Lithofacies Variability in Fine-Grained Mixed Clastic Carbonate Successions: Implications for Identifying Shale-Gas Reservoirs*

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Search and Discovery Article #50120 (2008)
Posted September 26, 2008

*Adapted from oral presentation at AAPG Annual Convention, San Antonio, Texas, April 20-23, 2008

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Abstract

Lithofacies variability in fine-grained, organic carbon-depleted interbedded carbonate clastic, sedimentary successions is poorly known relative to that present in other sedimentary strata. In most existing models, changes in the balance of clastic input, predominantly deposited from suspension settling, to primary productivity linked to subtle changes in pore water oxygen concentrations and substrate firmness are considered the main forcing mechanisms that underpin facies variability. In order to investigate the validity of these models, a fine-grained, organic matter poor, mixed carbonate-clastic, mud-dominated succession (Brigantian) exposed at Streedagh Point (Sligo, Ireland) has been investigated using a combination of field, optical, electron optical, and geochemical methods.

Analyses reveal that there is a great deal of cryptic lithofacies variability preserved on $<10^{-2}$ m scale in these strata. Individual depositional beds are very thin ($<10^{-2}$ m), commonly upward-fining, exhibit low angle ripple lamination, contain widely differing proportions of both detrital and productivity derived components (both silica and carbonate-dominated faunas), and have been subjected to varying bioturbation and early diagenesis.

Existing models used to explain lithofacies variability underestimate the dynamism and episodic character of this sedimentary system. In particular sediment dispersal by high energy, advective processes operating close to the sediment-water interface and changes in productivity from that dominated by organisms with calcareous tests to that dominated by organisms with siliceous tests has been missed. The implications of this variability for shale gas play exploration strategies are discussed.

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The problem

- Lithofacies variability in fine-grained sediments that constitute reservoirs in unconventional shale gas plays are poorly known.
- Geologists have begun to appreciate that "shales" (mudstones), in spite of commonly containing significant quantities of organic matter, are not uniformly good targets because their petrophysical properties (particularly their susceptibility to induced micro-fracturing) are highly variable.
- The units that are the best targets seem to contain both >2% organic matter to generate gas and be silica-rich to fracture favourably.
- The intervals that share these characteristics represent "economic oases" (sweet spots) amongst "uneconomic deserts".

Basin studies

Recognizing the “sweet spots”

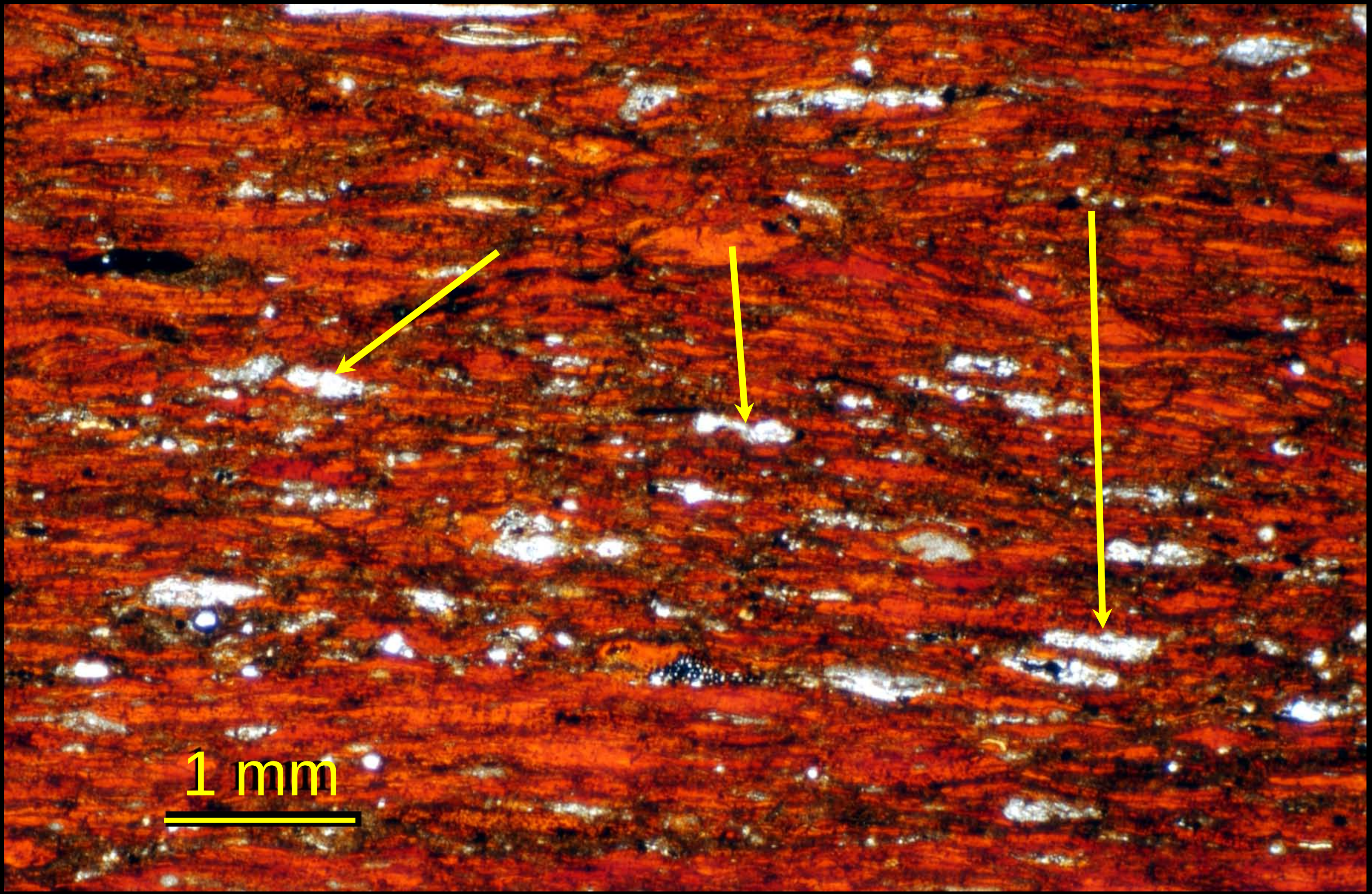
Aim

- To discuss the methods used by geologists to identify these “sweet spots” and how then to generate geologically relevant data to input into models to predict their distributions.

Background

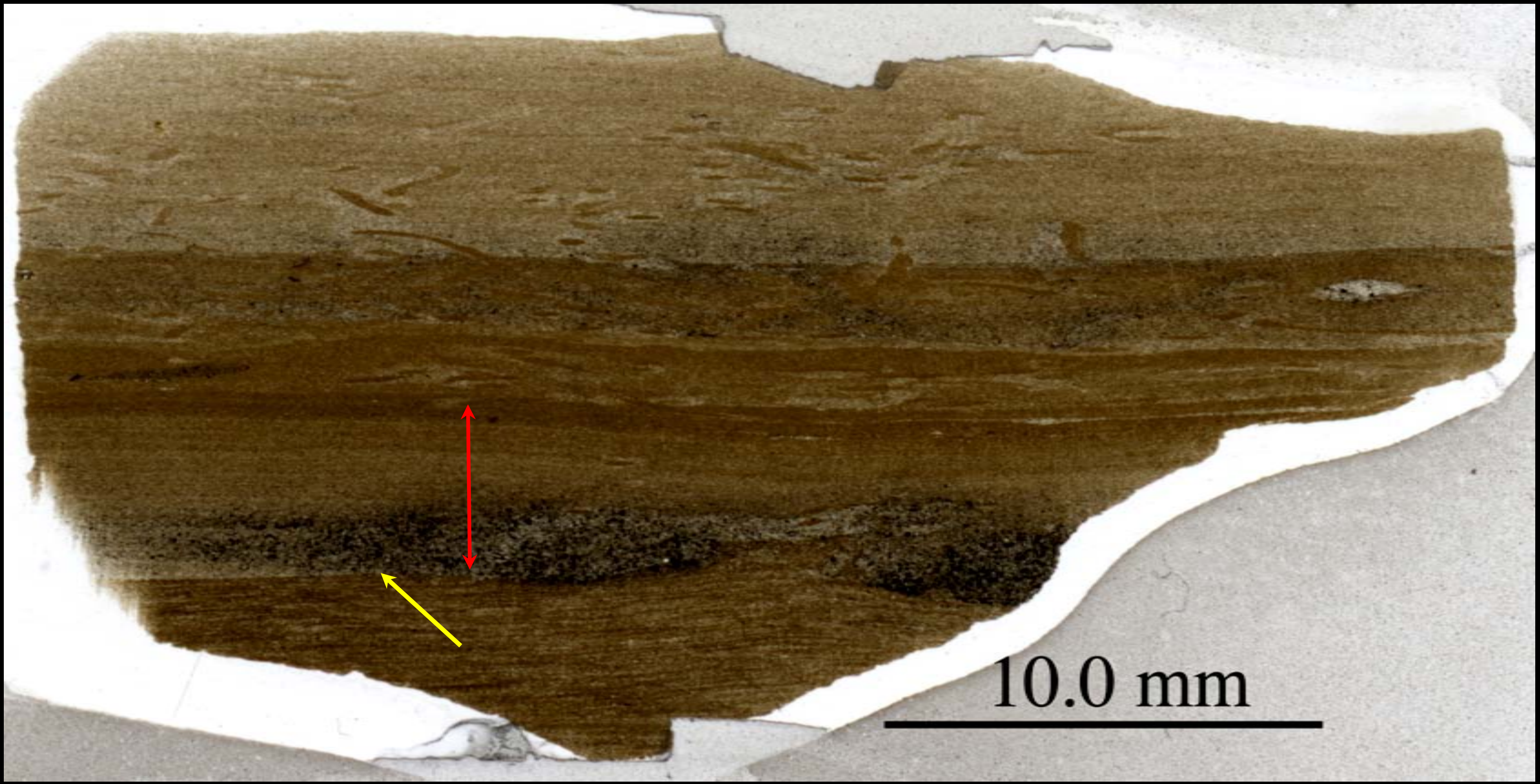
- Significant lithofacies variability has been observed in fine-grained sediments utilizing optical and electron optical methods to characterize unusually thin (20 μm), polished sections. Currently this variability remains largely undescribed and is very difficult to unravel from scalar proxy data.
- Petrographic methods generate data at 10^{-2} to 10^{-6} m scales and are extremely useful. These data challenge many of the existing paradigms (i.e. significance of anoxia and suspension settling) that deal with the origin of these sediments.

Examples of the petrographic data



- **Blackstone (44% TOC) with agglutinated benthic foraminifera (arrowed) and organo-mineralic fabric.**

Examples of the petrographic data



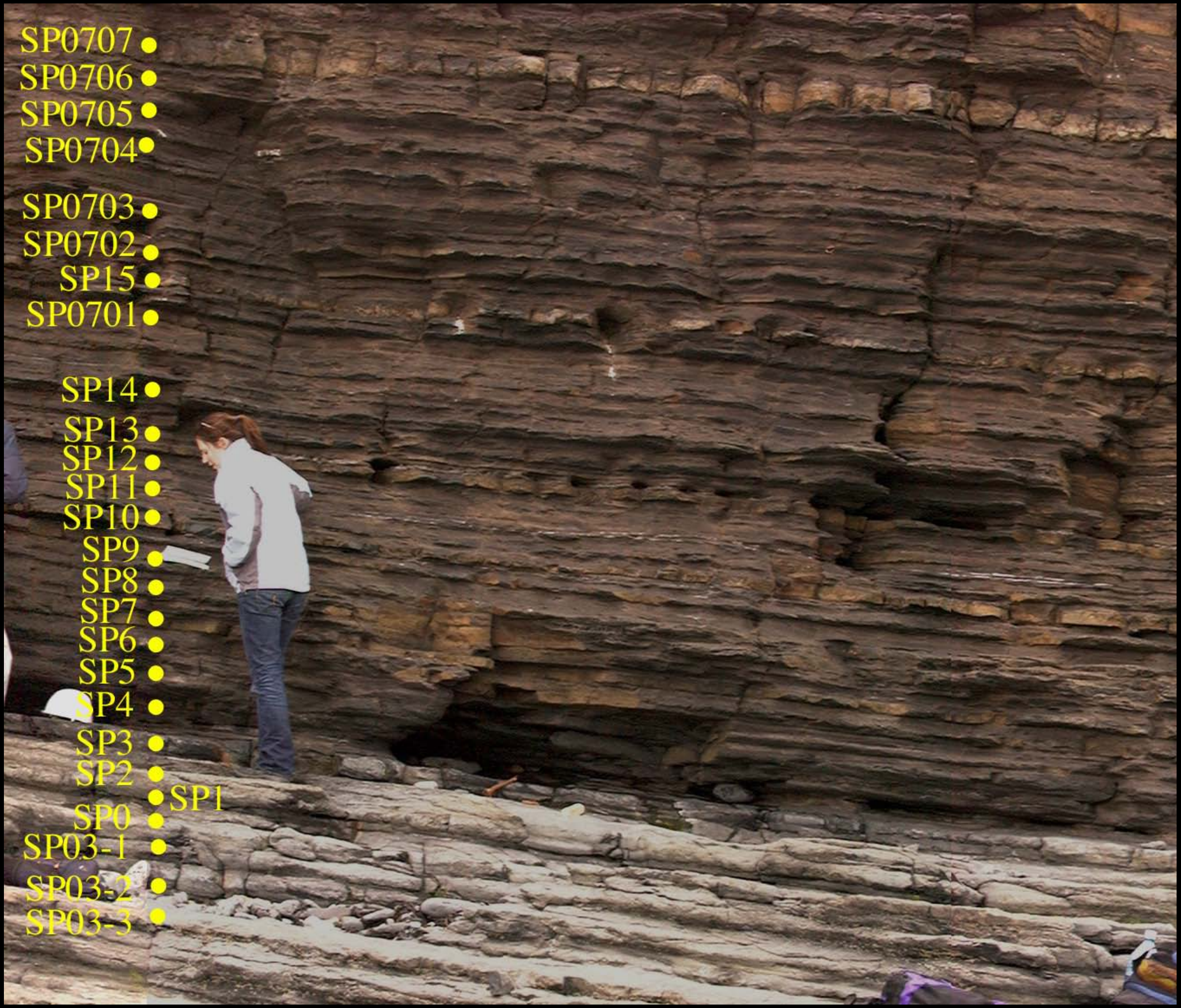
- Staithes 19. Stacked succession of thin-bedded mudstones (one genetic bed arrowed in red). Basal unit here exhibits ripple lamination and is separated from the unit above by a sharp erosion surface (arrowed yellow). The next unit upward fines and has homogenous silt-rich laminae at its base. These homogenous laminae are abruptly overlain by planar continuous laminae that in turn gradual upward-fine into burrowed clay-rich laminae.

Lithofacies variability - comments

- So there is a great deal of unrecognised small-scale lithofacies differences in fine-grained successions.
- Mudstones are highly variable in terms of components derived from a) clastic inputs, b) production in the water column and at the sediment water interface and c) diagenesis (both early and late).
- Bottom water anoxia is not a prerequisite for enhanced organic matter preservation.
- In fine-grained sedimentary successions genetic beds are much thinner than most geologists assume - easy to confuse with either fissility or lamination.
- In these fine-grained sediments, there is a great deal of evidence to indicate that sediment was being reworked prior to deposition and then dispersed by advective processes.
- Not all the sediment was delivered by suspension settling.
- Significant evidence of burrowing by diminutive organisms.

Lithofacies variability in mudstones specifics

- Mixed carbonate / clastic Brigantian-aged succession exposed at Streedagh Point (Sligo, Ireland), with up to 1% TOC.



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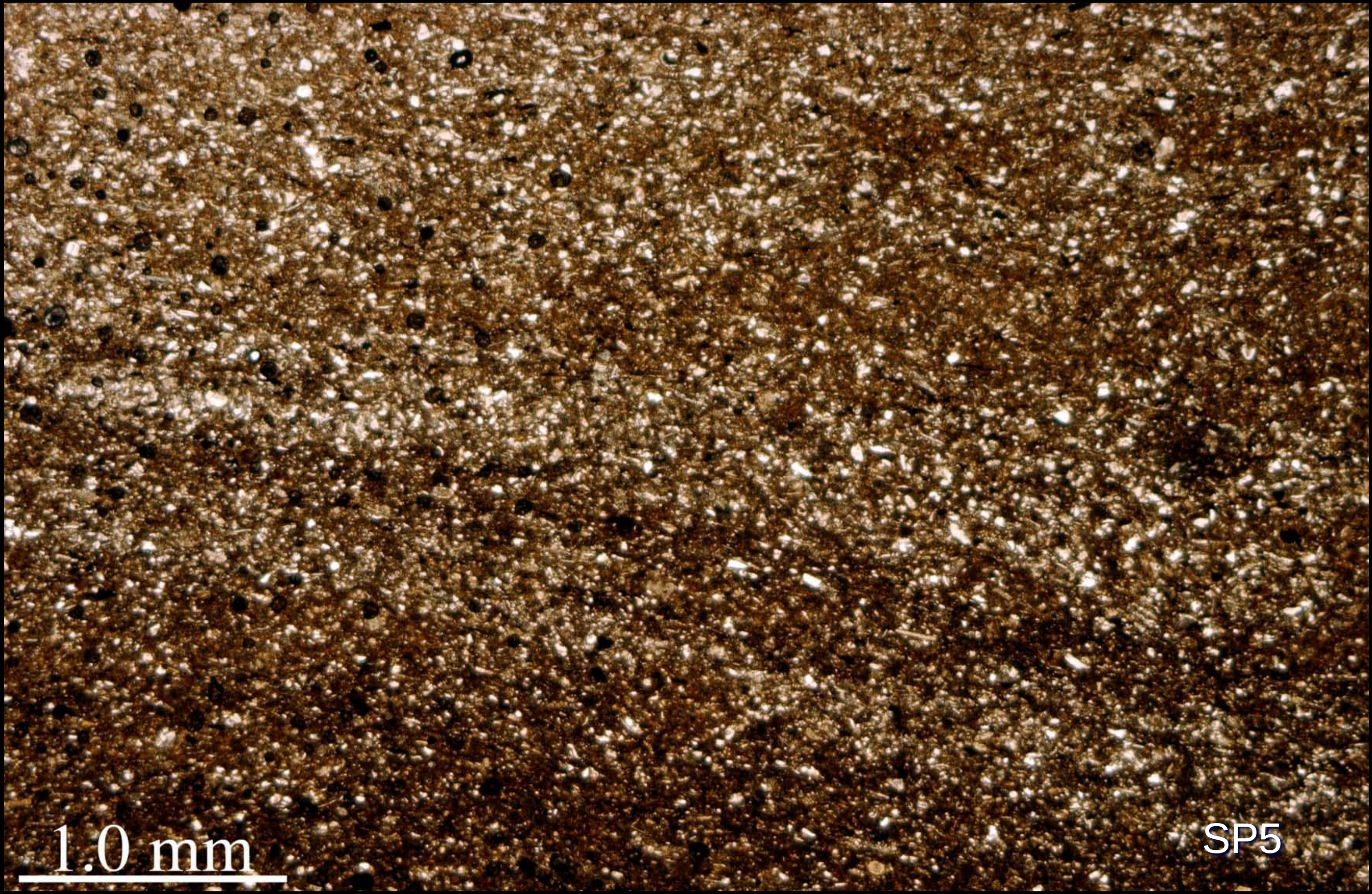
Component variability in mudstones

- Homogenized, silt-bearing, clay-rich mudstone. Framework grains composed of quartz and calcite. Matrix composed of fine grained carbonate, clay and organic matter.



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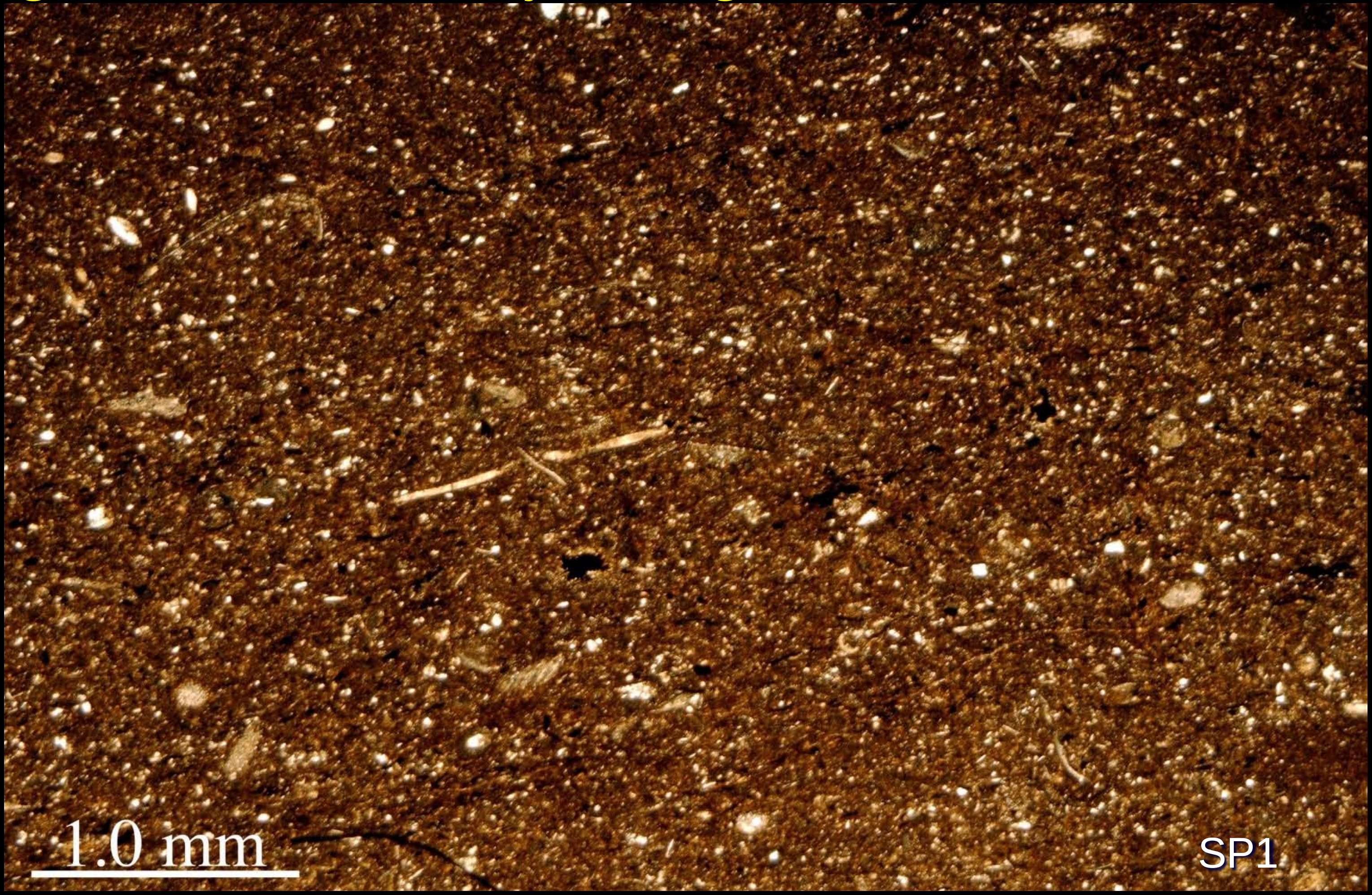
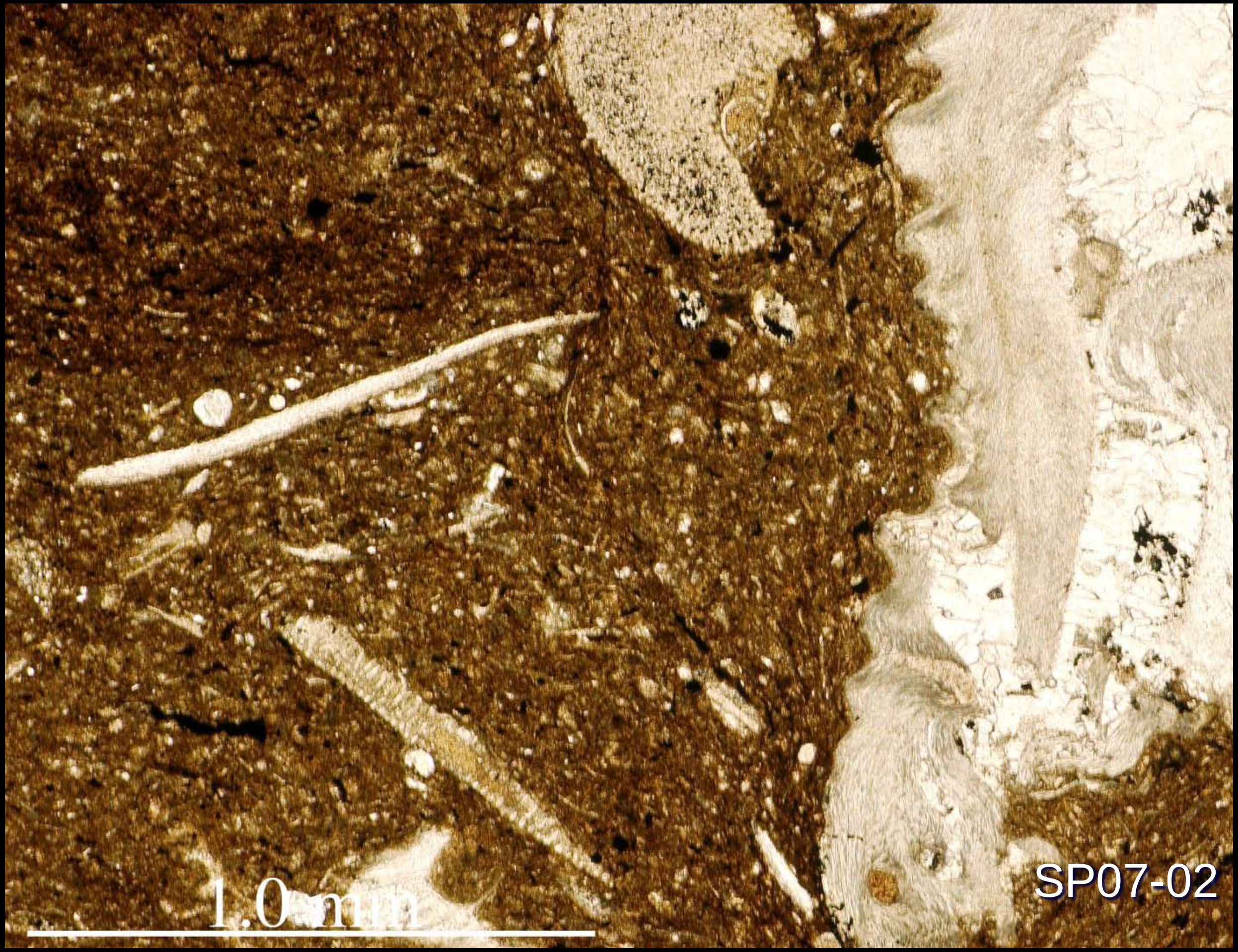


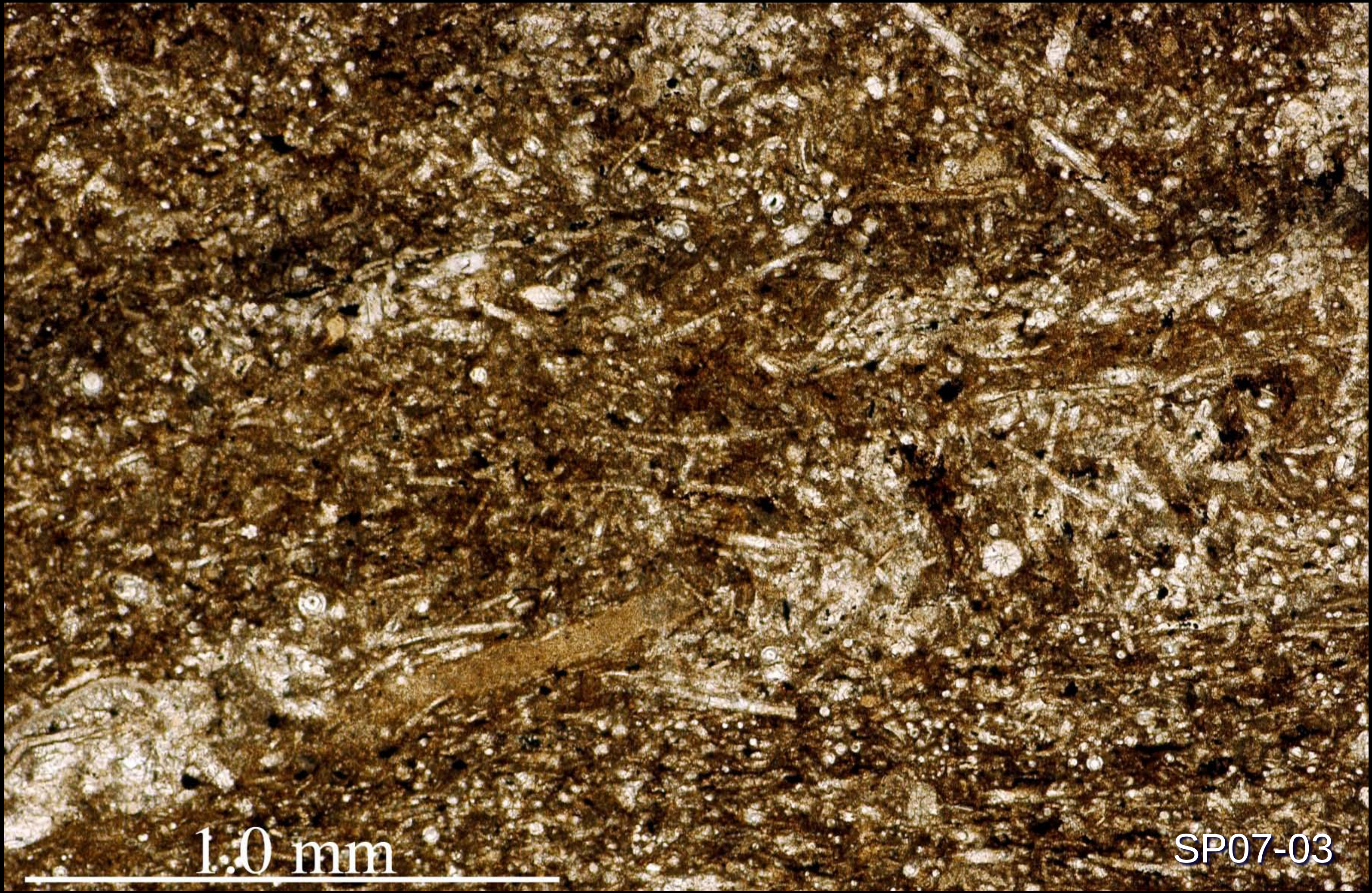
Component variability in mudstones

- Clay-rich mudstone. In this sample the framework grains are composed of disarticulated brachiopod and echinoderm debris. In contrast the matrix is composed of clay and silt-grains (composed of carbonate and quartz) with minor amorphous organic matter



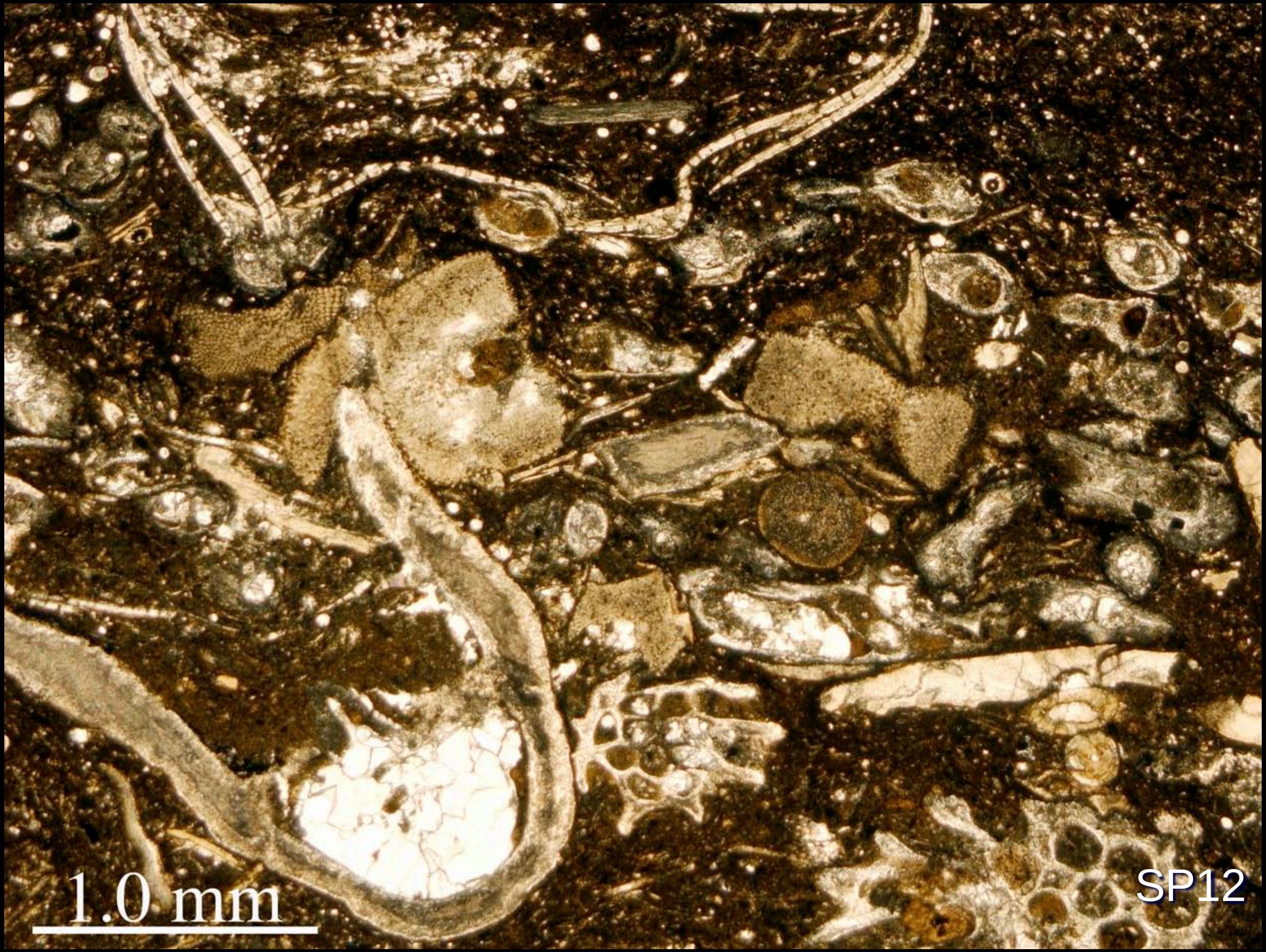
Component variability in mudstones

- In some levels the fine-grained matrix is dominated by sponge debris - now replaced by carbonate.



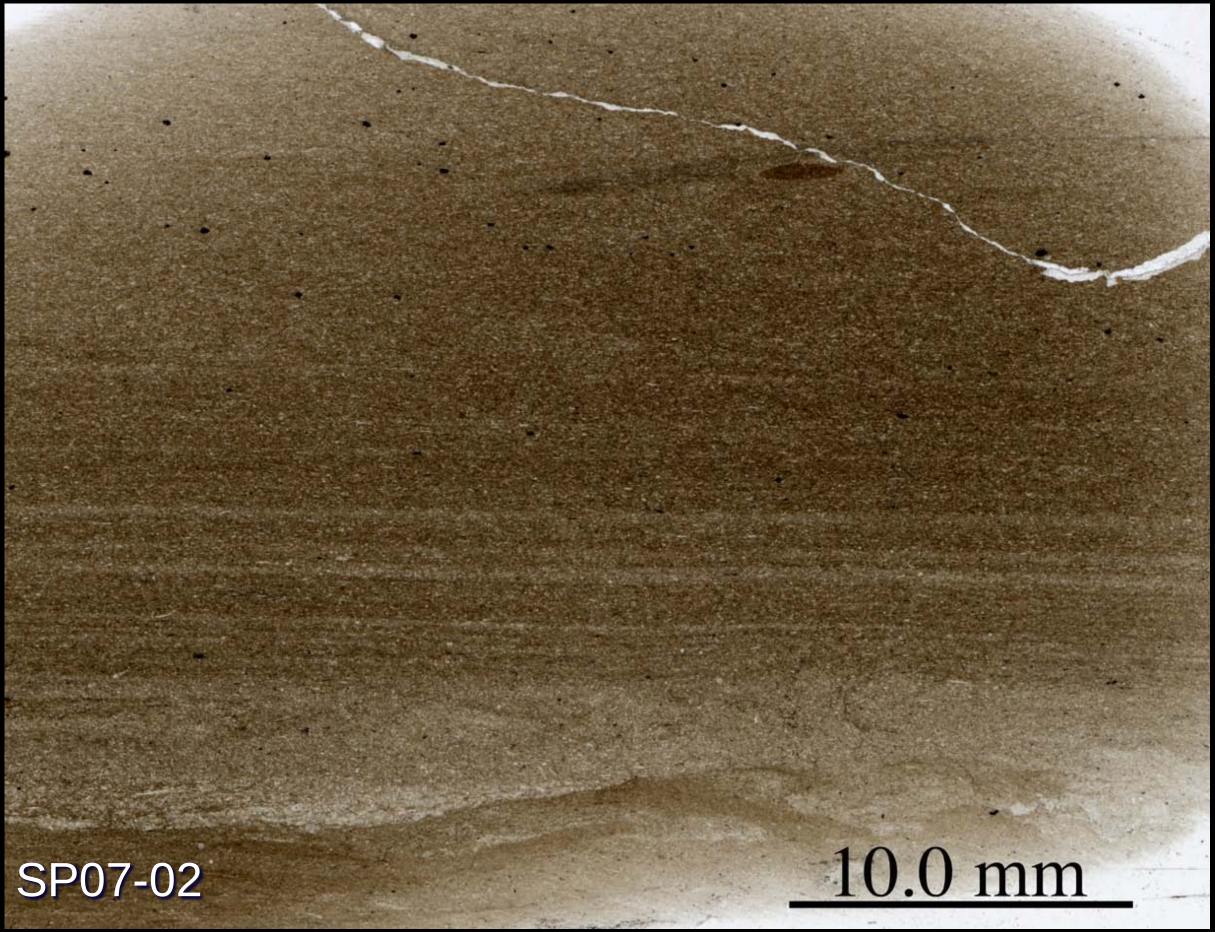
Component variability in mudstones

- In other units the sediment is dominated by coarse-grained macrofossil debris (corals, echinoids, bryozoans, brachiopods, foraminifer).



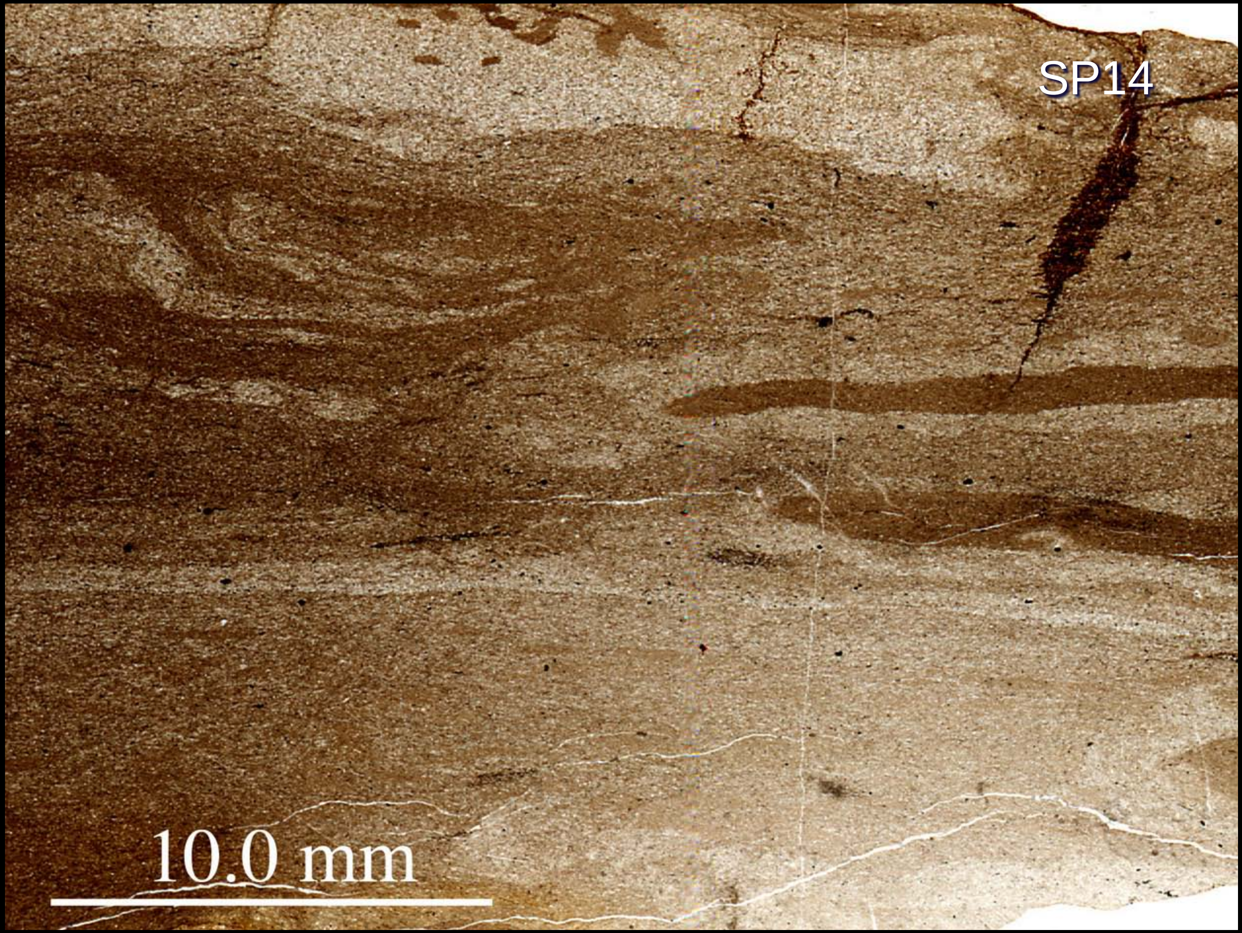
Textural variability in mudstones

- Where the units are not intensively homognized by burrowing organisms the fabrics present indicate that the beds are sharp-based, thin-bedded and upward fine. In this example the unit is composed of a silt-bearing clay-rich mudstone. Successive laminae here have very different geometries.



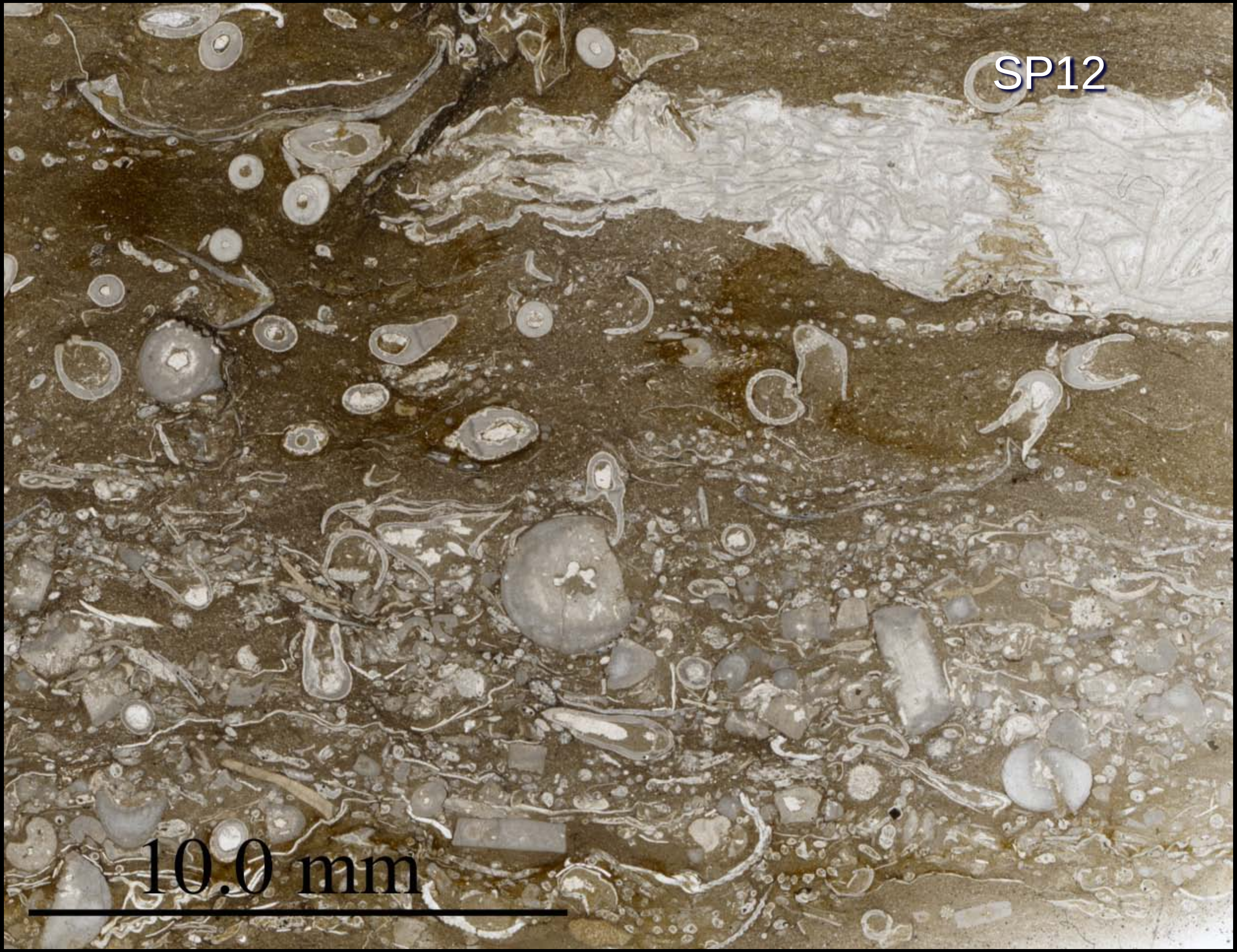
Textural variability in mudstones

- Where burrowing has been more pervasive the original bedding structures are harder to identify. Here thin-bedded, silt-bearing clay-rich mudstone and clay-rich carbonate mudstones with homogeneous planar laminae have been disrupted by an infauna (including *Planolites* isp. and *Phycosiphon* isp.).



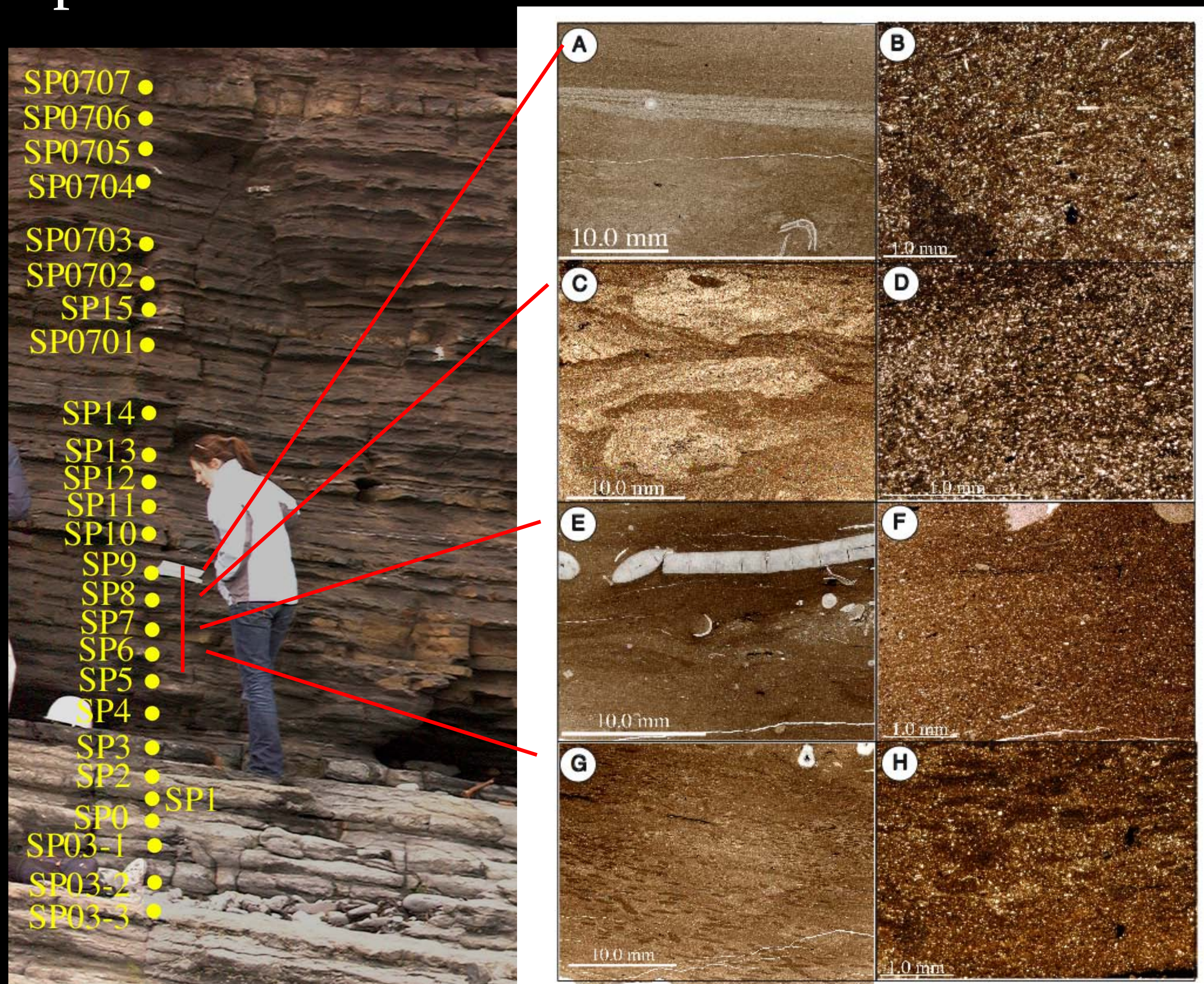
Textural variability in mudstones

- Stacked succession of bioturbated, silt-bearing, clay-rich mudstones are interbedded with a thin-bedded calcarenaceous sandstone that forms a discontinuous shell pavement. The fossil debris is fragmented.



Stacking pattern variability

- Systematic variations in grain size and framework components as well as in fabrics and cementation.



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Lithofacies variability in these Brigantian-aged rocks

- In spite of first appearances a large variety of lithofacies types are present in this succession, including:
  - *A) silt-bearing clay-rich mudstones; B) clay-rich mudstones; C) fossiliferous clay-rich mudstones; D) shell pavements. Moreover, some units preserve evidence of the processes responsible for their deposition; elsewhere infaunal colonization has destroyed primary fabrics.*
- Systematic variations in faunal contents with units that were deposited in relatively shallow water being dominated by a disarticulated macrofauna (including brachiopods, bryozoans, crinoids, etc.), while in deeper water they contain a hydrodynamically sorted fraction that includes large volumes of sponge spicules
- Genetic beds are thin and there is no evidence of anoxia.
- By no means was all the sediment delivered by suspension settling - evidence of advective sediment transport.
- Evidence of post-depositional silica mobilization.

Basin studies

Depositional setting of these Brigantian-aged rocks

- Systematic variations in stacking patterns indicate that lithofacies variability was in part controlled by relative changes in sea-level on a shallow marine ramp. These rocks are amenable to sequence stratigraphic analyses.
- The depositional environment was at least episodically energetic and sediment was transported across the shelf by advective processes - probably storm driven combined flows. In this distal setting, and following compaction, these events produced thin beds.
- Significant temporal variations in production inputs - most material hydrodynamically sorted.
- Once deposited most of the sediment was subjected to biological reworking.
- During diagenesis sponge spicules were replaced by carbonate and some of the shell fragments - particularly the brachiopod debris - were replaced by silica.

Implications for the shale gas play

- Here the all important silica could derive from a variety of processes, e.g.:
  - *Silt sized clastic detritus from weathering.*
  - *Silt-sized sponge spicules from production.*
  - *Pore filling silica cements - an early diagenetic product.*
  - *Silica cement replacing pre-existing shell fragments*
- Given their compositional similarity it is, however, very difficult to distinguish these components from one and another using proxy geochemical methods alone.
- Petrographic analyses reveals that here silica distributions are greatly influenced by late diagenetic processes - in spite of the occurrence of units enriched in sponge debris. This information allows valuable geological predictions to be made about silica distributions in the subsurface.
- Mudstones contain much readily accessible, useful information you must look at carefully!

For More Information...

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