The Grain-Coating Illite/Smectite (I/S): A New Discovery on Its Positive Effect on Porosity Preservation*

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Abstract

Devonian sandstone reservoirs have rarely been the main target for petroleum exploration in the UK. In part this is due to the perception that such ancient sandstones are likely to have low reservoir quality. However, our research reveals that such sandstones may have very good porosity and permeability due to the efficiency of grain coating smectite as a porosity-preserving mechanism. This study reports on the factors controlling reservoir quality of deeply buried Upper Devonian Buchan Formation in the Ardmore Field, Block 30/24, UK Central North Sea. Core material and well data from five wells were examined using sedimentological and petrographic analysis. Sedimentological analysis was performed through core logging and facies identification. Optical microscopy, X-ray diffraction, and SEM provided the database for the petrographic analysis. The sandstones with reservoir potential in the Upper Devonian Formation are interpreted as mixed fluvial-aeolian facies deposited in a semi-arid to arid climatic setting. Apart from conventional analysis on sandstone compositional and textural features, special attention was given to the positive effect and origin of smectite grain coatings. Thick (> 5 μm), continuous and well-developed smectite grain coatings occur only in aeolian facies sandstones. The clay coats effectively prevented precipitation of quartz overgrowth on the detrital grains. This was crucial for preservation of porosity in aeolian facies sandstones at deep burial depth. While smectite grain coatings are absent in fluvial facies sandstones and thus the primary porosity is significantly occluded by quartz overgrowth. This is the first time the effect of grain coating smectite and its influence on porosity preservation has been reported. Smectite grain coatings were formed by mechanical infiltration from adjacent fluvial-origin clay-bearing water at an early post-depositional stage and before the onset of any significant compaction. Furthermore, illitization is restricted in the Devonian strata due in part to the relatively shallow burial depth (< 500 m) until the end of Cretaceous, and then rapidly buried from Palaeocene to present day maximum burial depth (2.7-3.0 km). This research highlights the potential for similar age depositional facies to have reservoir potential in the North Sea and other hydrocarbon basins.

Introduction

The deeply buried (2.7 – 3.2 km) Upper Devonian Buchan Formation in Ardmore Field (Block 30/24, UK Continental Shelf) is a locally important reservoir composed by fluvial-aeolian sandstones. While the fluvial sandstones are extensively quartz cemented with porosity values ranging from 3.2 – 22.4% (avg. 14.4%); the porosity of aeolian sandstones ranges from 15 – 28% (avg. 20.2%) and was preserved by grain-coating clays preventing quartz overgrowth. The aeolian sandstones show higher porosity compared with the general depth-porosity trend of oil-bearing sandstones in the Central North Sea (Selley, 1978).

The petrographic analysis show that the grain coating clays only developed in aeolian sandstones and formed on the aeolian grain surface by mechanical infiltration before compaction. Although it is well known that chlorite and microcrystalline quartz coatings inhibit quartz cementation (Aase et al., 1996; e.g. Ehrenberg, 1993), our study does show that illite/smectite (I/S) coatings can also be effective in preventing quartz overgrowth. In the studied field, the grain-coating I/S were transformed from smectite precursor which had been introduced by fluvial clay-bearing water.

Illitization was observed to have occurred within a very limited degree, which could be explained by the Devonian strata were at consistently shallow burial depth (< 1 km) and low temperature (< 80°C) until Palaeocene and rapidly buried into its current depth and temperature of 110°C within a short time thus not giving enough time for illite to develop into hairy/fibrous shape. This phenomenon can be expected to occur only under particular circumstances, in which case it has a profound consequence for exploration.

Geological Setting

The Ardmore Field is located on the Argyll Ridge, a large SW-NE trending Palaeozoic age tilted fault block on the south-western flank of the Central Graben in Block 30/24, UK North Sea, about 350 km SE from Aberdeen. The field is a horst feature with the crest in the north and fault closure to the NE. It measures 2.5 km wide and 6 km long (Figure 1A). A combination of dip and faulting defines the limits of the field on the NW and SE flanks, while dip closure defines the southern limits of the field. The major fault trends are in two main directions, WNW–ESE cut by NW-SE faults. Top seal of the field is provided by Triassic shale to the far west, Jurassic shale in the mid-part of the field and impermeable Chalk at the north-eastern crest. The trap relies heavily on the major NW-SE trending graben edge faults to the NE and SW of the field while dip closure occurs to the NW and west (Figure 1B).

The Upper Devonian Buchan Formation comprises a thick, generally upward-coarsening succession of fluvial-aeolian sandy sediments formed on an alluvial fan system in an arid/semi-arid setting. The whole Buchan succession lacks clear seismic stratigraphic markers, a combination of log and core data has been used to divide the stratigraphic units for the Upper Devonian group: B01 is the oldest unit overlying the Middle Devonian Limestone, and B11 is the youngest unit (Figure 1B). In the absence of bio-stratigraphic data, sedimentary structures and lithofacies associations have been applied to help correlation (Gluyas et al., 2005). The total thickness of the Buchan Formation is about 300 – 800 m according to the seismic profile (Figure 1C).

Petrography and Diagenesis

The studied Buchan sandstones are litharenite to sub-litharenite and minor quartz-arenite, the aeolian sandstones ($Q_{82.1}F_{2.4}R_{15.5}$, upper fine to medium grained, moderate to good sorting, sub-rounded to well-rounded grains) are compositionally and textually more mature than fluvial sandstones ($Q_{76.1}F_{3.3}R_{20.7}$, very fine to medium grained, poor to moderate sorting, sub-angular to sub-rounded grains). The grain contact show point to linear and curved to concavo-convex in aeolian and fluvial sandstones, respectively.

In both sandstone types, quartz is dominantly monocrystalline, showing little undulose extinction; feldspar is commonly presented in trace amount and up to 7%, the main types are microcline, which occur as both fresh and nearly completely dissolved grains; most of the mica grains are muscovite presenting in all the samples and comprising up to 13% showing distortion due to the compaction; rock fragments are in variable quantities including micaceous and illitic mud clasts.

Authigenic dolomite is prevalent in all Buchan sandstones ranged from 0 – 36% with an average value 6.7%. Quartz overgrowth is absent in aeolian sandstones but shows highly variable in fluvial sandstone (0-16%, average value 3.2%). Kaolinite and illite are the two main types of authigenic clays in fluvial sandstones. Kaolinite mainly occurs as euhedral pseudo-hexagonal plates and vermicular or booklet aggregates filling primary pores. Illite occurs as fibrous or hairy crystals mainly based on kaolinite and shows the pore-bridging habit.

The grain-coating I/S is the most important clay type in aeolian sandstones and presents in two forms: a). Grain-coating I/S commonly occurs as cornflake or honeycomb morphology with filamentous terminations (Figure 2A), and consists of 1 – 5 μm thick rim coating all detrital grains in aeolian facies sandstones (Figure 2B and Figure 2C); it is absent in fluvial facies sandstones. It is also observed that quartz overgrowths are absent in aeolian facies sandstone samples where uniform and robust grain-coating I/S has developed. Pore-filling I/S is commonly presenting as flocculent aggregates existing in the intergranular pore space (Figure 2A), and is absent in fluvial facies sandstones.

The Source of Grain-Coating I/S

Mineralogically, the cornflake or honeycomb morphology observed under SEM supports that the I/S have formed from smectite precursor (Pollastro, 1985), and the smectite crystals would form an effective coat because they nucleate flatly attached to the detrital grain surface and curl away from that surface, this crystal morphology leads to a dense and effective coat (Pittman et al., 1992).

In terms of facies, the vertical fluvial-aeolian-fluvial variation generally represents a progradation-retreat-progradation cycle of the alluvial fan-based braided system with aeolian deposits occurred mainly between two main progradation periods. The distribution of grain-coating I/S is highly facies-controlled which is only found in aeolian sandstones, however, it is not considered as aeolian in origin. During aeolian dominated period, the studied area was only affected by distal sectors of fluvial distributary system. Thus, a very possible source of these smectite precursors is from fluvial clay-bearing water, within such an environment, the lower water table allowed muddy water to infiltrate through the coarser, porous and permeable aeolian sands; and the petrographic features do meet the criteria set by Wilson (1992) for identifying mechanical infiltrated clays.

The Effect of Grain-Coating I/S on Reservoir Quality

The grain-coating I/S in the aeolian sandstones show an excellent continuity around the grains (Figure 2C) and has effectively inhibited possible subsequent quartz overgrowth. By using 1D thermo-burial history and the theoretical model proposed by Walderhaug (1996), we calculated that quartz overgrowth would theoretically occupy 6 – 7% of porosity in the fine to medium grained aeolian sandstones if the grain-coating I/S is absent (Figure 3).

Despite this positive effect, the smectite-based clays are commonly known to be harmful to the reservoir quality due to its swelling property (Gray and Rex, 1965) and illitization (Le Gallo et al., 1998). However, the reservoir quality of the aeolian sandstones is not obviously affected by these two shortcomings due to: 1). the pore-filling I/S is only possessed in a minor amount (< 5%) thus would not significantly decrease permeability, and 2). the Devonian strata were consistently at shallow burial depth (< 1.5 km) and low temperature (< 80°C) until Palaeogene and rapidly buried into the current depth within a short time (Figure 4) which does not allow authigenic illite to develop into elongated hairy/fibrous crystals.

Conclusions

The grain-coatings observed in the studied field have been identified as illite/smectite. This study shows that I/S coatings can be very effective in preventing quartz cementation and thereby help preserve primary porosity. The I/S coatings in the Ardmore Field were generated from a smectite precursor, which had originated from fluvial clay-bearing water that represents the deposits of distal sectors of fluvial distributary system, and were formed as grain-coatings in aeolian sandstones by mechanical infiltration. The understanding of the positive effect on porosity preservation from grain-coating I/S may aid the predictions of high quality Devonian-associated reservoirs in the Central North Sea and other places with similar provenance.

References Cited

Aase, N.E., P.A. Bjorkum, and P.H. Nadeau, 1996, The Effect of Grain-Coating Microquartz on Preservation of Reservoir Porosity: American Association of Petroleum Geologists Bulletin, v. 80/10, p. 1654-1673.

Ehrenberg, S., 1993, Preservation of Anomalously High Porosity in Deeply Buried Sandstones by Grain-Coating Chlorite: Examples from the Norwegian Continental Shelf: American Association of Petroleum Geologists Bulletin, v. 77/7, p. 1260-1286.

Gluyas, J.G., B. Mair, P. Schofield, P. Arkley, and D. McRae, 2005, Ardmore Field: Rebirth of the First Offshore Oil Field, UKCS: Proceedings Geological Society, London, Petroleum Geology Conference Series, Volume 6, Geological Society of London, p. 367-388.

Gray, D., and R. Rex, 1965, Formation Damage in Sandstones Caused by Clay Dispersion and Migration: Proceedings of the Fourteenth National Conference on Clays and Clay Minerals, Berkeley, CA, p. 355-365.

Le Gallo, Y., O. Bildstein, and E. Brosse, 1998, Coupled Reaction-Flow Modeling of Diagenetic Changes in Reservoir Permeability, Porosity and Mineral Compositions: Journal of Hydrology, v. 209/1, p. 366-388.

Pittman, E.D., R.E. Larese, and M.T. Heald, 1992, Clay Coats: Occurrence and Relevance to Preservation of Porosity in Sandstones, *in* D.W. Houseknecht and E.D. Pittman (eds.), Origin, Diagenesis and Petrophysics of Clay Minerals in Sandstones: SEPM Special Publication 47, p. 241-264.

Pollastro, R.M., 1985, Mineralogical and Morphological Evidence for the Formation of Illite at the Expense of Illite/Smectite: Clays and Clay Minerals, v. 33, p. 265-274.

Selley, R., 1978, Porosity Gradients in North Sea Oil-Bearing Sandstones: Journal of the Geological Society, v. 135/1, p. 119-132.

Walderhaug, O., 1996, Kinetic Modeling of Quartz Cementation and Porosity Loss in Deeply Buried Sandstone Reservoirs: American Association of Petroleum Geologists Bulletin, v. 80/5, p. 731-745.

Wilson, M.D., 1992, Inherited Grain-Rimming Clays in Sandstones from Eolian and Shelf Environments: Their Origin and Control on Reservoir Properties, *in* D.W. Houseknecht and E.D. Pittman (eds.), Origin, Diagenesis, and Petrophysics of Clay Minerals in Sandstones: SEPM Special Publication 47, p. 209-225.
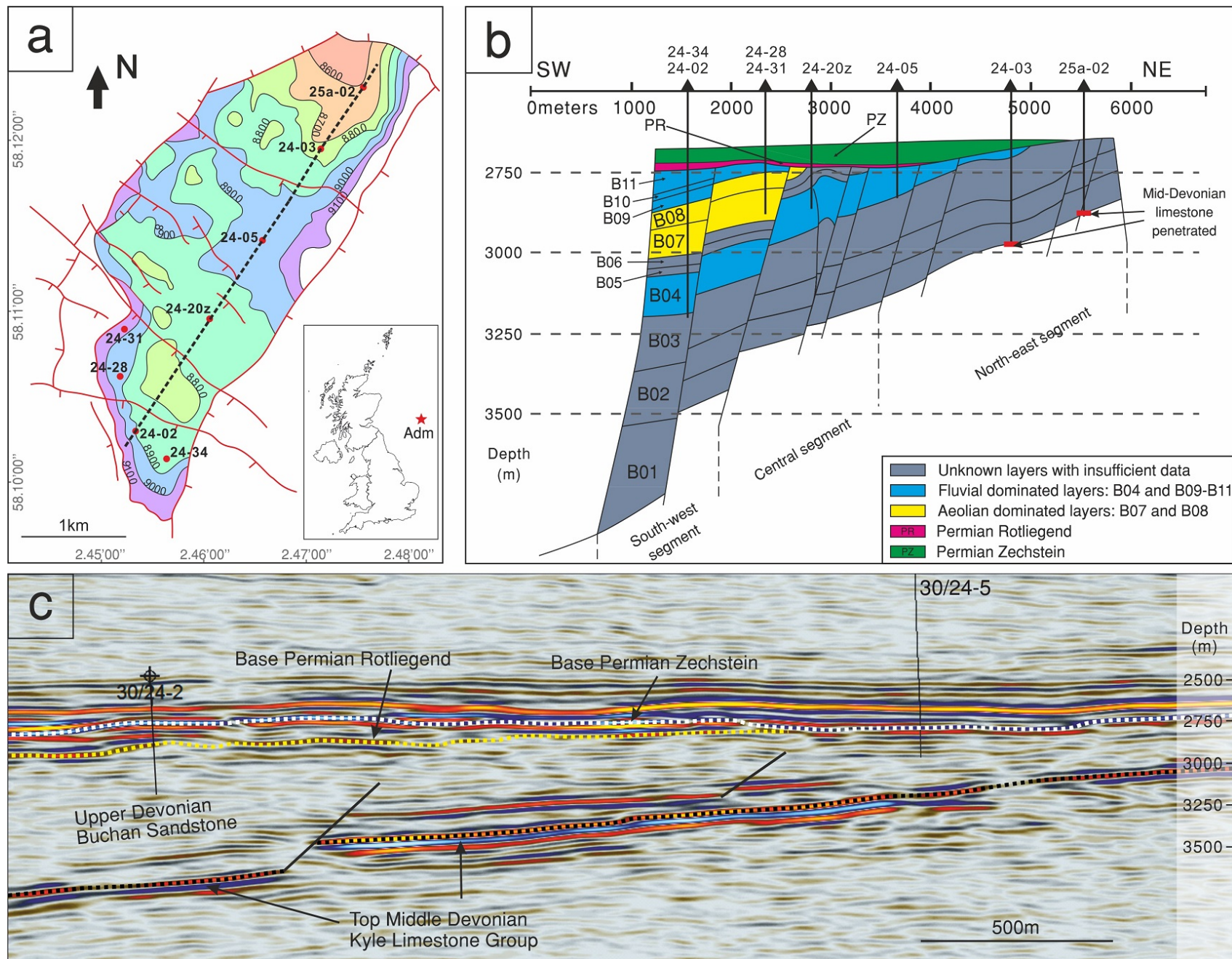
Figure 1. A. The location and structural contour map of Ardmore Field; B. A selected SW-NE vertical profile (line dash line in 1A); C. The seismic profile of selected dash line profile.
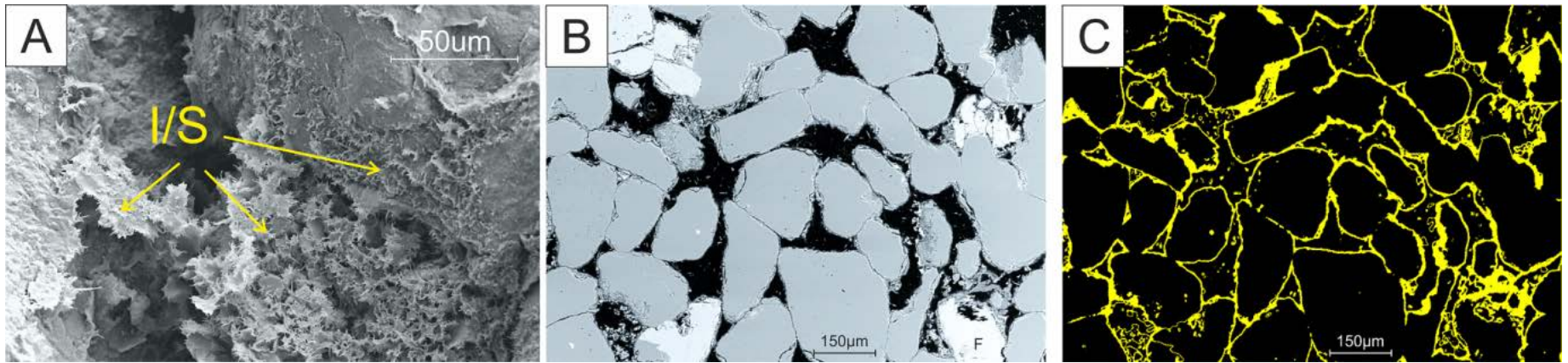
Figure 2. A. The SEM image of grain coating and pore-filling I/S; B. BSEM image of typical aeolian sandstone; C. The mineral facies map showing good continuity of the grain coating I/S.
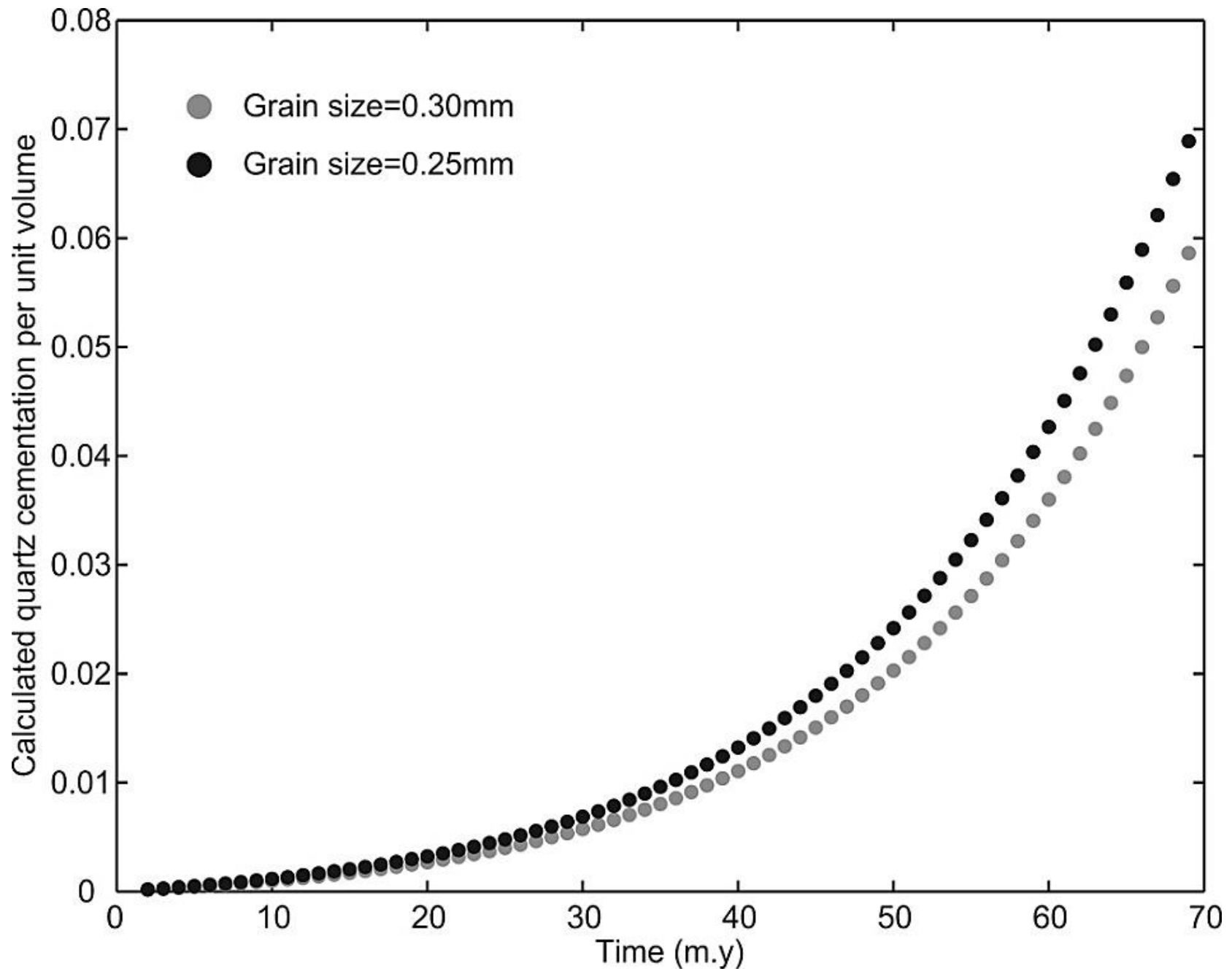
Figure 3. Theoretical quantity of quartz overgrowth in fine to medium grained aeolian sandstones if the grain coatings are absent, the algorithm is after Walderhaug (1996).
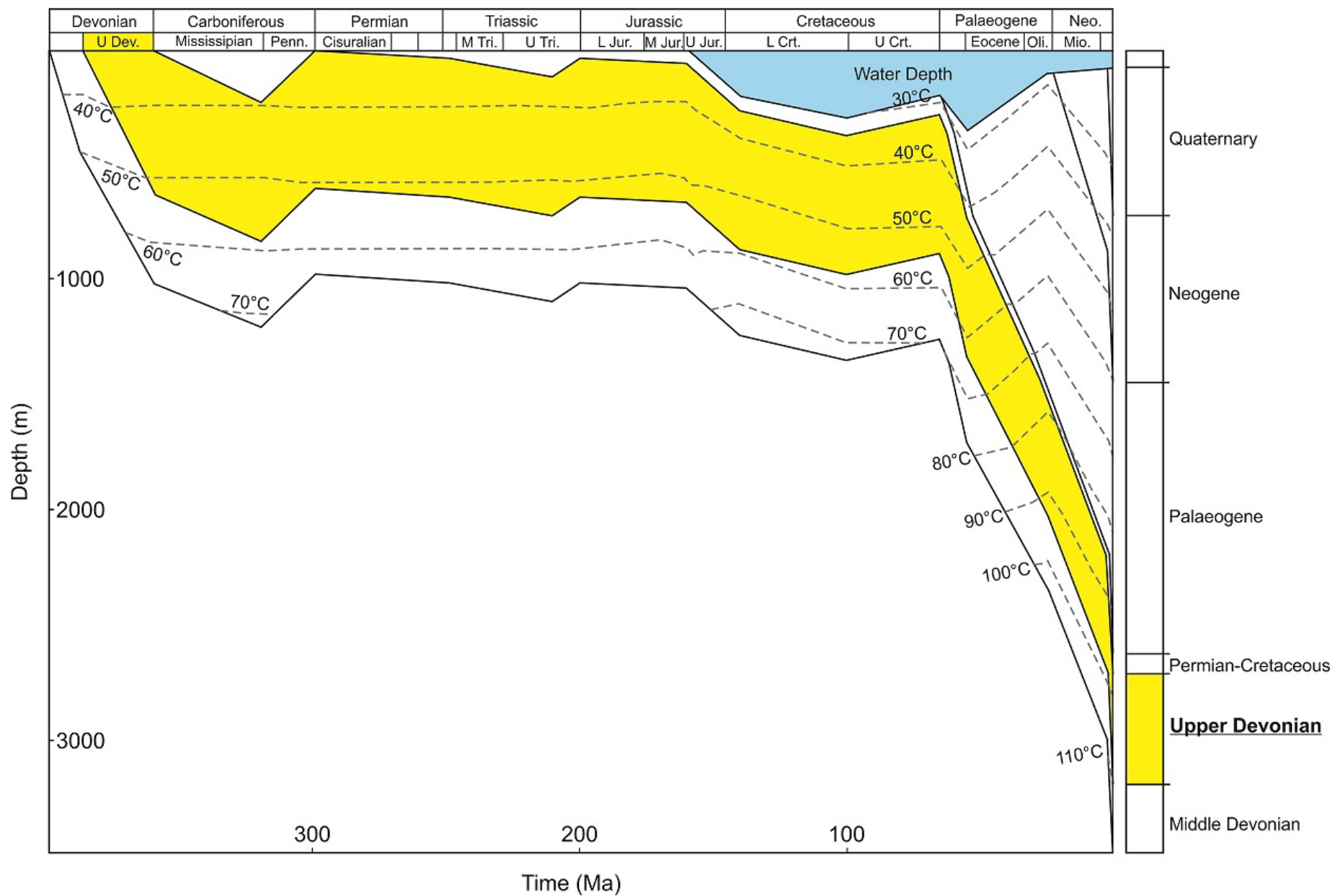
Figure 4. 1D burial and temperature history of the Ardmore Field.