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A Petrographic Analysis of the Relationship between Porosity and Organic Matter in the Permian Phosphoria Formation of Northeastern Utah

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Abstract

The Permian Phosphoria Formation is a reservoir for oil and gas in the western United States, as well as a major source of phosphate. This study examined the relationship between phosphate richness and porosity exhibited in the formation. Petrographic analysis was carried out on rock samples collected from the Phosphoria (Park City) Formation located north of Vernal, Utah, on the southern flank of the Uinta Mountains.

The analysis demonstrated an inverse relationship between organic richness and porosity in the Phosphoria Formation. Porosity is controlled by lithology, amount of cementation, weathering, and amount of fecal pellets, which are the source of phosphate within the unit. Fecal pellets in the Phosphoria Formation contain and concentrate phosphate. Porosity is highest in strata with low levels of organic matter, near the middle of the geological unit, with increased organic matter near the upper and lower contacts, yet the relationship between porosity and organic matter is not necessarily a linear one, as other factors likely control the amount of porosity observed in the unit. Contributing factors include acidic ground waters, diagentic history, and the amount of calcite cement.

A clear understanding of what controls porosity within the Phosphoria Formation has important implications for evaluating the unit as it is an important reservoir unit, as well as assessing phosphate richness for mineral extraction in the Western United States.

Introduction

As an important source for phosphate, a century of research has gone into the study of the Phosphoria Formation (Cheney, 1957 & Maughan, 1979). The formation is Permian in age and varies in thickness from 0 meters up to 67 meters (Maughan, 1979).

The Phosphoria Formation is exposed across Utah, Montana, Idaho, Nevada, Colorado, and Wyoming (McKelvey et. al, 1959), while the type locality for the formation is located near Georgetown, Idaho (Cheney, 1957). The Phosphoria Formation is the major contributing formation in the western phosphate field (Figure 2). The formation consists of marine limestone, siltstones, mudstones, chert, and shale, with certain beds rich in phosphate and fossils. The formation is divided into regional members based on slight differences in lithology. In the study area, on the Southern Flank of the Uinta Mountains the Phosphoria Formation is split into two members: the lower Meade Peak Phosphatic Shale Member and the upper Rex Chert Member (McKelvey et. Al, 1959). The Meade Peak Member is a sequence of mudstone and dolomite, with cherty intervals; the Rex Chert is a sequence of chert with limited beds of limestone.

Because of its high levels of porosity, the Phosphoria Formation historically has served as an important reservoir for water and hydrocarbons (Cheney, 1975; Inden, 1996). It is also an important source of phosphate (Inden, 1996). Phosphate is PO_4^{-3}, which originates from organic matter and is used as a fertilizer. Phosphate is an important part of plant cells and is a restricted resource in nature. The purpose of this study is to examine the petrography of the formation to better understand what controls porosity, particularly the relationship it has to organic matter and dissolution history within the unit's layers.

Research into the porosity and relationship with controlling factors is limited in the Phosphoria Formation. This research looks at expanding on the controlling conditions. The three research questions that are being examined to study this relationship are: 1) is there variability in porosity between the beds, 2) what is the

diagentic history of the porosity, and 3) what is the source of the phosphate deposits. These three question will expand on our knowledge of the Phosphoria Formation and increase availability of data to mineral exploration and petroleum companies.

Depositional Environment

The Phosphoria formation was deposited in the Phosphoria Sea during the mid-Permian (Ketner, 2009). According to Peterson (1984) and Inden (1996), the depositional environment of the Phosphoria Formation is identified as a broad carbonate ramp. Inden (1996), envisioned a depositional environment of shallow waters with limited terrestrial sediment influence and wave action similar to the environment found in present day Shark Bay, Australia. Shark Bay represents a marine bay, with a restricted connection to the open ocean. This type of depositional environment would have produced significant quantities of phosphate over time. However, geographically the Phosphoria Formation is widespread, covering much of the western United States; including Utah, Idaho, Colorado, Montana, Wyoming, and Nevada and was not limited to a specific restricted bay region like present day Shark Bay. Orogenic events likely resulted in the exceptionally large geographic extent of the formation. According to Maughan (1979), the unit formed in a “deep-water trough between the orogenic Antler foreland to the west and the North America Craton to the east”. The trough was wide enough and had a gentle enough slope that an extensive carbonate platform could form upon it. Phosphate deposition was enhanced by the upwelling of deeper cold ocean waters (McKelvey et al.,1959), which provided an abundance of nutrients for organisms living within the shallow waters. Phosphate accumulated over time as organisms died,

and contributed skeletal and fecal matter to the sedimentary record. After deposition, the phosphate could also have been concentrated through the movement of ground water and digenesis. This special regional geology helped to form an environment where massive amounts of phosphate could be deposited and today is an important economic source of phosphate.

Modeled as a carbonate ramp depositional system as according to Read (1985), the offshore slope would have been very gentle (usually less than one degree), with shallow wave agitation to transport sediment into deeper oceans. No break in the slope would be present, although Read (1985) classified two groups of carbonate ramps, homoclinal and distally steepened ramps, based on change in their slope. The depositional environment for the Phosphoria Formation would be considered a homoclinal ramp. Further characteristics of carbonate ramps (Ahr, 1973), include concentric facies belts that follow bathymetric contours, deposition of grainstones up dip and mudstones down dip, wedge shaped deposits that thicken towards the basin, and the absence of large reefs, although patch reefs could be present. Concentrations of phosphate rich carbonate matrix would be deposited in the lowest areas of the carbonate ramp. Research in the Phosphoria Formation demonstrates all these characteristics of a gentle widespread carbonate ramp (Ahr, 1973; Peterson, 1984; Read, 1985).

METHODS

Petrographic samples were collected from an outcrop on the southern flank of the Uinta Mountains, north of Vernal, Utah. The GPS location of the sampling site is 40° 34' 59.609" N 109° 35' 03.838" W, (see Figure 4). The unit lies near the top of the Phosphoria

Formation, and was subdivided into seven units based on surface lithology and porosity. The total section measured 2.68 meters in thickness. One hand sample was then taken from each bed, as well as specific samples from points of interest, as shown in Figure 6 and 7.

The hand samples were then made into thin sections (two per hand sample), measuring roughly 30 microns in thickness. The slides were studied under a Leica DM 750P light microscope and pictures were taken with a Leica ICC50 HD camera. The hand samples and slides were classified using Folk's and Dunham's classification schemes. The slides were then point counted to document the percentage of porosity in each bed. A total of 300 points were counted for each slide totaling 600 points per hand sample. Total organic carbon concentrations were determined using the aqueous method presented in Komada et. al. 2008. The total organic carbon research was conducted in the Utah State University biochemistry lab at the Unitah Basin. The point count data and total organic carbon concentrations are presented in Table 1.

Results

In the study area, the Phosphoria Formation is underlain by the Permian Weber Sandstone and is overlain by the Triassic Dinwoody Formation (Figure 3). In the study area the Meade Peak Phosphatic Shale Member is present, while the Rex Chert Member is absent. The studied section measures 2.68 meters (8.79 feet) in thickness. The research section is in the Upper Meade Peak Phosphatic Shale Member. Cheney (1957, pg. 28) described the Meade Peak Member as " mostly thin-bedded, light gray to grayish-brown, pelletal phosphate rock and subordinate amounts of mudstone." The observed lithology in

the study area (Figure 5) and in Cheney's paper is similar enough to draw the conclusion that they represent the same member, the Meade Peak Member.

The samples have micrite matrix as the cement and fecal pellets and other small organic grains as the grains (Figure 8). Some fragmentary fossils were intermixed with the grains, most were completely unrecognizable. Quartz, calcite and dolomite crystals were also present in low abundance resulting in the classification of a pelmicrite, using Folk's Classification. Using Dunham classification method the samples were a wackestone, because of the samples having more than 10% mud matrix. This classification compares closely with classifications done by Cheney (1957). He stated that most of the Meade Peak member near Vernal is mudstone.

All samples represented pelmicrite with varying degrees of pelletal material and porosity (Figure 8). Sampled beds differed by exposed surface weathering. The beds were divided based on the exposed surface characteristics, such as vugs, nature of bedding, and the presence of nodules, shown in Figure 6. The two main characteristics were surface porosity and surface lithology.

Point counting reveled that there was a large difference in porosity between beds (Table 1). Porosity varied from 1- 27 %. Comparing the two slides from each bed, the amount of pore space remained constant within the sample.

McKelvey et. al. (1959) mentioned that the Phosphoria Formation had abundant pore spaces or vugs. Vugs were present in both hand samples and thin sections. The formation of the vugs was through diagentic processes (McKelvey et. al.). The vugs were

determined to range in size depending on the bed in which they were found. See Figure 8A and 8B. The sizes ranged from over 200 µm down to less than 10 µm (Figure 8).

Two additional thin sections were made from bed 3. The sample was collected to examine the porosity of a nodule. It was hypothesized that the nodules were an area of increased phosphate and decreased porosity. The percentage of the porosity in the nodule was half of a percent less than that of the surrounding bed (Extra Samples, Table 1).

The Phosphoria Formation is known to have fecal pellets (McKelvey, et. al., 1959), but the organisms that produced the fecal pellets have not previously been identified (McKelvey et. al., 1959). During the point counting process it became apparent that the beds had an abundance of organic material, especially fecal pellets (Figure 9). Haven and Kraeuter (1970) examined modern fecal pellets produced by modern invertebrates in Virginia. Based on their descriptions, the fecal pellets from the Phosphoria Formation can be identified based on shape and size. The pellets appeared to be gastropod (Figure 9A & 9B). The conclusion was based on the overall shape and the ratio between the length and width of the specimen. The pellet has two areas in the interior which had been replaced by calcite. Originally a vug(s) formed inside the pellet. The vugs were later recrystallized with the present calcite crystals (Figure 9B). Also identified were crustacea fecal pellets based on shape and the segmentation of the pellets. Other pellets were broken up or had been completely re-crystallized by calcite or other minerals, (Figure 9D). Each of the conclusions is based on comparison between fossilized organisms present in the Phosphoria and modern day analogs.

The total organic carbon concentration for the studied samples varied from 0.063 to 3.156 percent of the total gases that were produced. The beds with the highest concentration of carbon were the upper and lower beds of the studied section; beds 1 and 7, see Figure 1.

Discussion

The point counting data strongly supports that there is a large degree of difference in porosity. The porosity varies across the sampled beds from 1 to 27 %.

Although each of the beds are a pelmicrite, research revealed that the amount of cementation has a direct effect on the modern porosity. Bed 4 is the least cemented of the seven beds, which resulted in the highest percentage of porosity at 27 %. Bed 6 was less cemented and had a percentage of porosity of 10 %. The beds which have the greater degree of cementation are the beds with the lowest porosity; for example bed 2 is very well cemented and the porosity is only 1 %.

The amount of dissolution both from weathering and in the subsurface increased porosity in the stratigraphic units. Surface weathering is an action of removing the rock, either through chemical or physical means. In this formation the exterior becomes weathered at a much higher rate than the interior. The weathering action on the exterior forms a rind on the exposed weathered rock, see Figure 7a. In this weathering rind, which is usually less than a quarter of a centimeter in thickness, the porosity is increased by as much as 5%. Internal weathering in the form of ground water moving through the beds causes new vugs to form. Crystallization and de-crystallization are the results of multiple dissolution events.

Observed fecal pellets are more abundant in stratigraphic units with the lowest porosity, indicating an inverse relationship between porosity and organic matter. The organic matter is not limited to fecal pellets, but can include calcareous fossils and miscellaneous organic matter (slime). Fecal pellets do not halt the formation of vugs but can restrict it. The vugs can form in the pellets or between pellets. In areas with denser amounts of organic matter including, fecal pellets, there is less probability for the formation of vugs, and hence less porosity.

McKelvey et al. (1959) theorized that the initial source of the phosphate resulted from upwelling of phosphate-rich deep ocean waters, which once near the surface, facilitated growth of shallow marine organisms on the carbonate shelf. Phosphate would precipitate over time both from the water column, as well as fecal pellets produced by the abundant marine organisms (Porter and Robbins, 1981).

Most organisms found in the Phosphoria grew calcite exoskeletons, enriched in phosphate. Once these organisms died and settled to shallow ocean floor their remains became buried (Piper, 2002). The phosphate would then build up in the rocks, and later be dissolved by acidic ground water. Once dissolved, the PO_4^{-3} ions could migrate in the subsurface and precipitate in higher concentrations to form large deposits (Piper, 2002).

Other researchers such as Ketner (2009), have found evidence that supports that the phosphate deposits were not a product of an upwelling event. The main supporting evidence was that the largest phosphate deposits were geographically isolated from epicenters of the upwelling events (Ketner, 2009). Ketner, states that the shallow sea that the formation was deposited in would have limited the ability of the phosphate to be

transported from the upwelling sites to the areas of deposition. Another valid hypothesis is that fecal pellets are the source of the phosphate.

Porter and Robbins (1981) suggest that fecal pellets produced by organisms living in the shallow waters contributed the largest amount of phosphate deposited in depositional environments. The peritrophic membrane surrounding the fecal pellets would contain the phosphate until ruptured during lithification of the rock layer. The released phosphate would contribute to the rich phosphate deposits observed today in the unit.

During this study, numerous un-ruptured and ruptured fecal pellets were observed in thin section (Figure 9), suggesting that biological activities within the depositional system contributed to the observed abundance of phosphate. However these fecal pellets, and the organic matter they contain also controlled the total amount of porosity observed in the samples. Higher porosity stratigraphic units contained fewer fecal pellets in thin section. Total organic carbon content within these units were typically lower, with highest amounts of organic carbon found in units with the least amount of porosity. Although other factors including, cementation, amount of phosphate, total amount of clay, and diagenetic history could control the amount of observed porosity. Highest levels of organic carbon were observed in the lower and upper boundaries of the measured section, suggesting some migration of organic carbon from bounding carbonaceous shales (Table 1 and Figure 1).

Conclusion

This petrographic study gives new understanding regarding the nature, distribution, and the relationship of porosity and organic richness in the Phosphoria Formation. This petrographic study of the Phosphoria Formation documents the relationship between the distribution of porosity within the unit, and phosphate-rich fecal pellets observed in thin section. Results show a measurable difference in the percent of porosity between various beds within the section. Porosity was found to be inversely proportional to the amount of observed fecal matter found within the thin sections. Total organic concentrations show an inverse relationship with the amount of porosity seen in the beds. Lithology, cementation, total organic matter, and surface weathering also contributed to the amount of porosity observed within each bed. Evidence for deposition of phosphate from biological fecal matter from marine organisms living on a shallow ocean carbonate platform is also documented.

The information gathered from this research gives insights into the role of fecal pellets in the formation of phosphate deposits in modern and ancient environments, as well as the relationship to observed porosity.

Appendix I

Bed and Slide Number	Vugs Present (Out of 300 points)	Porosity Percentage (%)	Porosity Percentage Average	Total Organic Carbon Concentrations (%)
Bed 1, Slide A	6	2.0		
Bed 1, Slide B	10	3.33	2.67	3.156
Bed 2, Slide A	3	1.0		
Bed 2, Slide B	3	1.0	1.0	0.117
Bed 3, Slide A	0	0		
Bed 3, Slide B	11	3.67	1.83	0.264
Bed 4, Slide A	80	26.67		
Bed 4, Slide B	84	28.0	27.33	0.101
Bed 5, Slide A	13	4.33		
Bed 5, Slide B	3	1.0	2.67	0.063
Bed 6, Slide A	31	10.33		
Bed 6, Slide B	29	9.7	10.0	0.170
Bed 7, Slide A	3	1.0		
Bed 7, Slide B	3	1.0	1.0	1.895

Extra Samples (Bed 3 phosphate nodule)				
Sample A, Slide A	4	1.33		
Sample A, Slide B	4	1.33	1.33	
Notes:	**300 Point Counts were conducted for each slide**			

Table 1: Point count data and total organic carbon concentrations (%).

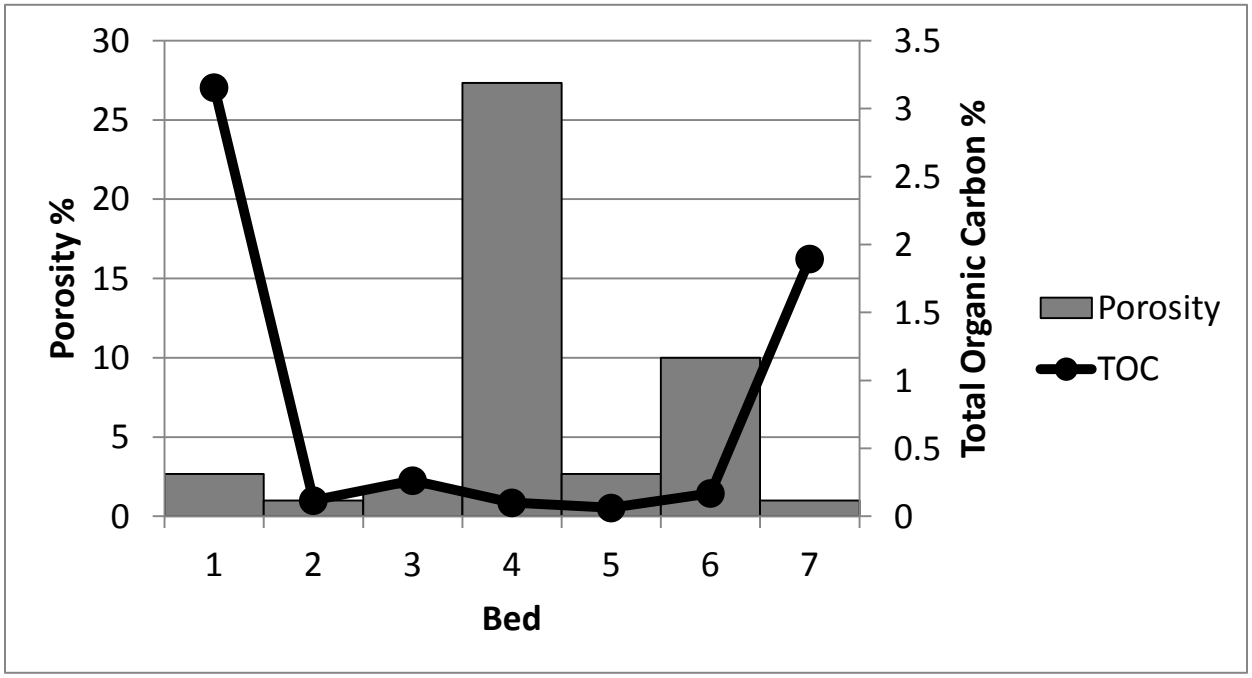


Figure 1: Correlation between porosity and total organic carbon in the sampled beds.

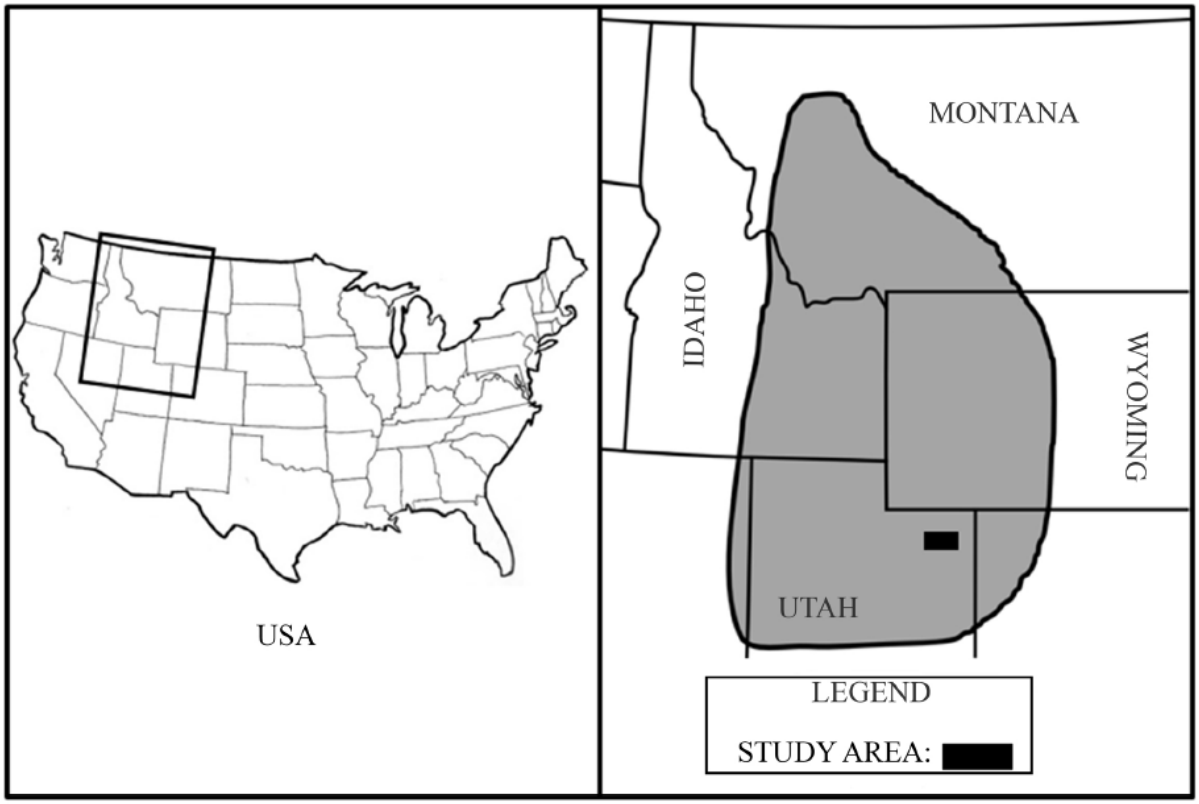


Figure 2: Shaded area shows the extent of the Western Phosphate Field (Phosphoria Formation) in the United States. (Modeled after McKelvey and others (1959).

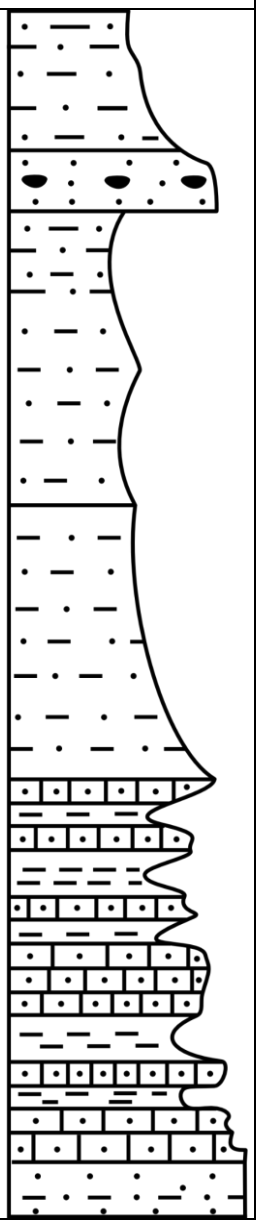
Age	Formation	Members (If Separated)	Thickness (meters)	Lithology
Triassic	Chinle Formation		70-140	
	Moenkopi Formation		160-340	
	Dinwoody Formation		0-60	
Permian	Phosphoria or Park City Formation	Meade Peak Member	20-75	
		Rex Chert Member		
	Weber SS		200-400	

Figure 3: Stratigraphic column of the research area located on the southern flank of the Uinta Mountains. (Modified from Sprinkel (2006)).

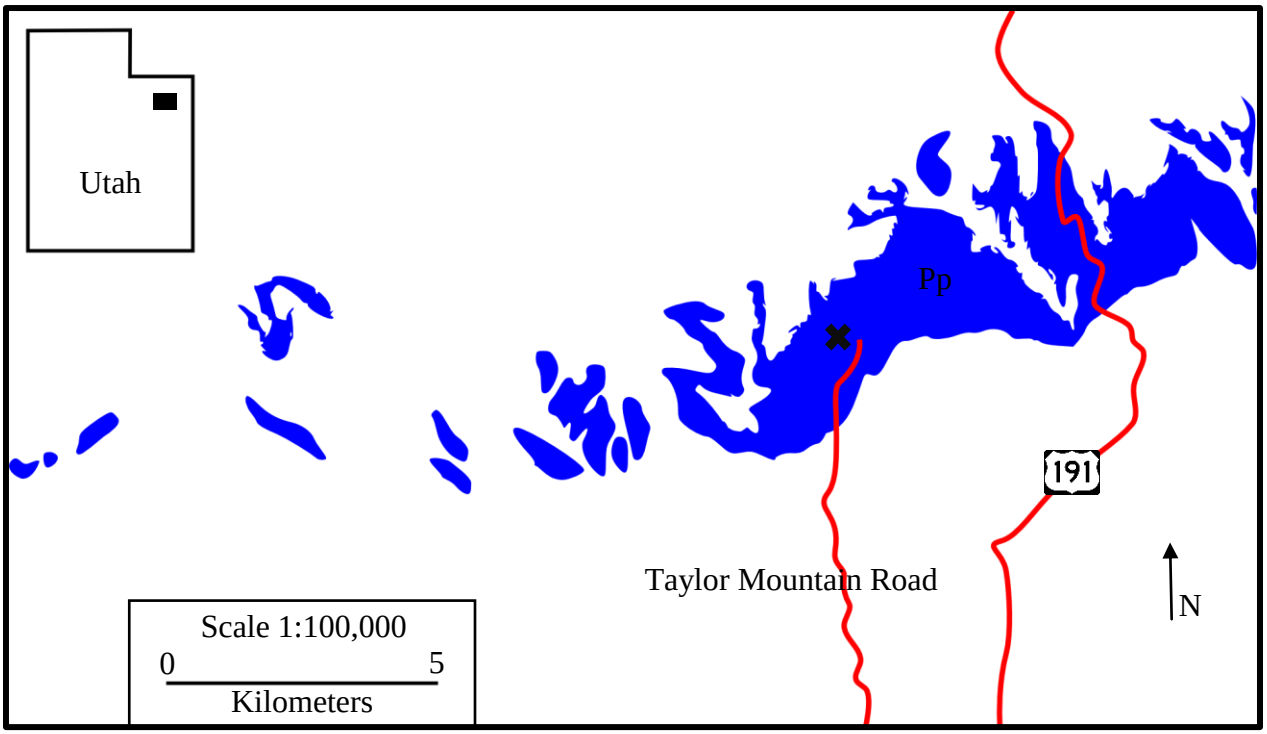


Figure 4: Map showing the studied area. The map shows the extent of the Phosphoria Formation (Pp) on the southern flank of the Uinta Mountains. (Modified from Sprinkel (2006).

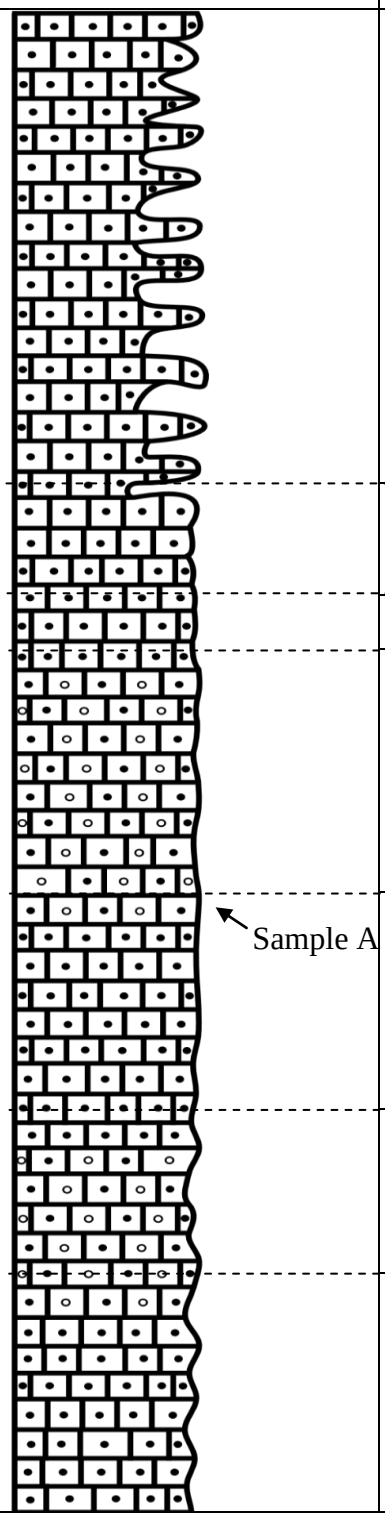
Age	Formation	Bed	Thickness	Lithology	Description
Permian	Phosphoria Formation	Bed 7	268 – 178		Platy Pelmicrite, fresh: pale orange (10YR 8/2), weathered: rusty/tan, fractured into plates
		Bed 6	178 – 160		Pelmicrite, fresh: pale orange (10YR 8/2), weathered: rusty/tan, bioturbation?, matted bedding
		5	160 – 155		Less porous Pelmicrite, blocky weathering
		Bed 4	155 – 109		Vuggy Pelmicrite, very pale orange (10YR 8/2), similar to unit 2
		Bed 3	109 – 69	Sample A	Pelmicrite, some large re-crystallized holes, holes secondary infilled with calcite
		Bed 2	69 – 49		Vuggy Pelmicrite, weathered and fresh: very pale orange (10YR 8/2)
		Bed 1	49 – 0		Massive quartzose , weathered and fresh: white (gr-VNT), blocky

Figure 5:
Stratigraphic column and field notes.

Legend		
Pelmicrite	Vuggy Pelmicrite	Scale
		1 in = 25 cm

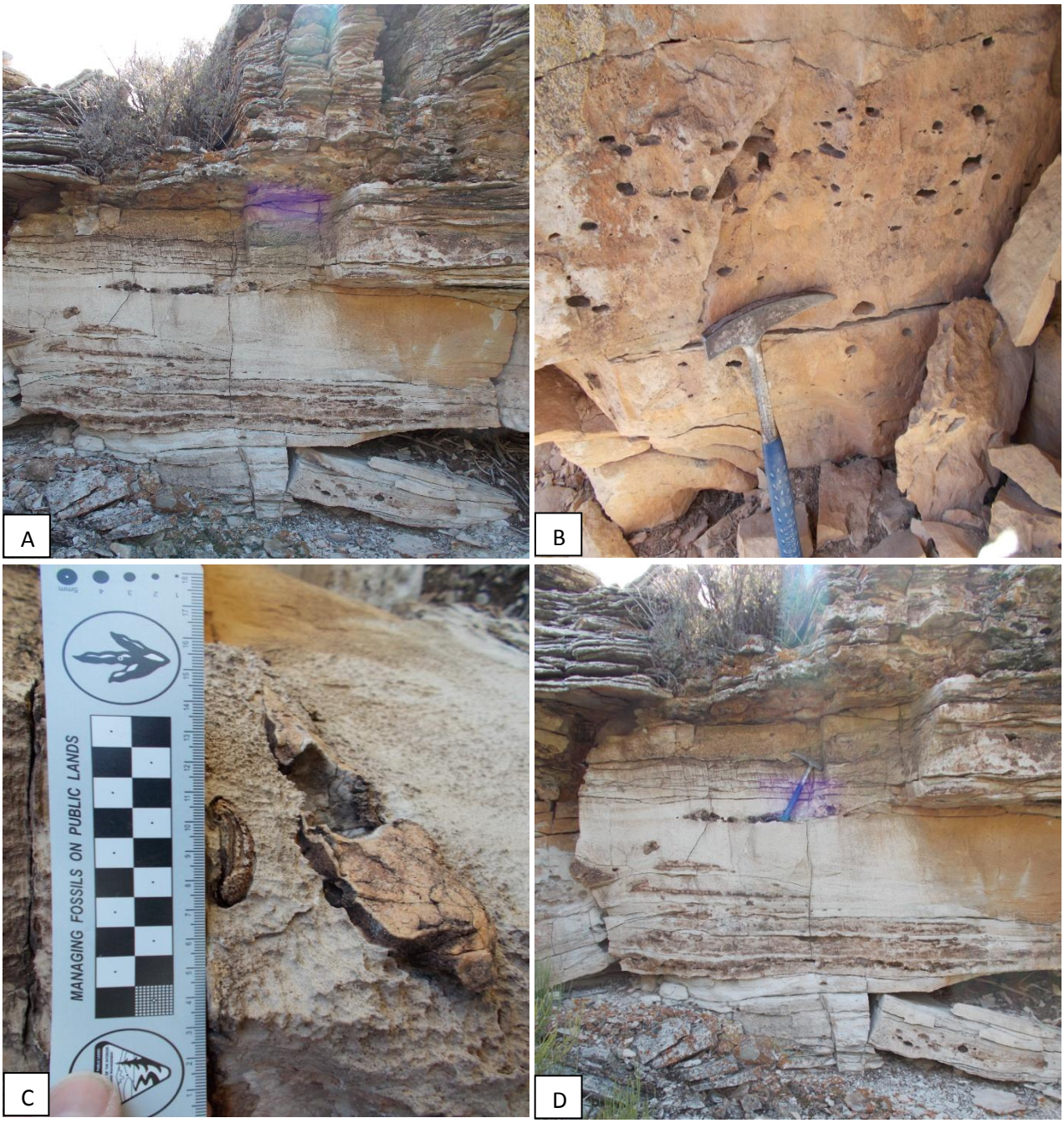


Figure 6: Pictures of research section. A) Full research section, bed 1 bottom and bed 7 at the top B) Vugs present in bed 2 C) Completely phosphatized brachiopod in bed 4 D) Closer picture of section shows the platy nature of bed 7.

Figure 7: Photos of cut hand samples. A) Bed 6, vugs and matted bedding. B) Bed 3, no internal structure or vugs. C) Bed 7, shows how porosity increases on the exterior where weathering occurs (weathering rind). D) Bed 4, loosely compacted and high number of large vugs.

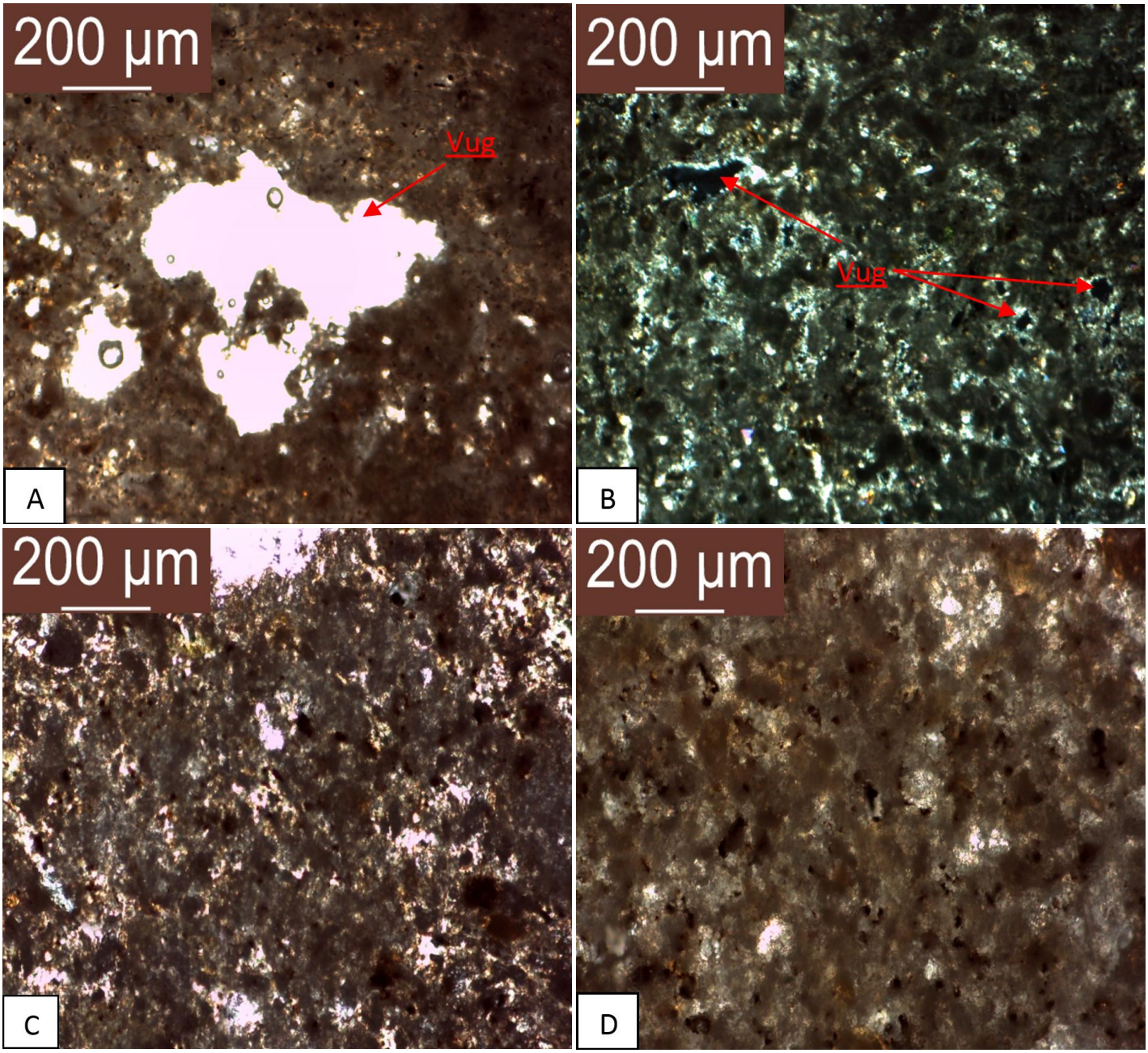


Figure 8: Pictures of thin sections. Beds consist of small grains and micrite matrix, vugs (size and number) and amounts of organic matter differ depending on the bed. A) Large vug in bed 6 in normal polarized light (NPL), B) Smaller vugs in bed 3 in crossed polar light (CP), C) bed 6 in NPL, D) bed 2 in NPL.

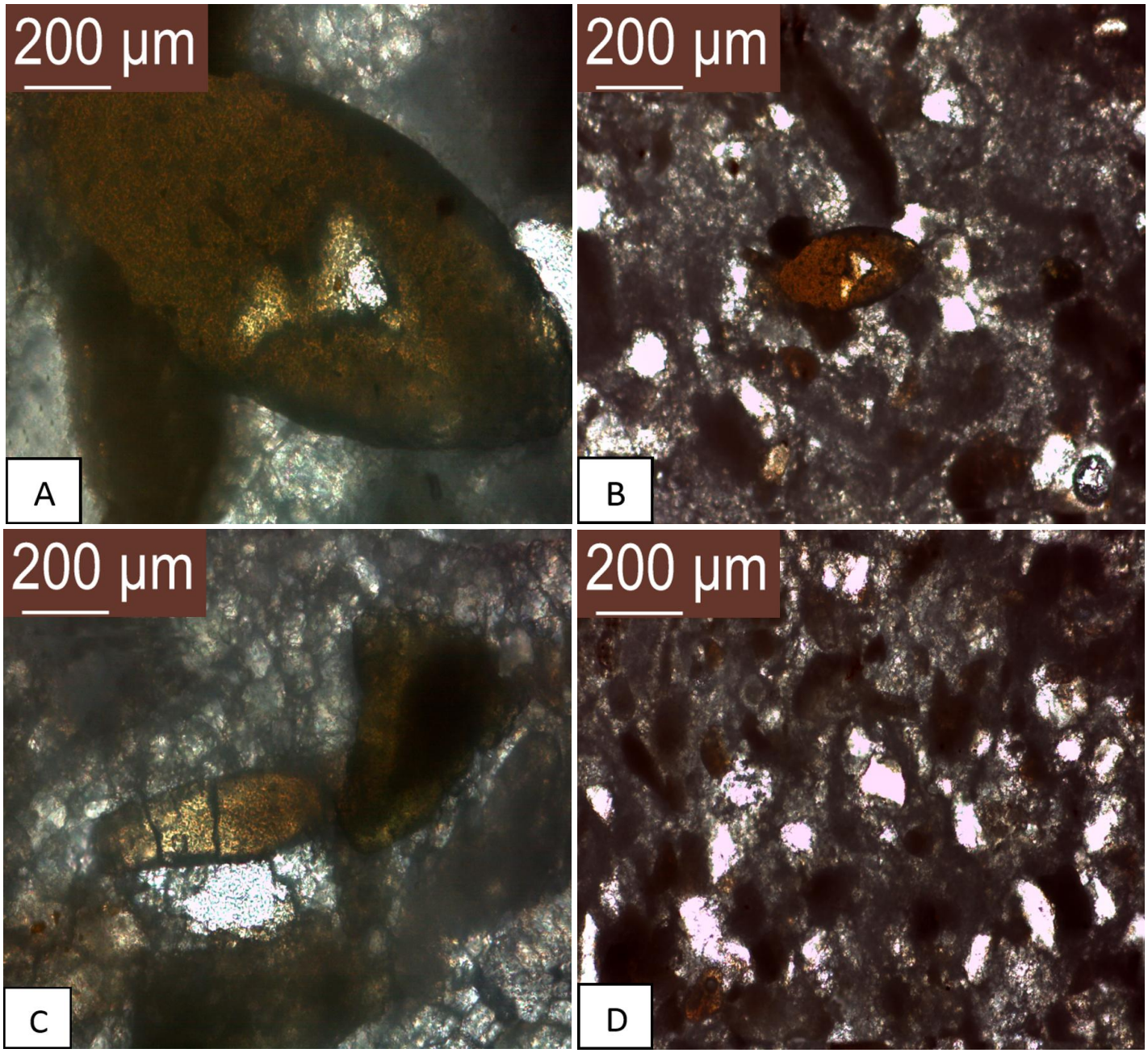


Figure 9: Photos of thin sections, normal polarized light A) Gastropod? fecal pellet B) Gastropod? fecal pellet C) Crustacean? fecal pellet, 10x D) slide with numerous fecal pellets and organic matter.

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