Sedimentology and Reservoir Properties of the Three Forks Dolomite, Bakken Petroleum System, Williston Basin, U.S.A.*

Ray Mitchell[1]

Search and Discovery Article #120079 (2013)*
Posted February 25, 2013

*Adapted from extended abstract prepared in conjunction with poster presentation at AAPG Hedberg Conference, Fundamental Controls on Flow in Carbonates, July 8-13, 2012, Saint-Cyr Sur Mer, Provence, France, AAPG©2012

[1] Subsurface Technology, ConocoPhillips, Bartlesville, Oklahoma, USA (ray.w.mitchell@conocophillips.com)

Abstract

Although commonly referred to as part of the "shale gas revolution", production from the Bakken Petroleum system is oil and mostly from interbedded carbonate intervals. The reservoir units include the Middle Bakken (a variety of siliciclastic and carbonate facies) and the Three Forks Formation (dolomite). The Upper and Lower Bakken Shales are the source rock and may contribute to storage. Development of the light oil in these reservoirs is facilitated by long horizontal wells and multi-stage fracs.

Introduction

The Three Forks Formation recovered in core commonly includes the upper Three Forks and partial recovery of the underlying middle Three Forks. Egenhoff et al (2011) identified six facies in the Three Forks; terrestrial paleosols, sabkha, subaerial gravity flows, intertidal, peritidal, and subtidal. Only the gravity flow, peritidal and sabkha deposits are common and widespread in the basin. Sabkha facies are not seen in the upper Three Forks cores in this study area.

The upper Three Forks (UTF) interval is subdivided into a number of units (Figure 1). The basal unit, UTF-1, is a massive to nodular, cemented dolosiltstone that is interpreted as a soil. The UTF-1 is typically overlain by heterolithic argillaceous, silty dolosiltstone UTF-3 facies (UTF-2 has a very limited areal distribution). The UTF-3 facies is characterized by alternating very thin beds to thick laminae of rippled silty dolostone and desiccation-cracked argillaceous flasers. The UTF-4 is typically a massive, bioturbated, dolomitic, argillaceous siltstone. The UTF-3 is the primary reservoir facies of the upper Three Forks; oil has migrated into the upper Three Forks from the overlying Lower Bakken Shale. The middle Three Forks is made up of dolomitic, intraclast-rich siliciclastic mudstones, interpreted as mudflows, with less common intervals of siltstone.

In our nomenclature, the UTF-1 corresponds to the terrestrial paleosol and UTF-3 to the peritidal/intertidal facies of Egenhoff et al (2011). The heterolithic bedding of the UTF-3 is commonly interpreted as "tidal" (Berwick, 2008; Egenhoff et al, 2011), but this style of heterolithic bedding occurs in many environments characterized by episodic and waning flow depositional events. The Three Forks UTF-3 interval lacks the definitive characteristic of tidal flat deposits - the shallowing-up sequence. Add to that the total lack of marine skeletal debris and diagnostic traces, and the marine or tidal origin of the deposit is in doubt.

Discussion

I propose a wholly continental origin for much of the Three Forks. The major processes include transportation of the sediment into the basin by wind, modification by soil processes, including caliche and intrasediment evaporite precipitation (paleosols and sabkha deposits of Egenhoff et al, 2011), reworking of loess by subaerial gravity flows (mudflows - common in the middle Three Forks) during rains and flooding events, and reworking of sediment in sand flats and mudflats in the shallow ephemeral lake. These latter settings formed the heterolithic sediments (UTF-3) near the end of Three Forks time.

The ancestral Williston Basin was an intracratonic basin in the late Devonian and early Mississippian separated from the open ocean and nearby basins by the Sweetgrass and Transcontinental Arches. With the transition to an icehouse world and the onset of glacial eustacy at the end of the Devonian, lower sea level may have resulted in the isolation of the basin from Devonian seas. Bioturbation and a skeletal macrofauna indicate that marine conditions are established only above the flooding surface at the top of the UTF-3. This marine transgression culminated in the maximum flood within the Lower Bakken Shale source facies.

The UTF-3 reservoir rocks are alternating thick laminae to very thin beds of silt-sized dolomite and green/grey (in some places red?) argillaceous mudstone. The dolosilt layers are the porous and permeable component of the UTF-3 (Figure 2). The dolosilt is typically current or wave-laminated with some climbing ripples, small-scale erosive surfaces, hummocky-cross stratification, and wave-modified current ripples (Figure 3). Intraclasts of dolosilt are rarely reworked in thin intraformational conglomerates. The dolosilt crystals are uniform in size. No larger grains or skeletal material is evident (Figure 4). Siliciclastic silt (quartz, feldspar) and hydrodynamically equivalent clay peloids are abundant in the silt layers. The argillaceous mudstone/claystone component occurs as laminae to very thin beds, often as flasers, commonly displaying simple desiccation cracks; most cracks are filled with dolosilt from the overlying layer.

Porosity in the dolosilts averages ~6% and the harmonic mean of air permeability is ~57 microdarcies. Porosity is dominantly intercrystalline. High-pressure mercury injection capillary pressure (MICP) and laboratory NMR analyses indicate that the pore throats are in the upper nano to micro range, and the pore sizes range from nano to meso (Figure 5).

The origin of the dolomite silt is somewhat problematic. The dolomite is most abundant in the coarser layers of the depositional couplets that typically display small-scale sedimentary structures of current or wave origin. Most samples are >50% fine crystalline dolomite, with the remainder a combination of siliciclastic silt (quartz and feldspars) and clays (both detrital and a small component of authigenic forms). The dolomite crystals occur with siliciclastic silt (quartz and feldspar) similar in size and sorting to the dolomite crystals. This suggests that the dolomite crystals were deposited as sediment of approximately the same size (or hydrodynamic equivalence) as the siliciclastic silt. The dolomite occurs as intergrown subhedral to euhedral crystals (Figure 6). It is unclear whether the carbonate was initially formed as dolomite (and then overgrown by dolomite cement to provide the euhedral crystal terminations) or formed as some other primary carbonate mineral and that was later replaced by dolomite. The dolomitic portion of the sediment displays no larger clasts, has no skeletal grains (or remnants), and is very uniform in size. The carbonate sediment did not originate as reworked macrofauna or older carbonate deposits transported into the basin by hydrodynamic processes. There is no evidence of intrabasinal precipitation of carbonate sediment in the Three Forks Formation, such as tufas, speleothems, or microfauna blooms.

Summary

Based on the sedimentologic and petrographic evidence, the sediment of the upper Three Forks is interpreted as a continental loess deposit, with the siliciclastic fraction and most of the carbonate sediment provided to the basin by aeolian processes. Reworking during wet periods formed the characteristic heterolithic bedding in the UTF-3 interval. Overdolomite cement reduced porosity and lithified the sediment.

References Cited

Berwick, B., 2008, Depositional environment, mineralogy, and sequence stratigraphy of the Late Devonian Sanish Member (upper Three Forks Formation), Williston Basin, North Dakota: MS thesis, Colorado School of Mines, Golden, Colorado, 156 p.

Egenhoff, S., A. Jaffri, and P. Medlock, 2011, Climate control on reservoir distribution in the Upper Devonian Three Forks Formation, North Dakota and Montana: AAPG Annual Convention, 10-13 April 2011, Long Beach, California, AAPG Search and Discovery (Abstract) #90124. Website accessed 16 January 2013. http://www.searchanddiscovery.com/abstracts/html/2011/annual/abstracts/Egenhoff2.html

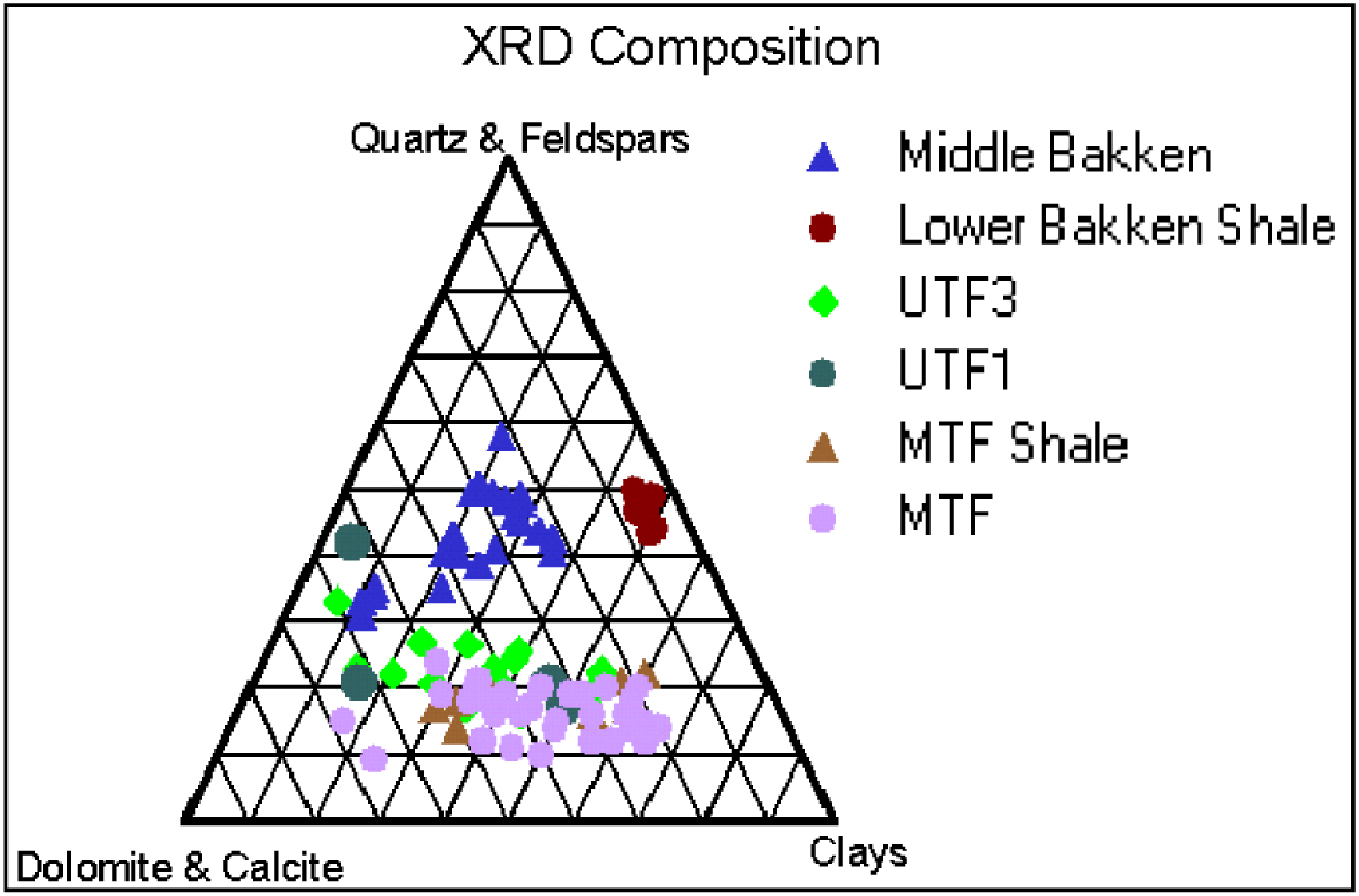

Figure 1. XRD Composition.

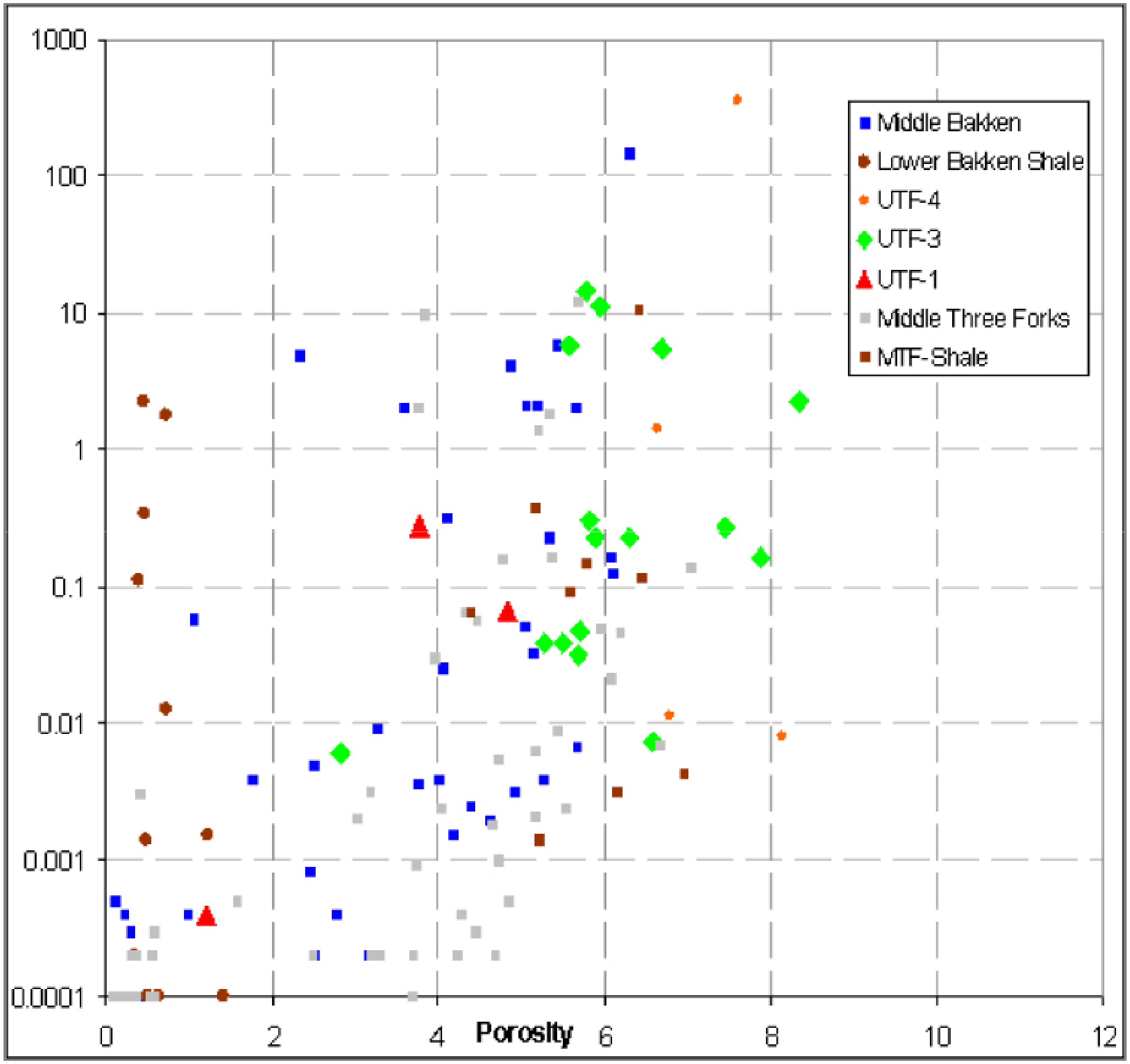

Figure 2. Porosity vs. permeability cross plot.

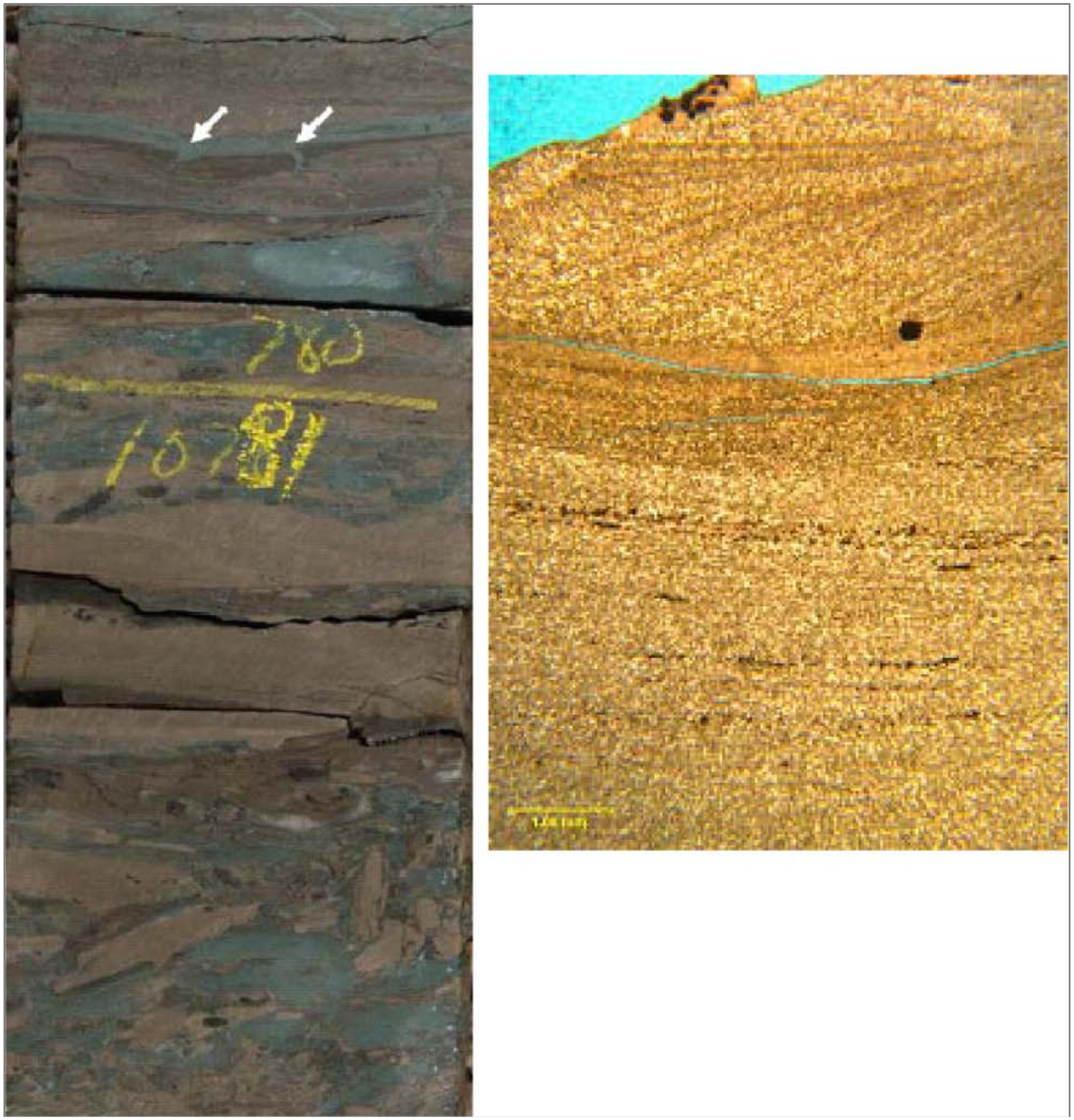

Figure 3. Core and thin section photographs of dolosilt / argillaceous mud couplets UTF-3.

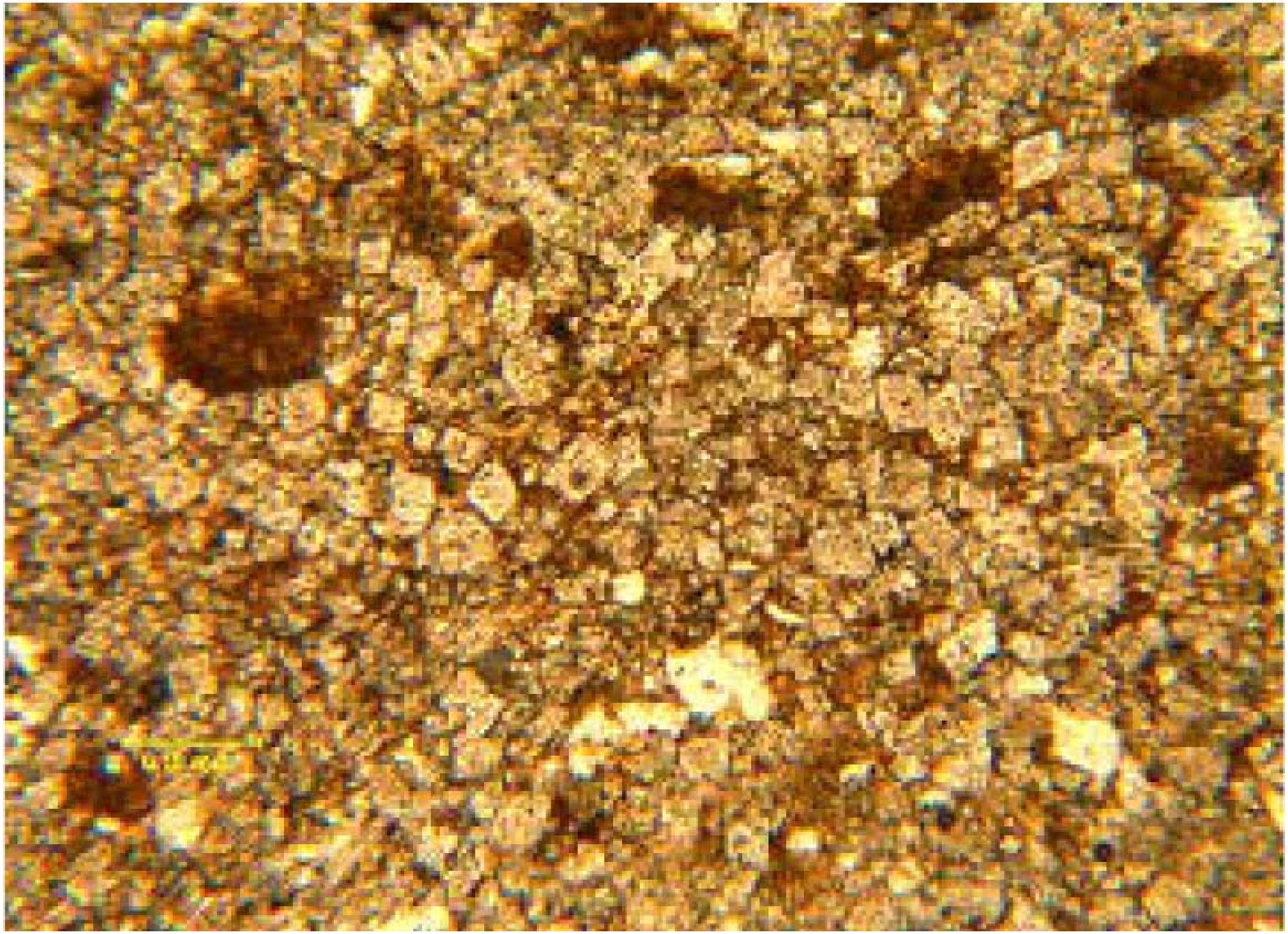

Figure 4. Thin section of dolosilt, with quartz silt and shale peloids.

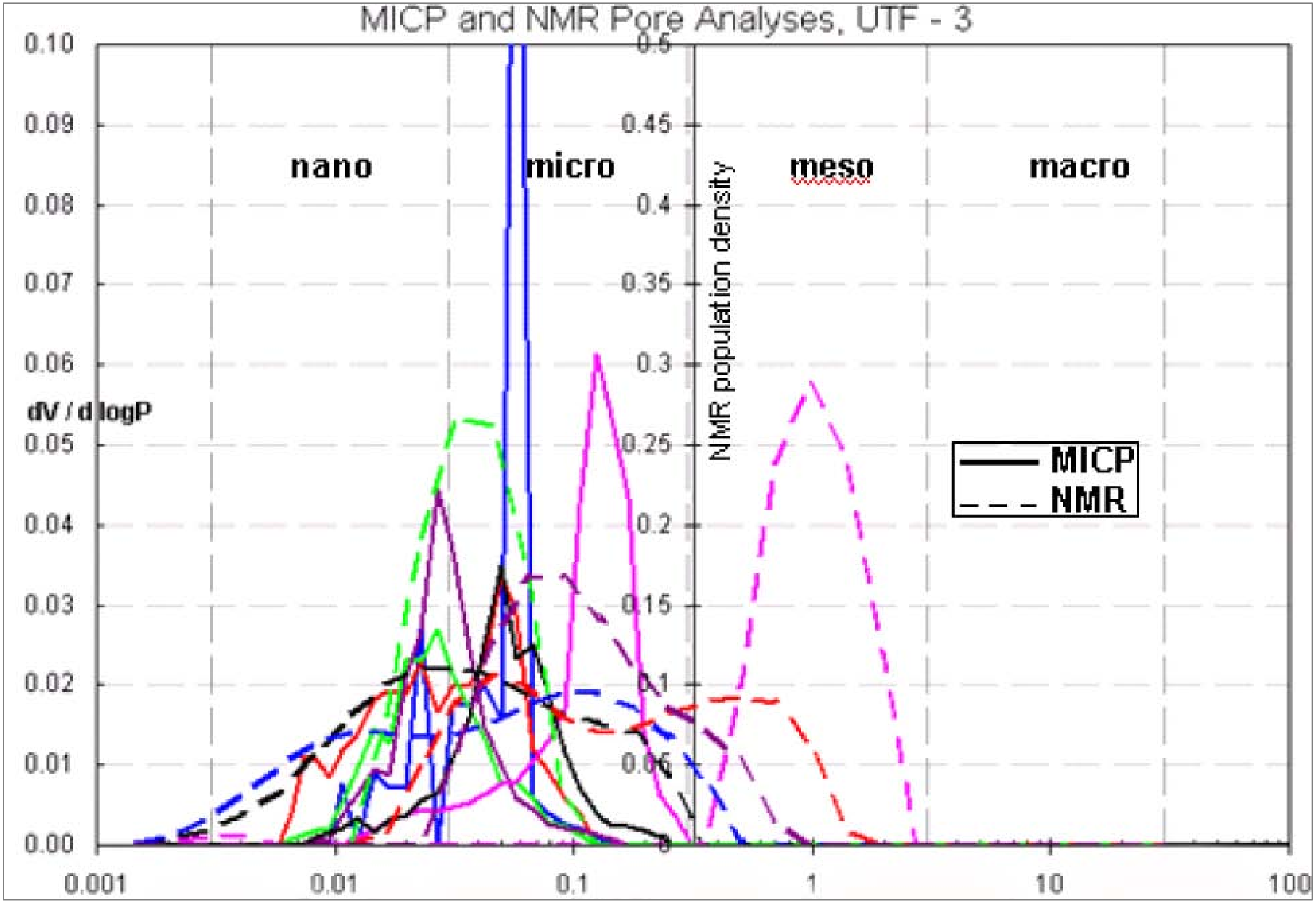

Figure 5. Pore-throat size and pore size in the UTF-3 dolosilts based on MICP and NMR, respectively.

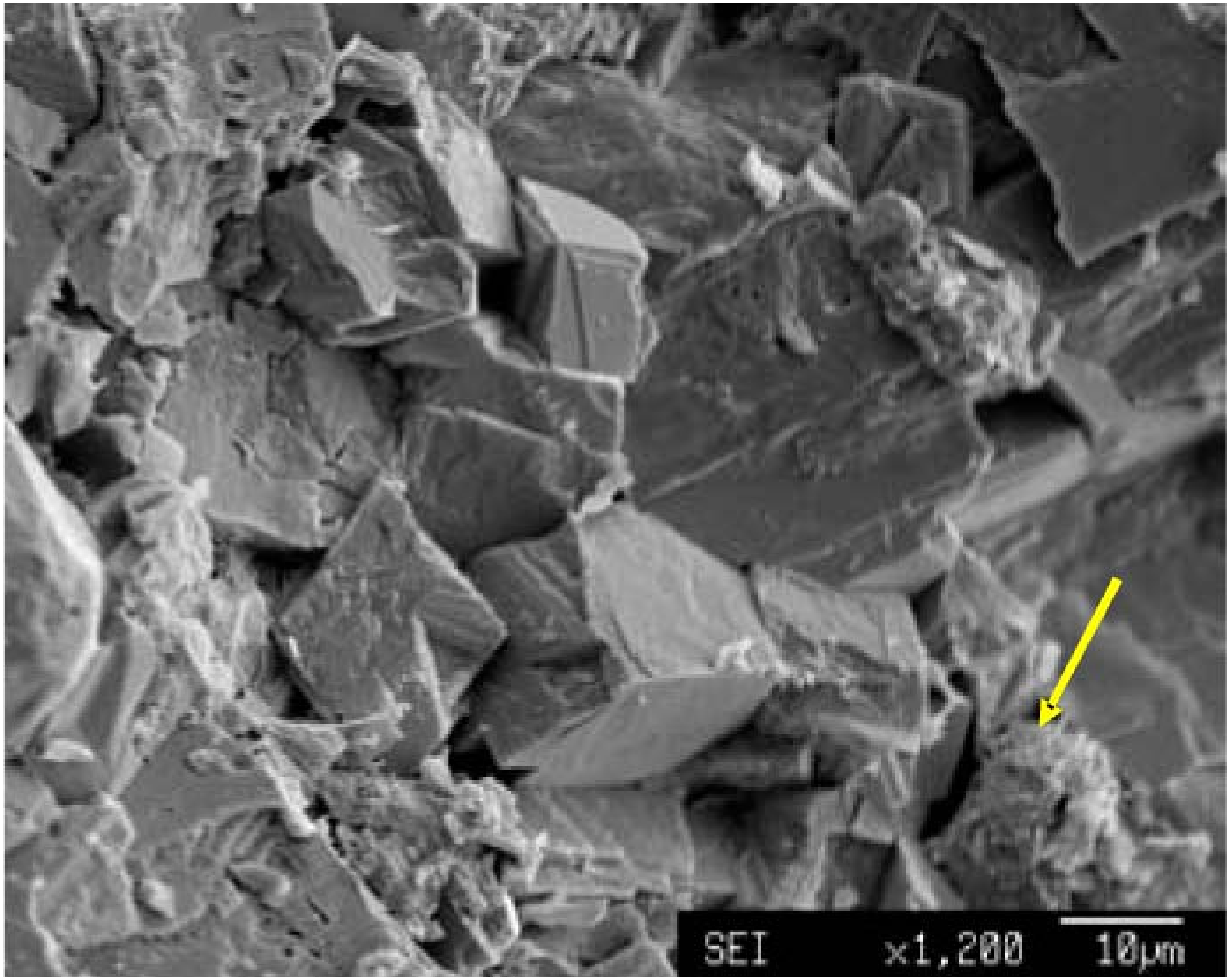

Figure 6. SEM of intergrown euhedral dolomite and intercrystalline porosity. Shale peloid (arrow).