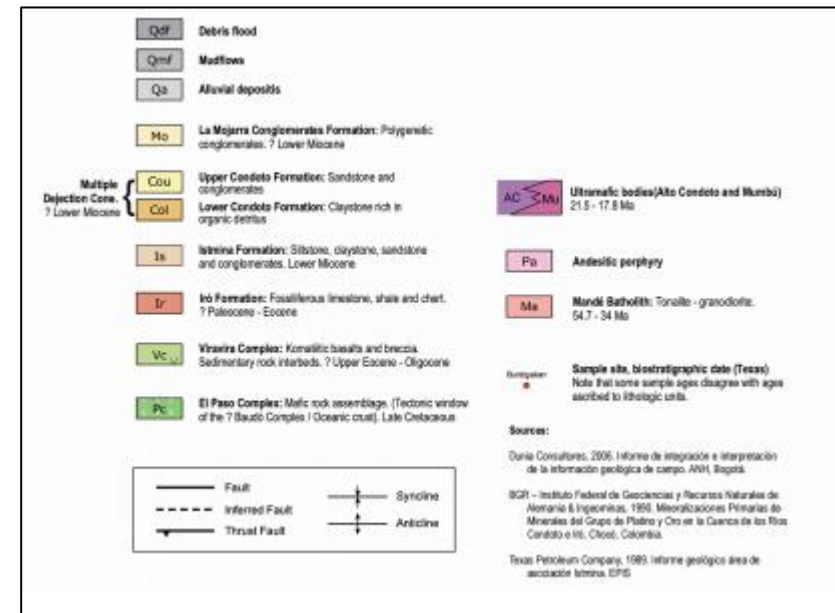
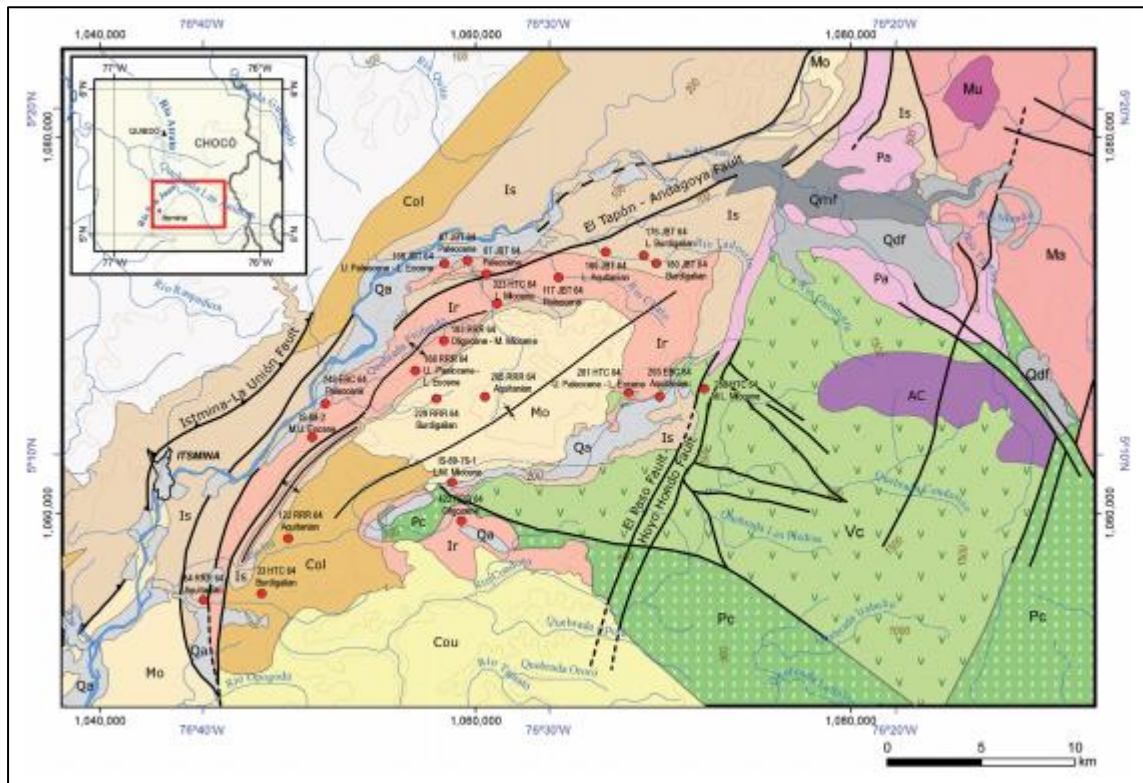


Figure 4. The Istmina-Condoto High (geological map). Source: Utah Minerals, 1980.

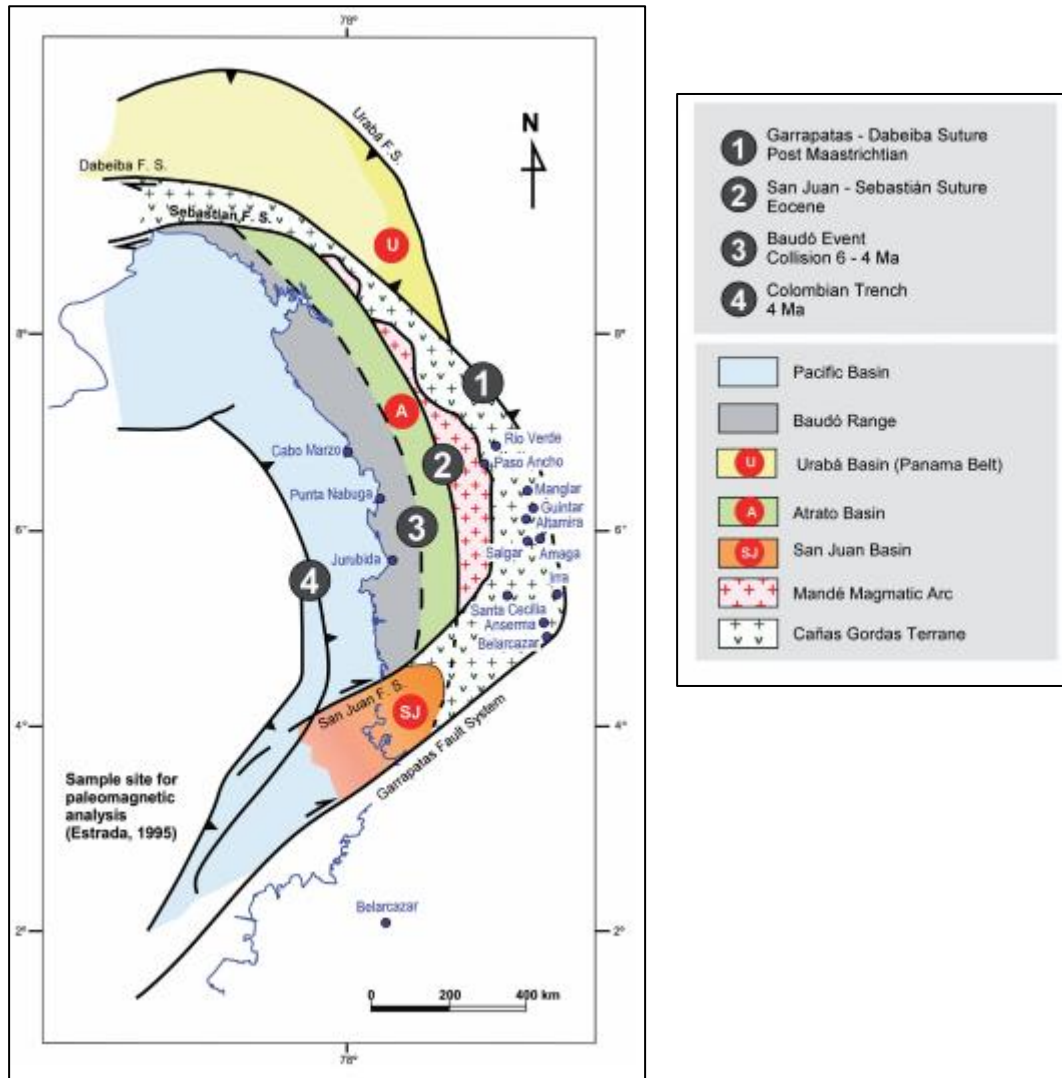


Figure 5. Sequence of major tectonic events in the Chocó Arc.

d) The subduction of the oceanic plate (El Paso?) and related Mandé magmatism developed until the relationship between density and buoyancy of the various plates curbed the process, substantially diminishing the rate of subduction. Continued compression produced a positive flexure in the oceanic plate, leading to the uplift of today's Baudó Range. This mechanism was enhanced by a rapid increase in sedimentary / lithostatic load in the forearc basin.

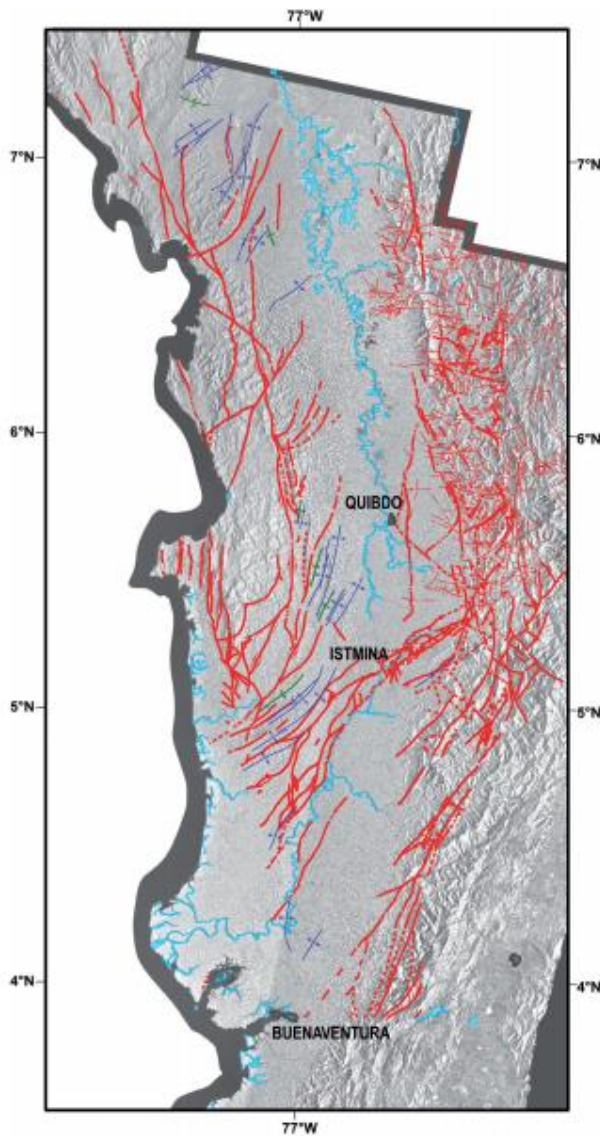


Figure 6. Surface structural map of the study area.
Note the SW-NE to SE-NW rotation (from south to north) of fold axes.

It is evident that the initial approach and collision of both the Cañasgordas Terrane and the El Paso Terrane were orthogonal. During subsequent tectonic migration a NW rotation occurred, liberating part of the collisional energy and leading to the morpho-structural development of the present-day Panamá-Chocó Arc. This rotation is inferred from the existence of tear faults and E-W trending lineaments, and from the progressive SW-NE to SE-NW orientation of fold axes mapped along the western flank of the Atrato Basin and in its extensions into Panamá (Figure 6).

The allochthonous character of the Cañasgordas Terrane and of the Baudó Range has been demonstrated using paleomagnetic evidence by Estrada (1995). Paleomagnetic data have significantly improved knowledge of the paleogeography and paleotectonics of the Chocó Arc. Some of the important conclusions of Estrada's work are summarized below:

The following facts, support the postulated sequence of tectonic events:

San Juan Basin basement is formed by the Cañasgordas Terrane, or alternatively by the Gorgona Terrane in the case that paleogeographic interpretations by Estrada (1995) are correct, as it shows a distinct gravimetric and magnetometric texture with respect to the one observed in the basement of the Atrato Basin.

The Atrato Basin basement is formed by the El Paso Terrane (Baudó Complex), which outcrops in a tectonic window in the Istmina-Condoto High (along the San Juan Suture).

The San Juan Basin is limited by two important sutures / subparallel transcurrent fault systems (the Garrapatas-Dabeiba Suture and the San Juan- Sebastián Suture). These structures controlled sedimentation since the Oligocene (?), and gave rise to a deltaic system which prograded in a NE to SW direction.

There are at least three distinct latitudinal provinces and ages for the rock assemblages in this region, including the Baudó Arc, Cañasgordas Terrane and Gorgona Terrane (the Chocó Terrane, Western Cordillera Terrane and Gorgona Terrane, respectively, of Estrada, 1995). The paleolatitudinal origins of these assemblages are directly associated with the tectonic evolution of the eastern Pacific plates. In this sense, it is known that since the Late Cretaceous, plate interactions along NW South America have been dominated by subduction of the Farallón Plate (Pardo-Casas & Molnar, 1987 as cited in Estrada, 1995) In these and others reconstructions the Farallón plate moved along a north-directed vector up to the Paleogene, when motion shifted to mainly SW to NE.

The relative motion of the Farallón plate suggests that terranes accreted against the western edge of South America were transported from southern latitudes. The Gorgona terrane is composed of a sequence of Mesozoic mafic and ultramafic rocks, including komatiitic flows. Paleomagnetic data indicates that the El Horno basalt (86 +/- 3 Ma) was located at about 25 S relative to South America in Late Cretaceous time. The longitude cannot be precisely fixed by paleomagnetic methods. However Estrada (1995) presented some reconstructions and possible trajectories that suggest a longitude of origin of 135 W. The accretion of the Gorgona Terrane is considered to be pre-Miocene (McGeary & Ben-Abraham, 1989 as cited Estrada, 1995) and was possibly followed by strike-slip faulting along the Buenaventura fault zone, resulting in the break up of the original terrane. Paleomagnetic data from the Gorgona Terrane doesn't have any clear correlation with data from the Caribbean Plate. The Cañasgordas Terrane and the Baudó Arc, present two groups of paleomagnetic data with the main group having a mean of about 10, suggesting equatorial paleolatitudes of origin.

Based upon preliminary geological mapping, the Baudó Arc, is comprised of oceanic basalts with interbedded sediments of late Mesozoic to early Cenozoic age. Samples recorded two sets of data, one compatible with a 15 paleolatitude origin, and a second with 5 to 10 equatorial paleolatitudes. The nature of the paleomagnetic data is not conclusive but the geological framework favors a southern provenance.

2.7 Surface structural expression

Faults and folds shown in the surface structural map (*Figure 6*) were compiled from data recorded during various field campaigns as well as from air photo interpretation. All of the available information was compiled at 1:500,000, and reinterpreted and corrected using a Digital Terrain Model (DTM) and radar images. Subsurface structural control is limited to the interpretation of gravity and magnetic-based geophysical studies. Faults, interpreted in various seismic campaigns, apparently don't reach the youngest strata. It appears that this recent cover is very thick and contemporaneous with deformation.

The Atrato Basin is limited to the west by faults which put the “Baudó Complex” in contact with several sedimentary units. Some of these “faults” or lineaments could correspond to stratigraphic unconformities. The general impression is that the entire fault system is formed by a series of growth faults of varying ages. Absence of field and subsurface data precludes a better understanding of the type of deformation which controls the basin's western flank. It is important to stress that the orientation of fold axes developed in the western flank of the basin shift progressively from SW-NE to SENW. This observation attests to stress field rotation, compatible with the geometry of the Chocó- Panamá Arc. The eastern flank of the Atrato Basin coincides with an almost rectilinear fault system with a preferential N-S orientation, which places part of the sedimentary sequence in contact with igneous rocks of the Mandé Magmatic Arc. Data from outcrop favors the interpretation of these faults as normal faults or as high-angle reverse faults. The geometric pattern of this fault system, and its location along the eastern boundary of the basin however, suggests that it records right lateral displacement during most of the Neogene. To the north, the Atrato Basin continues into Panamá, recorded as the Chuquanaque-Tuira Basin. The southern limit of the Atrato Basin is formed by the Isthmina-Condoto High, which is also the N-NW limit of the San Juan Basin. With respect to the San Juan Basin, at surface, no important structures are presently discernible, as recent sedimentary deposits mask more than 90% of its surface area. A distinct geomorphological architecture is apparent; it could potentially be interpreted from a structural standpoint. Such a study deserves future consideration.

3 STRATIGRAPHY

The so called Chocó Pacific Basin (ANH, 2007) is characterized by marine to continental deposits resting on an igneous sedimentary basement. However, stratigraphic characteristics recognized during the present revision, and the evaluation of available information, allow the differentiation of two distinct sedimentary basins: the Atrato and the San Juan. (*Figure 7*).

3.1 ATRATO BASIN

3.1.1 Introduction

Geologically, few cartographic studies have been undertaken in the Atrato Basin. The most comprehensive was completed by Haffer (1967), who also provided various biostratigraphic analyses. Haffer's 1967 lithostratigraphic descriptions are utilized in the present report. The Atrato sedimentary sequence is composed of six lithostratigraphic units ranging from the Lower Eocene to the Pliocene (*Figure 8*). Ages were determined utilizing the abundant planktonic and benthic foraminifera. Limits between lithostratigraphic units are similar to those recognized previously (Haffer, 1967; Duque-Caro, 1991), but have been updated to recent time scales (Gradstein et al., 2004). The Atrato Basin contains a thick

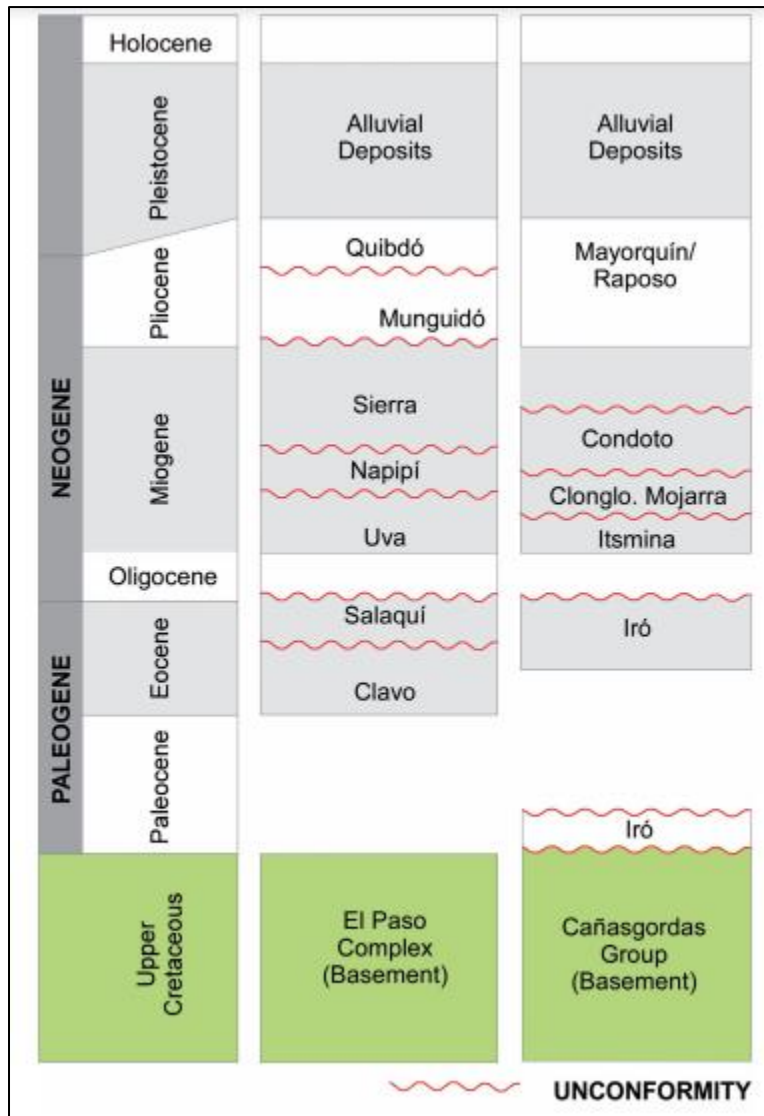


Figure 7. General lithostratigraphic sequence in the Atrato and San Juan Basins.

sedimentary sequence, deposited over an igneous sedimentary basement. The total thickness reaches 10 km and was deposited in marine environments with minor transitional and continental influences towards the Pliocene. The Uva, Napipí, Sierra, and Quibdó Formations outcrop extensively and are widely distributed over the western margin of the basin, and to a lesser extent, over the eastern margin of the upper Atrato River region. By contrast, the Clavo Formation is restricted to a single sector of the western margin of the basin. The Salaquí Formation outcrops along both margins. Each of these Formations purports unique lithologic characteristics, including internal facies variations, that represent differences in depositional conditions, as derived from field descriptions. The available information shows that there are sandier facies over the eastern margin of the basin.

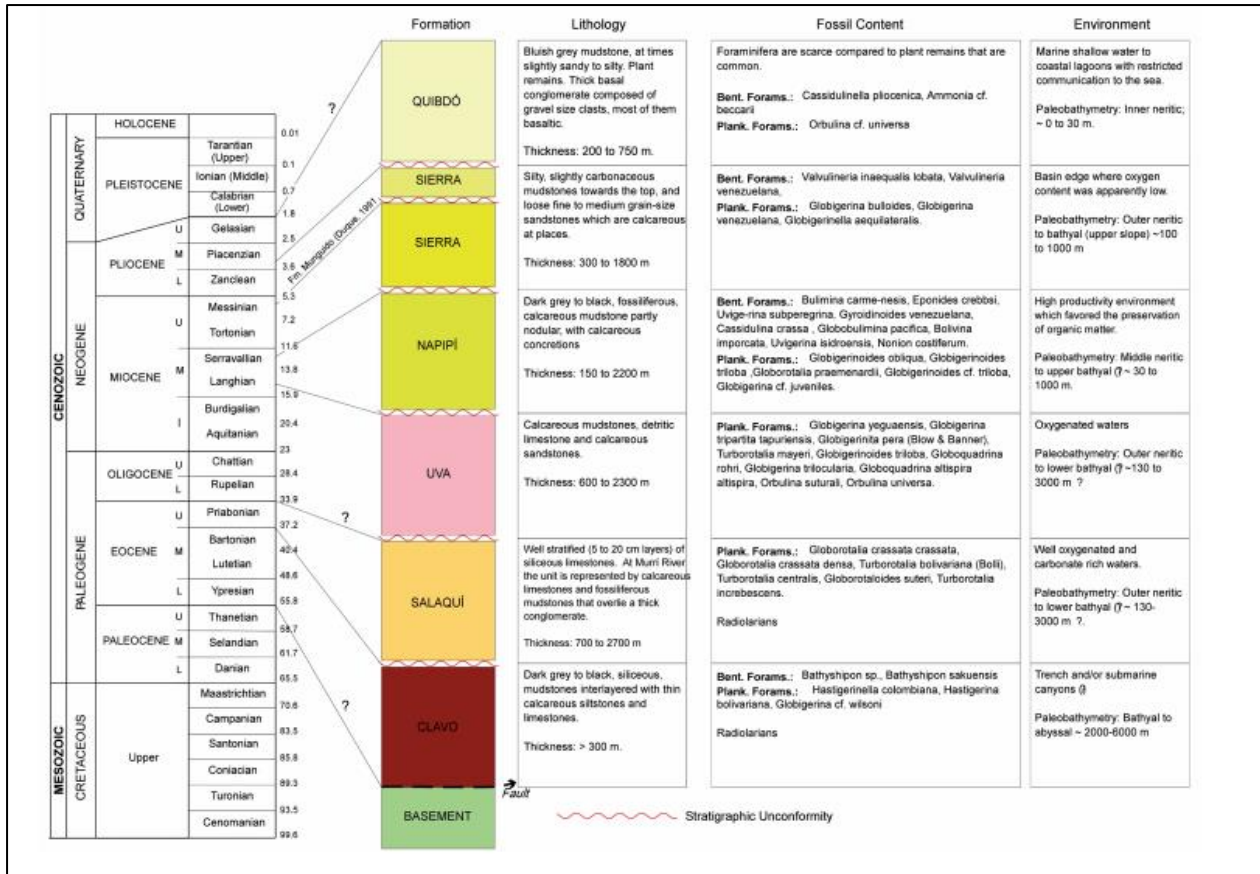


Figure 8. Chronostratigraphic chart and depositional environment of the Atrato Basin.

At present however, available data does not allow the definition of source and provenance directions. Correlation of these units clearly shows the degree of stratigraphic continuity, and relations at depth, according to the biostratigraphic interpretation of some wells (Figures 9 and 10), similarly, variations in thickness of each unit are evident, indicating sedimentary processes controlled by differential tectonic activity. In general terms, stratigraphic units tend to become thicker towards the south. This is most conspicuous for the Uva Formation whose thickness varies from approximately 1,200 m in the north to approximately 2,300 m in the south. It is also worth noting that the Salaquí Formation, in the Rio Murri section, outcrops in fault contact with the Quibdó Formation. In this section, the Salaquí Formation is composed of 1,700 m of conglomerates with two interbedded lava flows

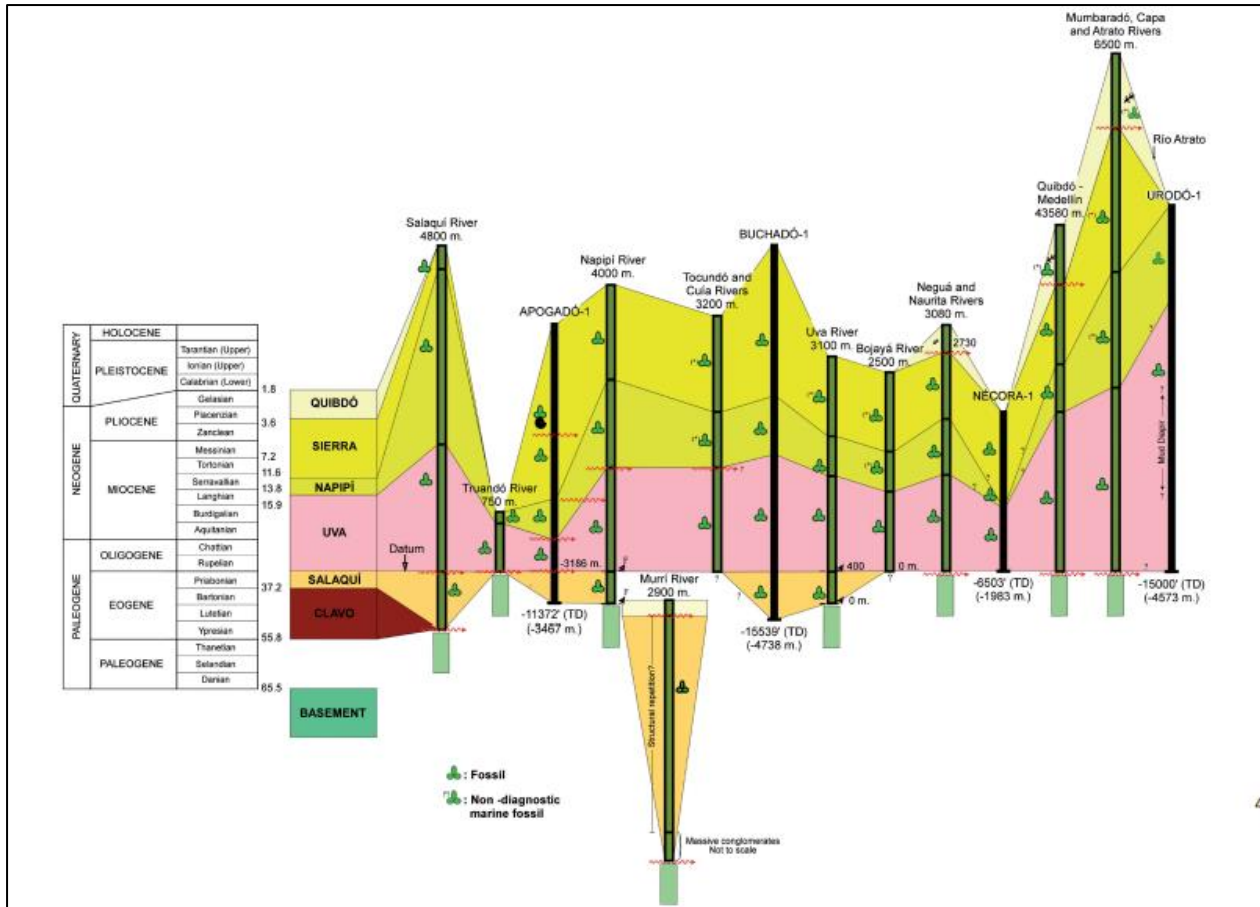


Figure 9. Lithostratigraphic correlation chart of the Atrato Basin

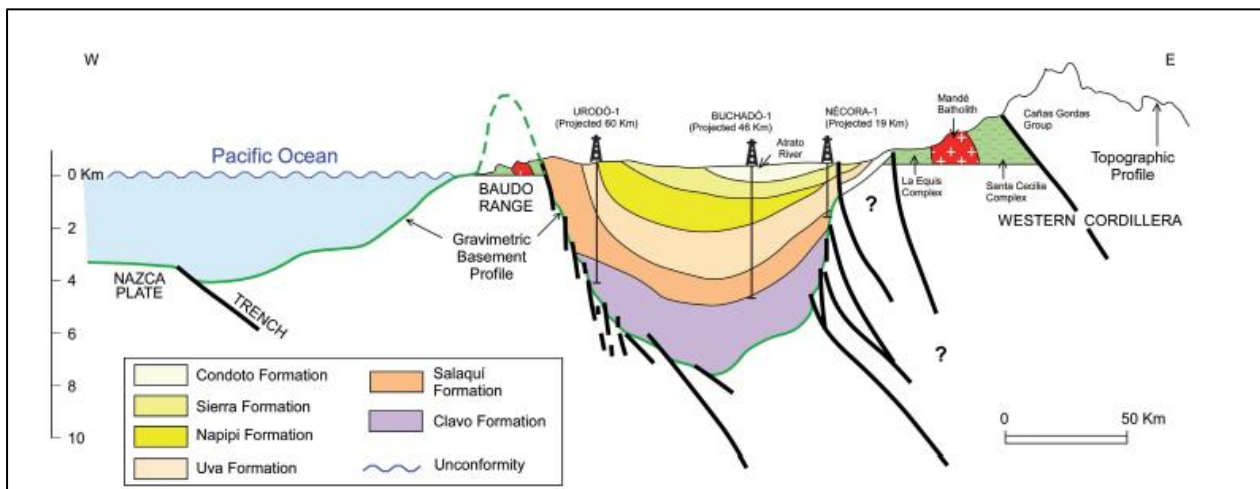
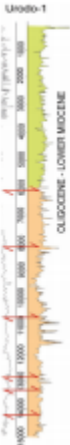


Figure 10. Schematic profile along parallel 6.0°N.

3.1.2 Exploratory wells in the atrato basin

Between 1953 and 1983, various oil companies drilled five wells in the Atrato Basin. The stratigraphic and biostratigraphic information of each well has been re-evaluated by various authors, looking to define more precisely the limits between each lithologic unit. The comparison of lithostratigraphic boundaries demonstrates incongruence in the definition of the tops and bases of each unit. With respect to the present study, only those biostratigraphic schemes considered most consistent were utilized in stratigraphic correlation between wells. Buchadó-1 was the first well drilled in the basin and the one that provides the most significant data (Table 1). Studies are mainly biostratigraphic, based on foraminifera. Table 2. shows the stratigraphic schemes for the Urodó-1 and Opogadó-1 wells. For the Urodó-1 the tops of each lithostratigraphic unit, as defined by Muñoz and Cogollo (2001) are based on biostratigraphic information. For the same well, Suárez (1990) and Duque-Caro (1991) defined each top according to seismic horizons tied to the Buchadó-1 and Opogadó-1 wells. Table 3. presents stratigraphic schemes for the Pacurita-1 and Nécora-1 wells. Muñoz and Cogollo (2001) presented schemes are based on biostratigraphy, whereas others are based on seismic reflectors tied to the Opogadó-1 well



BUCHADÓ-1 (T.D. 15539) (Richmond Petroleum Company, 1953)						
Formation	Richmond, 1954	Robertson, 1985	Robertson, 1988	Suárez, 1990	Duque-Caro, 1991	Muñoz y Cogollo, 2000
Quibdó	1320'	5000'	No samples above 6090'	1305'		
Munguadó						
Sierra	5805'	7000'	6300' (?)	8650'	~8659'	6750'
Napipi	6490'	11000'	8700' (?)	10140'	~10345'	
Uva	10160'	12740'	13400' (?)	13160'	~10120'	No samples below 6750'
Salaquí	13170'			15539'	Unknown sedimentary sequence 15539'	
Clavo	15539' (?)	15539' (?)	15424' (?)			

Table 2. Tops of the lithostratigraphic units as defined in the Buchadó-1

Table 1. Tops of the lithostratigraphic units as defined in the Buchadó-1

Formation	PACURITA-1 (T.D. 9489) (Asamera Inc., 1981)			NÉCORA-1 (T.D. 6503) (Asamera Inc., 1983)	
	Suárez, 1990	Duque-Caro, 1991	Muñoz y Cogollo, 2000	Suárez, 1990	Muñoz y Cogollo, 2000
Quibdó					No samples above 3170'
Munguadó					
Sierra	1605'	~1312'	2210' (?)	660'	3890'
Napipi	4550'	~3490'	6530' (?)	2860'	3980'
Uva	5405'			4630'	6503'
Salaquí	9489'	Unknown sedimentary sequence 9489'	No samples below 6530'	5600'	
Clavo				6503'	

Table 2. Tops of lithostratigraphic units as defined in the Urodó-1 and Opogadó-1

OPOGADÓ-1(T.D. 11372') (Continental de Col. & Oil Gulf Co., 1974)			
Cont. y Gulf, 1974	Robertson, 1985	Suárez, 1990	Duque-Caro, 1991
4650' (?)			
7350'	5600' (?)	7300'	7300'
9700'	9719' (?)	9050'	9050'
10050'	10382' (?)	9950'	10450'
		10450'	Unknow sedimentary sequence 11372'
11372' (?)	11372' (?)	11372'	

Table 3. Tops of lithostratigraphic units as defined in the Pacurita-1 and Nécora-1

3.2 SAN JUAN BASIN

3.1.3 Introduction

A large percentage of stratigraphic studies on the San Juan Basin are of local character and are concentrated in the Istmina Condoto High, in the upper San Juan River. From this point information has been extrapolated southward into the entire basin.

The sedimentary succession consists of five lithostratigraphic units that range in age from Paleocene to Pliocene. Temporal limits that were taken from the available biostratigraphic data are shown in *Figure 11*. According to its faunal content, most of the succession was deposited in marine environments with a strong continental influence. The possible absence of the Paleocene Eocene and Oligocene Upper Miocene, as evidenced in the Istmina Condoto high, suggests intense and long lasting erosive periods. The Pliocene Raposo and Mayorquín Formations out crop widely. The Iró and Mojarra conglomerates out crop exclusively in the Istmina - Condoto High, (*Figure 11*). The available information does not allow the construction of stratigraphic correlation models similar to those proposed for the Atrato Basin. However, the seismic profile and facies interpretation presented by Escobar (1993, *Fig. 12*) offers an excellent overview for the San Juan Basin.

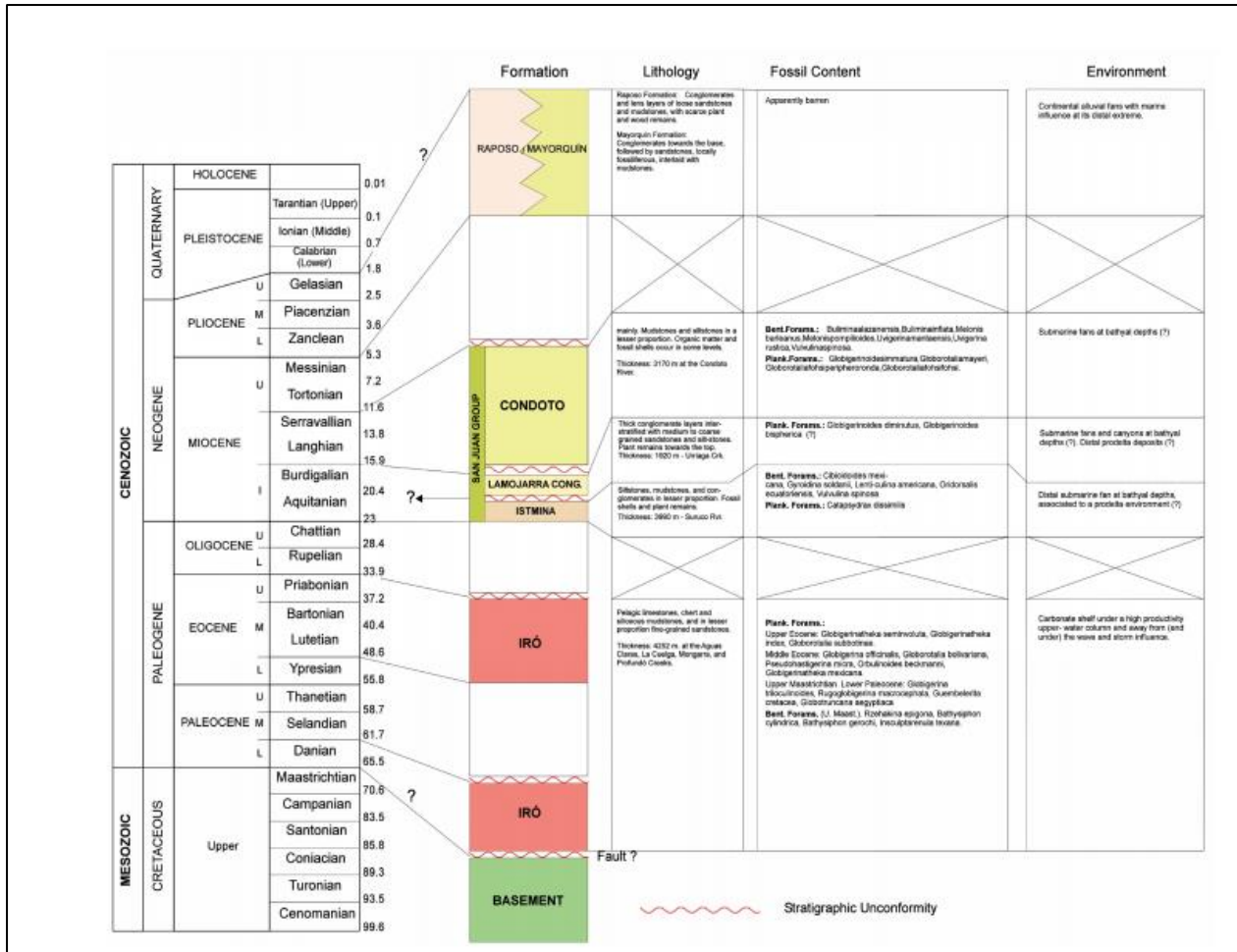


Figure 11.. Chronostratigraphic chart and deposit environment of the San Juan Basin.

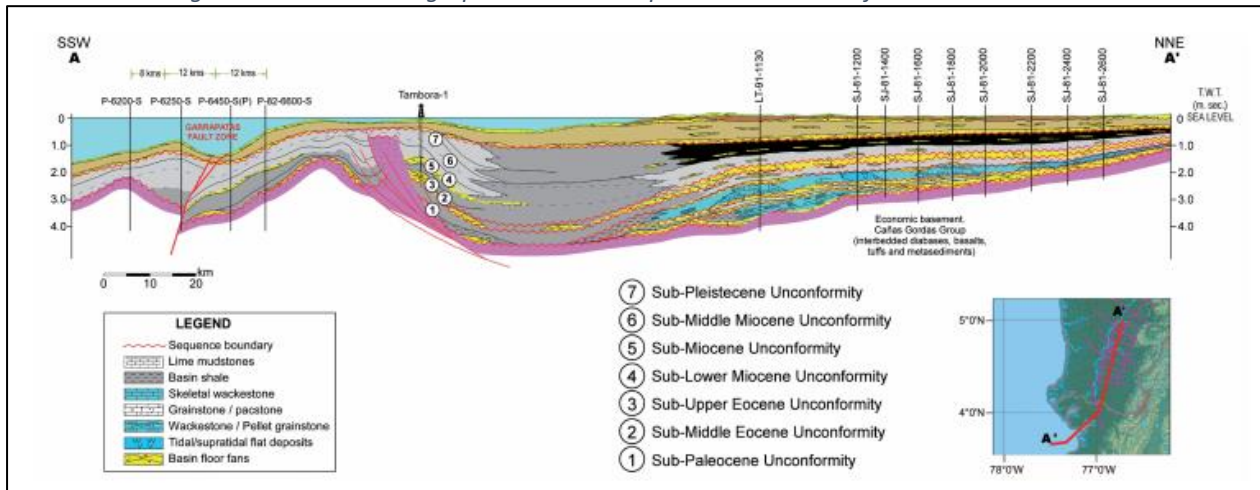


Figure 12. Schematic cross-section along the San Juan Basin. Modified after Escobar, 1993.

3.1.4 Exploratory wells in the san juan basin

The onshore portion of the San Juan Basin has not been drilled. Offshore, the Tambora 1 well (southwest of Buenaventura) has been used to tie-in seismic information from the San Juan Basin. According to biostratigraphic reports, most of Tambora-1 well material was barren. However, it is thought that the well did not reach the lower Miocene (Table 4.).

TAMBORA-1 (T.D. 11365) (Intercol, 1967)		
Formation	Robertson 1988	Muñoz y Cogollo, 2000
Raposo/Mayorquin	No samples above 2666'	?
Condoto	2696'	No samples above 8501'
Mojarra Cong.	4727'	8501' (?)
Istmina		
Iró	(6848' - 11252') barrel interval	No samples below 8501'

Table 4. Table 5. Lithostratigraphic units as defined in the Tambora-1

3.1.5 The san juan delta. a geological model for the cenozoic san juan basin

The present San Juan River delta covers a rectangular area of approximately 800 km², limited by latitudes 4o 20' N and 3o 40' N and longitudes 77o 20' W and 77o 40' W. Including the continental platform, maximum depths are around 1,000 m. Progressive widening of the continental platform and the extensive San Juan submarine lobe (defined to a depth of 1,000 m) confirms the presence of an accretionary prism, resulting from the accumulation and consolidation of sediments deposited under deltaic and marine transitional conditions, with a high sediment input due to important tectonic controls. (Figure 9 and figure 10). Furthermore, preliminary evidence of the presence of submarine canyons in the area, suggests turbiditic events were involved in prism development and modeling. Available geophysical data from the Golfo de Tortugas and Bahía Málaga identify major diapiric structures and additional structural anomalies ("structural highs") which have not yet been characterized. The Plio-Quaternary evolution of the region provides a good model for marine and transitional marine conditions under which abundant

organic matter may accumulate. North of the area, the San Juan River has developed a Holocene delta of approximately 800 km², which accommodates extensive fresh water and intertidal-brackish swamps containing luxuriant mangroves and humid tropical forests, developed under temperatures of 27o C and 10,000 mm average annual rainfall. This environment permits the production and accumulation of voluminous quantities of organic matter. Co-seismic subsidence related to large magnitude earthquakes frequently increases the capacity of the basin to accommodate additional sediments. A 4 m tidal range and strong coastal currents promote the formation of fine- and medium-grained sand bodies with

kilometric dimensions, represented by longitudinal fluvial tidal bars, extended tidal flats and at least four sequences of beach and barrier island-beach complexes, which indicate the overlapping of successive deltaic events.

With an average discharge of about 6000 m³ s⁻¹, the San Juan River alone supplies about 16x10⁶ tonne/year of suspended sediment. This material is distributed and deposited within the present prodelta and additionally contributes to the formation of the vast shallow platform which characterizes the Golfo de Tortugas, recipient of important amounts of organic muds supplied by the Raposo, Dagua and Anchicaya Rivers. Sedimentary coverage is varied and includes muds and calcareous muds with sandy patches. Geological data from the San Juan River delta (Correa & Restrepo, 1992; Restrepo et al., 2002) and a first approximation of understanding of the San Juan Basin, as derived from stratigraphy and sedimentary facies, enables us to conclude that during the Cenozoic the region provided a depocentre for calcareous, muddy and sandy sediments sourced from the north northeast. The sediments accumulated in a southwest- prograding delta whose migration was influenced by recurring seismic (tectonic) activity.

4 PETROLEUM SYSTEM

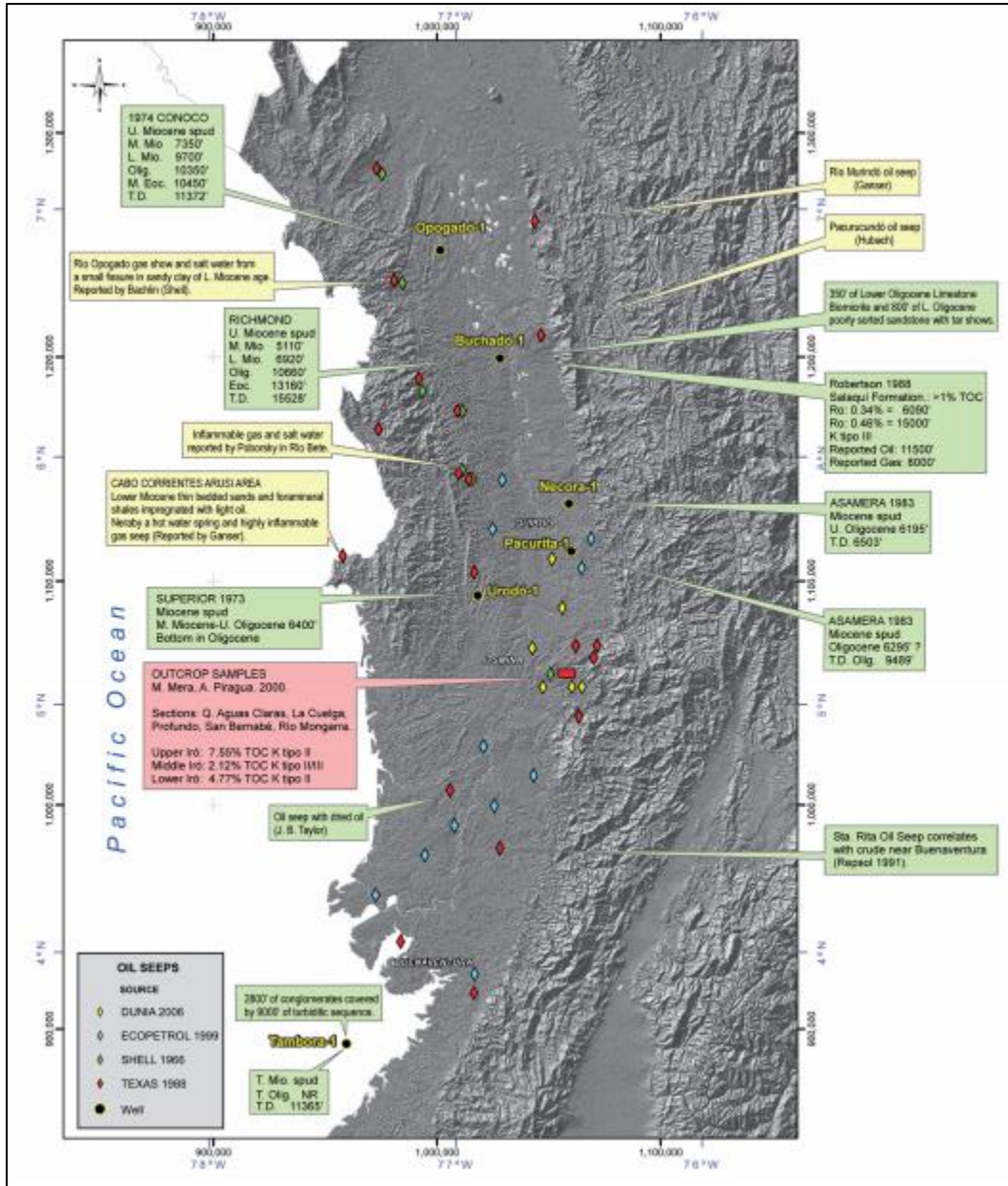
This chapter succinctly identifies and characterizes the basin's principal petroleum system elements and processes. Due to the diverse and complex stratigraphic nomenclature used by various authors, the most adequate for this exercise has been adopted. It is important to emphasize that the site chosen for 1-D geochemical modeling (in deep areas of the basin) represents hydrocarbon generation and expulsion conditions that are only valid for source rocks at that particular site. Extending these results beyond this site, or building general conclusions based on this site alone, is therefore inappropriate.

4.1 ATRATO BASIN

4.1.1 Elements and processes

Source Rock

(*Figure 13*) In the Atrato Basin, the rocks that can present favorable conditions for the hydrocarbon production are limestone and marls from the Salaquí Formation, (Eocene-Oligocene). This unit presents petrological similarities to the Iró Formation in the San Juan Basin (Paleocene- Eocene). On the other hand, the dark gray mudstones put in with limestone and calcareous siltstones from the Clavo Formation (Eocene) can also contain levels with some generating potential.



Figure

13. Geochemical source data available for the evaluation and modeling of the Atrato and San Juan Basins.

Reservoir Rock

The sequence Oligocene-Miocene composed by sandstones and conglomerates from the Uva, Napipí and Sierra Formations on the Eastern side of the Basin present favorable conditions for hydrocarbon accumulation. The calcareous and sandy sequence of the Paleocene can also have intervals with good reservoir potential. Up to date, there are no existing production fields for this Basin.

Seal Rock

The rocks that could act as a seal are the gray mudstones in the upper part of the Napipí Formation, the calcareous mudstone levels of the Sierra Formation (Middle Miocene), and the mudstones and shale in the basal part of the Munguidó Formation (Miocene Upper -Pliocene).

Trap

There are structural traps related mainly to anticlines and mud diapir in the western side and towards the center of the Basin. There are also stratigraphic traps within the Salaquí and Uva Formations as a result of the wedging against the Eastern side of the basin.

Charge

The charge would correspond to the section of rocks that are deposited between the Oligocene and the recent age.

Hydrocarbon Generation and Expulsion Processes

The results of the geochemical modeling indicate that the Clavo Formation reached enough levels of maturity for oil generation, including processes of hydrocarbon expulsion at the end of the Pliocene in the zones of greater depth for this unit.

4.1.2 Events chart

Figure 14. Illustrates the elements and processes of the speculative petroleum system proposed for the Atrato Basin.

4.1.3 Source rock properties

Organic Matter Quantity

The content of organic matter in the Buchadó-1 well is low, with average values of 0,9% of Total Organic Carbon (TOC). According to Robertson Research (1988), the percentage values of TOC are higher than 1 in the Salaquí Formation.

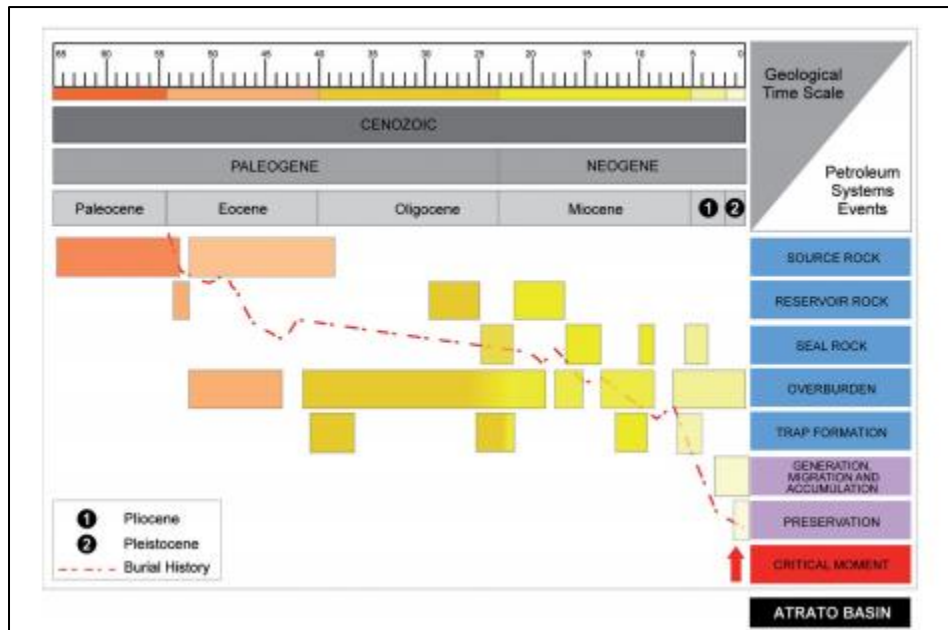


Figure 14. Event Chart of the Atrato Basin petroleum system. The red line corresponds to the burial curve of the Clavo Formation.

Organic Matter Quality

The organic matter that is characterized by pyrolysis in the Buchado-1 well corresponds to kerogen type III in 65% of the evaluated samples, while the other 35% is kerogen type IV (Figure 15). The previous information coincides with the results of the study carried out by Robertson Research (1988); in which organic petrography was used to identify 59% of Inertinite, 40% of Vitrinite and 1% of sapropel organic matter, therefore, poor quality organic matter with very low potential for liquid hydrocarbon production is expected. Because of the lithofacies similarities between the Salaquí Formation and the Iró Formation (of the San Juan basin), organic matter with similar characteristics of richness and quality could be expected, nevertheless, the little data that is available for the Salaquí Formation reveals very inferior characteristics to the ones measured in the Iró Formation.

Thermal Maturity of the Organic Matter

The maturity evaluated in this same well shows values near to 435° C of Maximum Temperature (TMax) and Vitrinite Reflectance (%Ro) below 0,6 corresponding to the beginning of the generation window. Figure 16. According to the study carried out by Arias, et al. (1988) to the Eocene -Miocene section, the reported Spore Coloration Index values (SCI) went from 3,0 to 5,5; and the values for vitrinite reflectance (%Ro) were between 0,23 and 0,61 equally reflecting low thermal maturity in the evaluated sectors. By means of 1D geochemical modeling in the deepest parts of the basin, it has been possible to consider values corresponding to the oil generation window.

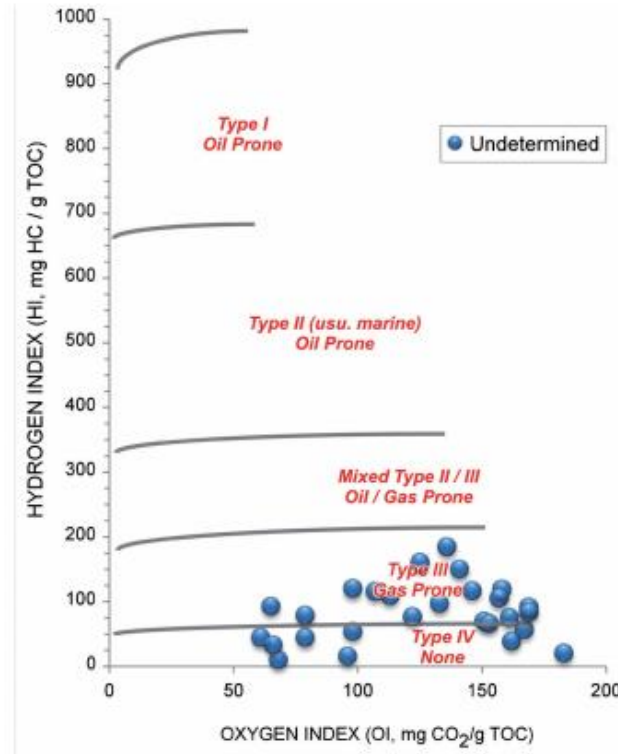


Figure 15. Modified Van Krevelen Diagram (HI Vs OI), kerogen type III and IV

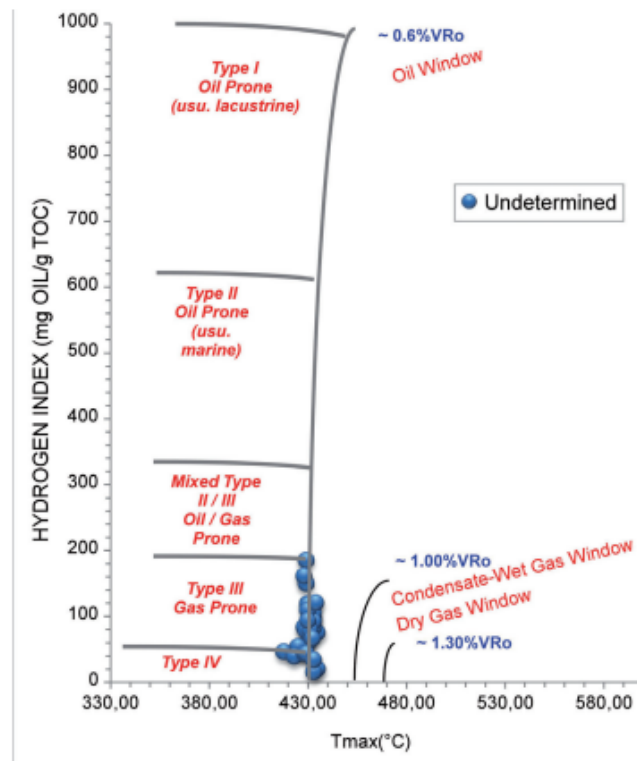


Figure 16.. Hydrogen index and thermal maturity of the organic matter. Samples located at the beginning of the generation window.

Hydrocarbon Generating Potential

The geochemical evaluation that was carried out to the rock samples coming from the deepest interval of the Buchado-1 well (units not differentiated), suggests a regular to good generating potential mainly for gaseous hydrocarbons. *Figure 17*. The generating potential considered for the Salaquí and Clavo Formations could be depreciated due to low availability of information, taking into account the lithofacies similarities with the Iró Formation in the San Juan Basin.

Figure 18 illustrates a synthesis of the main geochemical characteristics that can identify the Salaquí and Clavo Formations. Due to their similarities with the Iró Formation, they are considered to be the source rock of the basin. The presence of hydrocarbon shows on the surface suggests the existence of an active petroleum system; nevertheless, the lack of data does not give the possibility to establish the characterization.

4.1.4 Petroleum system models

The simulation of hydrocarbon generation and expulsion processes was carried out using a well in the deepest area of the Basin, tied up to the seismic line QA-1982-20. *Figure 19*. According to the geological evolution model for this sector of the Basin, the base of the sequence in the middle Eocene reached a maximum burial depth of 27000 feet during the Pleistocene and maximum temperatures of 372°F. *Figure 20*. A history of constant heat flow with an HF of 38 mw/m² was used. Based on the geochemical information of the regional and local rock, a generating interval to the top of the Clavo Formation was included in the model. The results of the simulation indicate that this unit reached levels of maturity in the rank of the delayed phase of oil generation (% Ro= 1,1, *Figure 21*), with processes of hydrocarbon expulsion at the end of the Pliocene, associated to the burial as a consequence of the Quibdó Formation deposit (3,5 - 1,8 m.a.) *Figure 22*.

4.1.5 Definition of the petroleum system

Integration of geological, geochemical and modeling information suggests the existence of an active petroleum system with evidence of hydrocarbon migration towards the surface (oil seeps), from the Clavo and Salaquí Formations towards the sandy sequences of the Uva

Formation. Petroleum system (Clavo -Salaquí) -Uva (?)

Since it has only been possible to estimate gaseous hydrocarbon generation with the little data that is available at the moment, the existence of liquid hydrocarbon on surface indicates lack of knowledge about the generating rock. *Figure 23* sets up the hypothetical geographic extension of the petroleum system (Clavo -Salaquí) -Uva (?) and the location of the well where the geochemical modeling was carried out.

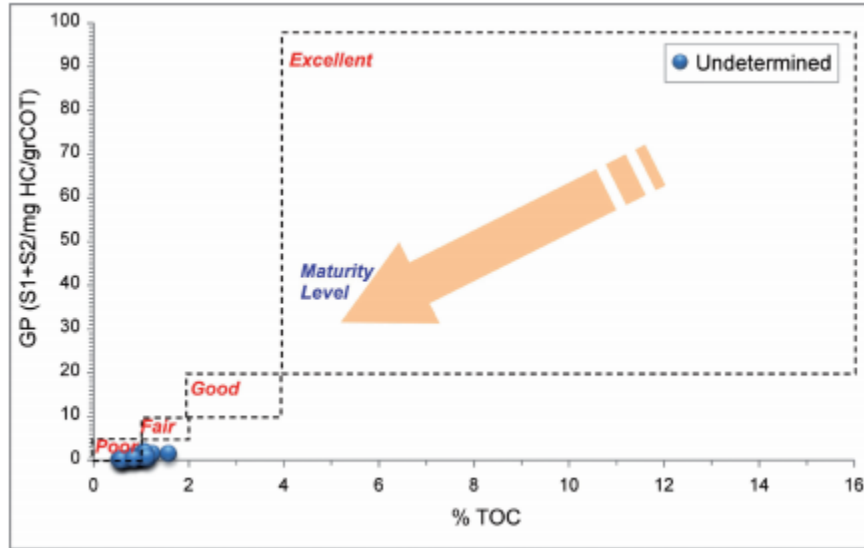


Figure 17. Diagram %TOC Vs GP (S1 + S2), showing the generating potential of the rock.

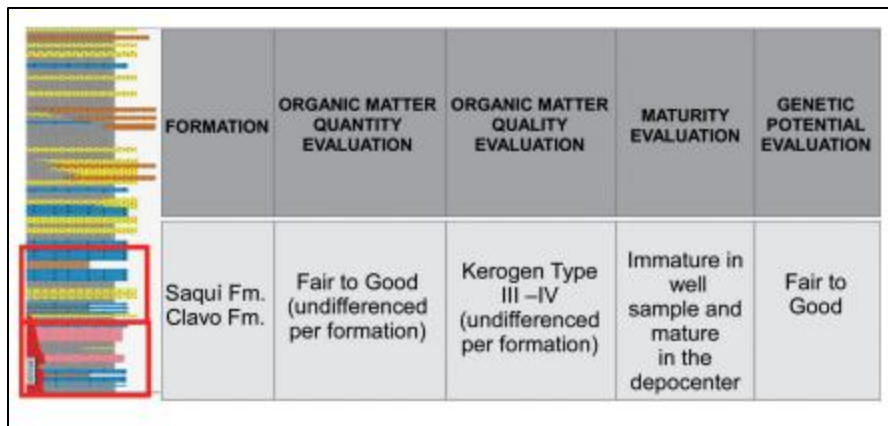


Figure 18. Synthesis of the geochemical evaluation using the data that is available for the Atrato Basin. The generating potential considered for these units could be depreciated due to low availability of information, taking into account the lithofacies similarities with the Iró Formation.

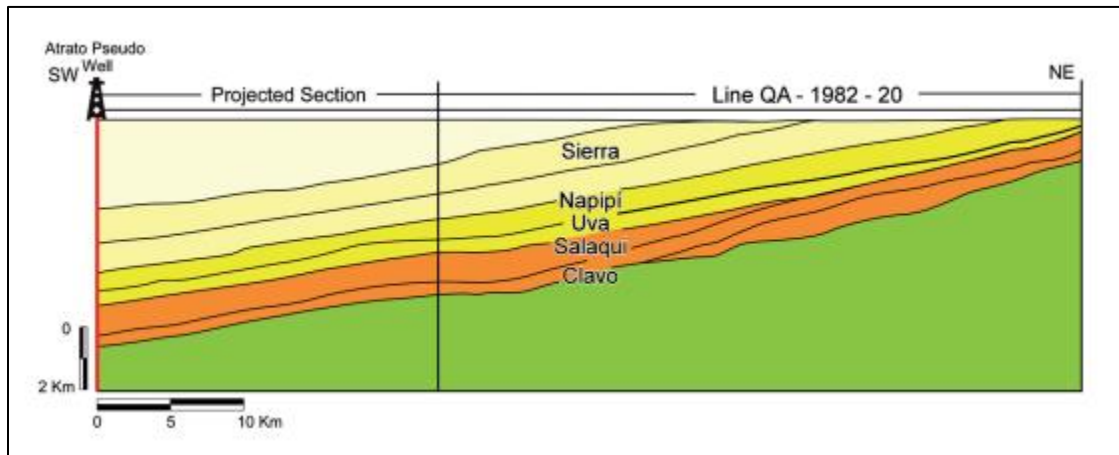


Figure 19. Location of the Atrato well on the seismic line QA-1982-20.

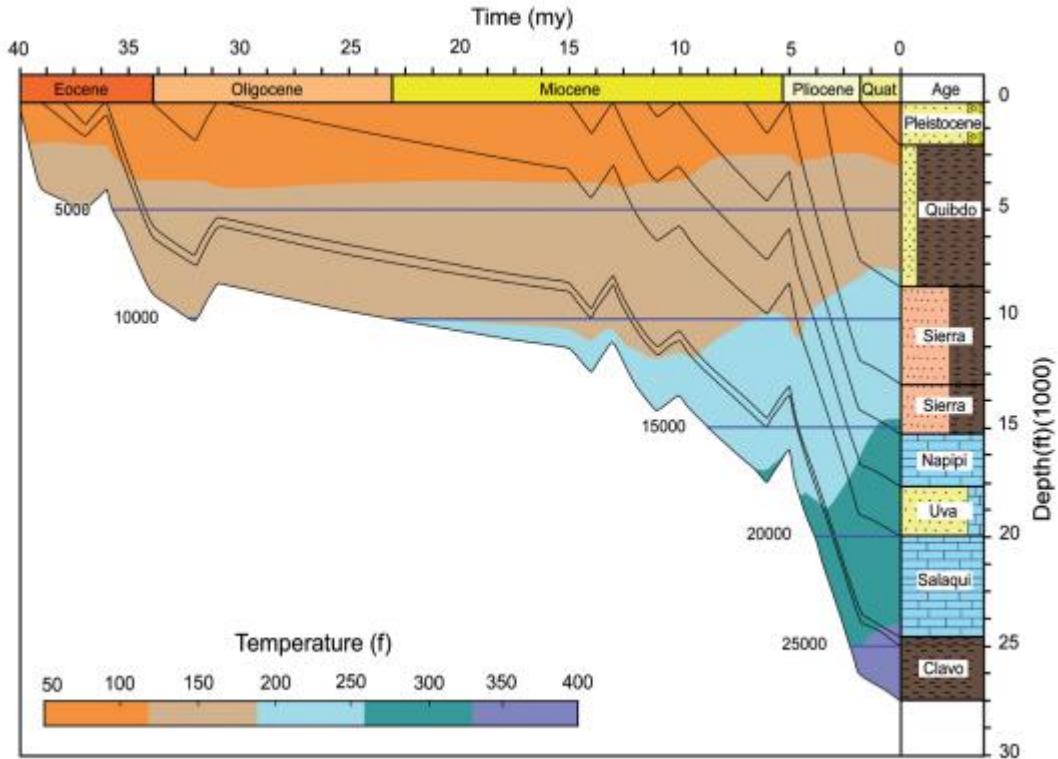


Figure 20. Burial curve in the area. Middle Eocene reached the maximum burial in the Pleistocene.

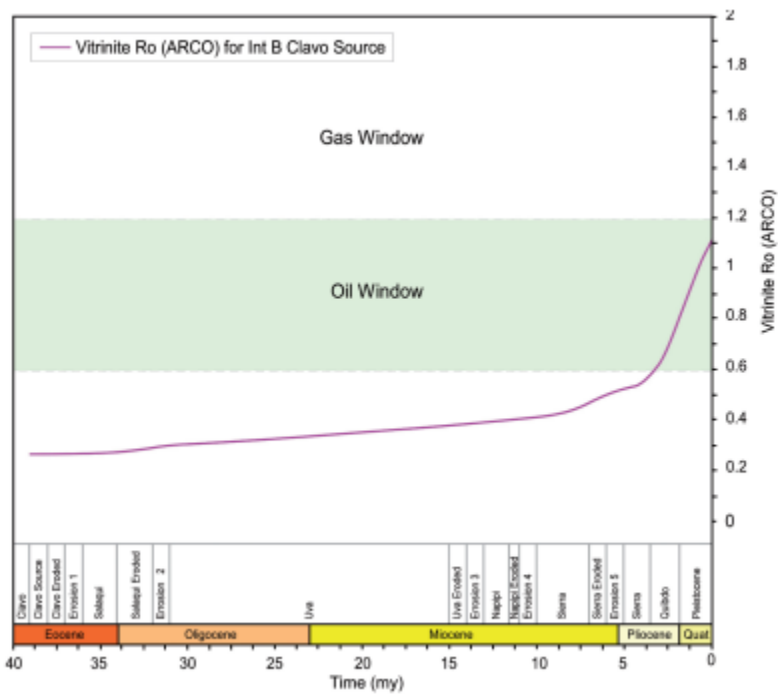


Figure 21. Rock maturity Profile through time. The top of the Clavo Formation reached the delayed maturity phase of oil generation.

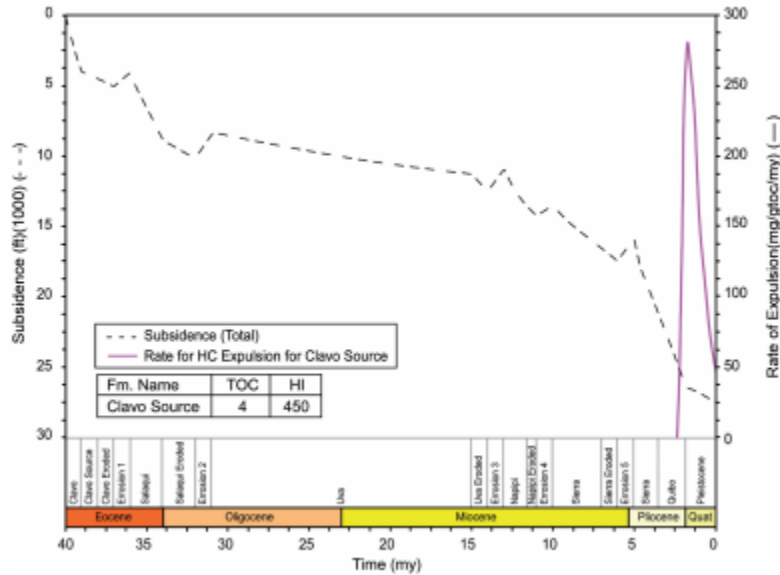


Figure 22. Hydrocarbon expulsion process at the end of the Pliocene in the Clavo Formation. The dotted blue line represents the burial curve; the continuous pink line shows the hydrocarbon expulsion.

4.2 SAN JUAN BASIN

4.2.1 Elements and processes

Source Rock

The main generating rock in the San Juan Basin is the Iró Formation (Paleocene -Eocene), which has three members: the upper and lower members are made of half way point thin layers of limestone with interbedded chert, bituminous shale (oil shale) and sandstone. The middle member is composed by medium grained sandstone interstratified with siltstones and dark shale. See *Figure 13*.

Reservoir Rock

Some possible reservoir rocks are identified within the Cenozoic sequence, the main ones being limestone and fractured chert from the upper and lower segments of the Iró Formation, sandstones from the Sierra Formation, sandstones from the Istmina Formation, and sandstones and conglomerates from the Condoto, La Mojarra and Munguidó Formations.

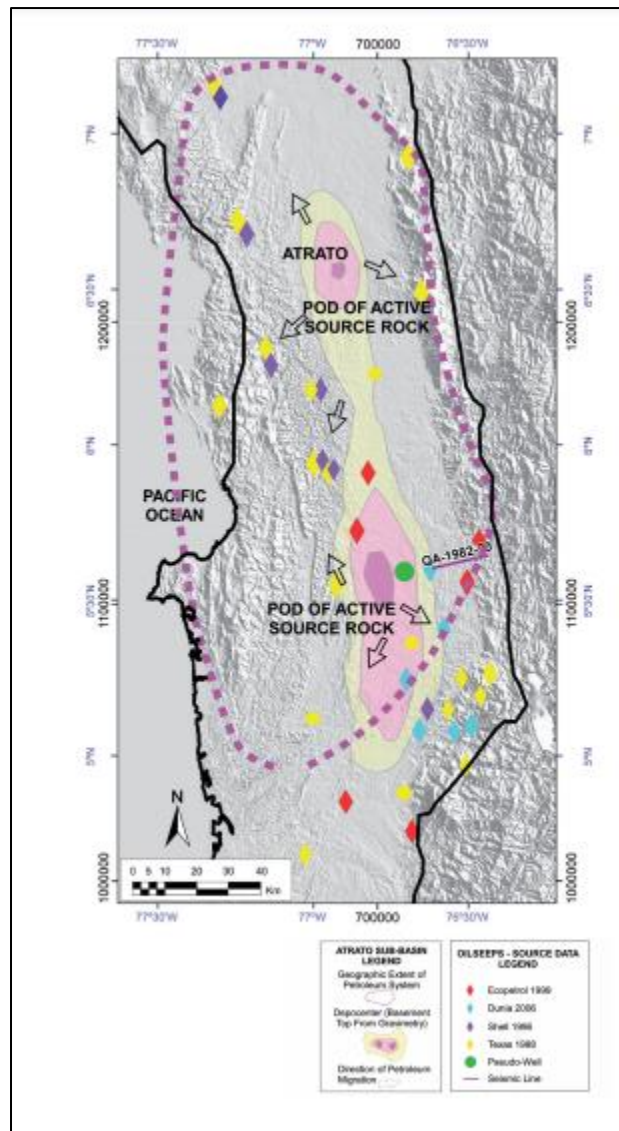


Figure 23. Map of the proposed hypothetical petroleum system. The map shows the depocenter at the upper limit of the plinth, the oil seeps reported in the Basin and the hypothetical area of system influence in this system.

Seal Rock

The seal rocks include the gray claystones and calcareous siltstones from the Itsmina Formation (Lower Part of the Early Miocene) and the mudstone and gray siltstones from the Condoto Formation (Upper Part of the Early Miocene). Some clayey levels in the Conglomerate of La Mojarrá Formation can also be effective seals.

Trap

There are some traps that are combined (structural and stratigraphic) and that appear associated with possible progradations that come from the south part of the Basin. There are also structural traps generated by anticlines and that are associated to inverse faults at the margins of the Basin. The Stratigraphic traps, associated with the piled up calcareous bodies, generally present

secondary porosity when they get to be exposed, therefore, they have great possibility of accumulating hydrocarbon (Universidad EAFIT, 2007).

Charge

The charge rock in this Basin is made up in the stratigraphic sequence from the Sierra Formation (Oligocene) to recent time.

Hydrocarbon Generation and Expulsion Processes

For the point that is modeled within the Basin, the hydrocarbon generation and expulsion processes mainly occur from the Late Miocene to recent time with a brief interruption towards the Middle Pliocene, and with a critical moment located towards the end of the Miocene period.

4.2.2 Events chart

The elements and processes for the petroleum system that is proposed are presented in Figure 24.

4.2.3 Source rock properties

Organic Matter Quantity The Iró Formation registers Total Organic Carbon (TOC) values from 1 to 15, locating this formation in the rank between good and excellent.

The upper member presents an average of 7,55% TOC, while the lower member presents an average of 4,77%. Analysis of the content of organic matter in the Istmina and Conglomerate La Mojarrá Formations register values below 1%, for this reason, these units are not considered generating levels.

Organic Matter Quality

The Hydrogen Index (HI), in the Iró Formation is up to 700 mg HC/g TOC, corresponding to marine environment kerogen type II with liquid hydrocarbon generation potential. This formation also registers low values that are typical of kerogen type III and IV with gas generation potential. *Figure 25.* The best Hydrogen Index values are found in the lower and upper members of the formation, while in the middle member, the values are lower.

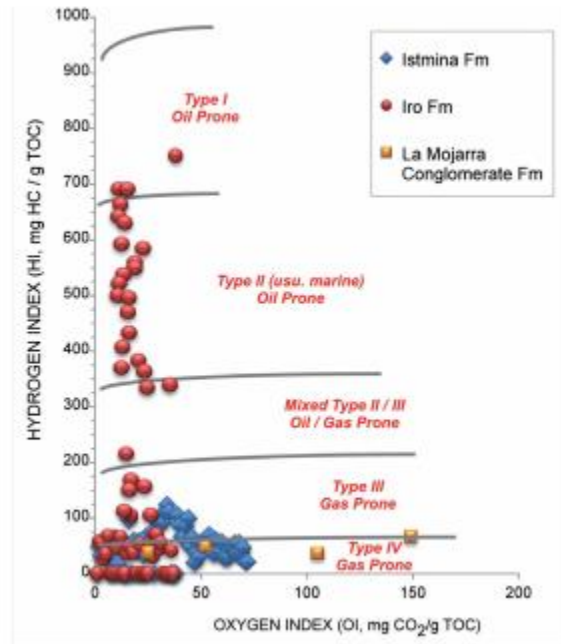


Figure 24. The Events Chart shows the elements and processes of the Iró petroleum system (.). The red line corresponds to the burial curve.

Thermal Maturity of the Organic Matter

The surface rocks in the Iró Formation that were sampled and analyzed are located at the beginning of the oil generation window. They registered Maximum Temperature (T_{max}) average values of 435° C and were characterized at the immature to early maturity stage (Figure 26). Nevertheless, and as it is indicated in section 7.6, this unit was able to reach maturity values corresponding to the oil generation window in the deepest parts of the basin.

Hydrocarbon Generating Potential

Due to its high content and good quality of organic matter, the Iró Formation presents a hydrocarbon generation potential ranked between good and excellent. Figure 27

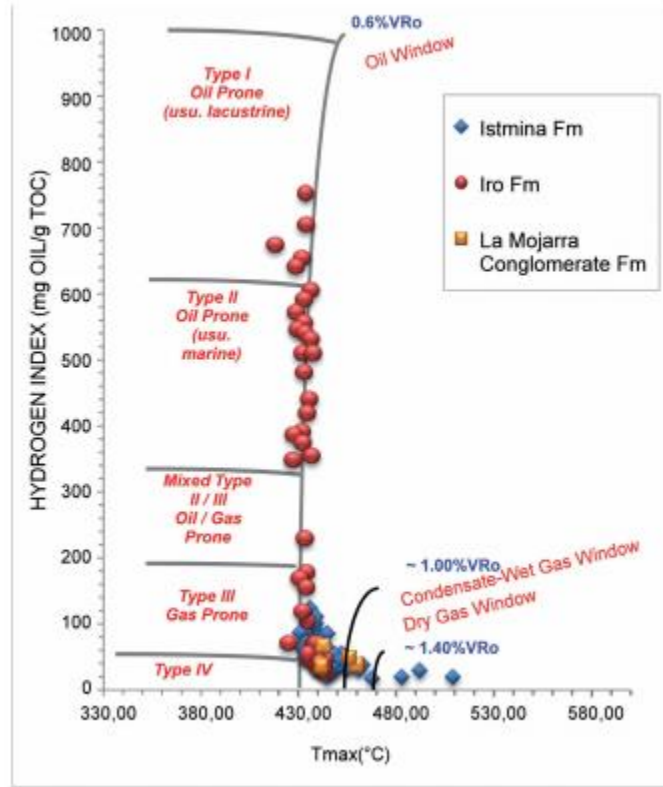


Figure 25. Modified Van Krevelen Diagram (OI Vs HI). The Iró Formation contains values corresponding to kerogen type II with oil generation potential.

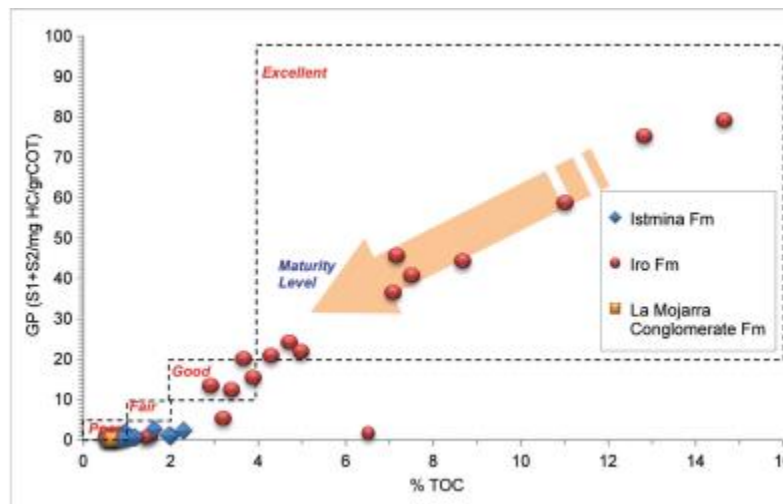


Figure 26. Diagram Tmax Vs HI. The analyzed samples of the Iró Formation are at the beginning of the generation window.

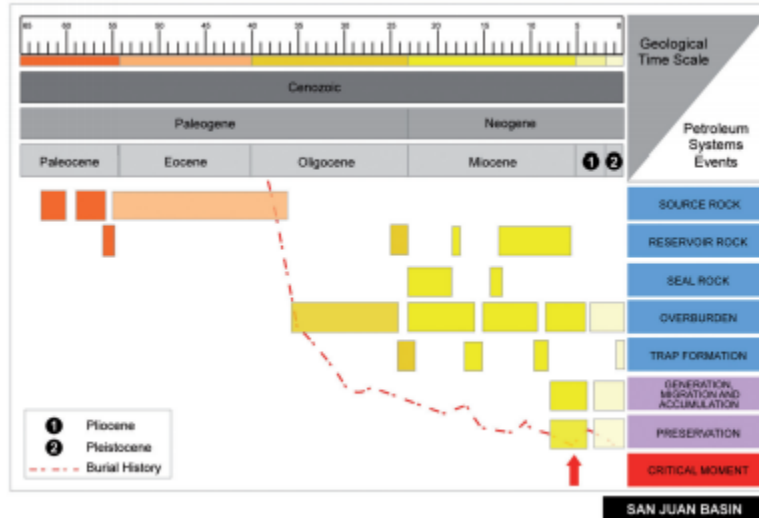


Figure 27. Diagram % TOC Vs GP (S1+S2). The Iró Formation registers the most favorable values. Illustrates a synthesis of the most important geochemical characteristics that identify the Iró Formation as a very good source rock

Extract Properties

The extracts from the Iró Formation that were analyzed in the San Juan Basin present average proportions of 50% resins + asphaltenes, 23% saturated and 25% aromatics. (Figure 28) The relations of the main biomarkers that were analyzed for these extracts make it possible to characterize an organic matter of algal type (ex., C27 Vs C29 Sterane), deposited in a suboxic marine atmosphere, with some carbonatic influence (Garcia et al., 2001). (Figures 29 to 31) There is no bulk analysis data to determine the quality of the crude.

Summary of Extracts and Dripping Places Properties

The main dripping places that were found in the Basin are located in the Iró Formation at the levels of fractured limestone (Herrera et al., 2006). Table 5 summarizes some of the main properties obtained from the geochemical data that is available for the rock extracts in the Iró Formation

Crude-Rock Correlation

The similarities that were found among the biomarkers' relations for the rock extracts and the oil seep crude, show a positive correlation between them (ex., Relation of Steranes C27 Vs C29, Figure 32), suggesting that the organic facies in areas of the Basin with greater thermal evolution degree in the Iró Formation could be the source of these crude manifestations on surface.

FORMATION	ORGANIC MATTER QUANTITY EVALUATION	ORGANIC MATTER QUALITY EVALUATION	MATURITY EVALUATION	GENETIC POTENTIAL EVALUATION
Iró	TOC Wt. %: Up to 9	Kerogen type: I and II (Oil prone)	Tmax: 435° - 445° %Ro: 0.35-0.51 Early mature	Excellent (Oil prone)

Figure 28. Summary of the geochemical evaluation to rocks in the San Juan Basin. This chart is obtained from the average values of the studied geochemical parameters

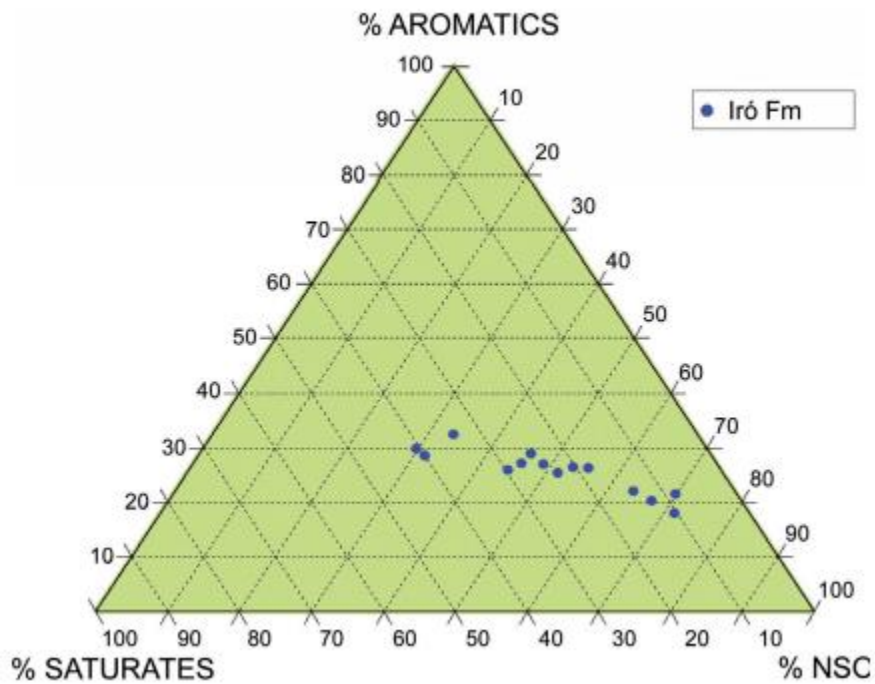


Figure 29. Ternary diagram showing the proportions of saturates, aromatics and resins plus asphaltenes. The last mentioned predominating over the analyzed extracts.

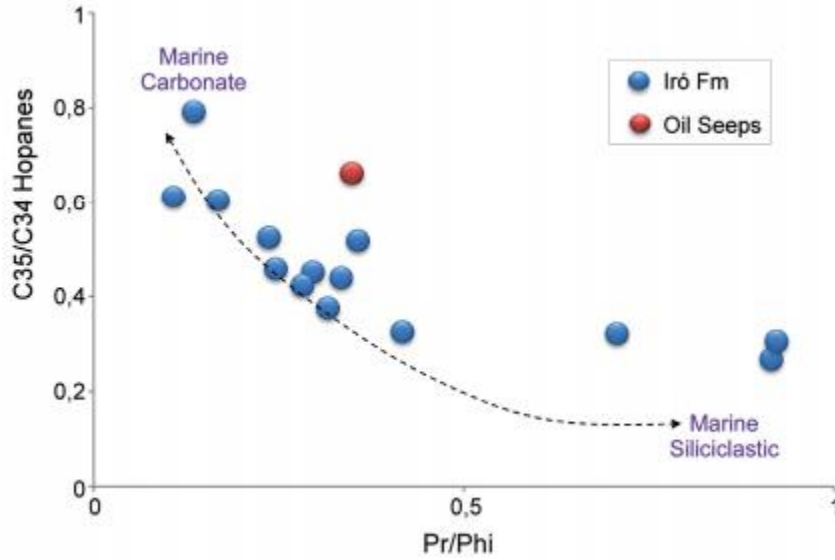


Figure 30. Pristano/Fitano Diagram Vs C35/C34 Hopanes in which the suboxic marine character of deposition is observed. (Modified by Garcia et al. 2001).

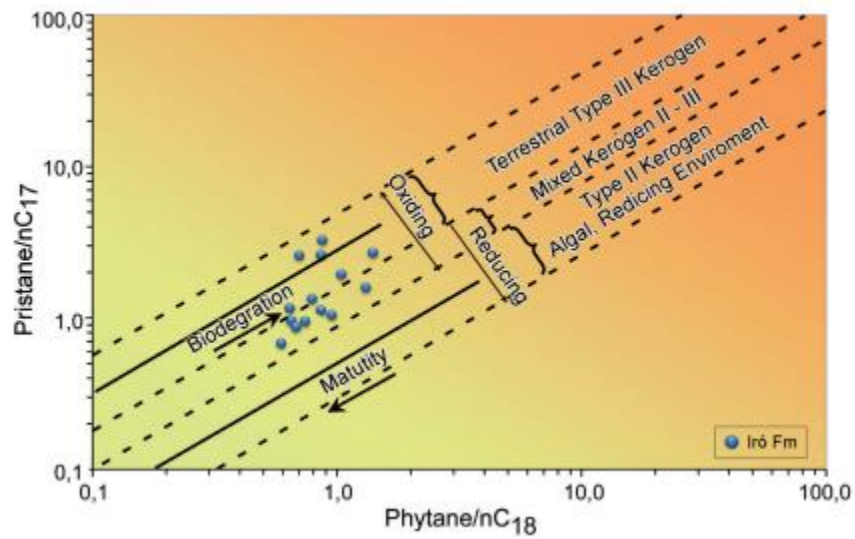


Figure 31. Fitano Diagram Vs Pristano. Suboxic environment. The analyzed samples show intermediate biodegradation.

Source Rock (Extracts)	Organic Matter Source	Depositional Environment	Maturity	Quality	Alterations
Iró Fm	Mainly Marine Algal (Kerogen Type II) Less Type III	Mainly: Marine Suboxic Some facies Marine carbonate	Inmature	Predominant Heavier Fraction (NSO and aromatics)	Non Biodegradated
Reservoir (Oil Seep)	Organic Matter Source	Depositional Environment	Maturity	Quality	Alterations
Iró Fm	Mainly Marine Algal (Kerogen Type II)	Marine Suboxic	Inmature	Predominant Heavier Fraction (NSO and aromatics)	Biodegradated

Table 6. Summarizes some of the main properties obtained from the geochemical data that is available for the rock extracts in the Iró Formation and the crude in the oil seep of the basin.

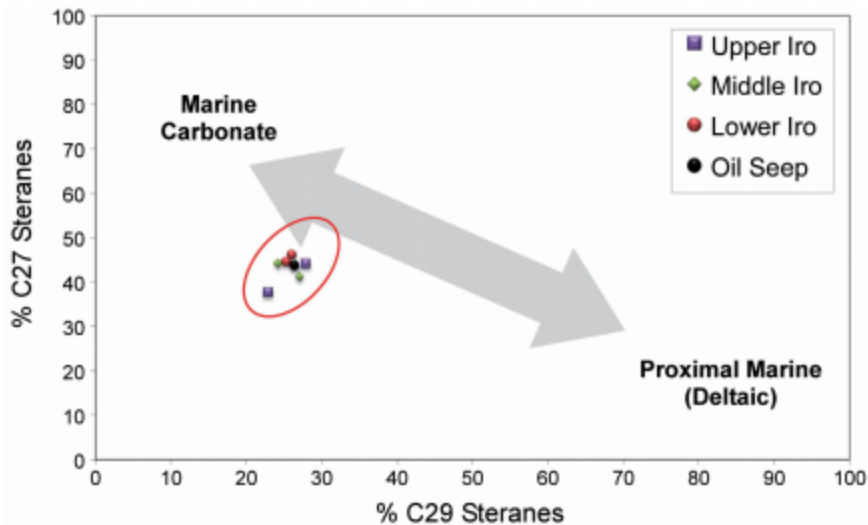


Figure 32. Diagram % C29 Steranes Vs C27 Steranes, indicating a high correlation in the organic matter type (marine algal), for the rock extracts and the oil seep crude

4.2.4 Petroleum systems modeling

The simulation of the hydrocarbon generation and expulsion processes in the San Juan Basin, southern area of the arch in Chocó, was made from a well on seismic line TB-91-1130 (Figure 33). According to the geological evolution model in this area of the Basin, the base of the Cretaceous sequence reached a maximum burial depth of 29000 feet and maximum temperatures of 337°F during the late Miocene (Figure 34). A history of constant heat flow with an HF of 38 mw/m² was used. Based on the regional and local rock geochemical information, the generating intervals A, B and C were included at the top of the Lower, Middle and Upper Iró Formation in the model. The results of the simulation indicate that these intervals reached the maturity levels in the rank of

the peak phase of oil generation (% Ro= 0,75, Interval C, Iró Inferior), and the Immaturity Phase (% Ro= 0.38-0.47, Interval A, Upper Iró and Interval B, Middle Iró, (Figure 35) with hydrocarbon expulsion processes only for interval C in the late Miocene, associated to the burial as a result of the Deposit of the Condoto Formation (11 - 8 M.y.) (Figure 36)

4.2.5 Definition of the petroleum system

Geological, geochemical and modeling integration of the San Juan Basin suggests the existence of a petroleum system with evidence of crude migration to the surface (oil seeps), from low maturity levels of limestone interspersed with dark mudstone from the Iró Formation (evaluated source rock), to outcrops from rock in the same unit, particularly, in the fractured limestone levels (possible reservoir). This is the reason for the Iró Petroleum System to be proposed. Figure 37 shows the geographic extension of the petroleum system and the location of the well where the modeling was carried out.

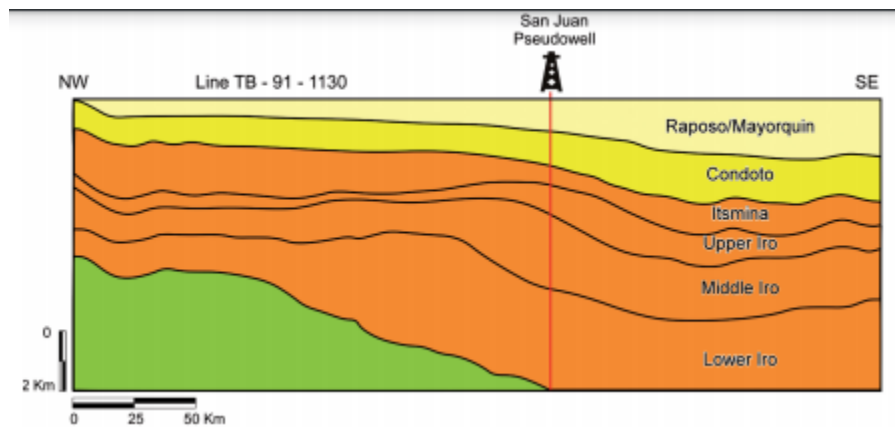


Figure 33. Location profile of the San Juan well on seismic line TB-91-1130.

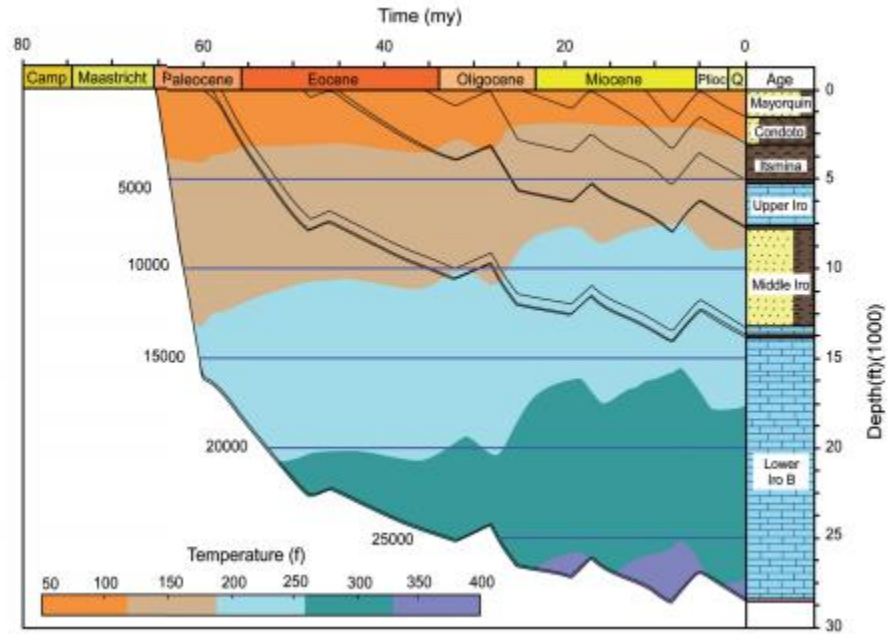


Figure 34. Curve of maximum burial occurred during the Miocene.

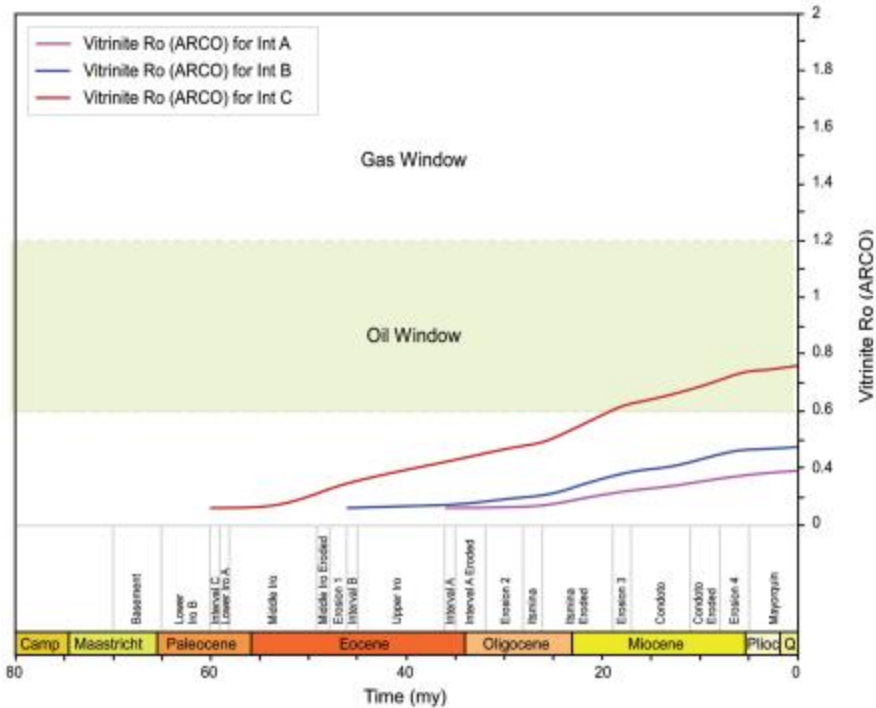


Figure 35. Profile of %Ro through the time, Lower Iró reached the peak of oil generation.

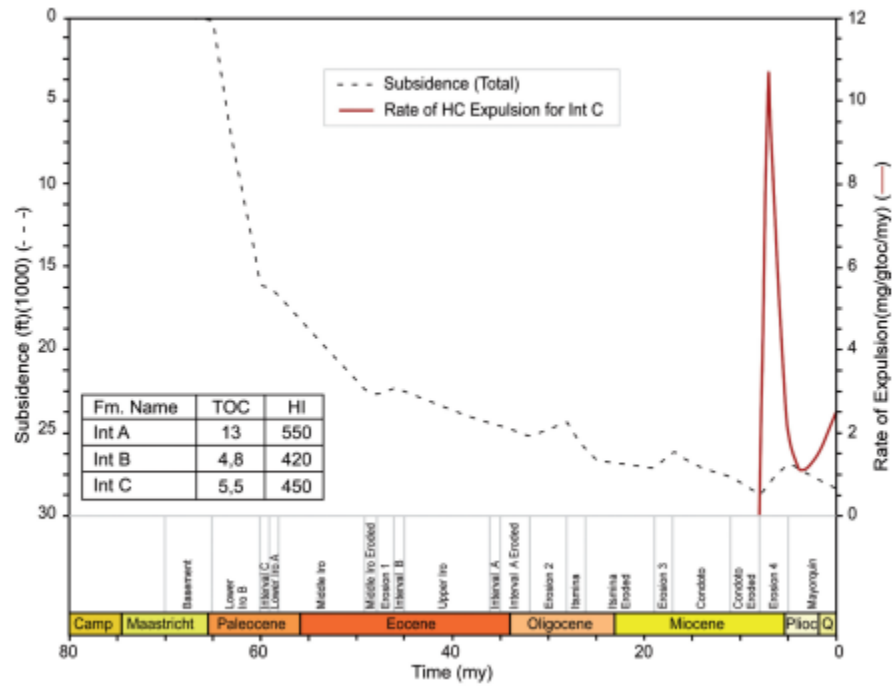


Figure 36. The expulsion process was reached only for Interval C

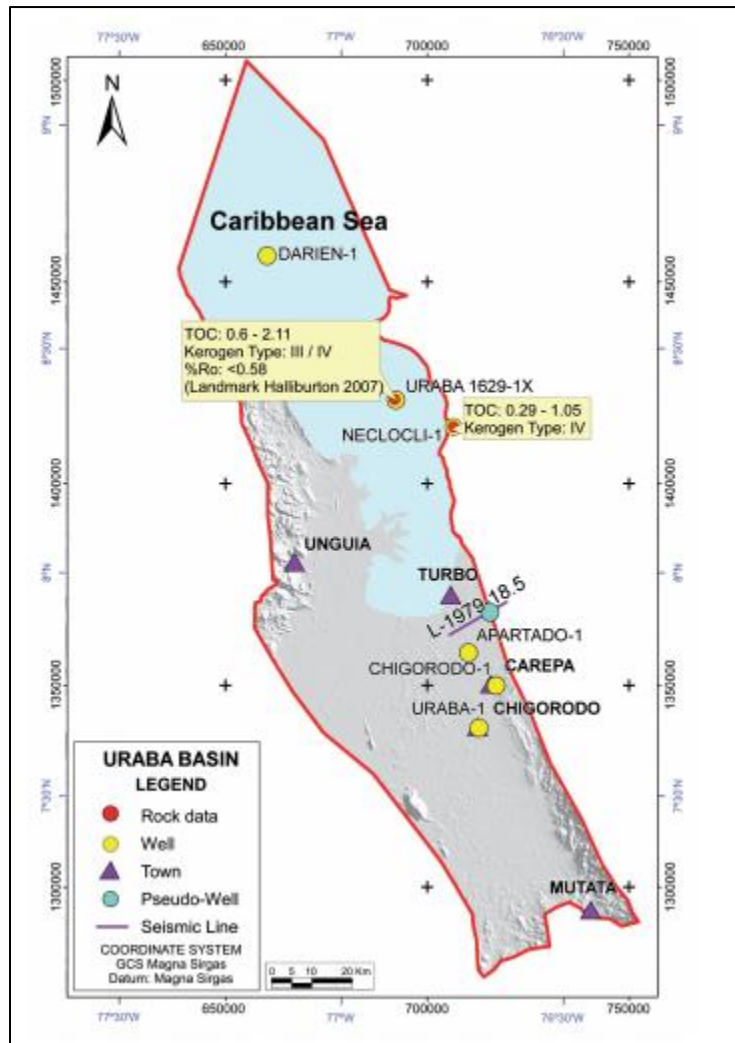


Figure 37. Location of the Urabá Basin, municipalities and wells based on the seismic line L1979-18-5.

