Chapter SS (Sequence Stratigraphy of the Pebble Shale Unit)

SEQUENCE STRATIGRAPHIC ANALYSIS OF THE LOWER PART OF THE PEBBLE SHALE UNIT, CANNING RIVER, NORTHEASTERN ALASKA

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in The Oil and Gas Resource Potential of the 1002 Area, Arctic National Wildlife Refuge, Alaska, by ANWR Assessment Team, U.S. Geological Survey Open-File Report 98-34.

1999

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ABSTRACT

The Lower Cretaceous pebble shale unit (North Slope of Alaska) is an important regional petroleum source rock. In spite of its economic importance, it is poorly known. This study was instigated to determine what lithofacies are present and whether there are systematic changes in grain size, mineralogy, and textures within this succession. In order to do this, 39 samples from the lower 13 m of a 30-m thick succession of pebble shale unit along the Canning River at the Emerald Island section were analysed using combined optical and electron optical (backscattered electron imagery) techniques.

These methods demonstrate that six lithofacies are present in the studied succession including: fine-grained muddy sandstones, sand-rich mudstones, silt-rich mudstones, clay-rich mudstones, carbonate cemented units and laminated mudstones. With the exception of the laminated mudstones all the facies were intensely bioturbated causing the original bedding to be destroyed. Where bedding is visible, the beds comprise sub-millimeter thick upward-fining couplets. Comparison of successive samples within the studied succession reveals that systematic upward-fining and upward coarsening is present on a one meter to ten meter scale and that carbonate cemented units are present at the levels where there are major changes in the stacking patterns.

These data suggest that for the lower 13 m of the pebble shale unit, deposition was mostly under an oxic water column with the individual beds being deposited in response to waning flow currents. Moreover, during deposition of this part of the pebble shale unit there were systematic changes in the length of the sediment path caused either by relative sea-level change or local tectonic effects, and it was this that produced the significant lithofacies variability. The lack of well constrained lateral samples makes sequence stratigraphic interpretations equivocal, however, the upward fining-succession at the base of the pebble shale unit is interpreted to be a candidate transgressive systems tract, the overlying upward-coarsening succession is interpreted to be a candidate highstand systems tract, while the intervening carbonate cemented unit is interpreted to be a maximum flooding surface. Detailed analyses of this succession suggest that the best petroleum source intervals (highest TOC) occur in the candidate highstand system tract and not in association with the maximum flooding surface.

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INTRODUCTION

Mudstones of the Lower Cretaceous pebble shale unit and the Upper and Lower Cretaceous Hue Shale (Fig. SR2) are considered to be important petroleum source rocks of the North Slope of Alaska based on numerous analyses of total organic carbon and a variety of geochemical parameters derived primarily from rock-eval analysis (Magoon and others, 1987; see also discussion and references in Magoon and others, Chap. PS). The facies variability, depositional environment, and sequence stratigraphic framework of the pebble shale has not been described in detail. Existing descriptions describe it variously as comprising a) “dark-gray to black, noncalcareous clayey to silty shale containing minor scattered, rounded and frosted, quartz grains” in addition to containing “common to rare matrix supported chert and quartzite pebbles ...” and “ironstone concretions” (Bird and Molenaar, 1987), and b) as being composed of “black anaerobic - dysaerobic shales, silty aerobic shales, pebbly mudstones and sandstones” (Blanchard and Tailleur, 1983). It is interpreted as having been deposited on the continental slope in association with a northward-transgressing sea in a tectonically active region (e.g. Blanchard and Tailleur, 1983, Bird and Molenaar, 1987). The geologic setting and regional extent of the pebble shale unit are discussed by Molenaar (1983) and Molenaar and others (1986). The underlying Lower Cretaceous Kemik Sandstone and the relationship of the pebble shale unit to the Kemik, as well as to the Lower Cretaceous unconformity (Fig SR2) are described by Mull (1987).

Given the above descriptions of the pebble shale unit, this study was undertaken to determine its detailed lithofacies and their stacking patterns so that these can be placed within a sequence stratigraphic context and the most favorable petroleum source rock intervals identified. The type of organic matter present in the pebble shale unit and its vertical variability is not known in detail at the scale of bedding, however, total organic carbon (TOC) has been analyzed on many scattered outcrop and subsurface samples and the pebble shale unit is reported to be gas prone near the 1002 area (Magoon and others, 1987). Bird and Molenaar (1987) report TOC values for the Pebble shale unit in Ignek Valley ranging from < 1 wt % to 6 wt % TOC (n=15). Magoon and others (1987) also report a similar range of TOC values from measurements on cuttings from wells west of the 1002 area of the ANWR. Keller and others (Chap. SR) report similar interval average TOC values for the pebble shale unit west of the 1002 area determined from wireline logs using the ΔLogR method (Passey and others 1990).

GEOLOGIC BACKGROUND AND CONTEXT OF STUDY

A rare opportunity to examine freshly exposed mudstones where they crop out on the North Slope of Alaska occurred in 1991 when the west bank of the Canning River (Fig. SS1) was cleared of its normal colluvium and vegetation by very erosive winter break-up waters flowing over extensive permafrost. The newly exposed section included a very complete mudstone succession overlying the Lower Cretaceous Kemik Sandstone. Bergman and others (1995) extensively trenched the exposure to obtain the least weathered rock samples for organic geochemistry, biostratigraphy, and chronostratigraphic analyses as well as obtaining detailed spectral gamma-ray measurements of the section (Fig. SS2). Their measured section indicates that the Kemik Sandstone is overlain by 240 m (≈ 800 ft) of Lower and Upper Cretaceous sediments, which comprise 30 m (≈ 100 ft) of Pebble shale unit mudstone overlain by Hue Shale mudstone and interbedded tuffs.

During the U. S. Geological Survey's field program in August, 1997, as part of the project to assess petroleum potential of the 1002 area of the Arctic National Wildlife Refuge, Macquaker and Keller had the opportunity to study and collect samples from the mudstone succession at this remote location on the Canning River -- informally called Emerald Island -- as well as at several lithologic or age equivalent sections along Marsh Creek (Fig. SS1). We also examined the section of pebble shale unit and Hue Shale at Hue Creek, and chose not to collect samples there due to the extreme weathering. In this report we describe lithofacies from our reconnaisance sampling of the lower 13 m of the pebble shale unit at the Canning River section (Fig. SS2) and give our interpretations of the lithofacies and facies sequence.

SAMPLING AND METHODOLOGY

In order to characterize the facies variability present within the upper part of the Kemik Sandstone and the lower part of the pebble shale unit, samples were collected either every 30-50 cm or wherever a facies change was visible in hand specimen. In order to minimize the effects of weathering, the worst of the weathered crust was cleared from the succession prior to sampling. In spite of this strategy, however, many of the samples were badly weathered and fragile. The fragility of the samples meant that they had to be encased in resin (Epotek) prior to thin section preparation in order to maintain their structural integrity.

Once the polished thin sections had been manufactured, the textures present and the mineralogy of each sample were characterized using conventional optical petrography (Nikon Labophot Pol), backscattered electron imagery (Link four quadrant backscattered electron detector mounted on a Jeol JSM 4600 electron microscope operating at 20Kv, 2 µA at an operating distance of 9 mm) and energy dispersive spectrometry (Link EDS detector attached to Link EXL mini computer running ZAF 4).

RESULTS

In the studied successions of the lowermost part of the pebble shale unit at "Emerald Island", six lithofacies were found (Fig. SS3). These comprise fine-grained muddy sandstones (Fig. SS4), sand-rich mudstones (e.g. Fig. SS5), silt-rich mudstones (e.g. Fig. SS6 and SS7), clay-rich mudstones (e.g. Fig. SS8), carbonate cemented strata and concretionary carbonates (e.g. Fig. SS9 and SS10), and laminated mudstones (Fig. SS11). Terminology is adapted from Macquaker and Gawthorpe (1993) and Macquaker and Taylor (1996).

The sandstones, which are present in the uppermost Kemik Sandstone, variously comprise quartz and glauconite in a clay matrix (Fig. SS4). In contrast, the mudstones variously comprise fine-grained dioctahedral mica (predominantly illite), pyrite, quartz, and amorphous organic matter (e.g. Fig. SS5 - SS7), and the carbonate cemented strata and concretionary carbonates comprise microsparry zoned ferroan dolomite and ankerite (Fig. SS9 and SS10). Internally, most samples contain few diagnostic sedimentary textures although indeterminate burrows and laminae were observed, and in places, flat elliptical silt-filled burrows are attributed to *Chondrites isp.* (Fig. SS6, SS8, and SS12) and *Phycosiphon isp.* Where lamination is preserved, sub-millimeter thick upward-fining couplets are visible (Fig. SS11). These couplets have erosional bases and comprise silt-rich mudstones overlain by clay-rich mudstones.

Comparison of successive samples reveals that significant vertical facies variations are present within the pebble shale unit including both meter-scale upward-fining and upward-coarsening stacking patterns (Fig. SS3). The upward-coarsening successions comprise laminated, clay and silt-rich mudstones overlain by silt and sand-rich mudstone units. In contrast, the upward-fining succession contains muddy sandstone overlain by clay-rich and laminated mudstone units.

Carbonate cemented strata and concretionary carbonates are associated with those units where stacking patterns change from both overall upward-fining to upward-coarsening and upward-coarsening to upward-fining. They are also found in silt-rich mudstone where no change was detected in the stacking pattern, as well as in association with the finest grained units where there are facies changes, for instance at the contact between the clay-rich mudstone and laminated mudstone units (Fig. SS3). The proportion of detrital material incorporated within these carbonate units is variable. Sample EI17 (Fig. SS9) contains very little silt in comparison with stratigraphically higher sample EI23 (Fig. SS13).

DISCUSSION

Systematic stratigraphic investigation of these rocks indicates that significant vertical lithofacies variability is present in the pebble shale unit. This variability is exhibited on a number of scales (sub-millimeter to millimeter and meter to 10 meter scale). The small-scale variability is evident in the laminated mudstones in the middle of the succession where upward-fining couplets, comprising silt-rich mudstones and clay drapes, can be identified (Fig. SS11). These couplets are very similar, albeit thinner, to those observed in the Cleveland Ironstone Formation (e.g. Macquaker and Taylor, 1997) and Oxford Clay Formation (Macquaker and Wares, in press) and are interpreted to have been deposited from waning flow current systems and are probably the distal expression of storm deposits. Given that the individual couplets are bounded by bedding surfaces it is most appropriate to define the couplets as beds (in the sense of Campbell, 1967) and to describe this

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part of the succession as being thinly bedded in addition to being laminated.

The preservation of lamination and absence of bioturbation in the finest-grained beds of the pebble shale unit suggest that the bottom waters were either anoxic or deposited very rapidly during deposition of these strata. Given the presence of anoxia in these units at the time of their deposition it would be reasonable to expect them to be the most enriched in organic matter. However, total organic carbon analyses from the pebble shale unit at "Emerald Island" (Bergman and others, written communication) reveal that this is not the case, and indeed they show that these units are relatively depleted in organic matter relative to units higher in the succession. Assuming that anoxia, rather than rapid sedimentation is the dominant process controlling the preservation of lamination in these units (which is reasonable given that their deposition is associated with the condensed section [see below]), then anoxia alone is not an essential prerequisite for organic matter preservation in mudstones deposited in shelf seas (compare with discussion in Pedersen and Calvert, 1990).

The majority of the strata that we examined within the pebble shale unit are neither laminated nor exhibit any sedimentary structures. The absence of these suggests that the sediments were bioturbated and that the bottom waters at the time of deposition were able to support an infauna. In a few samples small (<1 millimeter) burrows are present which are attributed to *Chondrites isp*. and *Phycosiphon isp*. Together these are assumed to indicate that the oxygen concentrations within the pore waters were sufficient to support at least a dysaerobic meiofauna if not an aerobic macrofauna for much of the deposition of the pebble shale unit.

Comparison of successive vertical samples illustrates that significant larger-scale (meter to 10 meter) variability within the pebble shale unit is present in the form of gradual upward coarsening and upward-fining cycles (e.g. Fig. SS3). The presence of this variability suggests that there were systematic changes in the length of the sediment transport path and accommodation availability (in the sense of Van Wagoner and others, 1990) through time. Given that the pebble shale unit was deposited on a continental shelf, this variability may have been caused by either relative changes in sea-level (caused by tectonic or eustatic

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processes) or by local changes in sediment supply (e.g. in response to changing fluvial architecture up-dip). In particular, the upward-coarsening successions were formed where the sediment transport was shortening or the accommodation was decreasing through time in contrast to the upward-fining succession where the sediment transport path was lengthening or the accommodation was increasing through time.

It is also worth mentioning that common to rare, matrix-supported pebbles or granules, and very rare cobbles occur throughout the pebble shale unit (Bird and Molenaar, 1987). However, no granules, pebbles, or cobbles were encountered in the Emerald Island succession as part of this study although they were observed at other localities, e.g. Marsh Creek and mentioned by other authors (e.g. Blanchard and Tailleur, 1983; Bird and Molenaar, 1987). These pebbles are very striking and their origin in the sediment has engendered much speculation including rafting by shore ice, kelp, or tree roots (Bird and Molenaar, 1987). Given that they do not appear to be particularly concentrated within any particular unit, which would be suggestive of them being associated with a stratal surface, and in the absence of any other data except that their anomalous grain size relative to the rest of the enclosing sediment suggests that they may have been emplaced by a different process, their ice rafted origin is considered a reasonable hypothesis. Blanchard and Tailleur (1983) note the abundant occurrence of very well rounded aeolian derived, floating quartz grains in Neocomian shale to the west of the Canning River, and Bird and Molenaar (1987) note that the pebble shale unit of the Sadlerochit Mountains contains minor scattered, rounded, and frosted quartz grains. So far, we have not observed rounded floating quartz grains in the pebble shale unit at the "Emerald Island" section.

The presence of carbonate cemented units or concretionary carbonates at the levels where the large-scale stacking patterns change suggests that their precipitation may be linked at these levels to periods where there were prolonged breaks in sediment accumulation. Prolonged breaks in sediment accumulation are a requirement for pervasive early cementation in the absence of any obvious substrate control in order that there is sufficient time to transport sufficient solutes to the site of precipitation to form a cemented layer (e.g. Raiswell, 1988; Macquaker and Gawthorpe, 1993). The presence of breaks at these particular

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levels suggests that the cements are forming close to the key stratal surfaces in this succession (i.e., parasequence boundaries and maximum flooding surfaces). Unfortunately, however, we have not sampled at sufficient resolution to determine precisely to which surface each of the cemented units is associated. It is worth noting that the proportion of detrital material incorporated within the cemented units does significantly vary. For instance those associated with the finer-grained parts of the succession (e.g. sample EI 7, Fig. SS9) contain very little silt in comparison with those units higher up (e.g. sample EI 23, Fig. SS13) which suggests that while they were indeed associated with breaks in sediment accumulation, their formation was not restricted to one stratal surface only.

Overall, however, given that bedding can be recognized on a sub-millimeter to millimeter scale, upward-fining and upward-coarsening can be observed on a meter to 10 meter scale, and that cemented units are developed in association with stratal surfaces, we interpret the overall upward fining succession to be a candidate transgressive systems tract, and the overall upward-coarsening successions to be candidate high stand systems tracts. Moreover, by extending this logic we are able to interpret a) the cemented unit where the large scale stacking patterns change from overall upward-fining to upward-coarsening to be a candidate maximum flooding surface, b) the contact between the Kemik Sandstone and the pebble shale unit to be a transgressive surface, and c) the fine grained laminated part of the succession in close proximity to the maximum flooding surface to be a candidate condensed section. We were not able to precisely identify the sequence boundary in the studied succession presumably because accommodation, at least in the study area, was available throughout deposition of the pebble shale unit. Unfortunately, given the limited lateral extent of this study and the likelihood that local tectonic effects had a significant bearing on the location of available accommodation we are not able to be more definite about our systems tract interpretations. We have therefore deliberately been conservative with our sequence stratigraphic interpretations. These data, however, do suggest that organic matter preservation is not always optimized in the condensed section (in the sense of Loutit and others, 1988), and that here it is likely that during deposition of this interval sedimentation rates were so slow that there was sufficient time for anaerobic decay processes to destroy much of the organic matter.

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CONCLUSIONS

Detailed investigation (utilizing combined optical and electron optical methods) of the lower part of the Lower Cretaceous pebble shale unit in the 1002 area of the ANWR shows it to be highly variable. These techniques enable 5 mudstone lithofacies to be identified in the pebble shale including: sand-rich mudstones, silt-rich mudstones, clay-rich mudstones, laminated mudstones and concretionary carbonates along with muddy sandstones in the top of the Kemik Sandstone.

Most of the studied successions were deposited beneath an oxic or episodically anoxic water column. Consequently the sediment was able to support a dysaerobic (*Chondrites isp.* and *Phycosiphon isp.*) if not a fully aerobic fauna. Bioturbation appears to have destroyed most of the primary sedimentological structures. The middle part of the lower succession, however, contains thinly-bedded, laminated mudstones. These preserve thin (mm-thick), upward fining couplets, separated from one and another by erosion surfaces. These upward-fining couplets are interpreted to be distal storm beds.

The vertical grain size variability suggests that during deposition of the pebble shale unit systematic changes in the length of the sediment transport path were present on a 1 to 10 m-scale. Given that bedding is present on a mm scale, and that both upward-coarsening and upward-fining are observed, this variability is interpreted to be occurring at a systems tract rather than parasequence scale. Given the lack of lateral facies control the upward-fining unit is interpreted to be a candidate transgressive system tract, the upward-coarsening successions to be candidate high stand systems tracts, and the carbonate cemented unit -- where the stacking pattern changes from upward-fining to upward-coarsening -- to be a candidate maximum flooding surface. It has neither been possible to unequivocally identify any sequence boundaries within this part of the pebble shale unit nor is it possible to assign the other cemented units to specific stratal surfaces.

Detailed analyses of the stacking patterns of marine mudstones suggests that the best petroleum source intervals (in terms of TOC concentration, composition, and preservation) occur in the candidate highstand system tracts and not in association with the maximum

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flooding surface (Macquaker and Jones, in press; Macquaker and others, in press). During deposition of this highstand systems tract within the pebble shale unit, sediment accumulation rates were sufficiently fast for organic matter to be rapidly incorporated into the sediment, but not so fast as to dilute the organic matter, consequently there was neither sufficient time for a significant proportion of the organic matter to be degraded nor was there sufficient detrital material for it to be significantly diluted. These data suggest that anoxia is not a prerequisite for organic matter preservation, and that the better source intervals are not always associated with the maximum flooding surface.

ACKNOWLEDGMENTS

We particularly thank Gil Mull of the Alaska Department of Natural Resources for guiding us to many Lower Cretaceous sections, for sharing his knowledge of the rocks, for assisting us in collecting samples, and for reviewing a preliminary version of the manuscript. We also thank Steve Bergman, John Decker, and others at ARCO for generously sharing their observations of the "Emerald Island" section. We appreciate the lively discussions, suggestions, insights, and humor of our field companions Gil Mull, David Houseknecht, Chris Schenk, and Mark Pawlewicz, and our reviewers Ken Bird and Kevin Evans.

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REFERENCES

Bergman, S.C., Decker, J., and Talbot, J., 1995, Upper Cretaceous tephra deposits, Canning River area, north Alaska [abs.]: Geological Society of America, Cordilleran Section Meeting, May 24-26, 1995, Abstracts with Program, v. 27, no. 5, p. 5.

Bird, K.J., and Molenaar, C.M., 1987, Stratigraphy, *in* Bird, K.J., and Magoon, L.B., eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska, U.S. Geological Survey Bulletin 1778, p. 37–59.

Blanchard, D. C., and Tailleur, I. L., 1983, Pebble shale (Early Cretaceous) depositional environments in National Petroleum Reserve in Alaska (NPRA) [abs.]: American Association of Petroleum Geologists Bulletin, v.67, no. 3, p.424 - 425.

Campbell, C.V., 1967, Lamina, laminaset, bed and bedset: Sedimentology, v. 8, p. 7- 26.

Loutit, T.S., Hardenbol, J., Vail, P.R., and Baum, G.R., 1988, Condensed sections: The key to age dating and correlation of continental margin sequences, *in* Wilgus, C., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea Level Change an Integrated Approach: SEPM Special Publication 42, p. 183-216.

Macquaker, J.H.S., 1994, A lithofacies study of the Peterborough Member, Oxford Clay Formation, an example of sediment bypass in mudstone successions: Journal of the Geological Society, London, v. 151, p. 161 - 172.

Macquaker, J.H.S., and Gawthorpe, R.L., 1993, Mudstone lithofacies in the Kimmeridge Clay Formation, Wessex Basin: Implications for the origin and controls on the distribution of mudstones: Journal of Sedimentary Petrology, v. 63, p. 1129 - 1143

Macquaker, J.H.S., and Taylor, K.G., 1996, A sequence stratigraphic interpretation of a mudstone-dominated succession: the Lower

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in the toolbar to return.

Jurassic Cleveland Ironstone Formation, U.K.: Journal of the Geological Society London, v. 153, p. 759-770.

Macquaker, J.H.S., and Taylor, K.G., 1997, A reply to: A sequence stratigraphic interpretation of a mudstone-dominated succession: the Lower Jurassic Cleveland Ironstone Formation, U.K.: Journal of the Geological Society London, v. 154, p. 913-916.

Macquaker, J.H.S., Gawthorpe, R.L., Taylor, K.G., and Oates, M.J, in press, Heterogeneity, stacking patterns and sequence stratigraphic interpretation in distal mudstone successions: examples from the Kimmeridge Clay Formation, U.K. *In:* Schieber, J., Zimmerle, W., and Sethi, P., eds., Recent Progress in Shale Research: Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

Macquaker, J.H.S., and Jones, C.R., in press, A sequence stratigraphic study of mudstone heterogeneity: a combined petrographic / wireline log investigation of Middle and Upper Jurassic mudstones from the North Sea (U.K.): American Association of Petroleum Geologists Bulletin.

Macquaker, J.H.S., and Wares, J.K., in press, Small scale (< 5 m) vertical heterogeneity in mudstones: implications for high resolution stratigraphy in siliclastic mudstone successions: Journal of the Geological Society, London.

Magoon, L.B., Woodward, P.V., Banet, A.C., Jr., Griscom, A.B., and Daws, T.A., 1987, Thermal maturity, richness, and type of organic matter of source rock units, *in* Bird, K.J., and Magoon, L.B., eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U.S. Geological Survey Bulletin 1778, p. 127–179.

Molenaar, C.M., 1983, Depositional relations of Cretaceous and Lower Tertiary rocks, northeastern Alaska: American Association of Petroleum Geologists Bulletin, v. 67, no. 7, p. 1066-1080.

Molenaar, C.M., Bird, K.J., and Collett, T.S., 1986, Regional correlation sections across the North Slope of Alaska: U.S.

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Geological Survey Miscellaneous Field Studies Map MF-1907, 1 sheet.

Mull, C.G., 1987, Kemik Sandstone, Arctic National Wildlife Refuge, northeastern Alaska, *in* Tailleur, I., and Weimer, P., Alaskan North Slope Geology: Pacific Section SEPM, Book 50, v. 1, p. 405-431.

Passey, Q.R., Creaney, S., Kulla, J.B., Moretti, F.J., and Stroud, J.D., 1990, A practical model for organic richness from porosity and resistivity logs: American Association of Petroleum Geologists Bulletin, v. 74, no. 12, p. 1777-1794.

Pedersen, T.F., and Calvert, S.E., 1990, Anoxia vs. productivity: What controls the formation of organic-carbon-rich sediments and sedimentary rocks: American Association of Petroleum Geologists Bulletin, v.74, p. 454-466.

Raiswell, R., 1988, Chemical model for the origin of minor limestone-shale cycles by anaerobic methane oxidation: Geology, v. 16, p. 641-644.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990, Siliciclastic Sequence Stratigraphy in Well Logs, Cores and Outcrops: American Association of Petroleum Geologists Methods in Exploration Series, **7**, 55 p.

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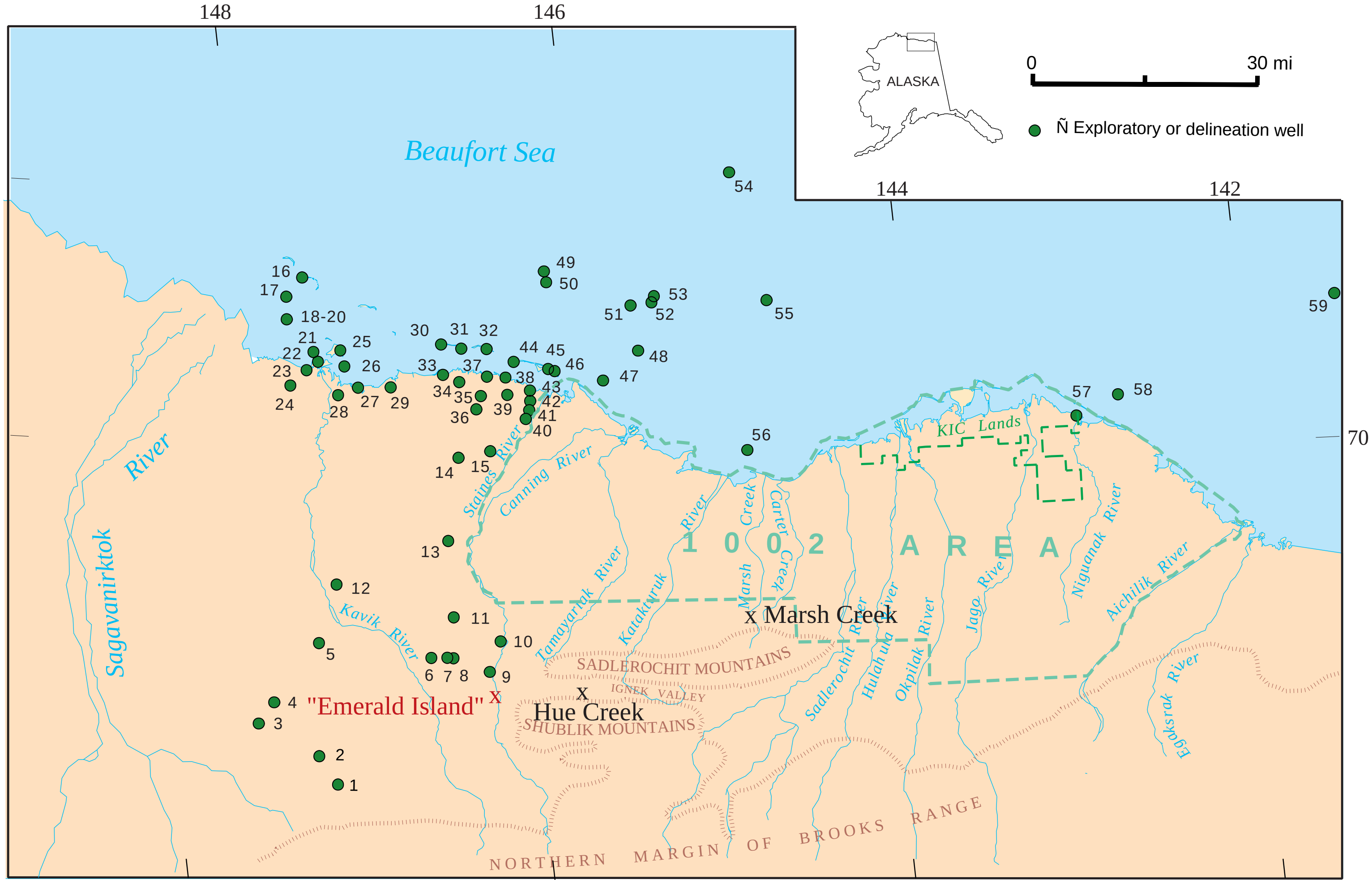

Figure SS1.-Map showing locations of key stratigraphic sections and wells near the 1002 area of the Arctic National Wildlife Refuge. See Figure SR3 for names of wells indicated by numbers.

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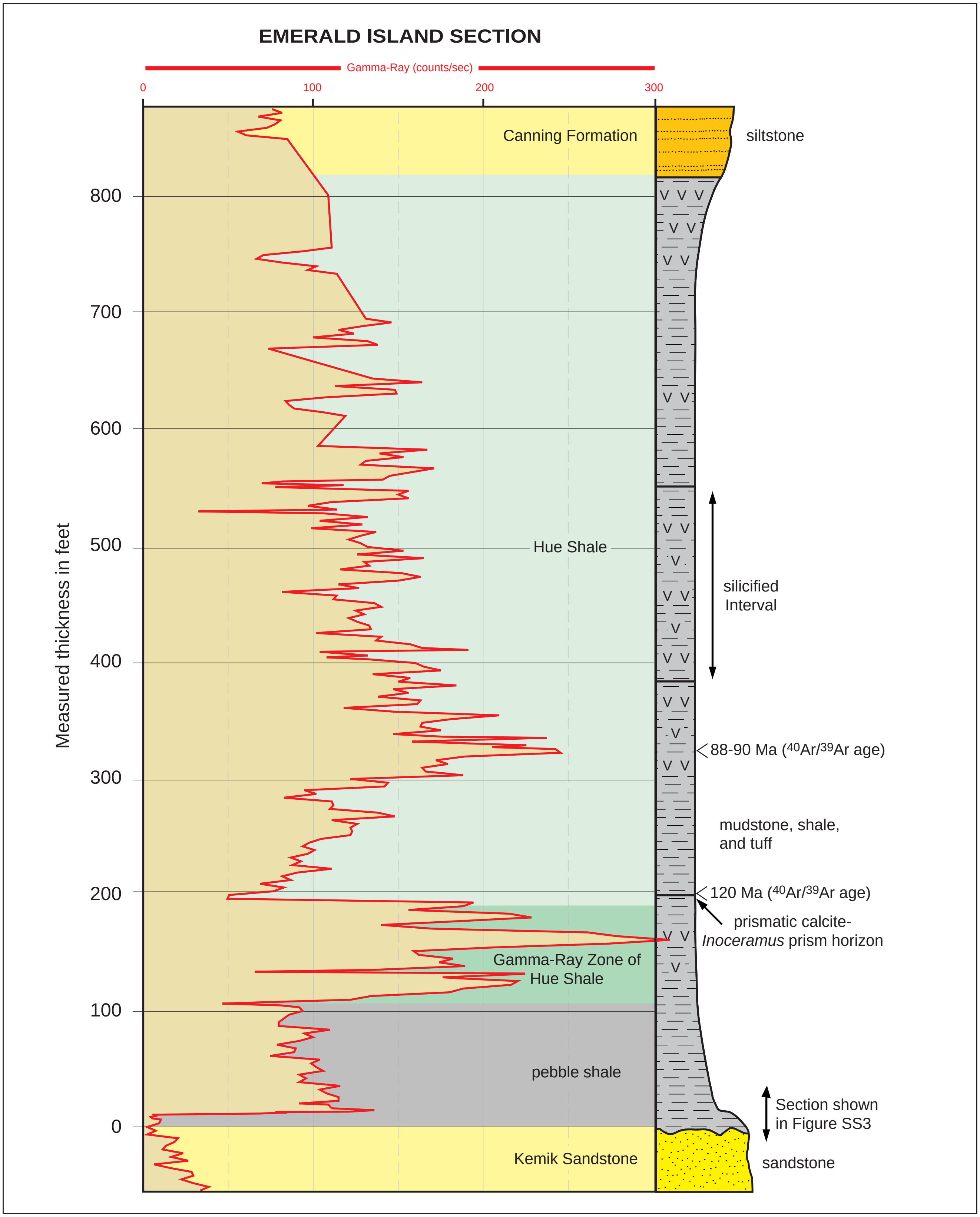

Figure SS2.–Stratigraphic column, gamma-ray profile, and radiometric age data for the "Emerald Island" section of Kemik Sandstone, pebble shale unit, and Hue Shale along the Canning River (from Bergman and others, 1995, and written communication, March, 1998).

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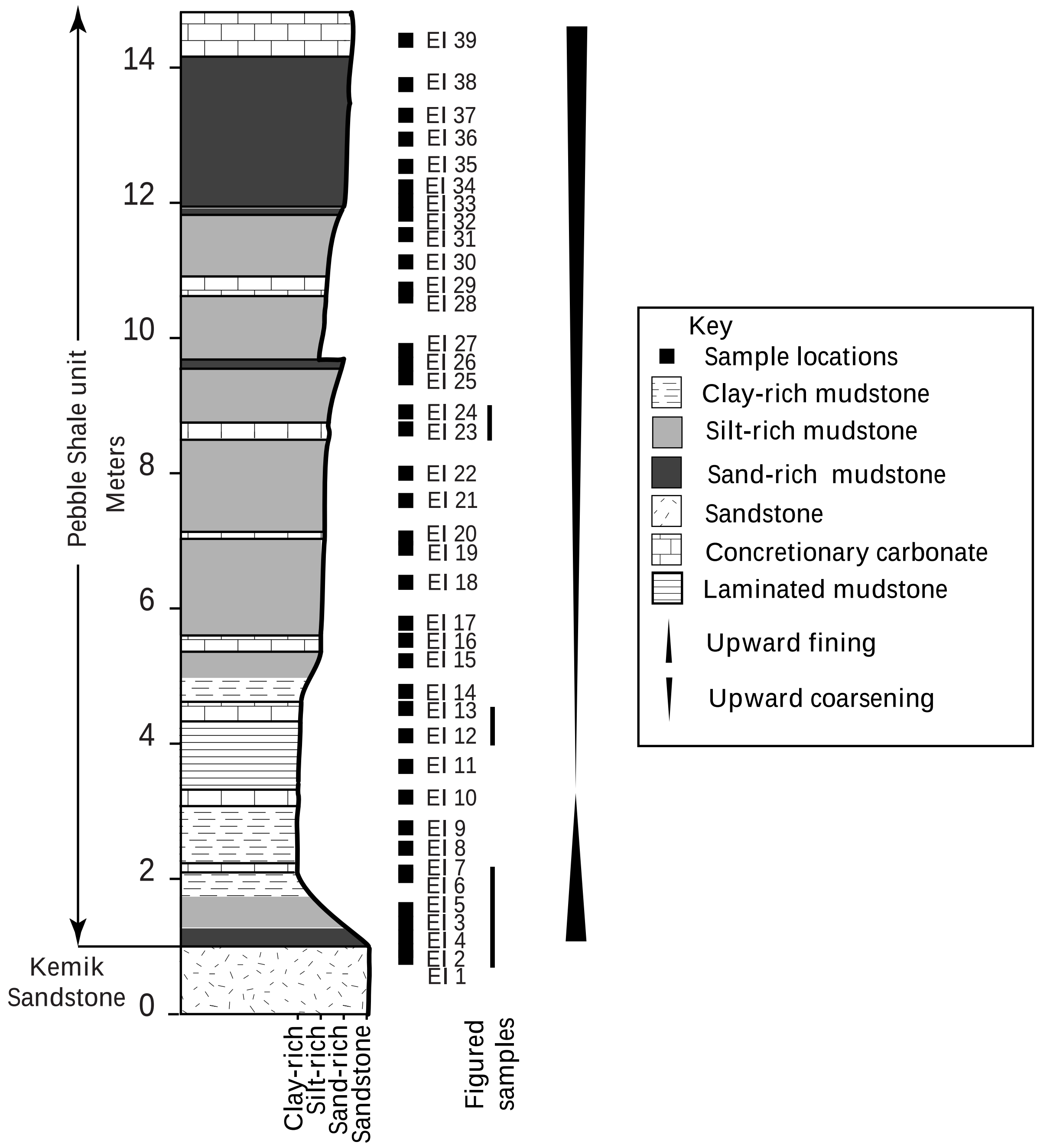

Figure SS3. Stratigraphic log of part of the "Emerald Island" section, showing location of samples, lithofacies, and sequence stratigraphic interpretations.

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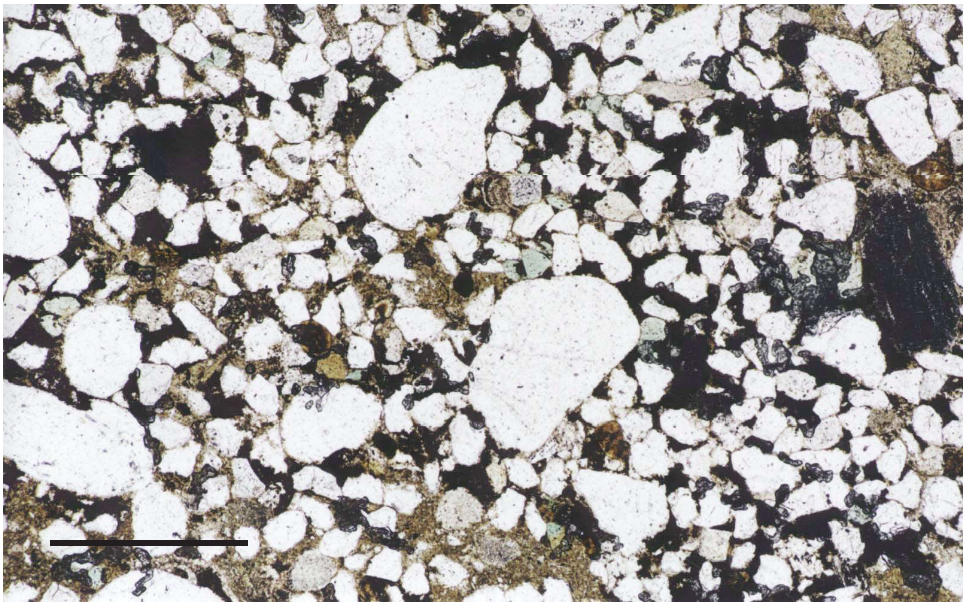

Figure SS4. Plane polarized light image of muddy sandstone (Emerald Island 2) from the top of the Kemik Sandstone just below the contact with the pebble shale unit. The sample comprises medium and fine sand (predominantly composed of quartz) in a clay (predominantly composed of illite) matrix. Minor detrital muscovite and glauconite are also present. Scale bar 580 µm.

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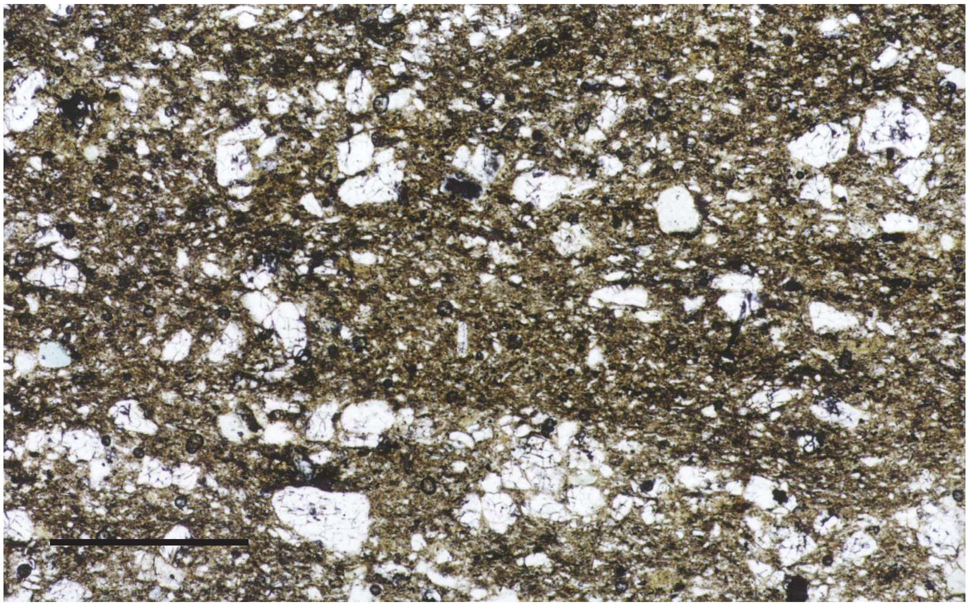

Figure SS5. Plane polarized light image of sand-rich mudstone (Emerald Island 4) from the base of the pebble shale unit just above (0.2 m) the contact with the Kemik Sandstone. This mudstone comprises up to 25% fine sand and silt (predominantly composed of detrital quartz) in a clay matrix (predominantly composed of illitic minerals). In addition to the major components, minor pyrite and glauconite are also present. Note the absence of any sedimentary structures. Scale bar 580 µm.

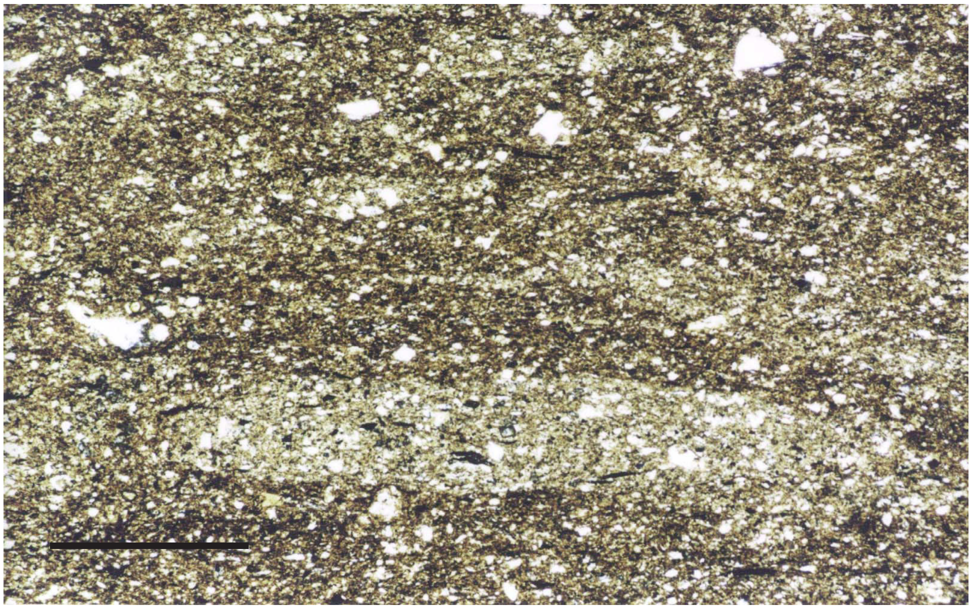

Figure SS6. Plane polarized light image of silt-rich mudstone (Emerald Island 3) from the base of the pebble shale unit 0.4 m above the contact with the Kemik Sandstone. This mudstone predominantly comprises detrital clay (illitic material) and up to 15% silt (predominantly quartz). Note the presence of a flattened, elliptical silt-filled burrow attributed to *Chondrites isp*. Scale bar 580 µm.

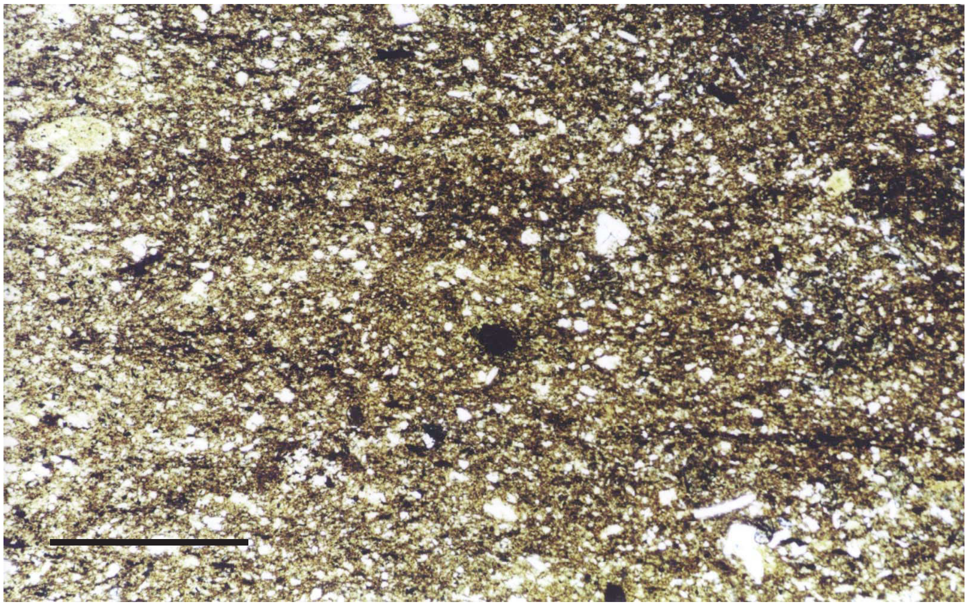

Figure SS7. Plane polarized light image of silt-rich mudstone (Emerald Island 5) from the base of the pebble shale unit 0.6 m above the contact with the Kemik Sandstone. This mudstone predominantly comprises detrital clay (illitic material) and up to 10% silt (predominantly quartz). Note the absence of any sedimentary structures. Scale bar 580 µm.

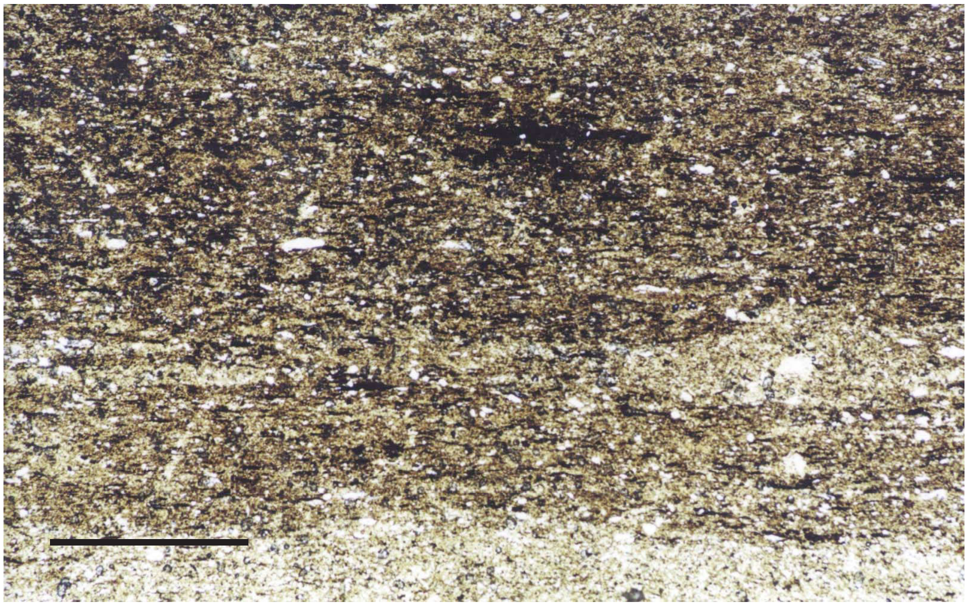

Figure SS8. Plane polarized light image of clay-rich mudstone (Emerald Island 6) from the base of the pebble shale unit1.1 m above the contact with the Kemik Sandstone. This mudstone predominantly comprises detrital clay (illitic material) and up to 5% silt (predominantly quartz). Note the presence of flattened, elliptical silt-filled burrows attributed to *Chondrites isp*. Scale bar 580 µm.

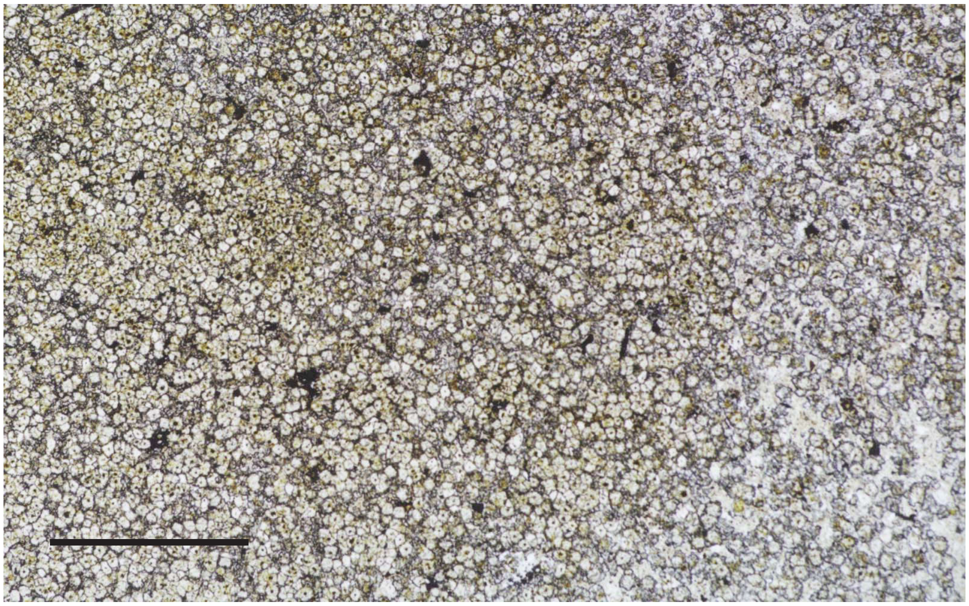

Figure SS9. Plane polarized light image of concretionary carbonate (Emerald Island 7) from the base of the pebble shale unit 1.15 m above the contact with the Kemik Sandstone. This mudstone predominantly comprises authigenic microcrystalline, zoned siderite rhombohedra which have grown within an uncompacted host sediment. Note the presence of a minor opaque phase attributed to pyrite. Scale bar 580 µm.

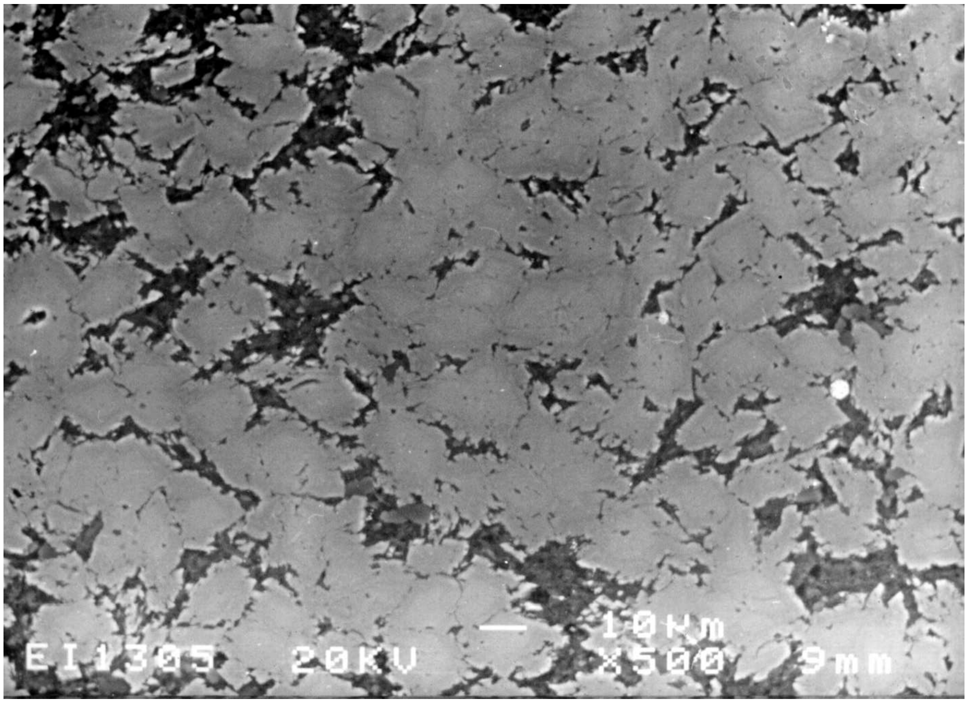

Figure SS10. Backscattered electon micrograph of concretionary carbonate (Emerald Island 13). This sample is predominantly composed of small (<15 µm) zoned siderite rhombohedra in a matrix of detrital clay (predominantly illitic material). The siderite in this sample probably precipitated prior to compaction into primary water-filled pore space. Scale bar 10 µm.

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Figure SS11. Plane polarized light image of laminated mudstone (Emerald Island 12) from the basal portion of the pebble shale unit 2.7 m above the contact with the Kemik Sandstone. Lamination is preserved within this mudstone. The individual laminae are picked by the prominant opaque organic-rich debris and the layers of silt. In addition, note that the silt-rich lamina upward fine into clay-rich lamina, and together these form an upward-fining couplet separated from couplets above and below by erosion surfaces. This sample is predominantly composed of detrital clay (illitic material) and up to 5% silt (predominantly quartz). Scale bar 580 µm.

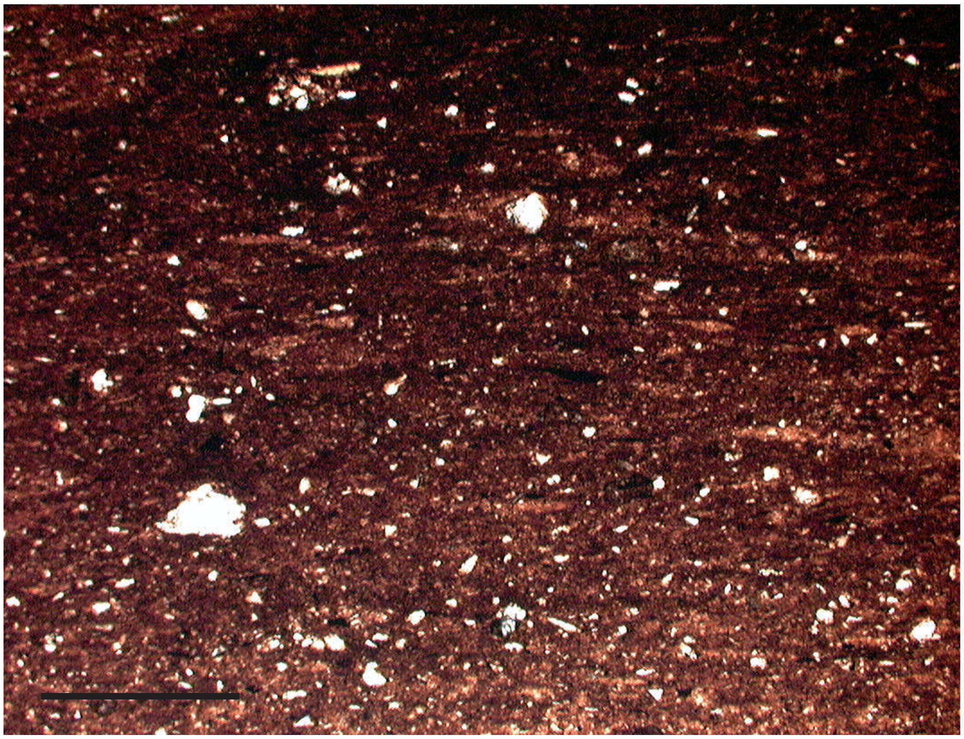

Figure SS12. Plane polarized light image of silt-rich mudstone (Emerald Island 24) from the middle of the pebble shale unit 7.9 m above the contact with the Kemik Sandstone. This mudstone predominantly comprises detrital clay (illitic material) and up to 15% silt (predominantly quartz). Note the presence of a flattened, elliptical silt-filled burrow attributed to *Chondrites isp*. Scale bar 580 µm.

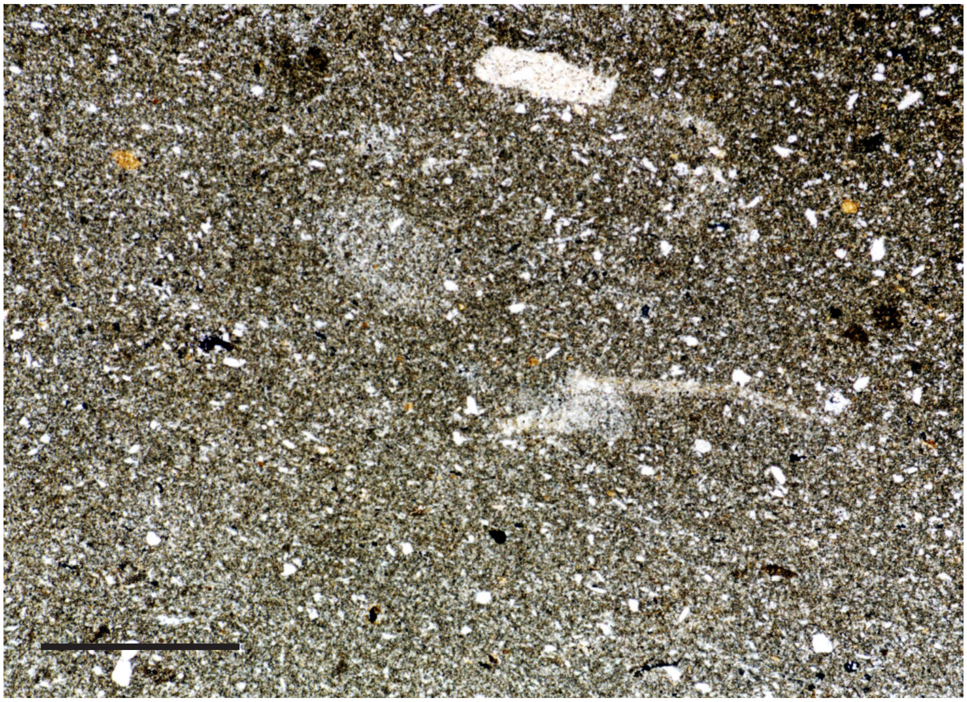

Figure SS13. Plane polarized light image of concretionary carbonate (Emerald Island 23) This sample is predominantly composed of small (<15 µm) zoned siderite rhombohedra in a matrix of detrital clay (predominantly illitic material) and detrital quartz grains (up to fine sand-size). The siderite in this sample probably precipitated prior to compaction into primary, water-filled pore space. Scale bar 580 µm.