[PS]# A Detailed Investigation of Facies Characterization, Pore-filling Clay Mineral Diagenesis, and Sediment Provenance in Pennsylvanian Clastic Reservoirs of the Anadarko Basin, Oklahoma*

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Abstract

The role of clay minerals in sandstone reservoirs has increasingly gained importance over the last few decades owing to the fact that clays readily occlude primary porosity and permeability, influence different petrophysical parameters, and react with drilling fluids thus affecting various oil recovery practices. Pennsylvanian sandstones of the Anadarko Basin in Oklahoma remain under-researched in that regard. By conducting a thorough analysis of clay parageneses, this study aims to shed more light on sandstone reservoir characteristics and ultimately achieve a better constraint of the basin's burial history.

Approximately 552 feet of core from two discrete wells specifically targeted a Pennsylvanian sandstone succession in the Anadarko Basin were analyzed using thin-section petrography, scanning and automated electron microscopy (SEM-EDS and QEMSCAN®), and X-ray diffractometry (XRD). The sandstone succession is comprised of interlaminated shaly sandstones to massive homogenous sandstones bounded by thick black shale intervals. Preliminary interpretation of QEMSCAN® data points to quartz and feldspar as the major mineral constituents of these sandstones. Carbonate cementation is widely present while pore-filling clays are dominantly of illitic and chloritic mineral chemistry. Measured porosity ranges from 5 to 10% and is in good agreement with 3D porosity results obtained from the conventional core analyses. XRD clay mineralogy further refined the pore-filling clay constituents, identifying detrital illite, mixed-layered illite-smectite (I-S), chlorite, and minor kaolinite minerals. Preliminary SEM-EDS investigation revealed authigenic I-S and chloritic minerals effectively filling porosity at certain depth intervals. Yet, more work is needed to deduce possible patterns linking stratigraphical facies, burial depths, and rock geochemistry with prevalent clay diagenesis trends.

Further data analyses and identification of distinct stratigraphical units, in concordance with the detailed quantification of porous clay content, will have a decisive impact on reservoir porosity calculation from density-based wire-line logging as well as future research seeking to reconstruct the stratigraphic distribution of reservoir properties in Pennsylvanian sandstones of the Anadarko Basin.

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Winchester, J.A., and P.A. Floyd, 1977, Geochemical discrimination of different magma series and their differentiation products using immobile elements: Chem. Geol., v. 20, p. 325-343.

A Detailed Investigation of Facies Characterization, Pore-filling Clay Mineral Diagenesis, and Sediment Provenance in Pennsylvanian Clastic Reservoirs of the Anadarko Basin, Oklahoma

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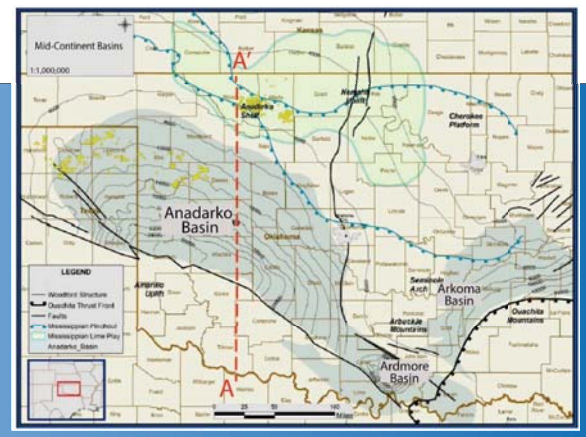
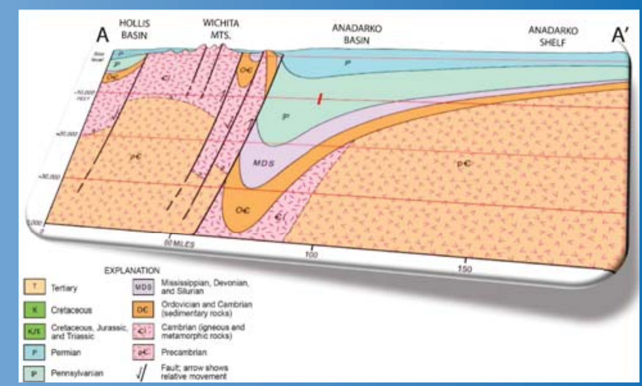
Introduction and Geological Background

The foreland Anadarko Basin in southeastern Oklahoma is one of the deepest basins in North America. Its thickest sedimentary succession consists of approximately 4000 m (~13100 ft) of alternating shale and sandstone layers of principally Pennsylvanian age. Yet, these sediments are relatively under-researched with respect to their overall composition, clay mineralogy, geochemistry, and diagenetic reactions in the context of the Anadarko Basin geological history. Therefore, the Anadarko Basin strata represent an excellent natural laboratory to investigate the dynamics of diagenesis in the deep burial environment, addressing at the same time the open questions with regard to the provenance of studied sediments.



The analytical approach in this study included X-ray diffraction (XRD) on global and clay fraction, automated scanning electron microscopy (QEMSCAN®), polarization microscopy, and inductively coupled plasma mass spectrometry (ICP-MS). Two cores (Firefly 13-2H and Mockingbird 28-1HR) derived from the Caddo County in Oklahoma were sampled at the depth of approximately 3000 m (9843 ft) targeting the Pennsylvanian clastic succession of the Hoxbar Group (Fig. 1). Total length of the material analyzed is 180 m (552 ft). Both cores are principally composed of the alternation of (1) laminated shaly-silty sandstone and sandy mudstone rich in bioturbations, (2) shale and (3) massive sandstone.



Data obtained from this study focused on the sandy intervals permitted one to distinguish several subfacies: (1) bioturbated sandstone, (2) clean sandstone that is further subdivided into comprising (a) siliciclastic cement or (b) carbonate cement, (3) sandstone with muddy interlayers, (4) sandstone with mixed carbonate and siliciclastic cement, (5) carbonate-rich sandstone with siderite nodules, and (6) horizons with siderite cementation (Figs. 2-6). Such defined vertical evolution is characteristic for tidal dominated sedimentation.

Facies Classification and QEMSCAN®

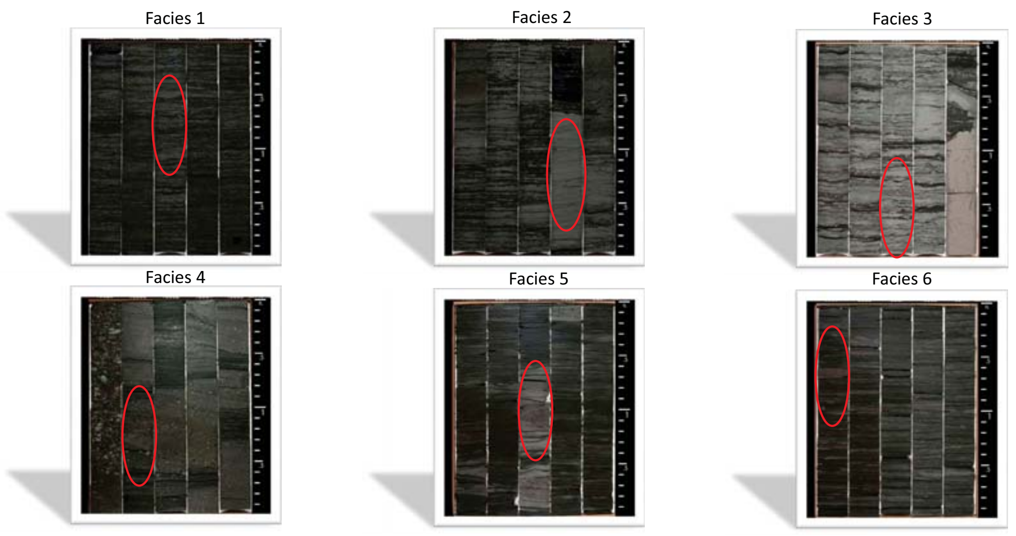


Fig. 2: (Above) Subfacies observed in both cores: (1) bioturbated sandstone, (2) clean sandstone that is further subdivided into comprising (a) siliciclastic cement or (b) carbonate cement, (3) sandstone with muddy interlayers, (4) sandstone with mixed carbonate and siliciclastic cement, (5) carbonate-rich sandstone with siderite nodules, and (6) horizons with siderite cementation. (Far Right) Subfacies observed by polarized microscopy.

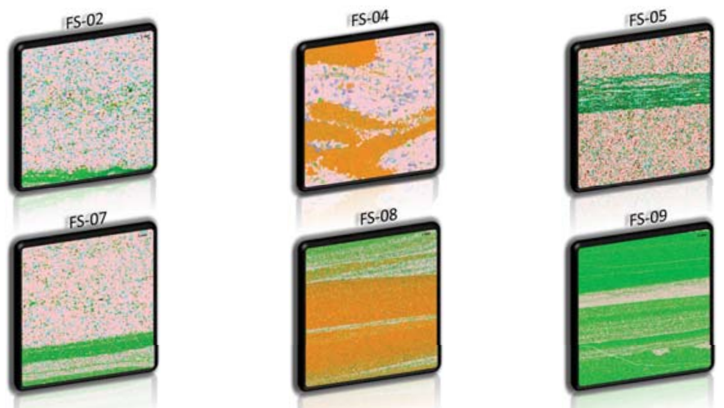


Fig. 3: QEMSCAN® images of selected Firefly 13-2H samples. Sample FS-02, FS-05, FS-07, and FS-09 are representative of *Facies 3* (sandstone with muddy interlayers); sample FS-04 is representative of *Facies 5* (carbonate-rich sandstone with siderite nodules); sample FS-08 is representative of *Facies 6* (horizons with siderite cementation).

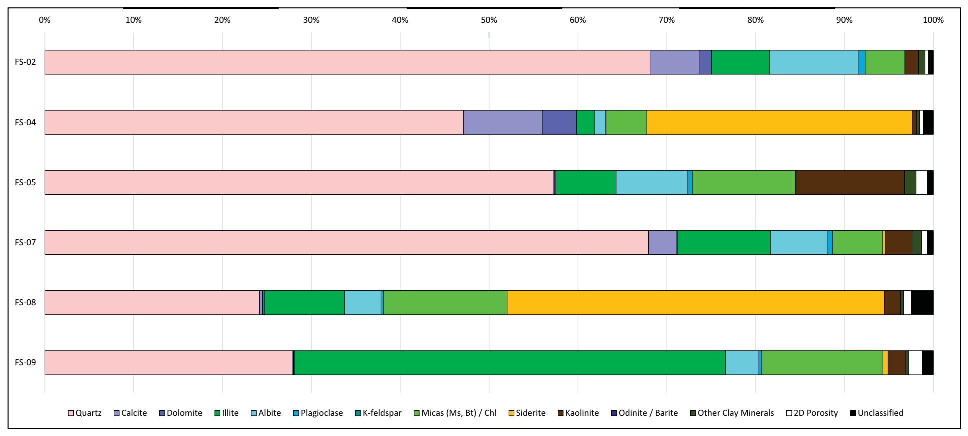


Fig. 4: QEMSCAN® Modal Mineralogy of 6 Firefly 13-2H samples

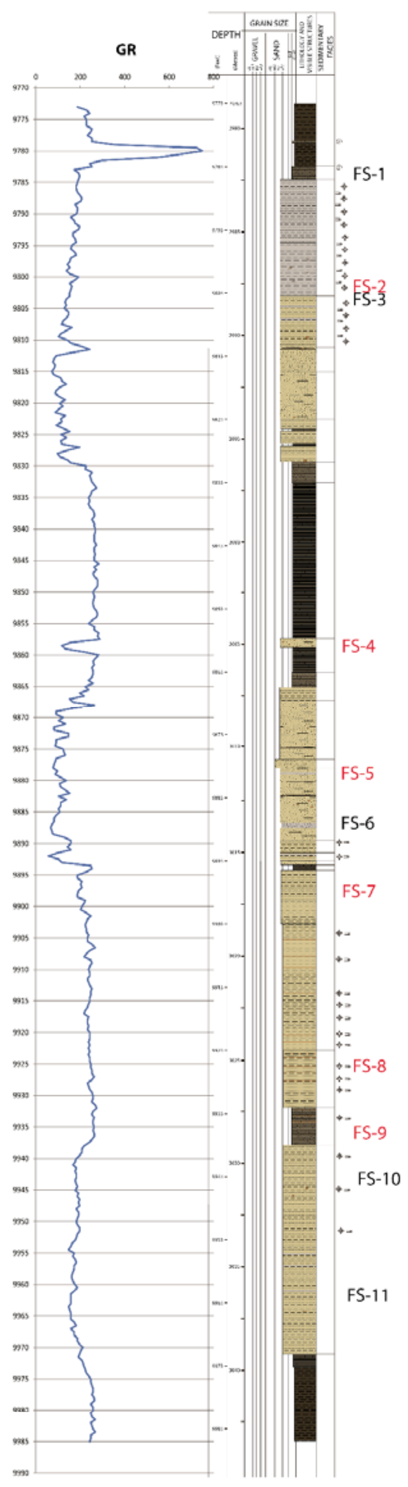
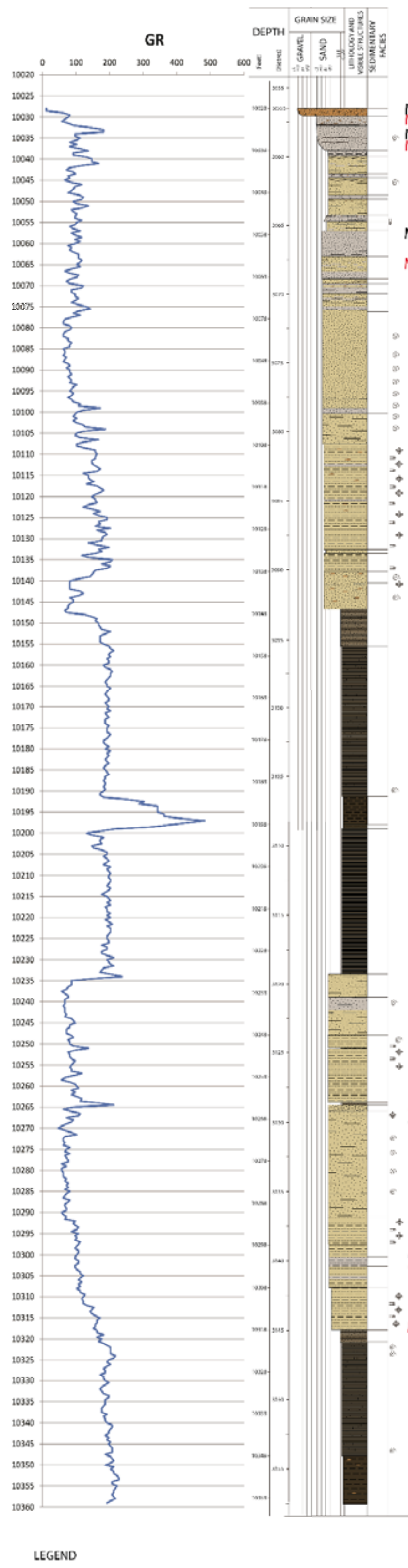



Fig. 1: Firefly 13-2H and Mockingbird 28-1HR cores (160 m) that sampled the clastic successions of the Pennsylvanian Hoxbar Group in the Anadarko Basin. A total of 44 samples have been selected in order to investigate clay mineralogy. (Red denotes samples selected for QEMSCAN® analysis)

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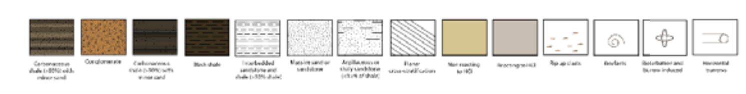

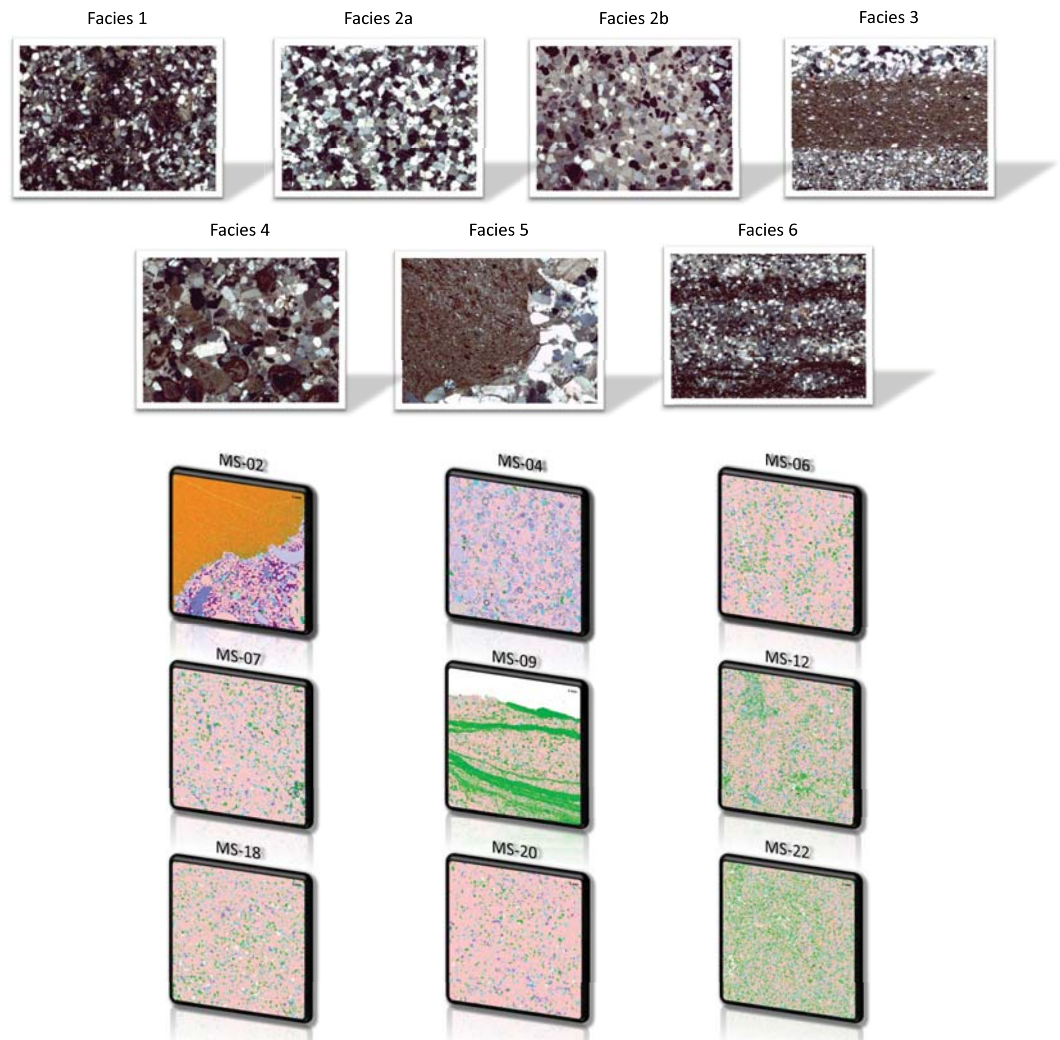

Fig. 5: QEMSCAN® images of selected Mockingbird 28-1H samples. Sample MS-02 is representative of *Facies 5* (carbonate-rich sandstone with siderite nodules); sample MS-04 is representative of *Facies 4* (sandstone with mixed carbonate and siliciclastic cement); Samples MS-06, MS-07, MS-18, and MS-20 are representative of *Facies 2* (clean sandstone); sample MS-09 is representative of *Facies 3* (sandstone with muddy interlayers); samples MS-12 and MS-22 are representative of *Facies 1* (bioturbated sandstone).

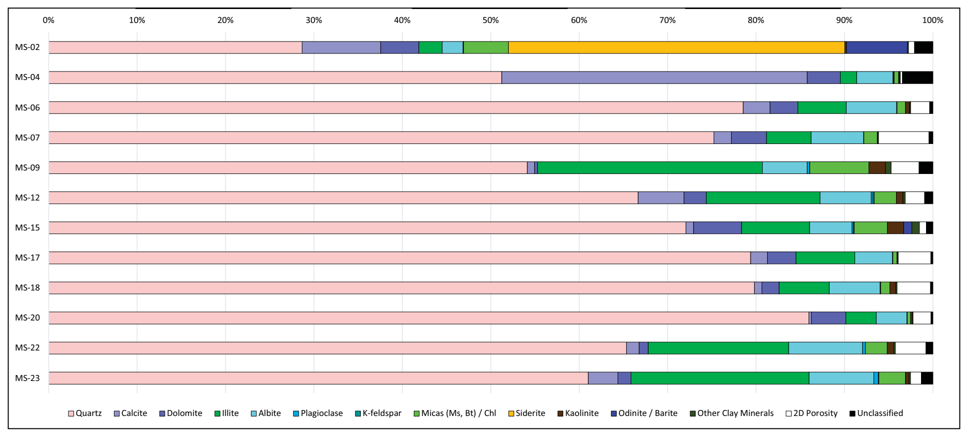

Fig. 6: QEMSCAN® Modal Mineralogy of 12 Mockingbird 28-1HR samples

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Diagenesis

Porous clay minerals in sandstones are known as reliable diagenetic indicators owing to their susceptibility to changing burial conditions. Illite and mixed-layer illite-smectite (I-S) are omnipresent in analyzed sediment. The broad range of I-S compositions reported in both cores is, however, facies controlled. Thus, *Facies 2* is dominated by illite-rich I-S, whereas in *Facies 1* and *Facies 3* I-S appears to be comparatively enriched in smectitic component. Additionally, in these facies, I-S of peculiar composition (i.e. rectorite) readily occurs. *Facies 4 and Facies 5* also show a comparatively higher smectite content of I-S suggesting an early cementation event that hampered higher rates of illitization (Fig. 7). On the other hand, it was observed that kaolinite presence is largely a diagenetic artifact. Kaolinite crystals are well developed, filling the sandstone porosity. Their content is inversely correlated with the 2D porosity values thus identifying kaolinite as the main clay mineral that occludes primary porosity. Across the facies it was found that kaolinite evolves into illite, which is a process known to be pervasive in diagenetic systems at temperatures greater than ~130°C (Fig. 8). This fits well with the depths from which the analyzed material was sampled.

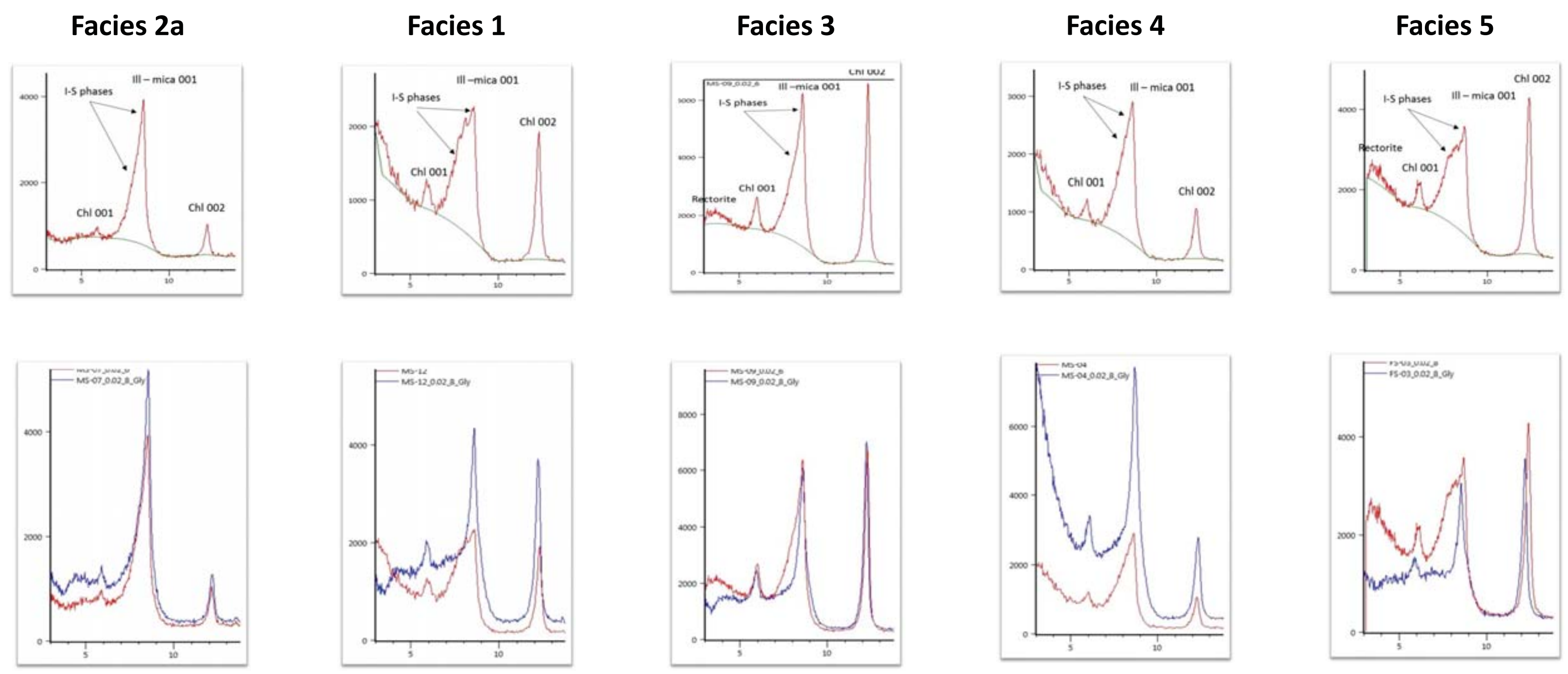

Fig. 7: Air-dried clay fraction XRD diffractograms (top row) and comparative analysis of air-dried to glycolated samples (bottom row). *Facies 2a* (sample MS-07) exhibiting a sharp peak at position 8-9° 2ϴ indicative of dominant illite-rich I-S; *Facies 1* (sample MS-12) and *Facies 3* (sample MS-09) exhibiting broadened peak at position 8-9° 2ϴ indicative of the abundance of smectitic component in I-S; *Facies 4* (sample MS-04) and *Facies 5* (sample FS-03) exhibiting comparatively higher smectite content of I-S suggesting an early cementation event that hampered higher rates of illitization.

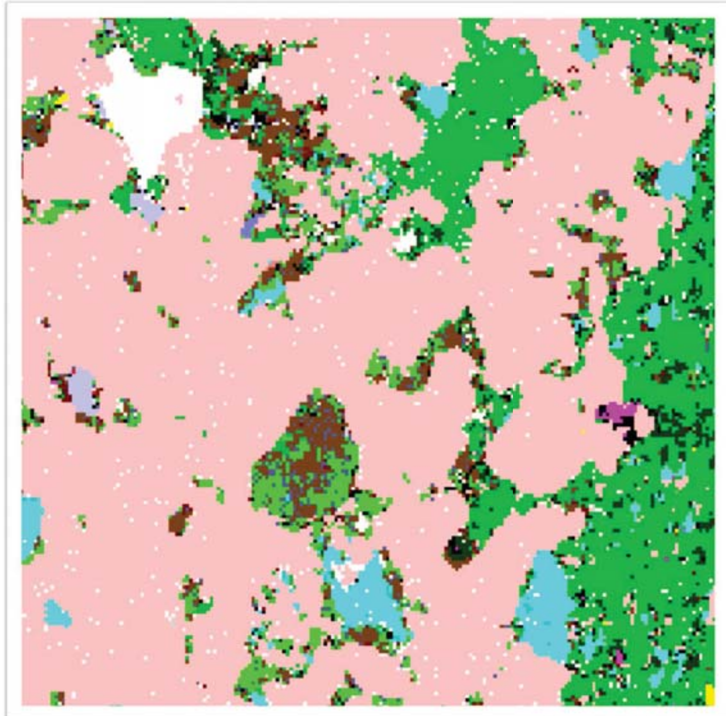

Fig. 8: Illitization of kaolinite in sample MS-09. It is interpreted to have been catalyzed through an external flux of K ions as no K-feldspar is reported in analyzed sediments which may have served as a source of K.

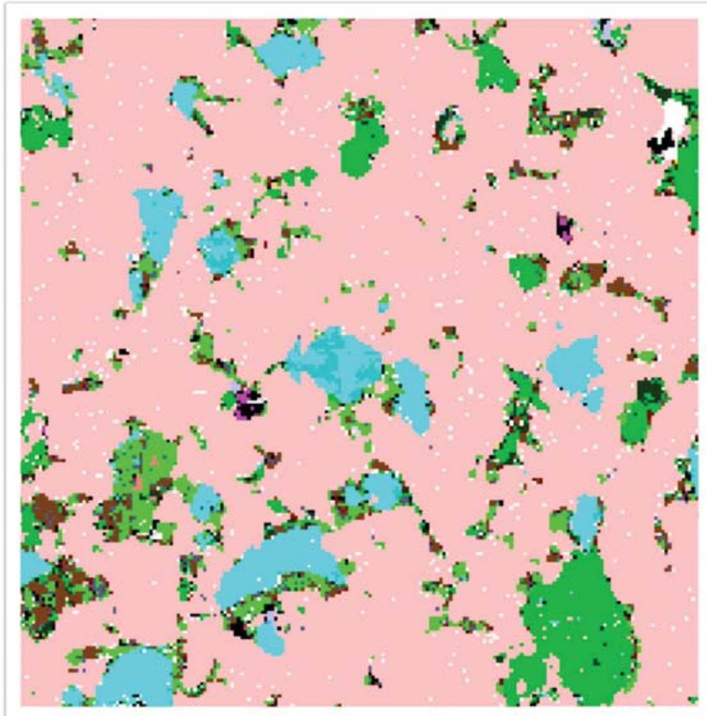

Fig. 9: Sample MS-09 exhibiting prograde albitization of detrital plagioclase and K-feldspars. In most of the samples the albitization is practically complete, indicating burial temperatures higher than 100°C.

Provenance

In sedimentary basins, provenance studies are particularly important not only for the understanding of the source(s) of sediment but also to infer about the history of the basin. High-field strength elements (HFS) and rare-earth elements (REE) stay relatively immobile during diagenetic processes because their content is controlled by clay minerals preventing the mobilization by aqueous fluids. Chondrite normalized abundances of REE shows trends typical of highly-fractionated intermediate to felsic magmas (Fig. 10). Their intermediate nature is corroborated by suprasubduction signatures showed by the some of HFS elements (i.e. Nb-Ta and P anomalies), as well as the Winchester & Floyd (1977) diagram of classification of volcanic rocks using Nb/Y and Zr/Ti ratios (Fig. 11). Active continental margins were further defined by Th/Yb-Ta/Yb plot of Pearce (2008) as a most liable geotectonic setting of parental rocks (Fig. 12). Assuming that suprasubduction characteristics are inherited from previous subduction events, it may be hypothesized that weathering of igneous rocks whose compositions closely correspond to S-granites yielded the sandstones analyzed herein. Heavy mineral assemblages reported in this study dominated by apatite, rutile, and zircon are in line with such a reasoning (Fig. 13). Original emplacement of the parental igneous rocks was likely in the interior of the American Midcontinent.

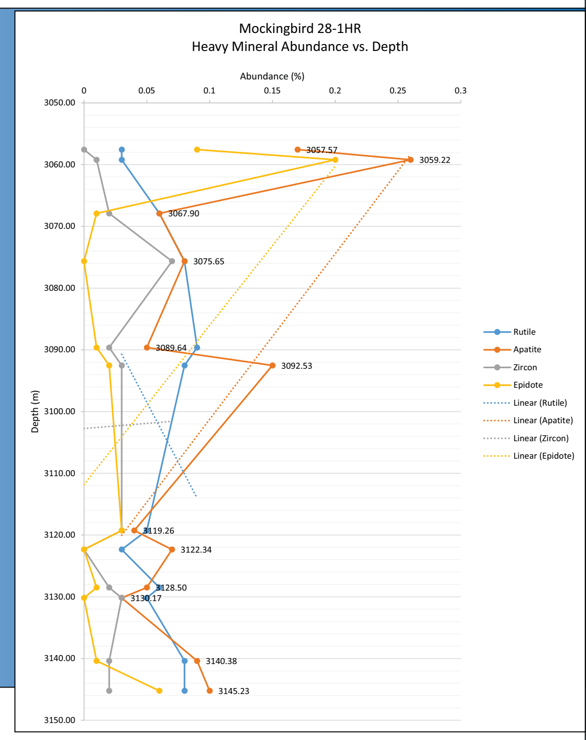

Fig. 13 (above): Heavy mineral assemblages (dominated by apatite, rutile, and zircon) correlated with depth in 12 samples of Mockingbird 28-1HR analyzed by ICP-MS. Assuming that suprasubduction characteristics are inherited from previous subduction events, it may be hypothesized that weathering of igneous rocks whose compositions closely correspond to S-granites yielded the sandstones analyzed herein.

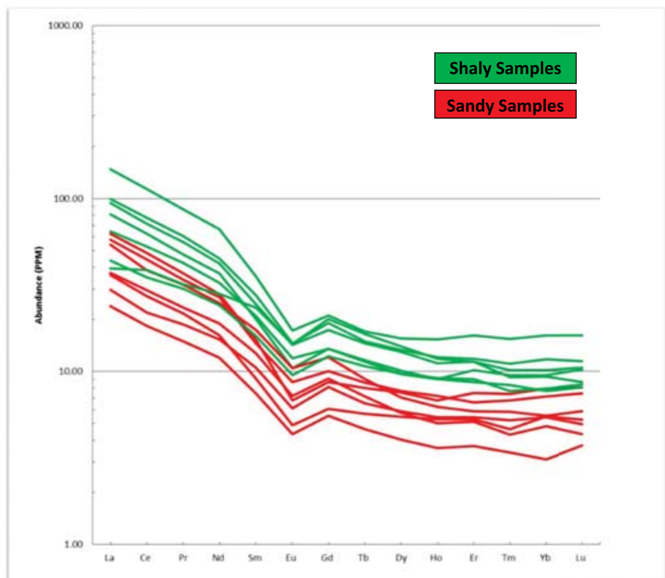

Fig. 10 (left): Chondrite normalized abundances of REE in 14 selected samples (6 from Firefly 13-2H and 8 from Mockingbird 28-1HR) showing trends typical of highly-fractionated intermediate to felsic magmas. Green denotes more "Shaly" samples while red denotes more "Sandy" samples.

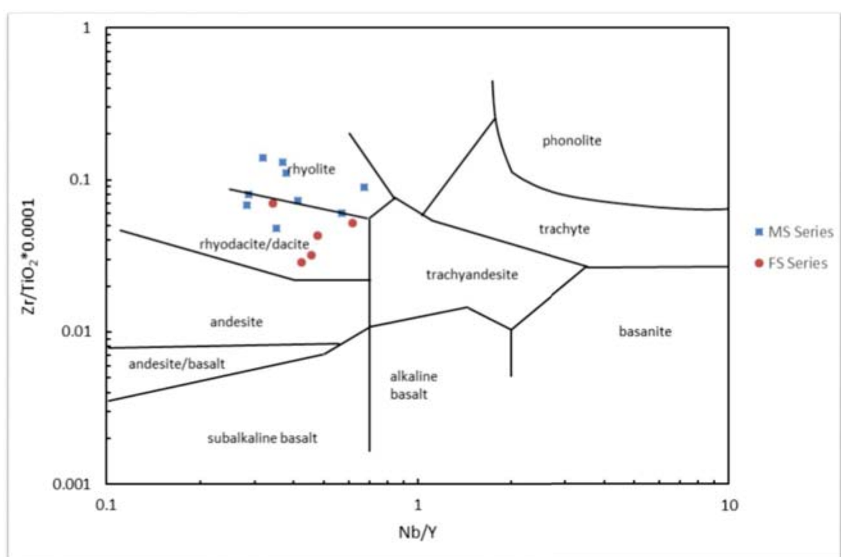

Fig. 11 (left): The Nb/Y and Zr/Ti diagram of classification of volcanic rocks (Winchester & Floyd 1977). The suite samples collected from both cores predominantly plot within the rhyodacite/dacite and ryholite fields.

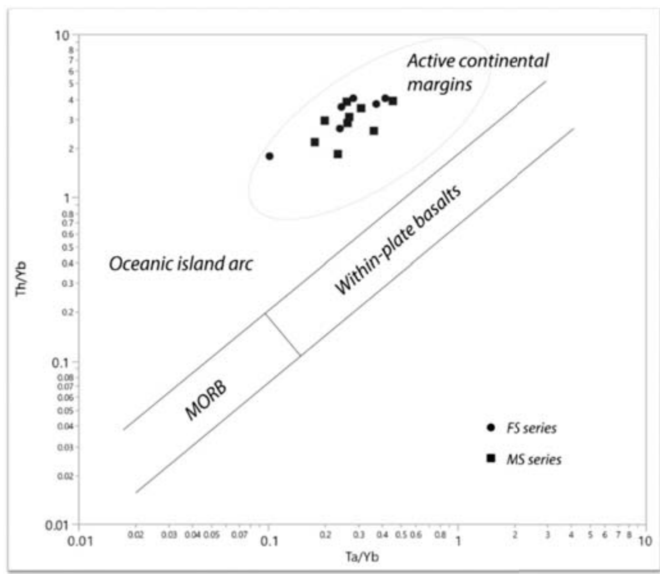

Fig. 12 (left): Active continental margins defined by Th/Yb-Ta/Yb plot of Pearce (2008). Lavas that have interacted with continental crust on ascent, or have a subduction component, are then displaced to higher Th/Yb values.

References

(1) PEARCE J.A. (2008): Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust. *Lithos*, 100, 14-48.
(2) WINCHESTER J.A. & FLOYD P.A. (1977): Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chem. Geol.*, 20, 325—343.