Oil Inclusions in Oil Sands from Western Saskatchewan: A Preliminary Petrographic and Microthermometric Study

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Abstract

Eight samples of oil sands from western Saskatchewan have been examined for oil inclusions. Three of them are chert pebbles in conglomerates of the Success Formation from the Kindersley area and five are siltstone, very fine- and fine-grained sandstones of the Mannville Group from the Lloydminster area. The purposes of the study are to examine whether or not oil inclusions are present in the oil sands and, if so, determine how abundant they are, identify their types (in terms of fluorescence) and how they occur, and assess the feasibility of microthermometry.

Oil inclusions are present in all the samples examined, and are abundant in the chert-pebble samples. The oil inclusions have brown, light brown to very light brown colour or are colourless. The brown oil inclusions are non-fluorescent, whereas the light-coloured and colourless oil inclusions show strong white, yellowish white, and blue-white fluorescence. The light-coloured oil inclusions probably represent the samples of oil that initially charged the reservoirs, whereas the brown, non-fluorescent oil inclusions represent the product of strong biodegradation. The oil inclusions occur in interstitial space or dissolution cavities in chert pebbles, lithic grains and matrix, and as isolated inclusions or in healed fractures in detrital quartz grains. The interstitial and cavity-filling oil inclusions, because they are not sealed within individual mineral crystals, show variable and unstable homogenization temperatures, and are unreliable for microthermometric studies. However, isolated oil inclusions occurring within detrital quartz grains are secondary in origin and have consistent homogenization temperatures, which can be used to estimate the minimum temperatures during the charging and evolution of the reservoirs. Preliminary results suggest that the Mannville oil sands were initially charged with relatively hot (homogenization temperatures from 76º to 109ºC) and light oil, which was later degraded into heavy oil and solid bitumen. The presence of light oil inclusions with homogenization temperatures as low as 29º to 35ºC suggests that oil degradation was heterogeneous and some light oil was still present after significant cooling of the reservoirs.

Keywords: *oil sands, oil inclusions, Mannville Group, Saskatchewan, Williston Basin, heavy oil.*

1. Introduction

Oil sands in the Lower Cretaceous Mannville Group in the Western Canada Sedimentary Basin (WCSB) represent one of the most important hydrocarbon resources in Canada (Creaney *et al.*, 1994; Pemberton and James, 1997). Minor oil sands also occur in subcrops beneath the Mannville Group (Creaney *et al.*, 1994). Previous studies of the hydrocarbons in the oil sands were based on analysis of the bitumen coating or filling pore space, which have been subject to various alterations since the charge of the reservoirs, especially biodegradation (*e.g.*, Rubinstein *et al.*, 1977; Riediger *et al.*, 2000; Obermajer *et al.*, 2004; Larter, 2006). In order to evaluate the initial composition and temperature-pressure conditions at the time of hydrocarbon charge, and to trace the changes that have taken place since then, it is important to study hydrocarbon inclusions entrapped at different stages of the reservoir evolution. Although hydrocarbon inclusions have been used as a tool for evaluating hydrocarbon systems elsewhere (*e.g.*, Apline *et al.*, 1999; Huntoon *et al.*, 1999; Chi *et al.*, 2000), they have not been studied for the oil sands in the WCSB.

As a first step for studying oil inclusions in the WCSB oil sands, we have selected eight samples (three in the Success Formation and five in the Mannville Group) from western Saskatchewan for preliminary petrographic and microthermometric investigations. The objectives of the study are to examine: 1) whether or not oil inclusions are present in the oil sands and how abundant they are, 2) the modes of occurrence of oil inclusions in diagenetic and detrital minerals, 3) the types of oil inclusions in terms of their fluorescence, and 4) the feasibility of microthermometric measurement of oil inclusions and the general range of homogenization temperatures. However,

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this paper is not intended to be a comprehensive examination and classification of oil inclusions in the WCSB oil sands. A more detailed study covering a wider area including eastern Alberta and western Saskatchewan will be carried out in an on-going project. The data thus obtained will be used to constrain large-scale basinal fluid flow models, which have been proposed to explain the formation of the oil sands (*e.g.*, Garven, 1989; Adams *et al.*, 2004), and the timing of oil migration and accumulation.

2. Geological Setting and Sample Locations

The WCSB can be broadly subdivided into a pre-Late Jurassic miogeocline-platform stage, during which sediment was sourced from the North American craton to the east, followed by a Late Jurassic to Early Eocene foreland basin stage, when sediment was mainly derived from the Cordilleran mountain belt to the west (Price, 1994). Siliciclastic rocks of the Jura-Cretaceous Success Formation were formed in fluvial and lacustrine environments in the early foreland basin stage, overlying a regional unconformity above the passive margin stage strata (Christopher, 2003). The Mannville Group was deposited following a significant fall in base level during Early Cretaceous Hauterivian and Barremian time which resulted in regional erosion across the entire foreland basin and formation of the sub-Mannville unconformity (Poulton *et al.*, 1994). Siliciclastic rocks of the Mannville Group were deposited in a variety of environments ranging from open-marine, shallow shelf to fluvial systems, and in a network of incised valleys filled with deltaic, brackish bay, and estuarine deposits (Christopher, 1984, 1997, 2003; Hayes *et al.*, 1994; Leckie *et al.*, 1997).

The stratigraphy of the Mannville Group is complex due to the diversity of depositional environments, and the strata have been subdivided into various formal and informal stratigraphic units (Christopher, 1984, 1997, 2003; Hayes *et al.*, 1994). In Saskatchewan, the Mannville Group is generally subdivided into the Cantuar and Pense formations ranging in age from Aptian to Early Albian (Christopher, 1984, 1997, 2003). The Cantuar Formation is further broken down into various members. In the Lloydminster area (Figure 1), the members of the Cantuar Formation are, in ascending order, the Dina, Cummings, Lloydminster, Rex, General Petroleums, Sparky, and Waseca, and the

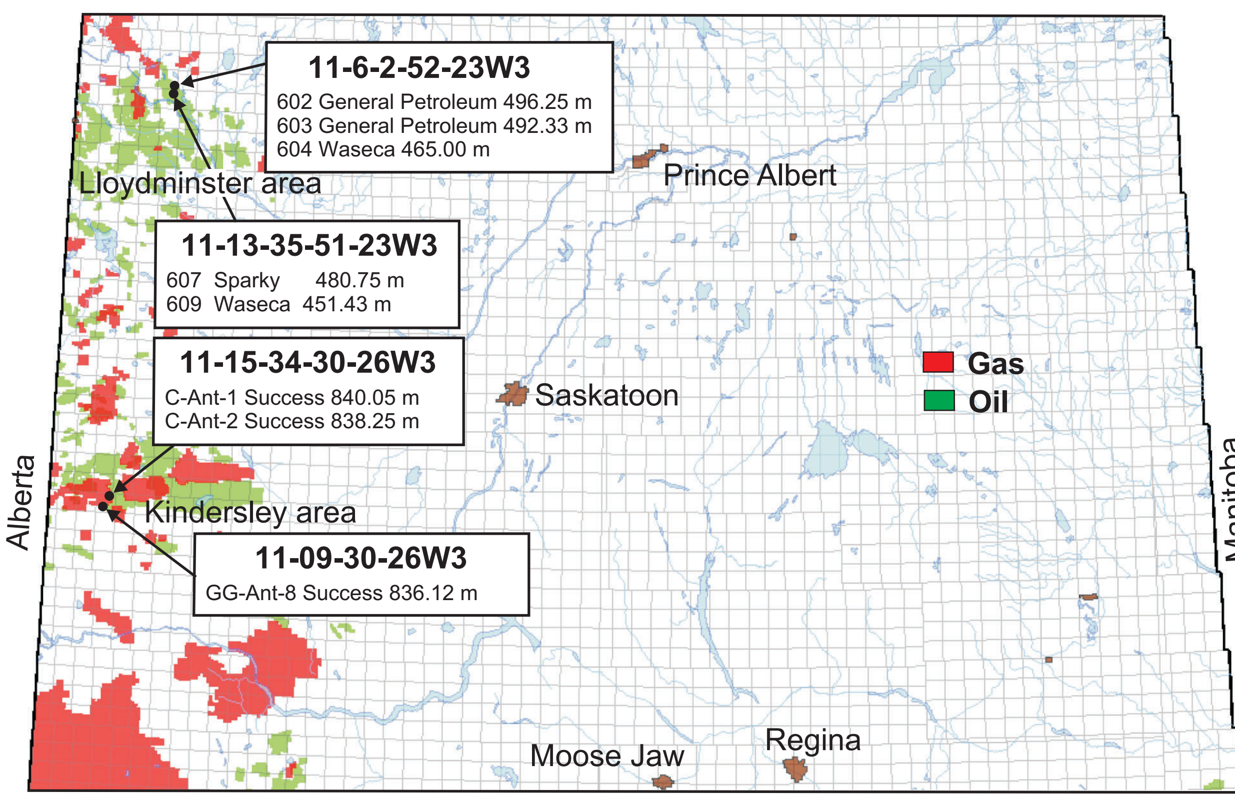

Figure 1 - Map of south-central Saskatchewan showing the locations of the wells from which the samples were collected. Also shown are the sample numbers, stratigraphic units, and depths of the samples.

Pense Formation is subdivided into the McClaren and Colony members (Christopher, 1997). In southwestern Saskatchewan, the Cantuar Formation is made up of the McCloud, Dimmock Creek, and Atlas members (Christopher, 1997) or McCloud, Glauconite, Dimmock Creek, Atlas, and Chokecherry Creek members (Leckie *et al.*, 1997).

Five oil-sands samples were collected from the Lloydminster area, and three from the Kindersley area (Figure 1). The samples from the Kindersley area are chert pebbles from sandy conglomerates or gravely sandstones in the Success Formation (Figures 2A, 2B, and 2C), whereas those from the Lloydminster area (Celtic Pool) are oil-charged sandstones and siltstones from the General Petroleums, Sparky, and Waseca members of the Mannville Group. Considering the scope of this study, no attempt of sedimentological and stratigraphic analysis of the sampled intervals has been made.

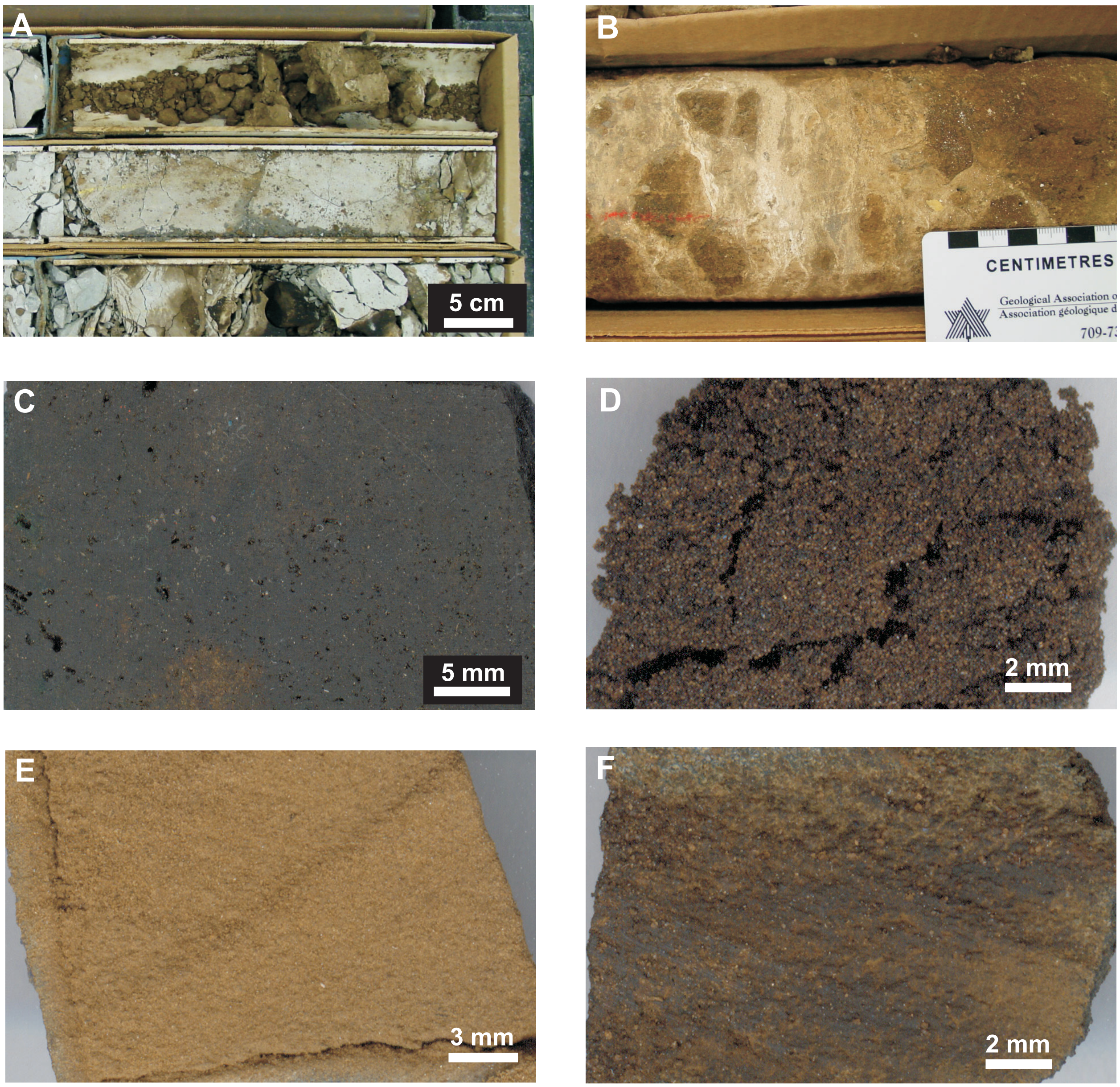

Figure 2 - Core pictures of analyzed oil-sands samples. A) Core from the 11-15-34-30-26W3 well showing oil-sands interval (chert-pebble conglomerate) in the Success Formation from which samples C-Ant-1 and C-Ant-2 were collected; B) core from the 11-09-30-26W3 well showing unevenly oil-charged chert-pebbly sandstones of the Success Formation from which sample GG-Ant-8 was collected; C) solid, dark brown chert pebble (C-Ant-2); D) unconsolidated, dark brown, oil sand (04GC-602); E) semi-consolidated, light brown, oil-stained sandstone (04GC-607); and F) consolidated, dark brown, oil-stained sandstone (04GC-603).

3. Petrographic Characteristics of Oil-Sands Samples

The oil-sands samples are described in cores and in thin sections, for which an Olympus BX51 microscope equipped with fluorescence accessories was used. Fluorescence was produced through excitation with UV light produced by an Olympus 12 V, 100 W mercury burner. The mirror unit turret was put at the WU3 position during observation.

The oil-sands samples range in colour from dark brown (Figures 2C, 2D, and 2F) to light brown (Figure 2E). Some of them are well solidified (Figures 2C and 2F), while others are semi-consolidated (Figure 2E) or unconsolidated (Figure 2D).

The chert pebbles (C-Ant-1, C-Ant-2, and GG-Ant-8) from the Success Formation occur in a matrix of sand; both pebbles and matrix are charged with bitumen (Figures 3A, 3B, and 3C). However, due to poor coherence between pebbles and sand matrix, matrix material was preserved in a small amount in only one thin section (Figure 3C). The chert pebbles contain abundant shell fragments (Figures 3A and 3B), many of which were dissolved and filled with micro-quartz (pore-filling chert) (Figures 3D, 3E, and 3F). Some of the dissolution pores remain open (Figures 3A, 3B, and 3D). The pore-filling chert is clean, with minor oil inclusions and no solid bitumen, in contrast with the remaining chert that contains abundant solid bitumen and oil inclusions (Figures 3E and 3F). The solid bitumen fluoresces bright blue.

The oil-sands samples from the Celtic Pool are composed of fine- and very fine-grained sandstones and siltstones (Figure 4). They are moderately to well sorted. The unconsolidated sample (04GC-602) contains brown organic matter in the interstitial space (Figure 4A), and the consolidated sample (04GC-603) contains abundant solid bitumen (Figure 4B). The semi-consolidated samples (04GC-604, -607, and -609) have both brown organic matter and solid bitumen in the interstitial space (Figures 4C and 4D). The solid bitumen fluoresces bright blue. Minor quartz overgrowth is present in the sandstones (Figures 4E and 4F), and calcite cement is occasionally seen (Figure 4E).

4. Types and Occurrences of Oil Inclusions

In the chert-pebble samples, oil inclusions can be divided into four types based on the colour under transmitted light and fluorescence colour: 1) brown oil inclusions with no fluorescence (Figures 5A and 5B), 2) light brown oil inclusions with weak yellow fluorescence (Figures 5C and 5D), 3) very light brown oil inclusions with strong yellowish white fluorescence (Figures 5E and 5F), and 4) colourless oil inclusions with strong blue-white fluorescence (in rectangles, Figure 5). Type 1 inclusions are very abundant, and the other types are common but less abundant.

Oil inclusions in the oil sands from the Celtic Pool are similar to those in the chert pebbles in terms of colour and fluorescence, but are significantly less abundant. The colour of the oil inclusions in transmitted light range from brown (Figure 6A), light brown (Figure 6C) to colourless (Figure 6E). Their fluorescence ranges from non-fluorescent and weak yellow (Figure 6B) to bright white (Figures 6D and 6F).

The majority of the oil inclusions are composed of two phases at room temperature, *i.e.*, a liquid oil and a gas bubble. Some of them are composed of only liquid (Figure 6A). The gas/liquid ratio is highly variable for the brown-coloured non-fluorescent oil inclusions, from liquid dominated to gas dominated (Figures 5A, 5C, 5E, and 6A), whereas the light-coloured luminescent oil inclusions are mainly liquid dominated (Figures 5C, 5E, 6C, and 6E).

The occurrences of oil inclusions can be classified into the following: 1) in interstitial space or dissolution vugs within chert pebbles, lithic grains, and matrix (Figures 5A, 5C, 5E, 7A, and 7B), 2) isolated in detrital quartz grains (Figures 6A, 6C, 6E, 7C, and 7D), 3) isolated in calcite cement (Figure 7E), and 4) distributed along microfractures in detrital quartz grains (Figure 7F). The first mode of occurrence indicates that the oil inclusions are not enclosed in individual mineral crystals, and may not be considered as a type of "fluid inclusion" in the strict sense. The isolated oil inclusions in detrital quartz grains are most likely secondary in origin, although they may appear to be primary; the oil may have migrated into the tip of a microfracture in the detrital quartz, and became sealed in the crystal with the healing of the microfracture. Isolated oil inclusions in calcite cement are possibly primary in origin, and probably indicate calcite cementation after oil charge. Oil inclusions along microfractures in detrital quartz are secondary inclusions.

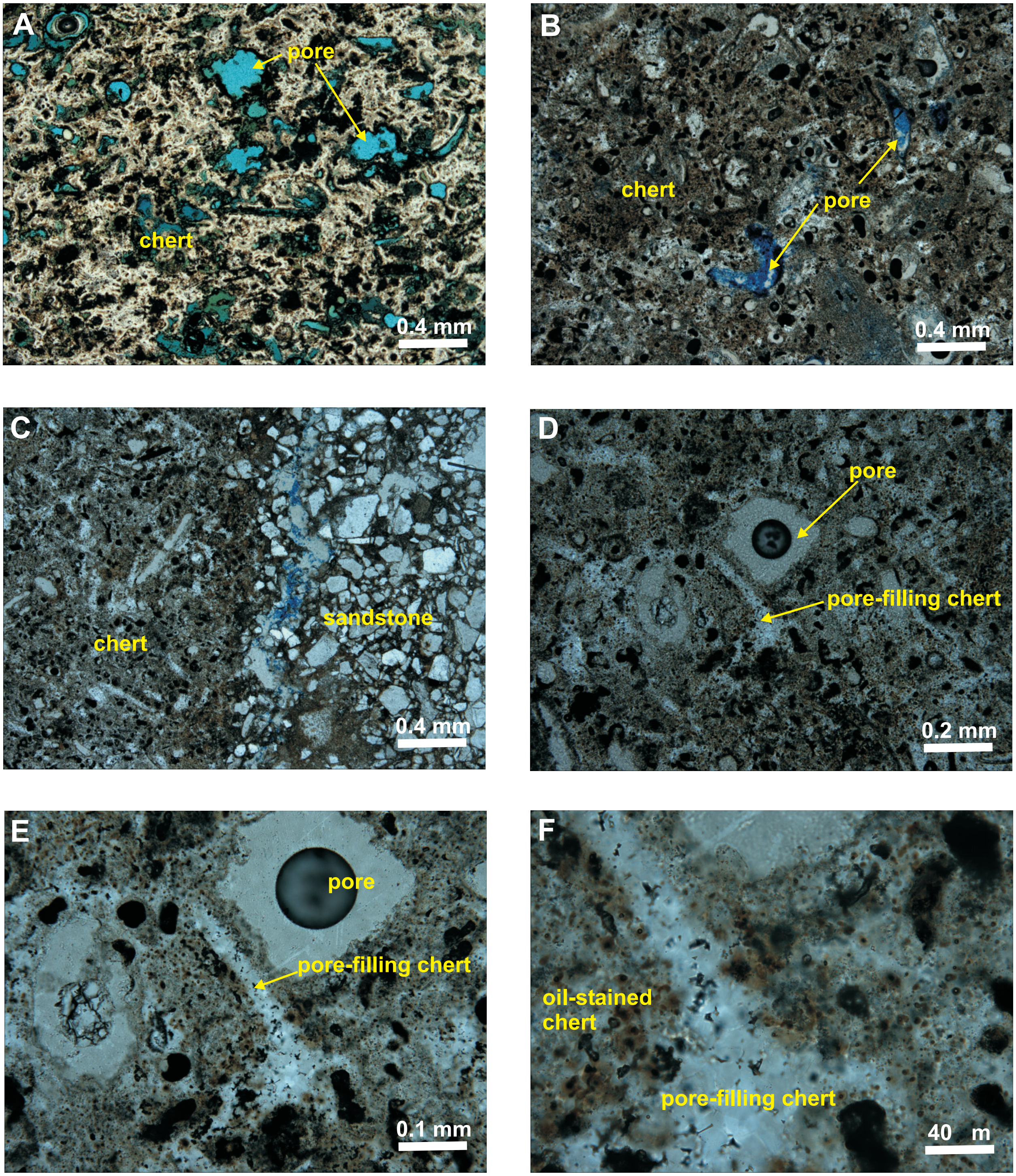

Figure 3 - Photomicrographs of chert pebbles containing oil inclusions, all in plane-polarized light. A) Chert pebble with abundant solid bitumen (opaque) inclusions, open pores (blue) and fossil fragments (C-Ant-2); B) chert pebble with abundant fossil fragments, solid bitumen (black), and a few pores (blue) (GG-Ant-8); C) a chert pebble in contact with sand matrix, both stained with bitumen (GG-Ant-8); D) three components within the chert pebble: chert with abundant oil inclusions, pore-filling chert (some of them mimicking moulds of shell fragments), and open pores (not filled with blue epoxy here) (GG-Ant-8); E) enlargement of D; note pore-filling chert is relatively clean; and F) enlargement of E; note abundant oil inclusions in the oil-stained chert and few in the pore-filling chert.

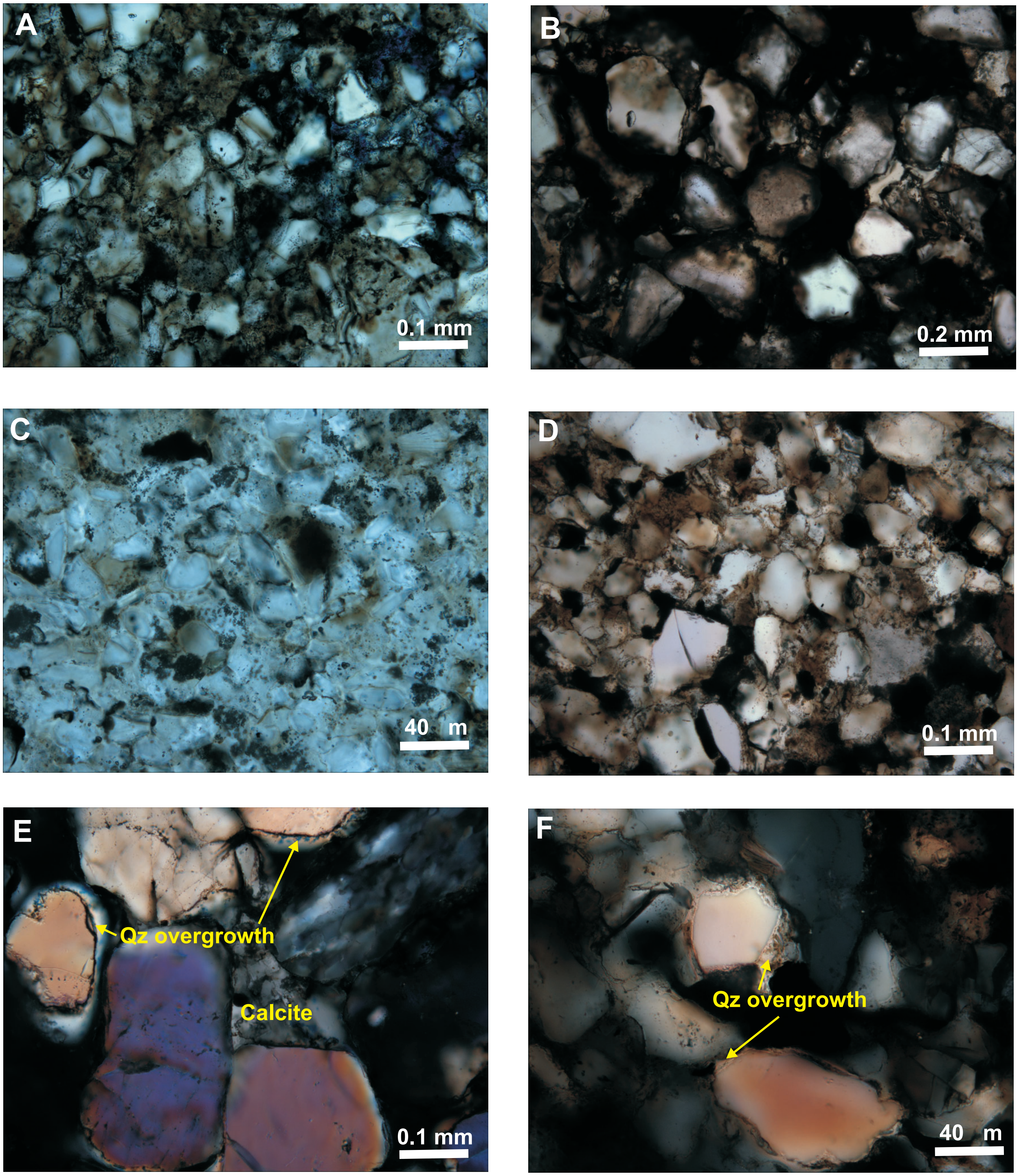

Figure 4 - Photomicrographs of oil sands from the Celtic Pool. A to D are in plane-polarized light, and E and F are in crossed polarized light. A) Very fine-grained sandstone (unconsolidated), brown interstitial material, minor solid bitumen (04GC-602); B) fine-grained sandstone (consolidated), abundant solid bitumen (04GC-603); C) medium-grained siltstone (semi-consolidated), brown interstitial material, minor solid bitumen (04GC-604); D) very fine-grained sandstone (semi-consolidated), abundant solid bitumen (04GC-607); E) fine-grained sandstone with minor quartz overgrowth and calcite cement (04GC-603); and F) very fine-grained sandstone with minor quartz overgrowth (04GC-607).

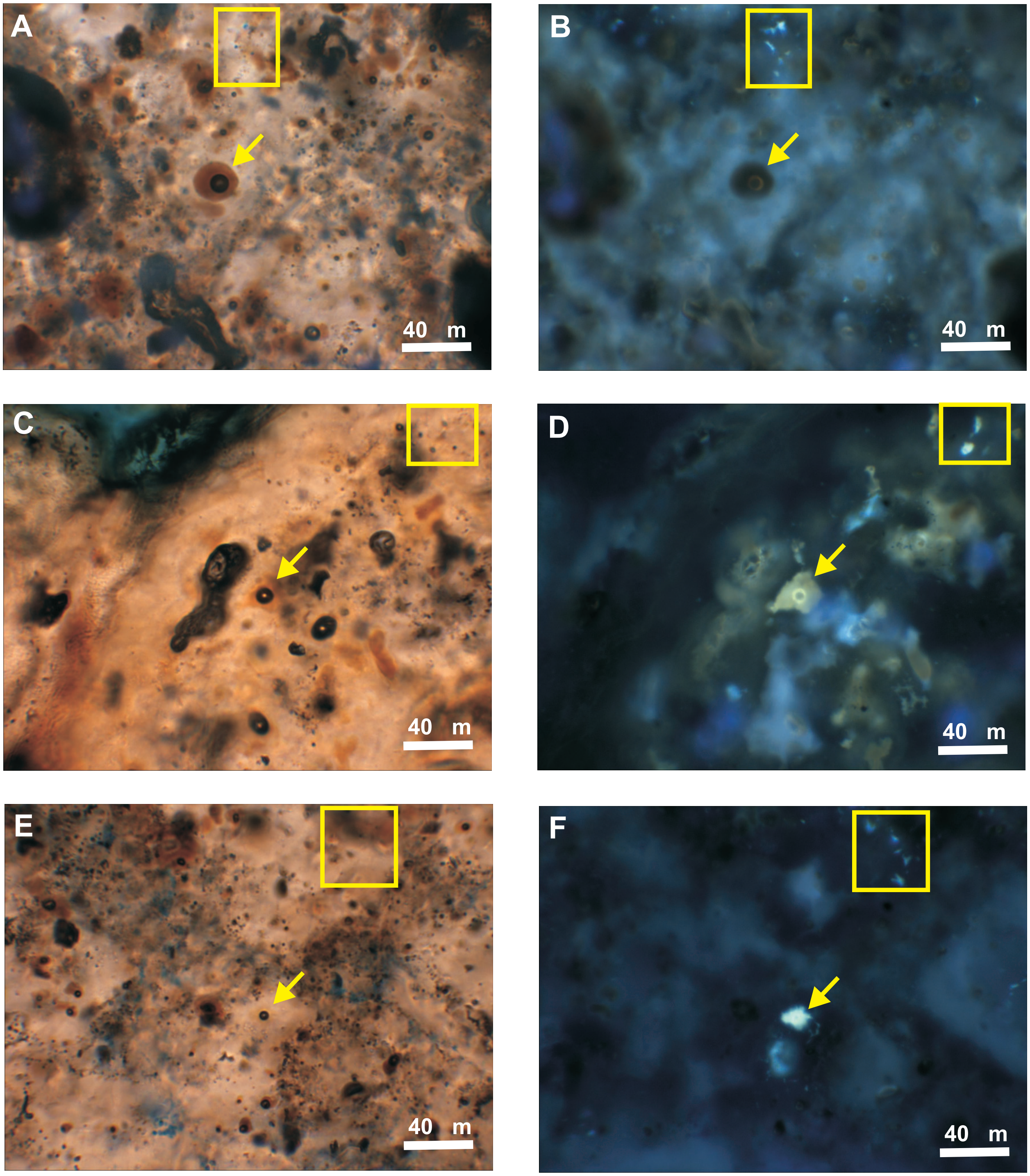

Figure 5 - Photomicrographs of oil inclusions in the chert-pebble samples under transmitted light and fluorescence. A) A brown oil inclusion (pointed by arrow) (GG-Ant-8); B) fluorescence of the same view as A; note the oil inclusion (arrow) is non-fluorescent except a thin rim around the bubble; C) a light brown oil inclusion (arrow) (C-Ant-2); D) fluorescence of the same view as C; weak yellow fluorescence; E) a very light brown oil inclusion (arrow) (GG-Ant-8); and F) fluorescence of the same view as E; strong yellowish white fluorescence. The rectangles in A, C, and E indicate occurrence of colourless oil inclusions under transmitted light (not visible), and those in B, D, and F correspond to the same view under fluorescence, indicating strong blue-white fluorescence of these oil inclusions.

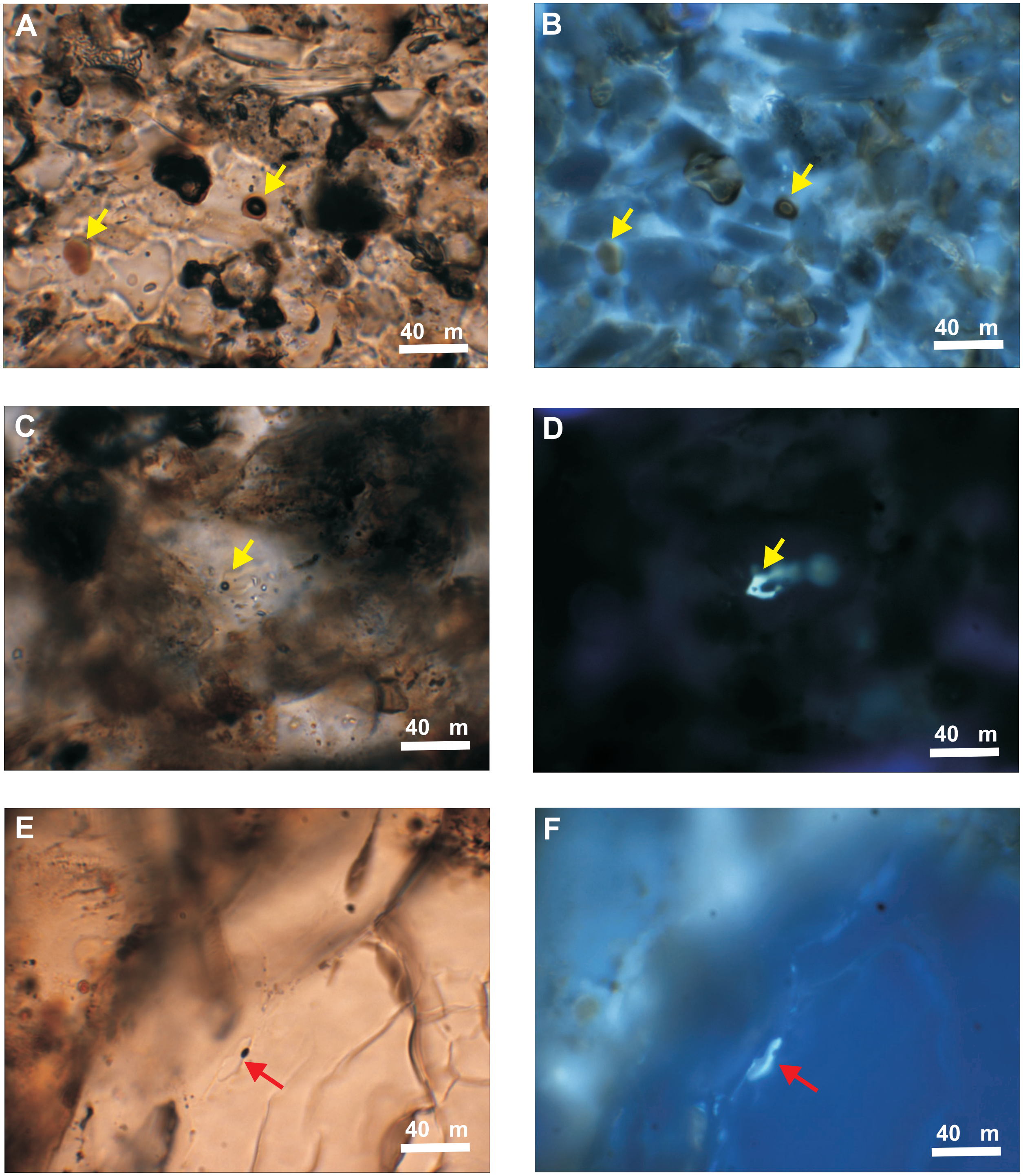

Figure 6 - Photomicrographs of oil inclusions in the oil-sands samples from the Celtic Pool under transmitted light and fluorescence. A) Brown oil inclusions (arrow) (04GC-604); B) fluorescence of the same view as A; one of the oil inclusions is non-fluorescent except for a thin rim around the bubble, and the other shows weak yellow fluorescence; C) a light brown oil inclusion (arrow) (04GC-607); D) fluorescence of the same view as C; strong white fluorescence; E) a colourless oil inclusion (04GC-603); and F) fluorescence of the same view as E; strong white fluorescence.

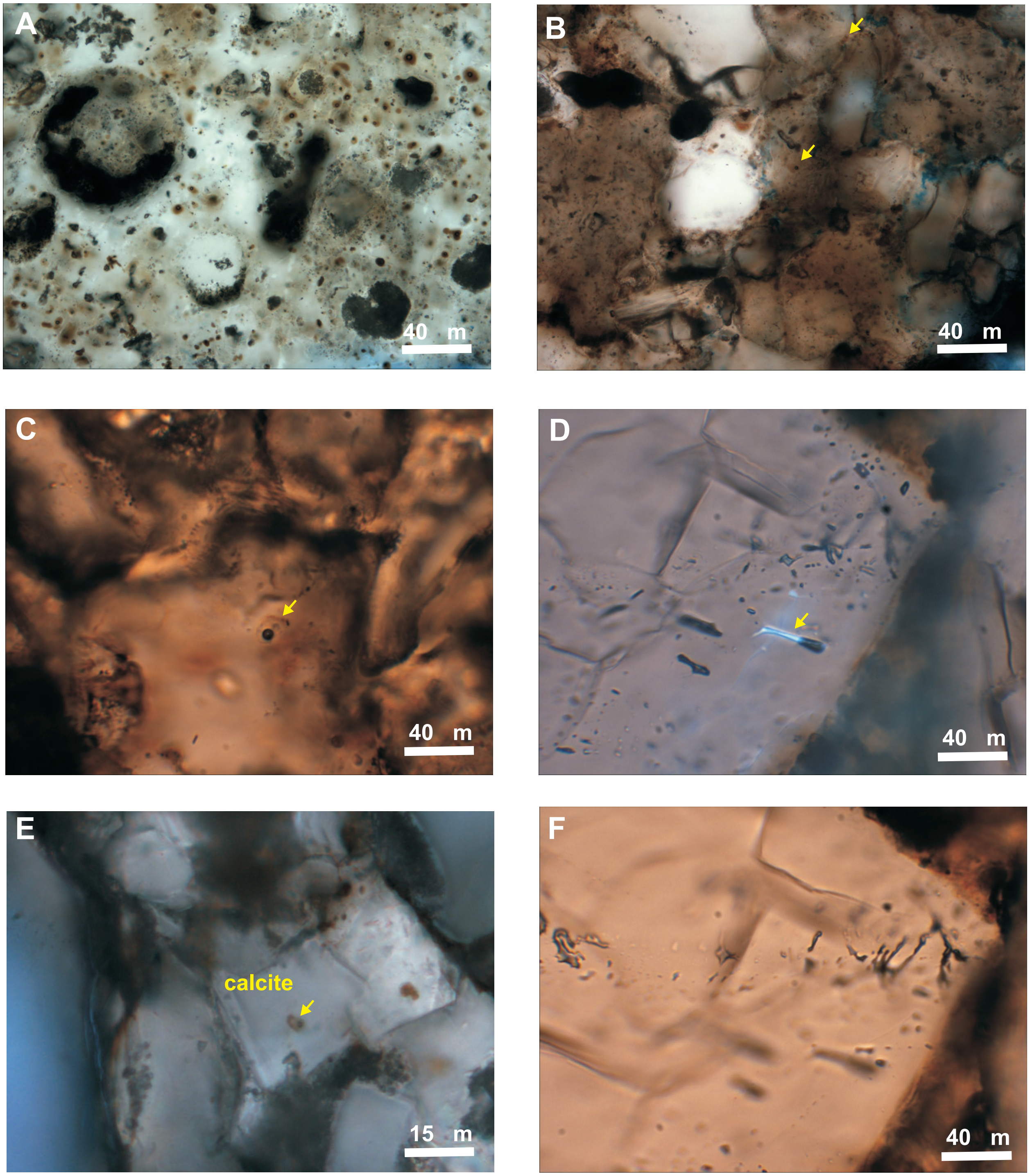

Figure 7 - Photomicrographs showing the various modes of occurrence of oil inclusions, all in plane-polarized light. A) Abundant oil inclusions in a chert pebble (GG-Ant-8); B) oil inclusions in interstitial space of matrix of oil sands (arrow) (04GC-607); C) an isolated oil inclusion (colourless, arrow) within a detrital quartz grain (04GC-609); D) an elongated, colourless oil inclusion (combined fluorescence and transmitted light, arrow) in a detrital quartz grain (04GC-603); E) an isolated oil inclusion (arrow) in calcite cement (04GC-603); and F) a trail of oil inclusions along a microfracture in a detrital quartz grain (04GC-603).

5. Microthermometry

The homogenization temperatures of oil inclusions from two chert-pebble samples (GG-Ant-8 and C-Ant-2) and one oil-sand sample (04GC-607) were measured using a Linkam THMS 600 Heating-Freezing stage, which has been calibrated with synthetic fluid inclusions. The precision of the measurement is ±1ºC.

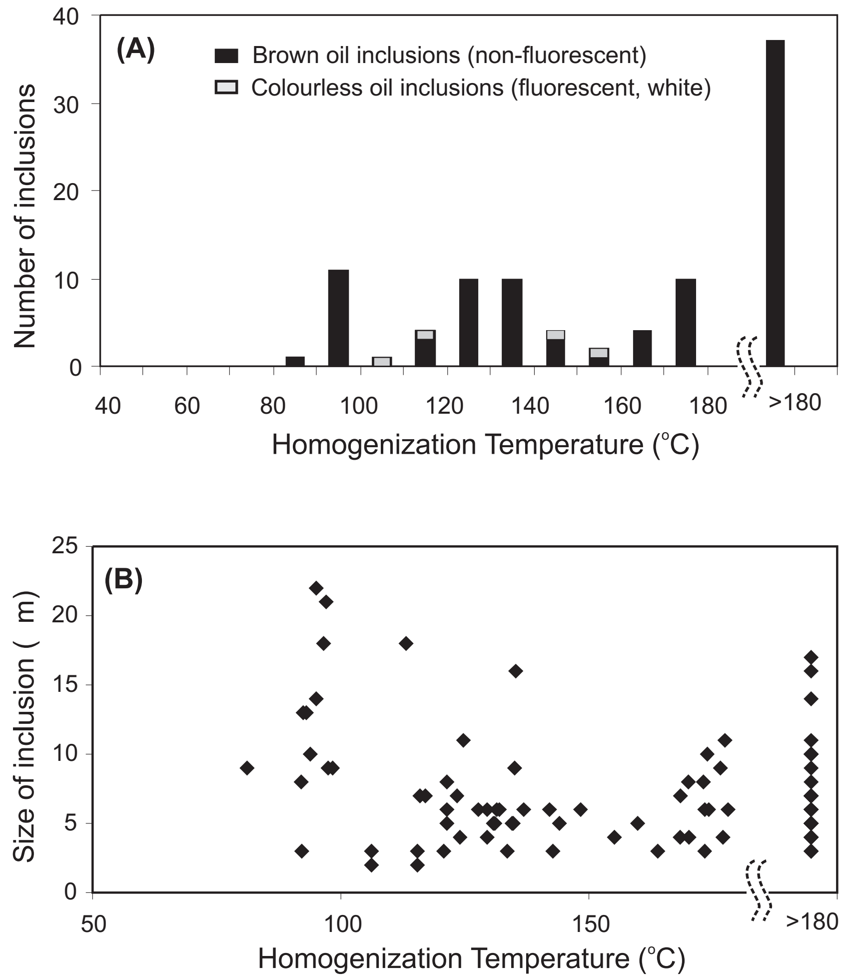

Figure 8 - Microthermometric data of oil inclusions from the chert-pebble samples. A) Homogenization temperatures of brown oil inclusions (non-fluorescent) and colourless oil inclusions (white fluorescence); and B) relationship between homogenization temperatures and sizes of oil inclusions.

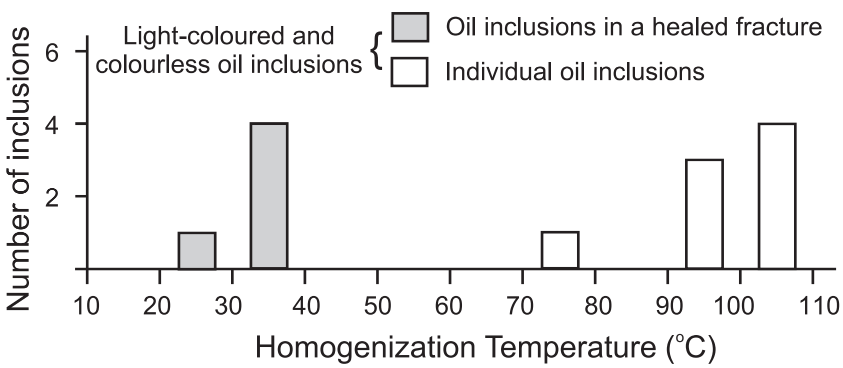

Figure 9 - A histogram of homogenization temperatures of light-coloured and colourless oil inclusions from the Celtic oil sands samples.

The homogenization temperatures of brown oil inclusions in the chert-pebble samples are highly variable, ranging from 81ºC to more than 180ºC (Figure 8A). Few homogenization temperature data were obtained for the colourless oil inclusions; they also show a wide range (100ºC to 160ºC) but do not exceed 180ºC (Figure 8A). The homogenization temperatures can be reproduced several times for some oil inclusions, but are variable with repeated runs for other inclusions, indicating that the inclusions are being modified with the heating runs. The homogenization temperatures do not appear to be correlated with the sizes of the inclusions (Figure 8B).

Oil inclusions in the oil-sands samples comprise brown-coloured (non-fluorescent) types and the colourless or very light brown (white fluorescence) types. The brown-coloured inclusions mainly occur in the matrix and in lithic grains; their homogenization temperatures are not measured because these inclusions, like those in the chert-pebble samples, are not well sealed. The colourless or light-coloured inclusions occur in isolation or trails in detrital quartz. The homogenization temperatures of those in a healed fracture range from 29ºC to 35ºC, and those of isolated inclusions range from 76ºC to 109ºC (Figure 9). The fluorescence of the oil inclusions in the healed fracture is slightly less strong than that of the isolated inclusions.

6. Discussion and Conclusions

Although different types of oil inclusions may record multiple charging events, it is more likely that they represent samples of the oil in the reservoirs at different stages of the reservoirs' evolution. The brown (non-fluorescent) oil inclusions are probably the products of strong biodegradation, whereas the light-coloured and colourless oil inclusions probably record the oil before significant degradation.

The brown oil inclusions are most abundant, and occur mainly in the chert pebbles and matrix of sandstones. These oil inclusions are likely not well sealed as indicated by the poor reproducibility of homogenization temperatures, and, therefore, cannot be reliably used to estimate the temperature conditions of the reservoirs, although the lower end of the spectrum of the homogenization temperatures (Figure 8A) may be close to the valid homogenization temperature. The colourless oil inclusions in the chert-pebble samples are not well sealed either, because they also occur in interstitial space and behave similarly to the brown inclusions.

The light-coloured and colourless oil inclusions occurring in detrital quartz grains in the oil sands, however, show fairly consistent homogenization temperatures. From the limited data obtained so far (Figure 9), it appears that at least two stages of the oil reservoir were recorded. The initial charge of the reservoir probably took place at temperatures higher than 76ºC and 109ºC (homogenization temperatures represent the minimum trapping temperatures in the case of homogeneous trapping). A later stage of the reservoir was recorded when temperature cooled to above 29ºC to 35ºC, as recorded by the oil inclusions in healed fractures.

Larter (2006) proposed that biodegradation was caused by micro-organisms that were descendents of those deposited with the reservoirs, and that a temperature of 80ºC probably represents the survival limit of these micro-organisms. Our microthermometric data appear to indicate temperatures above this limit. One possible explanation is that the oil inclusions entrapped both oil and gas (heterogeneous trapping), so the measured homogenization temperatures are actually higher than the trapping temperatures. This possibility needs to be evaluated in future studies, using the fluid inclusion assemblage concept. The significance of the temperature values cannot be fully understood until more data are collected and fluid pressures are calculated. Fluid pressure calculation is possible if the volumetric ratio of the bubble and oil is measured with confocal scanning laser microscopy (Pironon *et al.*, 1998; Apline *et al.*, 1999) and the composition of the oil is analyzed or the API value of the oil is estimated from fluorospectroscopy (Stasiuk and Snowdon, 1997; Chi *et al.*, 2000).

In conclusion, this study indicates oil inclusions are present in the oil sands and are locally abundant. The oil inclusions occur in interstitial space and dissolution vugs of chert pebbles, lithic grains and matrix, and as isolated inclusions or in healed fractures in detrital quartz grains. The oil inclusions range from brown to colourless. The brown inclusions are non-fluorescent, and the light-coloured oil inclusions show strong white fluorescence. Oil inclusions in interstitial space and dissolution vugs are not well sealed and are unsuitable for microthermometric study, whereas those occurring in detrital quartz grains (isolated and along healed fractures) yield consistent homogenization temperatures. The oil inclusions in quartz grains record the evolution of the reservoir after charging, and may be used to reconstruct the thermal history and timing of oil migration and accumulation.

7. Acknowledgments

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