The Influence of Fabric Arrangement on Oil Sand Samples from the Estuarine Depositional Environment of the Upper McMurray Member*

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Abstract

The Upper McMurray Member of Canada's McMurray Formation, and specifically samples from Athabasca's estuarine depositional settings, displayed high porosity based on initial study. This work involved thin section imaging and micro CT-scanning in determining reservoir characteristics. The results from the thin section analysis for the porosity estimation showed that the estimated porosity lay between 30 and 50%, which is analogous to tests performed in well laboratories. Data and results obtained from the two experiments were then used to compute the pore size distribution, connectivity of pores and estimates of the porosity and permeability of the reservoir. The analysis of the spatial arrangement and distribution of the oil sand constituents showed that bitumen was distributed within the quartz grains and between the quartz grains. Another distinctive feature was the distribution of bitumen in the non-connecting large pores (vugs). The micromass was observed to form bridges between the quartz grains and may be associated with larger clay bands. Importantly, soil structure was observed in thin section to be associated with Spodic horizons and the fabric of the grains ranged from Enaulic to Gefuric c/f related distribution patterns. This indicates that the oil and meteoric water migrated into a sandy material with inherited soil structure. An analysis of this type has the potential to differentiate between parts of the formation where connectivity will have a bearing on the relative ease and cost of production of steam-assisted gravity drainage (SAGD) projects. It should then be possible to identify "sweet" spots along the reservoir interval where completion design factors (such as sand/clay control or temperature/pressure profile control between injector and producer) can be employed more effectively to target specific intervals for optimum production.

Introduction

As there have been few large discoveries of conventional oil in recent times, research into unconventional oil, such as heavy oil and oil sand, is becoming increasingly inevitable. Oil sand is a naturally occurring mixture of sand, clay, water and extremely dense viscous oil (bitumen). With the demand for more oil, heavy oil is seen as a viable option. During previous low prices of oil, unconventional oil was not economic due to the cost involved in production and lack of appropriate technology for recovery. With the economic advantages from the recent advancement in technology, interest in heavy oil has substantially increased. Alberta's heavy oil deposit contains 1.7 trillion barrels of heavy oil and an estimated 179 billion barrels is recoverable based on current technology (Canada National Energy Board, 2004). With new technology, interest in Alberta's oil reserves is bound to intensify.

Regional Geology of Athabasca

The McMurray Formation is part of the Lower Cretaceous Mannville Group (Cant and Abrahamson, 1996). The formation lies at the base of the group, on an angular unconformity from the Devonian. It is comprised of limestone and calcareous shale in the east and carbonate rocks in the west. Sediments in the McMurray Formation were deposited in a north-south trending ridge and valley system that was originally formed by fluvial processes. The depositional environment later changed to marginal-marine during an Early Cretaceous sea-level rise.

Overall, the McMurray Formation has very complex sedimentary relationships that vary considerably, both laterally and vertically over short distances, indicating complex depositional environments with common transgression and regression cycles (Hein et al., 2001). The McMurray Formation is divided into three members, a Lower, Middle and Upper (Carrigy, 1959). Textural variations occur between the three members: the lower member is a conglomerate consisting of poorly sorted and argillaceous sand, silt and clay; the middle member is comprised of moderately well sorted, fine-grained sand and argillaceous silt; and the upper member consists of very fine-grained sands and argillaceous silt. Distinct facies, based largely on sedimentary features, characterise the three members. Bitumen is located throughout the formation.

Fabric of Athabasca Oil Sands

Much research has been carried out on the nature of the fluid in oil sands Athabasca. These studies took the form of PVT and viscosity analysis to establish the volumetrics, porosity and permeability. However, few studies have been carried out on the fabric of the Athabasca oil sands. Takamura (1982) did some of the early microscopic work. Takamura observed that connate water forms an up to 10 µm thick film of water as coatings around quartz grains and surround the grain. Bitumen fills voids between grains. The presence of this aqueous film has long been recognised as a characteristic feature of the Athabasca oil sands. The aqueous film or hydrophilic nature of the sand is important for the hot water (steam) extraction process of bitumen.

Previous descriptions of the arrangement of oil sands constituents were mostly carried out on disturbed samples. Other key fabric studies include Dusseault (1980) who performed analysis on in-situ oil sands samples with similar findings to Takamura (1982). He did note that fine-grained clay and feldspar minerals were dispersed through the water film surrounding the sand grains. Czarnecki et al. (2005) countered that even though the existence of aqueous film in the Athabasca oil sands remains reasonable, it is yet unproven postulate. They argued that the aqueous film separating clean, hydrophilic quartz and bitumen is stable under most conditions but unstable for acidic oil sand ores.

Material and Methods

The site selected for this study was the Hangingstone River area near Fort McMurray, Canada and from a well-documented estuarine-tidal depositional environment from the Upper McMurray Member (Hein et al., 2001). Notable sedimentary features in the Upper McMurray Member include those interpreted from a tidally influenced point bar and an estuarine depositional environment or, more specifically, brackish water trace fossil assemblages that indicate an estuary environment (Pemberton et al., 1982). These estuarine-tidal channels and point bars are significant facies as they are common bitumen-sand reservoirs. There are variations in oil content among the diverse sedimentary environments, although the estuarine environment is considered to have the highest oil saturation (Czarnecki et al., 2005).

Thin sections were prepared according to the usual process of production of soil thin sections (Jongerius and Heintzberger, 1975; and Fitzpatrick, 1984) although procedures were modified in order to maintain sample integrity and minimize alteration of the oil contained in the samples. Thin sections were analysed and described according to Stoop (2003).

Additionally, micro CT scans were carried out on the same material. The ultimate desktop X-ray Microtomograph SKYSCAN 1172 was used in this study. The cone microfocus beam source is based on a tungsten X-ray tube having a focal spot of 7 µm at 10A isowatts. Voltage can be set from 20 to 100 kV with current that meets 250 mA. An undisturbed subsample having a diameter of 3.2 cm was scanned at 1.3 and 8 µm resolution.

Results and Discussion

The concept of soil fabric was introduced by Kubiena (1938) as the arrangement of constituents of the soil in relation to each other. This concept was further developed by Brewer and Sleeman (1960) in reference to the relative distribution of ‘skeleton grains’ and ‘plasma’. According to Stoops (2003), important elements of fabric are spatial distribution, orientation, size, sorting and shape. Fabric can be determined according to size of component and spatial distribution. Coarse components of the groundmass are commonly single mineral grains, compound mineral grains or rock fragments, inorganic residues of biological origin and anthropogenic elements (Stoops, 2003). The fine mineral component of the groundmass forms a partial fabric known as the micromass and generally cannot be determined by its optical characteristics (Karale et al., 1974). The concepts of spatial units are based on coarse and fine (c/f) components. The c/f related distribution patterns ‘expresses the distribution of individual fabric units in relation to smaller fabric units and associated pores’ (Stoops and Jongerius, 1975). For this paper, a more traditional micromrophological approach is used.

As observed in thin section, the Athabasca oil sands from the estuarine depositional environment of the Upper McMurray Member consisted predominately of a coarse component of rounded to angular quartz grains imbedded in a micromass of silt and clay. Some of the quartz grains displayed different degrees of weathering. Bitumen was observed both within the micromass and as an exotic feature. The analysis of the spatial arrangement and distribution of the oil sand constituents showed that bitumen was distributed within the quartz grains and between the quartz grains.

Another distinctive feature was the distribution of bitumen in the non-connecting large pores (vugs). The results from thin section analysis for porosity showed that the estimated porosity lay between 30 and 50%, which is analogous to tests performed in well laboratories.

During thin section preparation, various resigns and hardeners were used. Little disturbance occurred when epoxy resin and epoxy diluents were included in sample preparation in order to lower viscosity for better penetration in the pores of the samples. The overall c/f related distribution pattern was Porphyritic (Figure 1). During sample preparation using polyester resins, the exothermic reaction of the epoxy resin polymerization could have induced the dissolution of oil between the grains. This dissolution of the oil between grains allowed for observation of the fabric arrangement, including the coarse components and micromass (Figure 2). The micromass was observed to form bridges between the quartz grains, which may be associated to larger clay bands, and the c/f related distribution pattern ranged from Enaulic to Gefuric according to Stoops (2003).

Importantly, unconsolidated material such as regolith and soil with an Enaulic to Gefuric c/f related distribution pattern is often associated with Spodic horizons. This agrees with Kotlyar et al. (1990) whose study on clays from Athabasca oil sands indicated Spodic horizons. The presence of a Spodic structure suggests that the oil sands migrated into a body of material with its own inherent characteristics including geochemical signatures.

A pore size distribution and connectivity analysis was carried out by a “successive opening” algorithm from micro CT scanning. The total porosity (percent volume of oil and empty pores) had a unimodal size distribution of 38.55% and 41.82%, calculated for 1.3 and 8 µm resolutions. The cumulative porosity for the 1.3 µm resolution consisted of 10% micropores with diameters ranging from 0 to 15 µm, 70% inter-particle pores with diameters ranging from 15 to 41 µm, and 20% vugs (>41 µm). The total porosity for the 8 µm resolution consisted of 10% micropores with diameters ranging from 0 to 40 µm, 65 % inter-particle pores with diameters ranging from 40 to 120 µm, and 25% vugs (>120 µm).

The pore medial axis network is presented in the visualization in Figure 3. Colors indicate the distance of the pore walls from the medial axis: red represents the medial axis inside the smaller pores, while yellow, green, blue and violet representing those inside progressively larger pores. Throat/pore radius ratio indicates a mean value around 0.5 while the average value of the pore tortuosity is 1.63.

Implications of the Fabric Arrangement

Steam assisted gravity drainage (SAGD) is the primary means by which bitumen is produced from oil sand deposits. In this process, steam is injected into a horizontal well where it mobilizes the bitumen deposit, largely by reducing viscosity, allowing the fluid to flow to a parallel, deeper horizontal production well. The in-situ viscosity of the bitumen can be reduced by orders of magnitude (Li et al., 2011) but the economics of the process are largely determined by the efficiency of generating steam and delivering sufficient heat through the sand formation and along the production tubing. A selective production approach would enable steam /oil ratios to be improved in favor of less steam, which ultimately means a reduced environmental impact, more efficient energy usage and less water processing.

An understanding of the influence of fabric arrangement, as described in this paper, has the potential to differentiate between parts of the formation sand where connectivity and fluid mobilities will have a bearing on the relative ease and cost of SAGD production. The micromass was observed forming distinct features such as clay bridges between grains. Initial findings indicate that the fluid constituents should still, in theory, be hydrophilic but findings reveal a more complex fabric than grains being encapsulated by a thin coating of water.

Studies on conventional oil reservoirs reveal that reservoir characteristics vary with different fabric arrangements. Ideally, the aim of determining fabrics and arrangements would be to identify “sweet” spots along reservoir interval, where completion design factors (such as sand/clay control or temperature/pressure profile control between injector and producer) can be employed more effectively to target specific wells or intervals for optimum production. The approach would be analogous to the way stacked reservoirs are selectively produced in conventional oil fields.

In the context of improved SAGD well completions, Bennion et al. (2009) identified clay content, wettability and flow velocity as having a major effect on the ability of the well completion to control sand influx into the SAGD production well, a factor which determines artificial lift performance and increases clean-up costs for surface facilities.

Recent simulation studies (Li et al., 2011) have shown that modifications to the SAGD process by adding solvents to the injected steam cannot always be expected to deliver improved productivity and, for heavy solvents, reservoir heterogeneity needs to be taken into account. It would seem that a better awareness of these heterogeneities would remove some of the uncertainty and could offer the prospect of a modified SAGD process being targeted to wells where an improved productivity could be predicted.

Summary and Conclusion

With the lack of new big discoveries of conventional oil in recent times, research into the fabrics of unconventional oil, such as heavy oil and oil sand, is becoming increasingly inevitable. Complex fabrics of the Athabasca oil sands should be further explored and used to identify plays with sweet spots. Once these areas can be identified, recovery can be maximized and issues such as water usage during recovery can be further addressed. Understanding the flow of heavy oil in porous media with complex fabrics will be paramount.

Acknowledgements

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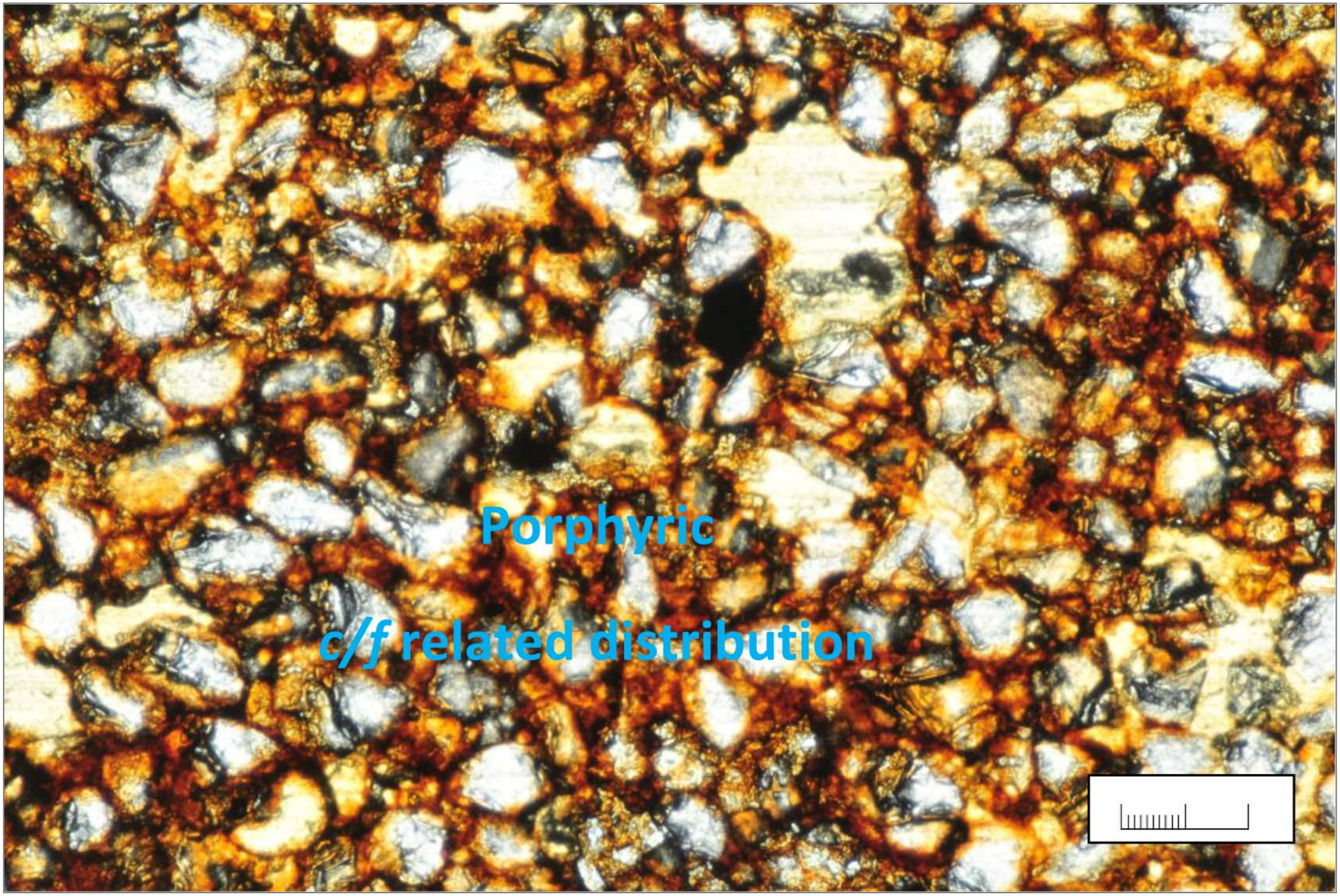

Figure 1. Components are quartz grains, micromass and bitumen in a Porphyric c/f related distribution pattern according to Stoops (2003).

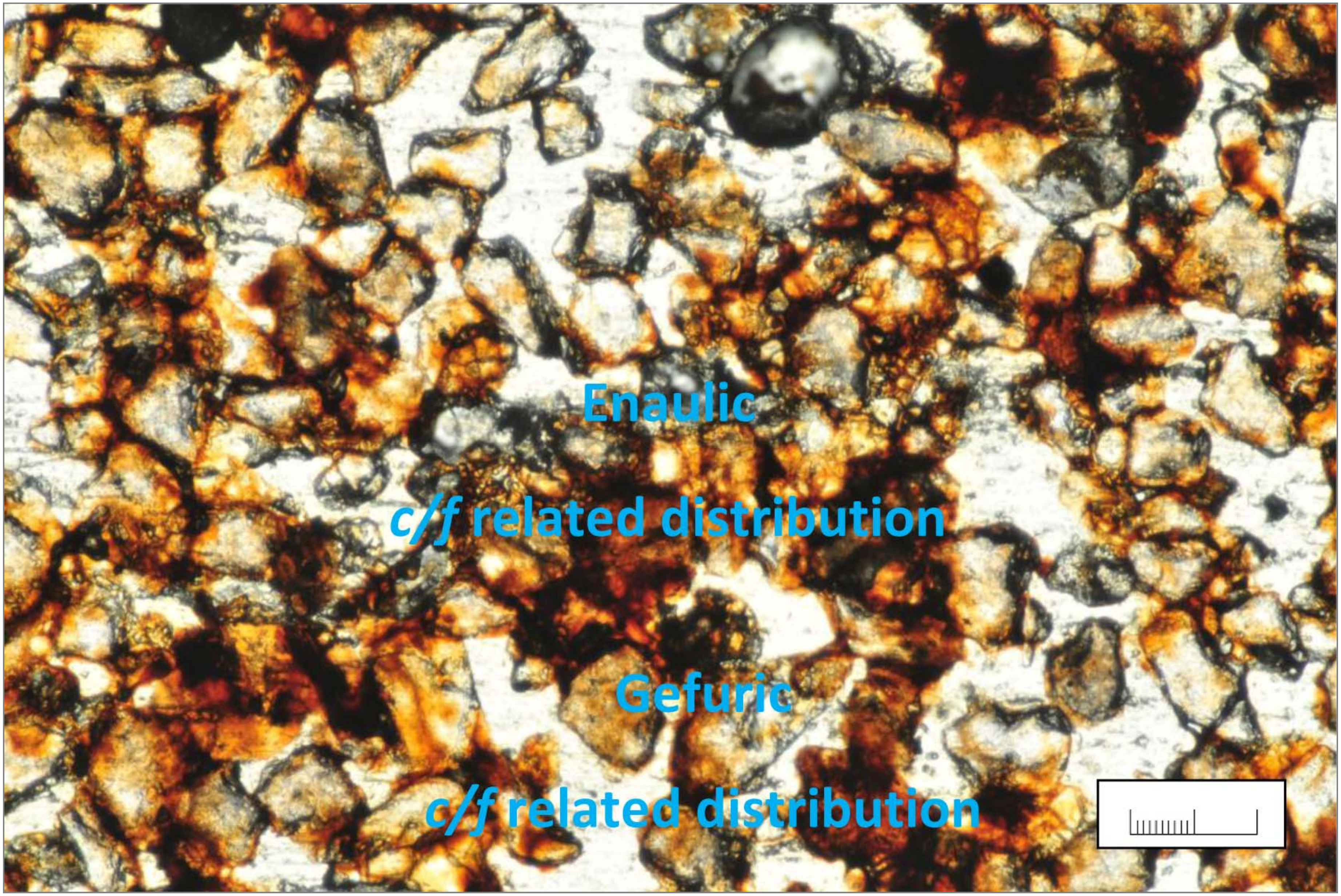

Figure 2. The c/f related distribution pattern ranges from Gefuric with the micromass bridging quartz grains to Enaulic where the micromass surrounds quartz grains according to Stoops (2003).

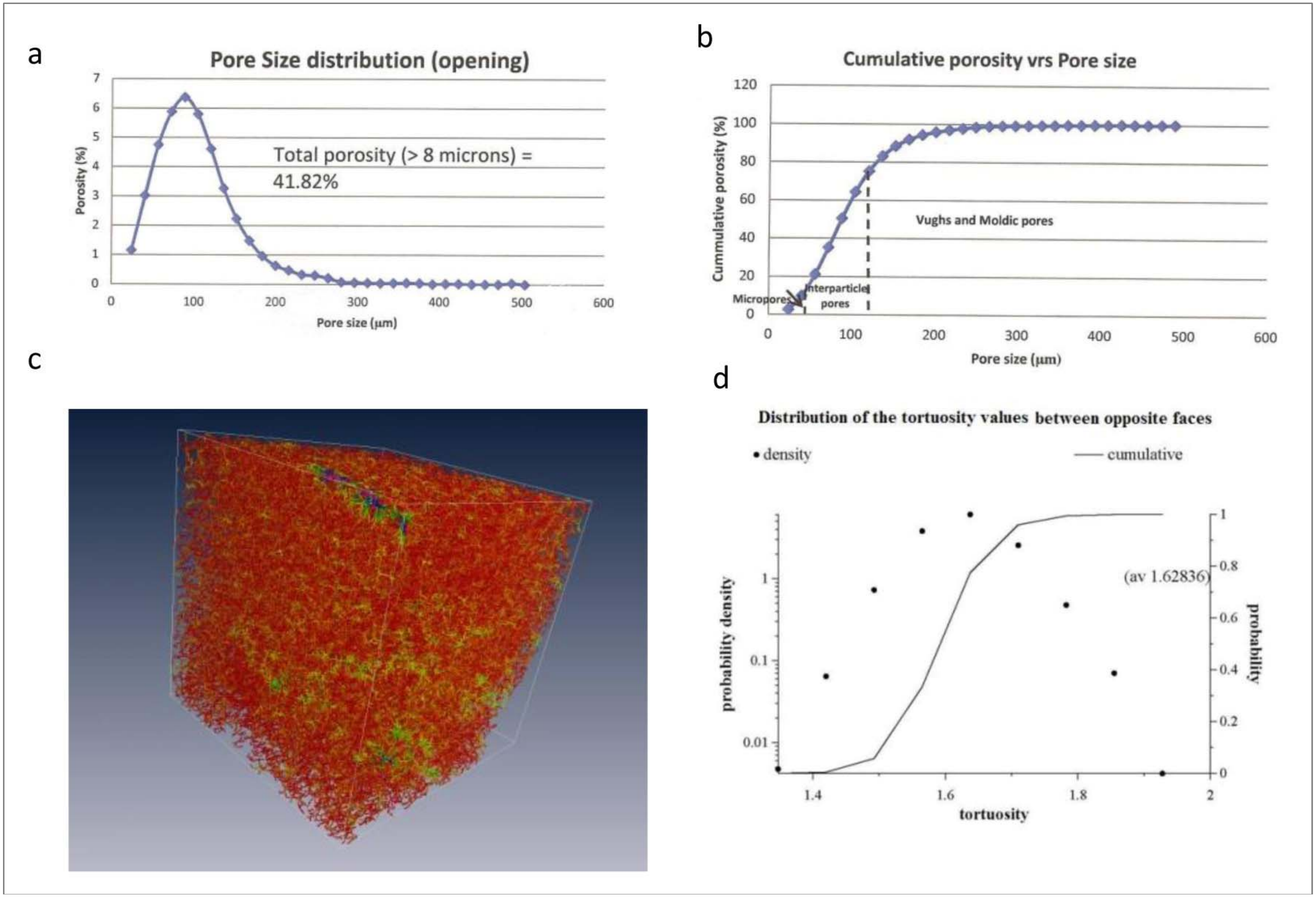

Figure 3. Results from micro CT scanning: a) pore size distribution from 8 µm; b) cumulative porosity and pore size for 8 µm; c) visualization of pore medial axis network, pore throat radii distribution; and d) tortuosity.