Hydrocarbon migration history in the Llanos Foothills Basin, Colombia, using fluid inclusions.

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Introduction

Fluid inclusions (commonly < 15 µm in diameter) are samples of oil and aqueous fluids that circulated through a sedimentary basin during its geological evolution. The presence of hydrocarbon bearing fluid inclusions (HCFI) in authigenic cements and in annealed fractures in detrital quartz grains in basin sandstones may reflect a history of petroleum migration and cementation during basin evolution (Burruss, 2003). Ultraviolet (UV) light microscopy is used to determine the presence of HCFI in basin sandstones and veins. This in turn identifies the stratigraphic levels where hydrocarbon migration has occurred. Petrographic studies of HCFI and aqueous fluid inclusions help develop a chronology of petroleum migration.

We report the results of fluid inclusion petrography (aqueous and HCFI), UV microscopy and microthermometric studies (HCFI) of the Llanos Foothills Basin, Colombia. Furthermore we demonstrate the use of fluid inclusion studies in the development of an oil charge history framework for the Llanos Foothills Basin.

Experimental

Nineteen fluid inclusion wafers from the following samples were studied: 2 samples of outcrops, 9 samples of cuttings from the Foothills 1 Well, 7 samples of core from the Foothills 3 Well, and 1 sample of core from the Foothills 6, (The names of the wells are changed to comply with Ecopetrol-ICP’S request for confidentiality).

A Nikon Diaphot microscope with an epifluorescence UV light source attachment (designed to transmit 365 nm wavelength light) was used both to examine the petrography of fluid inclusions and to determine the presence of HCFI. A Linkam THMS 600 heating–freezing stage mounted on a Nikon Labophot transmitted light microscope equipped with a range of objective lenses (including a x100 objective lens) was used for fluid inclusion microthermometry. Its calibration was made using synthetic fluid inclusion standards of pure CO\(_2\) and water. Precision is ± 0.2ºC at -56.5ºC and ± 2ºC at 300ºC. The following fluid inclusion data was recorded: 1) The homogenisation temperature (minimum trapping temperature of the fluid: TH) followed by the temperature of last ice melting (indication of the salinity of trapped fluid: TLM); 2) The number of phases (liquid ± gas ± solid) present in each inclusion; 3) Fluorescence colour of HCFI; 4) The volumetric proportion of liquid relative to the total volume of the inclusion, at room temperature, was determined using the Lucia software; 5) The salinity (calculated as equivalent wt% NaCl) was determined using the equation of state of Bodnar (1993). In the case of two-phase (liquid + vapour) aqueous inclusions isochores were constructed using the FLUID programme (Bakker, 2003). Isochores for two-phase (liquid + vapour) petroleum inclusions were constructed using VTFLINC programme.

Results and Discussion

Fluids present within quartz overgrowths

Microthermometric data from aqueous fluid inclusions found in authigenic quartz (Figure 1) indicates that quartz overgrowths were precipitated by fluids with minimum trapping temperatures between 92ºC and 130ºC. Last ice melting temperatures (TLM) indicate that both aqueous fluids with low salinities (0.5 to 4.8 eq. wt% NaCl) and fluids with CH\(_4\) ± CO\(_2\) were present at the time of quartz overgrowth formation.

![Detrital Quartz Fluid Inclusion](50 µm)

Figure 1. Primary fluid inclusions trapped in quartz overgrowths, from the Une Formation, Foothills 1 well. Photomicrograph in plane polarized transmitted light.

HCFI in quartz overgrowths are uncommon. This may indicate that the main phase of quartz overgrowth formation preceded significant
hydrocarbon migration. These HCFI contain oils characterized by API gravities between 40º-50º and homogenization temperatures between 92ºC and 113ºC. PVT modelling of coeval HCFI and aqueous fluid inclusions hosted within quartz overgrowths indicates trapping temperatures and pressures of ~120ºC and ~250 bars (Figure 2). Isochores were constructed using VTFLINC programme. This software was developed to process microthermometric and volumetric data from petroleum bearing fluid inclusions. The composition of the generic volatile oil reported by Burruss, (2003) was used as an input.

It should be noted here that fluorescence colours displayed by HCFI only provide at best a qualitative indication of the API gravity of oil trapped in the inclusions (Burruss, 1991; Goldstein and Reynolds, 1994; Parnell et al., 1998; O’Reilly et al., 1998; Feely and Parnell, 2003; Bodnar, 1990; Sellwood et al., 1993; Stasiuk and Snowdon, 1997), however this premise does not always hold true (George et al., 1997; George et al., 2001).

Fluids present within veins.

Fluid inclusion data from veins suggest a complex fluid migration history in the Llanos Foothills basin.

In a vein hosted within the Guadalupe Formation (Foothills 6 Well) petroleum inclusions were found as both primary and secondary. Primary hydrocarbon inclusions indicate that oil with an API gravity of 40º-45º and homogenization temperatures between 80ºC and 90ºC were present at the time of the vein formation. The presence of secondary trails of petroleum inclusions may also indicate later episodes of petroleum migration. Their homogenization temperatures range from 40ºC to 82ºC. They have an API gravity of 45º-50º. However the similar characteristics in both fluorescence colours and microthermometry data of primary and secondary inclusions may suggest a continuous hydrocarbon migration event.

In the veins from the Lutitas de Macanal Formation (outcrop) a wide range of salinities and homogenization temperatures have been recorded. These fluids can be divided into three main groups as follows: 1) A fluid with a high salinity (34 to 36 eq. wt. % NaCl) and homogenization temperatures between 240ºC and 290ºC. These fluids are found as primary inclusions; 2) A fluid with moderate salinity (10 to 17 eq. wt. % NaCl) and homogenization temperatures between 178ºC and 227ºC. They are hosted as secondary inclusions, and 3) A fluid with moderate salinity (3.4-7.2 eq.wt. % NaCl and 6.8–12.2 eq. wt. % CaCl2) and homogenization temperatures between 80ºC and 90ºC. These fluids may suggest a continuous hydrocarbon migration event.
temperatures between 97°C and 117°C. They are found as secondary inclusions.

**Discussion**

Based on the results of this study, an attempt has been made to build a fluid migration model for the Llanos Foothills Basin.

The first fluid event identified is associated with the formation of quartz overgrowths. Microthermometric data indicates that the fluids present in the formations at this time have minimum temperatures between 92°C and 130°C. They have low salinities (0.5 to 4.8 eq. wt % NaCl) and some also CH4 ± CO2. The low salinities indicate that they represent marine or meteoric waters trapped within the pore spaces of these rocks. The presence of CH4 ± CO2 may be due to their liberation from rocks rich in organic matter during the maturation process associated with the burial and consequent increase in pressure and temperature of the rocks. Hydrocarbon inclusions were only occasionally found in quartz overgrowths indicating that the main phase of quartz overgrowth formation preceded hydrocarbon migration. Rare HCFI hosted within overgrowths have minimum trapping temperatures of 92°C-113°C. They have a blue-white fluorescence colour (API gravity = 40º-50º). From modelling of petroleum and aqueous inclusions it is believed that these hydrocarbons were trapped during the Miocene (~10 Ma).

The second fluid event identified corresponds to fluid inclusions hosted within transgranular annealed microfractures in the sandstones. These fluid inclusions have been recorded cutting the quartz overgrowths. At least 2 aqueous and 2 hydrocarbon fluid migrations events were recorded: 1) fluid with low to moderate salinity (2.0 – 12 eq. wt. %NaCl) and homogenization temperatures between 100°C and 137°C; 2) An aqueous fluid with small volumes of either CH4 ± CO2. Their homogenization temperatures range from 102 to 127°C; 3) Hydrocarbon fluid with 40º-50º API gravity and homogenization temperatures between 64°C and 138°C; and 4) A Hydrocarbon fluid with 25º-30º API gravity, these inclusions are typically < 3µm. Because of their size they are difficult to resolve and no precise microthermometric data could be obtained from these inclusions. The presence of inclusions within trails long annealed fractures suggests that microfracturing was an important conduit for both petroleum and aqueous migration.

The third and final event identified corresponds to the fluid inclusions found within the veins. At least three aqueous and one hydrocarbon fluid migration events were recorded: 1) Fluid with high homogenization temperatures (240°C to 290°C) and high salinities (34 to 36 eq. wt %NaCl); 2) A fluid with moderate salinity (10 to 17 eq. wt. %NaCl) and high homogenization temperatures (178°C to 227°C); 3) A CaCl2 bearing fluid with moderate salinity (3.4-7.2 eq. wt. %NaCl and 6.8–12.2 eq. wt. %CaCl2) and homogenization temperatures of between 97°C and 117°C; y 4) A hydrocarbon fluid with API gravity of 40º-45º. Their homogenization temperatures range from 40°C to 90°C.

**Conclusions**

1. Fluid inclusion studies from the Llanos Foothills Basin reveal the presence of aqueous and hydrocarbon fluids hosted within quartz overgrowths and in annealed microfractures, indicating that these fluids were present during cementation and also during later episodes of microfracturing.

2. Petroleum fluid inclusions within the overgrowths zone are rare suggesting that the main phase of quartz overgrowth formation preceded hydrocarbon migration. These oils are characterized by API gravities between 40º-50º and homogenization temperatures between 92°C and 113°C. PVT modelling of coeval hydrocarbon and aqueous inclusions hosted within quartz overgrowths indicates trapping temperatures and pressures of these fluids at ~120°C and ~250 bars. Integration of trapping temperatures with the burial history suggests that these fluids were trapped during the Miocene (~10 Ma).

3. The majority of hydrocarbon inclusions are commonly found in annealed microfractures. They occur both as subparallel trails in detrital quartz grains and as secondary inclusions in trails that transect both detrital and authigenic quartz. This indicates that microfracturing was an important conduit for petroleum migration.

4. Microthermometric data indicates that quartz overgrowths were precipitated by fluids with minimum trapping temperatures between 92°C and 130°C. Last ice melting temperatures indicate that both aqueous fluid with low salinities (0.5 to 4.8 eq. wt% NaCl) and CH4 ± CO2 were present at the time of quartz overgrowth formation.

5. Microthermometric studies from the aqueous fluid inclusions hosted in transgranular annealed fractures, suggest at least two aqueous migration events post-diagenesis. These fluids can be divided as follows: 1) A fluid with low to moderate salinity (2.0 – 12 eq. wt.% NaCl) and homogenization temperatures between 100°C and 137°C; 2) An aqueous fluid containing CH4 ± CO2 and homogenization temperatures that range from 102°C to 127°C.

6. A wide range of compositions and homogenization temperatures
have been recorded from the fluid inclusions found within veins. These fluids can be divided into four main groups as follows: 1) A fluid with a high salinity (34 to 36 eq. wt. % NaCl) and homogenization temperatures between 240ºC and 290ºC; 2) A fluid with moderate salinity (10 to 17 eq. wt. % NaCl) and homogenization temperatures between 178ºC and 227ºC; 3) A fluid with moderate salinity (3.4–7.2 eq. wt. % NaCl and 6.8–12.2 eq. wt. % CaCl2) and homogenization temperatures between 97ºC and 117ºC; and 4) A hydrocarbon fluid with 40º–50º API and homogenization temperatures between 40ºC and 90ºC.

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References


