Preliminary Report on Sedimentology and Stratigraphy of the Late Devonian Mixed Carbonate-Evaporite Succession of the Duperow Formation, Southeastern Saskatchewan

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Abstract

The Duperow Formation of southeastern Saskatchewan is divided into four informal units (1 to 4). These units are defined by various lithofacies of laminated to thickly bedded bioclastic limestones, thinly to microbially laminated dolostone, laminated to nodular anhydrite, and rare halite deposits. Bioclasts in the limestone lithofacies include gastropods, bivalves, brachiopods, and stromatoporoids, and represent deposition within an open- to restricted-marine to lagoonal setting. The dolostone, anhydrite, and halite strata are interpreted as supratidal deposits. Limestone, dolostone, and anhydrite comprise the three prominent lithofacies and are preserved as "restricting-upward" rhythmites. The development of repetitive patterns of lithofacies is attributed to cycles of intermittent invasions of normal marine water which evolved to hypersaline brine by evaporative processes. The lateral continuity and regional significance of rhythmites of the Duperow Formation as exhibited by sedimentological, stratigraphic, and microfacies characteristics, and their impact on reservoir quality, are the focus of an on-going research project.

Keywords: *Duperow Formation, southeastern Saskatchewan, Late Devonian, carbonates, evaporites, rhythmic succession, shallow marine.*

1. Introduction

This study is focused on sedimentological and stratigraphic features of the Late Devonian Duperow Formation of southeastern Saskatchewan. The study area covers a rectangular area from the Saskatchewan-Manitoba border west to the 3rd Meridian, and from the U.S.-Canada border north to Township 20 (Figure 1). The Duperow Formation is a Late Devonian (Frasnian) carbonate-dominated stratigraphic unit which subcrops in southern Saskatchewan and was deposited on an epicratonic platform within the evolving Williston Basin. The Duperow Formation is the earliest stratigraphic unit of the Saskatchewan Group and is laterally equivalent to the hydrocarbon-producing Leduc reefs of the Alberta Basin (Stoakes, 1992a; Switzer *et al.*, 1994). Unlike the coeval Leduc reefs of Alberta and the Duperow Formation of North Dakota (Wilson, 1967; Dunn, 1975), Duperow strata in Saskatchewan do not have significant hydrocarbon production. This disparity is, in part, attributable to the less well understood stratigraphic, sedimentological, and diagenetic aspects of the formation in southern Saskatchewan.

Detailed microfacies analysis is required to decipher primary textural elements and secondary diagenetic alterations that have affected reservoir characteristics of the Duperow Formation of southern Saskatchewan. In adjacent North Dakota and Montana, sedimentological, stratigraphic, and diagenetic attributes, as well as structural controls on the reservoir intervals of the Duperow Formation, are relatively well documented (Pernichele, 1964; Rich and Pernichele, 1965; Wilson, 1967; Hoganson, 1978; Altschuld and Kerr, 1982; Flax, 1987; among others). Thus, a better understanding of the sedimentological attributes and reservoir qualities of the Duperow Formation in Saskatchewan is of considerable interest to petroleum exploration companies. The objective of this study is to provide a clear understanding of the lithostratigraphic characteristics, microfacies and reservoir quality analyses and depositional environments of the Duperow Formation in southeastern Saskatchewan. The results presented herein represent a very preliminary assessment of the stratigraphy and sedimentology of the Duperow Formation based on data collected from four cores in the study region.

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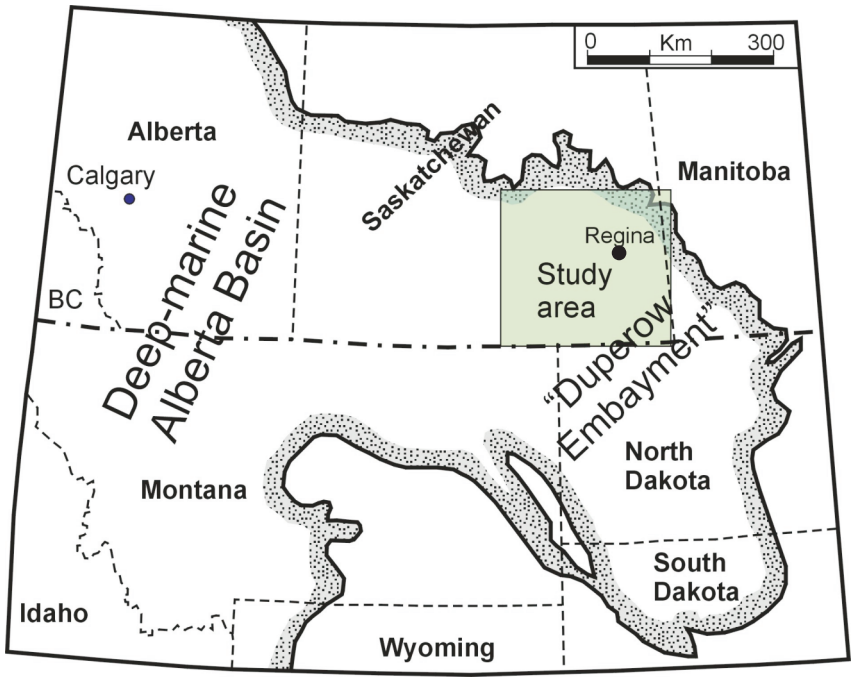

Figure 1 - Late Devonian extension of the "Duperow Embayment" and its connection to the Alberta Basin to the west. The square shows the project study area within which the rectangle outlines the area shown in Figure 5.

2. Geological Setting

The Duperow Formation was deposited in the southeastern peripheral part of the Western Canada Sedimentary Basin during Late Devonian time. The Devonian strata of this large basin are defined by broad, carbonate-dominated rhythmic megasequences, the result of large-scale sea-level fluctuations. These Devonian sequences include, in ascending order, the Upper Elk Point (Gedinnian-Givetian), the Beaverhill Lake (Givetian–Lower Frasnian), the Woodbend (Lower to Middle Frasnian), the Winterburn (Upper Frasnian–lowermost Famennian), and the Wabamun (Lower–Upper Famennian) (Wendte, 1992a, 1992b). These megasequences are relatively well developed in the Alberta Basin and become thinner eastward to Saskatchewan. The application of Devonian megasequence nomenclature is generally restricted to Alberta and northeastern B.C. The Duperow Formation is the basal unit of the Upper Devonian Saskatchewan Group. It is underlain conformably by the Souris River Formation of the Manitoba Group and overlain conformably by the Birdbear Formation of the Saskatchewan Group (Dunn, 1975; Kent, 1968, 1998; Figure 2). The Manitoba Group correlates with the Beaverhill megasequence of Alberta, the Duperow Formation with the Woodbend megasequence, and the Birdbear Formation with the Winterburn megasequence (Figure 3; Stoakes, 1992a). The Beaverhill, Woodbend, and Winterburn megasequences of the Alberta Basin are dominated by reefs, open-marine carbonates, and deep-marine shales (Campbell, 1992; Stoakes, 1992a, 1992b).

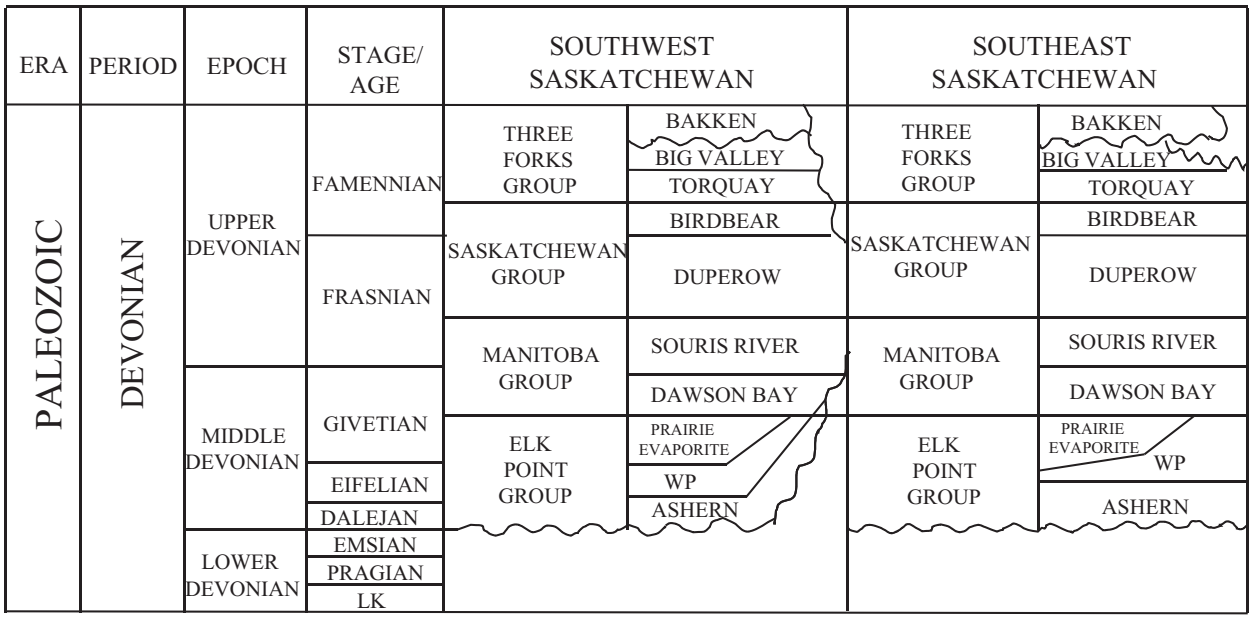

Figure 2 - Chart showing the Devonian stratigraphic succession of southwestern and southeastern Saskatchewan; LK, Lochkovian; WP, Winnipegosis (after Sask. Industry and Resources, 2003).

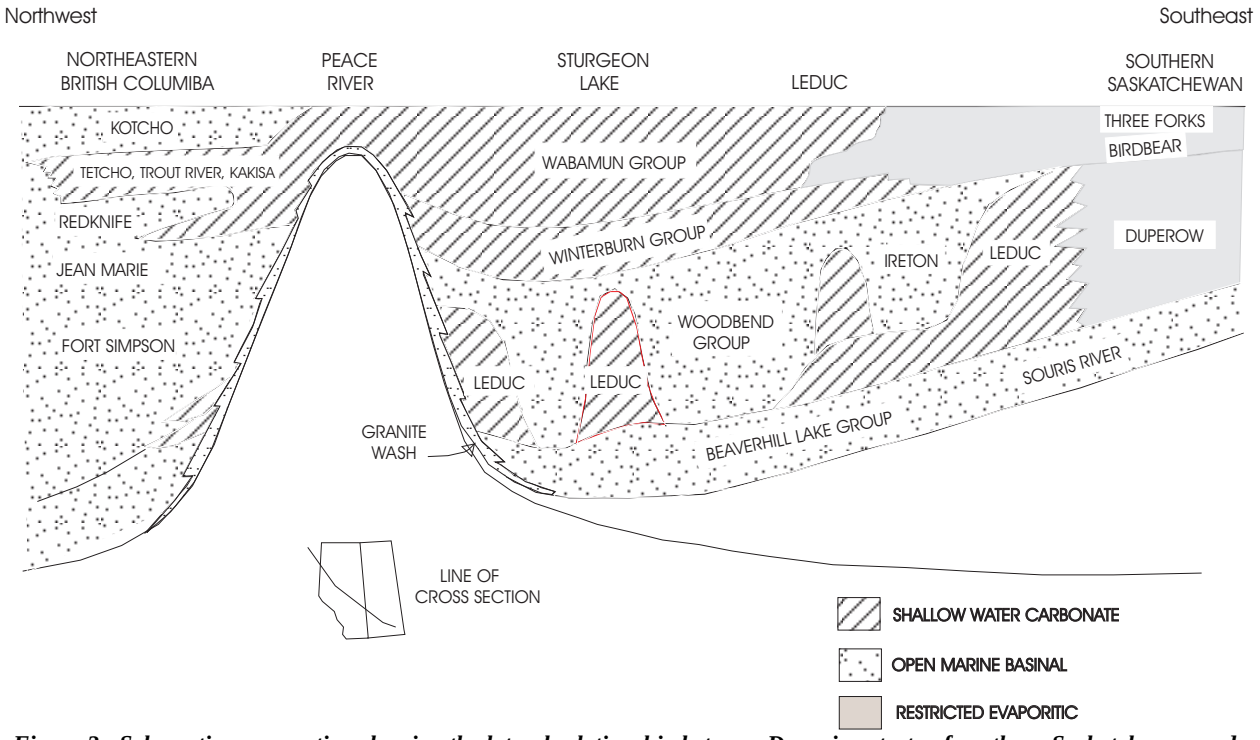

Figure 3 - Schematic cross section showing the lateral relationship between Devonian strata of southern Saskatchewan and of the Alberta Basin to the west (modified from Stoakes, 1992c).

Toward the east, typical depositional sites include reef-sheltered, shallow-marine to lagoonal settings where cyclic sedimentation of open- to restricted-marine carbonates and evaporites predominate. The Duperow Formation is characterized by rhythmically bedded, shallow-marine limestones, dolostones, and evaporates in a shoaling-upward rhythmic pattern (Wilson, 1967; Kent, 1968; Dunn, 1975; Wilson and Pilatzke, 1985). It was deposited in a shallow-marine inner platform setting here termed the "Duperow Embayment" (Figure 1).

3. Previous Work on the Duperow Formation

The Duperow Formation is well preserved in subsurface of southern Saskatchewan where its thickness ranges from 146 m (480 ft) to 229 m (750 ft) (Dunn, 1975). Previous work by Kent (1968) in southern Saskatchewan subdivided the Duperow Formation into four members that include, in ascending order, the Saskatchewan, Elstow, Wymark, and Seward members. These units were mainly recognized in the southwestern portion of Saskatchewan, and Dunn (1975) suggested these units can not be readily traced into the eastern side of the province. Dunn (1975) proposed four informal units (1 to 4) that do not strictly correlate with the members used by Kent (1968) (Figure 4). Recent work by Kent (1998) addressed diagenetic aspects of some stromatoporoid banks within the Duperow Formation of southern Saskatchewan. The Duperow is widely accepted to be of Frasnian age recently substantiated by conodont analyses by McCracken and Kreis (2003). Organic geochemical analyses by Fowler *et al.* (2002) and Stasiuk *et al.* (2002) have revealed that the Devonian strata of southern Saskatchewan contain significant mature source rocks. These organic analyses show that the Duperow strata are sandwiched between rocks containing good source rock intervals (*i.e.*, Souris River and Birdbear formations).

	Southwestern Saskatchewan (Kent, 1968)		Southeastern Saskatchewan (Dunn, 1975)	Southeastern Saskatchewan (this paper)
DUPEROW FM	Seward MB	Upper	Unit 4	Unit 4
		Lower		
	Wymark MB	Upper	Unit 3	Flat Lake Ev. / Unit 3
		Middle	Unit 2	Unit 2
		Lower	Unit 1	Unit 1
	Elstow MB			
	Saskatoon MB			

Figure 4 - Stratigraphic nomenclature applied to the Duperow Formation in southwestern and southeastern Saskatchewan. Note the disparities between the two nomenclatures. We are currently using nomenclature of Dunn (1975) for convenience, but the applicability of the formal units of Kent (1968) to the study area is under consideration; FM, Formation; MB, Member; Flat Lake Ev., Flat Lake Evaporite.

4. Sedimentological Attributes of the Duperow Formation

Although numerous wells penetrate the Duperow Formation in the study area, few wells have been cored and only one core contains the entire thickness of the formation. Four wells (16-11-6-25W2, 16-34-6-11W2, 6-33-7-8W2, and 3-26-4-20W2) with core of representative intervals of the four units of the formation have been used to compile a cross section (Figures 5 and 6). The informal lithostratigraphic classification of Dunn (1975) is used in this study with a slight modification to the definition of the lower boundary of unit 4 (Figure 4).

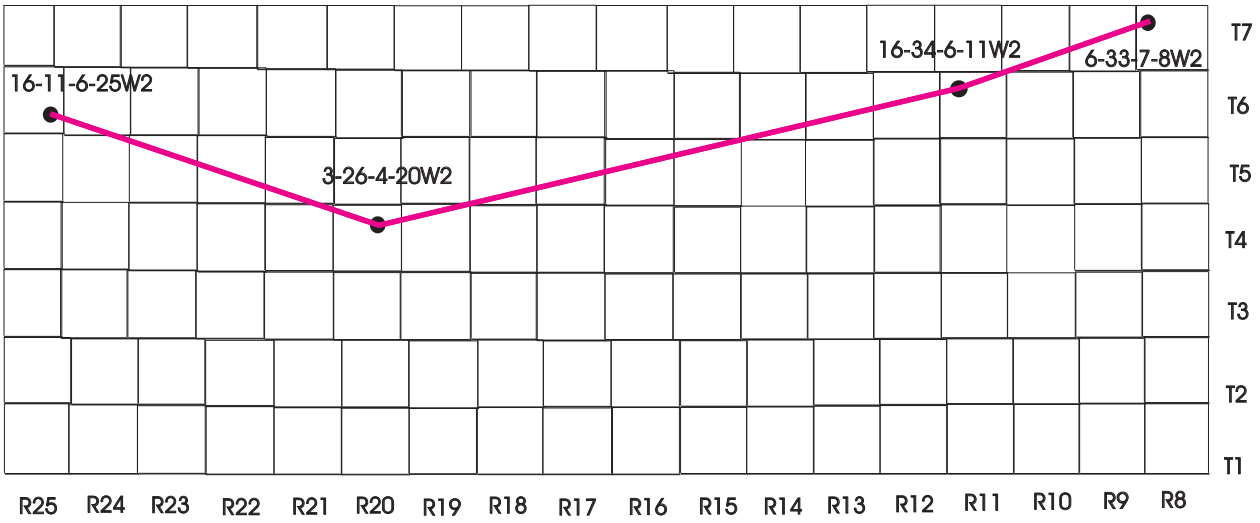

Figure 5 - Map showing locations of the studied wells and of the cross section shown in Figure 6.

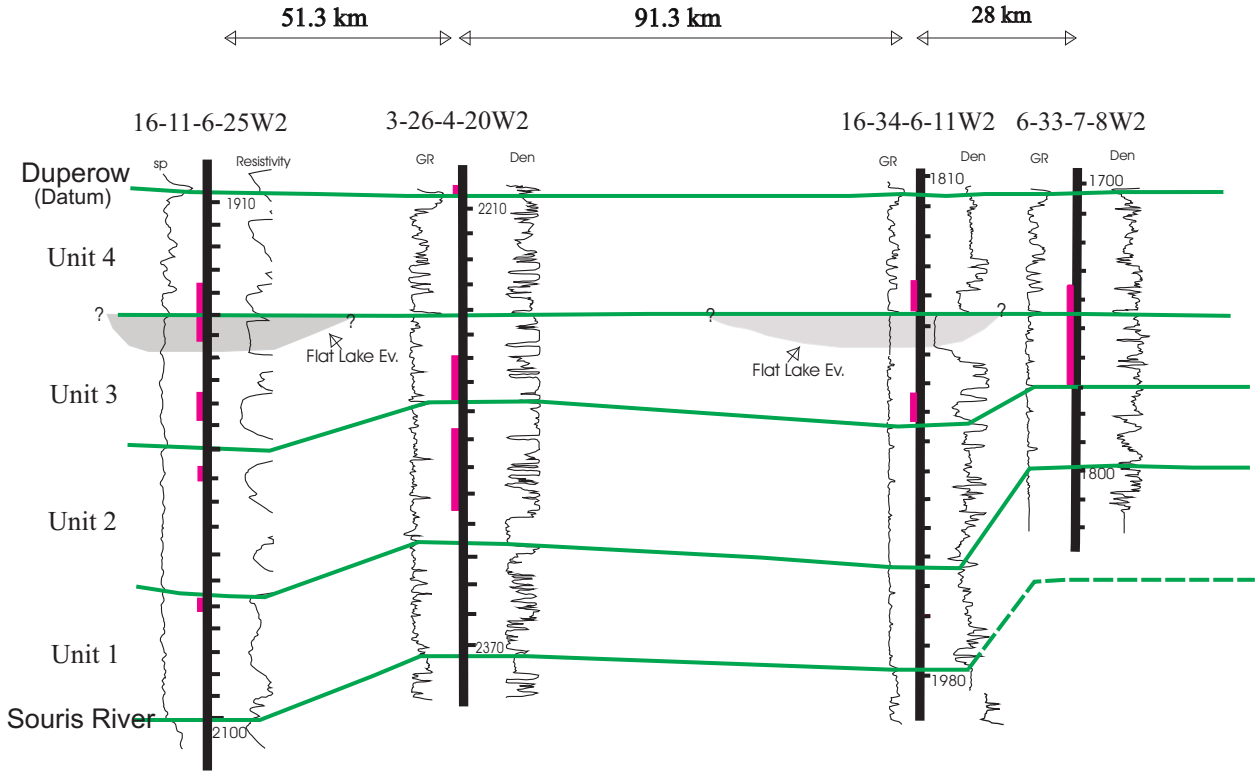

Figure 6 - Cross section showing west-east correlation of four cored sections of the Duperow Formation in southeastern Saskatchewan (see Figure 5 for section location). The Flat Lake Evaporite occurs as discontinuous lenses in the uppermost part of unit 3 within the study area.

a) Unit 1

General Characteristics

Unit 1 is the lowest stratigraphic unit of the Duperow Formation and has a conformable (gradational) contact with the underlying Souris River Formation. The thickness of unit 1 increases from about 27 m (87 ft) to 56 m (183 ft) northwestward. The unit is predominantly (>90%) carbonate with limestones being more common in the eastern part of the study area and dolostones more common westward (Dunn, 1975). Anhydrite and subordinate shale layers are also present in the unit.

Logged Core Section

Of the studied cores, only one relatively short 3.4 m thick (11 ft) section from well 16-11-6-25W2 contains this unit. The logged section (Figure 7) consists of various lithofacies of limestone, dolostone, and anhydrite. Subordinate shale layers are locally associated with dolostone lithofacies, forming argillaceous dolostone. The limestone lithofacies consists of dark brown bioclastic mudstone to floatstone. Sedimentary structures in this lithofacies include wavy to horizontal laminations and thin beds locally separated by dark argillaceous layers. Bioclasts in the limestone lithofacies include stromatoporoids and crinoids. The dolostone lithofacies is buff, thinly bedded and microcrystalline, although locally may be greyish green due to high clay content and argillaceous layers. Argillaceous dolostone is present throughout the formation (*e.g.*, unit 2 of Figure 8) and is characterized by high gamma counts that can be used as markers for correlation (Figure 6). The upper contact of the dolostone lithofacies is sharp to gradational with the anhydrite lithofacies prominent in the middle part of the core (Figure 7). The anhydrite is light blue, laminated, fine to medium crystalline, and has a sharp upper contact.

b) Unit 2

General Characteristics

Unit 2 occurs above unit 1 and below unit 3, and is conformable with both. According to Dunn (1975), the upper boundary of unit 2 is marked by a widespread marker bed of (argillaceous) dolomudstone, the presence of which is recognized beyond the Saskatchewan border (Wilson, 1967; Kent, 1968). Unit 2 ranges from 44 m (145 ft) to 79 m (258 ft) in thickness with an average of about 52 m (170 ft). Limestone is the most common lithofacies in this unit, and Kent (1998) has documented the presence of prominent stromatoporoid banks in a stratigraphic layer that correlates with the lower part of unit 2. Dolostone and anhydrite are also present and volumetrically increase westward. The limestone, dolostone, and anhydrite lithofacies represent restricting-upward cyclic sedimentation. The lateral continuity of these cycles is not well documented and is addressed in an ongoing M.Sc. thesis by the senior author.

Logged Core Sections

Cores from wells 16-11-6-25W2 and 3-26-4-20W2 cut through portions of unit 2 (Figures 5, 6, and 8). This unit is characterized by interbedded limestone, dolostone, and anhydrite lithofacies. The limestone lithofacies includes light to dark brown, bioclastic mudstone, wackestone, packstone, and grainstone that have planar to wavy laminations with common, organic-rich shale stringers that may display flaser bedding or nodular features (Figure 8A). Bioclasts include brachiopods, gastropods, bivalves, crinoids, and stromatoporoids (Figure 8). Bioturbation is locally intensive (Figure 8B); rare desiccation cracks are also observed. Diagenetic features in these limestones include stylolites and anhydrite nodules (Figure 8). The dolostone lithofacies is characterized by light to dark brown, thinly bedded to microbially laminated, microcrystalline dolomudstone. Anhydrite nodules of probable diagenetic origin are locally present. Clay seams associated with the dolomudstone lithofacies render a grey-green argillaceous sublithofacies characterized by a prominent gamma-ray “kick”. The dolostone lithofacies is usually overlain by anhydrite lithofacies and the contacts are either sharp or gradational as a mixture of dolomite and anhydrite nodules, or are a combination of the two due to contorted bedding. The contorted bedding may possibly be a result of anhydrite-crystal growth in the upper part of the dolomudstone in a hypersaline environment. The anhydrite lithofacies is characterized by light blue, medium-bedded, laminated to nodular anhydrite beds. The three lithofacies occur in a cyclical pattern where limestones are generally followed by dolostones, which are followed by anhydrite. This sequence is interpreted to record a “restricting-upward” shallow-marine to lagoonal depositional setting.

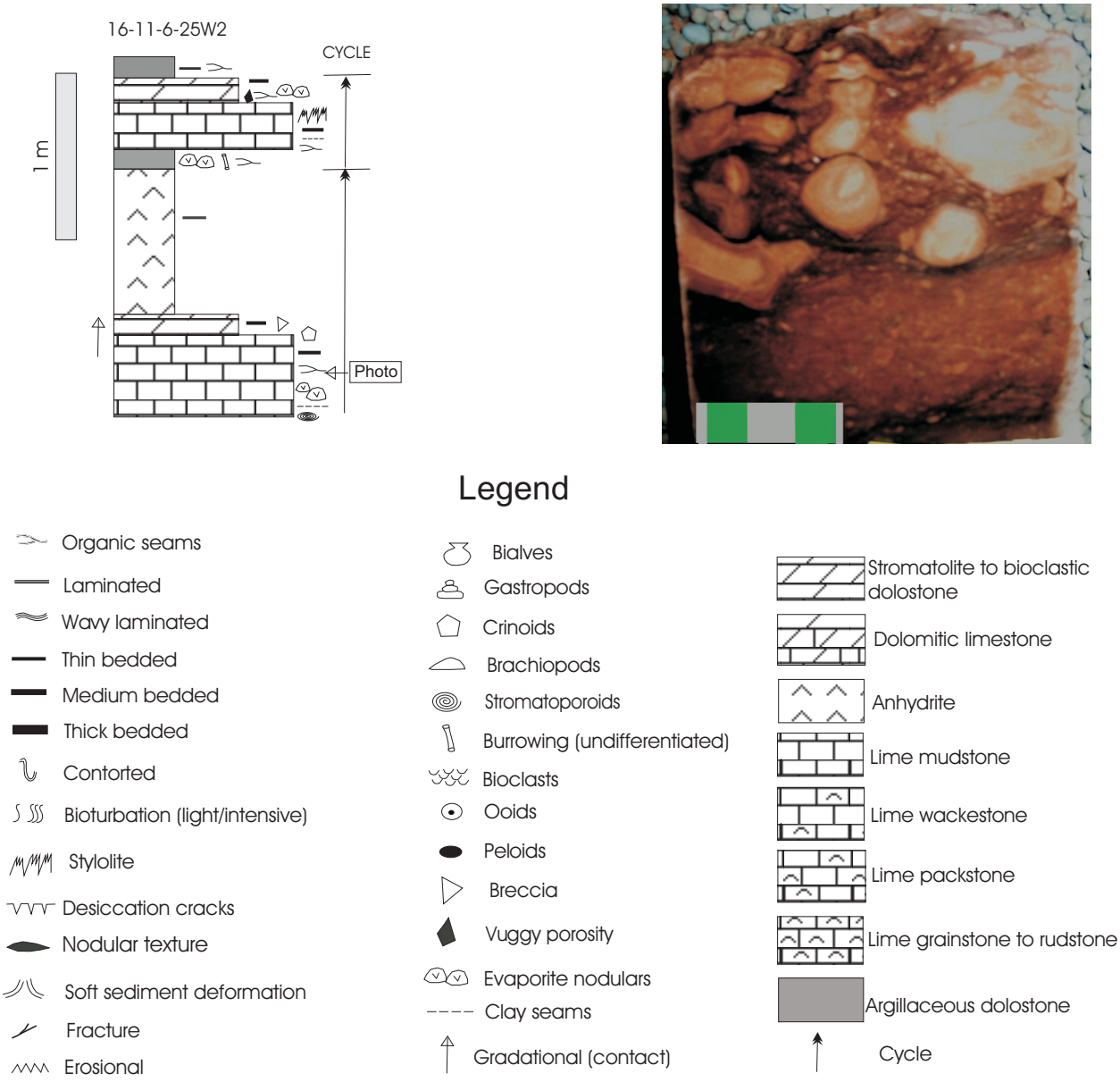

Figure 7 - Lithostratigraphic strip-log of a portion of unit 1 (interval: 2059.23 to 2062.58 m [6756 to 6767 ft], well 16-11-6-25W2, of the Duperow Formation). The photograph on the right side of the figure, taken from the lowest unit of the section, shows bioclastic lime mudstone followed by stromatoporoid-rich floatstone.

c) Unit 3

General Characteristics

Unit 3 conformably overlies unit 2 and its upper boundary is defined by a widespread argillaceous dolomudstone characterized on well logs by high gamma "kick". Based on subsurface mapping by Dunn (1975), the thickness of unit 3 ranges from 21 m (68 ft) to 61 m (201 ft), but most commonly is in the range of 31 m (100 ft) to 37 m (120 ft). Some of the variation in thickness of unit 3 is attributed to the presence of a discontinuous halite unit, the Flat Lake Evaporite (Figure 6). The prominent lithology in unit 3 is limestone, but dolostone and anhydrite beds are also present. The lithofacies of unit 3 also show rhythmic patterns that define restricting-upward successions. Discontinuous halite deposits up to 6 m thick are locally preserved in the uppermost part of unit 3. These halite "lenses" were named the Flat Lake Evaporite by Dunn (1975) and appear to represent a nearly complete drying out

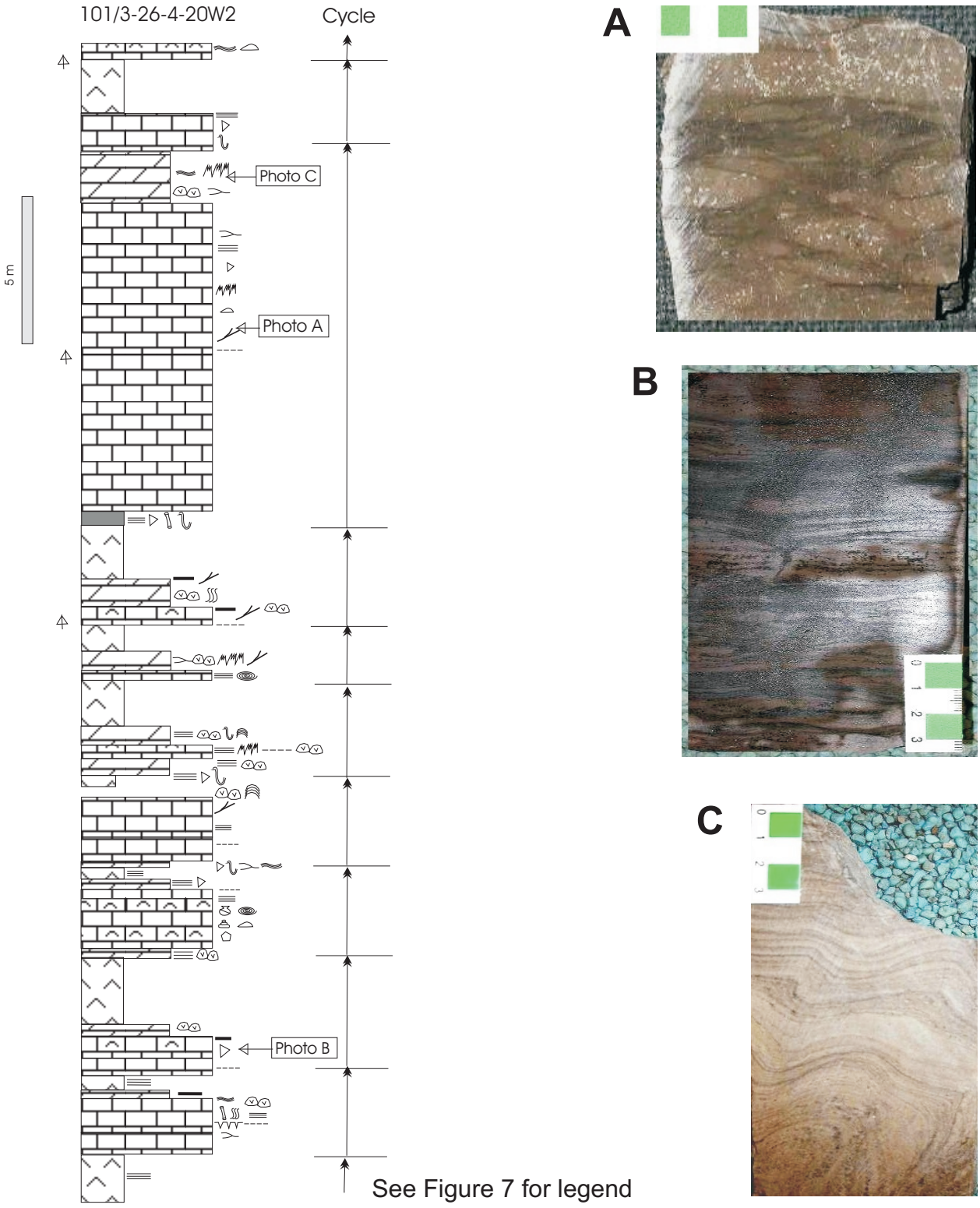

Figure 8 - Lithostratigraphic strip-log of unit 2 (interval: 2294.23 to 2324.71 m [7527 to 7627 ft]) from the well 101/3-26-4-20W2. Photograph A shows light brown, argillaceous lime mudstone lithofacies with abundant organic seams (dark wisps) (depth: 2301.09 m [7549.5 ft]); Photograph B shows wavy-laminated, argillaceous lime mudstone. Bioturbation and possible desiccation cracks are present (depth: 2322.73 m [7620.5 ft]); Photograph C shows buff, stromatolitic dolomudstone (depth: 2297.58 m [7538 ft]).

of the basin. Normal marine conditions were re-established during deposition of sediments that comprise unit 4, which overlies the halite deposits.

Logged Core Sections

Incomplete sections of this unit are present in the four cores studied; 16-11-6-25W2, 3-26-4-20W2, 16-34-6-11W2, and 121/6-33-7-8W2 (Figures 5 and 6). The lithology of the logged cores is dominated by limestone with subordinate dolostone and anhydrite. The two cored intervals in well 16-11-6-25W2 are not continuous. The upper interval is exclusively formed by the halite deposits of the Flat Lake Evaporite. Core 121/6-33-7-8W2 shows a near-complete succession of the unit (Figures 6 and 9), defining a roughly tripartite division of the unit with the lower and upper parts dominated by carbonates and the middle part by evaporites. The carbonates are almost exclusively bioclastic lime mudstone, wackestone, packstone, floatstone, and rudstone. The biocalsts include bivalves, gastropods, brachiopods, and crinoids. Other non-fossiliferous framework grains include peloids, intraclasts and rare ooids. Clay seams and burrows are also present and help impart a nodular appearance to the rock (Figure 9A). In well 16-34-6-11W2, the limestone lithofacies is partially dolomitized. The volumetrically subordinate dolostone lithofacies includes two sublithofacies: buff dolomudstone characterized by microbial laminations (Figure 9B), and thinly laminated, grey-green argillaceous dolomudstone. The anhydrite lithofacies dominates the middle part of the section (Figure 9); it is light blue and generally massive. Like the other units of the formation, the lithofacies of unit 3 are also arranged in rhythmic successions (Figure 9) that suggest “restricting-upward” depositional settings.

d) Unit 4

General Characteristics

Unit 4 forms the uppermost part of the Duperow Formation in apparently conformable contact with unit 3. The upper boundary of unit 4, which is also that of the formation, is conformable with the overlying Birdbear Formation. The average thickness of unit 4 is about 46 m (150 ft), but ranges between 31 m (103 ft) and 78 m (257 ft). The unit is lithologically dominated by limestone of various sublithofacies with dolostone and anhydrite becoming successively less abundant. Anhydrite is less common in this unit than in the other units of the formation (Dunn, 1975).

Logged Core Sections

Unit 4 is recognized in three of the logged four cores; 16-11-6-25W2, 16-34-6-11W2, and 6-33-7-8W2. These cores are dominated by a limestone lithofacies which includes medium- to thick-bedded, buff to light brown bioclastic rudstone and laminated to thinly bedded biocalstic mudstone to packstone (Figure 10). The rudstone sublithofacies shows intense vuggy porosity which is partially filled by anhydrite, halite or calcite (Figure 10A). Bioclasts include gastropods, bivalves, brachiopods, and indeterminate shell debris. This coarse-grained bioclastic limestone is characterized by a strong petroleum odour, and initial observations indicate that it has good reservoir quality. It may be an areally extensive reservoir subunit, and further mapping will address this matter. The mudstone to packstone sublithofacies is thin to medium bedded and contains intraclasts and bioclasts. As in unit 3, the dolostone lithofacies in unit 4 consists of two sublithofacies: buff, thinly to microbially laminated microcrystalline dolomudstone and grey-green, argillaceous dolomudstone. Fractures and rare vuggy porosity in the microcrystalline dolomudstone are filled by anhydrite or halite. Rare anhydrite beds are also present in unit 4. Cyclicity with unit 4 is similar to that recognized in the other three units, but the anhydrite component appears less developed in the logged sections of unit 4.

Depositional Environments

The rhythmic nature and the stacking pattern of the lithofacies that constitute the four units of the Duperow Formation represent cyclic sedimentation suggestive of restricting-upward settings. Basal units of the rhythmites are generally formed by open-marine carbonates characterized by biota of normal marine salinity, such as stromatoporoids, brachiopods, and crinoids (James and Bourque, 1992; Jones and Desrochers, 1992). These limestones are generally followed by burrowed to non-burrowed lime to dolomitic mudstone/wackestone suggesting semirestricted to restricted lagoonal environments (Shinn, 1983). Beds of this kind are most common in unit 2 of the Duperow Formation. Restricted, high-intertidal to supratidal-flat environments are suggested by stromatolitic, mostly dolomitized mudstone layers that are commonly associated with evaporites which form the uppermost parts of the rhythmites. Thus, the preliminary information from the logged cores suggests that the Duperow Formation was deposited within an intermittently flooded marginal-marine environment.

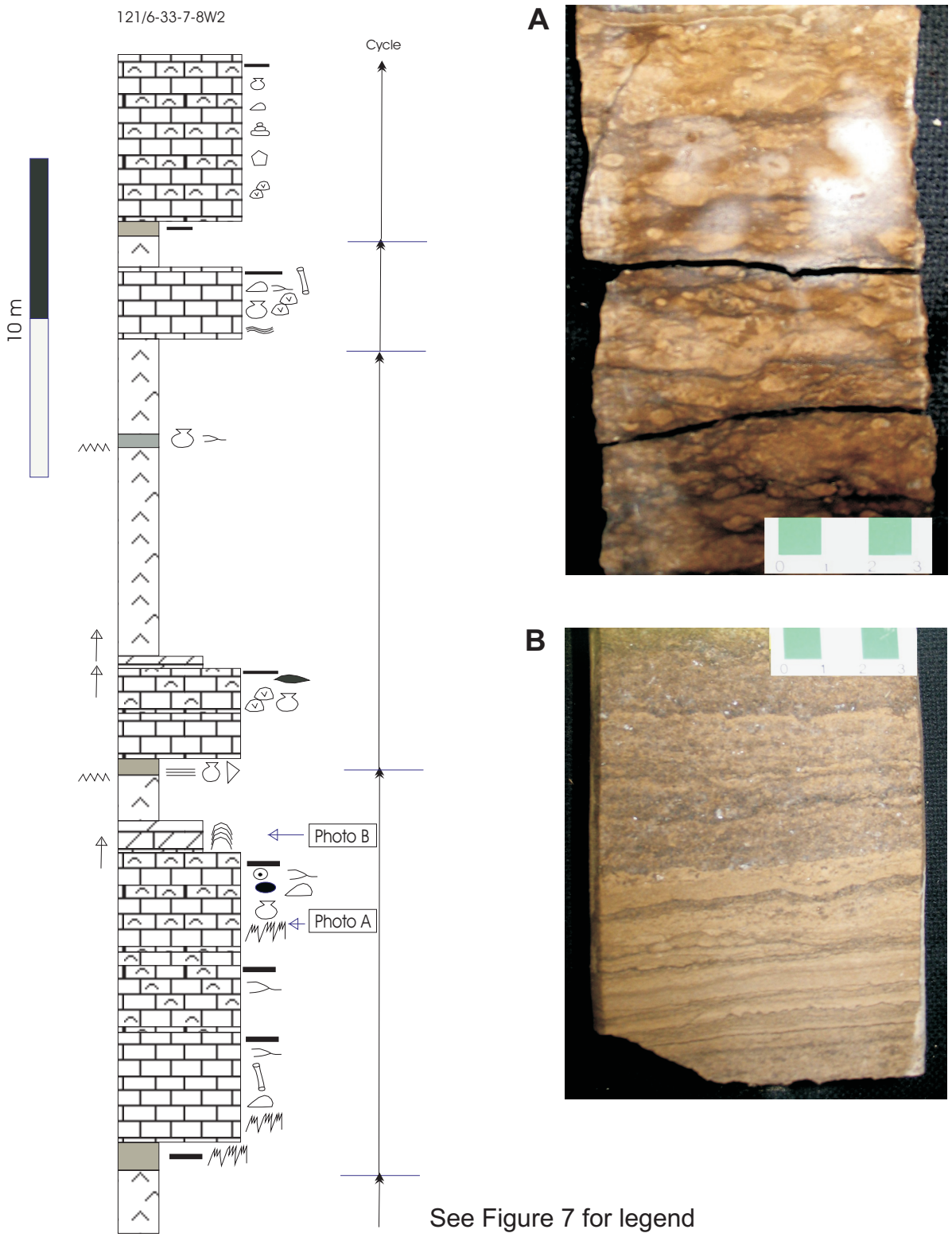

Figure 9 - Lithostratigraphic strip-log of part of unit 3 (interval: 1754 to 1772 m) from well 121/06-33-7-8W2. Photograph A shows dark brown, intraclastic, oolitic, peloidal wackestone to packstone sublithofacies. Shell fragments, organic seams (dark wisps), and burrows are also present (depth: 1764.7 m); Photograph B shows buff thinly (microbially?) laminated calcareous dolomudstone (depth: 1762.8 m).

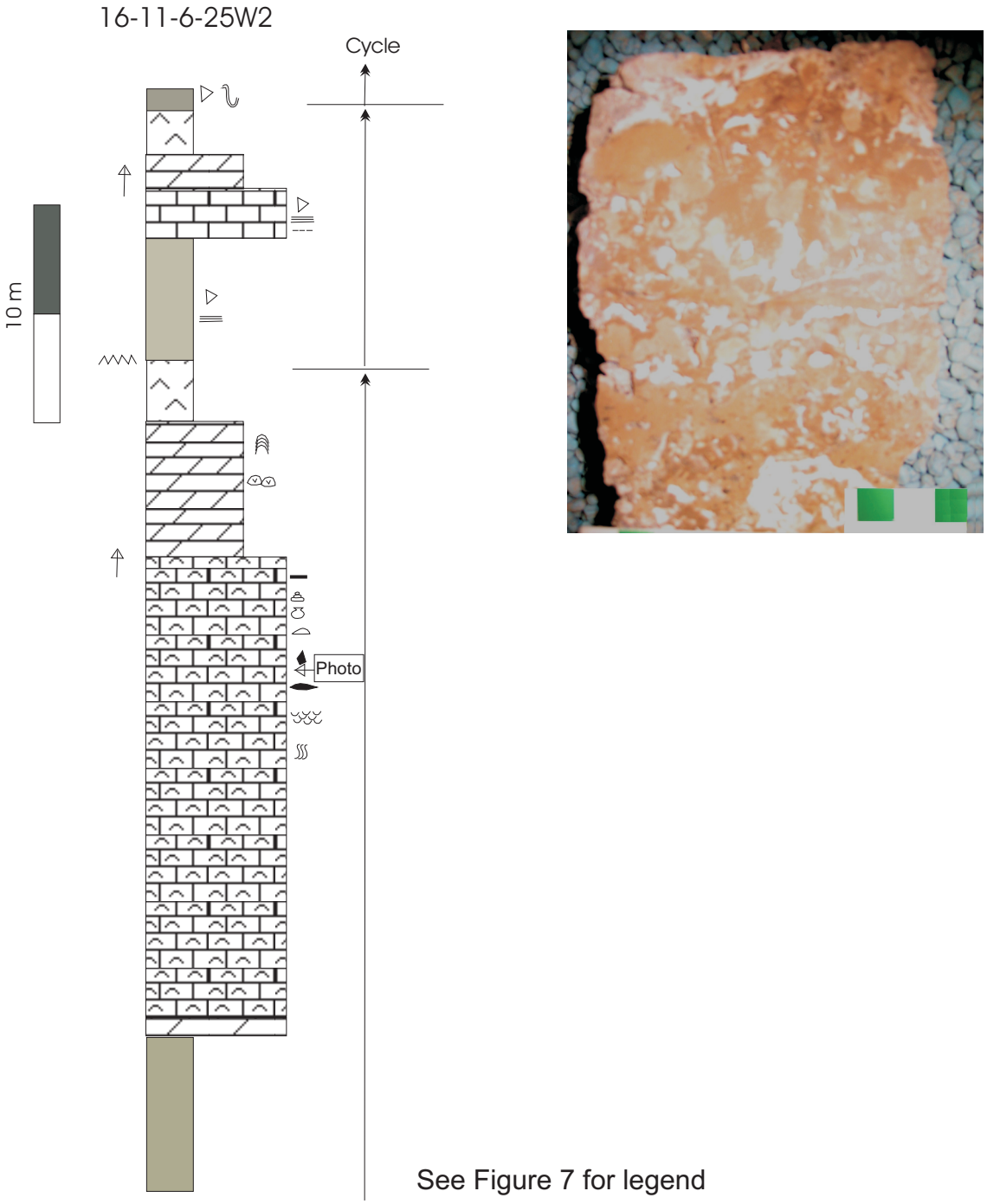

Figure 10 - Lithostratigraphic strip-log of part of unit 4 (interval: 1941.58 to 1953.16 m [6370 to 6408 ft]) from the 16-11-6-25W2 well. Photograph shows buff grainstone to rudstone sublithofacies; secondary vuggy porosity is filled by halite (white areas).

5. Conclusions

The Duperow Formation consists mainly of mixed carbonate and anhydrite lithofacies with subordinate halite and shales. The stratigraphic scheme adopted at this early stage of research is that proposed by Dunn (1975) which recognizes four informal units (units 1 to 4 in ascending order). Carbonates consist of limestone and dolostone that include fossiliferous and unfossiliferous subunits of mudstone, wackestone, floatstone, packstone, and rudstone. Most of the dolomitized facies are characterized by microcrystalline dolomudstone. Argillaceous dolostone is common and easily recognized on well logs by high-gamma counts and may be used as marker beds. The anhydrite lithofacies includes both laminated and nodular beds that are locally associated with clay seams. Halite is volumetrically subordinate, laterally discontinuous and confined in the uppermost part of unit 3. The various lithofacies units of the formation are stacked in restricting-upward successions, suggesting that normal salinity (marine flooding or, less likely, freshwater flux) was followed by increasingly saline conditions due to evaporation and restricted circulation that produced microbially laminated dolomudstone and, ultimately, evaporites that dominate the upper portions of the cycles. Future research will address lateral continuity of the cycles, and petrographic and geochemical characteristics to provide better understanding of reservoir potential in the area.

6. Acknowledgments

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