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SEDIMENTOLOGY, FACIES ARCHITECTURE, AND RESERVOIR

CHARACTERIZATION OF LACUSTRINE ROCKS, EOCENE

GREEN RIVER AND COLTON FORMATIONS,

UINTA BASIN, UTAH

by

Andrew W. Taylor

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Geology

Approved:

UTAH STATE UNIVERSITY
Logan, Utah

2002

ABSTRACT

Sedimentology, Facies Architecture, and Reservoir Characterization of Lacustrine Rocks,

Eocene Green River and Colton Formations, Uinta Basin, Utah

by

Andrew W. Taylor, Master of Science

Utah State University, 2002

Major Professor: Dr. Bradley D. Ritts
Department: Geology

Outcrop and petrographic studies of the Eocene Green River and Colton

formations in the Uinta basin, Utah, document the facies architecture and heterogeneity

characteristic of lacustrine reservoirs. A southwest-northeast transect of Eocene strata in

the Uinta basin records three main marginal lacustrine depositional environments: fluvial,

deltaic, and wave-dominated. Heterogeneity exists between and within individual

depositional systems.

Reservoir rocks of Outcrops One and Two (the fluvial facies of the Colton

Formation and the deltaic facies of the Green River Formation, respectively) consist of 2

to 18 m thick lenticular, tabular, or undulatory channel-fill, distributary channel, and

distributary mouth bar deposits that are partially to entirely compartmentalized, or

encased, by mudstone units. These reservoir analog intervals are dominated by large-

scale heterogeneity, in that sand bodies show a variety of connectivity and lateral

continuity. Small-scale heterogeneity exists within these sand bodies in the form of mud

chip lag surfaces, large mud clast horizons, and discontinuous finer-grained beds.
These features add complexity to the systems by reducing flow transmissibility or acting
as flow baffles. The complex heterogeneity characteristic of these reservoir analogs
confirms the need for detailed reservoir characterization studies on all scales in order to
improve exploration and production efficiency in such systems.

Outcrop Three (the wave-dominated facies of the Green River Formation) is
dominated by thinner (2 to 4 m) tabular and laterally extensive offshore bar deposits that
are compartmentalized by mudstone units. Large-scale heterogeneity is minimized in
these reservoir analogs, in that sand bodies exhibit excellent lateral continuity and less
complex amalgamation. Therefore, documentation of the smaller-scale heterogeneities
(similar to those mentioned in the previous two outcrops) is necessary to better address
exploration and production potential in these types of reservoirs.

Data collected in this study were utilized in geostatistical simulations and fluid
flow models in an attempt to document the effects of reservoir heterogeneity on
hydrocarbon exploration and production efficiency in lacustrine basins. Further studies
of this type are necessary if predictable classification systems and hierarchies of
bounding surfaces are to be derived for lacustrine reservoirs.

(152 pages)

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This thesis is in memory of my grandma, Margaret Gale, who passed away one week prior to my thesis defense. Grandma, you touched my life more than you will ever know. You were always so proud of my accomplishments, and one of my biggest fans. I will never forget the countless hours sitting on your couch talking about life. Our relationship and your knowledgeable advice have been so instrumental in whom I have become. Your memory and our friendship will forever live in my heart. I miss you!

Andrew W. Taylor

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INTRODUCTION

Lacustrine rocks are increasingly recognized as important components of petroleum systems worldwide (Ruble *et al.*, 2001). Such attention has led to new exploration potential and advances in oil recovery from lacustrine reservoirs. These new opportunities require a better understanding of the three-dimensional geometry, facies architecture, and internal heterogeneity of the lacustrine reservoirs that are produced. These intrinsic reservoir properties are a product of depositional systems, and have proven to be integral components for understanding fluid migration and compartmentalization in other deposystems due to their lateral and vertical predictability (Tyler and Finley, 1991). It is the purpose of this study to document the types of facies architecture and internal reservoir characteristics that exist in lacustrine basins, and what effects they have on fluid flow.

Few studies of this type in lacustrine rocks exist in the published literature. As a result, the potential heterogeneity of lacustrine reservoirs is not well-documented (Tyler and Finley, 1991). In the Uinta basin lacustrine reservoir studies have primarily included subsurface components, or one-dimensional vertical measured sections (Garner and Morris, 1996; Bruhn, 1999; Borer, 2001). These studies, although useful, do not explicitly address facies geometry and lateral heterogeneity in lacustrine deposits. In contrast, recent studies in other deposystems have utilized detailed two- and three-dimensional outcrop maps or well-constrained subsurface data to successfully construct models of depositional lithosomes, reservoir geometry, and reservoir heterogeneity (Miall and Tyler, 1991). Therefore, utilization of these techniques in lacustrine reservoir analogs is over-due, and can provide a first step for reservoir modeling in these systems.

The Green River and Colton formations in northeastern Utah record a nonmarine depositional setting that filled the Uinta basin in the Paleocene and Eocene. The southwest and northeast Uinta basin record two distinct styles of lacustrine shoreline depositional systems, fluvial-deltaic and wave-dominated, respectively (Fouch, 1975; Borer, 2001). These portions of the basin exhibit prolific petroleum production because of well-developed reservoirs. Facies maps and multiple vertical measured sections were completed at two outcrops in the southwest portion of the basin, and one outcrop in the northeast portion of the basin. Field results and petrographic analyses were integrated and used to document the types of heterogeneity that exist in each depositional setting, and to compare how reservoir characteristics vary across the Uinta basin. With adequate documentation of the three-dimensional geometry, facies architecture, and internal heterogeneity of lacustrine reservoirs of the Eocene Green River and Colton formations, geostatistical models can be generated to predict reservoir characteristics, and flow models can be run to simulate flow of fluids in the subsurface (Robbana, 2002). Therefore, this study provides an integral step in quantifying reservoir-scale heterogeneity and in classifying different types of reservoir facies in lacustrine systems.

BACKGROUND GEOLOGY AND PETROLEUM

SYSTEM SUMMARY

The Uinta basin

The Uinta basin encompasses an area of approximately 24,000 km^2 in northwestern Colorado and northeastern Utah (Fig. 1; Johnson, 1985). During the Paleocene and Eocene the basin was bounded to the north by the Uinta Mountains, to the west by the remnant Sevier fold and thrust belt, to the east by the Douglas Creek Arch, and to the south by the San Raphael Swell and Uncompahgre Uplift (Fig. 1; Abbott, 1957; Bradley, 1995). The Uinta basin is asymmetric, with the deeply-downwarped part of the basin near the Uinta uplift to the north (Fig. 2; Fouch, 1975). Approximately 5,000 meters of lacustrine, fluvial, and alluvial sedimentary rocks filled the basin from the Late Cretaceous to the Early Oligocene (Figs. 2, 3; Johnson, 1985).

During the Late Cretaceous, the Uinta basin was covered by the Cretaceous Interior Seaway and bounded to the west by the eastward-propagating thin-skinned Sevier fold and thrust belt (Bruhn *et al.,* 1983, 1986). As the seaway retreated and thick-skinned Laramide uplifts began to rise within the foreland during the latest Cretaceous and early Tertiary, sedimentation became partitioned within rapidly subsiding broken foreland basins (Dickinson *et al.,* 1988; Franczyk *et al.,* 1992). Lakes Flagstaff and Uinta (ultimately coalescing into Lake Uinta) formed in this setting within the Uinta basin, where subsidence rates exceeded sedimentation rates (Ryder *et al.,* 1976). The Eocene Green River Formation records this extensive lake system. As Laramide uplifts and fluctuations in lake size persisted throughout the Paleocene and Eocene, fluvial-alluvial
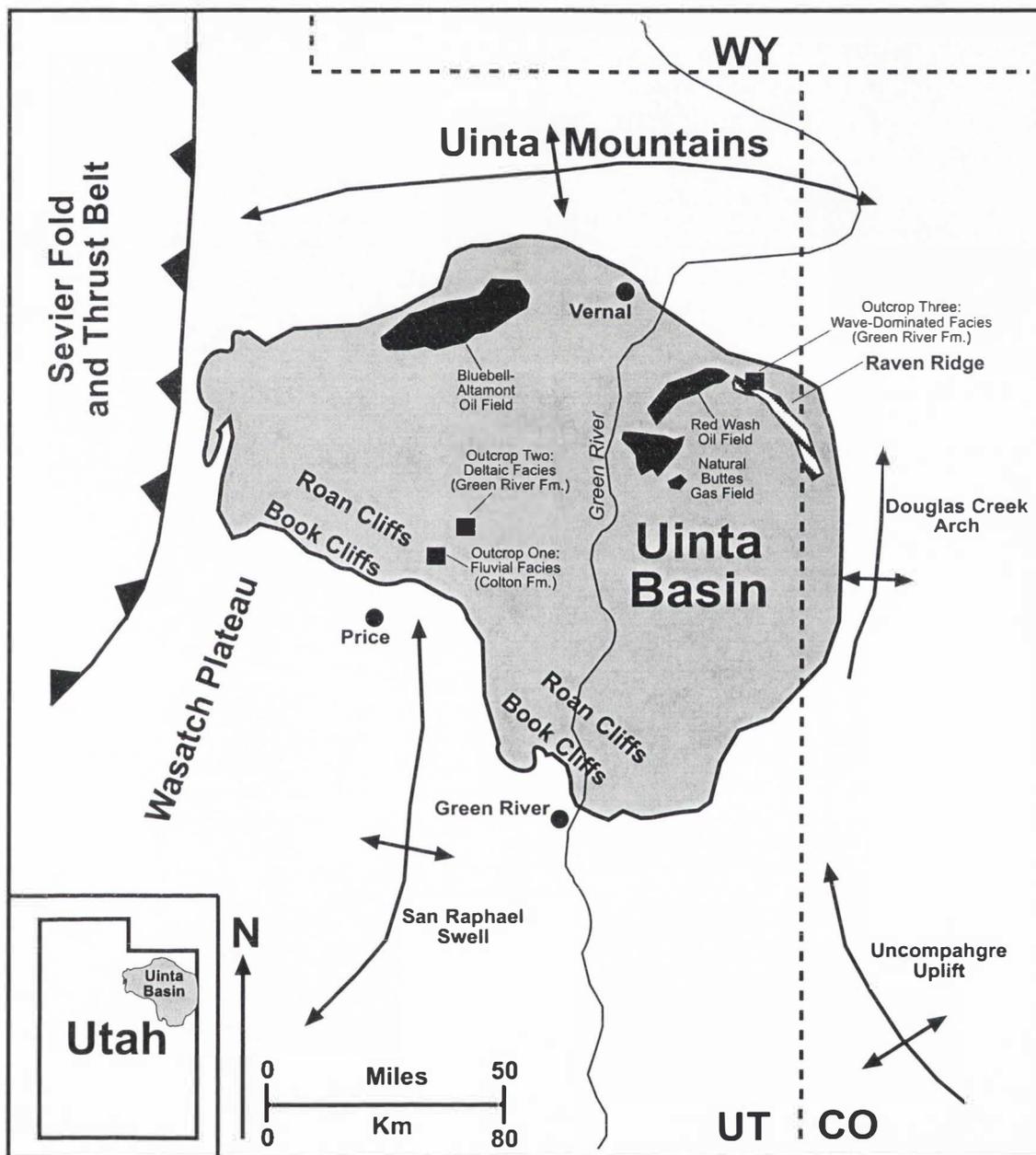
Fig. 1. Schematic paleogeographic map of the Uinta basin and surrounding areas, including outcrop locations for this study and major oil and gas producing fields (modified after Castle, 1990).
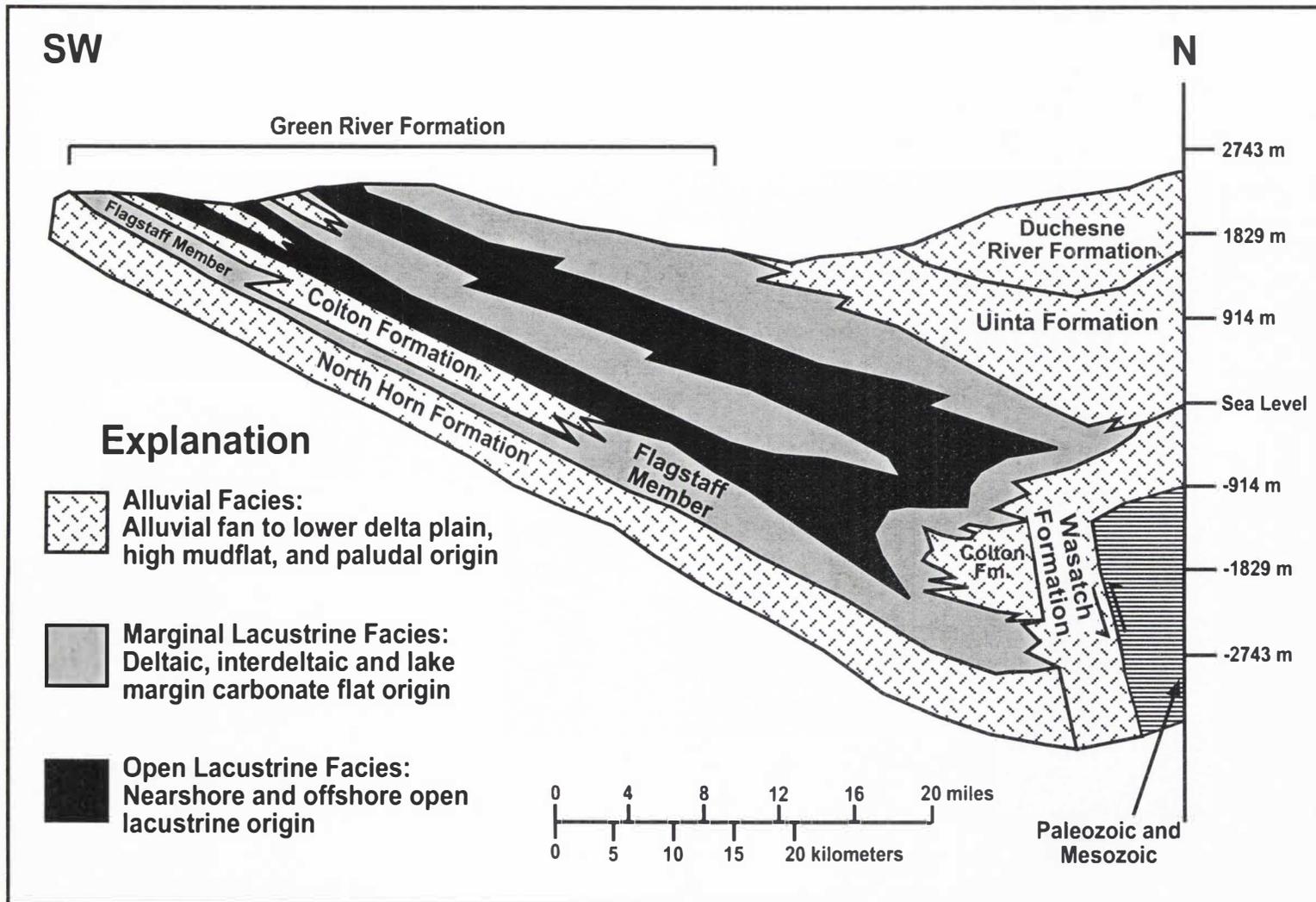
Fig. 2. General structural and stratigraphic cross section of the Uinta basin, from southwest to north-central. Notice the asymmetric geometry and complex intertonguing of facies (modified after Fouch, 1975).
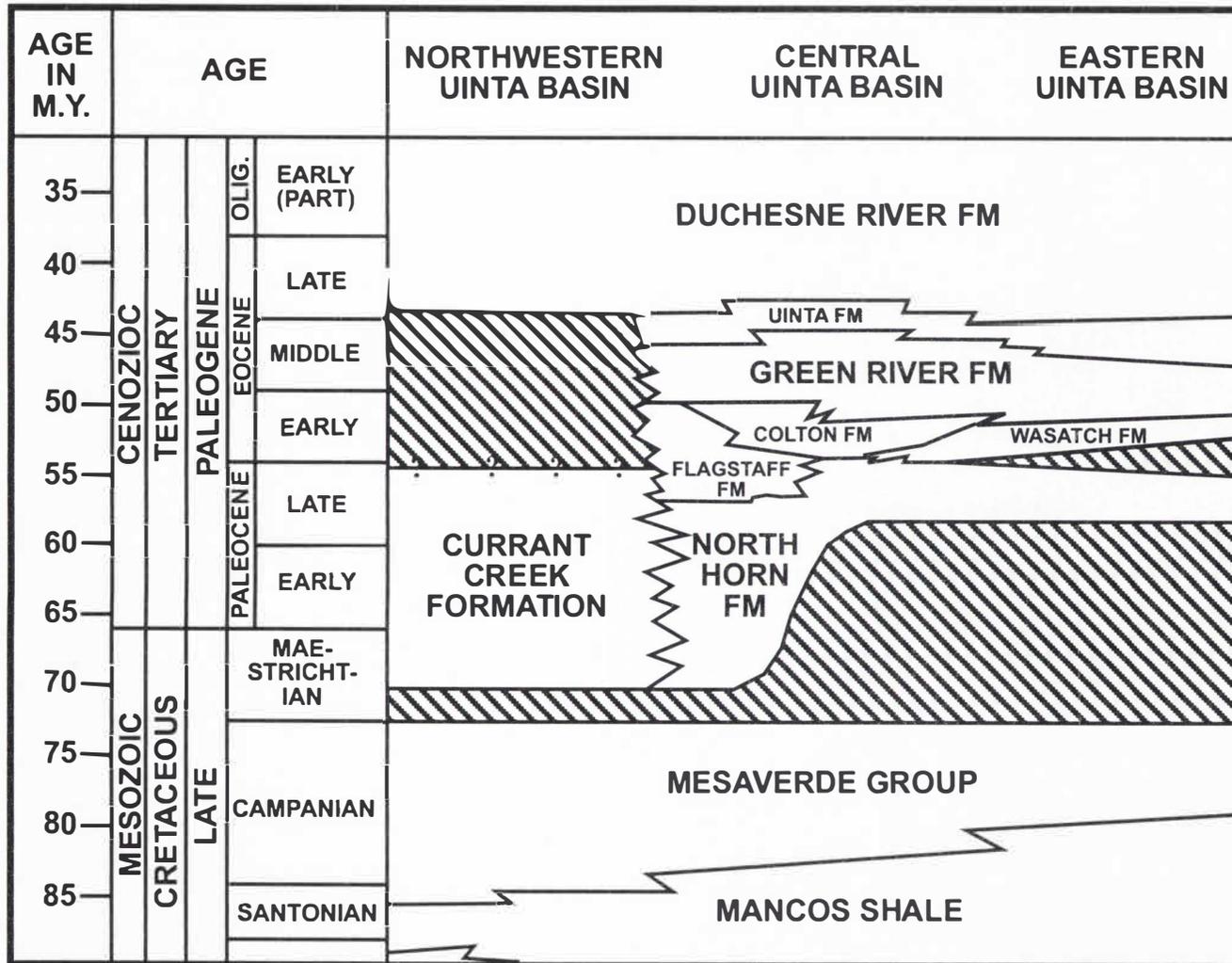
Fig. 3. Generalized chronostratigraphic chart of Upper Cretaceous to Lower Tertiary rocks of the Uinta basin (modified after Isby and Picard, 1985).

systems dominated areas surrounding the lake margins, resulting in the complex

intertonguing of lacustrine, alluvial, and fluvial sediments that are preserved in the Uinta

basin (Fig. 2; Ruble and Philp, 1998). These synorogenic fluvial-alluvial deposits are

recorded in the Currant Creek, North Horn, Colton, and Uinta formations (Figs. 2, 3;

Fouch, 1975; Isby and Picard, 1985).

Sedimentology and stratigraphy of the
Green River and Colton formations

The stratigraphy and sedimentology of the Green River Formation in the Uinta

basin is well documented due to its abundant hydrocarbon reserves and excellent

exposure, however the lithostratigraphy within the basin is extremely complex (Bradley,

1931; Dane, 1954; Picard, 1955, 1967, 1985; Abbott, 1957; Sanborn and Goodwin, 1965;

Picard and High, 1970; Picard *et al.,* 1973; Cashion and Donnell, 1974; Fouch, 1975,

1976; Ryder *et al.,* 1976; Bruhn *et al.,* 1983, 1986; Dickinson *et al.,* 1986; Castle, 1990;

Remy, 1992; Wiggins and Harris, 1994; Borer, 2001; Ruble and Philp, 1998; Keighley *et*

al., 2002). Therefore, the stratigraphy and sedimentology of the Green River and Colton

formations will only be addressed in the areas that pertain to this study.

Outcrops of the Green River Formation chosen for this study are located in the

south-central and northeastern portions of the Uinta basin due to the abundance of coarse

clastic intervals in these areas, which provide adequate analogs for lacustrine petroleum

reservoirs (Fig. 1). The gently dipping southern margin of the basin experienced less

subsidence and abundant sediment influx throughout the Paleocene and Eocene, resulting

in the deposition of a large fluvial-deltaic complex (Picard and High, 1970; Fouch, 1975;

Ryder *et al.,* 1976; Dickinson *et al.,* 1986; Remy, 1992). Sandstone units of this deltaic

complex are interpreted to be derived from the Laramide-style San Luis uplift in south-central Colorado (Dickinson *et al.,* 1986). This interval of the lower to middle Green River Formation was named the Sunnyside delta by Remy (1992), and is described as a 375 m thick unit of fluvial-deltaic sandstone, mudstone, and carbonate (Fig. 4a). Outcrop Two of this study, located in Parley Canyon, corresponds to this interval of the Green River Formation (Figs. 1, 4a).

In contrast to the gently sloping southern margin of the basin, the northern margin of the basin experienced higher subsidence rates and lower sediment influx, resulting in a different style of lacustrine shoreline deposition (Castle, 1990; Borer, 2001). Outcrop studies at Raven Ridge and subsurface studies from its downdip equivalent in the Red Wash field have resulted in multiple depositional environment interpretations, namely fluvial-deltaic, open lacustrine, and near-shore lacustrine (Sanborn and Goodwin, 1965; Picard, 1967; Castle, 1990; Borer, 2001). Borer (2001) cautions the use of fluvial-deltaic as a depositional environment for these rocks, and provided evidence for a wave-dominated system that records multiple fluctuations between open lacustrine and foreshore environments. Outcrop Three of this study, located at Raven Ridge, corresponds to this interval of the Green River Formation, and is stratigraphically in the lower Douglas Creek Member of Bradley (1931), and Chatfield (1972) (Figs. 1, 4b).

The Colton Formation outcrops from Soldier Summit to Sunnyside, Utah, in the southern portion of the Uinta basin (Morris *et al.,* 1991). The Colton Formation lies stratigraphically above the Flagstaff Member of the Green River Formation, and is overlain by the main body of the Green River Formation (Figs. 3, 4a; Fouch, 1975; Ryder *et al.,* 1976; Zawiskie *et al.,* 1982; Franczyk *et al.,* 1991; Morris *et al.,* 1991; Fouch *et al.,*
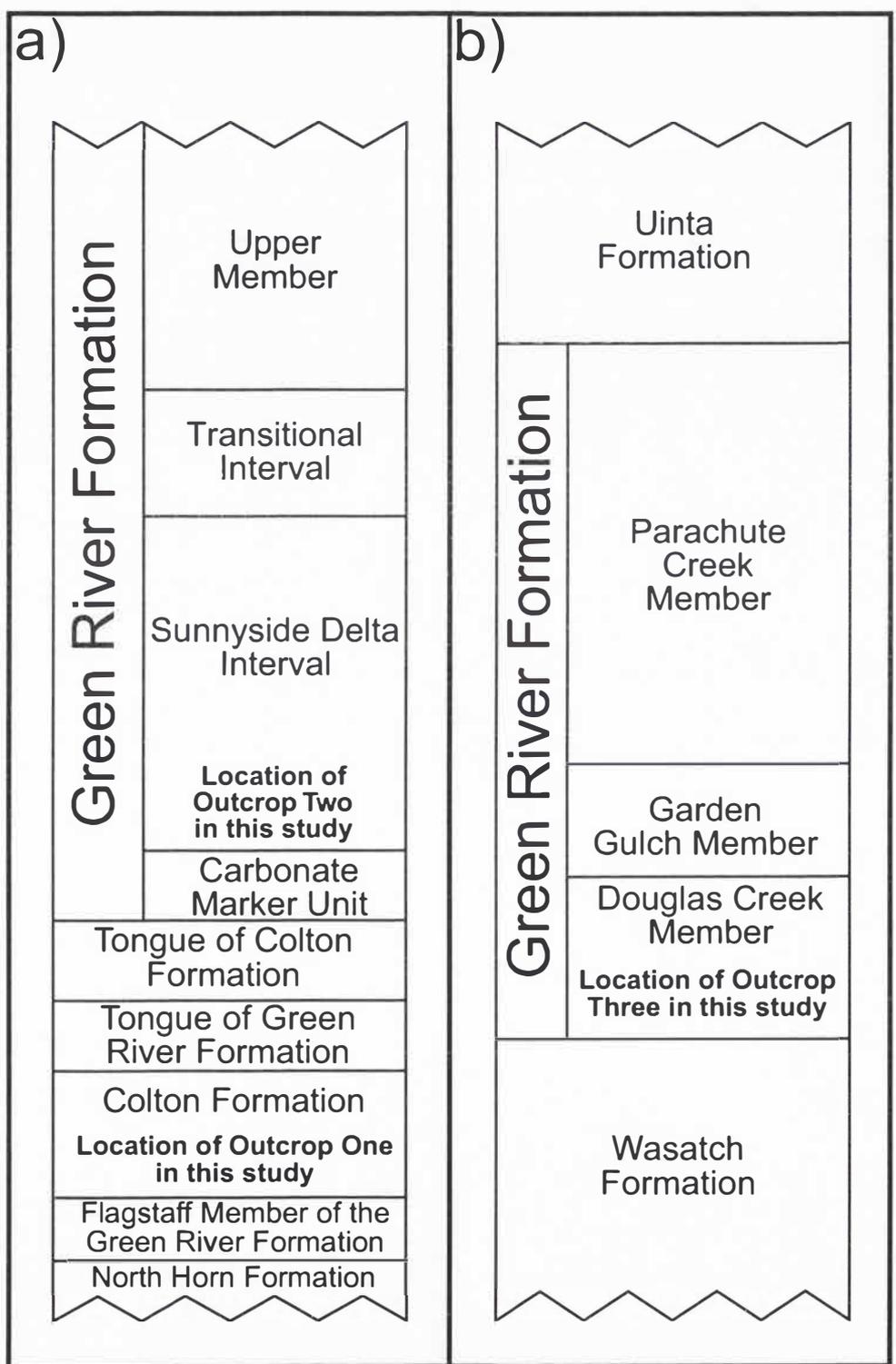
Fig. 4. Generalized stratigraphic columns of lower Tertiary rocks in the Uinta basin, illustrating stratigraphic location of outcrops in the study.
a) The south-central portion of the Uinta basin, in Nine Mile Canyon (after Remy, 1992). b) The northeastern Uinta basin, encompassing Raven Ridge and Red Wash areas (after Bradley, 1931; Chatfield, 1972; Castle, 1990).

1992; Morris and Richmond, 1992; Remy, 1992). The Colton Formation thins

northward and westward, where the main body of the Green River Formation

conformably overlies the Flagstaff Member, forming a continuous lacustrine sequence

(Ryder *et al.,* 1976). Rocks of the Colton Formation represent a progradational fluvial-

deltaic wedge of red and green sandstone and mudstone that built into ancient Lakes

Flagstaff and Uinta from the southeast (Ryder *et al.,* 1976; Remy, 1992). The

provenance of sandstone in the Colton Formation is the same as that of the Sunnyside

delta (Dickinson *et al.,* 1986). Facies analyses of the Colton Formation show a gradual

change from mud-dominated lower delta plain deposits to sand-rich upper delta

plain/lower alluvial plain deposits from west to east (Morris *et al.,* 1991). Outcrop One

of this study, located near where Nine Mile Canyon enters the Roan Cliffs, corresponds

to the bed-load channel system of the Colton Formation described by Morris *et al.,*

(1991) (Figs. 1, 4a).

The Green River petroleum system

The Uinta basin has become one of the most intensely studied lacustrine

sequences in the world due to its occurrence of oil shale, solid hydrocarbons, tar sands,

productive oil and gas fields, and evaporite minerals (Chatfield, 1972; Fouch, 1975;

Picard, 1985; Castle, 1990; Fouch *et al.,* 1992, 1994; Morris and Richmond, 1992; Ruble

and Philp, 1998; Ruble *et al.,* 2001). As of 2001, approximately 500 million barrels of

oil and more than 2.5 trillion cubic feet of gas derived from source rocks in the Green

River Formation had been produced from reservoirs in the Green River, Colton, Uinta,

and North Horn formations (Fouch *et al.,* 1992; Utah Division of Oil, Gas, and Mining,

2002). The source rocks for oil and gas in the Green River Formation are open-lacustrine rocks of the Green River Formation that contain type I kerogen, marginal-lacustrine rocks of the Green River Formation that contain type I, II, and III kerogen, and an alluvial facies containing type III kerogen (Fouch *et al.,* 1994). Reservoir rocks of the Uinta basin are lenticular and tabular fluvial and deltaic sandstone, tabular lacustrine sandstone and carbonate, and near-shore lacustrine bar and beach sandstone (Fouch *et al.,* 1992, 1994; Ruble *et al.,* 2001). Most of the hydrocarbons in the Uinta basin are trapped stratigraphically where alluvial rocks that are encased in mudstone create impermeable barriers that trap most oil and gas in down-dip open- and marginal-lacustrine reservoirs (Fouch *et al.,* 1994).

IMPORTANCE OF OUTCROP RESERVOIR

CHARACTERIZATION STUDIES

Multiple reservoir characterization studies in fluvial systems have utilized two- and three-dimensional outcrop photomosaics to document facies geometry and architecture, and internal heterogeneity (Miall, 1988*a*, 1988*b*; Bromley, 1991; Dubiel, 1991; Eschard *et al.,* 1991; Hirst, 1991; Lang and Fielding, 1991; Lorenz *et al.,* 1991; Dreyer *et al.,* 1993). Some of these studies have focused on defining architectural elements and a hierarchical ordering of bounding surfaces, a technique first presented by Allen (1983). Architectural elements are packages of rock that are distinguishable by their internal geometry, shape and size, and lithofacies assemblages, and are produced by a specific sedimentological process or a multitude of processes that occur within a depositional system (Miall, 1985, 1991). This work has led to the formalization of a predictable hierarchy of scales within fluvial reservoirs, where depositional units at multiple magnitudes of scale are characterized by a specific time interval of deposition, and are separable by internal bounding surfaces (Miall, 1985, 1991). Such a classification has become extremely useful in fluvial reservoirs due to their strong heterogeneity and restricted lateral continuity. Studies of this type have also been successfully conducted in eolian, deltaic, and marine depositional systems (Brookfield, 1977; Kocurek, 1981; Kocurek *et al.,* 1991; Ori *et al.,* 1991; Soegaard, 1991; Surlyk and Noe-Nygaard, 1991). Therefore, using this approach in reservoirs of the Green River and Colton formations will provide a preliminary assessment of the predictability of scales and architectural elements characteristic of lacustrine depositional systems.

Ambrose *et al.* (1991) and Tyler and Finley (1991) attribute the continuity and distribution of reservoir compartments to three-dimensional architecture and internal heterogeneity, which are predictable products of depositional systems. They further emphasize that reservoirs with complex facies architecture and internal heterogeneity compartmentalize large amounts of hydrocarbons, while those with less complex facies architecture and internal heterogeneity are usually drained efficiently. Therefore it is necessary that the intrinsic characteristics within the complex reservoirs of the depositional systems in the Green River and Colton formations be well documented, so that predictable models can be constructed and utilized to extract as much hydrocarbon as possible from reservoirs of this type.

Past studies of major oil fields in Texas have concluded that ultimate recovery efficiencies in sandstone reservoirs range from 8 to 80 % depending on the lateral and vertical complexity and internal heterogeneity of the reservoir (Fisher and Galloway, 1983; Tyler *et al.,* 1984; Tyler and Finley, 1991). These studies also concluded that oil recovery nationwide has averaged only 34 % of the total mobile oil. The remaining oil in these reservoirs is either immobile residual oil held in pores by physical and chemical processes, or unrecovered mobile oil. This unrecovered mobile oil is typically bypassed or uncontacted during primary recovery methods due to a limited knowledge of the complexity of reservoir heterogeneity and facies architecture at multiple scales within the system. For example, mudstone interbeds or shale drapes deposited in a fluvial system during channel migration and abandonment may compartmentalize the reservoir, if continuous, or act as flow baffles, if discontinuous. At a smaller scale, cross-stratified sandstone beds in a channel deposit may exhibit a grain size contrast that could

potentially decrease horizontal permeability. Therefore, by increasing the control on

internal reservoir heterogeneity and facies architecture, hydrocarbon recovery can

become more efficient, resulting in a decrease in dependence of secondary, tertiary, and

enhanced recovery methods (e.g., water or gas injection, targeted infill drilling,

waterflood redesign, and recompletions) (Tyler and Finley, 1991).

METHODS

Field methods

Photomosaics of three outcrops in the Uinta basin were constructed utilizing techniques described by Wizevich (1991). The outcrops expose rocks of different lacustrine depositional settings, and were chosen based on their exposure, abundance of sandstone, and accessibility. These outcrops are not intended to provide direct analogs for currently producing fields in the Uinta basin, particularly the Red Wash and Altamont-Bluebell fields. Outcrop One is located in the southern portion of the basin approximately 20 miles northeast of Wellington, Utah, on the north side of Nine Mile Canyon National Back Country Byway, and exposes fluvial rocks of the Colton Formation (NW ¼ Sec. 26 and NE ¼ Sec. 27, T12S, R12E) (Fig. 5). Outcrop Two is located approximately 7 miles northeast of Outcrop One, on the northwest side of Parley Canyon, and exposes deltaic- and open-lacustrine rocks of the Green River Formation (NW ¼ Sec. 32, T11S, R14E) (Fig. 5). Outcrop Three is located in the northeast portion of the basin, approximately 1 ¼ miles south of Highway 40, and 25 miles southeast of Vernal, Utah (SW ¼ Sec. 29, T6S, R25E) (Fig. 5). This outcrop is the northern most exposure of Raven Ridge, and records wave-dominated lacustrine rocks of the Green River Formation. It is worth noting that Outcrop Three is stratigraphically lower and less complex than rocks previously studied by Borer (2001) at Raven Ridge.

Three stratigraphic sections were measured at centimeter scale for each outcrop to document grain size, lithology, sedimentary structures, textures, and bounding surfaces. These data provide constraints on the lateral and vertical facies relationships within each
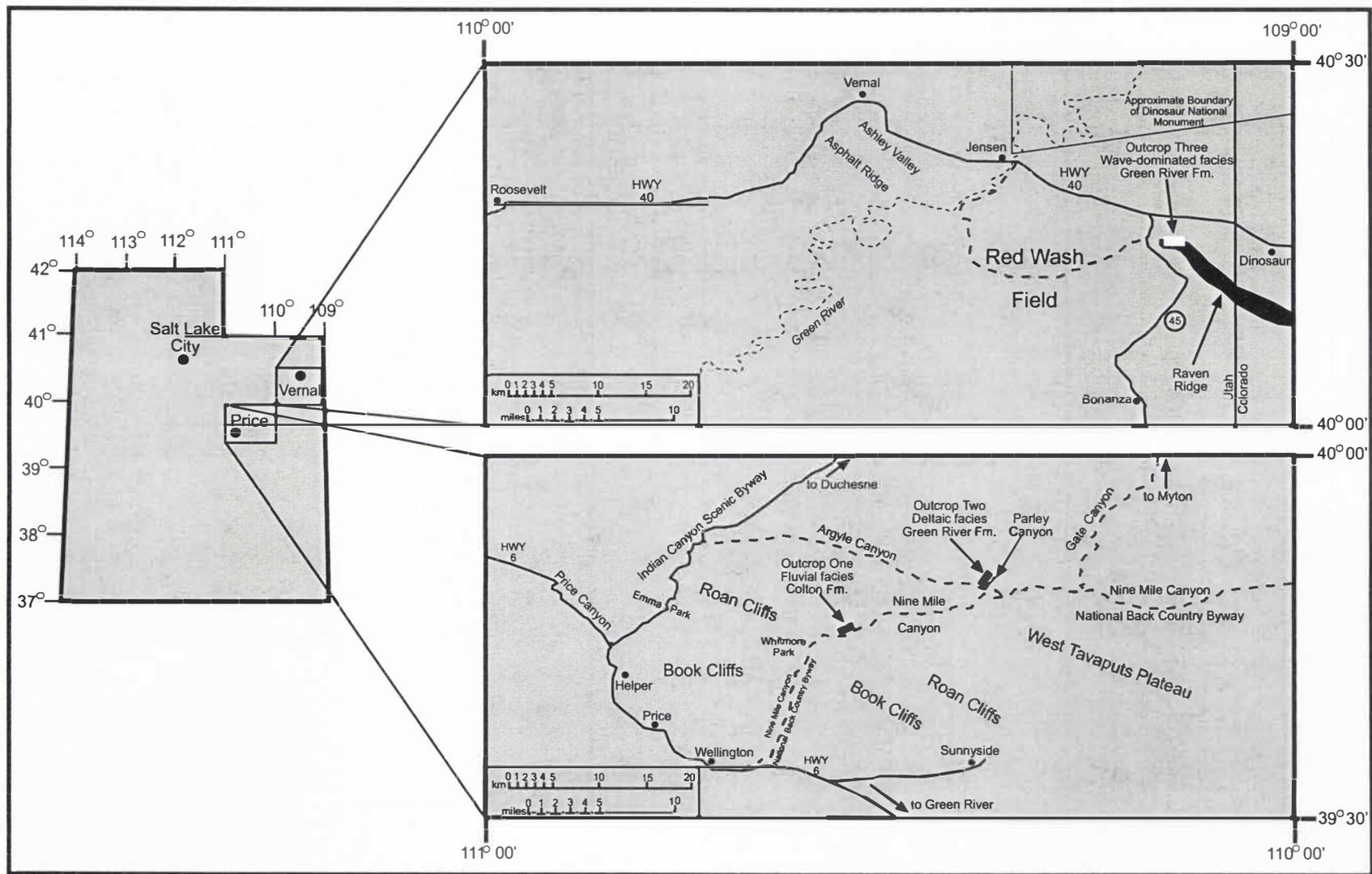
Fig. 5. Geographic maps of the Uinta basin, illustrating outcrop localities in this study.

outcrop. Vertical sandstone sampling was also conducted for each measured section at

half-meter to meter vertical intervals. Selected samples were later utilized in

petrographic analyses. Facies analysis and mapping was conducted on the outcrop

photomosaics. This technique was used to define lithosomes and their bounding surfaces,

resulting in the documentation of lithosome architecture and heterogeneity, and the

hierarchy of surfaces for each reservoir analog that was studied. The surfaces and

measured section traces were digitally recorded using an electronic total station.

Laboratory methods

Forty to 45 sandstone samples from one measured section at each outcrop were

cut into thin sections and impregnated with blue epoxy. A total of 123 thin sections were

point counted (500 grains/slide) on a flat-stage petrographic microscope with an

automatic point counter using the Gazzi-Dickinson point-counting method (Dickinson,

1970; Ingersoll *et al.*, 1984). Point count analyses were conducted to identify grain types,

cement, matrix, and their relative abundances, as well as to calculate porosity values for

each thin section. In addition to point count analyses, each of the 123 thin sections were

analyzed for grain size. These data were compiled by measuring the long axis of 400

grains on digital images from each thin section. It is worth noting that dimensions of

grains in thin section are different from their true dimensions because of the random

sectioning of the grains. Sieving of disaggregated rock samples is another possible

technique for recording grain size data. Past studies addressing this issue have resulted in

the derivation of correction factors for converting thin section grain size data to sieve

grain size data, and vice versa (Rosenfeld *et al.*, 1953; Friedman, 1958, 1962; Adams,

1977; Harrell and Eriksson, 1979). These studies conclude that thin section measurements will generally underestimate true grain size. However, Johnson (1994) summarizes these empirical studies, addressing the flaws of each, and highlights certain issues that have yet to be sufficiently rectified utilizing such correction factors. With such ambiguity, thin sections were utilized to compile grain size data for this study, providing sufficient results for the purpose of this research.

RESULTS

The sedimentology and lithofacies assemblages of the three lacustrine sub-environments are described below and are illustrated in one representative measured section from each outcrop (Fig. 6). The complete set of measured sections is presented in Plate 1, and includes all data collected in the field. Facies codes are defined in Table 1. Descriptions of the geometry and nature of lithofacies assemblages and important bounding surfaces characteristic of each outcrop are also presented below. A hierarchy of bounding surfaces was utilized to assist in the description of Outcrop One, and is summarized in Fig. 7. The application of this hierarchy, along with a visual documentation of the lithofacies assemblage architectures, important bounding surfaces, measured sections localities, and other points of interest that pertain to each outcrop, are illustrated in Figs. 8, 9, and 10. A more detailed illustration of the photomosaics, which contains the complete data set collected in the field, can be found in Plate 2. Petrographic analyses are also discussed below. The complete petrographic data set can be found in the Appendix.

**Outcrop One: Fluvial facies of the
Colton Formation**

Sedimentology

Description. This outcrop is composed of three lithofacies assemblages (LAs): 1) trough cross-stratified sandstone - low-angle cross-stratified sandstone - massive sandstone - plane bedded sandstone - rippled sandstone (St-Sl-Sm-Sh-Sr); 2) massive
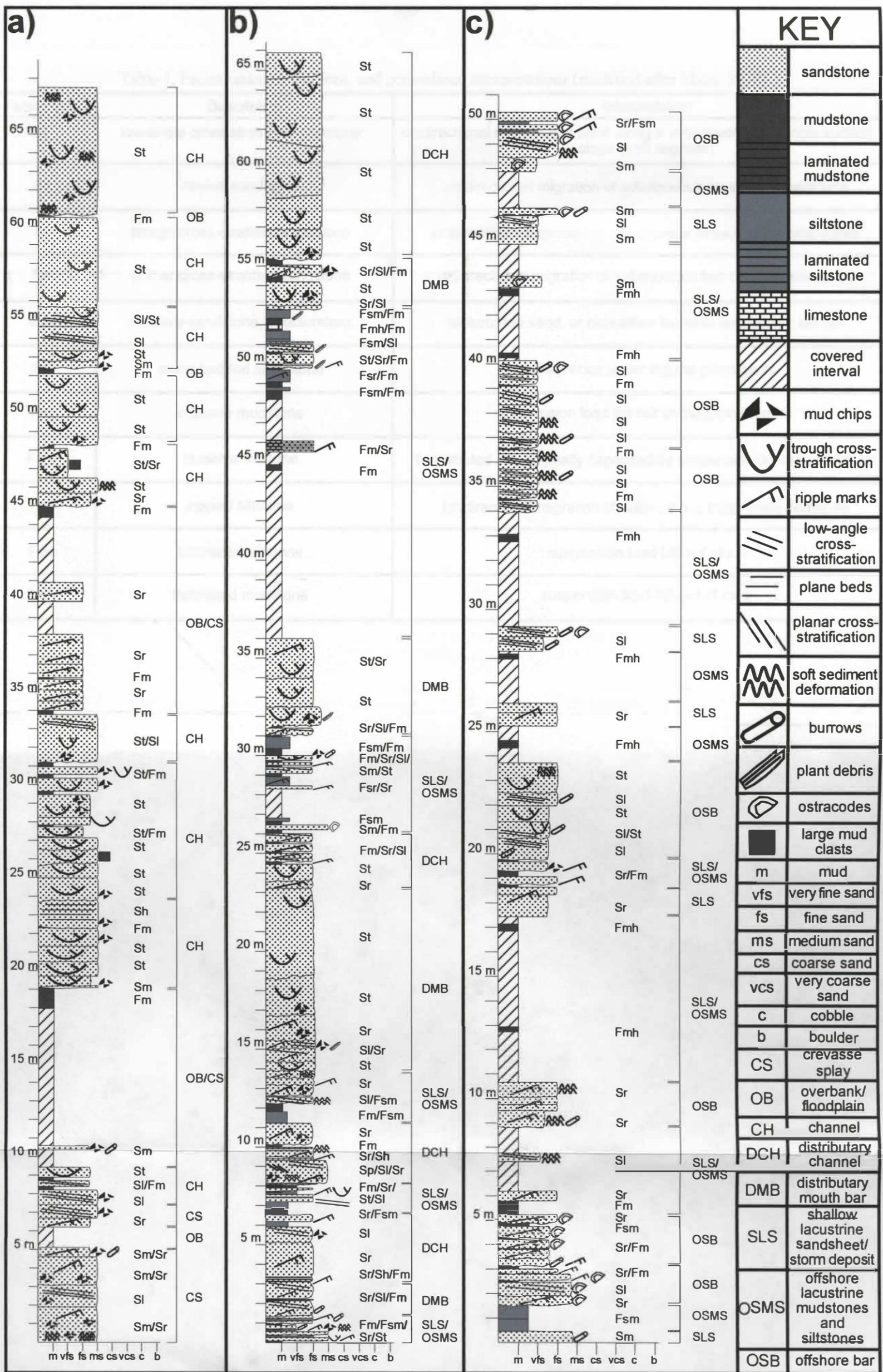
Fig. 6. Representative measured sections. Locations are illustrated in Figs. 8a, 9a, and 10a. Facies codes are described in Table 1. a) Measured section # 1 of Outcrop One: fluvial facies of the Colton Formation. b) Measured section # 1 of Outcrop Two: deltaic facies of the Green River Formation. c) Measured section # 2 of Outcrop Three: wave-dominated facies of the Green River Formation.

Table 1. Facies codes, definitions, and generalized interpretations (modified after Miall, 1978).

Facies Code	Description	Interpretation
Sl	low-angle cross-stratified sandstone	unidirectional migration of sand along a subaqueous low-angle surface or slope (<10 degrees)
Sr	rippled sandstone	unidirectional migration of subaqueous small scale bedforms
St	trough cross-stratified sandstone	unidirectional migration of subaqueous three-dimensional dunes
Sp	planar cross-stratified sandstone	unidirectional migration of subaqueous two-dimensional dunes
Sm	massive sandstone, structureless	bioturbated sand, or deposition by rapid suspension fall-out
Sh	plane bedded sandstone	subaqueous upper regime plane beds
Fm	massive mudstone	suspension load fall-out of mud, bioturbated
Fsm	massive siltstone	bioturbated silt, originally deposited by suspension fall-out or traction
Fsr	rippled siltstone	unidirectional migration of subaqueous small scale bedforms
Fsh	laminated siltstone	suspension load fall-out of silt
Fmh	laminated mudstone	suspension load fall-out of mud

Key:

(stippled pattern)	channel and channel complex deposits
(gray pattern)	overbank deposits
(black)	non fluvial deposits
(trough symbol)	trough cross-stratification
(low-angle lines)	low-angle cross-stratification

Hierarchy:

#	Description
1	envelope entire fluvial systems
2	envelope channel-belts
3	envelope individual channel-fills (CH)
4	envelope other lithosomes (CS)
5	separate beds of different facies
6	separate beds of similar facies

Fig. 7. Hierarchy of bounding surfaces for a fluvial dominated system (modified after Miall, 1988a; and Dreyer et al., 1993). The surfaces are further described in the text, and are applied to Outcrop One in Fig. 8b.
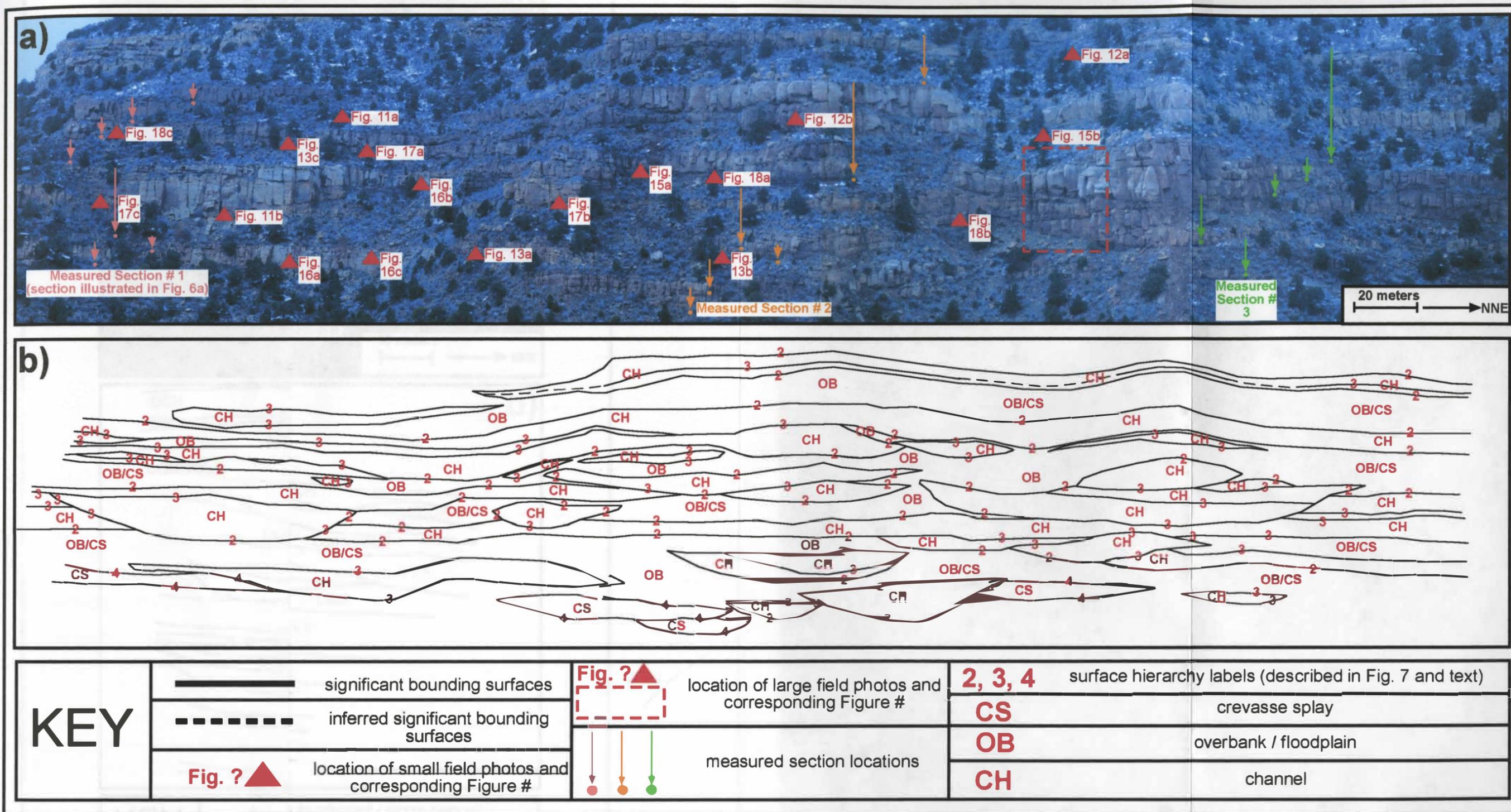
Fig. 8. Outcrop: Fluvial facies of the Colton Formation. a) Photomosaic of Outcrop One illustrates the localities of measured sections and field photos. b) Surface trace of Outcrop One illustrates important surfaces, lithofacies assemblage architecture and stacking pattern, and the surface hierarchy.
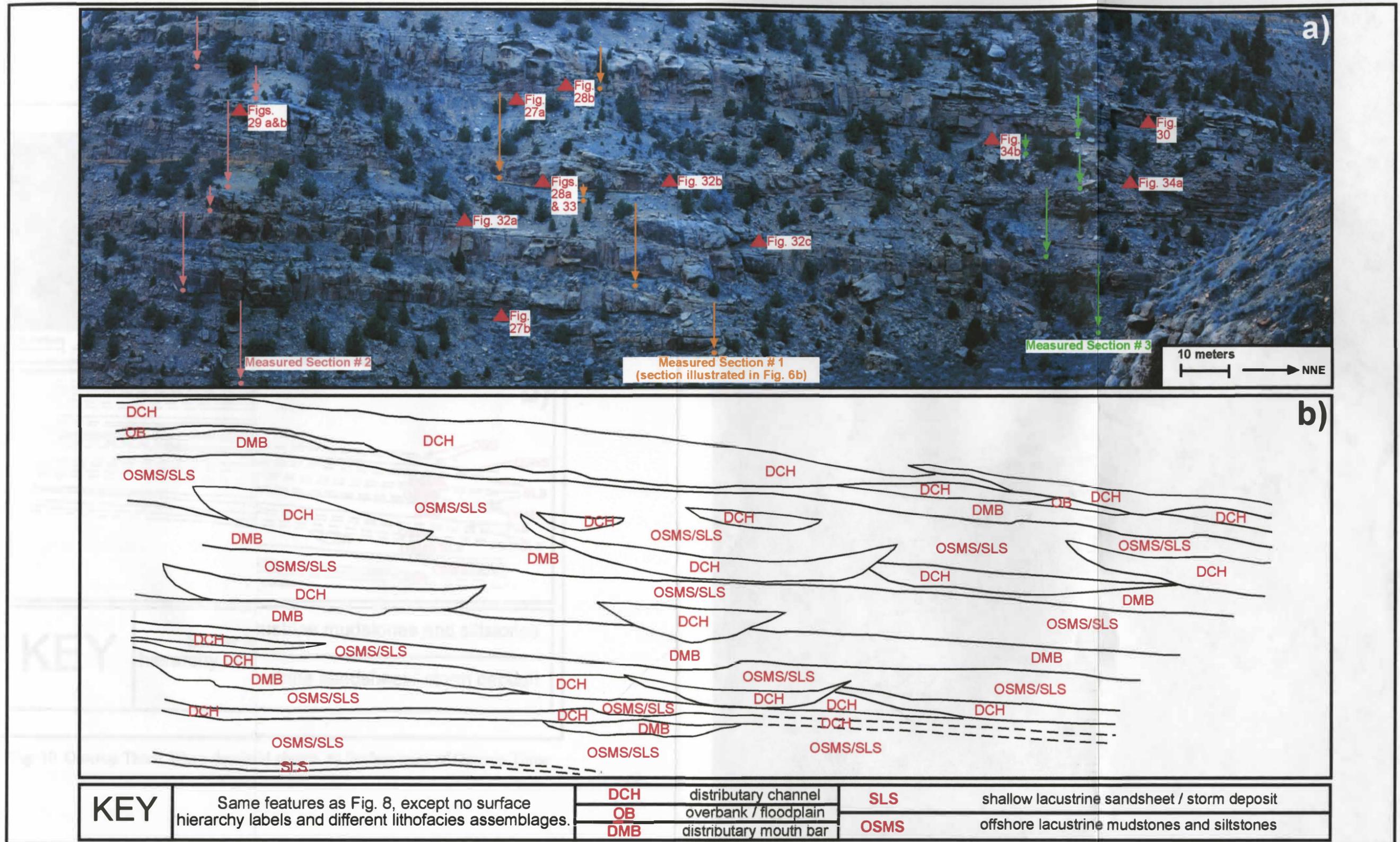
Fig. 9. Outcrop Two: Deltaic facies of the Green River Formation. a) Photomosaic of Outcrop Two illustrates the localities of measured sections and field photos. b) Surface trace of Outcrop Two illustrates important surfaces and lithofacies assemblage architecture and stacking pattern.
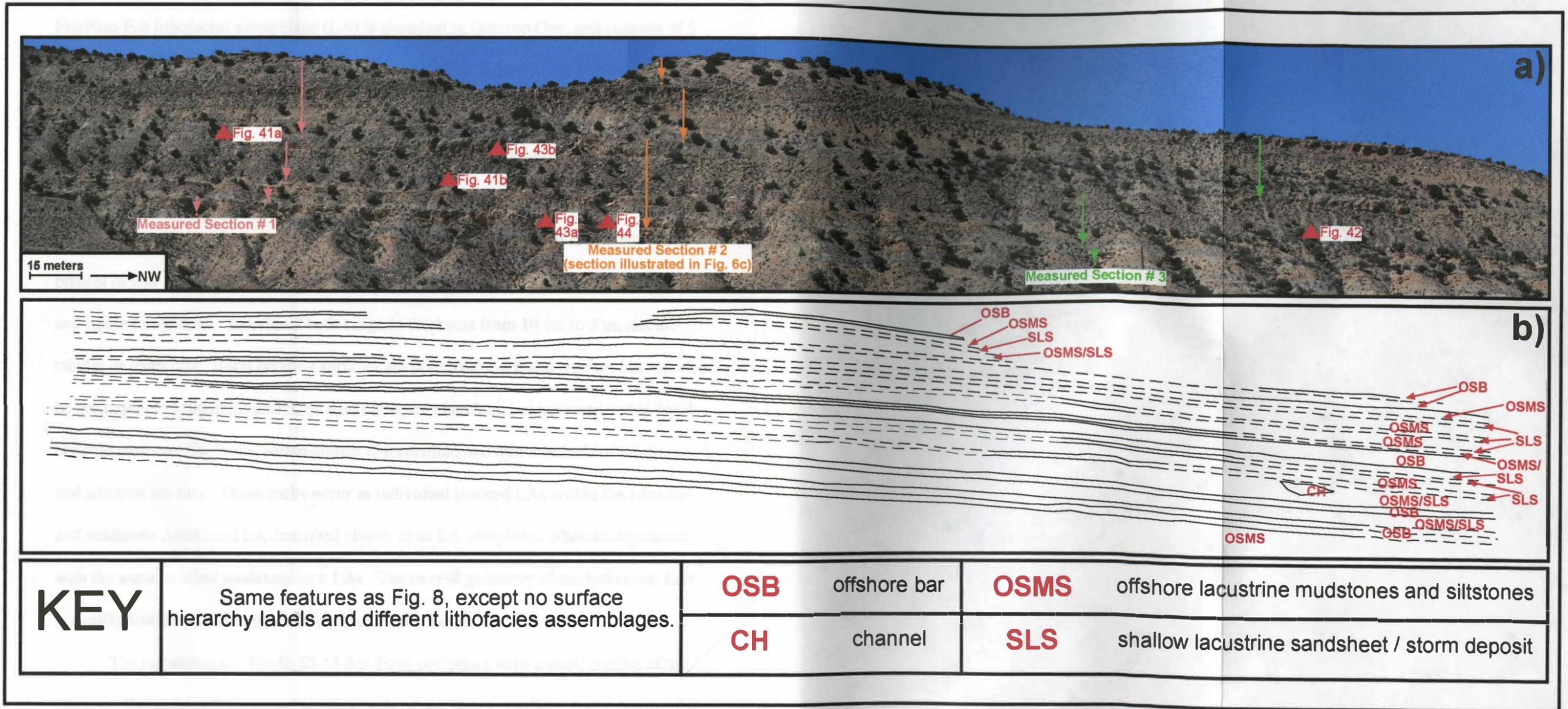
Fig. 10. Outcrop Three: Wave-dominated facies of the Green River Formation. a) Photomosaic of Outcrop Three illustrates the localities of measured sections and field photos. b) Surface trace of Outcrop Three illustrates important surfaces and lithofacies assemblage architecture and stacking pattern.

mudstone - massive siltstone - laminated siltstone (Fm-Fsm-Fsh); 3) rippled sandstone - trough cross-stratified sandstone - plane bedded sandstone – low-angle cross-stratified sandstone – massive sandstone – massive siltstone (Sr-St-Sh-Sl-Sm-Fsm) (Fig. 6a). The Fm-Fsm-Fsh lithofacies assemblage (LA) is abundant in Outcrop One, and consists of 5 cm to 1 m thick beds of red or buff, massive to laminated, mudstone and siltstone that are laterally extensive and tabular, except where truncated by erosive sandstone dominated LAs. Circular calcite nodules and vertical burrows are common, and mud chips are rare. The St-Sl-Sm-Sh-Sr LA is also abundant in this outcrop, and consists of tan or red, fine to medium grained, trough cross-stratified and low-angle cross-stratified sandstone. Also present in less abundance are tan or red, fine to medium grained, massive, plane-bedded, and rippled sandstone. Individual beds range in thickness from 10 cm to 3 m, and are tabular or lenticular. Basal bedding surfaces are primarily sharp and erosive, but can also be gradational. Mud chips and large mud clasts are abundant, but not restricted to basal bedding surfaces. Burrows, soft-sediment deformation, and thin interbeds of mudstone and siltstone are rare. These rocks occur as individual isolated LAs within the siltstone and mudstone dominated LA described above, or as LA complexes when amalgamated with the same or other sandstone-rich LAs. The overall geometry of the individual LAs is usually lenticular, although undulatory examples occur.

The remaining LA (Sr-St-Sh-Sl-Sm-Fsm) comprises only a small portion of the outcrop. It consists of 10 cm to 1 m thick beds of red, fine to medium grained, massive, rippled, low-angle cross-stratified, trough cross-stratified, and plane-bedded sandstone. Also present in less abundance is red massive siltstone. Of the lithofacies previously mentioned, Sr, St, and Sh are the primary constituents of this LA. Basal bedding surfaces

can be gradational, but are more typically erosive. Burrows, soft-sediment

deformation, and basal mud chip lags are common. Thin interbeds of mudstone and

siltstone are rare. These individual LAs are typically entirely encased by rocks of the

siltstone- and mudstone-dominated LA, but can also be found in LA complexes when

amalgamated with the same or other sandstone-rich LAs. The geometry of this LA is

usually wedge- or lens-shaped, but can be tabular in places.

Interpretation. Rocks of the Fm-Fsm-Fsh LA are interpreted to be deposited by

suspension load fall-out of mud and silt in a low energy subaqueous environment that

was at times well-oxygenated and subaerially exposed. The depositional environment is

interpreted to be an overbank, or floodplain, in a fluvial system (Miall, 1996). This LA

will further be termed OB (Figs. 6a, 8b). Evidence supporting this interpretation includes

the presence of burrows, as well as the abundance of calcite nodule-rich paleosol

horizons (Figs. 6a, 11). Because of the dominance and excellent preservation of OB

deposits in the outcrop, the system is interpreted as meandering fluvial (Cant, 1982).

The mechanism of deposition for the St-Sl-Sm-Sh-Sr LA is interpreted to be

unidirectional migration of subaqueous sandy bedforms of varying sizes in channelized

flow conditions (St, Sl, Sh, and Sr). Massive sandstone (Sm) beds are interpreted to be

the result of bioturbated or suspension load fall-out of sand during waning flow stages.

The depositional setting of this LA is interpreted as channel-fill deposits of a meandering

fluvial system, and is termed CH (Figs. 6a, 8b). The unidirectional and channelized

interpretation is supported by the abundance of St and Sl in this LA, which suggests that

flows were confined (Figs. 6a, 12). Further evidence for channelization is the dominance
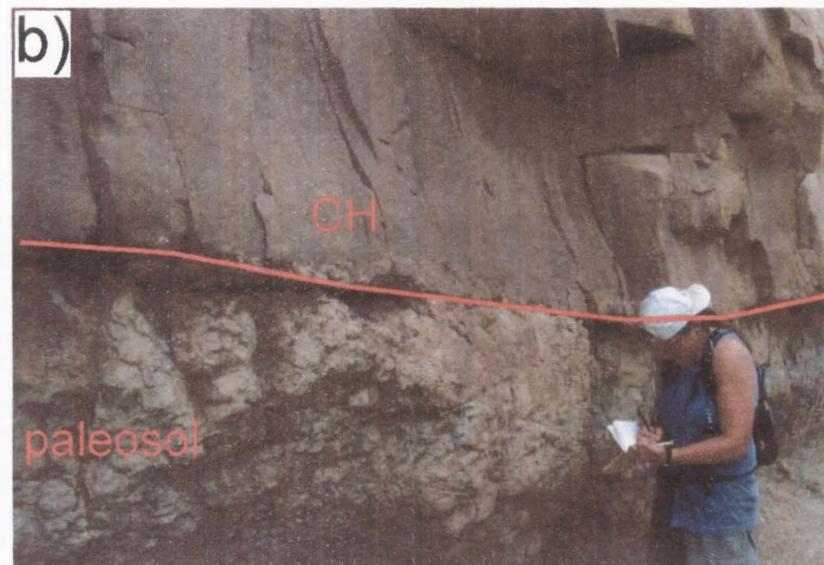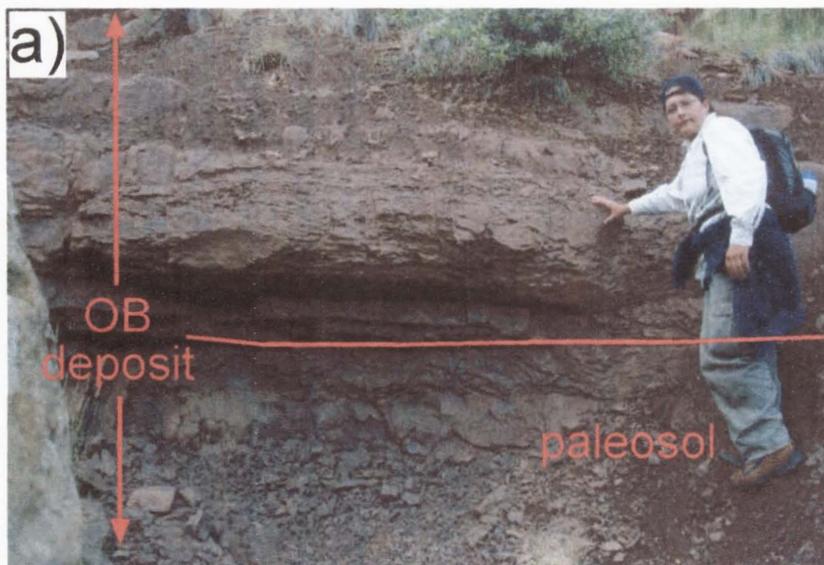
Fig. 11. Overbank deposits and associated paleosol horizons characteristic of Outcrop One. a) Overbank fines overlying paleosol horizon. b) Paleosol horizon truncated by channel-fill lithofacies assemblage (Photo locations illustrated in Fig. 8a).
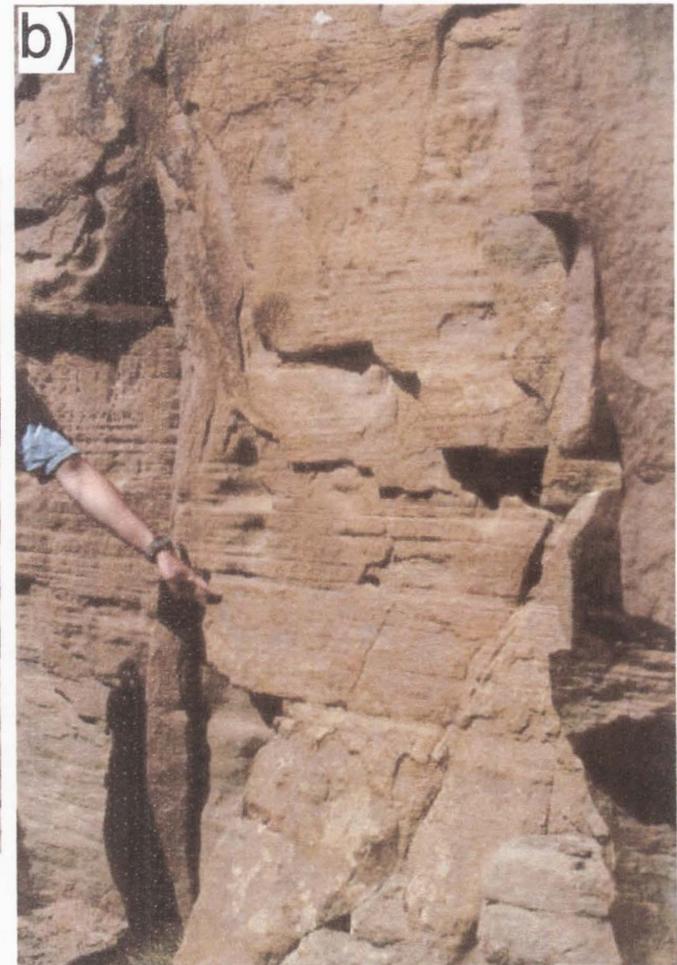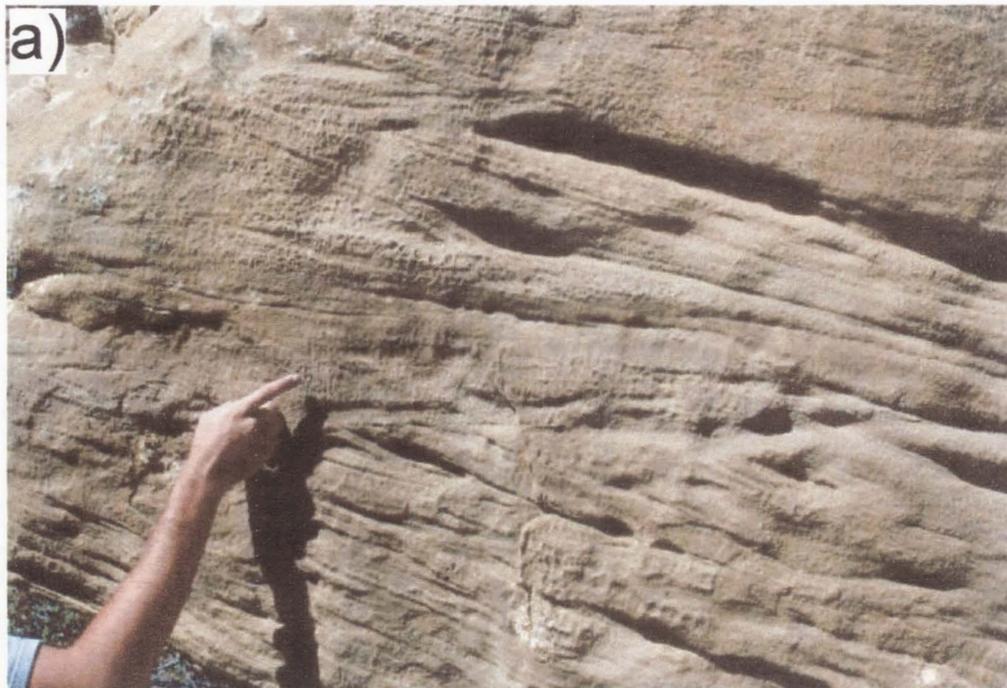
Fig. 12. Sedimentology of the channel-fill lithofacies assemblage. a) Trough cross-stratified sandstone of the channel-fill lithofacies asseblage. b) Low-angle cross-stratified sandstone of the channel-fill lithofacies assemblage (Photo locations illustrated in Fig. 8a).

of lenticular LAs over undulatory LAs in the system (Fig. 8b). Mud chip lags, large mud clasts, a dominance of St, and the presence of upper flow regime plane beds (Sh) provide evidence that the deposits were high energy and erosive (Fig. 13). This depositional environment interpretation is consistent with Miall (1996), in that CH does not contain components of downstream- or lateral-accretion macroform deposits.

Rocks of the Sr-St-Sh-Sl-Sm-Fsm LA are interpreted as deposits resulting from unidirectional migration of subaqueous sandy bedforms of varying sizes and flow regimes (Sr, St, Sl, and Sh), and bioturbated or rapid suspension load fall-out of sand and silt (Sm and Fsm). This LA is interpreted to represent sheet flood or crevasse-splay deposits that spread laterally from the channels into the floodplains (Mjos *et al.,* 1993; Miall, 1996). This LA is further termed CS (Figs. 6a, 8b). The presence of basal mud chip lags, burrows, and occasional finer-grained sediments suggest that flow conditions were unsteady. These deposits contain sedimentological features similar to those described in the CH deposits, except that Sr and Sh are the dominant constituents of the LA (Fig. 6a). These rocks also differ from CH deposits in that their beds are much thinner and their geometry is primarily wedge- or lens-shaped. Typically individual large CS LAs are isolated in the OB intervals, but they can also be truncated by CH LAs. Smaller CS LAs are found interbedded with OB deposits.

LA architecture and bounding surfaces

Concurrent with the architectural descriptions of LAs in Outcrop One, bounding surfaces are addressed utilizing a classification system modified from Dreyer *et al.* (1993) (Fig. 7). This hierarchy of bounding surfaces is a modification of the fluvial
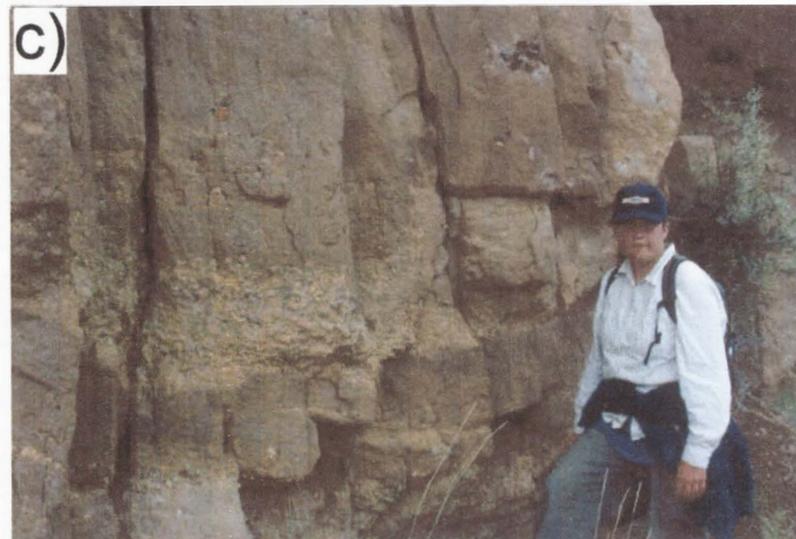
Fig. 13. Sedimentology of the channel-fill lithofacies assemblage. a) Plane bedded sandstone of the channel-fill lithofacies assemblage. b and c) Mud chip lags common in basal portions of the channel-fill lithofacies assemblage (Photo locations illustrated in Fig. 8a).

classification of Miall (1988*a*), and is summarized briefly in the following two paragraphs. Application of this classification scheme is illustrated in Fig. 8b. Because this classification system was erected for fluvial outcrops, its use is restricted to Outcrop One and cannot be used to classify bounding surfaces in Outcrops Two and Three. The construction of this type of classification system requires the compilation and integration of data from numerous outcrops containing similar sedimentological and depositional features. No attempt is made to erect a similar scheme for Outcrops Two and Three, as they are simply a first step in describing lacustrine-deltaic and wave-dominated lithofacies architectures and bounding surfaces. With more studies of similar outcrops, lithofacies assemblages can be better classified and bounding surfaces can be placed into a workable hierarchy.

In fluvial systems, sixth-order bounding surfaces are surfaces that envelope individual facies. These surfaces separate beds of the same lithofacies, and indicate no apparent change in flow conditions across the surface. This order of surface is not included in the hierarchy of Dreyer *et al.* (1993), but added in this study for the purpose of capturing heterogeneity at a smaller-scale (Fig. 7). Fifth-order bounding surfaces are surfaces that envelope cosets of genetically related lithofacies or lithofacies sequences, and represent the smallest-scale in the hierarchy of Dreyer *et al.* (1993). These surfaces separate beds that were deposited by different flow conditions. For example, a fifth-order surface will mark the boundary between beds comprised of St and Sl (Fig. 7). Fourth-order bounding surfaces are surfaces that envelope fluvial lithosomes, or individual LAs. These bodies of rock include all architectural elements of Miall (1988*a*) that form within channels (i.e. lateral- and downstream-accretion LAs), with the exception of the CH

element, as well as those that form in the OB environment (i.e., CS and levee LAs). Because CH is the only channel architectural element present in this outcrop, fourth-order surfaces will only envelope CS LAs (Fig. 7). Third-order bounding surfaces are surfaces that envelope individual channel-fills, or CH LAs (Fig. 7). Rocks bounded by this order of surface will either be isolated in OB LAs, or amalgamated with other CH and CS LAs to form LA complexes. Second-order bounding surfaces are surfaces that envelope entire channel-belts (Fig.7). Bodies of rock within these surfaces include any channel architectural element of Miall (1988a). CH is the only element of this type present in Outcrop One, therefore LA complexes bounded by second-order surfaces will be segmented internally by third-order surfaces. Finally, first-order surfaces represent those surfaces that envelope an entire fluvial system, separating it from rocks of other depositional systems (Fig. 7). Because all of the rocks in Outcrop One are of fluvial origin, first-order surfaces are not illustrated in Fig. 8b. Sixth- and fifth-order surfaces are also not illustrated in Fig. 8b because the photomosaic does not adequately capture surfaces of such small-scale. In general, these smaller-order surfaces segment LAs bounded by fourth-, third-, and second-order surfaces (Fig. 7).

Rocks of the CH LA are the dominant constituents of Outcrop One, and exhibit a diverse range in architecture (Fig. 8b). There are three types of CH LAs characteristic of this outcrop that are based on overall geometry and stacking patterns: 1) isolated lenticular; 2) amalgamated lenticular; 3) amalgamated undulatory. The isolated lenticular CH LAs make up approximately 23 % of all CH LAs in the outcrop. These LAs are completely enveloped by OB and CS intervals (Fig. 8b), and have a maximum thickness of 3 to 8 m, with mean maximum thickness of 5 m. These LAs eventually pinch-out,

element, as well as those that form in the OB environment (i.e., CS and levee LAs).

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surfaces will only envelope CS LAs (Fig. 7). Third-order bounding surfaces are surfaces

that envelope individual channel-fills, or CH LAs (Fig. 7). Rocks bounded by this order

of surface will either be isolated in OB LAs, or amalgamated with other CH and CS LAs

to form LA complexes. Second-order bounding surfaces are surfaces that envelope entire

channel-belts (Fig.7). Bodies of rock within these surfaces include any channel

architectural element of Miall (1988*a*). CH is the only element of this type present in

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segmented internally by third-order surfaces. Finally, first-order surfaces represent those

surfaces that envelope an entire fluvial system, separating it from rocks of other

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origin, first-order surfaces are not illustrated in Fig. 8b. Sixth- and fifth-order surfaces

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Rocks of the CH LA are the dominant constituents of Outcrop One, and exhibit a

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this outcrop that are based on overall geometry and stacking patterns: 1) isolated

lenticular; 2) amalgamated lenticular; 3) amalgamated undulatory. The isolated lenticular

CH LAs make up approximately 23 % of all CH LAs in the outcrop. These LAs are

completely enveloped by OB and CS intervals (Fig. 8b), and have a maximum thickness

of 3 to 8 m, with mean maximum thickness of 5 m. These LAs eventually pinch-out,

resulting in a continual decease in thickness laterally. Width of individual isolated lenticular LAs range from 16 to 134 m, with mean width of 60 m (Fig. 14). Basal bounding surfaces of these LAs are typically erosive, sharp, concave or concavo-convex, and dominated by mud chips lags (Fig. 8b). Upper bounding surfaces are sharp, planar or undulating, and convex or concavo-convex (Fig. 8b). Both the basal and upper bounding surfaces are third-order bounding surfaces because they encase only CH LAs that are not within a channel-belt (Fig. 8b). Internally, the individual LAs of this group are segmented by sixth- and fifth-order bounding surfaces that separate individual lithofacies and lithofacies sequences.

The amalgamated lenticular type of CH LAs makes up approximately 48 % of all CH LAs in the outcrop. Individual amalgamated lenticular LAs have a maximum thickness of 5 to 18 m, with mean maximum thickness of 10 m. LA thickness decreases laterally by pinch-out into OB intervals, but also through truncation by other individual CH LAs of this type (Figs. 8b, 15a). Width of the individual LAs ranges from 40 to 192 m, with mean width of 100 m (Fig. 14). The individual lenticular CH LAs amalgamate to form LA complexes. These LA complexes contain a minimum amalgamation of two individual CH LAs, but can reach as many as seven if LAs of the amalgamated undulatory group are considered (Fig. 15b). This results in vertically continuous LA complexes that can reach approximately 48 m in thickness (Fig. 8b). Basal bounding surfaces are sharp, erosive, and concave or concavo-convex when OB intervals are below (Figs. 16a, 16b). These surfaces are commonly dominated by mud chip lags. Basal bounding surfaces are sharp or gradational, erosive, concave or concavo-convex, and planar or undulating when other CH LAs are below (Fig. 8b). Mud chip lags are less
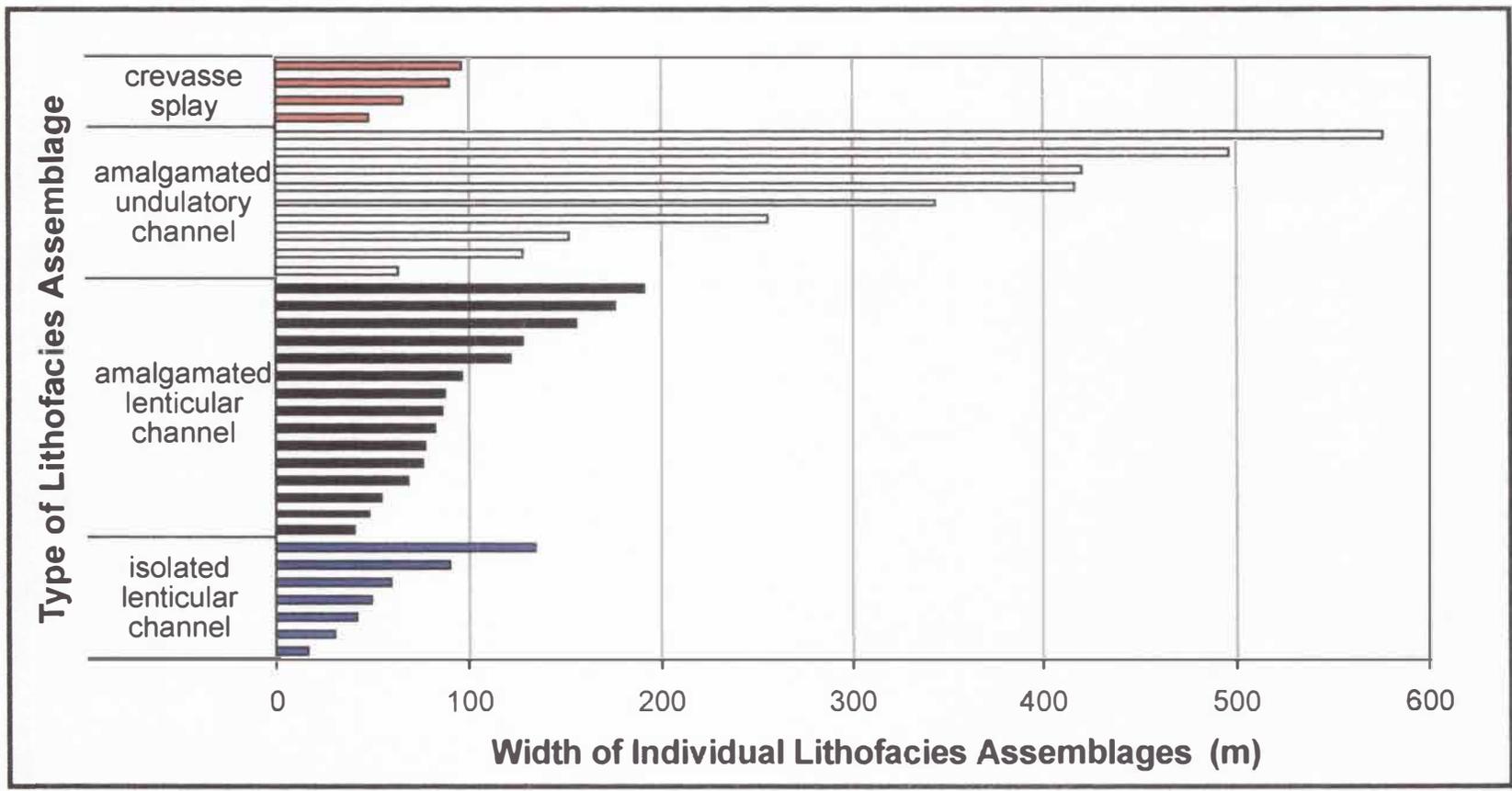
Fig. 14. Graph illustrating the width dimensions of sandstone-dominated lithofacies assemblages in Outcrop One.
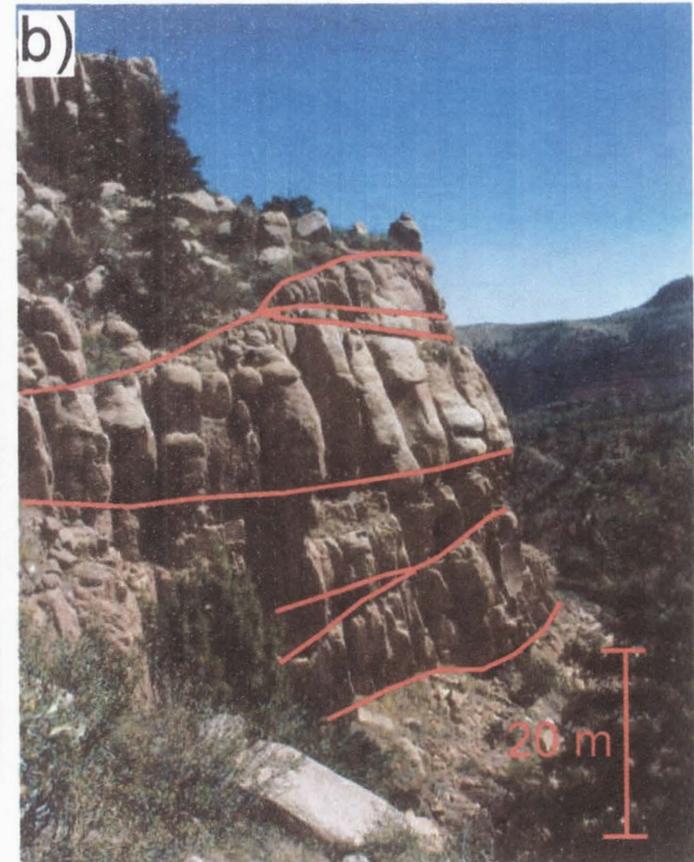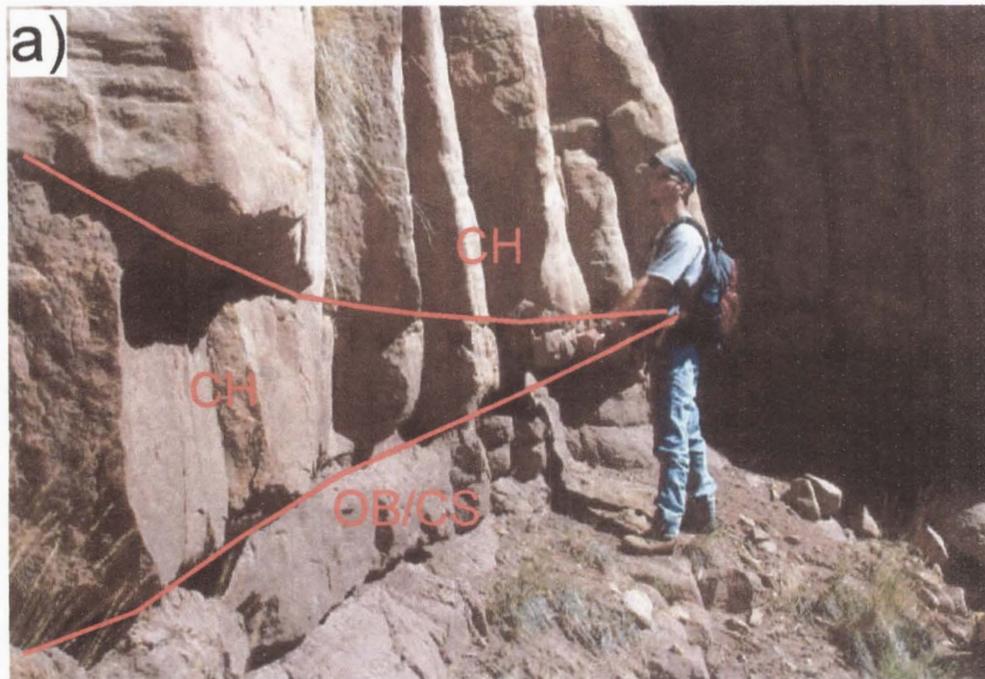
Fig. 15. Channel-fill lithofacies assemblage architecture. a) Lenticular channel-fill lithofacies assemblage truncating other lenticular channel-fill lithofacies assemblage. b) Stacked lenticular and amalgamated undulatory channel-fill lithofacies assemblages (Photo locations illustrated in Fig. 8a).
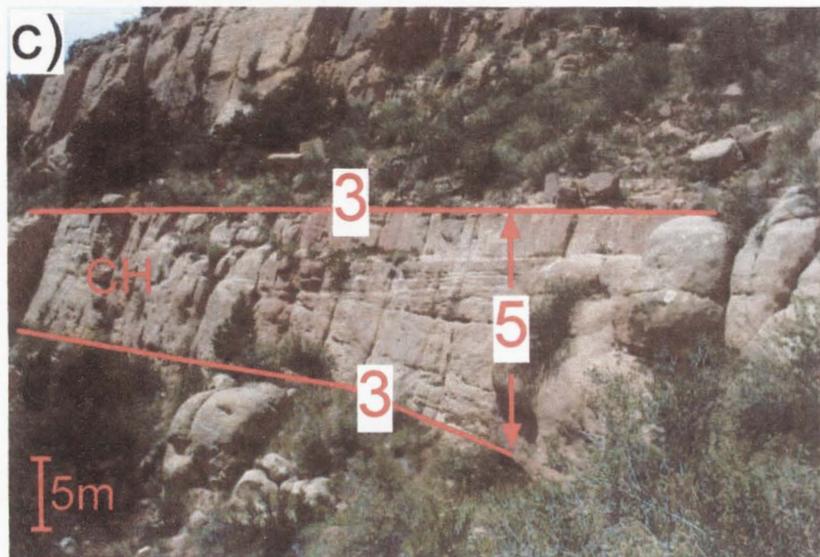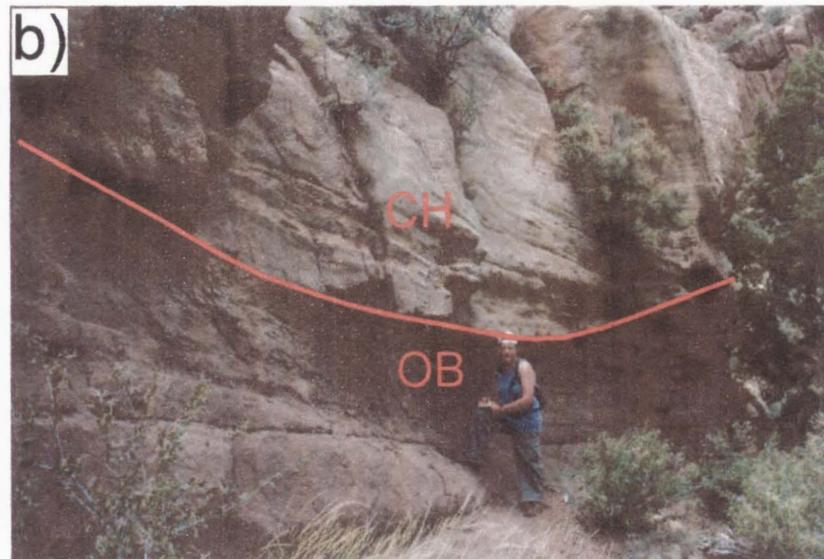
Fig. 16. Amalgamated lenticular channel-fill lithofacies assemblage architecture. a and b) Sharp, erosive, and concave basal bounding surfaces of amalgamated lenticular channel-fill lithofacies assemblages where overbank deposits are below. c) Amalgamated lenticular channel-fill lithofacies assemblage bounded by third-order bounding surfaces and segmented by fifth-order bounding surfaces (Photo locations illustrated in Fig. 8a).

common on these surfaces. Upper bounding surfaces are sharp, concavo-convex, and

undulating when OB intervals are above, and eroded, sharp or gradational, concavo-

convex, and planar or undulating when other CH LAs are above (Fig. 8b). These

surfaces are second-order bounding surfaces if marking the boundary of a channel-belt,

and third-order bounding surfaces if separating individual CH LAs within an LA complex

(Fig. 8b). When separating a CH LA from a CS LA in an LA complex, the surface is a

fourth-order bounding surface (Fig. 8b). Similar to the isolated CH LAs, individual

amalgamated lenticular CH LAs are segmented by sixth- and fifth-order bounding

surfaces (Fig. 16c).

The amalgamated undulatory type of CH LAs comprises the remaining 29 % of

all CH LAs in the outcrop. Individual LAs can either be amalgamated with one another,

or with individual LAs of the amalgamated lenticular CH LAs (Figs. 8b, 17a), to form

LA complexes. Individual amalgamated undulatory CH LAs have a maximum thickness

of 4 to 14 m, with mean maximum thickness of 8 m. Thickness of the individual LAs can

be as low as 3 m when truncated laterally or vertically by amalgamated erosive CH LAs

(Figs. 17b, 17c). Width of the individual LAs can reach 576 m when continuous across

the outcrop, with a minimum of 64 m when truncated laterally (Fig. 14). The mean width

for individual CH LAs of this type is 316 m. Basal bounding surfaces are sharp, erosive

or nonerosive, and planar or undulating when OB intervals are below (Fig. 8b). These

surfaces are often dominated by mud chip lags. When other sandstone units are below,

the basal bounding surfaces are sharp or gradational, erosive or nonerosive, and planar or

undulating, with mud chip lags concentrated in the erosive areas (Fig. 8b). Upper

bounding surfaces are sharp, and planar or undulating when OB deposits are above, and
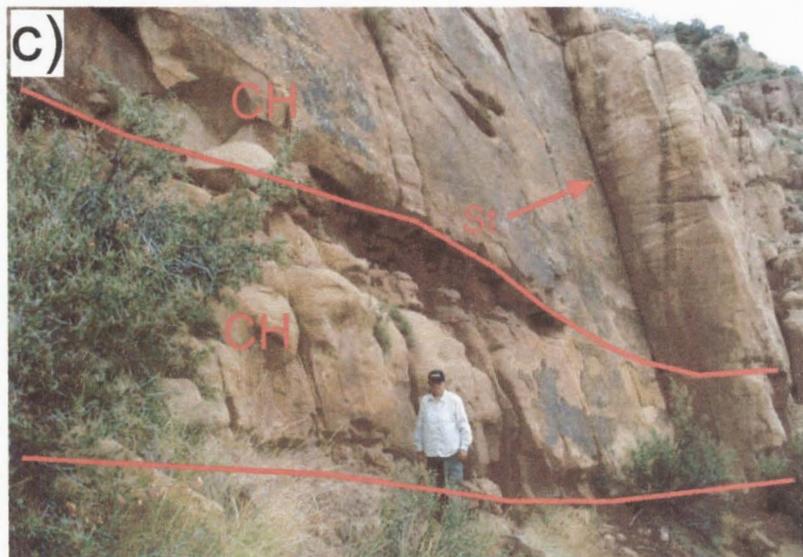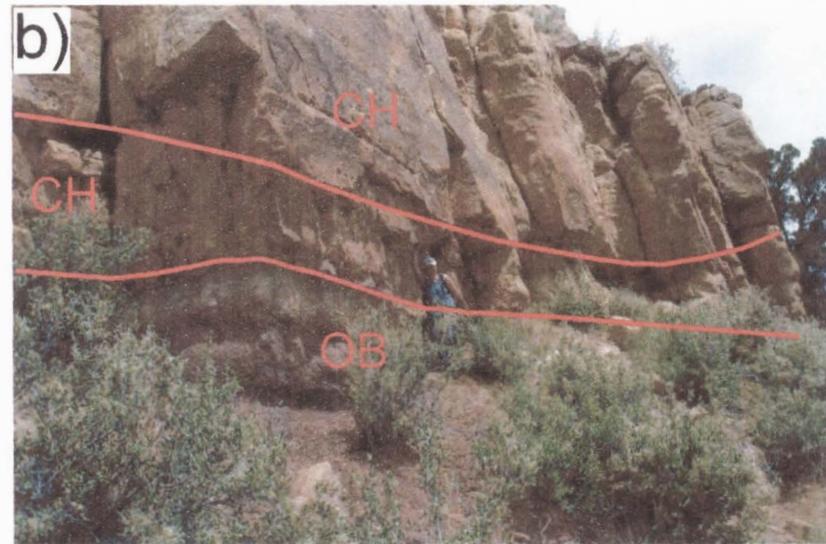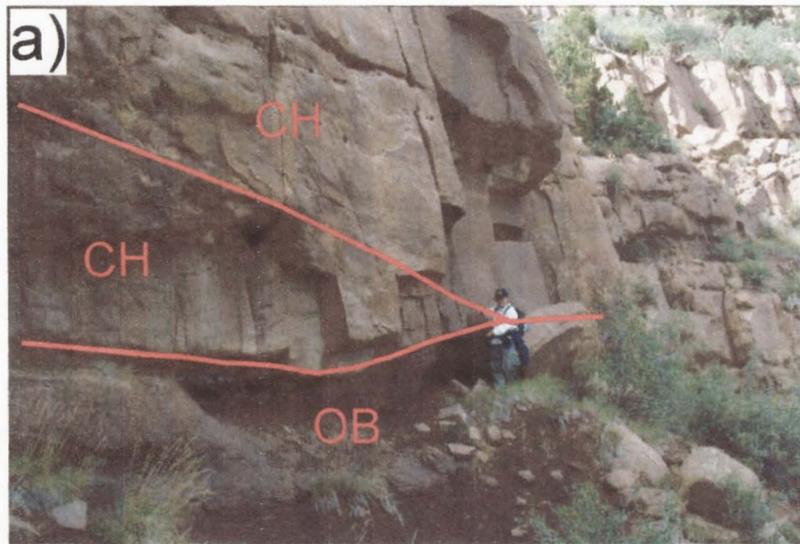
Fig. 17. Amalgamated undulatory channel-fill lithofacies assemblage architecture. a) Amalgamation of two undulatory channel-fill lithofacies assemblages. b and c) Amalgamated undulatory channel-fill lithofacies assemblages being truncated by overlying amalgamated lenticular channel-fill lithofacies assemblages (Photo locations illustrated in Fig. 8a).

sharp or gradational, eroded, and planar or undulating when sandstone units are above

(Fig. 8b). These surfaces are second-order bounding surfaces if marking the boundary of

a channel-belt, and are third-order bounding surfaces if separating individual CH LAs in

an LA complex within the channel-belt (Fig. 8b). Sixth- and fifth-order bounding

surfaces also segment the individual amalgamated undulatory CH LAs.

Rocks of the CS LA are rare in Outcrop One. The individual LAs are lens- or

wedge-shaped, and are either amalgamated with other CS LAs, or truncated by adjacent

CH LAs (Fig. 8b). Both cases form LA complexes. Rocks of the CS LA also occur as

small tabular units within OB intervals (Figs. 8b, 18a). These smaller units are relatively

thin and are not traceable across the outcrop because of covered intervals, resulting in an

inability to map the surfaces on the photomosaic. These CS deposits are labeled in Fig.

8b, but are not utilized when addressing LA architecture and bounding surfaces.

Individual CS LAs have a maximum thickness of 6 to 10 m, with mean maximum

thickness of 8 m. Thickness decreases laterally in these LAs as they pinch-out into OB

deposits, or by truncation of adjacent or overlying CS or CH LAs (Fig. 8b). The width of

the individual CS LAs ranges from 48 to 96 m, with mean width of 72 m (Fig. 14). Basal

bounding surfaces of these LAs are sharp, erosive, concave, and undulating when OB

deposits are below, and sharp or gradational, erosive, and planar or undulating when

other CS LAs are below (Fig. 8b). Mud chip lags are common on these surfaces. Upper

bounding surfaces are sharp, and planar or undulating when OB deposits are above, and

sharp, eroded, and planar or undulating when other CS LAs are above (Fig. 8b). These

surfaces are fourth-order bounding surfaces, including those cases where the surfaces
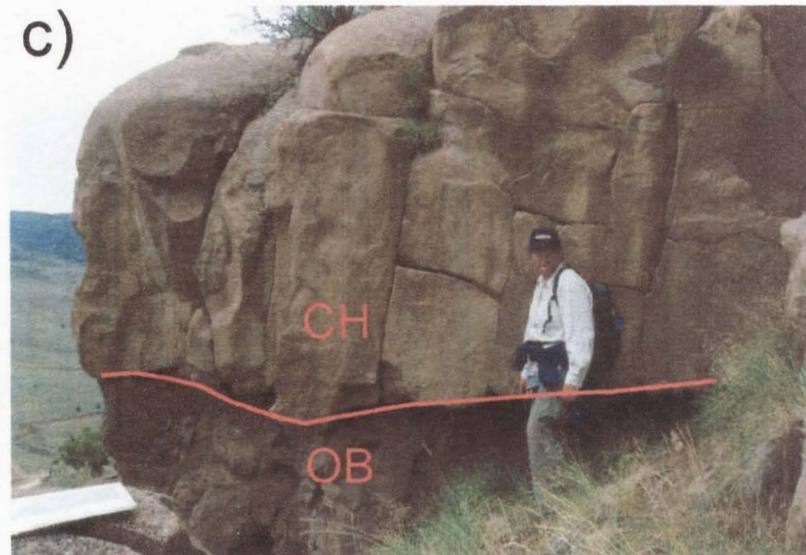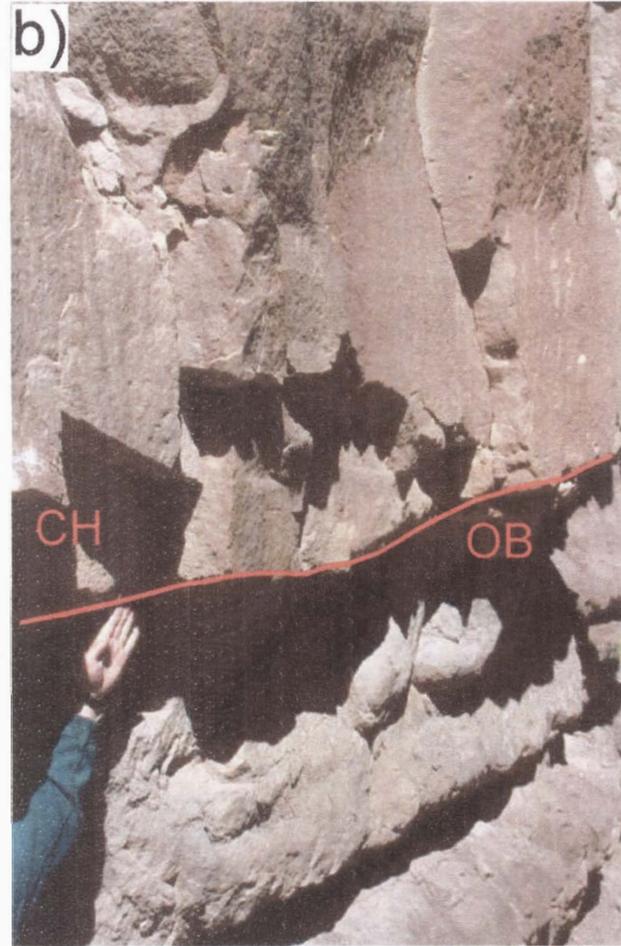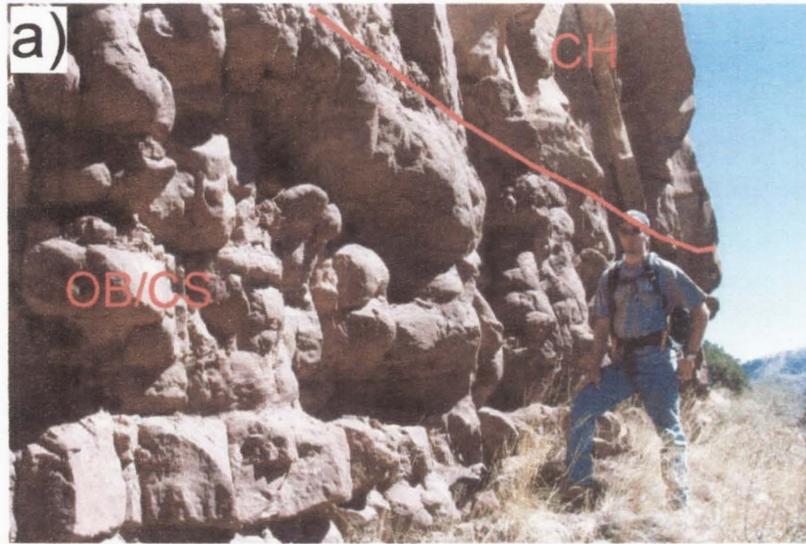
Fig. 18. Overbank and crevasse splay architecture. a) Tabular overbank and crevasse splay lithofacies assemblages truncated by channel-fill lithofacies assemblage. b and c) Truncation of overbank deposits by channel-fill lithofacies assemblages (Photo locations illustrated in Fig. 8a).

separate CS LAs from adjacent erosive CH LAs (Fig. 8b). Sixth- and fifth-order

bounding surfaces segment individual CS LAs.

Encasing all of the CH and CS LAs in Outcrop One are OB deposits (Fig. 8b).

These units are relatively tabular and laterally extensive, except where truncated by

individual or complexes of CH and CS LAs (Figs. 18b, 18c). Continual segmentation by

sand-rich units, combined with extensive covered intervals in the OB areas, results in the

inability to properly document LA architecture and bounding surfaces. The thickness of

these units is quite variable. In areas where CH and CS LAs are absent, OB deposits can

stack vertically to produce a continual 26 m interval (Fig. 8b). Conversely, in areas

where CH and CS LAs are abundant and form LA complexes, OB deposits may be as

thin as 10 cm.

Petrography

This section summarizes petrographic data pertaining to the outcrop as a whole,

as well as to the CH and CS LAs discussed above. Sandstone samples of Outcrop One

were point counted using ten categories: pore space, calcite cement, clay cement, lithic

framework, quartzofeldspathic framework, silt matrix, mud matrix, replaced grains, mica,

and mud chips. Percentages of these individual parameters are presented below, along

with grain type, grain size, sorting, and roundness data. The % mud matrix, % mica, and

% mud chips categories have been combined to form a % detrital mud category. The

mean grain size of sandstone samples in Outcrop One ranges from 0.226 to 0.414 mm

(fine to medium sand), with average mean grain size of 0.321 mm (medium sand) (Fig.

19). Porosity ranges from 0.4 to 19.6 %, with average porosity of 10.2 % (Fig. 20).
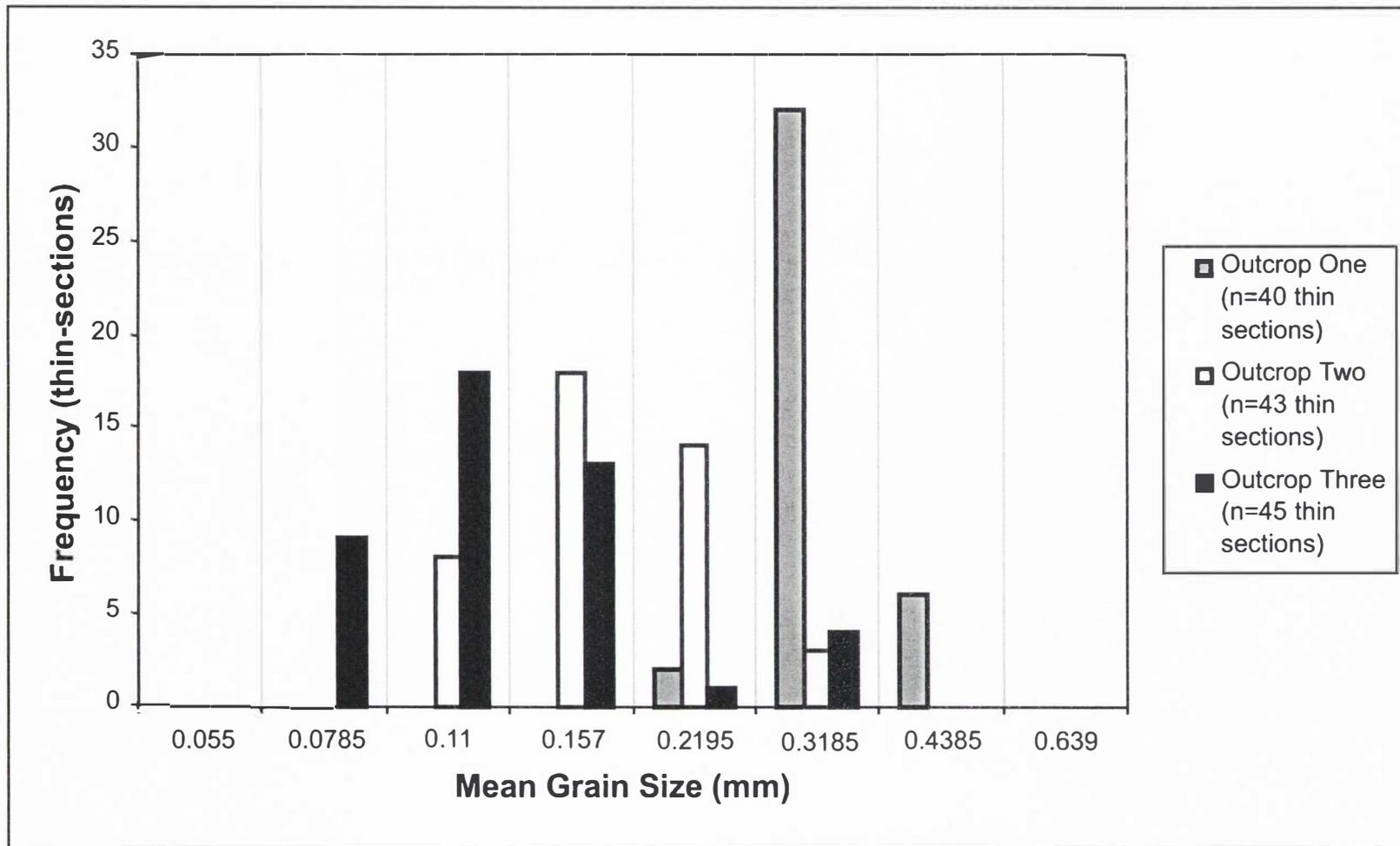
Fig. 19. Histogram of mean grain size for sand-dominated samples of each outcrop. Outcrop One has the highest mean grain size, with a peak at medium sand. In contrast, Outcrop Three has the lowest mean grain size, with a peak at very fine to fine sand (Data used for this graph are summarized in the Appendix).
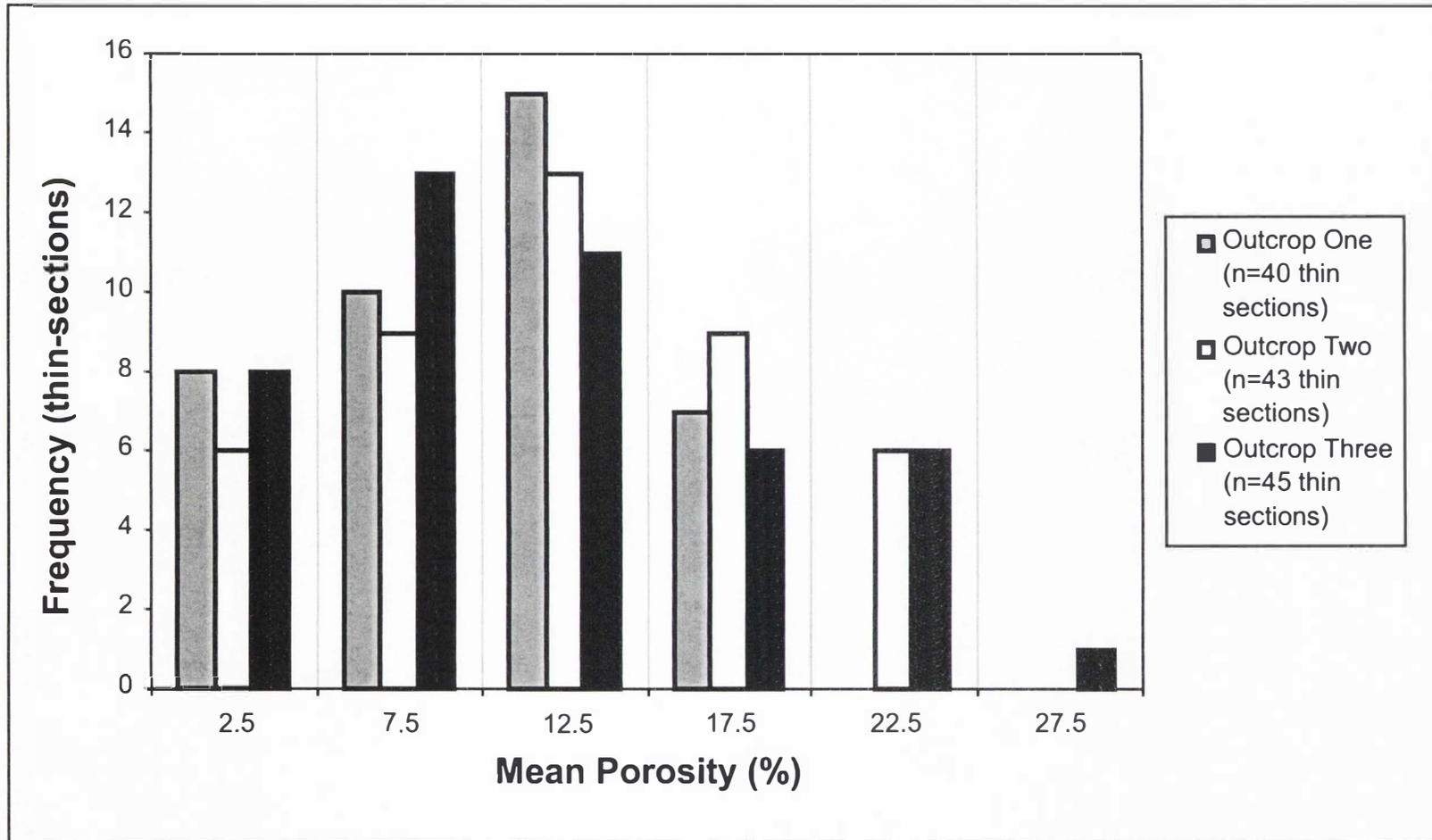
Fig. 20. Histogram of mean porosity for sand-dominated samples of each outcrop. Outcrop Three has the largest range in mean porosity, whereas Outcrop One has the smallest range in mean porosity. All outcrops show a peak in mean porosity between 5 and 15 %. This is consistent with the average porosity range of the three outcrops, which is between 10.2 and 13.3 % (Data used for this graph are summarized in the Appendix).

Outcrop percentages of calcite cement range from 12.6 to 43.6 % of the samples, with an average of 21.9 %. The anomalously high calcite cement percentages are most likely attributed to the difficulty of differentiating calcite-replaced grains from calcite cement. Detrital mud percentages range from 0.4 to 15 %, with average of 7.3 %. Comparisons of these values illustrate that there is no relationship between porosity and mean grain size (Fig. 21). In contrast, calcite cement content and porosity show a direct relationship (Fig. 22).

Sandstone samples of the CH LA have an average mean grain size of 0.331 mm (medium sand). Quartzofeldspathic framework grains make up between 44.4 and 66.2 % of the samples, with average of 54.3 % (Appendix). The grains are poorly to well sorted, angular to well rounded monocrystalline quartz with minor amounts of polycrystalline quartz, chert, plagioclase feldspar, and potassium feldspar. Grains replaced by calcite typically make up between 0.8 to 5.2 % of the samples. Lithic framework grains typically make up < 1 % of the samples. Calcite is the dominant cement, making up 21.9 % of the samples on average, with a maximum of 43.6 % (Fig. 23a). Clay cement is less abundant, and ranges from 1.4 to 6.6 % of the samples. Detrital mud averages 7.8 % of the samples, and is typically highest in the basal portions of individual CH LAs (Fig. 23b). This observation can be attributed to the concentrations of mud chip lags that are characteristic of these areas. Pore space makes up between 0.4 and 18.2 % of the samples, with an average of 9.8 % (Figs. 23a, 24). The amalgamated undulatory CH LAs preserve a greater amount of sandstone samples with high porosity and mean grain size values than do the other CH LAs of Outcrop One. Further, these higher values are typically characteristic of samples of the St lithofacies.
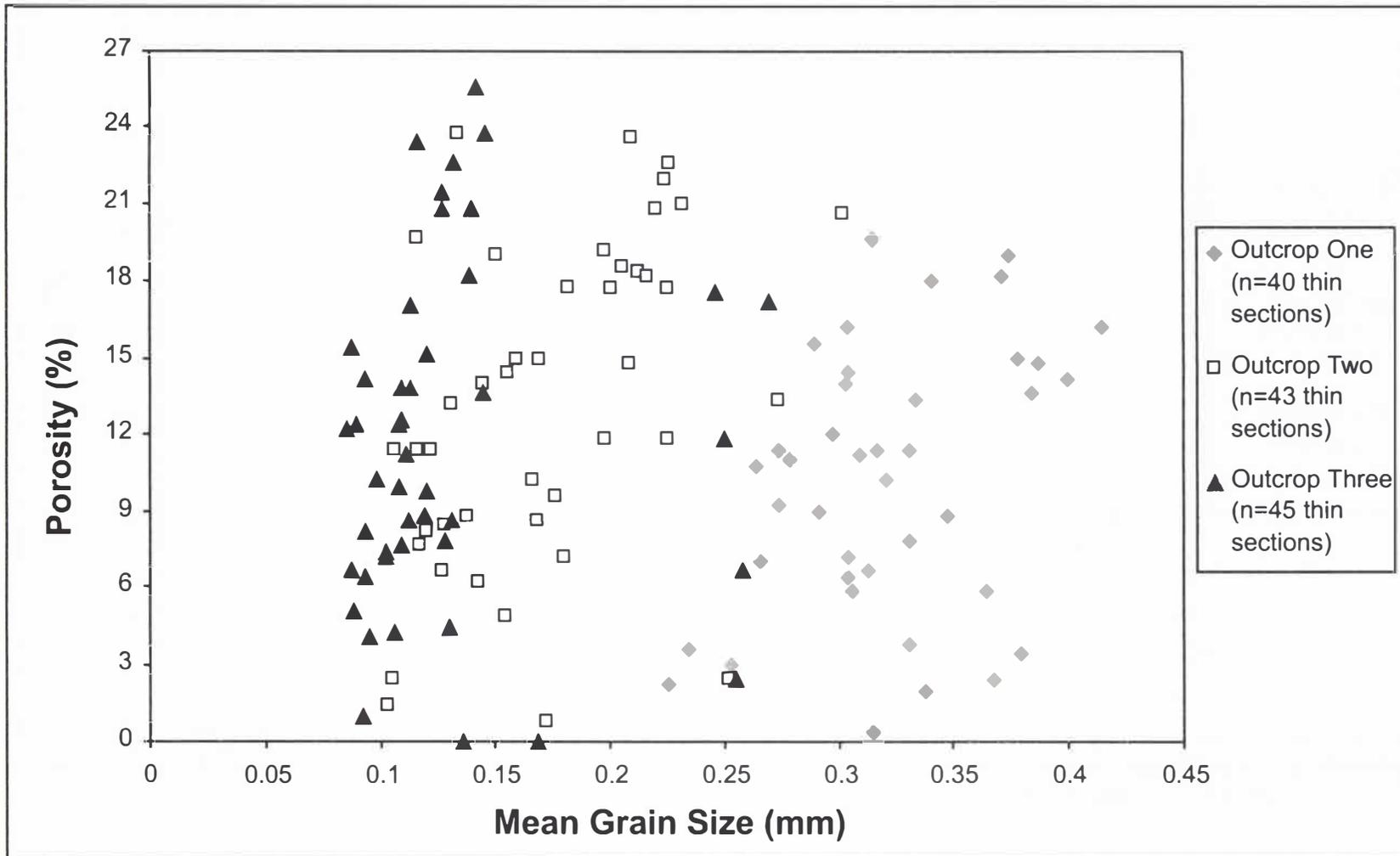
Fig. 21. Distribution of mean grain size versus percent porosity for sand-sized samples of each outcrop. Note that there is no relationship between these two parameters in any of the outcrops. Therefore, mean grain size is not a good proxy for petrophysical parameters (Data used for this graph are summarized in the Appendix).
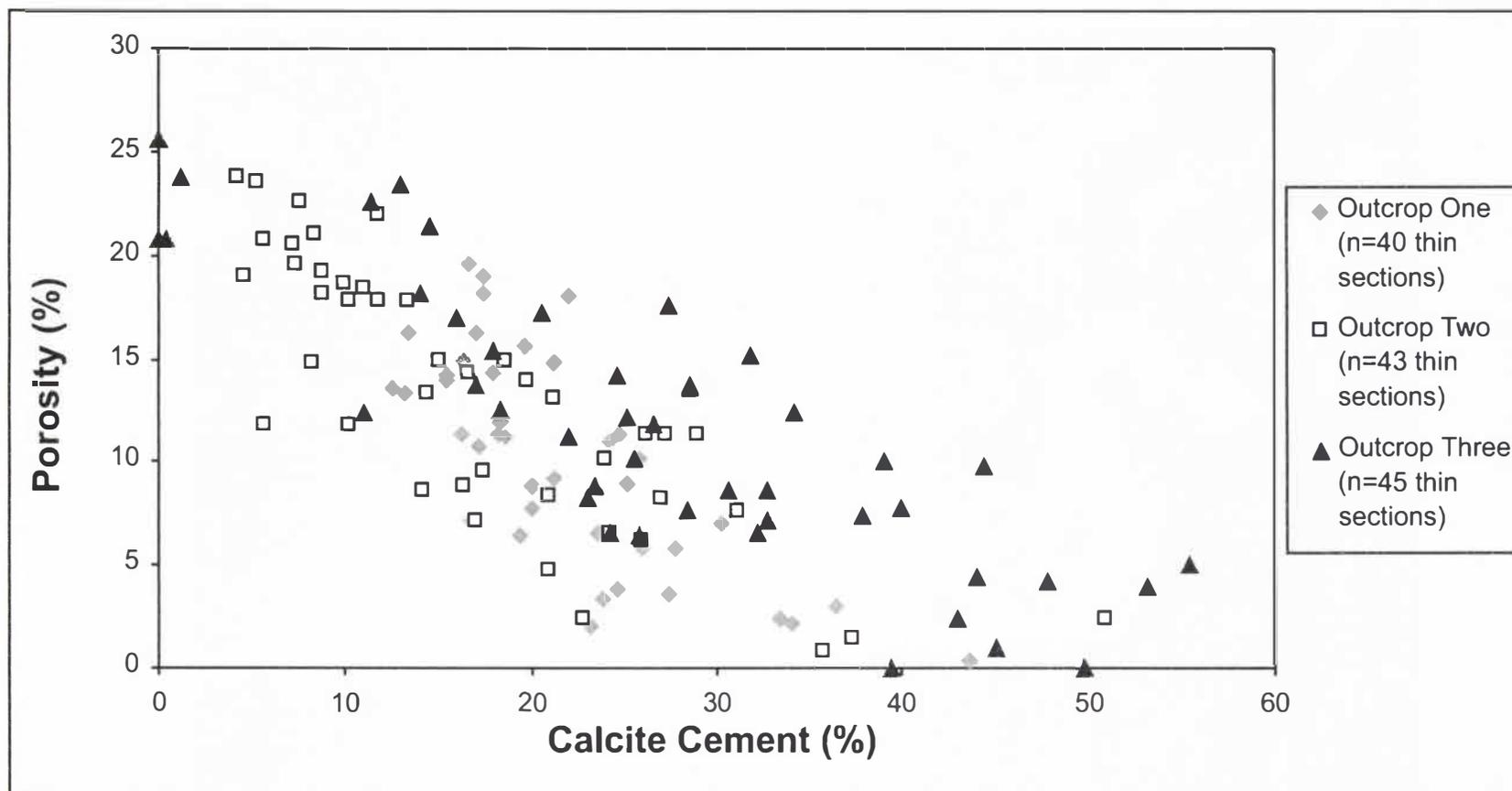
Fig. 22. Distribution of percent porosity versus percent calcite cement for samples of each outcrop. Note the direct relationship between these two parameters in each outcrop, suggesting diagenesis is the primary control on porosity (Data used for this graph are summarized in the Appendix).
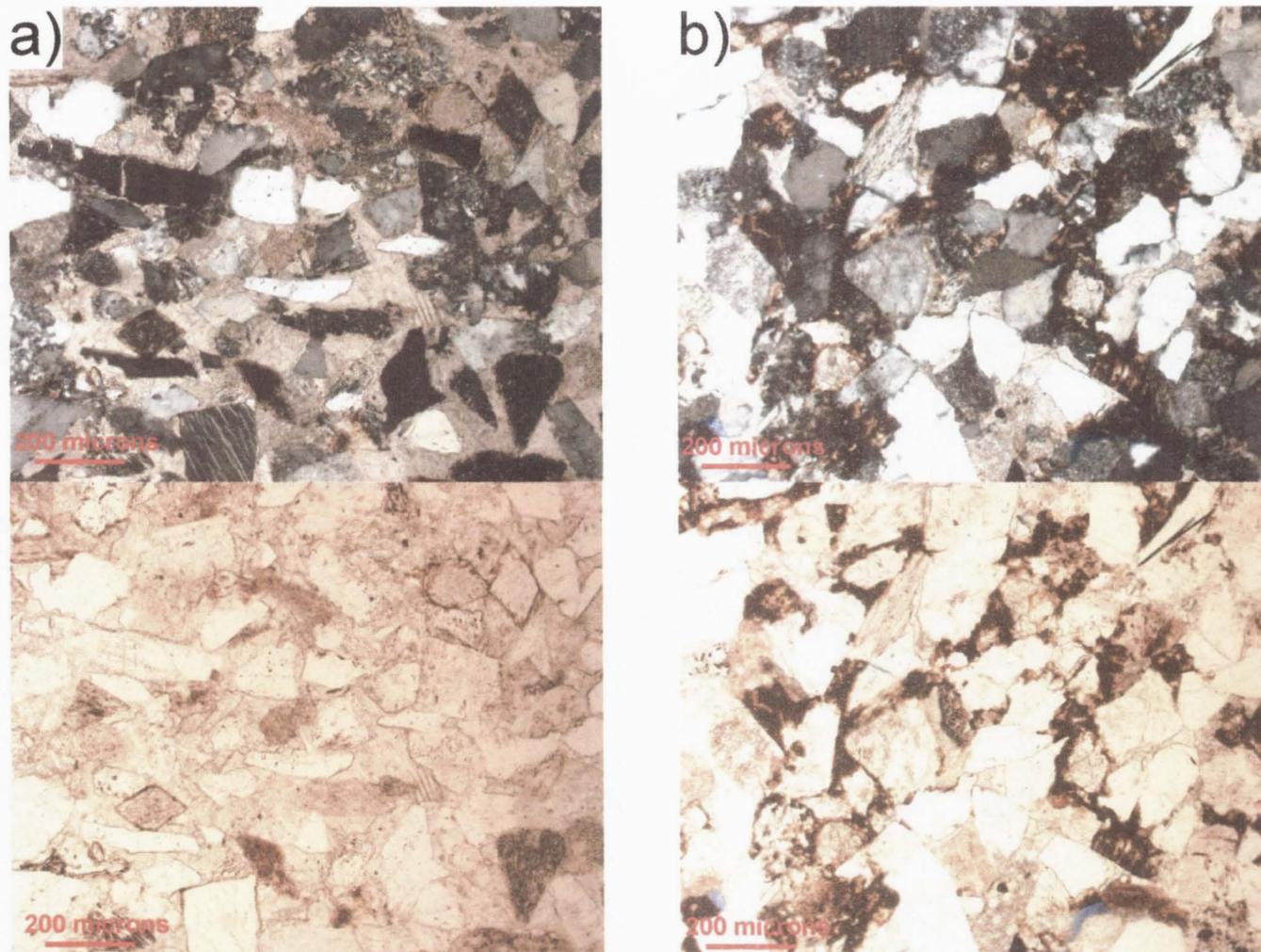
Fig. 23. Photomicrographs of channel-fill sandstone samples. a) (sample 01-21) low porosity and abundant calcite cement. b) (sample 01-32) abundant detrital mud (top photos are under cross polarized light and bottom photos are under plane polarized light).
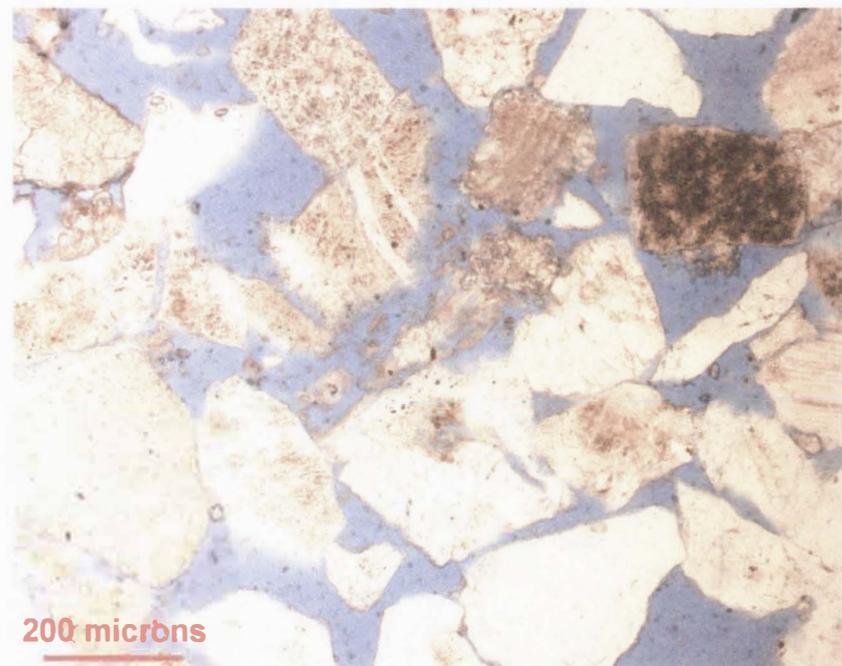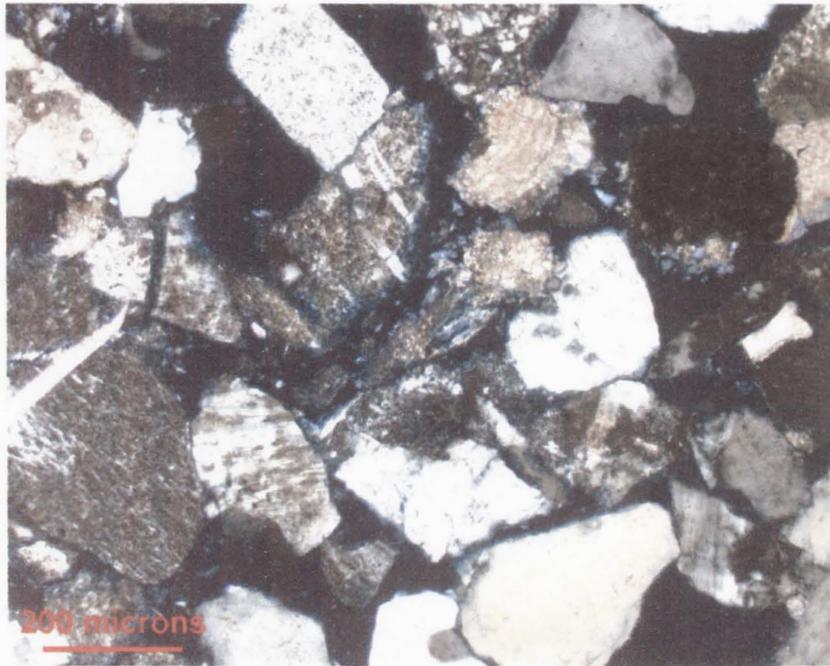
Fig. 24. Photomicrographs of a channel-fill sandstone sample exhibiting good porosity (sample 01-59)
(left photo is under cross polarized light and right photo is under plane polarized light).

Sandstones of the CS LA have an average mean grain size of 0.293 mm (medium sand). Quartzofeldspathic grains are the dominant constituents of framework grains in these samples, making up 44.6 to 57.6 % of the samples, with average of 50.4 % (Appendix). Grain types, sorting, and roundness are similar to sandstone samples of the CH LA, except that calcite replaced grains make up only 0.4 to 3.4 % of these samples. Calcite cement has a higher percentage in samples of the CS LA, making up 24 % of the samples on average (Figs. 25, 26). In contrast, clay cement is less abundant in these samples, ranging from 1.8 to 4.8 %. Detrital mud also makes up less of these samples, with an average of 6 %. Pore space comprises 2.2 to 19.6 % of the sandstone samples in this LA, with an average of 11.1 % (Figs. 25, 26). Petrographic trends noticeable in the CS LAs include an abundance of samples with higher porosity values in the basal portions of individual CS LAs and higher porosity and mean grain size values in sandstone samples of the St lithofacies.

Outcrop Two: Deltaic facies of the Green River Formation

Sedimentology

Description. Outcrop Two is composed of five LAs: 1) trough cross-stratified sandstone - rippled sandstone – low-angle cross-stratified sandstone - plane bedded sandstone – planar cross-stratified sandstone - massive sandstone (St-Sr-Sl-Sh-Sp-Sm); 2) trough-cross stratified sandstone – rippled sandstone – low-angle cross-stratified sandstone (St-Sr-Sl); 3) low-angle cross-stratified sandstone – rippled sandstone – trough cross-stratified sandstone – massive sandstone – rippled siltstone (Sl-Sr-St-Sm-Fsr); 4)
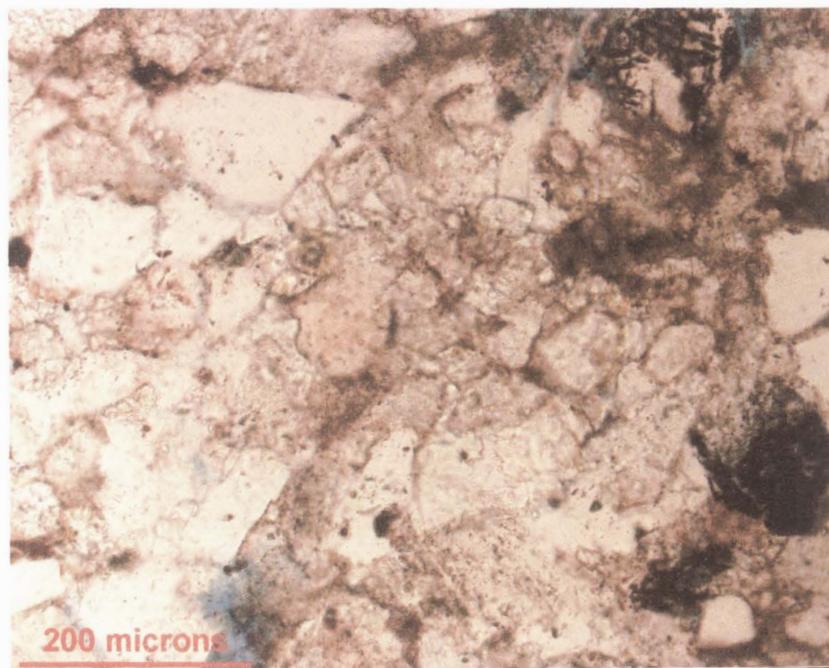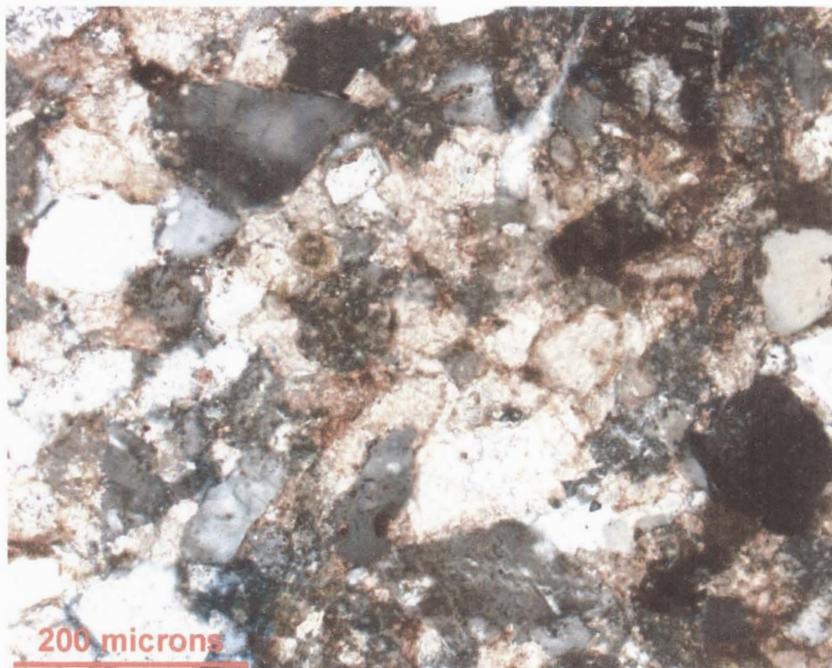
Fig. 25. Photomicrographs of a crevasse splay sandstone sample exhibiting low porosity and abundant calcite cement and detrital mud (sample 01-40) (left photo is under cross polarized light and right photo is under plane polarized light).
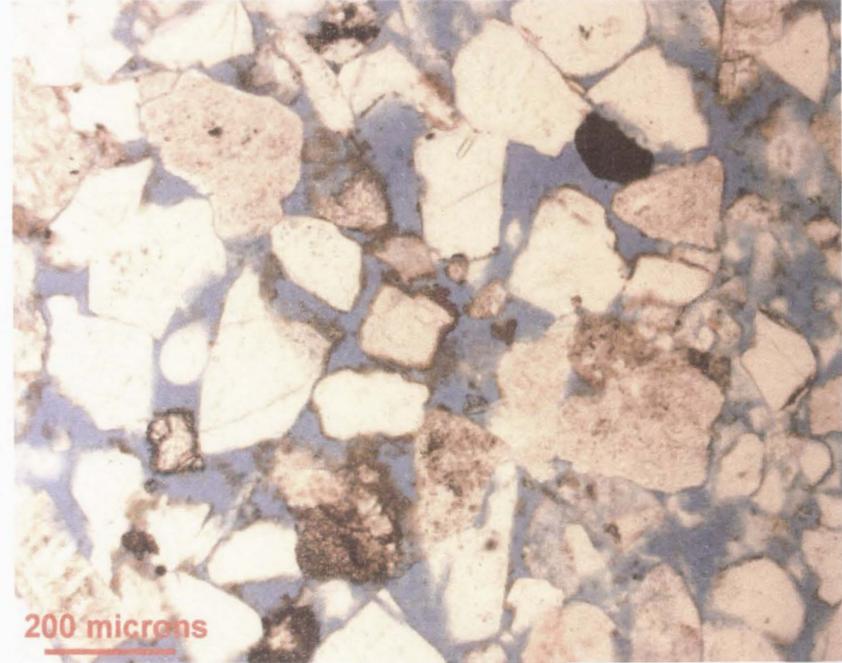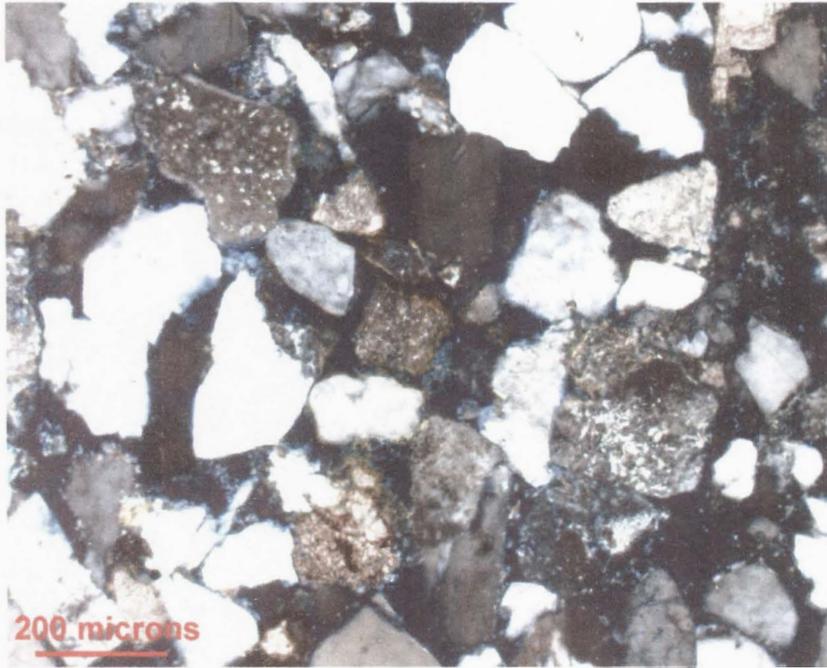
Fig. 26. Photomicrographs of a crevasse splay sandstone sample exhibiting good porosity with little calcite cement (sample 01-9) (left photo is under cross polarized light and right photo is under plane polarized light).

laminated siltstone – massive siltstone – massive mudstone – laminated mudstone –

carbonate (Fsh-Fsm-Fm-Fmh-carbonate); 5) massive siltstone – massive mudstone (Fsm-

Fm) (Fig. 6b). The St-Sr-Sl-Sh-Sp-Sm LA is abundant in the outcrop, and consists of tan

or red, fine to medium grained, trough cross-stratified, and rippled sandstone. In less

abundance are tan or red, fine to medium grained, low-angle cross-stratified, plane

bedded, planar cross-stratified, and massive sandstone. Individual beds range in

thickness from 50 cm to 4.5 m, and are tabular or lenticular. Basal bedding surfaces are

sharp or gradational, and are frequently erosive. 10 to 30 cm thick discontinuous beds of

massive siltstone and mudstone are occasionally interbedded with individual sandstone

beds of this LA. Mud chips, large mud clasts, and soft-sediment deformation are

common, but not restricted to basal bedding surfaces. These rocks occur as isolated

individual LAs within the siltstone- and mudstone-dominated intervals, or as LA

complexes when amalgamated with the same and other sandstone-rich LAs. Geometry of

these individual LAs ranges from lenticular to undulatory. The St-Sr-Sl LA is another

major constituent of Outcrop Two, and consists of 20 cm to 2 m thick beds of tan or red,

fine to medium grained, trough cross-stratified, low-angle cross-stratified, and rippled

sandstone. Beds are primarily tabular and laterally extensive, but can also be lenticular.

Basal bedding surfaces are either gradational or sharp, and frequently erosive. Sandstone

beds of this LA are also frequently interbedded with 10 to 30 cm thick beds of massive

siltstone and mudstone. Mud chips and soft-sediment deformation are common, but not

restricted to basal bedding surfaces. Plant debris and burrows are rare. The geometry of

these individual LAs is tabular and laterally extensive across the entire outcrop, and is

usually encased by mudstone- and siltstone-rich LAs, except where truncated by other

sandstone rich LAs. In parts of the outcrop, rocks of this LA are inferred due to extensive covered intervals.

The Sl-Sr-St-Sm-Fsr LA consists of 10 to 70 cm thick beds of tan, fine to medium grained, low-angle cross-stratified, rippled, trough cross-stratified, and massive sandstone, and rippled siltstone. Rocks of this LA are frequently calcareous. Individual beds are primarily tabular and laterally extensive. Basal bedding contacts are sharp or gradational, and are frequently erosive. Mud chips and soft-sediment deformation are common, and are restricted to basal bedding surfaces. Plant debris and ostracodes are also common. Burrows are rare. The Fsh-Fsm-Fm-Fmh-carbonate LA contains 10 cm to 1 m thick beds of reddish-gray or green, massive, and laminated siltstone and mudstone. Also present in less abundance are beds of tan or orange micrite. The clastic mudstone and siltstone beds of this LA are also very calcareous. Individual beds are tabular and laterally extensive, with basal surfaces that range from gradational to sharp. Burrows, plant material, and shell fragments are common in this LA. Rocks of the previous two LAs are typically interbedded with each other, and encase the sandstone-rich LAs of the outcrop. These LAs are tabular and laterally extensive across the outcrop, except where truncated by the thick-bedded sandstone-rich LAs mentioned in the previous paragraph. The lateral and vertical extent of these LAs is frequently inferred due to extensive covered intervals.

Rocks of the Fsm-Fm LA are least abundant in Outcrop Two, and consist of 10 cm to 1 m thick beds of green massive siltstone and mudstone. Beds are tabular and laterally extensive, with basal bedding surfaces that are typically sharp. Plant debris and burrows are common. Rocks of this LA are hard to decipher from those of the other

mudstone- and siltstone-dominated LA, primarily because they are frequently covered. However, this LA is exposed in the top portion of the outcrop, where it is truncated by rocks of the lenticular and undulatory sandstone-rich LAs.

Interpretation. Rocks of the Fsh-Fsm-Fm-Fmh-carbonate LA are interpreted as deposits of suspension load fall-out of silt and mud in a quiet water organic-rich environment. The LA is interpreted to represent deposition in an offshore lacustrine environment during times of low clastic input (Fouch and Dean, 1982). These deposits are characteristic of the prodelta setting described by Bhattacharya and Walker (1992). These rocks are named offshore lacustrine mudstone and siltstone deposits, and will further be termed OSMS (Figs. 6b, 9b). The presence of shell and plant fragments, bioturbation, calcareous siltstone and mudstone beds, and rare micritic beds indicate that this depositional environment had favorable living conditions (Figs. 6b, 27a). Interbedded with the OSMS deposits are rocks of the Sl-Sr-St-Sm-Fsr LA. Together, these two LAs encase the thick-bedded sandstone-dominated LAs in the outcrop. The mechanism of deposition for rocks of the Sl-Sr-St-Sm-Fsr LA is interpreted as unidirectional migration of subaqueous sand and silt bedforms of varying sizes and flow regimes (Sl, Sr, St, and Fsr), and bioturbated or rapid suspension load fall-out of sand (Sm). This LA is interpreted as shallow lacustrine sandsheet, or storm deposits, and will further be named SLS (Figs. 6b, 9b). This interpretation is consistent with shallow lacustrine features described by Fouch and Dean (1982), and with proximal prodelta features described by Bhattacharya and Walker (1992). Because the relatively thin-bedded rocks of this LA are typically interbedded with OSMS deposits, their
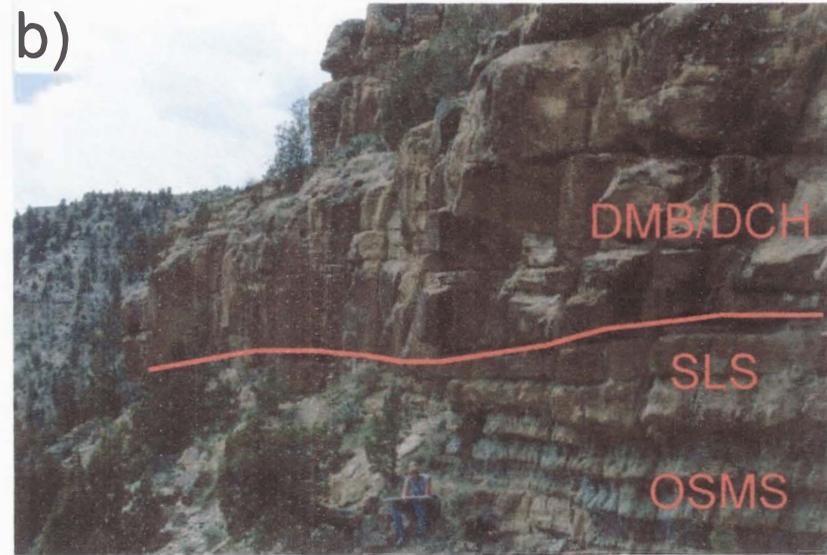
Fig. 27. Offshore lacustrine mudstone and siltstone and shallow lacustrine sandsheet/storm lithofacies assemblage architecture. a) Tabular and laterally extensive carbonate rich offshore lacustrine mudstone and siltstone deposits. b) Interbedded offshore lacustrine mudstone and siltstone and sand-rich shallow lacustrine sandsheet/storm lithofacies assemblages below distributary mouth bar and distributary channel lithofacies assemblages (Photo locations illustrated in Fig. 9a).

environment of deposition is also interpreted as offshore lacustrine (Fig. 27b).

However, rocks of this LA are characteristic of times when energy was higher in the

system. This is supported by the presence of erosive basal bedding surfaces with

common mud chip lags, horizons filled with ostracode fragments, and an abundance of

sand (Fig. 6b). A lack of burrows provides further support that living conditions were

minimized, potentially as a result of this high-energy environment.

Rocks of the St-Sr-Sl LA are typically found overlying the OSMS and SLS

deposits in Outcrop Two (Fig. 9b). These rocks are interpreted as deposits of

unidirectional migration of subaqueous sandy bedforms of varying sizes and flow

regimes. This LA is interpreted to represent distributary mouth bar deposits of the delta

front setting, and will further be termed DMB (Figs. 6b, 9b). This interpretation is

consistent with descriptions of these types of deposits by Coleman and Prior (1982), and

Elliott (1986). Evidence supporting the high-energy unidirectional nature of flow that

produced these deposits includes erosive basal bedding surfaces, mud chip lags that are

not restricted to basal bedding surfaces, the dominance of St, Sr, and Sl beds, and a lack

of burrowing (Figs. 6b, 28). Rocks of this LA form thick tabular and laterally extensive

LAs that are persistent across the outcrop, except where truncated by overlying lenticular

or undulatory sandstone-rich LAs (Fig. 9b).

The mechanism of deposition for rocks of the St-Sr-Sl-Sh-Sp-Sm LA is

interpreted as unidirectional migration of channelized subaqueous sandy bedforms of

varying sizes and flow regimes (St, Sr, Sl, and Sp), and bioturbated or rapid suspension

load fall-out of sand (Sm). This LA is interpreted as distributary channel deposits of the

delta plain setting, and is further termed DCH (Figs. 6b, 9b). This interpretation is

Fig. 28. Sedimentology of the distributary mouth bar lithofacies assemblage. a) Rippled sandstone in the distributary mouth bar lithofacies assemblage. b) Rippled to small-scale trough cross-stratified sandstone with minor soft-sediment deformation in the distributary mouth bar lithofacies assemblage
(Photo locations illustrated in Fig. 9a).

supported by descriptions of settings of this type by Coleman and Prior (1982), and Elliott (1986). Unidirectional flow indicators dominate in the rocks of this LA (Sl, Sr, St, and Sp), and St is the most abundant lithofacies (Fig. 6b). The abundance of St illustrates that flows were high velocity and probably confined. Further evidence for channelization is the abundance of lenticular LA geometry (Fig. 9b), and evidence for high-energy deposition includes mud chip lags and large mud clasts, erosive basal bedding surfaces, and the presence of upper regime plane beds (Sh) (Figs. 6b, 29). These rocks are either isolated individual LAs in OSMS and SLS intervals, or erosively amalgamated with underlying DMB LAs.

The Fsm-Fm LA is interpreted as suspension load fall-out deposits of mud or silt that were later bioturbated or pedoturbated. Because rocks of this LA are only found in the upper portion of the outcrop associated with amalgamated DCH LAs, they are interpreted as overbank or floodplain deposits of the delta plain setting, and will further be termed OB (Figs. 6b, 9b). This interpretation is supported by the presence of plant debris and burrows, which are common in these settings. Individual beds of this LA are typically thicker than those of the OSMS LA, and the green color of the rocks is very distinct (Fig. 30). These characteristics, along with the absence of SLS interbeds, provide support to separate these rocks from those of the OSMS LA.

LA architecture and bounding surfaces

Rocks of the DCH LA are a dominant constituent of Outcrop Two, and are very diverse in terms of LA architecture (Fig. 9b). There are three types of DCH LAs characteristic of this outcrop: 1) isolated lenticular; 2) amalgamated lenticular; 3)
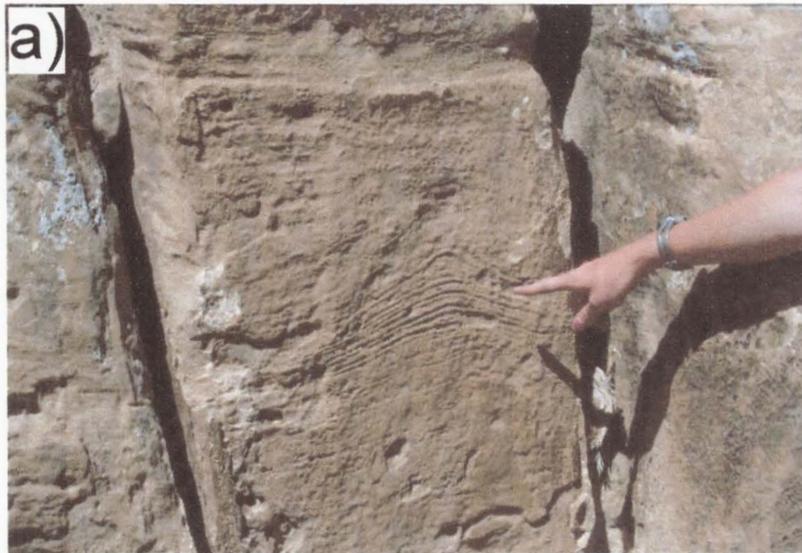
Fig. 29. Sedimentology of the distributary channel lithofacies assemblage. a) Soft-sediment deformation in sandstone of the distributary channel lithofacies assemblage. b) Large mud clasts (indicated by arrows) common in sandstone of the distributary channel lithofacies assemblage
(Photo locations illustrated in Fig. 9a).
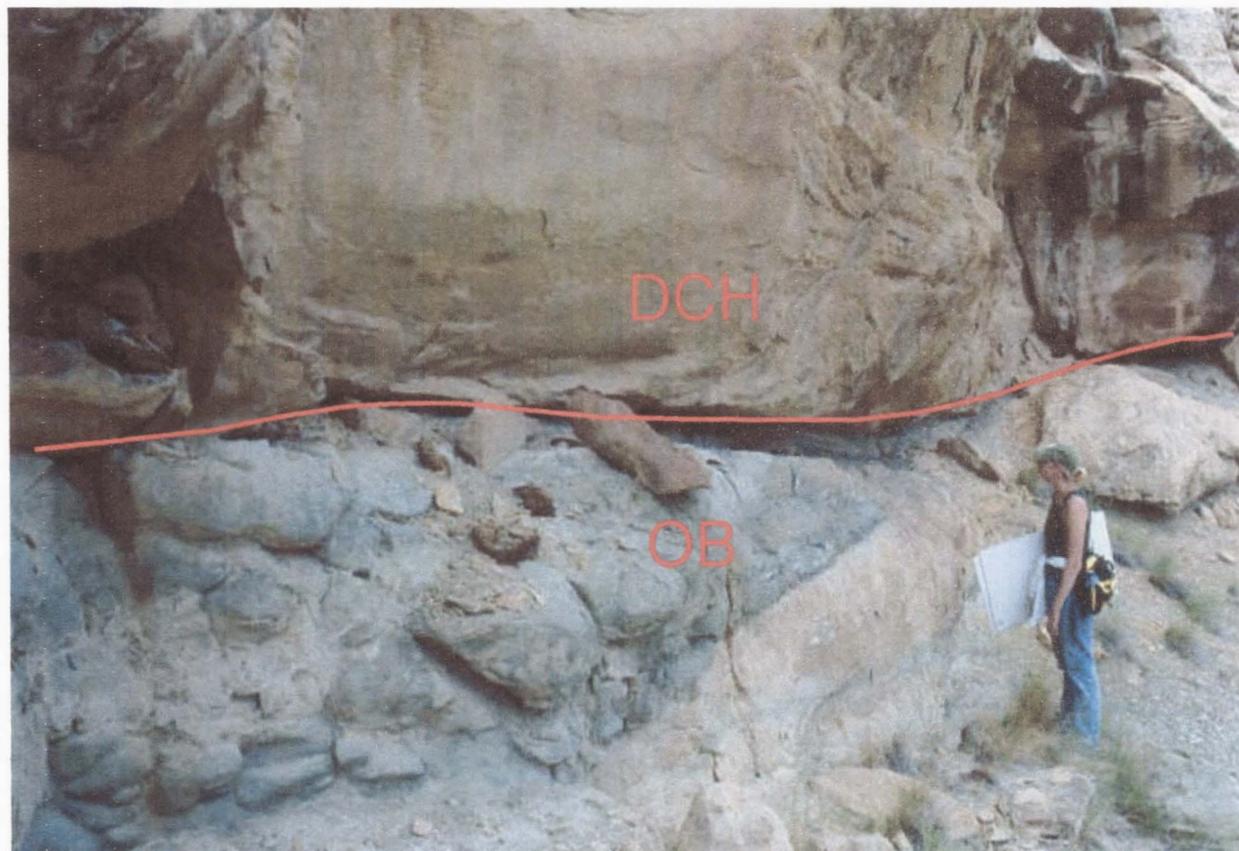
Fig. 30. Distributary channel lithofacies assemblage truncating green mudstone-dominated unit characteristic of the overbank lithofacies assemblage (Photo location illustrated in Fig. 9a).

amalgamated undulatory. The isolated lenticular DCH LAs make up approximately 18

% of all DCH LAs in the outcrop, and are completely encased by OSMS and SLS LAs

(Fig. 9b). The individual isolated lenticular LAs have a maximum thickness of 2 to 3 m.

Thickness in these LAs decreases laterally as they pinch-out into the mudstone- and

siltstone-dominated LAs (Fig. 9b). Width of the individual LAs ranges from 8 to 41 m,

with mean width of 29 m (Fig. 31). Basal bounding surfaces of these LAs are erosive,

sharp, and concave, and rarely contain mud chips lags. Upper bounding surfaces are

planar or undulating and sharp. These LAs are further segmented by smaller-order

surfaces that are similar to the sixth- and fifth-order bounding surfaces of the fluvial

hierarchy.

The amalgamated lenticular DCH LAs comprise approximately 64 % of all DCH

LAs in Outcrop Two. Individual DCH LAs of this type have a maximum thickness of 3

to 9 m, with an average maximum thickness of 5 m. LA thickness decreases laterally by

pinch-out into OSMS and SLS LAs, or as a result of truncation by other DCH LAs (Fig.

9b). Width of individual amalgamated lenticular LAs ranges from 27 to 75 m, with mean

width of 54 m (Fig. 31). Basal bounding surfaces of these LAs are sharp, erosive, and

concave or planar when mudstone or siltstone deposits are below, and sharp or

gradational, erosive, concave or planar when sandstone deposits are below (Fig. 9b).

Both instances are dominated by mud chip lags. Upper bounding surfaces are sharp,

concavo-convex or planar when mudstone and siltstone deposits are above, and eroded,

sharp or gradational, and convex when sandstone deposits are above (Fig. 9b). Similar to

the isolated lenticular DCH LAs, individual amalgamated lenticular DCH LAs are also

segmented by smaller-order surfaces that separate individual lithofacies and lithofacies
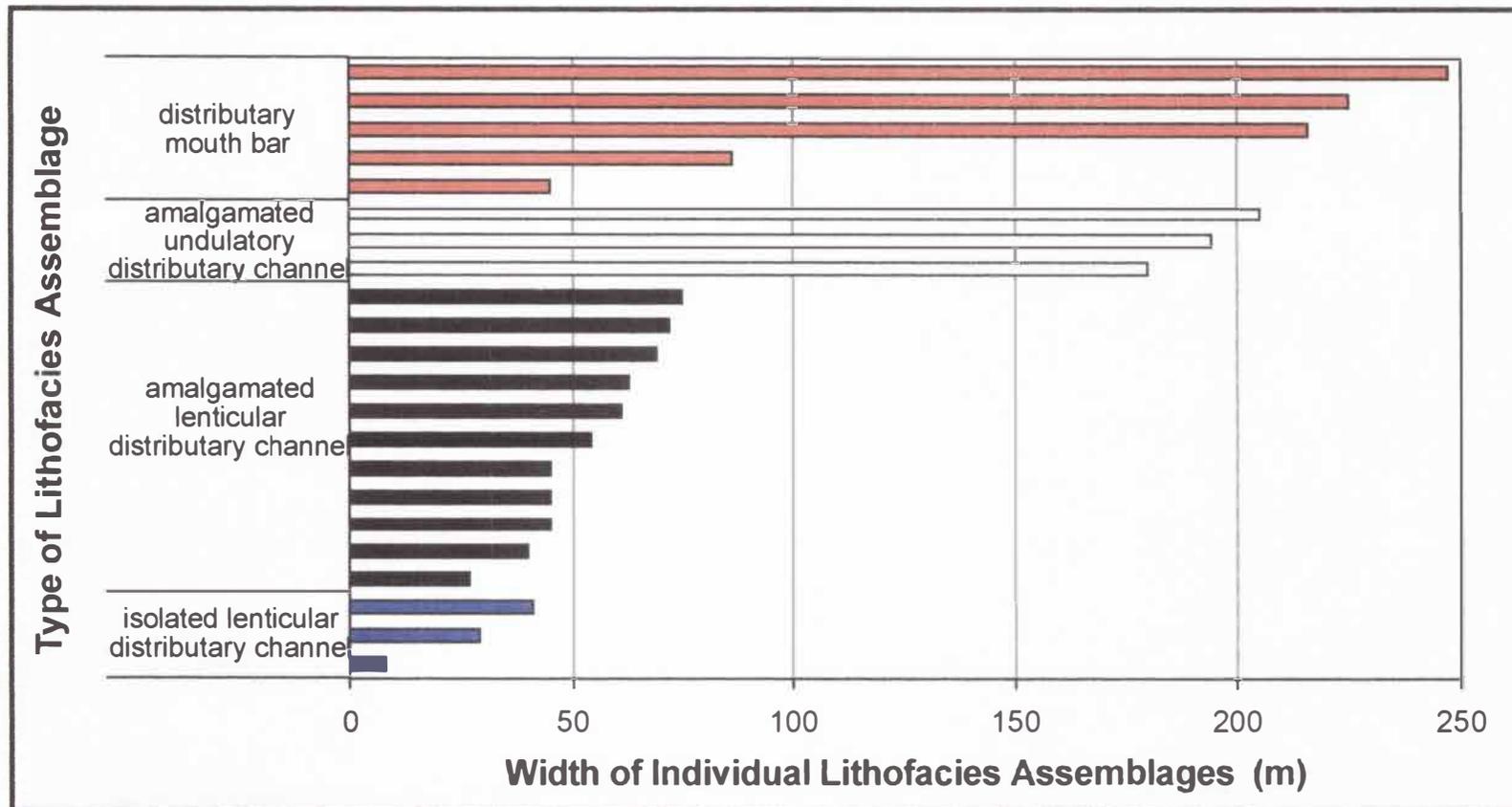
Fig. 31. Graph illustrating the width dimensions of sandstone-dominated lithofacies assemblages in Outcrop Two.

sequences. These LAs are typically erosively amalgamated with the upper portions of DMB LAs, but also amalgamate with other lenticular and undulatory DCH LAs (Figs. 9b, 32). The minimum amalgamation of DMB and DCH LAs in the outcrop is two, but can reach as many as four. These amalgamations result in vertically continuous sandstone-rich LA complexes that can reach 15 m in thickness.

Individual amalgamated undulatory DCH LAs typically truncate and amalgamate with DMB LAs, and are truncated and amalgamated by lenticular DCH LAs (Fig. 9b). Both instances form LA complexes. This type of DCH LA makes up the final 18 % of all DCH LAs in Outcrop Two. Maximum thickness of these individual LAs ranges from 3 to 11 m, with mean maximum thickness of 6 m. LA thickness typically decreases laterally due to truncation by other sandstone-rich erosive LAs (Fig. 9b). In the absence of these truncations, the individual LAs would continue across the entire outcrop. Width of these individual LAs ranges from 180 to 205 m, with average width of 193 m (Fig. 31). Basal bounding surfaces are sharp, erosive, planar or undulating, and concavo-convex where underlain by mudstone and siltstone deposits (Fig. 9b). The same characteristics exist where amalgamated with DMB and other DCH LAs, however the surface can be more gradational in such cases. Mud chip lags are common in both instances. Upper bounding surfaces are planar or undulating (Fig. 9b). When overlain by mudstone and siltstone deposits, the surface is typically sharp, and when overlain by sandstone of other individual DCH LAs, the surface is eroded and sharp or gradational (Fig. 9b). Smaller-order bounding surfaces further segment individual LAs in this type of DCH LAs.
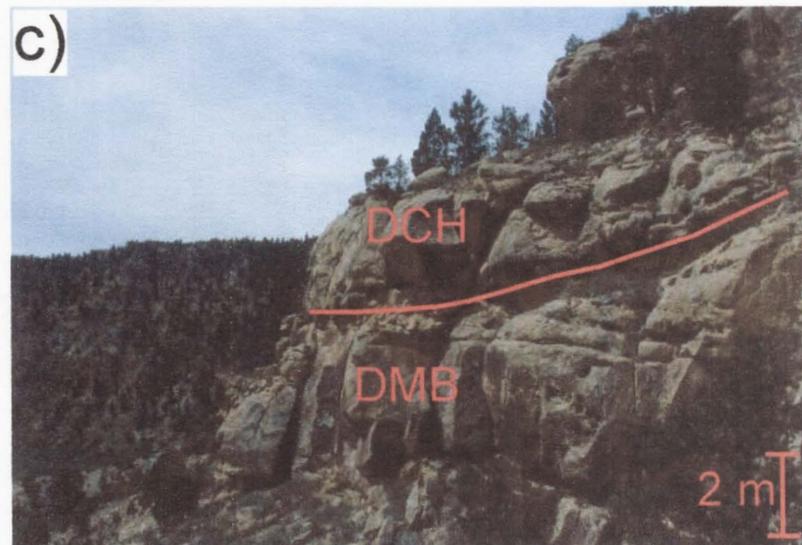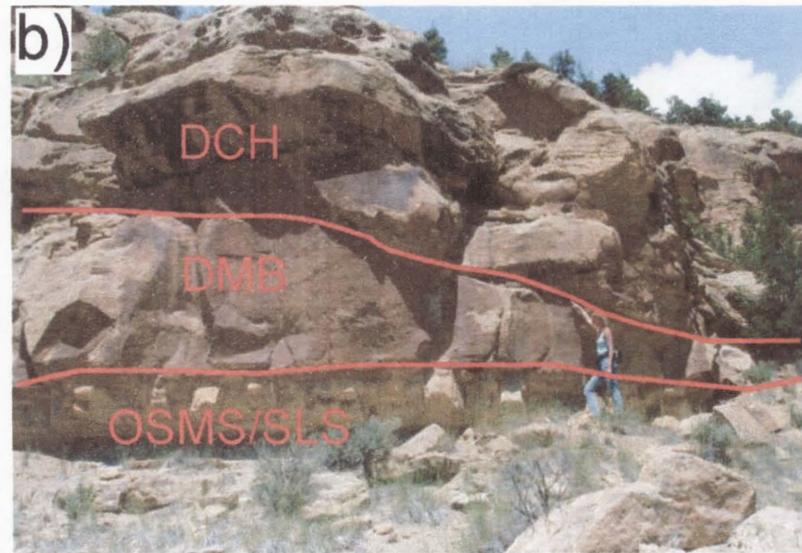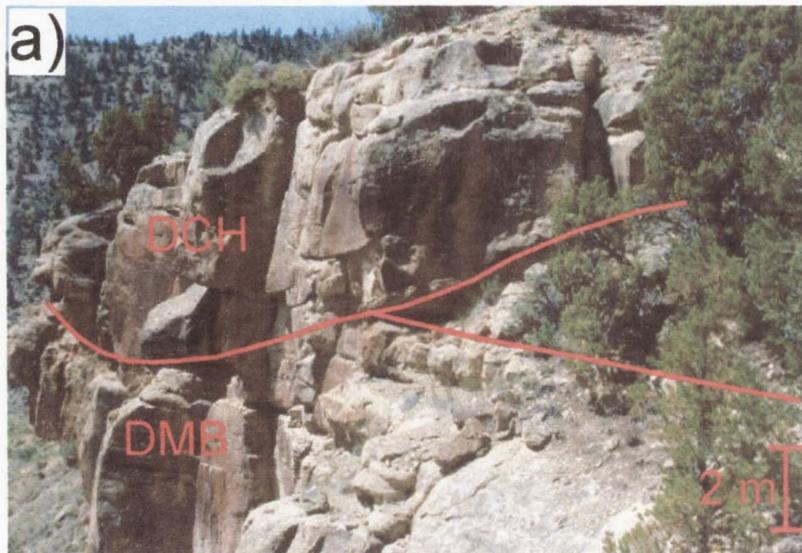
Fig. 32. Distributary channel and distributary mouth bar lithofacies assemblage architecture. a, b, and c) Erosive lenticular distributary channel lithofacies assemblages amalgamated with, and truncating distributary mouth bar lithofacies assemblages (Photo locations illustrated in Fig. 9a).

The DMB LA makes up the rest of the thick sandstone-dominated LAs in Outcrop Two. Individual DMB LAs are tabular and laterally extensive across the entire outcrop and are encased entirely by OSMS and SLS deposits, except where truncated by erosive DCH LAs, in which case LA complexes are formed (Figs. 9b, 32). Individual DMB LAs have a maximum thickness that ranges from 2 to 10 m, with average maximum thickness of 5 m. In areas where individual overlying DCH LAs are undulating and do not entirely truncate DMB LAs, thickness of the DMB LAs is extremely variable and can be < 1 m (Fig. 9b). Width of individual DMB LAs ranges from 45 to 247 m, with mean width of 164 m (Fig. 31). Basal bounding surfaces are sharp, planar or undulating, erosive or non-erosive, and typically contain mud chip lags (Fig. 33). Upper bounding surfaces are planar or undulating and sharp when overlain by mudstone and siltstone deposits, and planar or undulating, eroded, and sharp or gradational when overlain by sandstone deposits (Fig. 9b). Smaller-order bounding surfaces also segment individual DMB LAs.

Rocks of the OSMS, SLS, and OB LAs encase all of the DCH and DMB LAs and LA complexes in Outcrop Two (Fig. 9b). These thin-bedded deposits are tabular and laterally extensive across the outcrop, except where truncated by individual DCH and DMB LAs and LA complexes (Figs. 30, 34). Similar to Outcrop One, the finer-grained and thinner-bedded LAs of Outcrop Two are difficult to address in terms of LA architecture and bounding surfaces due to continual segmentation by thick erosive sandstone units and extensive covered intervals. In areas where DCH and DMB truncation is rare, rocks of the OSMS, SLS, and OB LAs stack vertically to produce
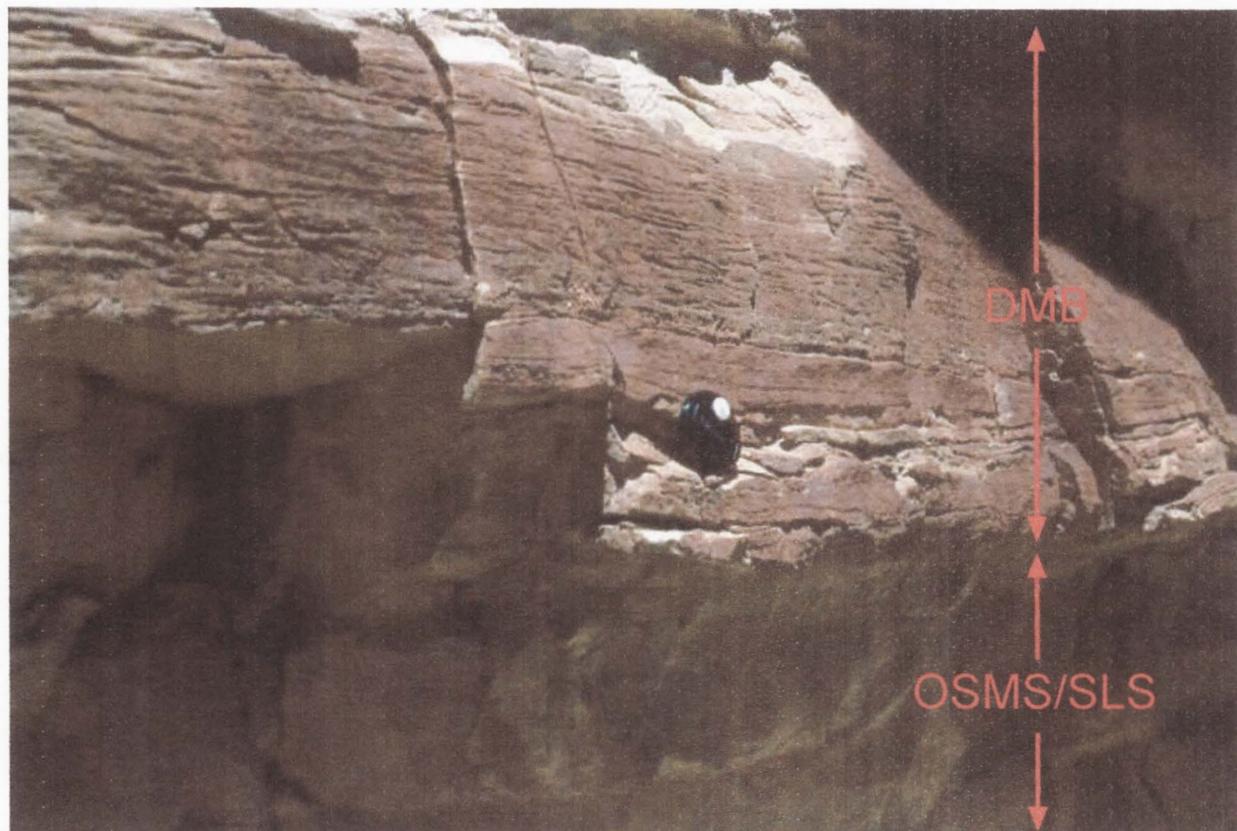
Fig. 33. Erosive, planar or undulating, and sharp basal bounding surface typical of the distributary mouth bar lithofacies assemblages (Photo location illustrated in Fig. 9a).
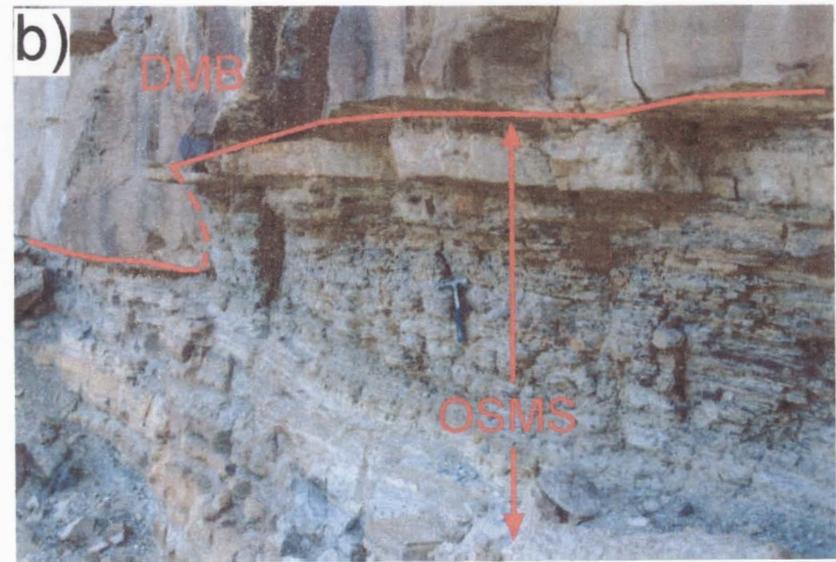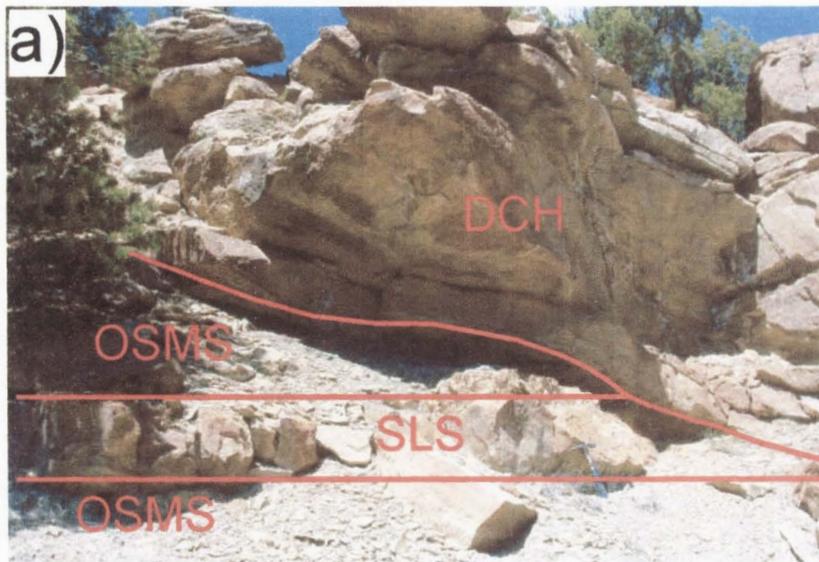
Fig. 34. Erosive nature of distributary channel and distributary mouth bar lithofacies assemblages. a) Amalgamated lenticular distributary channel lithofacies assemblage truncating tabular and laterally extensive shallow lacustrine sandsheet/storm and offshore lacustrine mudstone and siltstone lithofacies assemblages. b) Erosive distributary mouth bar lithofacies assemblage truncating tabular and laterally extensive offshore lacustrine mudstone and siltstone deposits (Photo locations illustrated in Fig. 9a).

intervals that reach 12 m thick (Fig. 9b). In contrast, these units can also be as thin as 10 to 20 cm where individual DCH and DMB LAs and LA complexes are abundant.

Petrography

Sandstone samples of Outcrop Two were point counted using the same categories as Outcrop One, with the addition of an ostracode category. The mean grain size of samples in Outcrop Two ranges from 0.103 to 0.302 mm (very fine to medium sand), with average mean grain size of 0.175 mm (fine sand) (Fig. 19). Porosity ranges from 0.8 to 23.8 %, with average porosity of 13.3 % (Fig. 20). Calcite cement ranges from 4.2 to 51 %, with mean of 17.1 %, and detrital mud ranges from 1.2 to 17 %, with an average of 6.6 %. As with samples of Outcrop One, calcite cement percentages are high in a few samples from Outcrop Two. This can be attributed to the difficulty in deciphering calcite cement from calcite-replaced grains. Comparison of these petrographic values illustrates that there is no relationship between percent porosity and mean grain size (Fig. 21). However, as with Outcrop One, there is a direct relationship between percent calcite cement and percent porosity in Outcrop Two (Fig. 22).

Sandstone samples of the DCH LA have an average mean grain size of 0.179 mm (fine sand). Quartzofeldspathic framework grains make up between 39 and 75 % of the samples, with an average of 55.6 % (Appendix). The grains are poorly sorted to very well sorted, angular to well-rounded monocrystalline quartz with minor amounts of polycrystalline quartz, chert, plagioclase feldspar, and potassium feldspar. Grains replaced by calcite make up between 0 and 5.6 % of the samples, and lithic framework grains typically comprise 0 to 2.2 % of the samples. Calcite is the dominant cement,

making up 18 % of the samples, whereas clay cement typically averages 1.4 %.

Calcite cement is typically highest in samples from the basal portions of the DCH LAs

(Fig. 35). Detrital mud makes up 7.1 % of the samples on average, and is also highest in

the basal portions of the DCH LAs where mud chip lags are common (Fig. 35). Pore

space averages 12.5 % of the samples, with a maximum of 22.6 % (Fig. 36). The

amalgamated lenticular DCH LAs typically contain more samples with high porosity and

larger mean grain size, as well as better sorting, than do the other DCH LAs. Similar to

Outcrop One, samples from the St lithofacies typically exhibit these higher values.

Sandstone samples of the DMB LA have the highest mean grain size average of

the three sandstone-rich LAs in Outcrop Two. Grain size ranges from 0.116 to 0.273 mm

(very fine to medium sand), with average mean grain size of 0.186 mm (fine sand).

Quartzofeldspathic grains dominate framework grains in these sandstone samples,

making up 44.8 to 68.4 % of the samples, with an average of 58.5 % (Appendix). Grain

types, abundances, and roundness are similar to samples of the DCH LA. Sorting in

these samples is the best of all LAs in Outcrop Two, ranging from well sorted to very

well sorted. Calcite cement and detrital mud percentages of DMB sandstone samples are

the lowest of all LAs in Outcrop Two, with averages of 13.8 % and 4.9 % of the samples,

respectively (Fig. 37). These percentages are highest in samples from mud chip

dominated basal portions of DMB LAs. Pore space in DMB sandstone samples ranges

from 8.4 to 23.6 % of the samples, with average of 16.2 % (Fig. 38). Thus, sandstone

samples of the DMB LA have higher average porosity than the other LAs in Outcrop

Two. Samples from the St lithofacies exhibit the highest porosity and largest mean grain

size values.
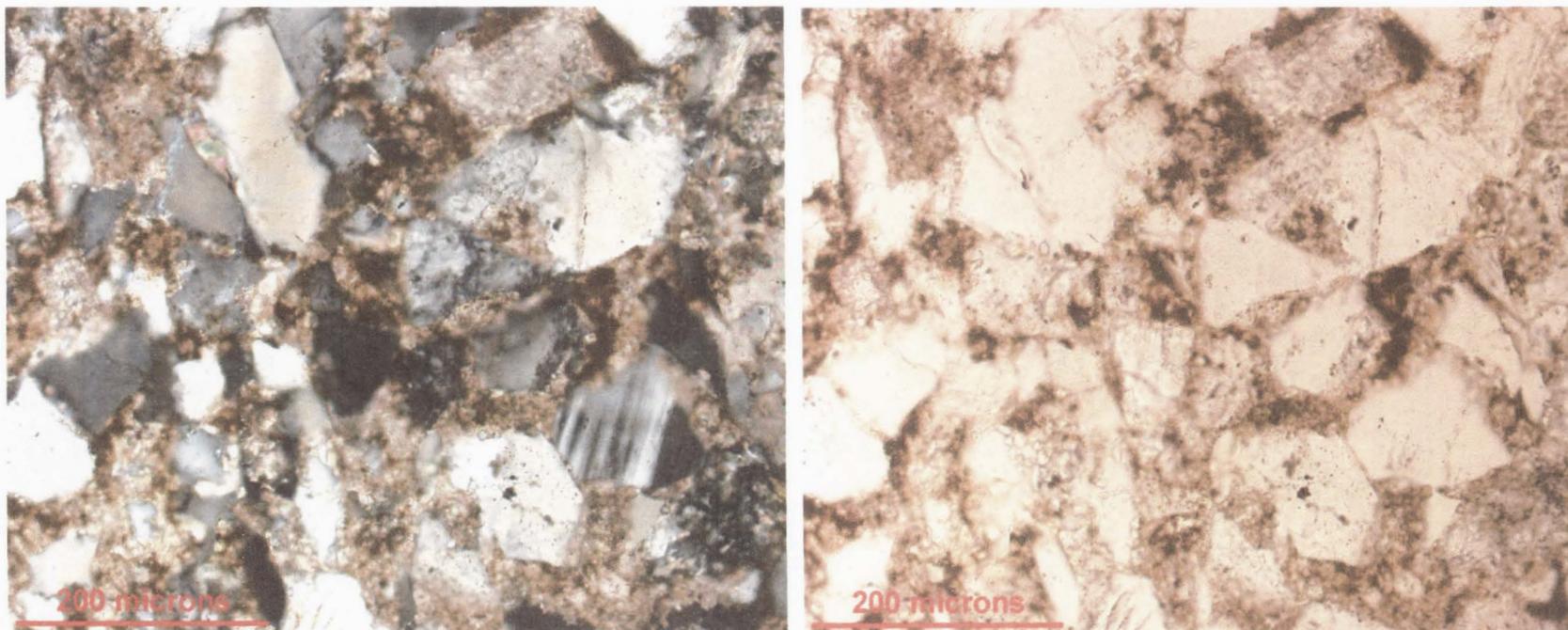
Fig. 35. Photomicrographs of a basal distributary channel sandstone sample exhibiting low porosity and abundant calcite cement and detrital mud (sample 02-63) (left photo is under cross polarized light and right photo is under plane polarized light).
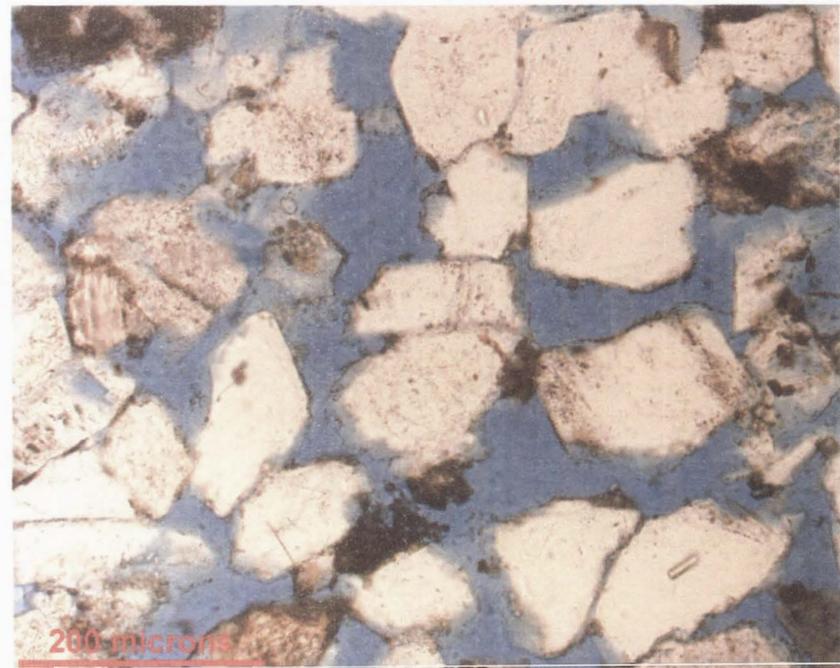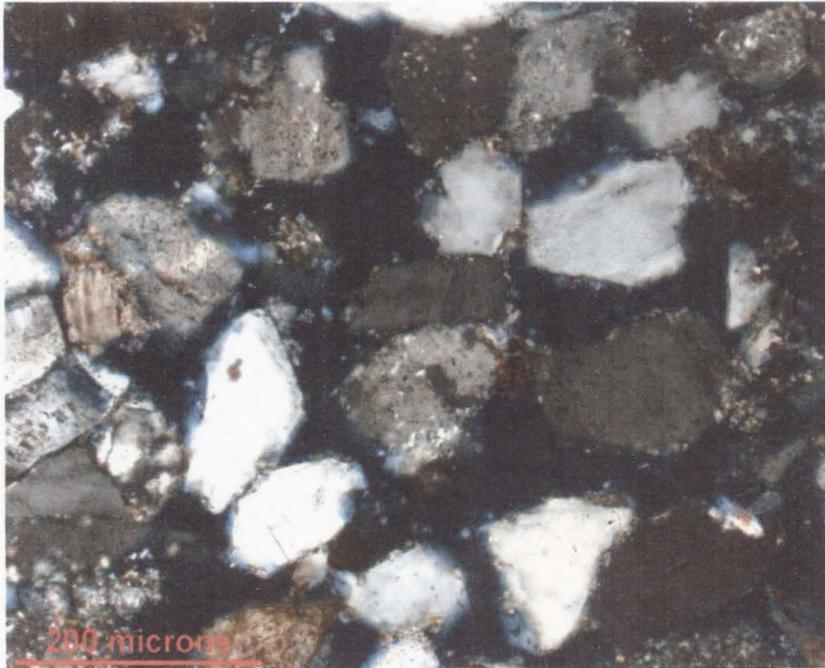
Fig. 36. Photomicrographs of a distributary channel sandstone sample exhibiting good porosity with minimal calcite cement and detrital mud (sample 02-121) (left photo is under cross polarized light and right photo is under plane polarized light).
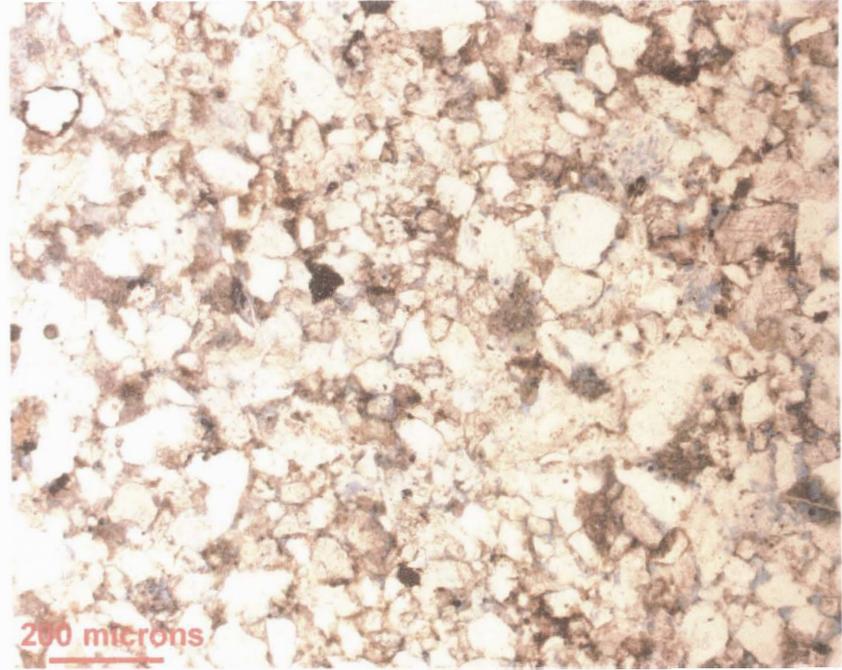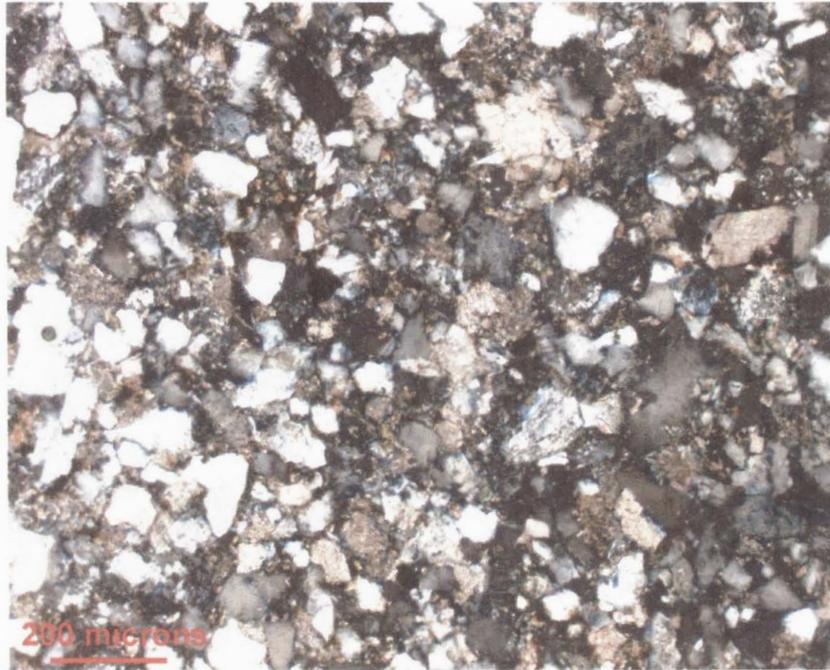
Fig. 37. Photomicrographs of a distributary mouth bar sandstone sample illustrating abundant calcite cement and detrital mud (sample 02-62) (left photo is under cross polarized light and right photo is under plane polarized light).
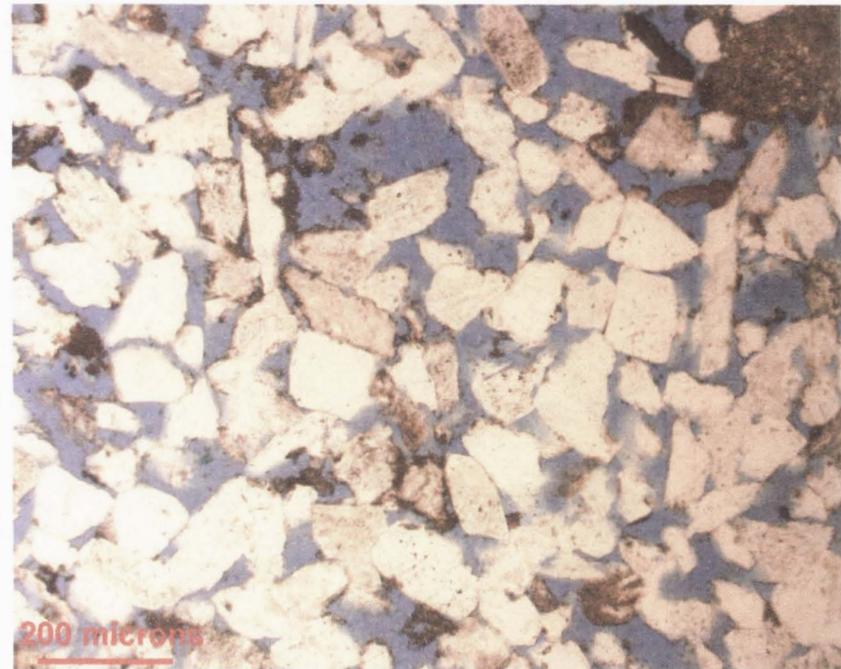
Fig. 38. Photomicrographs of a distributary mouth bar sandstone sample exhibiting good porosity (sample 02-79) (left photo is under cross polarized light and right photo is under plane polarized light).

Samples of the SLS LA have the lowest average mean grain size of all LAs in Outcrop Two, with average of 0.131 mm (fine sand). Quartzofeldspathic grains are the dominant constituents of framework grains in these samples, making up 38.6 to 59.2 % of the samples, with an average of 51 % (Appendix). Grain types, abundances, roundness, and sorting are all similar to those of the DCH LA, with the exception of minor amounts of ostracodes in two of the samples from the SLS LA. Sandstone samples of the SLS LA have the highest average percent calcite cement, percent detrital mud, and percent clay cement than sandstone samples of the DCH and DMB LAs, averaging 22 %, 9.3 %, and 2.5 % of the samples, respectively (Fig. 39). In contrast, sandstone samples of the SLS LA have the lowest average porosity, averaging only 8.9 % of the samples (Fig. 40). Within individual SLS LAs, upward decrease in porosity and mean grain size, and upward increase in the abundance of silty matrix are common.

Outcrop Three: Wave-dominated facies of the Green River Formation

Sedimentology

Description. Outcrop Three is composed of four LAs: 1) massive siltstone – massive mudstone – laminated mudstone (Fsm-Fm-Fmh); 2) trough cross-stratified sandstone (St); 3) rippled sandstone – low-angle cross-stratified sandstone – massive sandstone – rippled siltstone (Sr-Sl-Sm-Fsr); 4) rippled siltstone – low-angle cross-stratified sandstone – trough cross-stratified sandstone – massive sandstone (Sr-Sl-St-Sm) (Fig. 6c). The Fsm-Fm-Fmh LA makes up a large portion of Outcrop Three, and consists of gray or black, calcareous laminated mudstone beds, with lesser amounts of calcareous
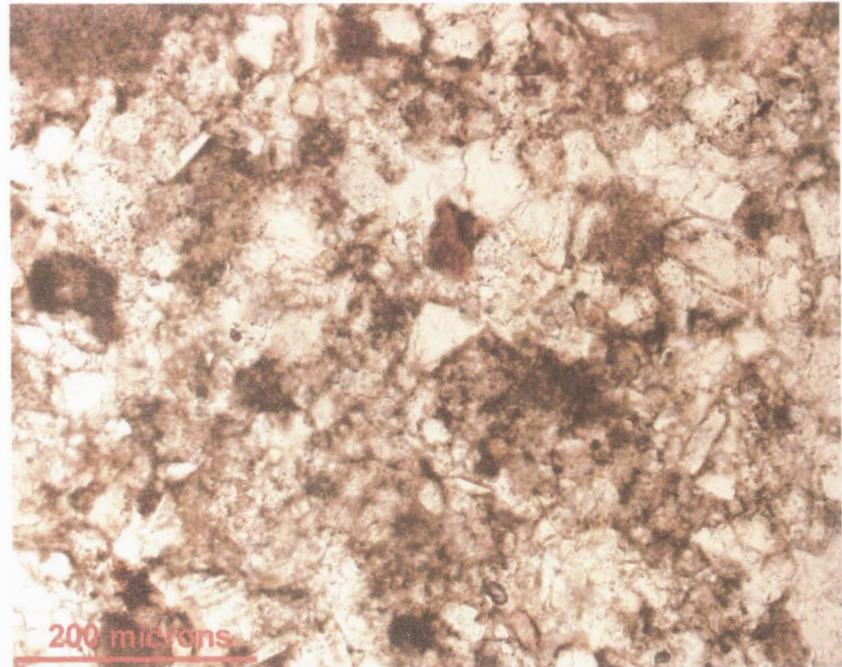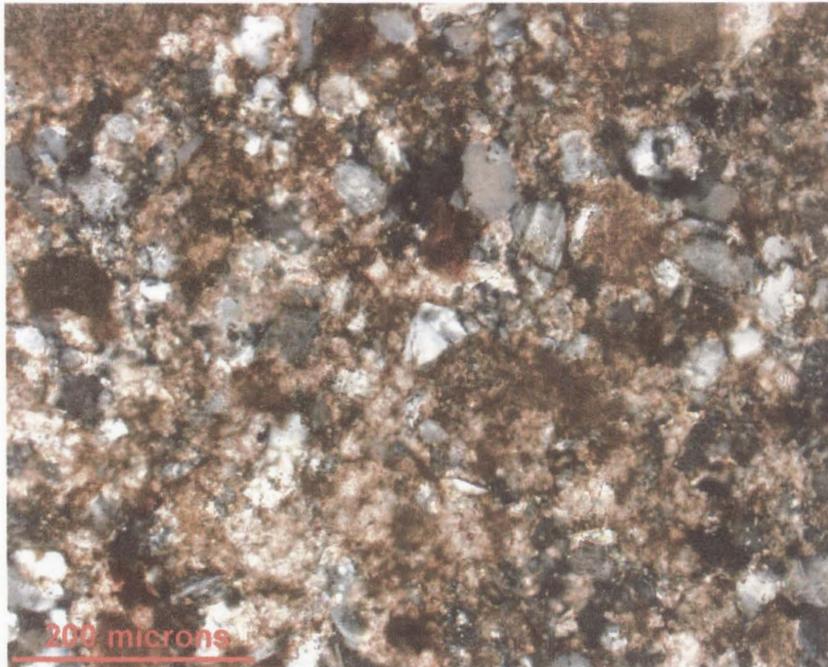
Fig. 39. Photomicrographs of a shallow lacustrine sandsheet/storm sandstone sample exhibiting poor porosity and abundant detrital mud (sample 02-74) (left photo is under cross polarized light and right photo is under plane polarized light).
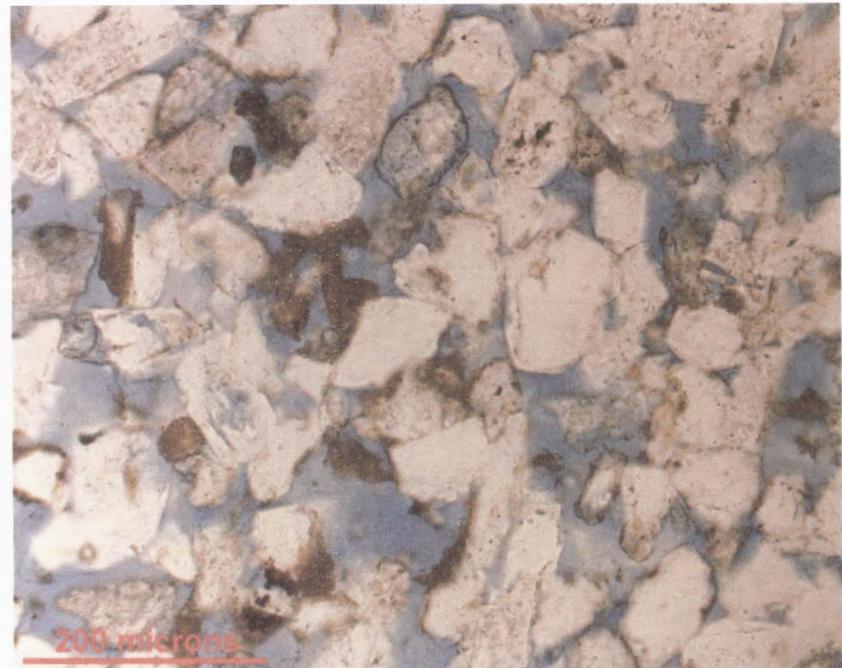
Fig. 40. Photomicrographs of a shallow lacustrine sandsheet/storm sandstone sample exhibiting good porosity and minor detrital mud (sample 02-24) (left photo is under cross polarized light and right photo is under plane polarized light).

massive siltstone and mudstone beds. Individual beds range in thickness from 10 to 60 cm, and are tabular and laterally extensive. Basal bedding surfaces are sharp or gradational. Rocks of this LA typically encase the sandstone-rich LAs, forming tabular and laterally extensive mudstone and siltstone units that continue across the outcrop. These rocks also occur as discontinuous or continuous thin mudstone and siltstone beds that are interbedded with rocks of the sandstone-rich LAs. Individual beds are difficult to trace across the outcrop due to extensive covered intervals. The St LA is the least abundant LA in the outcrop, only occurring in one location. This LA consists of gray, fine to medium grained, trough cross-stratified sandstone. Beds range in thickness from 10 to 40 cm, and are tabular or lenticular. Basal bedding surfaces are typically sharp and erosive, and contain mud chip lags. These rocks form a lenticular LA isolated in the mudstone- and siltstone-rich LAs.

Rocks of the Sr-Sl-Sm-Fsr LA consist of gray or tan, very fine to fine grained, rippled, and low-angle cross-stratified sandstone. Very fine to fine grained massive sandstone and rippled siltstone occurs in lower abundance. All rocks of this LA are very calcareous. Individual beds are typically tabular and laterally extensive, and range in thickness from 10 to 80 cm. Basal bedding surfaces are sharp and commonly erosive when in contact with mudstone and siltstone intervals, and sharp or gradational and erosive when in contact with sandstone intervals. Mud chip lags are rarely associated with the erosive bedding surfaces. Burrows, soft-sediment deformation, and ostracodes are common. Rocks of this LA occur as relatively thin sandstone and Fsr dominated units encased by the mudstone- and siltstone-rich LA mentioned above, and form tabular and laterally extensive LAs that are persistent across the outcrop. 10 to 30 cm thick beds

of continuous and discontinuous Fm and Fsm commonly separate successive beds within this LA. Similar to the mudstone- and siltstone-dominated LA, rocks of this LA are also affected by extensive covered intervals, resulting in the inability to trace units or individual beds across the outcrop.

Rocks of the Sr-Sl-St-Sm LA are also a dominant constituent of Outcrop Three, and consist of gray to tan, very fine to medium grained, rippled, and low-angle cross-stratified sandstone. In lower abundance are gray to tan, very fine to fine grained, trough cross-stratified, and massive sandstone. As with the other LAs of this outcrop, sandstone beds of this LA are typically calcareous. Individual beds range in thickness from 10 cm to 2 m, and are primarily tabular and laterally extensive. Basal bedding surfaces are sharp and occasionally erosive when in contact with mudstone or siltstone units, and sharp or gradational and commonly erosive when in contact with other sandstone-rich units. The erosive bedding surfaces are rarely associated with mud chip lags. Ostracodes, burrows, and soft-sediment deformation are abundant. These rocks are encased by the mudstone- and siltstone-rich LA, and occur as thick tabular and laterally extensive LAs that are persistent across the outcrop. These LAs can either be isolated or amalgamated with one another, forming LA complexes in the latter case. Similar to rocks of the other sandstone-rich LA, individual beds within this LA are also commonly separated by 5 to 30 cm thick beds of continuous and discontinuous Fm and Fsm. Beds of this LA are not always traceable across the outcrop because of covered intervals.

Interpretation: Rocks of the Fsm-Fm-Fmh LA are interpreted as suspension load fall-out deposits of mud and silt, often bioturbated (Fm and Fsm), in a quiet water setting. These rocks exhibit very similar characteristics to the OSMS LA of the deltaic outcrop, in

that they are calcareous, bioturbated, and dominated by laminated mudstones (Fig. 6c).

Therefore rocks of this LA are also interpreted as offshore lacustrine mudstone and

siltstone deposits, and are similarly termed OSMS (Figs. 6c, 10b). Interbedded with the

OSMS LAs of Outcrop Three, are rocks of the Sr-Sl-Sm-Fsr LA. The mechanisms of

deposition interpreted for these rocks are unidirectional migration of subaqueous sand

and silt bedforms of varying sizes and flow regimes (Sr, Sl, and Fsr), and bioturbated or

rapid suspension load fall-out of sand (Sm). This LA exhibits similar characteristics to

the SLS LA of the deltaic outcrop, and is therefore interpreted as shallow lacustrine

sandsheet or storm deposits, and termed SLS (Figs. 6c, 10b, 41). The St LA is only

represented by one sandbody in Outcrop Three (Fig. 10b). Rocks of this LA are

interpreted to be deposits resulting from unidirectional migration of subaqueous sandy

bedforms in confined flow conditions. This LA is therefore interpreted as a channel, and

will further be termed CH (Fig. 10b). Erosive basal bedding surfaces with mud chip lags,

St as the only lithofacies in the LA, and a lenticular LA geometry provide support for this

interpretation (Figs. 10b, 42).

The Sr-Sl-St-Sm LA is the dominant sandstone-rich constituent of Outcrop Three.

These rocks occur as thick tabular and laterally extensive LAs that are encased by OSMS

and SLS intervals (Fig. 10b). The mechanisms of deposition interpreted for this LA are

unidirectional migration of subaqueous sandy bedforms of varying sizes and flow

regimes (Sr, Sl, and St), and bioturbated or rapid suspension load fall-out of sand (Sm).

This LA is interpreted to represent an offshore bar environment, and will further be

termed OSB (Figs. 6c, 10b). This interpretation is consistent with descriptions of similar
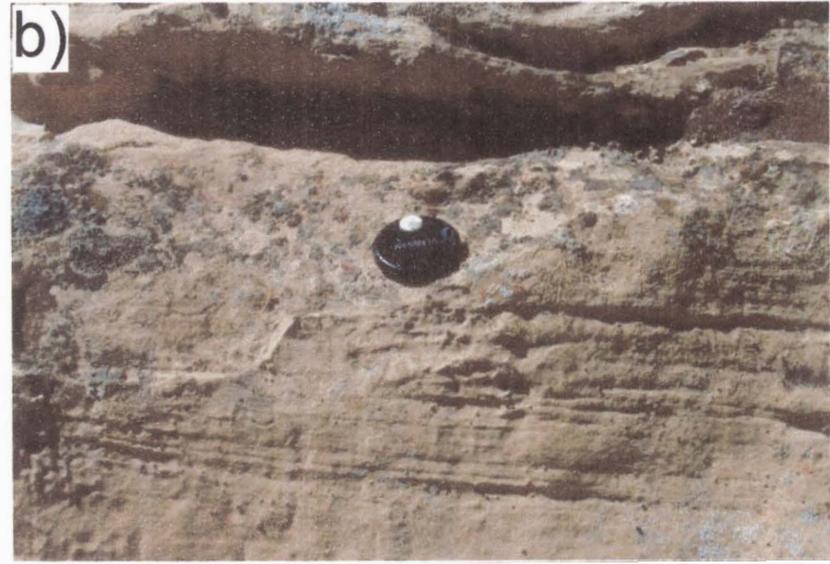
Fig. 41. Sedimentology of the shallow lacustrine sandsheet/storm lithofacies assemblage. a) Rippled sandstone of the shallow lacustrine sandsheet/storm lithofacies assemblage. b) Low-angle cross-stratified sandstone of the shallow lacustrine sandsheet/storm lithofacies assemblage (Photo locations illustrated in Fig. 10a).

Fig. 42. Channel lithofacies assemblage dominated by trough cross-stratified sandstone. Basal bounding surface is erosive, sharp, concave, and contains mud chips (Photo location illustrated in Fig. 10a).

deposits by La Fon (1981), Walker and Plint (1982), and Greenwood and Mittler (1985). The dominance of Sr and Sl beds over beds of St provides evidence that flows were rarely confined (Figs. 6c, 43). Mud chip lags on basal bedding surfaces and beds with abundant ostracode fragments support times of high energy in the system (Fig. 6c). Conversely, times of low-energy, or less clastic input, are indicated by an abundance of thin continuous and discontinuous mudstone and siltstone beds that separate individual sandstone beds in this LA (Fig. 6c). OSB deposits are often difficult to differentiate from beach deposits due to their sedimentological and geometric similarities. Because rocks interpreted as OSB deposits in this outcrop lack fundamental features of subaerial exposure such as root traces, soil zones, or coal, a beach environmental interpretation is less favorable (La Fon, 1981).

LA architecture and bounding surfaces

Rocks interpreted as OSB deposits occur as thick tabular and laterally extensive LAs that extend across the outcrop (Fig. 10b, 44). The individual OSB LAs are either isolated in OSMS- or SLS-dominated intervals, or are amalgamated with one another forming an LA complex (Fig. 10b). The maximum number of stacked individual OSB LAs is two, resulting in up to 6 m of continuous vertical sandstone intervals in places (Fig. 44). The individual LAs have a maximum thickness of 2 to 4 m, with average maximum thickness of 2.8 m. Thickness of individual OSB LAs typically remains consistent across the outcrop. Width of the individual LAs ranges from 456 to 480 m, with average width of 469 m (Fig. 45). Basal bounding surfaces are sharp and planar or undulating when overlying OSMS deposits, and sharp or gradational and planar or
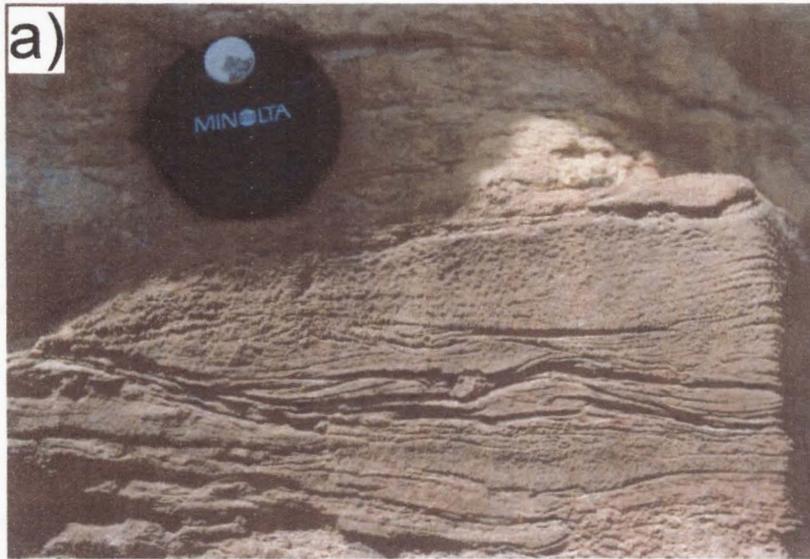
Fig. 43. Sedimentology of the offshore bar lithofacies assemblage. a) Rippled sandstone of the offshore bar lithofacies assemblage. b) Burrowed low-angle cross-stratified sandstone of the offshore bar lithofacies assemblage (Photo locations illustrated in Fig. 10a).
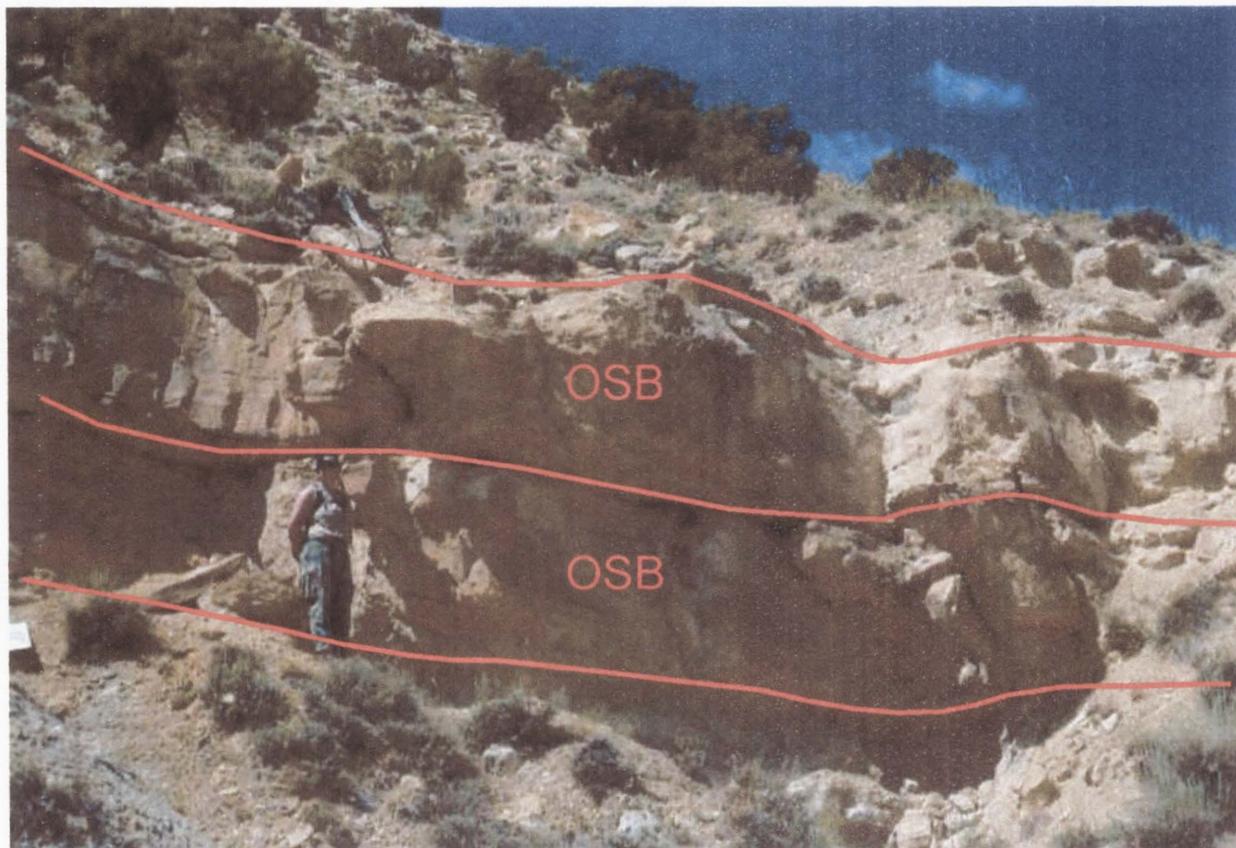
Fig. 44. Tabular and laterally extensive stacked offshore bar lithofacies assemblages. Basal and upper bounding surfaces are sharp, planar or undulating, and slightly erosive (Photo location illustrated in Fig. 10a).
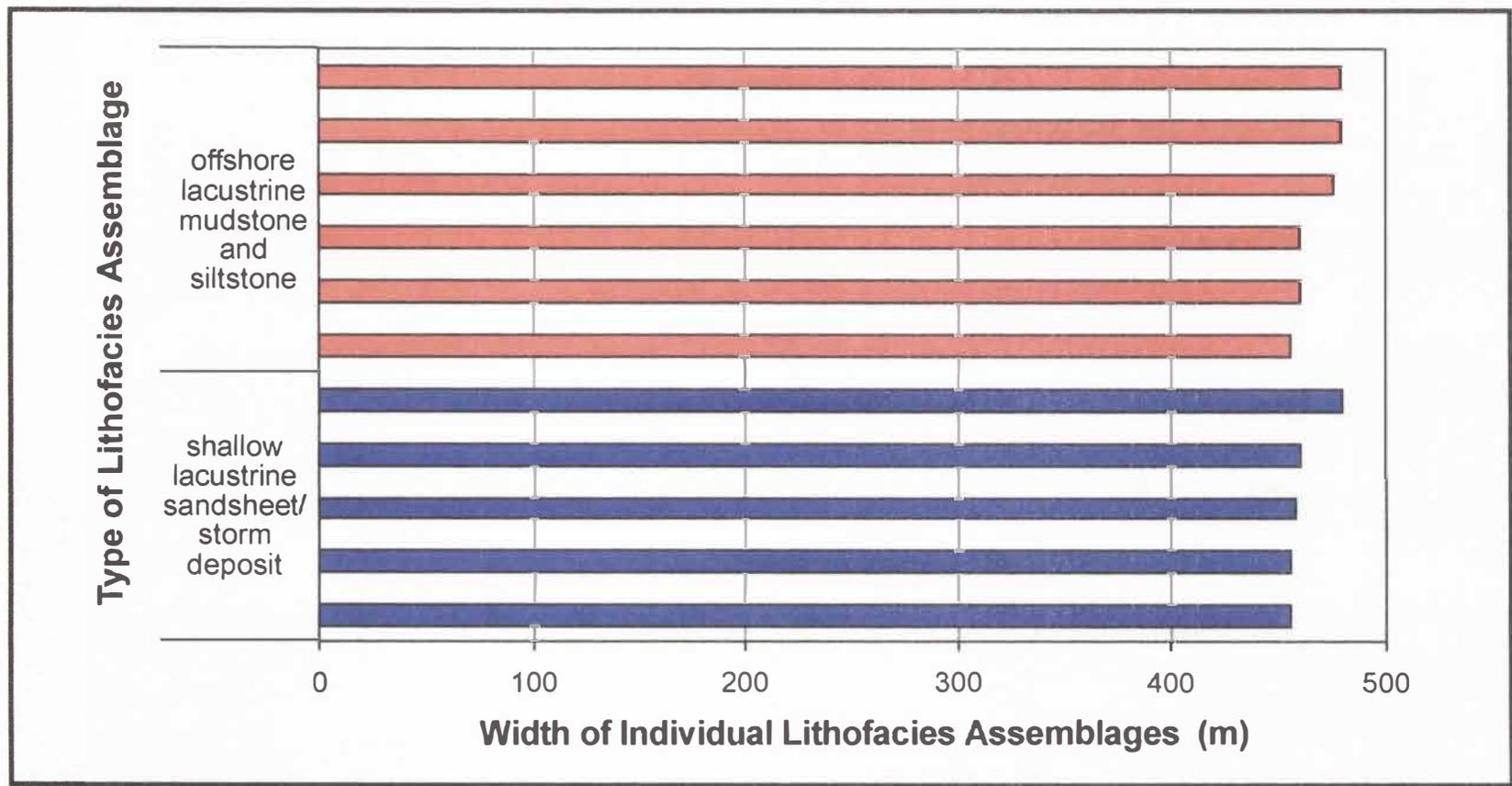
Fig. 45. Graph illustrating the width dimensions of sandstone-dominated lithofacies assemblages in Outcrop Three.

undulating when overlying another individual OSB LA (Figs. 10b, 44). When basal

surfaces are sharp they are typically erosive, and are sometimes associated with mud chip

lags. Upper bounding surfaces are sharp and planar or undulating when overlain by

OSMS deposits, and sharp or gradational, commonly eroded, and planar or undulating

when overlain by another OSB LA (Figs. 10b, 44). The individual OSB LAs are

internally segmented by smaller-order bounding surfaces, which are comparable to sixth-

and fifth-order bounding surfaces of the fluvial hierarchy.

Rocks interpreted as SLS deposits occur as relatively thin tabular and laterally

extensive LAs that are persistent across the outcrop, and are commonly found

interbedded with the OSMS LAs (Fig. 10b). Not all SLS LAs are factored when

calculating average thickness and width values. Many of the SLS LAs in Outcrop Three

are extremely thin and are untraceable across the outcrop due to covered intervals.

Therefore the following description of these units is based primarily on the SLS LAs that

are mappable (those that are greater than 50 cm in thickness). The individual SLS LAs

have a maximum thickness of 50 cm to 1.5 m, with average maximum thickness of 1.2 m.

As with the individual OSB LAs, the thickness of individual SLS LAs remains fairly

consistent across the outcrop (Fig. 10b). Width of individual SLS LAs ranges from 456

to 480 m, with average width of 462 m (Fig. 45). Because these LAs are interbedded

with OSMS LAs and are not amalgamated with other sandstone-rich LAs, basal and

upper bounding surfaces are sharp and planar or undulating. Basal bounding surfaces are

occasionally erosive with associated mud chip lags. The individual SLS LAs are also

subdivided by smaller-order surfaces at the lithofacies and lithofacies sequence scale.

The St LA is represented by one lenticular sand body in the outcrop that is entirely encased by OSMS and SLS deposits (Fig. 10b). This LA has a maximum thickness of 3 m, and a width of 16 m. Thickness of the LA decreases laterally as it pinches out into mudstone and siltstone beds of the OSMS and SLS LAs. The basal bounding surface of this LA is sharp, concave, and erosive with associated mud chip lags (Fig. 42). The upper bounding surface is sharp and concavo-convex.

Rocks of the OSMS LA are thin-bedded tabular and laterally extensive mudstone and siltstone units that encase the sandstone-rich LAs of Outcrop Three (Fig. 10b). Similar to the finer-grained LAs of Outcrops One and Two, the OSMS LAs of Outcrop Three are difficult to address in terms of LA architecture and bounding surfaces due to extensive covered intervals that are associated with these slope-forming deposits. However, it is important to note that the thickness of OSMS intervals ranges from less than 1 m, to as much as 7 m of vertically continuous mudstone and siltstone (Fig. 10b). Bounding surfaces are sharp, planar or undulating, and typically eroded when overlain by sandstone units, and sharp and planar or undulating when underlain by sandstone units.

Petrography

Sandstone samples of Outcrop Three were point counted using the same categories as Outcrop Two. The mean grain size of sandstone samples in Outcrop Three ranges from 0.086 to 0.269 mm (very fine to medium sand), with average mean grain size of 0.130 (fine sand) (Fig. 19). Porosity values range from 0 to 25.6 %, with average porosity of 11.6 % (Fig. 20). Calcite cement values range from 0 to 55.4 %, and average 27.2 %. Detrital mud ranges from 0 to 19 %, with an average of 2.8 %. Similar to

Outcrops One and Two, extremely high calcite cement percentages are likely attributed to the inability to distinguish all calcite-replaced grains in thin section. As with Outcrops One and Two, there is no relationship between porosity and mean grain size in Outcrop Three (Fig. 21); however, there is a direct relationship between calcite cement content and porosity (Fig. 22).

Samples of the SLS LA have average mean grain size values that range from 0.93 to 0.258 mm (very fine to medium sand), with average mean grain size of 0.130 mm (fine sand). Similar to sandstone samples of the other outcrops, quartzofeldspathic grains are the dominant framework of samples in Outcrop Three. Quartzofeldspathic framework grains make up between 25 and 74.2 % of the samples, with an average of 54.8 % (Appendix). The quartzofeldspathic grains are poorly to very well sorted, angular to well-rounded monocrystalline quartz with minor amounts of polycrystalline quartz, chert, potassium feldspar, and plagioclase feldspar. Ostracode fragments make up between 0 and 6.2 % of the samples, with an average of 0.81 %, and calcite replaced grains make up 0 to 4.2 % of the samples, with an average of 1.2 % (Fig. 46). Lithics are not present in samples of Outcrop Three. Calcite cement makes 22.2 % of the samples on average, whereas clay cement averages 3.3 % (Fig. 47). Detrital mud makes up 3.0 % of the samples on average, and is commonly highest in the basal portions of SLS LAs where mud chip lags are abundant (Fig. 47). With an average porosity of 13.3 %, SLS samples have higher porosity than OSB samples (Fig. 48). Sandstone samples from the Sr lithofacies typically exhibit the best sorting, porosity, roundness, and largest mean grain sizes when not associated with mud chips.
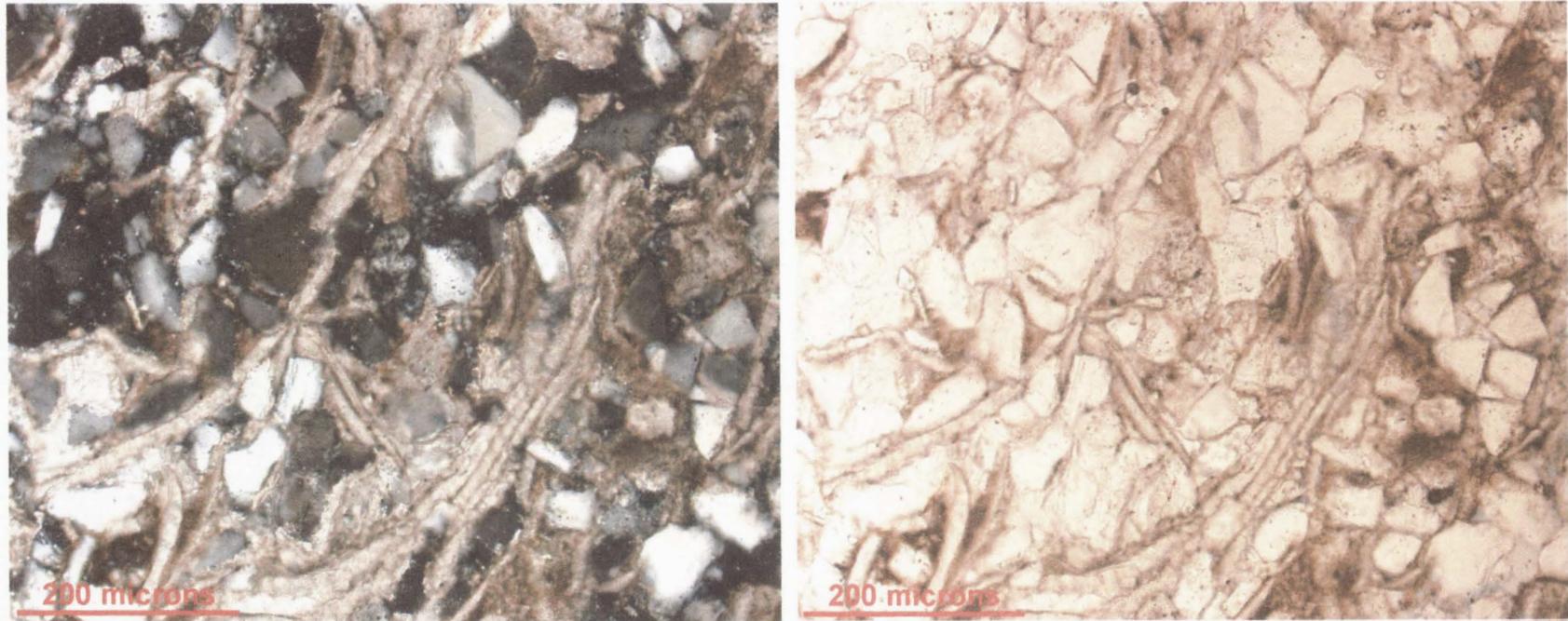
Fig. 46. Photomicrographs of a shallow lacustrine sandsheet/storm sandstone sample exhibiting abundant ostracode fragments (sample 03-46) (left photo is under cross polarized light and right photo is under plane polarized light).
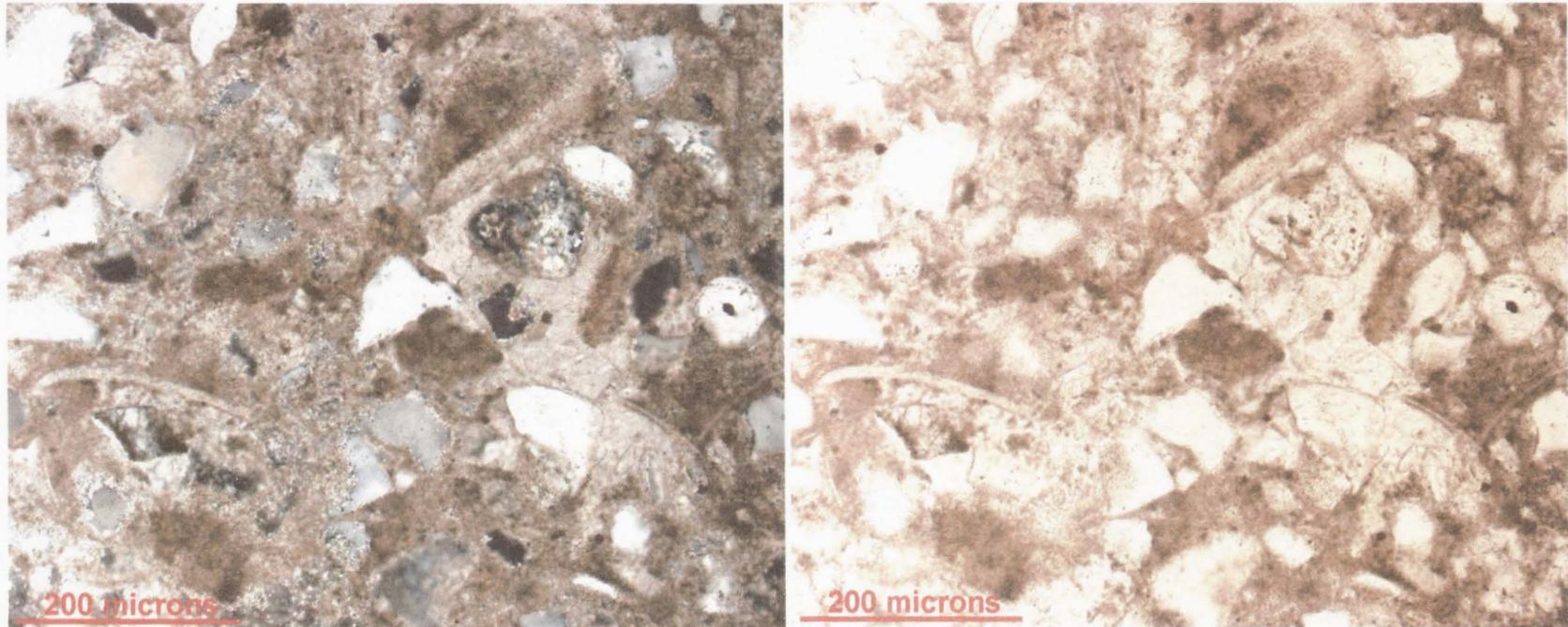
Fig. 47. Photomicrographs of a shallow lacustrine sandsheet/storm sandstone sample exhibiting poor porosity and abundant calcite cement and detrital mud (sample 03-49) (left photo is under cross polarized light and right photo is under plane polarized light).
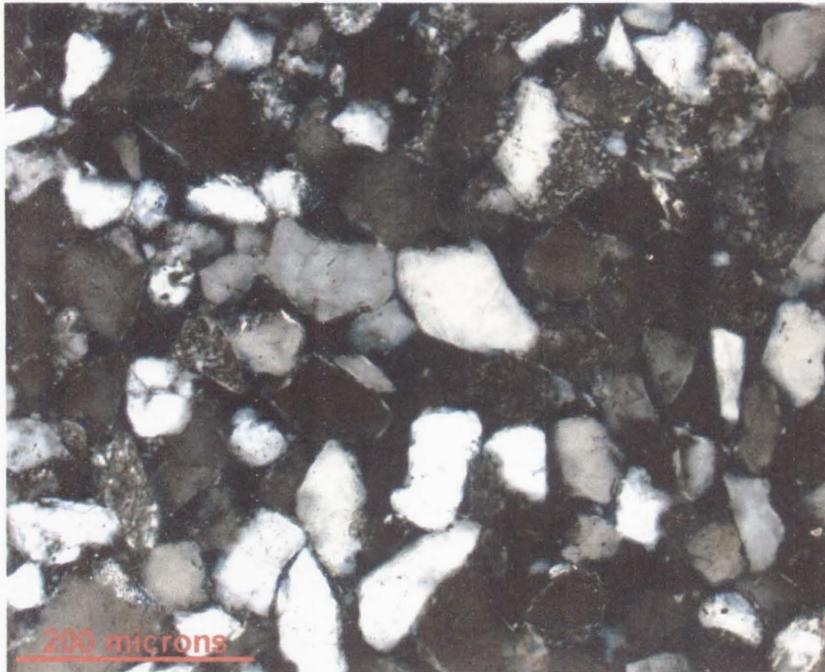
Fig. 48. Photomicrographs of a shallow lacustrine sandsheet/storm sandstone sample exhibiting good porosity and minimal calcite cement and detrital mud (sample 03-28) (left photo is under cross polarized light and right photo is under plane polarized light).

Sandstone samples of the OSB LA have mean grain size values similar to those of the SLS LA. Quartzofeldspathic grains are the dominant constituents of framework grains, making up 30 to 61.8 % of the samples, with an average of 50 % (Appendix). Grain types, abundances, roundness, and sorting are similar to those of the SLS LA, however replaced grains make up 2.6 % of the OSB samples, on average. Calcite cement content is higher than in the SLS LA, making up 13 – 55.4 % of the samples, and averaging 29.6 % (Fig. 49). Once again, the anomalously high calcite cement values are likely attributed to abundant calcite-replaced grains that are not distinguishable from calcite cement. In contrast, detrital mud is less abundant in sandstone samples of the OSB LA, making up 2.7 % of the samples, on average. Similarly, pore space is also less abundant in this LA, averaging 10.7 % of the samples (Fig. 50). In contrast to the SLS samples, OSB samples typically exhibit the best sorting, porosity, roundness, and largest mean grain sizes in samples of the Sl and St lithofacies. These samples also have relatively low percentages of detrital mud and calcite cement. In Sl and St dominated OSB LAs, porosity tends to increase vertically. Sandstone samples of the Sr and Sm lithofacies typically are finer grained, poorly sorted, dominated by calcite cement, and have lower porosity.
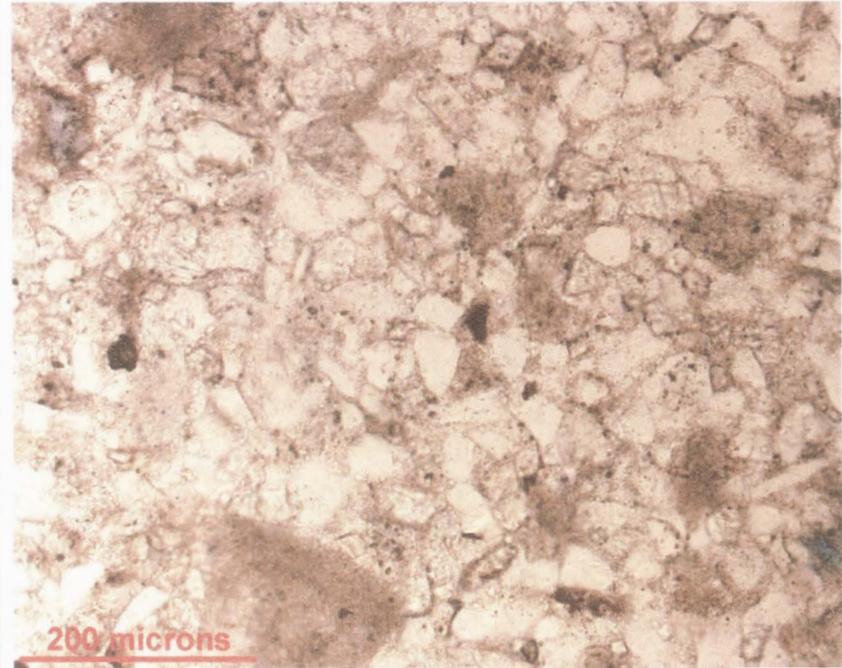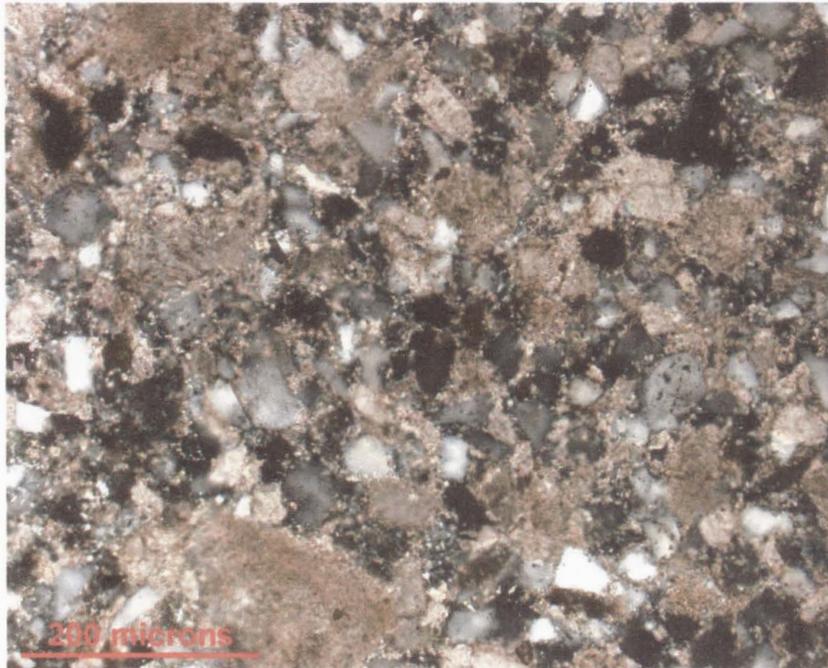
Fig. 49. Photomicrographs of an offshore bar sandstone sample exhibiting abundant calcite cement and detrital mud (sample 03-45) (left photo is under cross polarized light and right photo is under plane polarized light).
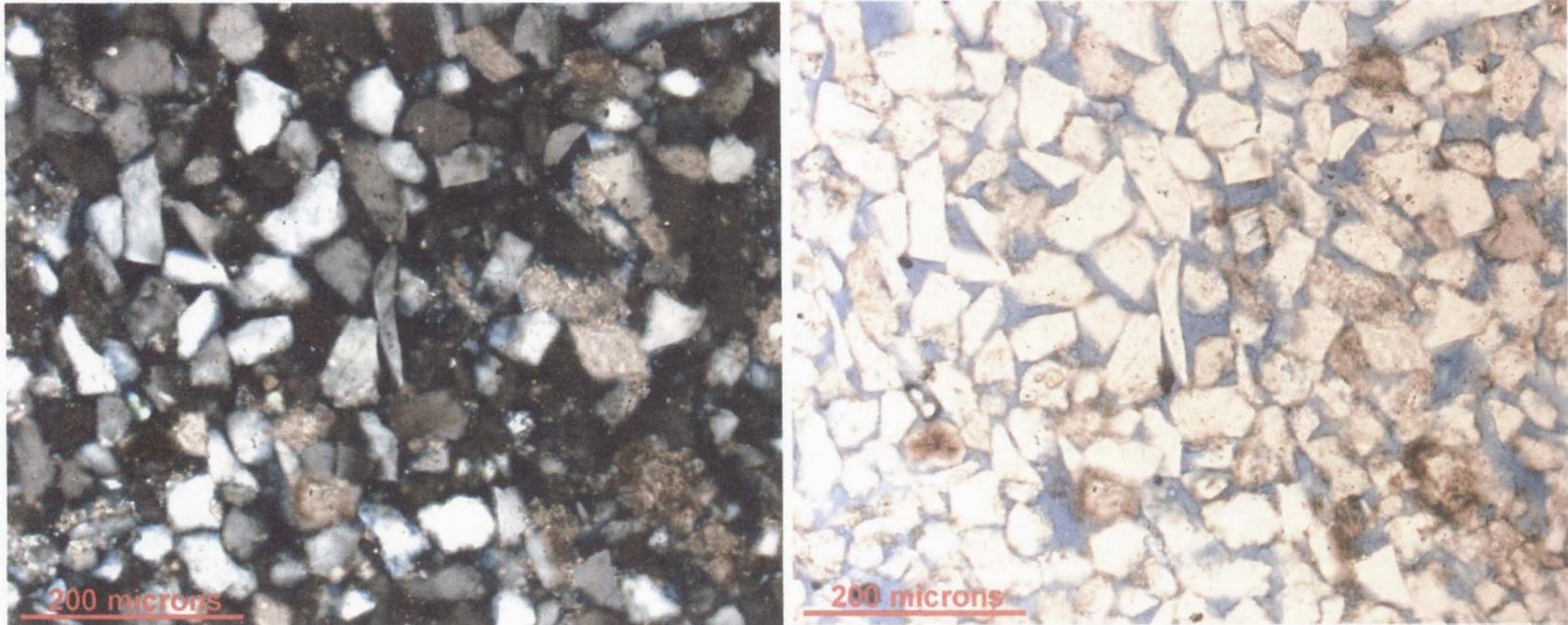
Fig. 50. Photomicrographs of an offshore bar sandstone sample exhibiting good porosity and minor calcite cement and detrital mud (sample 03-39) (left photo is under cross polarized light and right photo is under plane polarized light).

DISCUSSION

The field and petrographic data presented above not only illustrate the complexity of facies architectures and scales of heterogeneity that exist within each outcrop, but also the range in diversity between two contrasting lacustrine shoreline systems tracts in the Uinta basin. The three outcrops were chosen in part due to their abundance of sandstone-rich deposits, which range from extremely complex in Outcrops One and Two (the fluvial facies of the Colton Formation and the deltaic facies of the Green River Formation, respectively), to fairly simple in Outcrop Three (the wave-dominated facies of the Green River Formation). These sand-rich units are the primary analog reservoir intervals of the outcrops and are partially to entirely encased by thick mudstone units, thus requiring more attention in regards to sand body connectivity, compartmentalization, and internal heterogeneity. Detailed documentation of these features in outcrop allow the fluid flow implications of the same features in the subsurface to be better understood, resulting in efficient production of similar lacustrine reservoirs.

Outcrop One

Reservoir rocks of Outcrop One are sandstone-rich CH and CS LAs that are either isolated in thick OB intervals, or constituents of LA complexes where laterally or vertically amalgamated with one another. These amalgamated units, separated by thick mudstone-rich units, are analogs to major reservoir compartments with complex facies architecture and extensive internal heterogeneity. Petrographically, rocks of Outcrop One exhibit the highest average mean grain size and percent detrital mud values, and the lowest percent porosity values of the three outcrops. Internally, the CS LAs have greater

percent porosity and lower percent detrital mud than the CH LAs, however CS LAs are typically lens- or wedge-shaped and are either amalgamated with other CS LAs, truncated laterally by CH LAs, or entirely isolated within OB deposits. This architecture results in poor lateral continuity, high vertical compartmentalization, and minimal connectivity with other sandstone-rich LAs, thereby minimizing reservoir potential. CS rocks also occur as thin tabular and laterally extensive LAs that are entirely encased by OB deposits. Extensive covered intervals in these slope-forming areas of the outcrop, along with the thin nature of these LAs, result in an inability to map these units on the photomosaic.

Rocks of the CH LA represent the dominant reservoir intervals of Outcrop One due to their abundance, thickness, and common amalgamation that produces vertically and laterally connected LA complexes. In decreasing order of abundance in the outcrop, CH rocks occur as amalgamated lenticular, amalgamated undulatory, and isolated lenticular LAs. The former two are partially to entirely encased by mudstone intervals, while the latter are entirely encased by mudstone intervals. Maximum individual LA thickness of CH LAs ranges from 2 to 18 m. When amalgamated these LAs form LA complexes that can produce vertically continuous sandstone packages that reach 48 m in thickness. Of the three CH LA types, the amalgamated undulatory LAs exhibit the best porosity and largest average mean grain size values.

The isolated lenticular type of CH LAs are uncommon in Outcrop One, and typically pinch-out laterally into OB deposits. In terms of reservoir properties, this type of CH LAs exhibits no connectivity with other sandstone-rich LAs. In contrast, individual LAs of the amalgamated undulatory type of CH LAs are persistent across the

outcrop, except where laterally or vertically truncated by similar or amalgamated lenticular CH LAs. Therefore, these thick reservoir intervals exhibit good connectivity, and moderate to high lateral continuity and vertical compartmentalization. The amalgamated lenticular type of CH LAs is the dominant constituent of Outcrop One, and coincidentally accounts for most of the heterogeneity in the outcrop. The thickness and lateral extent of individual amalgamated lenticular CH LAs varies considerably. Commonly they are vertically and laterally amalgamated with other lenticular CH LAs, but are also amalgamated with the undulatory CH LAs and CS LAs. Therefore, this group exhibits very good connectivity, low to moderate lateral continuity, and low to high vertical compartmentalization.

Aside from the complex geometry and stacking patterns of LAs in Outcrop One, the higher-order bounding surfaces which envelope these LAs and LA complexes are also considered large-scale heterogeneity and need to be addressed in terms of their fluid flow implications. First-order bounding surfaces are those surfaces that envelope the entire fluvial system, and will not be addressed here because their magnitude of scale is too high for this study. Second-order bounding surfaces are those surfaces that envelope channel-belts. Because the channel-belts are typically surrounded by thick mudstone units, these surfaces represent baffles or barriers to flow. Internally, the channel-belts are segmented by third-order bounding surfaces, or those surfaces that envelope individual CH LAs. These surfaces are vertically transmissive where amalgamated individual CH LAs produce sand on sand contacts with similar sedimentological features on either side of the surface. However, these surfaces may also exhibit reduced vertical transmissibility, act as baffles, or represent barriers to flow where mud chips,

discontinuous mudstone beds, or continuous mudstone beds are present, respectively. Where individual CH LAs extend into thick OB deposits, the third-order bounding surfaces are baffles or barriers to flow. Fourth-order bounding surfaces are those surfaces that envelope other fluvial lithosomes (CS deposits of this outcrop), and exhibit the same fluid flow implications as those discussed for third-order bounding surfaces.

Within the sandstone-rich reservoir analog intervals of Outcrop One, smaller-scale internal features add further complexity to the system, and are also critical components in terms of fluid flow. CH and CS LAs and LA complexes enveloped by second-, third-, and fourth-order bounding surfaces are segmented by smaller-scale fifth- and sixth-order bounding surfaces. Fifth-order bounding surfaces are those surfaces that separate beds of different lithofacies composition. These surfaces are vertically transmissive where grain size and sedimentary structure differences are minimal, but can exhibit reduced vertical transmissibility where grain size differences are greater, or when mud chips are present. For example, when a fifth-order bounding surface separates a bed of well-rounded, very well sorted, medium grained trough cross-stratified sandstone from a bed of angular, poorly sorted, fine to medium grained massive sandstone, the surface exhibits reduced vertical transmissibility due to petrophysical differences across the surface. In contrast, sixth-order bounding surfaces are those surfaces that separate individual beds of similar lithofacies composition, resulting in a surface that is commonly vertically transmissive. An example of a sixth-order bounding surface is a surface that separates successive beds of well-rounded, very well sorted, medium grained trough cross-stratified sandstone. In this case, petrophysical differences are minimal between the two beds, resulting in similar flow parameters across the surface. The added

complexity that these smaller-order bounding surfaces exert on fluid flow in the reservoir is further supported by petrographic analyses. For example, in many of the individual CH LAs, mud chips are common near basal bedding surfaces, resulting in an abundance of detrital mud and minimal percent porosity in samples taken from these areas. Further, individual lithofacies of the CH LAs, such as trough cross-stratified sandstone, exhibit larger mean grain size values, higher percent porosity, and better roundness and sorting than the other lithofacies. These petrographic trends represent the smallest-scale of heterogeneity documented in this study, and cannot be neglected in comprehensive reservoir characterization studies due to their influence on fluid flow.

Outcrop Two

Sandstone-rich intervals of Outcrop Two include DMB, DCH, and SLS LAs that are either individual LAs isolated in thick OSMS and OB deposits, or constituents of LA complexes when laterally or vertically amalgamated with one another. Similar to Outcrop One, reservoir complexity and heterogeneity is high in Outcrop Two. Petrographically, rocks of the deltaic facies exhibit the lowest average porosity values of the three outcrops. Internally, the SLS LAs have the highest percent detrital mud and the lowest average mean grain size and percent porosity values of the three sandstone-rich LAs in Outcrop Two. These poor reservoir qualities, along with small individual LA thickness and common isolation in OSMS intervals, prevent SLS LAs from being good reservoir candidates. In contrast, DMB and DCH LAs exhibit larger mean grain size and percent porosity values, and lower percent detrital mud values of the sandstone-rich LAs

in Outcrop Two. Rocks of the DMB typically have the best petrographic reservoir qualities.

The DCH LAs are the dominant sandstone-rich constituents of Outcrop Two. Similar to the individual CH LAs of Outcrop One, the individual DCH LAs exhibit a wide variety of geometry and architecture. In decreasing order of abundance individual DCH LAs are amalgamated lenticular, amalgamated undulatory, and isolated lenticular. The former two are partially to entirely encased by mudstone-dominated units, while the latter are entirely encased by mudstone units. Average maximum thickness of individual DCH LAs ranges from 2 to 11 m, and when amalgamated with other DCH or DMB LAs in LA complexes can produce vertically continuous sandstone packages that reach 15 m in thickness. The individual DMB LAs of Outcrop Two have an average maximum thickness of 2 to 10 m, and occur as tabular and laterally extensive LAs that are entirely encased by mudstone-dominated intervals, except where vertically or laterally truncated by individual DCH LAs.

The individual isolated lenticular DCH LAs pinch-out into OSMS, OB, and SLS intervals. In terms of reservoir properties, this type of DCH LAs exhibits no connectivity with other sandstone-rich reservoir intervals of the outcrop, resulting in poor lateral continuity and high vertical compartmentalization. Because these LAs are entirely encased by mudstone-dominated units, basal and upper bounding surfaces act as barriers to flow. Individual amalgamated undulatory DCH LAs are typically persistent across the outcrop except where truncated by lateral or vertical amalgamated lenticular DCH LAs. Commonly these truncations cause the thickness of individual amalgamated undulatory DCH LAs to be quite variable, and in some cases the LAs are completely truncated.

Therefore, these reservoir intervals exhibit good connectivity, variable lateral continuity, and moderate to high vertical compartmentalization. Bounding surfaces of this type of DCH LA are barriers to flow when juxtaposed against mudstone units, baffles when mud chip horizons or discontinuous thin mudstone beds separate these units from other reservoir intervals, or vertically transmissive when juxtaposed against other reservoir intervals with similar petrophysical properties. The amalgamated lenticular DCH LAs show wide variation in thickness and lateral extent. These LAs are typically amalgamated laterally and vertically with other DCH LAs, and vertically with underlying DMB LAs. In both cases, such amalgamations form LA complexes. Reservoir properties of the amalgamated lenticular DCH LAs include good connectivity and low to moderate lateral continuity and vertical compartmentalization. Bounding surfaces of the amalgamated lenticular DCH LAs are characterized by the same fluid flow implications as those mentioned above for the amalgamated undulatory DCH LAs. The DMB LAs of Outcrop Two are typically persistent across the outcrop, however individual LA thickness varies due to truncation by overlying DCH LAs. Individual DMB LAs are thick reservoir units that exhibit good connectivity, moderate to high lateral continuity, and low to moderate vertical compartmentalization. Bounding surfaces of the DMB LAs are also characterized by the same fluid flow implications as the previous two types of DCH LAs.

Similar to Outcrop One, reservoir analog intervals of Outcrop Two are segmented by smaller-scale bounding surfaces, resulting in further reservoir complexity and heterogeneity. These smaller-order surfaces are analogous to the fifth- and sixth-order surfaces of the fluvial hierarchy, and exhibit identical fluid flow implications as those previously mentioned for Outcrop One. Outcrop Two reservoir analog intervals also

share similarity with Outcrop One, in that samples of the trough cross-stratified sandstone lithofacies in both DCH and DMB LAs typically exhibit larger average mean grain size values, higher percent porosity, and better roundness and sorting than other lithofacies.

Outcrop Three

Sandstone-rich intervals of Outcrop Three include OSB, SLS, and CH LAs. At Outcrop Three, CH rocks occur as a single LA isolated entirely within OSMS and SLS deposits, resulting in poor lateral continuity and high vertical compartmentalization. This group is therefore not considered as a good reservoir interval in Outcrop Three. The OSB and SLS LAs are the dominant constituents of the outcrop, and occur as tabular and laterally extensive LAs that are entirely encased by OSMS and less prominent SLS deposits. In contrast to Outcrops One and Two, Outcrop Three is characterized by tabular LAs that persist across the outcrop with minimal amalgamation, resulting in less large-scale reservoir complexity and heterogeneity. Petrographically, rocks of Outcrop Three exhibit the lowest average mean grain size and the lowest percent detrital mud values than the other two outcrops. Internally, the SLS and OSB LAs exhibit identical average mean grain size values. However, SLS samples show higher percent porosity and percent detrital mud values than samples of the OSB LA. Because SLS LAs are typically thin (50 cm – 1.5 m), are not amalgamated with other SLS or OSB LAs, are encased entirely by mudstone, and exhibit higher percent detrital mud values than samples of the OSB LA, reservoir potential is decreased, relative to the OSB LAs. Individual SLS LAs show poor connectivity with other sandstone-rich LAs, excellent

lateral continuity, and high vertical compartmentalization. Consequently, bounding surfaces of the SLS LAs are barriers to flow.

Rocks of the OSB LA are the dominant reservoir analog intervals of Outcrop Three due to greater thickness (2 – 4 m) and frequent amalgamation with one another, resulting in vertically stacked sandstone packages that reach 6 m in thickness. Similar to the SLS LAs, OSB LAs are encased entirely by OSMS and less prominent SLS deposits. In terms of reservoir properties, individual OSB LAs exhibit low to moderate connectivity, excellent lateral continuity, and moderate to high vertical compartmentalization. Bounding surfaces of individual OSB LAs are barriers to flow when juxtaposed against OSMS and thin SLS intervals, and vertically transmissive when juxtaposed against other OSB LAs that exhibit similar petrophysical features. These surfaces are baffles when mud chips or discontinuous mudstone beds separate the LAs, or show reduced vertical transmissibility when sandstone beds of slightly different petrophysical features exist on either side of the surface.

As with Outcrops One and Two, reservoir analog intervals of Outcrop Three are also segmented by smaller-order surfaces that are analogous to fifth- and sixth-order bounding surfaces of the fluvial hierarchy. Thus, the influence that these surfaces have on fluid flow within the LAs is identical to that described above for Outcrop One. Smaller-scale reservoir heterogeneity also exists in Outcrop Three in the form of petrographic trends. Rocks of the SLS LA typically show the best reservoir properties in samples from the rippled sandstone lithofacies, while rocks of the OSB LA exhibit better reservoir properties in samples from the low-angle cross-stratified and trough cross-stratified sandstone lithofacies. Further, OSB LAs dominated by low-angle cross-

stratified and trough cross-stratified sandstone commonly exhibit a vertical increase

in pore space.

Geostatistical simulation and
fluid flow modeling

This section is a brief summary of a master's thesis in petroleum engineering

completed by Enis Robbana at Texas A & M University (Robbana, 2002). The main

objective of the geostatistical and fluid flow modeling is to provide better documentation

of the effects of geological heterogeneity and compartmentalization on performance in

lacustrine reservoirs. Modeling of Outcrop Two (the deltaic facies of the Green River

Formation) began with the construction of a two-dimensional geological model utilizing

important geologic bounding surfaces determined in the field, vertical measured sections,

and petrographically derived porosity and grain size data (this study). Permeability data

were extrapolated from a porosity-permeability relationship derived from well data in the

Red Wash field (Robbana, 2002). The petrographic data (grain size and porosity) were

assigned on a layer-by-layer basis by matching every point of the measured section on the

outcrop to a layer in the model. Following the construction of the underlying layers in

the two-dimensional model, a three-dimensional model was constructed and channel sand

bodies (individual DCH LAs of this study) were introduced to determine their effect on

fluid behavior (Fig. 51). Traditionally, Cartesian gridding methods are used in studies of

this type. Because lateral pinch-out of sand bodies and complex stacking patterns are

abundant in Outcrop Two, cornerpoint gridding was utilized when erecting the three-

dimensional model. This technique allows for the reproduction of complex sand bodies
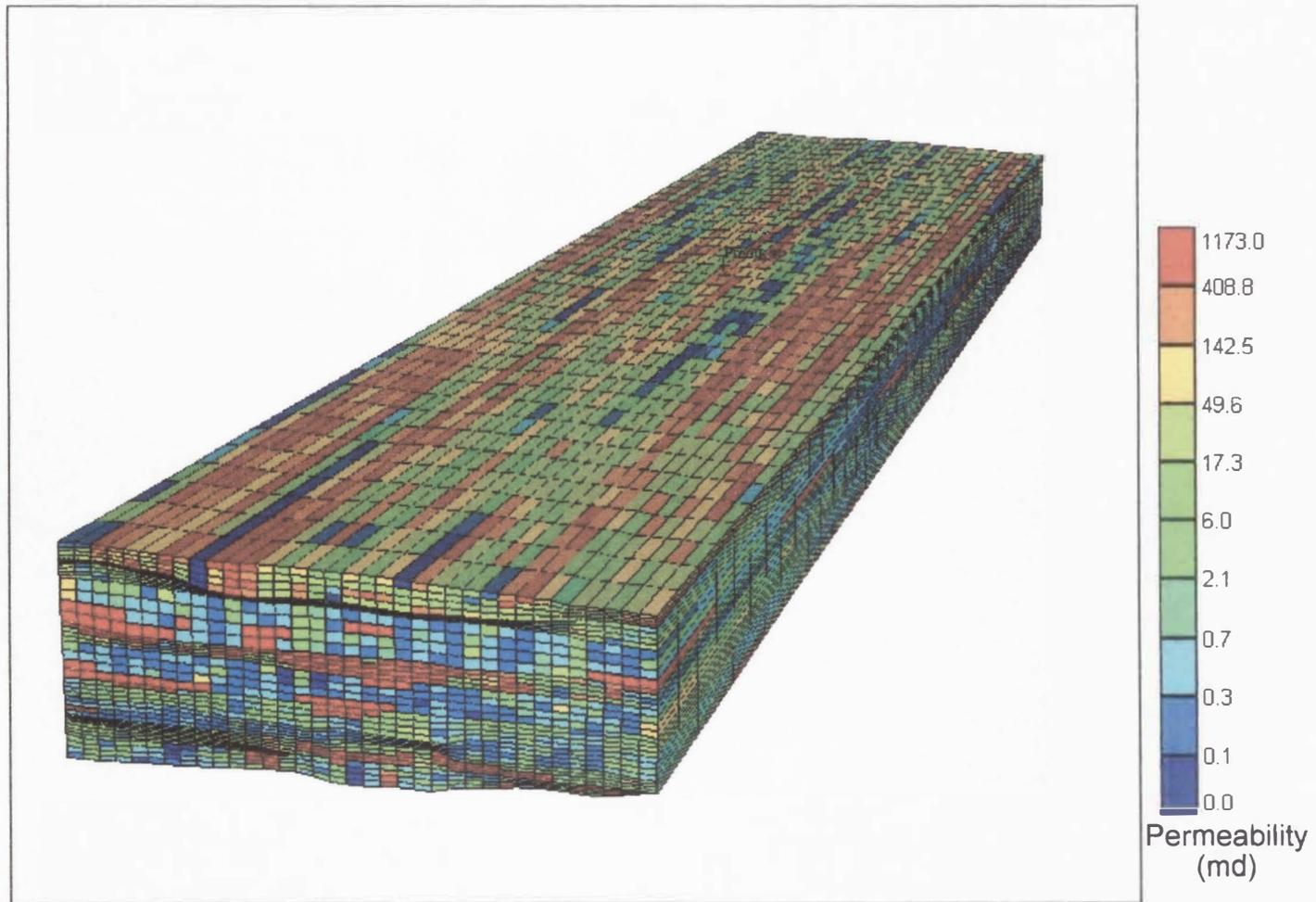
Fig. 51. Three-dimensional model of Outcrop Two populated with field and petrographic data collected in this study (from Robbana, 2002). Dark red units are channels (distributary channel lithofacies assemblages of this study).

with greater accuracy, and is increasingly being utilized in the industry to model complex reservoirs (Robbana, 2002).

Several model realizations were run to investigate the importance of channel heterogeneity and recovery strategy on production. To investigate the influence of channels on performance, the number of channels was varied, as were channel properties such as porosity and permeability, channel connectivity, and channel sinuosity. In order to investigate effects of recovery strategy on performance, models were run using both primary and enhanced recovery strategies, as well as cases with different water injection patterns.

Channel properties were an important control on production, in that cumulative production and production rate were better with higher number of channels that exhibit good porosity and permeability (Figs. 52, 53); performance improved with increased channel penetration; higher sinuosity channels had slightly better performance than low sinuosity channels; and sinuosity of channels had little effect when the channels were amalgamated, or connected. Model results of recovery strategy on performance demonstrated in each case that water injection outperformed natural depletion and gas injection (Figs. 54, 55, 56, 57). Improvement in final recovery over natural depletion was about 15 % for the water injection, compared to only 8 % for the gas injection. However, early water breakthrough can be a limiting factor for water injection in lacustrine reservoirs and cannot be completely overcome by changing the well placement pattern. Finally, a staggered line drive was the best waterflood pattern for this type of reservoir (Fig. 58).
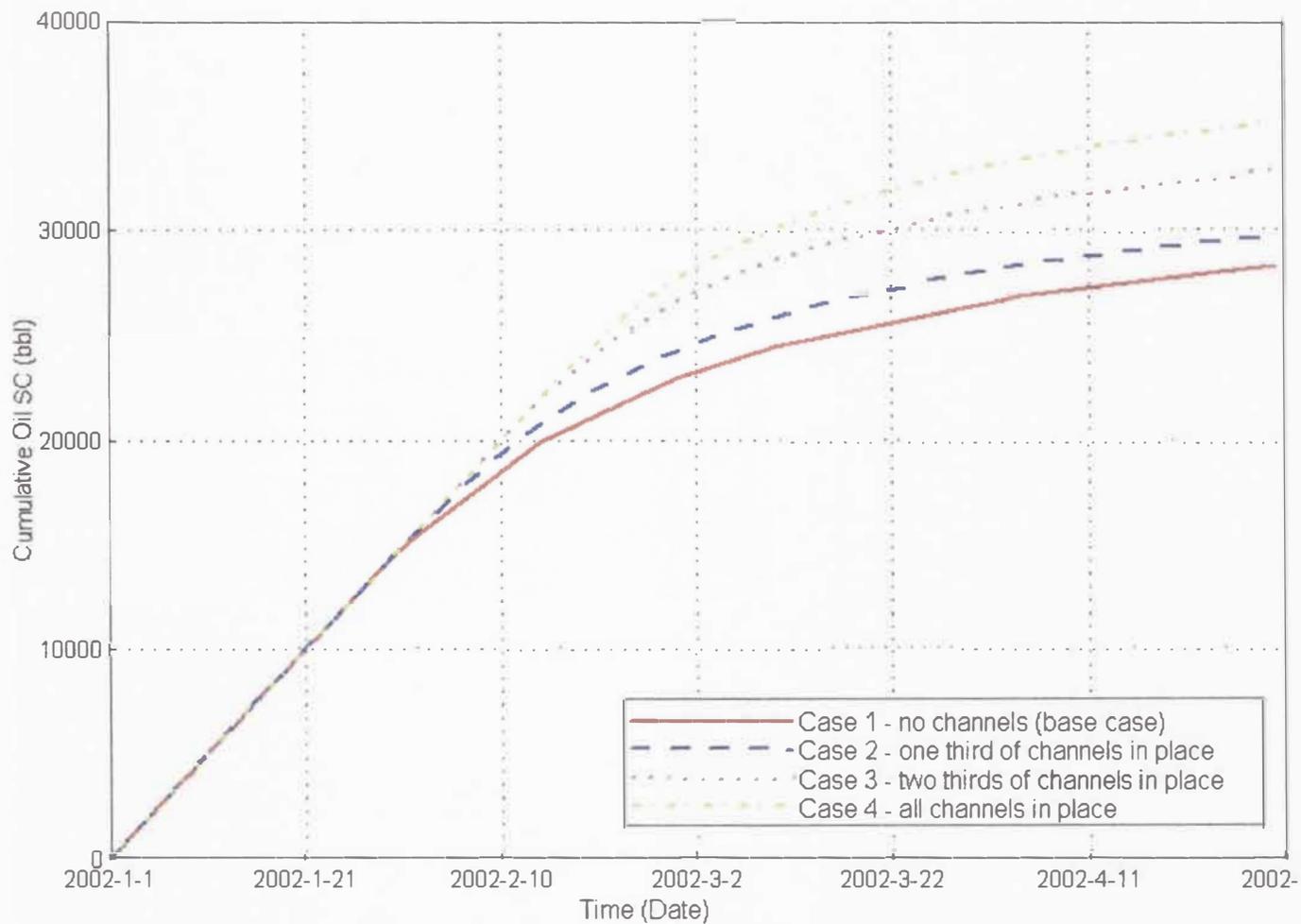
Fig. 52. Graph illustrating the effect of the number of channels on cumulative production. Three-dimensional models were run varying the number of channels allowed in the model (from no channels to all channels). Note that cumulative production is best when all channels are in place (SC = surface conditions) (from Robbana, 2002).
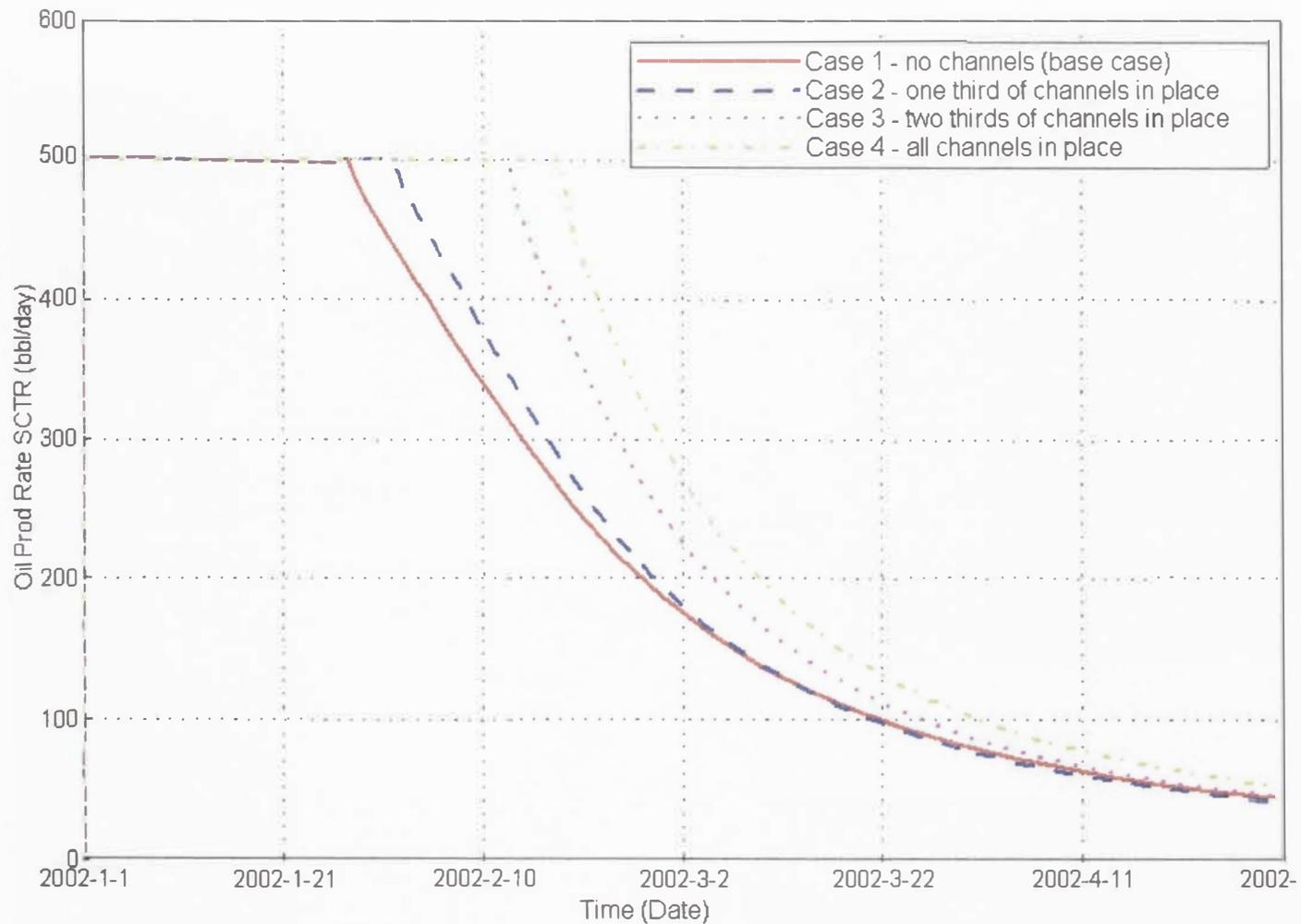
Fig. 53. Graph illustrating the effect of the number of channels on production rate. Three-dimensional models were run varying the number of channels allowed in the model (from no channels to all channels). Note that the production rate is best when all channels are in place, similar to Fig. 52 (SCTR = sector, meaning a result that applies to the entire field) (from Robbana, 2002).
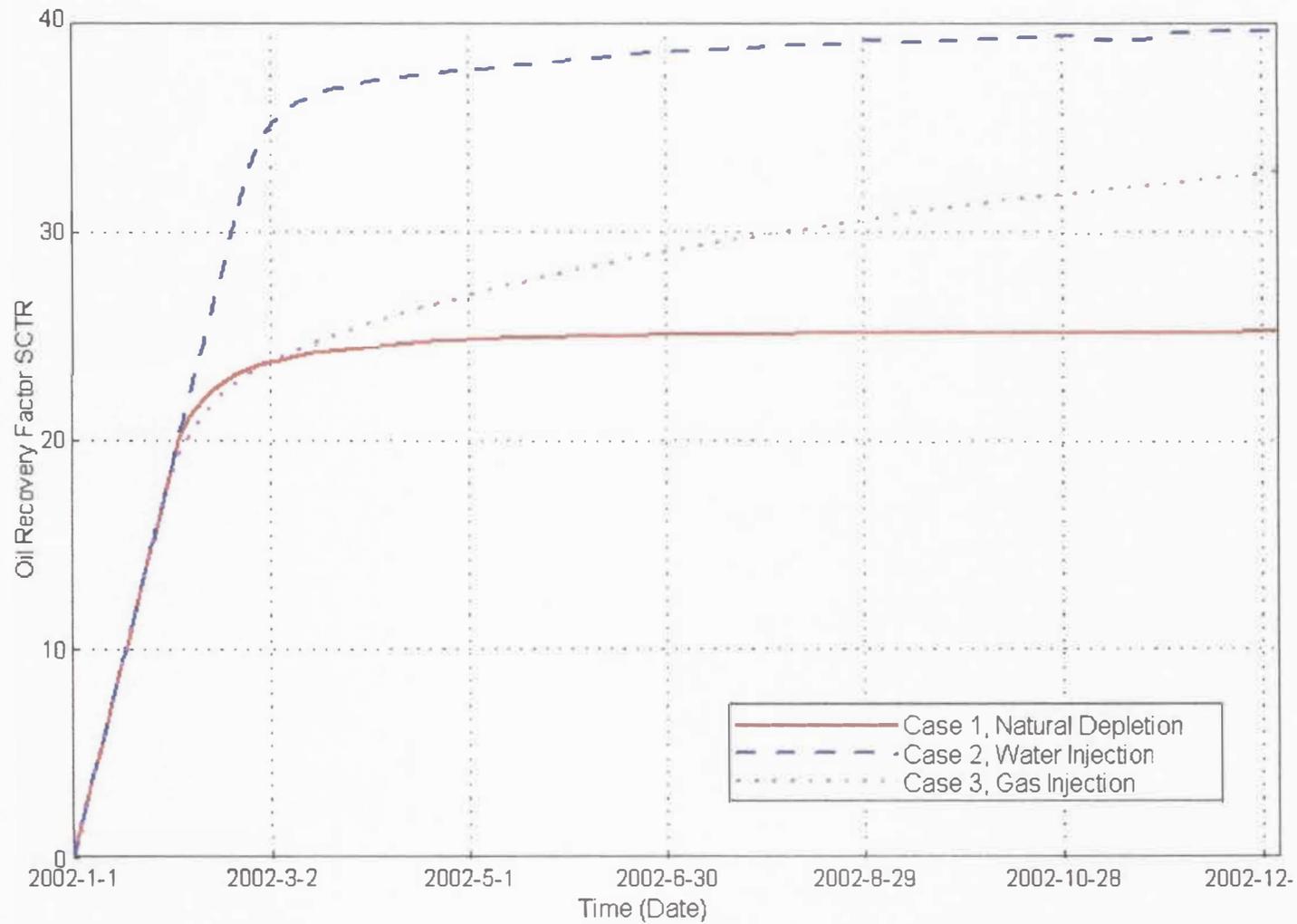
Fig. 54. Graph illustrating the effect of recovery strategy on recovery efficiency. Three-dimensional models were run varying the recovery strategy. Note that the best recovery strategy is water injection (SCTR = sector, meaning a result that applies to the entire field) (from Robbana, 2002).

Case 1 - Natural Depletion
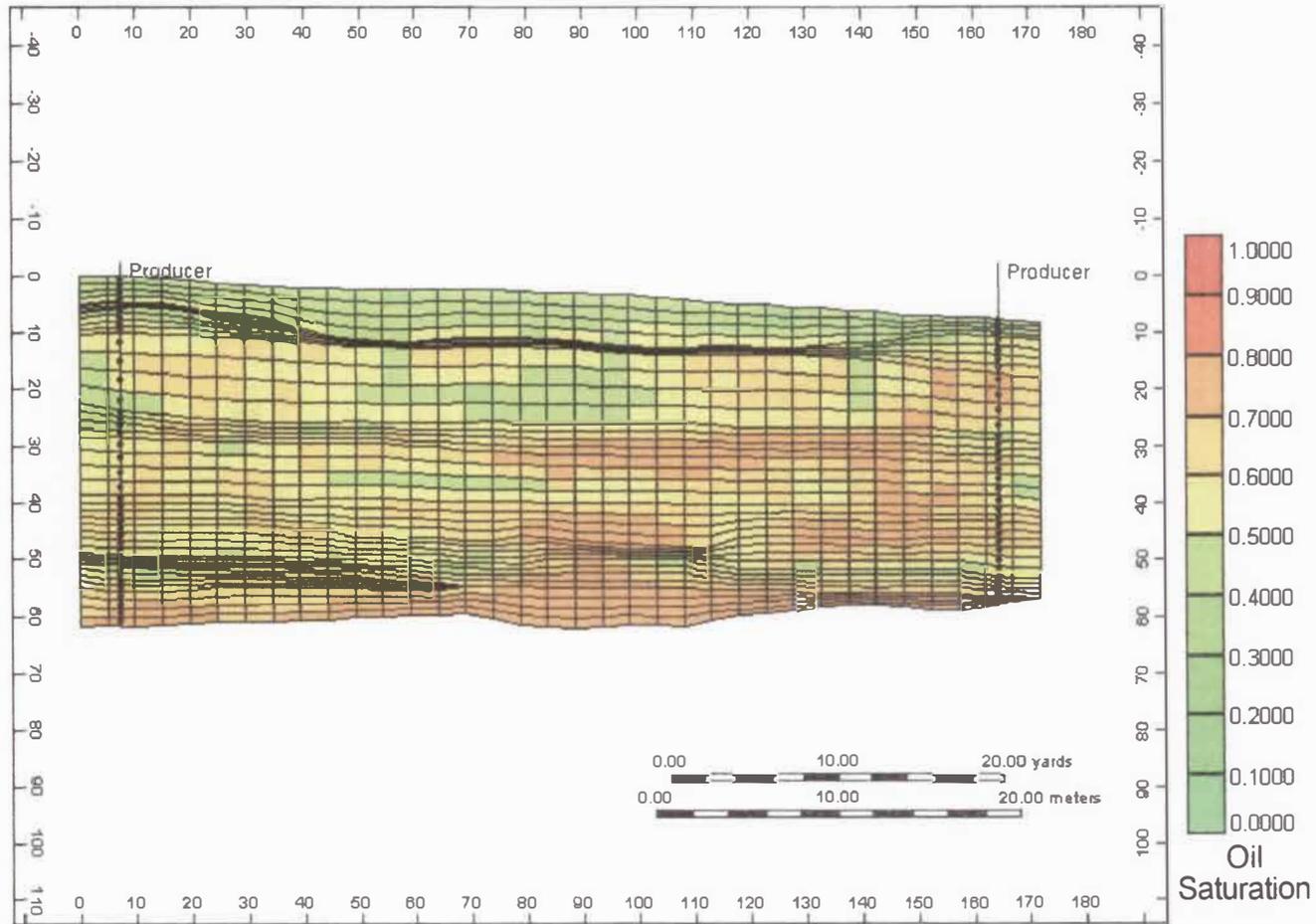
Fig. 55. Oil saturation distribution in a cross section of the reservoir using natural depletion as the recovery strategy. When compared with Figs. 56 and 57, the natural depletion cross section remains oil saturated, and is therefore the least efficient recovery strategy (from Robbana, 2002).

Case 2 - Water Injection
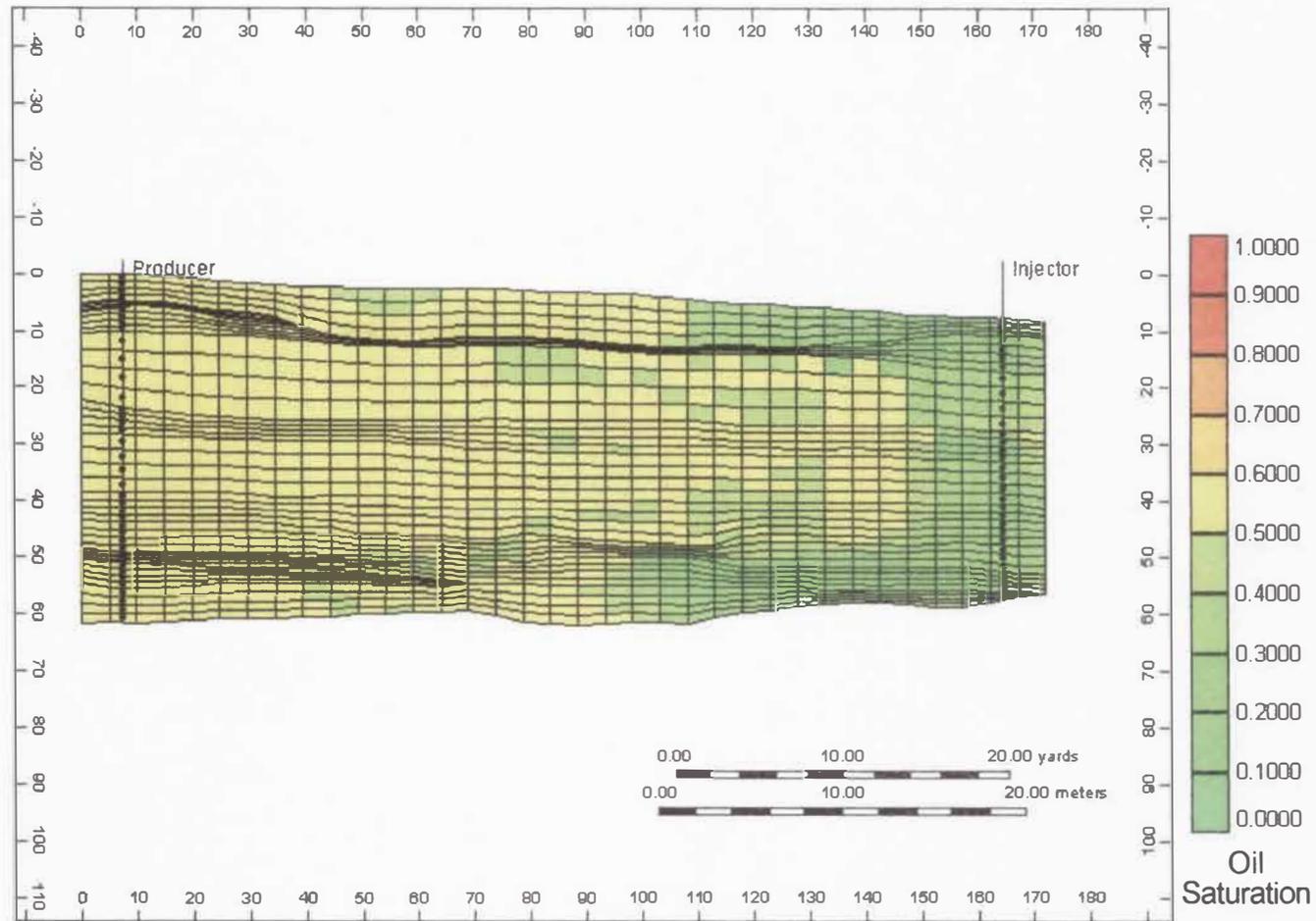
Fig. 56. Oil saturation distribution in a cross section of the reservoir using water injection as the recovery strategy. When compared with Figs. 55 and 57, water injection results in less bypassed oil, and is therefore the most efficient recovery strategy (from Robbana, 2002).

Case 3 - Gas Injection
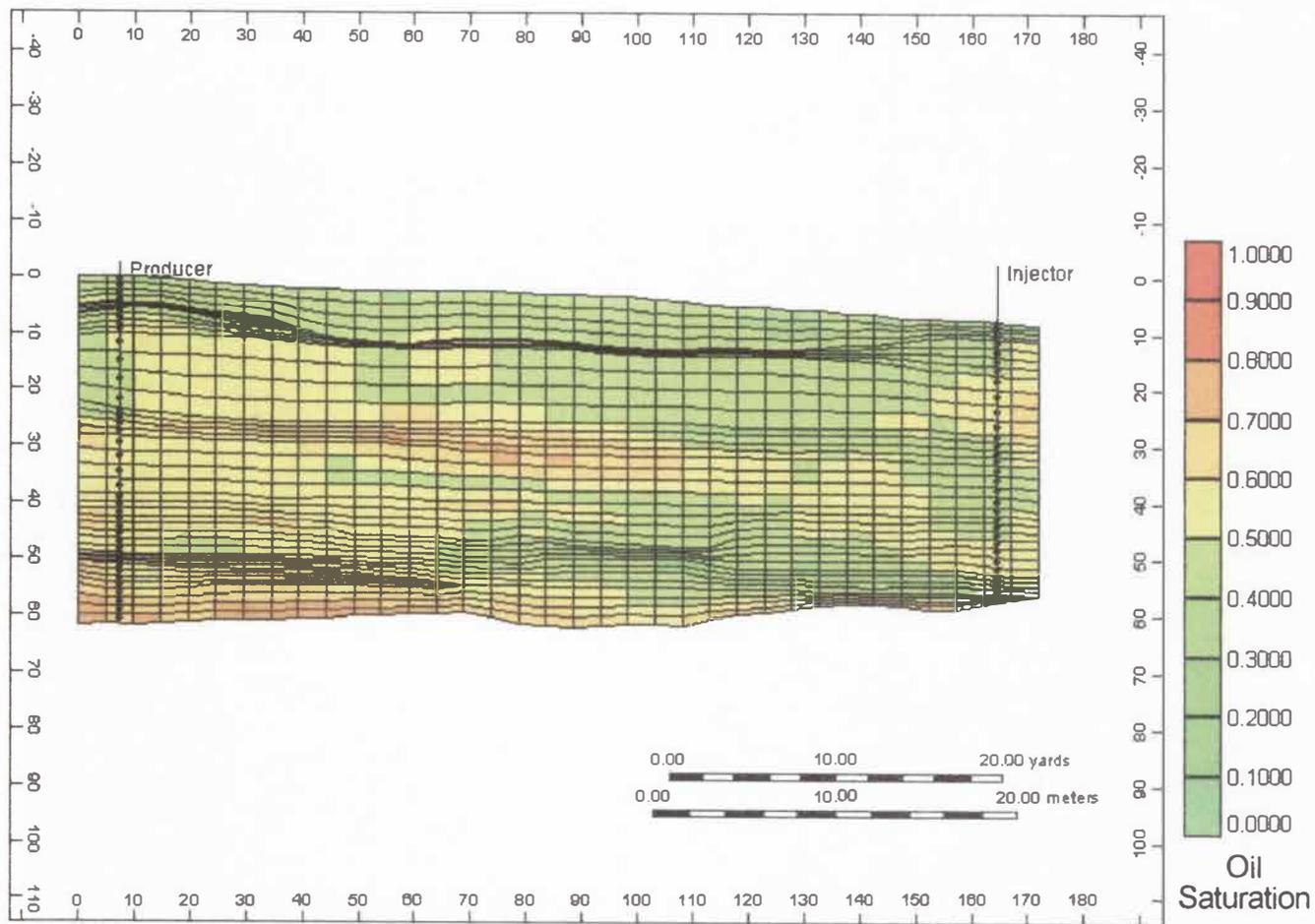
Fig. 57. Oil saturation distribution in a cross section of the reservoir using gas injection as the recovery strategy. When compared with Figs. 55 and 56, gas injection is the second best recovery strategy (from Robbana, 2002).
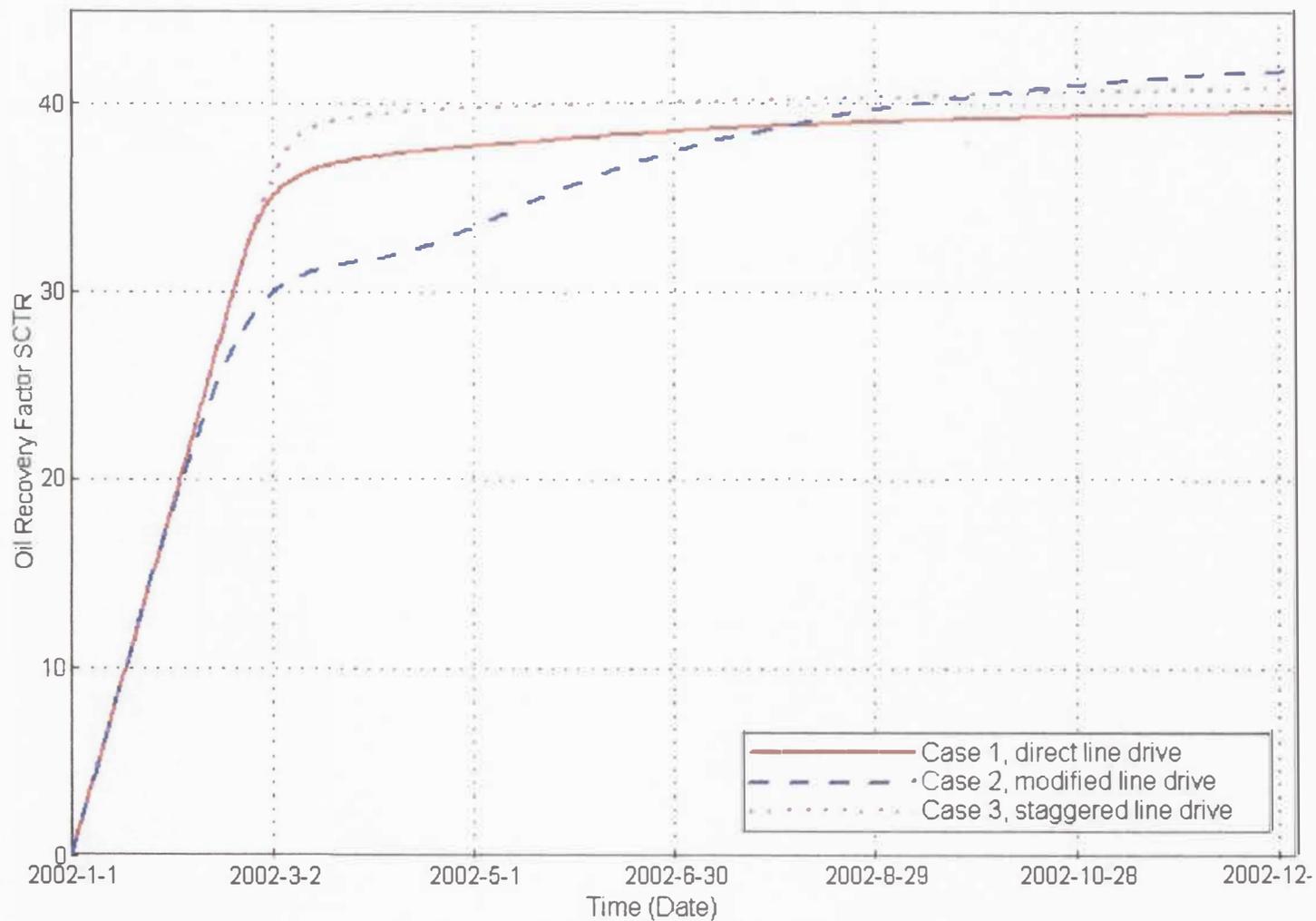
Fig. 58. Graph illustrating the effect of waterflood pattern on recovery efficiency. Three-dimensional models were run varying the type of waterflood pattern used for production. Note that the best waterflood pattern is a staggered line drive (SCTR = sector, meaning a result that applies to the entire field) (from Robbana, 2002).

Results of the fluid flow modeling can be further supported by the geological features characteristic of Outcrop Two. Because the channel sand bodies (DCH LAs of this study) are typically amalgamated with one another or with underlying DMB LAs, they account for most of the connectivity in the outcrop. Therefore, with increased number of channels in the system, connectivity between sandstone-rich intervals increases, resulting in better cumulative production and production rate. Hydrocarbon flowing through the thick DMB LAs would eventually make their way into the overlying lenticular or undulatory DCH LAs, where compartmentalization is possible due to thick overlying mudstone-dominated intervals. This compartmentalization is greatest in the amalgamated lenticular DCH LAs, as they are typically encased laterally and vertically by such mudstone units. Therefore, with more amalgamated lenticular channels penetrated during production, less hydrocarbons will be left behind in bypassed compartments, resulting in increased production efficiency.

As illustrated in Figs. 54 – 57, natural depletion is the least effective recovery strategy for Outcrop Two, exhibiting an abundance of bypassed oil (Fig. 55). Areas of bypassed oil coincide with lenticular DCH LAs that are amalgamated with underlying DMB and undulatory DCH LAs. Because the producing wells are located at both ends of the cross section, many of the vertically and laterally compartmentalized lenticular DCH LAs are not penetrated, resulting in inefficient drainage. In contrast, oil saturation is lower in the top portion of the reservoir in the natural depletion case (Fig. 55), as a result of the excellent connectivity of sandstone-rich DMB and DCH LAs across the entire upper portion of the outcrop, along with minimal amalgamated lenticular DCH LAs to compartmentalize the hydrocarbons in a localized area.

Also illustrated in Figs. 54 – 57, is that water injection is the most efficient

recovery strategy for Outcrop Two. The cross section in Fig. 56 shows less oil saturation

than the other recovery methods, and a variation in oil saturation across the cross section

from the water injecting well at the far right to the producing well at the far left. Low oil

saturation zones are concentrated near the water injecting well, whereas zones of higher

oil saturation dominate the center and left portions of the cross section. This can be

attributed to the moderate lateral connectivity of the DMB and DCH LAs. However, oil

will still be bypassed using this recovery strategy because of occasional amalgamated

lenticular DCH LAs that are not efficiently swept due to their lateral and vertical

compartmentalization. It is important to note that although water injection outperforms

natural depletion and gas injection in terms of recovery strategies for a reservoir of this

type, water injection still results in abundant bypassed hydrocarbons, in that oil saturation

can still be 60 % (Fig. 56).

CONCLUSIONS

Outcrop and petrographic studies of the Green River and Colton formations in the Uinta basin record multiple types and scales of heterogeneity that exist in lacustrine systems, and the variation in heterogeneity between three subenvironments of two distinct lacustrine shoreline deposystems. Each of the lacustrine sub-environments has distinct sandstone-rich reservoir compartments and sand body stacking patterns. These compartments have internal heterogeneity that becomes less significant at smaller-scales. This study was not designed to produce direct outcrop analogs to the currently producing fields in the Uinta basin, but to begin to document the facies architecture, bounding surfaces, and internal petrophysical properties that characterize lacustrine reservoirs in general.

Outcrop One (the fluvial facies of the Colton Formation) is characterized by channel-fill, crevasse splay, and overbank lithofacies assemblages. The best reservoir rocks are amalgamated lenticular and amalgamated undulatory channel-fill lithofacies assemblages due to their strong connectivity and lateral continuity. Average maximum thickness of individual channel-fill lithofacies assemblages ranges from 4 to 18 m. Vertical amalgamation of these lithofacies assemblages results in continuous sandstone packages that can reach 48 m in thickness. Mud chips, large mud clasts, and discontinuous mudstone and siltstone beds within these lithofacies assemblages are common. Grain size is primarily medium sand, and porosity ranges from 0.4 to 18.2 %.

Outcrop Two (the deltaic facies of the Green River Formation) is dominated by distributary channel, distributary mouth bar, shallow lacustrine sandsheet/storm, offshore

lacustrine mudstone and siltstone, and overbank lithofacies assemblages. Lenticular and undulatory amalgamated distributary channel lithofacies assemblages, as well as tabular distributary mouth bar lithofacies assemblages account for the primary reservoir rocks in this outcrop due to their lateral continuity and connectivity. Average maximum thickness of individual distributary channel and distributary mouth bar lithofacies assemblages ranges from 2 to 11 m. Amalgamation of these lithofacies assemblages produce vertically continuous sandstone packages that can reach 15 m in thickness. Mud chips, large mud clasts, and discontinuous mudstone and siltstone beds are also common within these units. Grain size is very fine to medium sand, and porosity ranges from 0.8 to 23.6 %.

Outcrops One and Two are dominated by thick amalgamated and laterally extensive lenticular and tabular lithofacies assemblages and lithofacies assemblage complexes that are partially to entirely compartmentalized by mudstone units. These reservoir units are dominated by large-scale heterogeneity, in that individual lithofacies assemblages show a wide variety of connectivity and lateral continuity. Smaller-scale heterogeneity such as discontinuous mudstone and siltstone beds, mud chip lags, and large mud clasts within the lithofacies assemblages add more complexity to the systems by potentially reducing vertical transmissibility or acting as flow baffles. Complexity of hydrocarbon flow and compartmentalization in these types of reservoirs is high, therefore careful documentation of reservoir characteristics at all magnitudes of scale is imperative in order to better address production potential.

Outcrop Three (the wave-dominated facies of the Green River Formation) is characterized by offshore bar, shallow lacustrine sandsheet/storm, channel, and offshore

lacustrine mudstone and siltstone lithofacies assemblages. The best reservoir rocks are tabular laterally extensive offshore bar lithofacies assemblages that are entirely compartmentalized by thick mudstone units. Average maximum thickness of individual offshore bar lithofacies assemblages ranges from 2 to 4 m, with occasional amalgamations that produce vertically continuous sandstone packages that reach 6 m in thickness. Grain size is very fine to medium sand, and porosity ranges from 0 to 23.4 %. Unlike Outcrops One and Two, large-scale heterogeneity is less important in reservoirs similar to Outcrop Three, as sand bodies exhibit excellent lateral continuity and less complex amalgamation. Small-scale heterogeneity such as basal mud chips within sandstone beds and discontinuous mudstone and siltstone beds between sandstone beds may reduce vertical transmissibility or create flow baffles. Therefore, focusing on the documentation of internal sedimentological and reservoir characteristics is necessary to better address production potential in these types of reservoirs.

Geostatistical simulation and fluid flow models run for Outcrop Two suggest that reservoir performance improved with increased number of channels in the system, increased channel penetration, and channel sinuosity (Robbana, 2002). These results are consistent with the geologic features of the outcrop. With increased number of channels in the system there is more amalgamation, resulting in more compartmentalized units contacted by the well. Recovery strategy results indicated that water injection is the optimal secondary recovery strategy, with a staggered line drive as the best waterflood pattern (Robbana, 2002). Although water injection outperforms other recovery strategies, a reservoir of this type can still have 60 % oil saturation following production. Therefore, even the best recovery strategy for a specific reservoir can leave large amounts

of hydrocarbons in place when facies architecture and stacking patterns are complex.

The integration of field and petrographic studies with fluid flow modeling in lacustrine reservoirs of the Green River and Colton formations represents the first step in documenting the types of sand bodies and the multiple scales of heterogeneity that exist in lacustrine reservoirs, and how these reservoir characteristics influence fluid flow migration and compartmentalization. In order to adequately derive a classification system and hierarchy of bounding surfaces that can be applicable to all lacustrine reservoirs, more studies of this type are needed. Well-exposed side canyons that are perpendicular and parallel to the outcrops of this study are prime settings to conduct similar outcrop studies, as sand bodies and important bounding surfaces may be connectable. These studies are necessary in order to produce predictable three-dimensional reservoir-scale models that can be utilized as analogs to reservoirs in other lacustrine systems.

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APPENDIX

Sandstone Petrographic Data:

Mean Grain Size Data (400 grains measured per thin section)								
Outcrop # 1			Outcrop # 2			Outcrop # 3		
Sample #	microns	(mm)	Sample #	microns	(mm)	Sample #	microns	(mm)
01-2	265.7	0.266	02-1	176.1	0.176	03-1	258.4	0.258
01-4	308.8	0.309	02-6	154.4	0.154	03-2	250.6	0.251
01-7	303.9	0.304	02-11	105.1	0.105	03-3	269.4	0.269
01-9	374.0	0.374	02-12	119.7	0.120	03-4	255.1	0.255
01-10	314.8	0.315	02-16	142.7	0.143	03-7	89.4	0.089
01-14	321.2	0.321	02-21	115.8	0.116	03-9	120.0	0.120
01-15	289.9	0.290	02-24	133.5	0.133	03-10	112.1	0.112
01-17	291.0	0.291	02-27	155.3	0.155	03-11	131.1	0.131
01-19	278.9	0.279	02-30	159.2	0.159	03-12	131.7	0.132
01-21	314.7	0.315	02-33	144.3	0.144	03-13	102.3	0.102
01-22	306.3	0.306	02-35	122.0	0.122	03-14	92.8	0.093
01-24	273.9	0.274	02-40	116.7	0.117	03-15	144.4	0.144
01-25	263.5	0.264	02-41	130.5	0.131	03-16	130.4	0.130
01-27	303.1	0.303	02-46	106.7	0.107	03-18	102.8	0.103
01-28	304.6	0.305	02-47	166.0	0.166	03-19	126.7	0.127
01-29	304.5	0.305	02-54	197.9	0.198	03-20	139.6	0.140
01-31	317.4	0.317	02-59	169.8	0.170	03-21	93.8	0.094
01-32	337.3	0.337	02-62	127.8	0.128	03-22	93.1	0.093
01-34	367.4	0.367	02-63	172.1	0.172	03-24	109.5	0.110
01-35	333.6	0.334	02-65	168.7	0.169	03-25	113.3	0.113
01-36	330.5	0.331	02-68	127.1	0.127	03-26	126.7	0.127
01-37	273.4	0.273	02-70	151.1	0.151	03-28	142.2	0.142
01-39	234.4	0.234	02-73	138.2	0.138	03-29	145.7	0.146
01-40	252.7	0.253	02-74	103.0	0.103	03-30	93.5	0.093
01-42	226.0	0.226	02-76	212.2	0.212	03-31	138.8	0.139
01-46	384.4	0.384	02-79	209.8	0.210	03-33	86.1	0.086
01-47	378.5	0.379	02-84	232.1	0.232	03-34	98.0	0.098
01-48	379.0	0.379	02-88	206.2	0.206	03-35	87.2	0.087
01-49	347.5	0.347	02-92	224.3	0.224	03-36	111.7	0.112
01-50	330.7	0.331	02-94	221.0	0.221	03-37	109.3	0.109
01-51	364.2	0.364	02-99	225.8	0.226	03-38	88.0	0.088
01-53	340.4	0.340	02-100	209.0	0.209	03-39	116.6	0.117
01-54	304.6	0.305	02-103	180.3	0.180	03-41	113.3	0.113
01-55	297.1	0.297	02-106	181.7	0.182	03-42	118.9	0.119
01-57	313.1	0.313	02-108	216.8	0.217	03-44	109.4	0.109
01-59	414.2	0.414	02-111	116.1	0.116	03-45	89.1	0.089
01-60	400.3	0.400	02-113	273.4	0.273	03-46	95.9	0.096
01-61	331.3	0.331	02-117	201.3	0.201	03-47	108.5	0.109
01-62	386.6	0.387	02-118	252.4	0.252	03-48	108.8	0.109
01-63	371.3	0.371	02-119	302.0	0.302	03-49	168.1	0.168
			02-120	225.4	0.225	03-50	106.2	0.106
			02-121	226.8	0.227	03-51	119.9	0.120
			02-122	198.0	0.198	03-52	246.0	0.246
						03-53	136.3	0.136
						03-54	128.4	0.128
Minimum	226.0	0.226	Minimum	103.0	0.103	Minimum	86.1	0.086
Maximum	414.2	0.414	Maximum	302.0	0.302	Maximum	269.4	0.269
Mean	320.9	0.321	Mean	174.8	0.175	Mean	130.2	0.130
Median	314.8	0.315	Median	169.8	0.170	Median	113.3	0.113
Standard Deviation	45.09	0.045	Standard Deviation	48.79	0.049	Standard Deviation	48.67	0.049

Outcrop # 1: Fluvial facies of the Colton Formation Point Count Data (500 counts per thin section)												
Thin Section #	% Pore Space	% Calcite Cement	% Clay Cement	% Lithic Frame- work	% Quartzo- feldspathic Framework	% Silt Matrix	% Mud Matrix	% Calcite Replaced Grains	% Mica	% Mud Chips	% Ostracode Fragments	Total %
01-2	7.0	30.2	2.6	1.0	47.2	1.8	6.8	2.0	0.2	1.2	0	100
01-4	11.2	18.6	3.4	1.4	54.4	3.8	6.2	0.4	0.4	0.2	0	100
01-7	14.4	18.0	2.4	0.6	57.6	3.0	2.6	1.2	0.0	0.2	0	100
01-9	19.0	17.4	2.8	0.8	54.6	1.2	1.6	2.0	0.0	0.6	0	100
01-10	19.6	16.6	3.0	0.4	52.6	4.2	2.8	0.6	0.0	0.2	0	100
01-14	10.2	25.8	4.8	0.6	46.8	3.4	6.0	1.6	0.0	0.8	0	100
01-15	15.6	19.6	2.2	0.4	52.0	2.6	4.0	2.6	0.0	1.0	0	100
01-17	9.0	25.2	4.2	0.2	47.8	4.2	6.8	0.8	0.8	1.0	0	100
01-19	11.0	24.2	3.4	0.4	50.8	4.4	3.6	1.2	0.6	0.4	0	100
01-21	0.4	43.6	1.8	0.0	45.6	2.2	3.4	2.4	0.2	0.4	0	100
01-22	5.8	27.8	4.6	0.2	44.4	2.8	10.0	2.8	0.0	1.6	0	100
01-24	11.4	16.2	3.2	0.2	53.4	2.6	9.4	1.8	0.6	1.2	0	100
01-25	10.8	17.2	3.0	0.4	51.0	2.0	13.4	1.8	0.0	0.4	0	100
01-27	14.0	15.4	2.0	0.2	54.4	2.0	9.4	2.4	0.0	0.2	0	100
01-28	7.2	16.8	4.2	0.2	55.2	2.0	12.6	1.2	0.0	0.6	0	100
01-29	16.2	17.0	2.0	0.4	50.0	3.0	8.0	2.8	0.4	0.2	0	100
01-31	11.4	18.2	3.4	0.2	50.8	3.4	9.4	2.6	0.2	0.4	0	100
01-32	2.0	23.2	2.4	0.0	54.8	1.6	14.8	1.0	0.2	0.0	0	100
01-34	2.4	33.4	3.6	0.8	52.8	2.4	3.8	0.8	0.0	0.0	0	100
01-35	13.4	13.2	6.6	0.8	57.2	3.2	4.2	1.2	0.2	0.0	0	100
01-36	3.8	24.6	6.0	0.4	53.6	3.2	6.0	2.4	0.0	0.0	0	100
01-37	9.2	21.2	4.2	0.8	47.2	3.2	10.6	3.4	0.2	0.0	0	100
01-39	3.6	27.4	5.6	0.0	46.0	3.2	8.8	5.2	0.2	0.0	0	100
01-40	3.0	36.4	2.6	0.2	44.6	2.2	7.0	3.4	0.0	0.6	0	100
01-42	2.2	34.0	1.8	0.2	45.6	2.4	10.6	3.0	0.2	0.0	0	100
01-46	13.6	12.6	1.8	0.6	65.8	0.2	3.0	2.2	0.0	0.2	0	100
01-47	15.0	16.4	1.4	0.2	60.4	0.6	3.6	2.2	0.2	0.0	0	100
01-48	3.4	23.8	2.2	0.2	55.4	1.6	10.8	1.8	0.0	0.8	0	100

Outcrop # 1: Fluvial facies of the Colton Formation Point Count Data (500 counts per thin section)												
Thin Section #	% Pore Space	% Calcite Cement	% Clay Cement	% Lithic Frame-work	% Quartzo-feldspathic Framework	% Silt Matrix	% Mud Matrix	% Calcite Replaced Grains	% Mica	% Mud Chips	% Ostracode Fragments	Total %
01-49	8.8	20.0	2.6	0.0	60.2	0.8	6.0	1.4	0.0	0.2	0	100
01-50	7.8	20.0	3.4	0.0	55.8	1.0	10.8	1.0	0.0	0.2	0	100
01-51	5.8	26.0	5.4	0.0	55.6	1.0	4.4	1.6	0.0	0.2	0	100
01-53	18.0	22.0	2.2	0.0	49.8	1.6	5.0	1.4	0.0	0.0	0	100
01-54	6.4	19.4	4.4	0.0	55.4	0.4	11.8	1.8	0.2	0.2	0	100
01-55	12.0	18.4	2.6	0.0	57.6	0.6	5.8	2.4	0.0	0.6	0	100
01-57	6.6	23.6	2.8	0.2	52.0	0.2	11.4	3.0	0.0	0.2	0	100
01-59	16.2	13.4	1.8	0.0	66.2	1.0	0.4	1.0	0.0	0.0	0	100
01-60	14.2	15.4	2.0	0.0	60.8	1.0	5.2	1.4	0.0	0.0	0	100
01-61	11.4	24.8	3.4	0.0	52.0	1.0	5.8	1.4	0.2	0.0	0	100
01-62	14.8	21.2	2.4	0.0	55.8	0.4	4.4	1.0	0.0	0.0	0	100
01-63	18.2	17.4	2.8	0.0	54.8	1.0	4.2	1.6	0.0	0.0	0	100
Minimum	0.4	12.6	1.4	0	44.4	0.2	0.4	0.4	0	0	0	
Maximum	19.6	43.6	6.6	1.4	66.2	4.4	14.8	5.2	0.8	1.6	0	
Mean	10.2	21.9	3.2	0.3	53.2	2.1	6.9	1.9	0.1	0.3	0	
Median	10.9	20.0	2.8	0.2	53.5	2.0	6.0	1.8	0	0.2	0	
Standard Deviation	5.3	6.7	1.3	0.3	5.3	1.2	3.5	0.9	0.2	0.4	0	

Thin Section #	% Pore Space	% Calcite Cement	% Clay Cement	% Lithic Frame-work	% Quartzo-feldspathic Framework	% Silt Matrix	% Mud Matrix	% Calcite Replaced Grains	% Mica	% Mud Chips	% Ostracode Fragments	Total %
02-1	9.6	17.4	2.6	2.4	59.2	1.8	3.2	2.2	0.8	0.6	0.2	100
02-6	4.8	21	6.2	0.8	57.2	4.8	1.8	0.8	0.8	0.4	1.4	100
02-11	2.4	22.8	1.2	0.6	55.6	1.8	14.2	0.8	0.2	0.4	0	100
02-12	8.2	27	2.8	0.8	39	5.6	10.4	5.6	0.4	0.2	0	100
02-16	6.2	26	5.2	1.2	40	8.2	8	3.4	1.6	0.2	0	100
02-21	11.4	29	2.4	0.8	39.8	4	5.8	5	0.8	1	0	100
02-24	23.8	4.2	2.2	1.8	56.2	0.4	8.6	2.4	0.4	0	0	100
02-27	14.4	16.6	3.4	1.2	54	3.8	3.4	2.2	0.8	0.2	0	100
02-30	15	18.6	2	0.4	49	7.4	4	2.6	0.8	0.2	0	100
02-33	14	19.8	1.6	1	50.2	3.4	5.4	1.8	1.4	1.4	0	100
02-35	11.4	27.2	1.6	1	47.4	2	5.6	3	0.6	0.2	0	100
02-40	7.6	31.2	2	1.6	44.8	2.8	5	2.6	1.8	0.6	0	100
02-41	13.2	21.2	1.6	2.2	49.8	2.6	5	2.2	1.6	0.6	0	100
02-46	11.4	26.2	2.2	1.6	42.2	3.6	8.2	2.8	1.4	0.4	0	100
02-47	10.2	24	1.4	2.2	44.8	5.2	9.2	2.2	0	0.8	0	100
02-54	11.8	10.2	0.6	1	65.8	2.4	5.4	2	0.6	0.2	0	100
02-59	15	15	1.4	0.8	55.6	2.8	4.6	4.4	0.2	0.2	0	100
02-62	8.4	21	1.8	1.2	52.2	3.6	4.6	5.6	0.6	1	0	100
02-63	0.8	35.8	0	0	48.4	1	12.8	0	0.8	0.4	0	100
02-65	8.6	14.2	1	0.4	60.6	1.2	10	3.4	0.4	0.2	0	100
02-68	6.6	24.2	1	0.4	48.6	2.4	9.6	4.4	2.8	0	0	100
02-70	19	4.6	0.6	0.2	56	1.8	9.6	4.6	0.4	3.2	0	100
02-73	8.8	16.4	2.4	0.4	56.8	3.2	4.4	5.4	1.6	0.6	0	100
02-74	1.4	37.4	0.4	0.2	38.6	3.2	16	1.8	0.4	0.6	0	100
02-76	18.4	11	0.2	0	66.6	0.6	0.8	1.6	0.6	0.2	0	100
02-79	23.6	5.2	0.2	0.2	63.6	0.4	3.4	1.2	1.2	1	0	100
02-84	21	8.4	0.4	0	62.6	1.6	3	1.2	0.4	1.4	0	100
02-88	18.6	10	1	0.8	60.2	1.2	3.4	1.8	1	2	0	100

Outcrop # 2: Deltaic facies of the Green River Formation Point Count Data (500 counts per thin section)												
Thin Section #	% Pore Space	% Calcite Cement	% Clay Cement	% Lithic Frame-work	% Quartzo-feldspathic Framework	% Silt Matrix	% Mud Matrix	% Calcite Replaced Grains	% Mica	% Mud Chips	% Ostracode Fragments	Total %
02-92	22	11.8	1.4	1	59.4	1.2	1.2	1.6	0.4	0	0	100
02-94	20.8	5.6	0.8	1.2	64.4	1.6	2.8	1.2	1.2	0.4	0	100
02-99	11.8	5.6	0.6	0.2	75	2.2	1.4	2	1.2	0	0	100
02-100	14.8	8.2	0.8	0.4	68.2	1.2	3	1.8	1.2	0.4	0	100
02-103	7.2	17	1.4	0.2	63.8	2.6	3.8	2.8	0.4	0.8	0	100
02-106	17.8	11.8	0.4	0.4	58.8	1.6	7	1.8	0.2	0.2	0	100
02-108	18.2	8.8	0.4	1	62.6	1.8	5	0.2	1.4	0.6	0	100
02-111	19.6	7.4	0.2	0.8	68.4	0.8	1.4	1	0	0.4	0	100
02-113	13.4	14.4	1	0.6	65.2	2.4	2	0.6	0.4	0	0	100
02-117	17.8	13.4	0.2	0.2	60.4	2.6	2	1.8	1.4	0.2	0	100
02-118	2.4	51	1.2	0	41	1.6	1.2	0.4	0.6	0.6	0	100
02-119	20.6	7.2	1.4	0.2	67	2.4	0.8	0	0.4	0	0	100
02-120	17.8	10.2	1.2	0.6	59.8	3	5.4	1.6	0.4	0	0	100
02-121	22.6	7.6	0.6	0.6	62.8	0.6	3.2	1.2	0.4	0.4	0	100
02-122	19.2	8.8	0.6	1	65.4	1.6	3	0	0.2	0.2	0	100
Minimum	0.8	4.2	0	0	38.6	0.4	0.8	0	0	0	0	
Maximum	23.8	51	6.2	2.4	75	8.2	16	5.6	2.8	3.2	1.4	
Mean	13.3	17.1	1.4	0.8	56.0	2.6	5.3	2.2	0.8	0.5	0.04	
Median	13.4	15	1.2	0.8	57.2	2.4	4.6	1.8	0.6	0.4	0	
Standard Deviation	6.4	10.2	1.2	0.6	9.4	1.7	3.7	1.5	0.6	0.6	0.2	

Outcrop # 3: Wave-dominated facies of the Green River Formation Point Count Data (500 counts per thin section)												
Thin Section #	% Pore Space	% Calcite Cement	% Clay Cement	% Lithic Frame-work	% Quartzo-feldspathic Framework	% Silt Matrix	% Mud Matrix	% Calcite Replaced Grains	% Mica	% Mud Chips	% Ostracode Fragments	Total %
03-1	6.6	32.2	2.6	0	56.8	1	0.4	0	0	0	0.4	100
03-2	11.8	26.6	2.4	0	53.2	1.4	1.6	0.4	0	0.2	2.4	100
03-3	17.2	20.6	1	0	57.8	0.8	1.6	0.4	0	0	0.6	100
03-4	2.4	43	0	0	49	0	4.4	0.4	0.2	0.2	0.4	100
03-7	12.4	34.2	5.2	0	45.6	1.6	0.8	0.2	0	0	0	100
03-9	15.2	31.8	3.2	0	48.6	0	0.6	0.6	0	0	0	100
03-10	8.6	30.6	7.2	0	47	0	0	0.6	0	0	6	100
03-11	8.6	32.8	2.6	0	51	0.4	0	0.2	0	0	4.4	100
03-12	22.6	11.4	0.8	0	61.6	0.2	0.2	2.6	0.2	0.2	0.2	100
03-13	7.2	32.8	5	0	49.2	1.6	0.4	3.4	0	0.2	0.2	100
03-14	1	45	3.4	0	47.6	1.8	0	1.2	0	0	0	100
03-15	13.6	28.6	4.2	0	45.2	0.4	4.4	3.6	0	0	0	100
03-16	4.4	44	1.8	0	46.2	0	2.4	1.2	0	0	0	100
03-18	7.4	37.8	4	0	44.8	0.4	4.4	1.2	0	0	0	100
03-19	20.8	0	6.6	0	68.6	4	0	0	0	0	0	100
03-20	20.8	0.4	0.6	0	72.2	0.2	5.6	0	0	0.2	0	100
03-21	6.4	25.8	6.2	0	51	1.8	4.4	3.6	0	0.8	0	100
03-22	8.2	23	6	0	51.4	1.2	7.4	2.6	0	0.2	0	100
03-24	12.6	18.4	1.8	0	55.8	0.2	4.4	3.8	0	3	0	100
03-25	17	16	0	0	58.6	0.4	3.2	4.2	0.6	0	0	100
03-26	21.4	14.6	0.4	0	59.4	0.6	1.6	2	0	0	0	100
03-28	25.6	0	1.4	0	72.4	0.6	0	0	0	0	0	100
03-29	23.8	1.2	0.6	0	74.2	0.2	0	0	0	0	0	100
03-30	14.2	24.6	10.8	0	43.4	3.2	1.4	2.4	0	0	0	100
03-31	18.2	14	0.6	0	62.4	0.8	1.4	0.6	0	0	2	100
03-33	12.2	25.2	4.4	0	52	3.2	0.6	2.4	0	0	0	100
03-34	10.2	25.6	1.4	0	50	1	6.6	5.2	0	0	0	100
03-35	6.6	24.2	8.2	0	50.4	4.2	2.6	3	0.2	0.6	0	100

Outcrop # 3: Wave-dominated facies of the Green River Formation Point Count Data (500 counts per thin section)												
Thin Section #	% Pore Space	% Calcite Cement	% Clay Cement	% Lithic Frame-work	% Quartzo-feldspathic Framework	% Silt Matrix	% Mud Matrix	% Calcite Replaced Grains	% Mica	% Mud Chips	% Ostracode Fragments	Total %
03-36	11.2	22	4.2	0	55	1.8	0.6	5	0	0.2	0	100
03-37	7.6	28.4	6.8	0	48.4	2.2	2.8	3.6	0	0.2	0	100
03-38	15.4	18	7.8	0	51.2	5	0.4	1.8	0	0.4	0	100
03-39	23.4	13	0	0	56	1.2	2.4	4	0	0	0	100
03-41	13.8	17	0.8	0	61.8	0.6	1.2	4	0	0.8	0	100
03-42	8.8	23.4	2.8	0	53.6	1	2.2	8.2	0	0	0	100
03-44	13.8	28.6	2	0	41.8	0.8	3.2	8.2	0	1	0.6	100
03-45	5	55.4	0	0	30	1.4	2.2	4.4	0	0	1.6	100
03-46	4	53.2	1.2	0	27.8	2.2	4.8	4.2	0	0	2.6	100
03-47	12.4	11	6.6	0	66.8	1.8	1	0.2	0	0.2	0	100
03-48	10	39	3.2	0	45.6	1.6	0	0	0	0	0.6	100
03-49	0	49.8	0	0	25	0	19	0	0	0	6.2	100
03-50	4.2	47.8	0.6	0	44.4	0.8	0.6	1	0	0	0.6	100
03-51	9.8	44.4	1	0	40.6	1.2	1	1.4	0	0	0.6	100
03-52	17.6	27.4	0	0	50.8	0	2.4	1.4	0	0.2	0.2	100
03-53	0	39.4	0.2	0	51	0.6	6.2	1.8	0	0.2	0.6	100
03-54	7.8	40	0.4	0	42.6	0.8	4.6	2	0	0	1.8	100
Minimum	0	0	0	0	25	0	0	0	0	0	0	
Maximum	25.6	55.4	10.8	0	74.2	5	19	8.2	0.6	3	6.2	
Mean	11.6	27.2	2.9	0	51.5	1.2	2.6	2.2	0.027	0.2	0.7	
Median	11.2	26.6	2	0	51	0.8	1.6	1.8	0	0	0	
Standard Deviation	6.6	14.1	2.7	0	10.5	1.2	3.2	2.1	0.101	0.5	1.5	

Plate 1: Measured Sections

Outcrop One: Fluvial facies of the Colton Formation

Outcrop Two: Deltaic facies of the Green River Formation

Outcrop Three: Wave-dominated facies of the Green River Formation
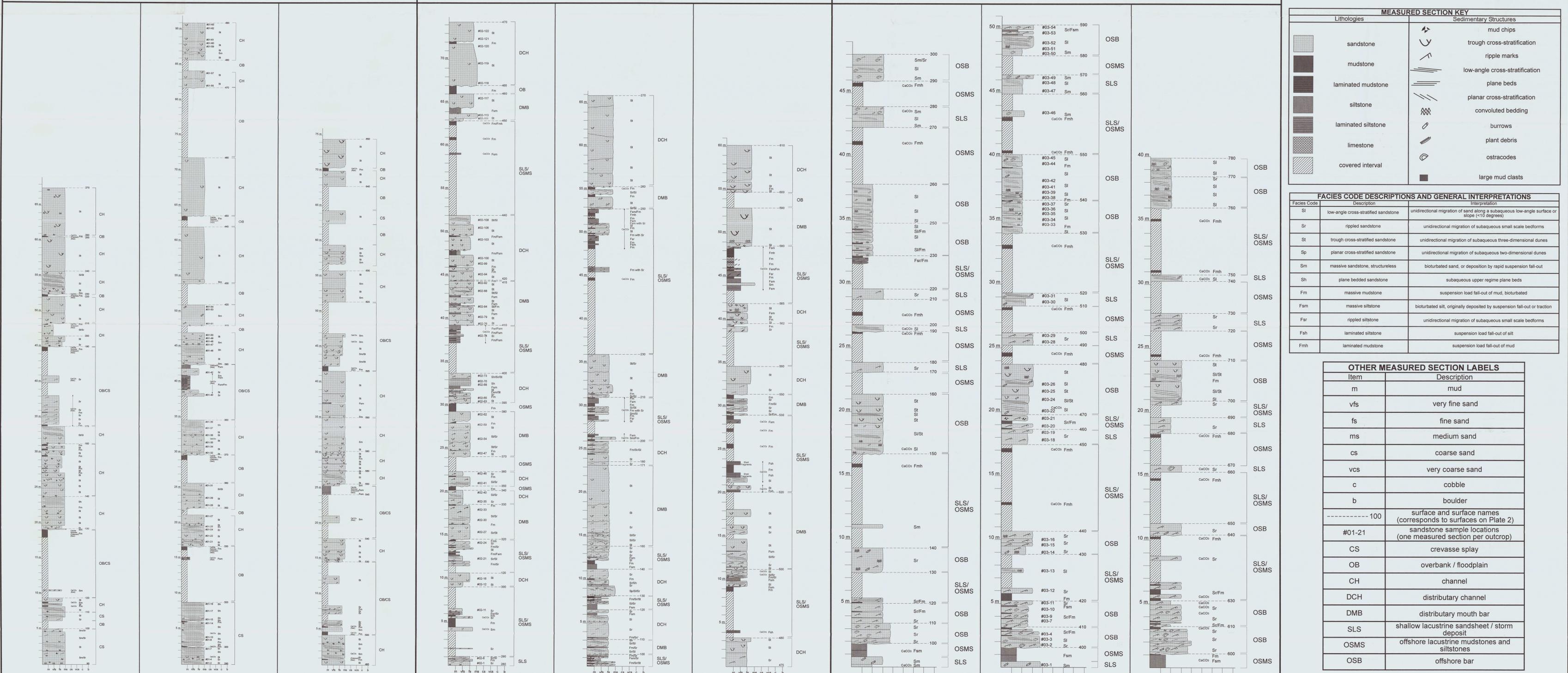
Measured Section # 1 Measured Section # 2 Measured Section # 3 Measured Section # 2 Measured Section # 1 Measured Section # 3 Measured Section # 1 Measured Section # 2 Measured Section # 3

MEASURED SECTION KEY

Lithologies	Sedimentary Structures
sandstone	mud chips
mudstone	trough cross-stratification
laminated mudstone	ripple marks
siltstone	low-angle cross-stratification
laminated siltstone	plane beds
limestone	planar cross-stratification
covered interval	convoluted bedding
	burrows
	plant debris
	ostracodes
	large mud clasts

FACIES CODE DESCRIPTIONS AND GENERAL INTERPRETATIONS

Facies Code	Description	Interpretation
Sl	low-angle cross-stratified sandstone	unidirectional migration of sand along a subaqueous low-angle surface or slope (<10 degrees)
Sr	rippled sandstone	unidirectional migration of subaqueous small scale bedforms
St	trough cross-stratified sandstone	unidirectional migration of subaqueous three-dimensional dunes
Sp	planar cross-stratified sandstone	unidirectional migration of subaqueous two-dimensional dunes
Sm	massive sandstone, structureless	bioturbated sand, or deposition by rapid suspension fall-out
Sh	plane bedded sandstone	subaqueous upper regime plane beds
Fm	massive mudstone	suspension load fall-out of mud, bioturbated
Fsm	massive siltstone	bioturbated silt, originally deposited by suspension fall-out or traction
Fsr	rippled siltstone	unidirectional migration of subaqueous small scale bedforms
Fsh	laminated siltstone	suspension load fall-out of silt
Fmh	laminated mudstone	suspension load fall-out of mud

OTHER MEASURED SECTION LABELS

Item	Description
m	mud
vfs	very fine sand
fs	fine sand
ms	medium sand
cs	coarse sand
vcs	very coarse sand
c	cobble
b	boulder
----------100	surface and surface names (corresponds to surfaces on Plate 2)
#01-21	sandstone sample locations (one measured section per outcrop)
CS	crevasse splay
OB	overbank / floodplain
CH	channel
DCH	distributary channel
DMB	distributary mouth bar
SLS	shallow lacustrine sandsheet / storm deposit
OSMS	offshore lacustrine mudstones and siltstones
OSB	offshore bar

Plate 2: Outcrop Photomosaics

Outcrop One: Fluvial facies of the Colton Formation
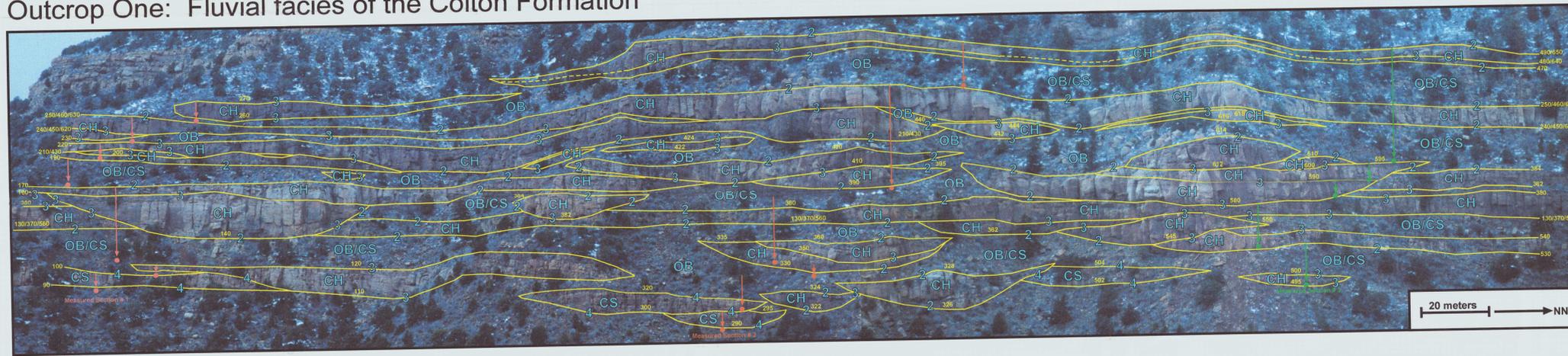
Outcrop Two: Deltaic facies of the Green River Formation

Outcrop Three: Wave-dominated facies of the Green River Formation
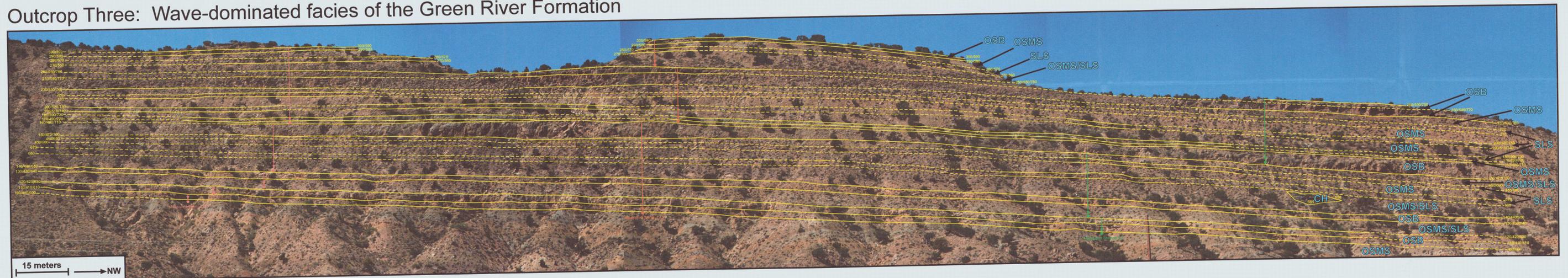
PHOTOMOSAIC KEY	
Item	Description
——100	surface and surface names (corresponds to surfaces on Plate 1)
------100	inferred surface and surface names (corresponds to surfaces on Plate 1)
(arrows)	measured section locations
2, 3, 4	surface hierarchy labels (described in text)
CS	crevasse splay
OB	overbank / floodplain
CH	channel
DCH	distributary channel
DMB	distributary mouth bar
SLS	shallow lacustrine sandsheet / storm deposit
OSMS	offshore lacustrine mudstone and siltstone
OSB	offshore bar