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Diagenetic Environment of Sandstones from the Ermaying Formation (Middle Triassic), North-eastern Margin of the Ordos Basin, China: Implications for the Erosion Vulnerability of the Pi Sandstone

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Abstract. A hard layer of calcite cemented sandstones overlaid weakly consolidated mudstones occur in the Middle Triassic, Ermaying Formation in the eastern margin of the Ordos Basin, China, were examined to reveal the diagenetic environment of Pi sandstone. The Pi sandstone refers to a type of terrigenous clastic rock assemblage composed mainly of sandstone, siltstone and mudstone with red and white color, which is characterized by exposing or being covered with sand or loess, vulnerable to weathering and erosion, distributed in the contiguous area of Shaanxi province, Inner Mongolia autonomous region and Shanxi province in China, and formed during Late Paleozoic–Mesozoic. The “Pi” comes from the folk name (pishuang) of arsenic in Chinese, the appellation of the “Pi sandstone” means that it is harmful to soil and water conservation. The Pi sandstone samples were collected from a sheet-like sandstones deposited in ephemeral river. Petrographic observation show that the samples studied carry a semi-arid climate signal, are cemented by micritic (microcrystalline calcite), sparry (coarse-crystalline) calcite as well as quartz overgrowths. The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of calcite in the studied are -6.2 to -3.8 ‰ PDB and from -10.2 to -8.9 ‰ PDB, respectively. The evidence from petrography and stable isotopes suggests that the cementation of the sandstone mainly occurred in the vadose - phreatic environment.

1. Introduction

The Pi sandstone refers to a type of terrigenous clastic rock assemblage composed mainly of sandstone, siltstone and mudstone with red and white color, which is characterized by exposing or being covered with sand or loess, vulnerable to weathering and erosion, distributed in the contiguous area of Shaanxi province, Inner Mongolia autonomous region and Shanxi province in China (figure 1), and formed during Late Paleozoic–Mesozoic [1]. The “Pi” comes from the folk name (pishuang) of arsenic in Chinese, the appellation of the “Pi sandstone” means that it is harmful to soil and water conservation. In recent years, Great progress has been made in soil erosion control in the Pi sandstone distribution area [2], however, the origin of the erosion vulnerability of the Pi sandstone has not been



fully understood. Although many researchers assume that the low strength of diagenesis is the main reason [3], there has never been a related study.

In this paper, we examine the petrography and geochemistry of the Pi sandstones of the Ermaying Formation (Middle Triassic) exposed in the northeastern margin of the Ordos Basin, China. The objectives of this study are to document the petrology and stable isotope geochemistry of the Pi sandstones, and to infer their diagenetic environment.

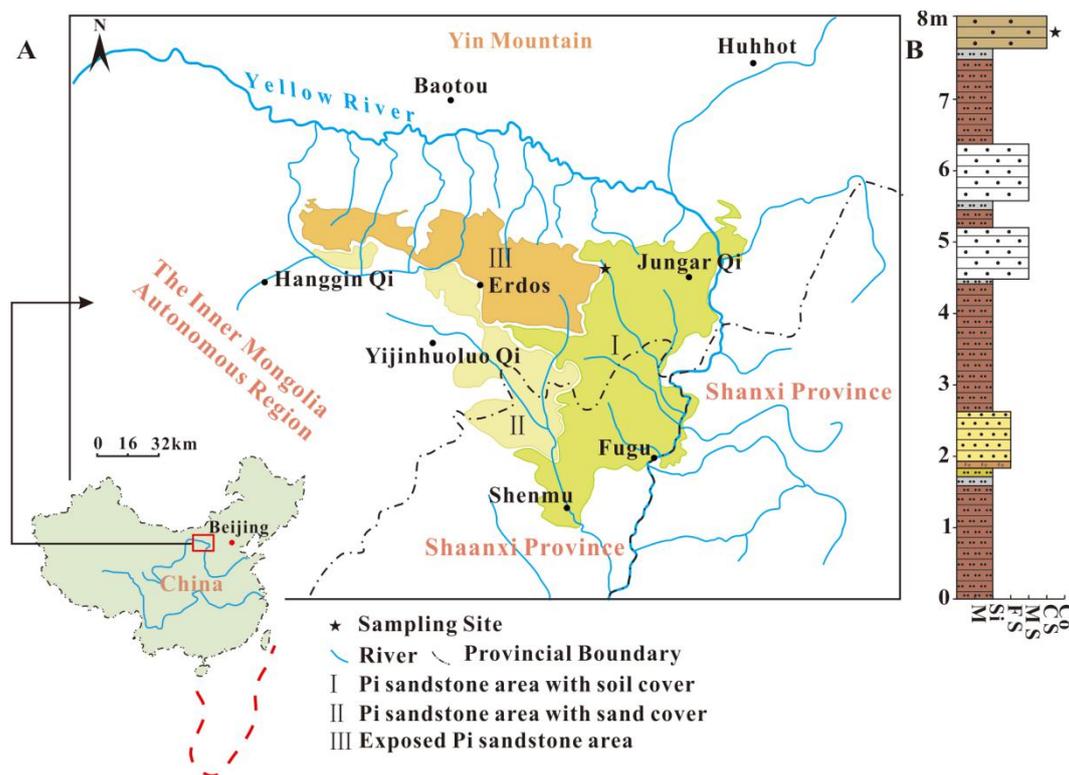


Figure 1. (A) Simplified distribution map of the Pi sandstone in China (modified after Wang et al. [1]) showing the location of the measured stratigraphic section and (B) Comprehensive lithologic section showing sampling location (black Pentagon) (Rock type: M-Mudstone, Si-Siltstone, Fs-Fine sandstone, Cs-Coarse sandstone, Co- Conglomerate).

2. Materials and Methods

The Pi sandstone samples were collected from the Middle Triassic Ermaying Formation in the eastern margin of the Ordos Basin, China, where is in so called “exposed Pi sandstone area” (figure 1A). The Ordos Basin is a typical superimposition basin developed during Mesoproterozoic to Cenozoic [4]. The Middle Triassic Ermaying Formation was deposited in the “Mesozoic depression stage” of the basin evolution. Sedimentary environments at this stage were characterized by fluvial, delta and lacustrine. The Ermaying Formation is mainly composed of dark purple or gray medium coarse grained sandstone and red mudstone, which were deposited in the meandering river [5].

The samples used for this study were collected from a “hard layer” which exposed to the top of the Profile-B (figure 1B). The Profile-B was deposited at the upper part of the Ermaying Formation. “Hard layer” take the appearance of tight, hard sandstone layers in outcrop, which consists of laterally extensive, amalgamated, erosive-based sheet-like sandstones deposited by a semi-channelized river. The thickness of the “hard layer” is between 1 and 5m. The lateral extending distance of individual “hard layer” is between 100 and 300 m. All “hard layer” covers weakly consolidated mudstones of floodplain.

A total of 30 sandstone samples were collected. Detailed petrographic examination was performed on 14 thin sections. The sandstone framework composition was determined from 30 thin sections by counting 300–400 points per thin section and cements were quantified by line-notation under 10 views per thin section. Carbon and oxygen isotope analyses of calcite were performed on 6 calcite-cemented sandstone samples using MAT253 isotopic ratio mass spectrometers at the Analytical Laboratory of CNNC Beijing Research Institute of Uranium Geology.

3. Results and discussions

3.1 Petrography

The Ermaying Formation sandstones are dominantly medium to coarse grained, with rounded to subrounded grains that are moderately to well sorted. The framework of the studied sandstone samples is dominated by quartz with minor feldspar and lithic fragments. Monocrystalline quartz is the dominant detrital constituent. Detrital feldspars include K-feldspar and plagioclase. Lithic fragments are mainly volcanic and low grade metamorphic in origin, with trace amounts of granitic fragments. Mica is also present.

According to the scheme proposed by Folk (1980) [6], most of the samples from the Ermaying sandstone are classified as subarkose, except for one sample that falls in quartz arenites field (figure 2).

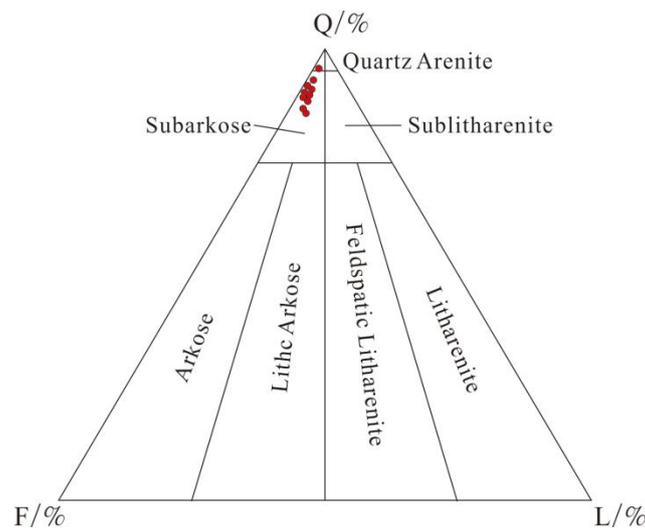


Figure 2. Triangular diagram of QFL from Folk [6] showing sandstone classification from the Ermaying sandstones.

Most of the Ermaying sandstones are plotted in the semi-arid field, suggesting that the palaeoclimatic conditions is likely predominant by the semi-arid during deposition of the Ermaying Fm (figure 3).

Cements in samples from the Ermaying sandstone, besides a small amount of quartz overgrowths, are mainly calcite (range 3.7 – 12%, av. 7.5 %) which can be divided into micrite (microcrystalline calcite) and sparry calcite (coarse-crystalline) according to the degree of crystallization.

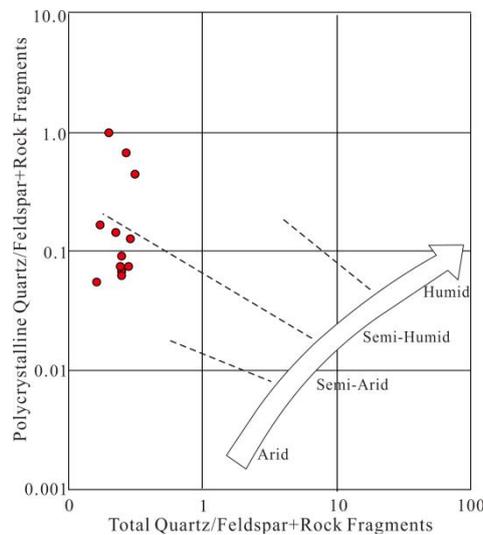


Figure 3. Log (Total Quartz / Feldspar + Rock Fragments vs log (Polycrystalline Quartz / Feldspar + Rock fragments) after Suttner and Dutta [7] showing the estimation of palaeoclimatic conditions during deposition of the Ermaying Fm.

Micrite cements include micrite coatings, pendant cements (microstalactitic) and micrite veins. Micrite coatings are composed of microcrystalline calcite. It looks a bit dirty because of the impurities. The surface of micrite coatings runs roughly parallel to the detrital grain surface on which they form. In the majority of cases micrite coatings cover only 1/3 to 1/2 of the surface of detrital grains. Micrite coatings can wrap single detrital grain or cover the surface of several grains (figure 4a-c). Microcracks in detrital grains are sometimes filled with micrite to form micrite veins (Figure 4f), indicating that the microcracks may be formed by strong physical weathering before they were filled. pendant cements are the special form of micrite coatings and also composed of microcrystalline calcite (figure 4e-f). The direction of the drooping end of pendant cements is often consistent in the same thin section.

Sparry calcite cement has blocky aggregates and poikilotopic pore-filling textural habits. Blocky aggregates tend to fill remaining pores after precipitation of micrite, and thus post-dates, micrite (figure 5a). In contrast to blocky aggregates, poikilotopic pore-fillings often replace partially to totally detrital quartz and other detrital grains (figure 5b). Micrite-spar microtexture is, as a very common textural habit, where grains or groups of grains are coated with micritic cements, and the areas in between are filled with sparry calcite (Figure 5c).

Quartz overgrowths are observed only in one thin section (figure 5d). Observation under polarizing microscope shows that precipitation of quartz overgrowths (Qa) is followed by, and hence pre-dates, sparry calcite (Sp).

3.2 Carbon and oxygen isotope

Isotopic values from the Ermaying sandstones showed $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values ranging from -6.2 to -3.8 ‰ PDB and from -10.2 to -8.9 ‰ PDB, respectively (Table 1) (figure 6). The isotopic temperature calculated for calcite from the Ermaying sandstone is about 20 °C (Table 1).

3.3 Environments of calcite formation

Petrographic observation and isotopic analysis indicate that calcite and quartz overgrowths are precipitated in the vadose - phreatic environment. Among them, micrite coating, pendant cements and micrite veins are formed in the vadose environment. Micrite coatings are formed by slowly percolating water becoming trapped on the bottom of detrital grains in the vadose zone. Subsequent desiccation by evaporation supersaturates the trapped water with CaCO_3 . CaCO_3 then precipitates in microlayers on the bottom of detrital grains [10]. Pendant cements are also formed in the process of meteoric water

infiltration. As a matter of fact, in the vadose zone immediately above the water table there is often an excess of water with CaCO_3 that accumulates at the base of detrital grains as droplets. Sparry calcite is most often associated with precipitation in the phreatic zone [11]. Micrite-spar cement textures could have initially formed in the vadose zone as micrite coatings. Upon burial or rising of the phreatic level these vadose cements would provide sites for further calcite precipitation and the unfilled pores could subsequently be filled with sparry calcite in the phreatic zone [12]. Compared with burial, fluctuation of the phreatic level is a short-term geological event which may have greater influence on calcite cementation. In general, fluctuation of the phreatic level depends on the climate conditions.

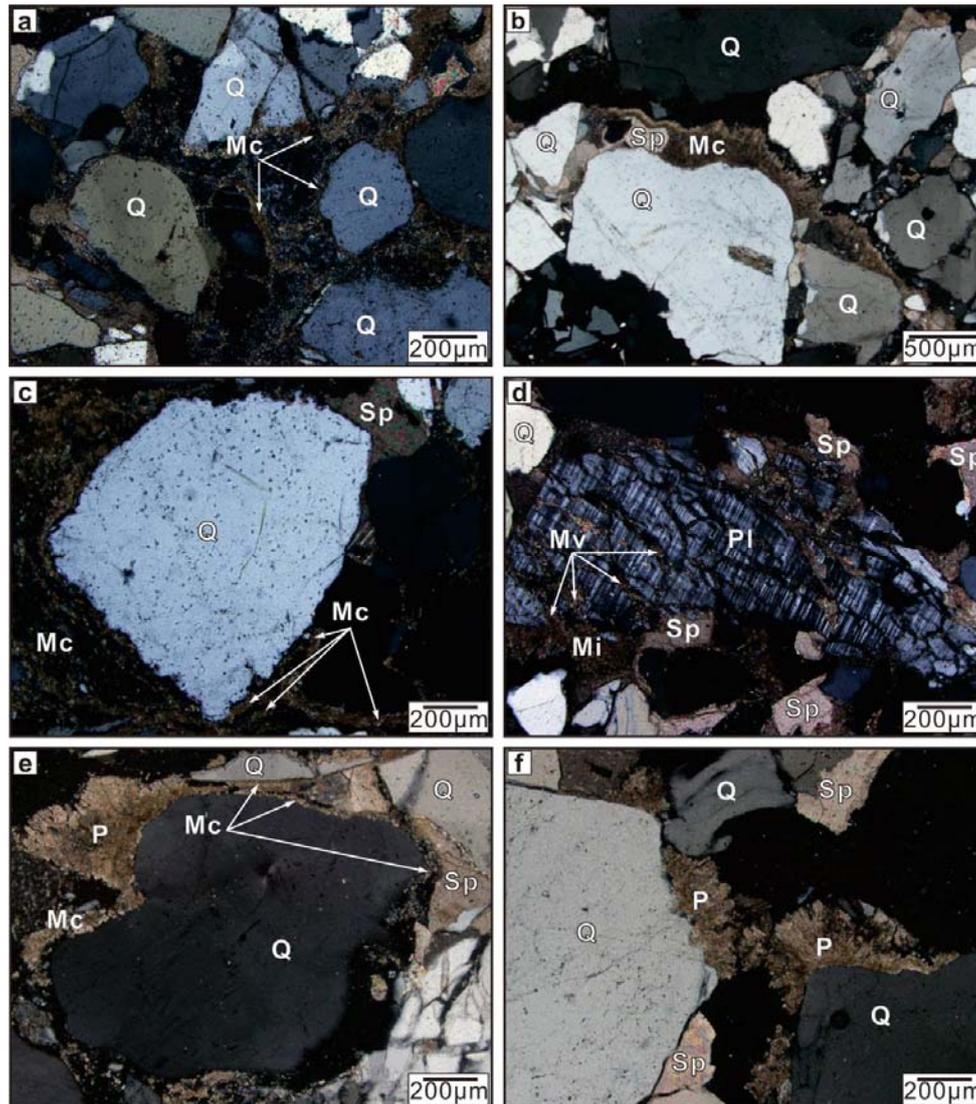


Figure 4. Representative photomicrographs (cross-polarized) of various micrite fabric in the Ermaying sandstone. (a) Micrite coatings (Mc) around single detrital quartz (Q). (b) Micrite coatings (Mc) along several detrital quartz (Q) grains and embedded sparry calcite (Sp) within micrite coatings. (c) Layered micrite coatings (Mc) and thin micrite coatings around single detrital quartz (Q), as well as sparry calcite (Sp) filled in pores. (d) Micrite veins (Mv) filled in microcracks of detrital plagioclase (Pl), which coexist with micrite matrix (Mc) and sparry calcite (Sp). (e) Pendant cements (P) and micrite coatings (Mc) accumulated around detrital quartz (Q) grain, and sparry calcite (Sp) filled residual pore space, thus post-dates pendant cement and micritic coatings. (f) Pendant cements (P) accumulated on the edge of detrital quartz (Q) and sparry calcite (Sp) filled residual pores.

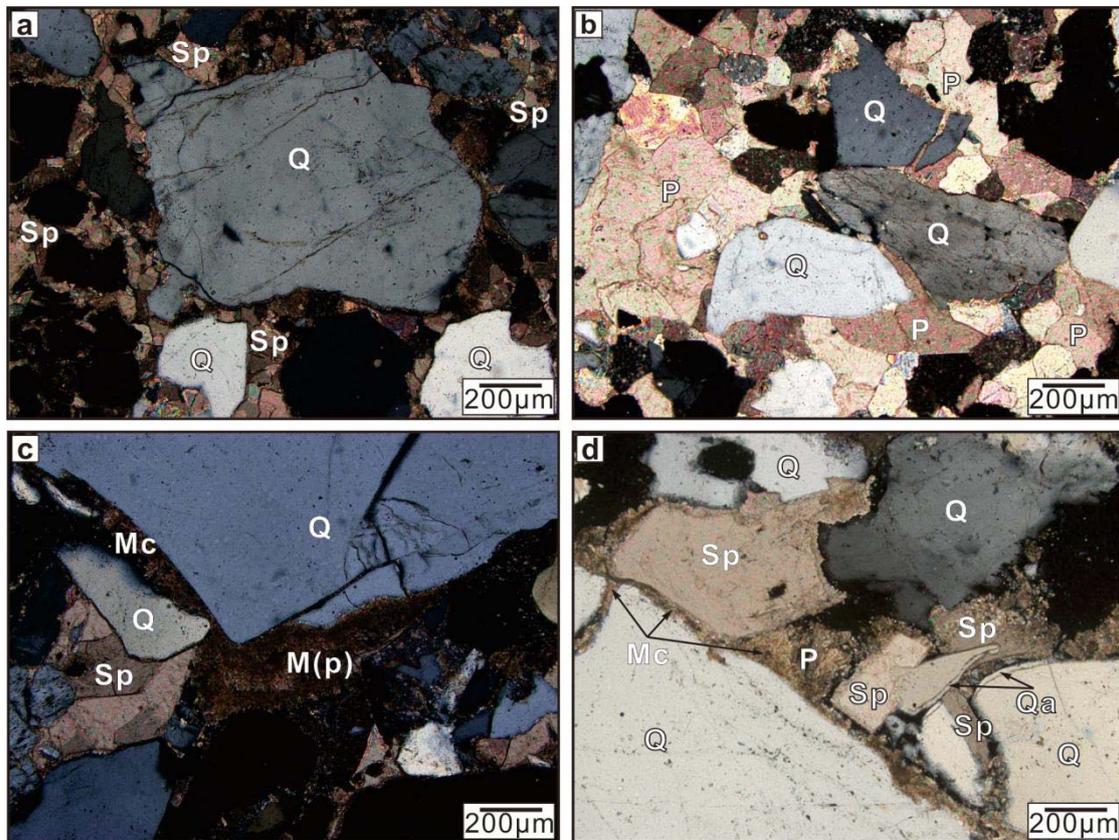


Figure 5. Representative photomicrographs (cross-polarized) of sparry calcite, micrite and quartz overgrowths. (a) sparry calcite (Sp) occurs as blocky pore-filling cements. (b) sparry calcite (Sp) occurs as poikilotopic cements that replaces partially to totally detrital quartz and other detrital grains. (c) Micrit-spar microtexture. Detrital quartz (Q) grains are coated with micrite (Mc), and the space between is filled with sparry calcite (Sp). Sparry calcite commonly engulfs, and thus post-dates, pendent cements. (d) Precipitation of quartz overgrowths (Qa) is followed by, and hence pre-dates, sparry calcite (Sp). Micrite coatings (Mc) and pendent cements (P) are engulfed by, and hence pre-dates, sparry calcite (Sp).

Table 1. Carbon and oxygen isotopic composition for calcite

Sample no.	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{SMOW}}$	$T_{\text{isotopic}} [^{\circ}\text{C}]$
P13-4	-6.2	-9.4	21.3	19.7
P13-5	-3.8	-9.4	21.2	19.7
P13-7	-6.2	-10.2	20.3	23.4
P13-10	-5.9	-8.9	21.8	17.5
P13-13	-4.1	-9.2	21.5	18.8

Notes: T_{isotopic} = isotopic temperature calculated according to the formula modified by Fontes et al [8]. The $\delta^{18}\text{O}_{\text{w}}$ value (-8.5) used in the calculation is derived from the analysis data published by Shi [9].

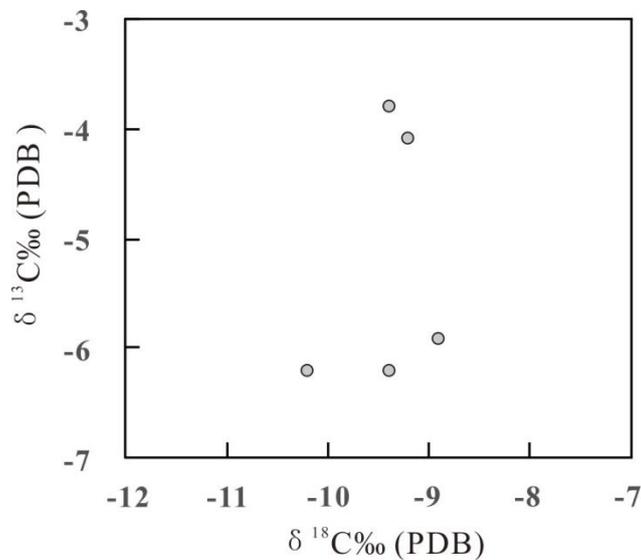


Figure 6. Plot of $\delta^{13}\text{C}$ vs. $\delta^{18}\text{O}$ values for calcite in the Ermaying sandstone

Field observation and reconstruction of paleoclimate (figure 3) show that the Ermaying sandstones are deposited in ephemeral river under a semi-arid climate. The shortage of water during dry seasons leads to declining of the phreatic level, and favors for the formation of the vadose cements, whereas the rising of the phreatic level may cause the previous vadose zone to be submerged in ground water, and then form the coexistence of the vadose and phreatic cements in the sandstone. Thus, it is reasonable to believe that calcite cementation in the Ermaying sandstone is related to local fluctuation of the phreatic level.

Calcite cements analyzed from the Ermaying sandstone display $\delta^{13}\text{C}$ values (-6.2‰ to -3.8‰) that fall in the range (-10‰ to -3‰) of authigenic carbonates forming in vadose and shallow phreatic zones [13]. Also, $\delta^{13}\text{C}$ values presented by Beckner et al. [12] for calcite forming in vadose and phreatic zones, are comparable to those from the Ermaying sandstone. Because of the absence of C4 plants prior to the Miocene, the $\delta^{13}\text{C}$ values of calcite cements reflect mixed sources of dissolved carbon derivation from the decay of C3 plants and from atmospheric CO_2 . The $\delta^{18}\text{O}$ of pedogenic carbonates is controlled by the oxygen isotopic composition of meteoric water, from which carbonates originate [14]. Increasing evaporation leads to higher $\delta^{18}\text{O}$ depletion in pedogenic carbonates. The $\delta^{18}\text{O}$ values (-10.2‰ to -8.9‰) of calcite cements have a narrow range of variation, this means that calcite cements are formed in similar climatic settings and temperature conditions.

In light of the petrography observation and stable isotope analysis the formation of quartz overgrowths is slightly earlier than sparry calcite, and the isotope temperature of calcite is about 20 °C, therefore, quartz overgrowths are most likely to be formed in the vadose environment.

Based on the above results, we consider that the host sandstone of calcite cements and its associated rocks have never experienced significant burial, This may be the main reason for the erosion vulnerability of the Pi sandstone.

4. Conclusions

Based on the sedimentology, petrography and geochemistry, the Ermaying sandstones were deposited in ephemeral river under a semi-arid climate. The cementation of the sandstone mainly occurred in the vadose - phreatic environment. The results show that the Ermaying Formation has never been buried significantly.

Acknowledgment(s)

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