SEQUENCE STRATIGRAPHY IN LACUSTRINE BASINS: A MODEL FOR PART OF THE GREEN RIVER FORMATION (EOCENE), SOUTHWEST UINTA BASIN, UTAH, U.S.A.

DAVID KEIGHLEY,[1]* STEPHEN FLINT,[1] JOHN HOWELL,[1] AND ANDREA MOSCARIELLO[2]
[1] *Stratigraphy Group, Department of Earth Sciences, University of Liverpool, Brownlow Street, Liverpool, L69 3BX, United Kingdom*
[2] *Shell Expro, P.O. Box 4, Lothing Depot, Lowestoft, NR32 2TH, United Kingdom*

ABSTRACT: **In the middle Green River Formation of central Nine Mile Canyon, Uinta Basin, Utah, several lacustrine-dominated intervals ~10 m thick comprise aggradational carbonate parasequence sets and a progradational clastic parasequence. Maximum flooding surfaces are best identified within profundal oil shale that caps some of the clastic parasequences. These lacustrine transgressive systems tracts therefore exhibit parasequence stacking patterns unlike typical marine sequences. Two types of sequence boundary are identified. Type A sequence boundaries display evidence for a basinward shift in facies across a regionally mappable surface that is an angular or, rarely, parallel unconformity, and they typically juxtapose amalgamated braided fluvial channel sandstone (late lowstand systems tract) onto the profundal oil shale. They also bound depositional sequences that show a distinct asymmetry, being dominated by transgressive systems tracts 5–80 m thick. Highstand systems tracts are less than 4 m thick and may be removed completely, by erosion on overlying sequence boundaries. Other surfaces satisfy only some of the standard criteria of sequence boundaries and are termed type B sequence boundaries.**

Type A sequence boundaries mark pronounced base-level falls following times when the Uinta Lake had merged with a lake in an adjacent basin to form a much deeper lake. Such merging permitted the establishment of a new threshold at higher elevation following lake-level balancing. Type B sequence boundaries are interpreted as marking base-level falls from a barely merged lake or a lake that had an outflow. Over a 200 m stratigraphic thickness, type A sequence boundaries are more common upsection, indicating that, with time, a pluvial climate became more pronounced or that the adjacent lake was more easily filled. Type A sequence boundaries also become angular rather than parallel unconformities upsection, suggesting increased tilting of the basin margin over time.

INTRODUCTION

Purpose

Strata within nonmarine closed basins (i.e., isolated from marine base-level control) are increasingly being analyzed and interpreted using the concepts of sequence stratigraphy, using both subsurface data (e.g., Liro 1993; Scholz et al. 1998; Strecker et al. 1999; Keighley 2000) and high-resolution outcrop examples (e.g., Oviatt et al. 1994; Dam et al. 1995; Milligan and Lemons 1998). The Nine Mile Canyon region of the Uinta Basin, east-central Utah, contains three-dimensional exposure of alluvial–lacustrine strata from the Eocene middle Green River Formation (Fig. 1), for which Fouch et al. (1994) developed a basic sequence stratigraphic interpretation. A succession approximately 200 m thick (henceforth, the study package) of predominantly mudstone with subordinate sandstone and minor carbonate has recently been investigated with respect to correlation and the geometries of the fluvial sandstone beds (Keighley et al. 1999; Keighley et al. 2002). This paper attempts to (1) briefly comment on the status and terminology of lacustrine sequence stratigraphic models, (2) summarize the sedimentology and architecture of the study package, and (3) present a high-resolution sequence stratigraphic interpretation of the package. The paper highlights the variability inherent in lake systems and emphasizes that the study package represents only a part of the lateral and vertical stratigraphy within the Uinta Basin. However, analysis of stratal patterns and application of appropriate sequence-stratigraphic concepts permits (1) larger-scale stratigraphic distribution patterns and their correlation, (2) interpretation of basin evolution concepts such as nested basins, and (3) speculation on the relative importance of climatic and tectonic driving mechanisms.

* Present address: New Brunswick Department of Natural Resources and Energy, P.O. Box 6000, Fredericton, New Brunswick, E3B 5H1, Canada.

Structural and Paleogeographical Setting

Paleogene basins of the U.S. Western Interior are thought to have originated from the compressional partitioning of the ramp-style Western Interior marine foreland basin (Franczyk et al. 1992; Crews and Ethridge 1993; Olsen 1995) when ongoing thin-skinned tectonic activity (Sevier Orogeny) was supplemented by basement-involved tectonics (Laramide Orogeny) during Late Cretaceous time. This deformation (reviewed in Dickinson et al. 1988; Bump 2003) resulted in the uplift of fault-bounded blocks, domes, and swells along ancient structural trends, producing a series of separate nonmarine basins (Lawton 1986). The Uinta Basin was one of the largest basins, and its erosional remnant now crops out within a gentle syncline in eastern Utah and westernmost Colorado (Fig. 1A). The study area is located on the gently dipping ($< 5°$) southern limb of the syncline. The southern margin of the original basin has been eroded, but it must have been more than 50 km south of the study area, on the basis of known Green River Formation and equivalent outcrop.

The depositional filling of the Uinta Basin was asymmetric, with over 4 km of accumulated sediment at the depocenter to the north of the field area, proximal to the rapidly uplifting Uinta Mountains (Fig. 1A). Alluvial strata encircle lacustrine strata, indicating primarily internal drainage. In the northeast, sandstone is interpreted to be mainly of lacustrine and alluvial-fan origin (Picard and High 1972; Castle 1990; Borer and McPherson 1998). On the southwestern side of the remnant basin, fluvial and deltaic sandstone predominates. Laramide basin lakes may have been permanent and stratified (e.g., Bradley 1964) or playa lakes (e.g., Lundell and Surdam 1975); others have noted that both may be applicable but at different times (e.g., Eugster and Surdam 1973; Boyer 1982). The basins were separated in places only by low saddles across which they were hydrologically connected during pluvial periods as the lakes of individual basins expanded and merged (Surdam and Stanley 1980). Periodic connection of the Uinta Basin with the Piceance Creek and other basins was across the Douglas Creek Arch (Pitman 1982; Young 1995; Fig. 1A). Whether there was ever an outflow to the sea (and if so, which sea) is disputed (Hansen 1990).

Lithostratigraphy

Tertiary strata of the Uinta Basin are assigned to several formations (Fig. 1B). Following Ruble and Philp (1998), gray mudstone and interbedded carbonate, oil shale, and salt are usually included within the Green River Formation, and interpreted as lacustrine facies. Oil shale and evaporitic strata are more common higher in the Green River Formation and toward the basin center. Major basal interfingerings of coarse-grained clastic beds and red mudstone, included in the North Horn and Colton (Wasatch) for-

JOURNAL OF SEDIMENTARY RESEARCH, VOL. 73, NO. 6, NOVEMBER, 2003, P. 987–1006
 1527-1404/03/073-987/$03.00

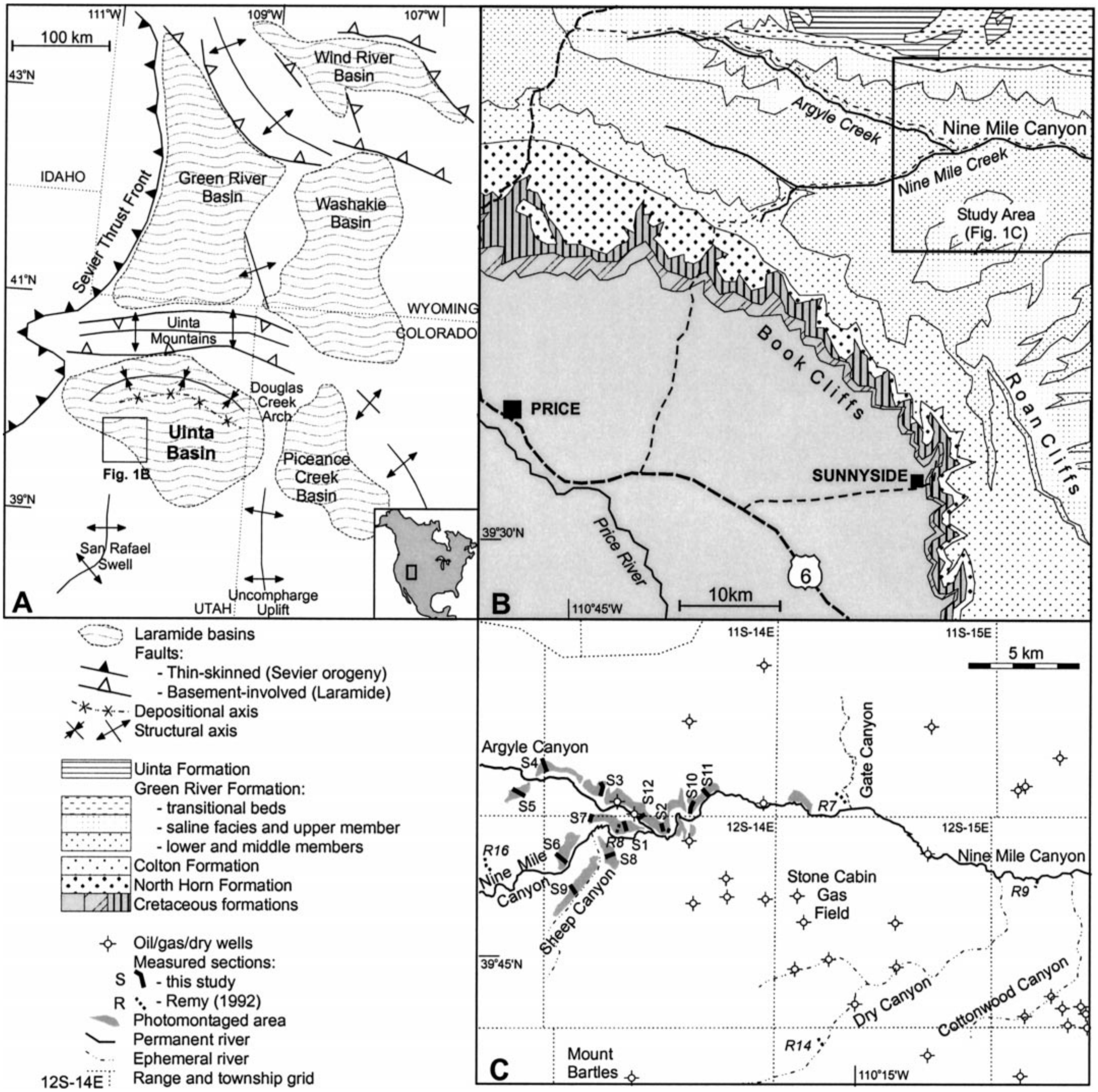


FIG. 1.—Lithostratigraphic and lithofacies relationships of Uinta Basin deposits and underlying Cretaceous foreland-ramp strata. **A**) Tertiary intermontane basins of the western US (after Dickinson et al. 1988), with general depositional and structural axes marked for the Uinta Basin (after Cashion 1995). **B**) Lithostratigraphic map of southwest Uinta Basin and Price area (after Witkind 1995). **C**) Location of studied outcrops, measured sections, and hydrocarbon exploration and production wells in the central part of Nine Mile Canyon.

mations, reflect fluvial incursions into the basin. Toward the top of the Green River Formation, red-brown shale and coarse-grained clastic intercalations of the Uinta Formation (prodelta and delta-top facies) are capped by red interbedded sandstone and mudstone of the Duchesne River Formation (fluvial-floodplain facies).

Lithostratigraphic subdivisions of the Green River Formation are only locally applicable. Correlatable markers are few because of variable exposure, a limited subsurface dataset, and basinwide variation in the type and succession of lithofacies due to the asymmetry of basin fill. For the Nine Mile Canyon area in the southwest of the basin, Remy (1992) provided a high-resolution correlation, adopted from the D–A marker beds of Jacob (1969). This paper deals with the package of strata from Jacob's D marker up to the C2 marker, within what has been variously considered by other workers in the area, the ''delta facies,'' ''Green Shale Facies,'' and the ''Middle Member'' subdivisions of the Green River Formation (Ruble and Philp 1998; Morgan et al. 2002).

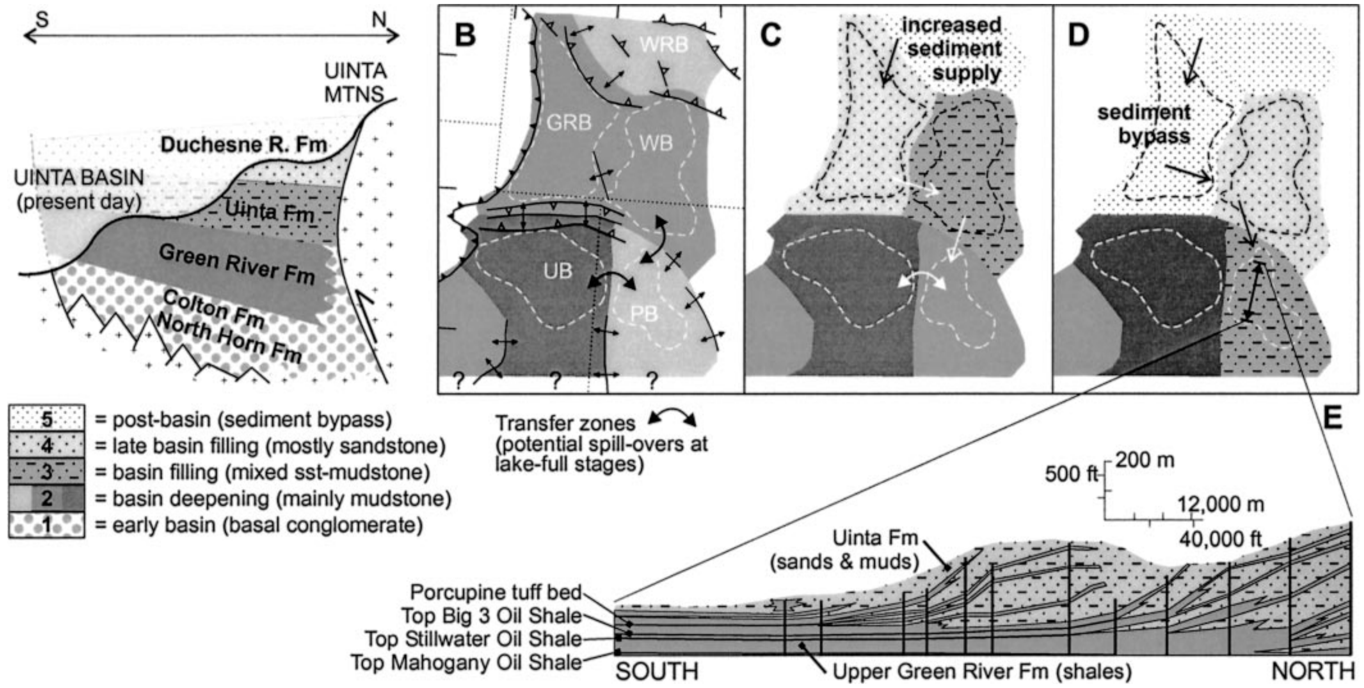


FIG. 2.—**A**) Lambiase's (1990) five-stage tectonic sequence for lacustrine rift basins, as applied in a general sense to the Uinta Basin, a compressional Laramide basin. **B**) Lambiase's (1990) model proposes that, during and following initial basin development (stage 1), subsidence rate exceeds sediment supply rate. The small watersheds (different shades of solid gray) act to further limit sediment influx. This sediment-starved stage (stage 2) results in extensive mudstone deposition. **C, D**) As accommodation was filled (stages 3 and 4), as a result of increasing sediment supply from the north, basins were progressively bypassed (Surdam and Stanley 1980) in a clockwise direction (stage 5). Note that the Washakie and Green River basins usually acted as one large basin (Greater Green River Basin) but with two or more depocenters: the western area infilled with fluvial clastics during the early middle Eocene, the eastern area in the late middle Eocene (Roehler 1993). **E**) Basin infilling of much of the Piceance Creek and Uinta basins was by thick progradational fluviodeltaic strata of the Uinta Formation (Dane 1954; Johnson 1981).

Lacustrine Sequence Stratigraphic Models

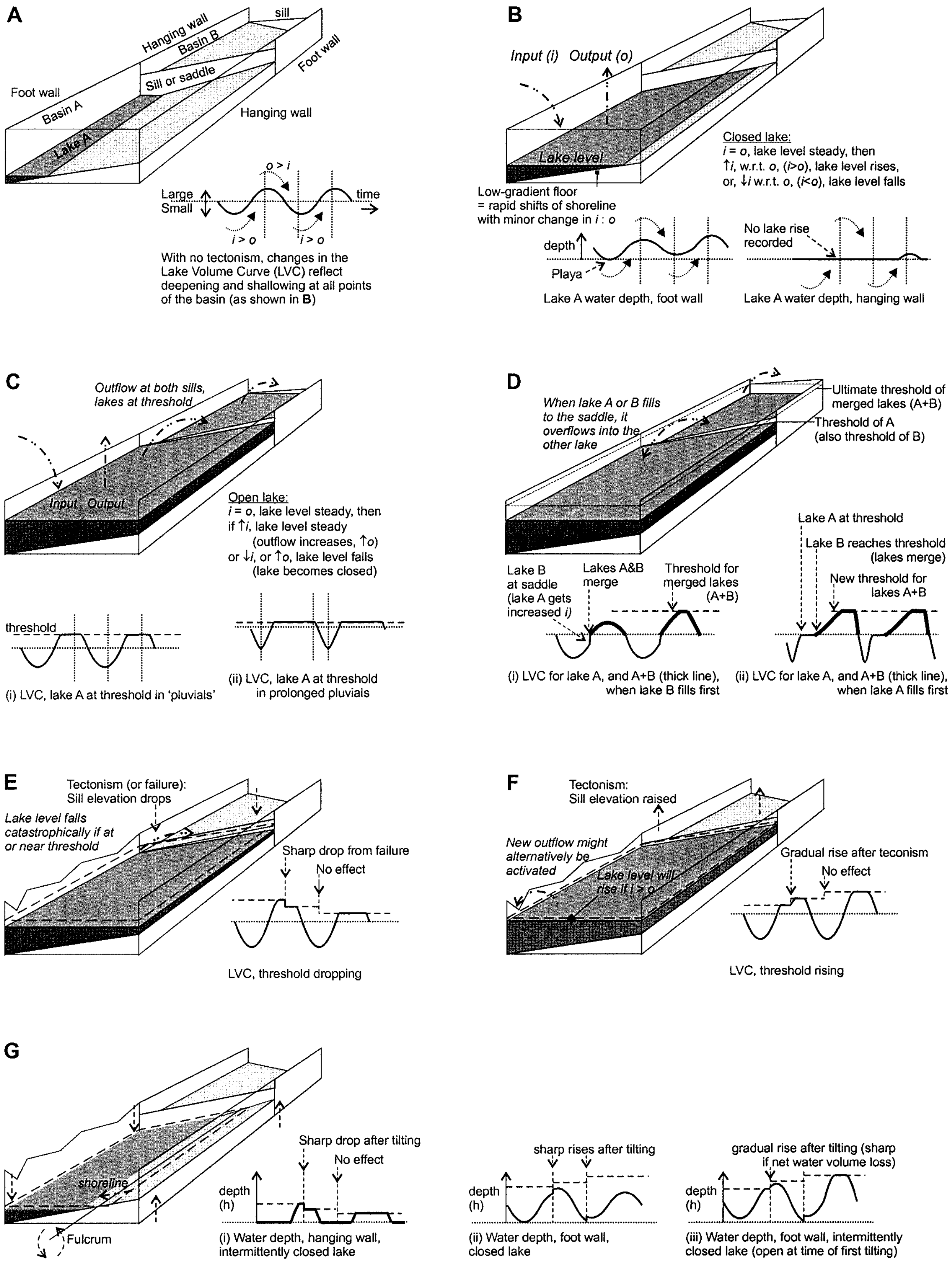
Many original definitions within sequence stratigraphy, such as parasequences and systems tracts, relate to marine shelfal and shelf-margin sequences but have been successfully extended to terrestrial environments (e.g., Aitken and Flint 1995). However, lacustrine and intermontane basin sequence stratigraphic concepts, terminology, and models are still developing. It is therefore necessary to clarify which developments will be incorporated into our interpretations before discussing how the sedimentology and architecture of the study package is interpreted in a sequence stratigraphic context. In particular, we comment on the spatial and temporal scale of lacustrine basins and behavior of lacustrine base level, illustrated with reference to modern analogues.

We do not consider the commonly used hierarchy of sequences reflecting global sea-level curves equivalent or appropriate for lacustrine basins, because base level fluctuates much more rapidly and basin lifespan is much shorter, typically a few million years maximum. Similarly, ''high-frequency'' and ''low-frequency'' sequences imply a time constraint. Discussion thus refers to the level of detail (resolution) relative to the entire basin fill. However, when considering nested sequences it must be appreciated that, as in the marine setting, the position of high-resolution sequences within the lower-resolution accommodation regime can augment (or lessen) the base-level rise or fall component of the high-resolution sequence.

Low-Resolution Sequences: Tectonic Models.—These models illustrate some of the conceptual differences that exist in comparison to basins influenced by global sea level (e.g., Lambiase 1990; Schlische and Olsen 1990). During the early and continued development of a tectonically active lacustrine basin, subsidence or basin-margin uplift produces accommodation volume at a higher rate than supplied sediment can infill this volume, otherwise any basin would quickly fill (Lambiase 1990). However, in these earlier stages of a nonmarine basin-fill succession (Fig. 2A–C), sediment starvation is enhanced because drainage areas are small and fragmented, and axial sediment supply is limited.

Low-Resolution Sequences: Climate Models and Base Level.—Other conceptual differences from marine systems can be demonstrated in relation to base level, which in nonmarine basins is defined by lake level and watertable. If the lake is closed, even slight changes in annual precipitation (input) and evaporation (output) can change base level (Fig. 3A, B). In contrast, if a lake expands to its threshold and there is drainage spillover at the sill of the basin, further significant base-level rise is impossible (Carroll and Bohacs 1999). Regardless of further increases in input, the lake is balanced by increased spillover output, and base level is relatively stable (Fig. 3C). An exception exists where the lake in an adjacent basin can fill to the elevation of the aforementioned sill (i.e., the sill is in effect a saddle), and the lakes merge, the adjacent basin lacking a sill at a lower elevation. For example, such nested sub-basins exist within the Bonneville Basin of Utah (cf. Currey et al. 1984), one of which contains Utah Lake, currently at threshold. If the adjacent Great Salt Lake were to expand, it could merge with Utah Lake, forming a new Lake Bonneville (Fig. 3Dii, where lake A = Utah Lake, lake B = Great Salt Lake). Note that in Figure 3Di, lake B would have a period at threshold, while lake A received greater input to bring its lake level up to the elevation of the saddle, after which the level of the merged lakes would rise more slowly than for the individual lakes.

The duration of each hydrologically open or closed phase exerts a primary control on basin fill (Olsen 1990; Scholz et al. 1998; Carroll and Bohacs 1999; Bohacs et al. 2000). If the basin exists under a primarily wet climate (overfilled lake basin of Carroll and Bohacs 1999), clastic sediment accumulates around the basin margins to form terraced aprons and highstand deltas, which may have high relief if the sill permits deep lakes to form. With a periodically drier climate, base level can drop well below threshold and fluctuate rapidly (balanced-fill lake basin of Carroll and Bo-



A
Hanging wall
Basin B
sill
Foot wall
Sill or saddle
Foot wall
Basin A
Hanging wall
Lake A
o > i
Large
Small
time
i > o
i > o
With no tectonism, changes in the Lake Volume Curve (LVC) reflect deepening and shallowing at all points of the basin (as shown in B)
B
Input (i) Output (o)
Lake level
Closed lake:
i = o, lake level steady, then
↑i, w.r.t. o, (i>o), lake level rises,
or, ↓i w.r.t. o, (i<o), lake level falls
Low-gradient floor
= rapid shifts of shoreline
with minor change in i : o
No lake rise recorded
depth
Playa
Lake A water depth, foot wall
Lake A water depth, hanging wall
C
Outflow at both sills,
lakes at threshold
Input Output
Open lake:
i = o, lake level steady, then
if ↑i, lake level steady
(outflow increases, ↑o)
or ↓i, or ↑o, lake level falls
(lake becomes closed)
threshold
(i) LVC, lake A at threshold in 'pluvials'
(ii) LVC, lake A at threshold
in prolonged pluvials
D
When lake A or B fills
to the saddle, it
overflows into the
other lake
Ultimate threshold of
merged lakes (A+B)
Threshold of A
(also threshold of B)
Lake A at threshold
Lake B reaches threshold
(lakes merge)
New threshold for
lakes A+B
Lake B
at saddle
(lake A gets
increased i)
Lakes A&B
merge
Threshold for
merged lakes
(A+B)
(i) LVC for lake A, and A+B (thick line),
when lake B fills first
(ii) LVC for lake A, and A+B (thick line),
when lake A fills first
E
Tectonism (or failure):
Sill elevation drops
Lake level falls
catastrophically if at
or near threshold
Sharp drop from failure
No effect
LVC, threshold dropping
F
Tectonism:
Sill elevation raised
New outflow might
alternatively be
activated
Lake level will
rise if i > o
Gradual rise after teconism
No effect
LVC, threshold rising
G
shoreline
Fulcrum
Sharp drop after tilting
No effect
depth
(h)
(i) Water depth, hanging wall,
intermittently closed lake
sharp rises after tilting
depth
(h)
(ii) Water depth, foot wall,
closed lake
gradual rise after tilting (sharp
if net water volume loss)
depth
(h)
(iii) Water depth, foot wall, intermittently
closed lake (open at time of first tilting)

hacs 1999). Shorelines and associated facies similarly fluctuate in their position and, depending on the duration of the dry period, partial to complete incision and reworking of the apron deposits may occur (Olsen 1990). An underfilled lake basin occurs where lake level rarely reaches threshold (Carroll and Bohacs 1999). Models promoting both a permanent, stratified lake and a playa lake in the Uinta Basin can be accommodated within these latter two classifications.

Interaction of Climatic and Tectonic Controls.—Tectonic and climatic controls influence base level to varying degrees, depending on their interplay. When the lake is at threshold (open lake), increases in precipitation can lead to higher sedimentation rates but no significant rise in base level or increase in accommodation. Tectonism around the basin margin can raise or lower the sill and hence base level. The sill can be lowered through erosion (Fig. 3E). For example, the threshold of Utah's Pleistocene Lake Bonneville dropped catastrophically following erosion of its poorly lithified sill (Currey et al. 1984). Tectonism could also introduce a new sill and new sediment supply points, whereas tilting of basin-floor fault blocks can cause an instantaneous relocation of shorelines and depocenters (Fig. 3F, G). For example, if the shoreline (lake level) is on the downthrown side of the hinge line, fault movement will relocate the shoreline toward the downthrown side and a deeper lake forms (Strecker et al. 1999). Such tilting can result in an open lake becoming closed if the volume of the basin (accommodation below threshold elevation) is increased by such tectonism. To qualify Strecker et al. (1999), with time the lake may again reach its threshold but only if a positive water budget is maintained.

Climate-influenced base-level change is more pronounced in balanced and closed lake basins, where the water budget is periodically negative. In underfilled lake basins, tectonic influences within the basin are limited to changes of orientation of the basin-floor fault block(s) that suddenly shift shorelines and depocenters. Ongoing basin subsidence or uplift of the sill simply increases the potential accommodation that might be made available following renewed rise in base level. Additionally for closed lake basins, sediment deposited in a lake displaces water volume, and so the case can arise where reductions in aqueous input can still be reflected in a relative rise in lake level (Einsele and Hinderer 1997, 1998).

High-Resolution Sequences.—Using the Gilbert Deltas of Utah's Pleistocene Lake Bonneville as a case study, Milligan and Chan (1998) suggested that lacustrine sequence boundaries should be based on the established lake-level hydrograph rather than the physical stratal surfaces. This may be advisable at the scale of the current Lake Bonneville cycle (300 m rise and fall over $>$ 20,000 years), because the sequence boundary is yet to complete its formation and how much of the regressive Provo sediments will actually enter into the rock record is not yet known. However, in the Uinta Basin we maintain the physical definition to sequence boundaries (cf. Van Wagoner et al. 1990) because we can demonstrate surfaces that fulfill the physical criteria of sequence boundaries. Note also that Milligan and Chan's (1998) Bonneville–Provo unconformity, formed following collapse of the Bonneville threshold, is an example of a higher-resolution sequence boundary, significant only at temporal and spatial scales below that of a Lake Bonneville cycle.

SEDIMENTOLOGY

The study package is well exposed across $>$ 25 km^2 of canyons in central Nine Mile Canyon and its tributaries, and was logged in detail at 12 localities (Figs. 1C, 4). Marker beds and major sandstone bodies identified from the logs were walked out in the field and traced onto photomontages (Fig. 5), and summary fence diagrams and maps were constructed. Spectral gamma ray (SGR) profiles were obtained at four of the localities to provide a direct comparison with nearby logged exploration wells that penetrate through the package (Figs. 1C, 4; Keighley et al. 2002).

Numerous workers have provided details of the sedimentology of the Green River and associated formations in the Uinta and adjacent basins (e.g., Picard and High 1968, 1972; Ryder et al. 1976; Stanley and Collinson 1979; Pitman et al. 1982; Roehler 1987, 1993; Castle 1990; Franczyk et al. 1991; Fouch et al. 1992; Morris and Richmond 1992; Crews and Ethridge 1993; and others referenced below). Our interpretations of lithofacies associations, which are based on these works, are presented in Table 1 and summarized briefly below. Lacustrine settings follow the terminology of Ferber and Wells (1995, table 1 and fig. 2).

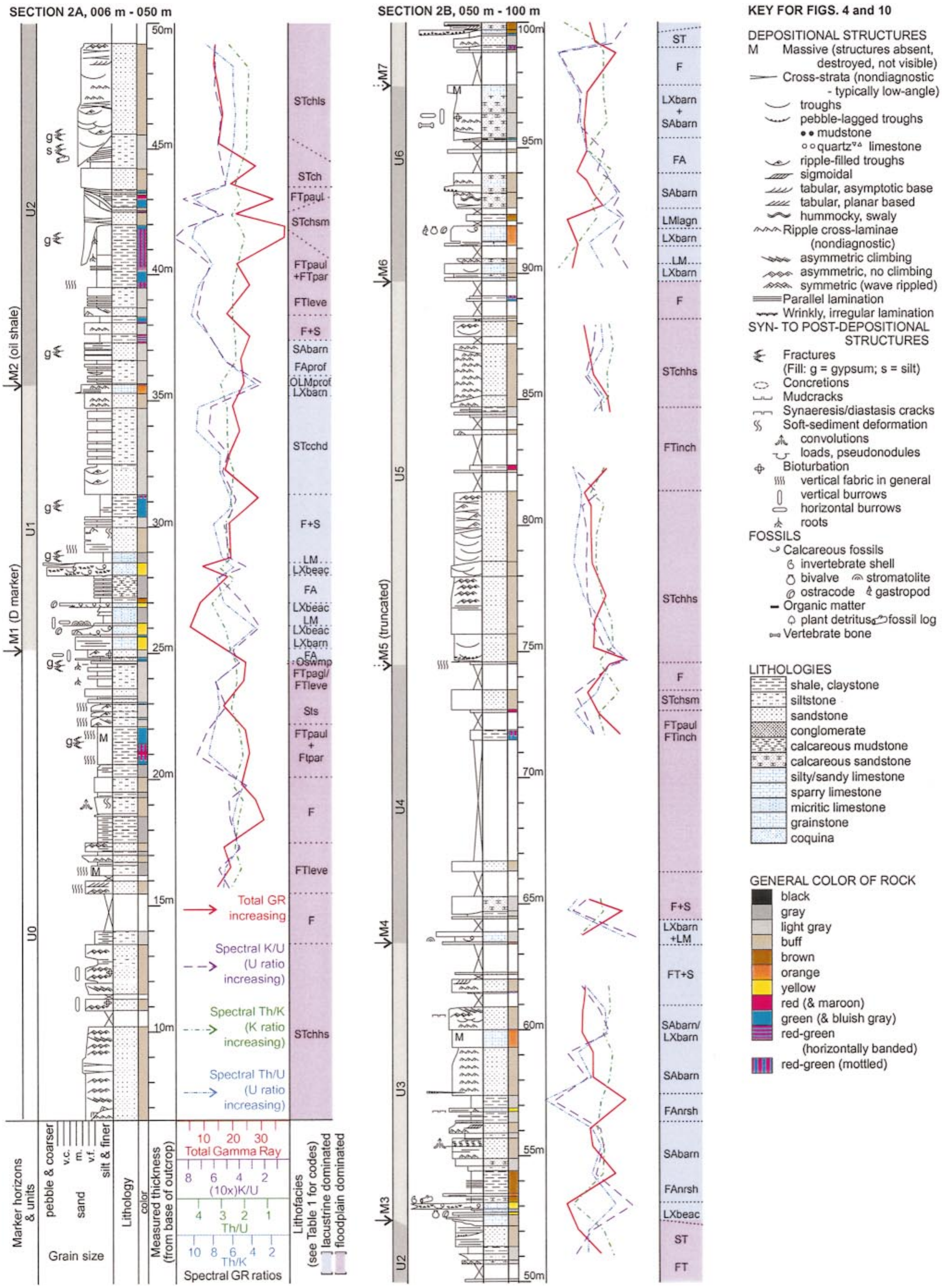
Finely Crystalline Carbonate and Oil-Shale Deposits

These strata, incorporating micrite plus variable dolomicrite, pyrite, claystone, and kerogen (oil shale) are only a minor component of the study package. However, they may have been produced in a variety of settings including lagoons, shallow-water (littoral) embayments, and offshore (below wave base; profundal) lakes (Williamson and Picard 1974; Ferber and Wells 1995). For example, one thin dolomitic oil shale occurs toward the top of what, in places, is a set of lacustrine strata, only 0.4 m thick, bounded by fluvial or sheetflood cross-stratified sandstone (Fig. 6A). Elsewhere, the same oil shale may pass upward into a laminated shale and siltstone that has subsequently undergone pedogenesis (Fig. 6B). Ruble (personal communication 1999) has shown by hydrous pyrolysis that this oil shale has a geochemical signature that lacks any indicators of terrestrial origin (cf. Ruble and Philp 1998). This oil shale is laterally continuous, extending across the entire study area and, at isolated locations in Sheep Canyon (near S8), thickens into a silty, fining upward unit with isolated pebbles that is interpreted as a distal turbidite facies (cf. Dyni and Hawkins 1981).

Massively bedded micrite lacks features diagnostic of a particular setting, and interpretation of a lagoonal, littoral, or profundal setting (Williamson and Picard 1974) requires assessment of associated lithotypes and their vertical and lateral trends. For example, in the study package, micrite and organic-rich fines that have a significant terrigenous organic signature are associated with lithofacies that collectively suggest a lagoonal origin (Fig. 6C, D).

←

FIG. 3.—Some theoretical examples of base-level behavior in lacustrine basins as a result of various isolated factors (many others can be envisioned). **A**) General terms. **B**) Variations in water budget inputs (*i*) and outputs (*o*), with no tectonism involved, results in uniform deepening or shallowing across the basin. The basin and the lake are termed ''closed'' unless the lake is at threshold (i.e., has an outflow). **C**) Situation where *i*:*o* increases to bring the lake A to threshold (open lake), resulting in outflow to lake B in an adjacent basin. Lake B is also at threshold, with outflow across its sill, which is at a lower elevation than the sill for lake A. Base level is steady while lake A is at threshold. **D**) The effect of nested basins: because the sill between the two basins is at a lower elevation than any other potential sills, when either lake B (i) or A (ii) fills to threshold, it can spill over into the other lake, increasing the input into that lake. **E**) Lake levels may drop because of basin-margin tectonism, or by erosion of the sill. Marginal tectonism or catastrophic erosion results in uniform and sudden shallowing across the basin, if the contained lake is at threshold because volume available is reduced. **F**) A tectonic rise in the sill results in a gradual rise in lake level to the new sill elevation, because the increased volume has to be filled by subsequent inputs to the lake. **G**) Internal basin tectonism, whereby the block underlying the lake tilts relative to the marginal blocks (the fulcrum is within the basin), results in the lake shallowing at some locations (situation i) while other locations display a deepening (situation ii). If the lake was open at the time of basin floor tilting, and the tilting resulted in increased volume becoming available, then at the footwall a sharp rise from the actual tilting would be followed by a gradual rise as continued inputs then brought the lake back to threshold (situation iii).


SECTION 2A, 006 m - 050 m
SECTION 2B, 050 m - 100 m
KEY FOR FIGS. 4 and 10
DEPOSITIONAL STRUCTURES
M Massive (structures absent, destroyed, not visible)
Cross-strata (nondiagnostic - typically low-angle)
troughs
pebble-lagged troughs
mudstone
quartz limestone
ripple-filled troughs
sigmoidal
tabular, asymptotic base
tabular, planar based
hummocky, swaly
Ripple cross-laminae (nondiagnostic)
asymmetric climbing
asymmetric, no climbing
symmetric (wave rippled)
Parallel lamination
Wrinkly, irregular lamination
SYN- TO POST-DEPOSITIONAL STRUCTURES
Fractures
(Fill: g = gypsum; s = silt)
Concretions
Mudcracks
Synaeresis/diastasis cracks
Soft-sediment deformation
convolutions
loads, pseudonodules
Bioturbation
vertical fabric in general
vertical burrows
horizontal burrows
roots
FOSSILS
Calcareous fossils
invertebrate shell
bivalve
stromatolite
ostracode
gastropod
Organic matter
plant detritus
fossil log
Vertebrate bone
LITHOLOGIES
shale, claystone
siltstone
sandstone
conglomerate
calcareous mudstone
calcareous sandstone
silty/sandy limestone
sparry limestone
micritic limestone
grainstone
coquina
GENERAL COLOR OF ROCK
black
gray
light gray
buff
brown
orange
yellow
red (& maroon)
green (& bluish gray)
red-green (horizontally banded)
red-green (mottled)
Total GR increasing
Spectral K/U (U ratio increasing)
Spectral Th/K (K ratio increasing)
Spectral Th/U (U ratio increasing)
Marker horizons & units
Grain size
pebble & coarser
sand
v.c.
m.
v.f.
silt & finer
Lithology
color
Measured thickness (from base of outcrop)
Total Gamma Ray
(10x)K/U
Th/U
Th/K
Spectral GR ratios
Lithofacies (see Table 1 for codes)
lacustrine dominated
floodplain dominated
M1 (D marker)
M2 (oil shale)
M3
M4
M5 (truncated)
M6
M7
U0
U1
U2
U3
U4
U5
U6

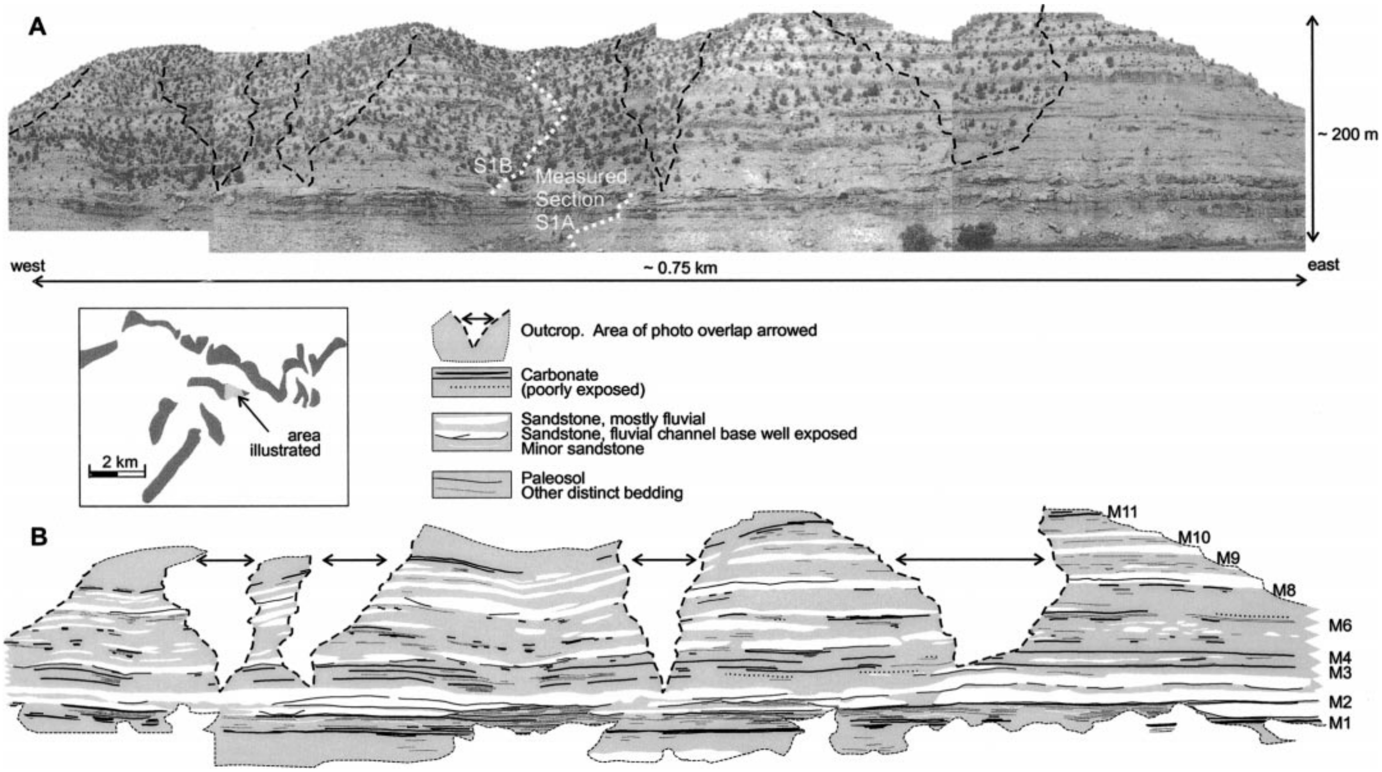


FIG. 5. —Outcrop correlations. **A**) Photomontage of canyon walls at the locality of Section S1, central part of study area, and **B**) facies correlations from the photomontage. M1 to M11 indicate the carbonate marker beds used for correlation across the field area.

Coarse-Grained Carbonate Deposits

These strata are also uncommon in the study package. The presence of beds of coated grains (ooids, pisoids, oncoids) indicates a littoral, wave-influenced setting (Weiss 1969) such as a lacustrine bar, barrier, shoal, or shoreline (Table 1, Fig. 6E). Fossiliferous limestone that contains freshwater ostracodes and mollusks (Swain 1956; La Rocque 1956) indicates at least seasonally oxygenated and destratified, shallow-water lakes (holomictic). Carbonate grainstone, commonly current rippled, also occurs toward the base of some lenticular fluvial sandbodies, and represents reworking of precursor lacustrine bars (Fig. 6D).

Fine-Grained Clastic Deposits

Siltstone and mudstone form the major component (approximately 45–60%) of the package, and where they are not in association with lacustrine carbonate they often display pedogenic modification. Paleosol types are recognized from field analysis and thin sections only, and their classification has been based primarily on criteria from other Paleogene basins of the western U.S. (e.g., Retallack 1988, tables 5 and 6; Kraus and Bown 1988). Where exposure permits, identification of degree of maturity and of amalgamated (cumulate and compound) soils follows the criteria of Kraus and Bown (1988), Bown and Kraus (1993), and Wright and Marriott (1996). Gleysols are recognized by the presence of gray coloration, distinct angular to subangular blocky peds, and low-density vertical piperock (root traces). Rarely, they are capped with a thin ($<$ 10 mm thick), laterally discontinuous coaly bed. Gleysols are commonly overlain by lacustrine strata and are indicative of high watertables prior to lacustrine transgression. Paleosols entirely enclosed within terrestrial strata can have well-differentiated profiles. A-horizons can be rooted, mottled, and have granular peds; B-horizons are oxidized, clay enriched, low in carbonate, and have granular or blocky peds (Andersson 1998). Those with a thick granular B-horizon and root mottling are considered the most mature, and they may be occasionally composite or welded where older and newer soil profiles overlap (Fig. 6F). Soils that retain a relict horizontal lamination, emphasized by differential spodic (sandy), sesquioxic (ochre-colored Fe compounds) laminae, are less mature. Immature paleosols are noted as having developed on previously deposited fluvial or even lacustrine sands and muds when there was subsequently no net subaerial sediment accumulation. Where outcrop is poor, only a mottling of the weathered fines gives indication of a potential paleosol.

Some fine- to very-fine-grained to silty heterolithic sandstone contains current ripples and root casts, is massive (bioturbated or structureless), or simply weathered. Where the heteroliths are inclined and truncated, they are interpreted as the fine-grained fills of delta distributary channels (Fig. 6G, H). The heteroliths that are tabular and interbedded with similarly tabular, fining- or coarsening-upward sandstone might alternatively represent levee deposits (*sensu* Coleman 1969). The interbedded sandstone itself would represent overbank sheetfloods or crevasse splays (which of these

←

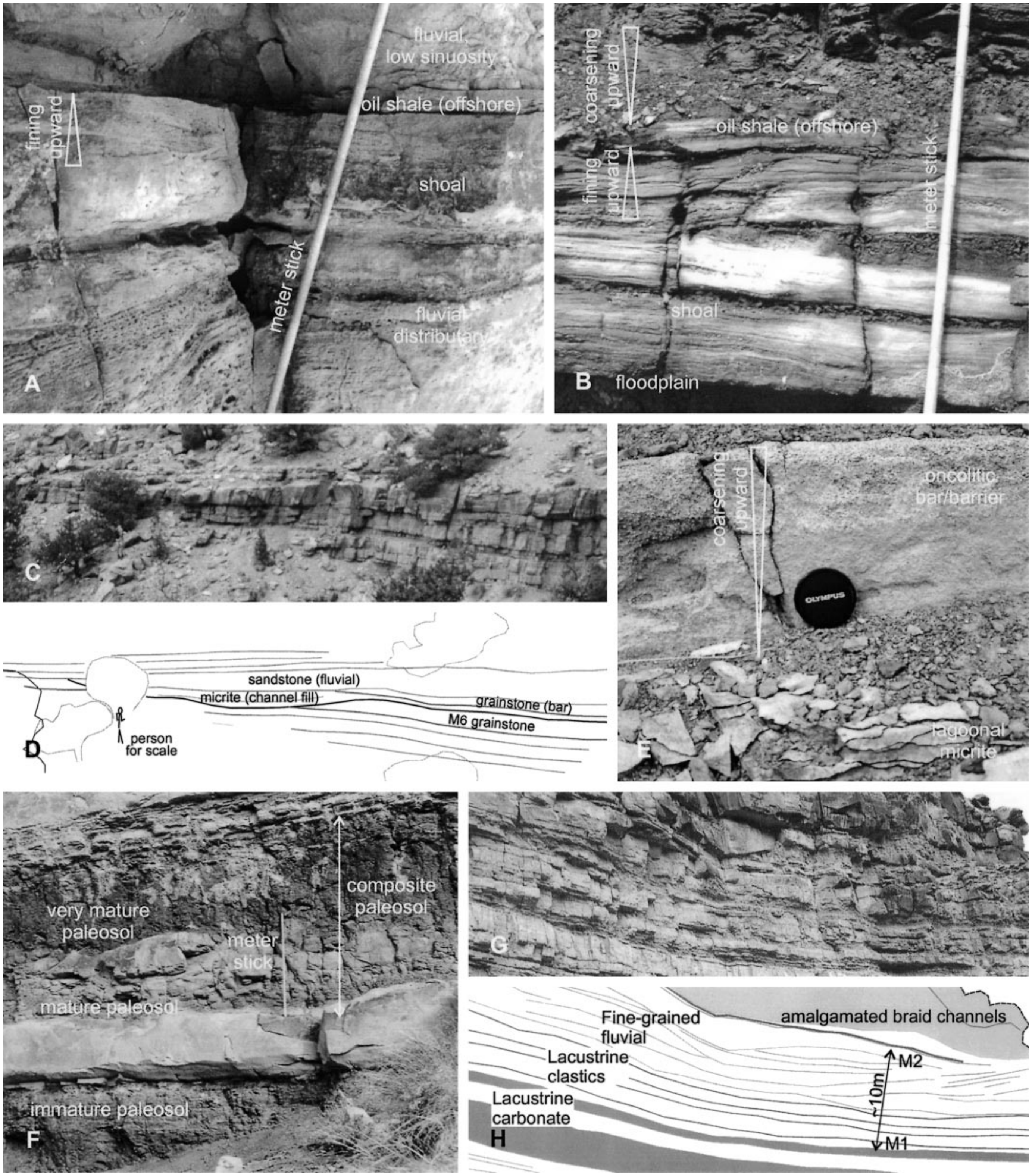
FIG. 4.—Lithologic log for the lowermost 100 m of Section S2. Log includes location of carbonate marker beds and units, lithofacies interpretations (for codes, see Table 1), and spectral gamma ray profiles. Ratios between the various components that make up the total gamma ray count permit changes in the components' abundance to be observed (i.e., increase in uranium counts, relative to potassium and thorium, can be observed across most flooding surfaces; see Keighley et al. 2002 for further discussion).

TABLE 1.—*Lithofacies Associations and their Interpreted Depositional Setting*

Key Lithofacies Associations	Interpreted Depositional Setting	Code
Sandbody, downcutting, lenticular or tabular, single fining-upward set or, if present, few gently inclined heterolithic sets, containing trough or planar cross-stratified and/or current rippled (paleocurrent direction at low angle to direction of any heterolithic-set inclination) medium- to, mostly, fine- and very-fine-grained sandstone (mud drapes are rare and if present thin and discontinuous). Laterally adjacent facies typically interpreted as alluvial floodplain. Planform may also be mappable in outcrop.	Low-sinuosity fluvial channel	STchls
Sandbody, downcutting, lenticular. Heterolithic sets inclined (moderate to high angle), of trough or planar cross-stratified and/or current rippled (paleocurrent direction at high angle to direction of heterolith-set inclination) medium- to fine-grained sandstone and variably thick siltstone or mudstone. Laterally adjacent facies typically alluvial floodplain. Planform may also be mappable in outcrop.	High-sinuosity fluvial channel	STchhs
Sandbody, downcutting, lenticular. Heterolithic sets inclined (very low to high angle), of current (± minor wave) rippled (paleocurrent direction at high angle to direction of heterolithic-set inclination) fine- or very-fine-grained sandstone and thick siltstone or mudstone. Laterally adjacent facies typically lacustrine, such as lagoonal. Planform may also be mappable in outcrop.	High-sinuosity distributary channel	STchhd
Sandbody, small, downcutting, lenticular, of variable internal structure. Laterally adjacent facies typically alluvial floodplain.	Minor fluvial stream	STchsm
Sandbody, downcutting. Typically lenticular with some evidence of unidirectional flow structures. Laterally adjacent facies typically alluvial floodplain. Poor-quality exposure limits detailed observations.	Fluvial channel, undifferentiated	STch
Sandbody, nonchannelized, tabular (typically < 1 m thick), current rippled, fine- or very-fine grained (may fine up near top). Interbedded with paleosols and other fine-grained floodplain deposits.	Floodplain, overbank, or ephemeral sheetflood	STsfld
Sandbody, nonchannelized, tabular to convex up, coarsening-upward (very-fine- to fine-grained sandstone) sets of current and/or climbing ripples and megaripples. Appears to radiate from a point source or passes laterally into a channelized sandbody.	Floodplain, crevasse splay	STsply
Sandbody, nonchannelized, tabular, with some evidence of unidirectional flow structures. Laterally adjacent facies typically alluvial floodplain. Poor-quality exposure limits detailed observations.	Floodplain, sheet sand, undifferentiated	STs
Sandbody, nonchannelized, tabular or convex up, calcareous, coarsening upward (siltstone, very-fine to fine grained sandstone), horizontally laminated passing up into hummocky cross-strata and/or large-scale wave-rippled sandstone. Typically underlain by lacustrine carbonates.	Lacustrine, littoral, shoal or barform	SAbarn
Sandbody, nonchannelized, tabular or convex-up, interbedded wavy/hummocky and current rippled, calcareous very-fine- to fine-grained sandstone. Laterally adjacent facies typically fine-grained lacustrine.	Lacustrine, littoral, delta-mouth bar	SAbard
Sandbody, nonchannelized, tabular, with some evidence of bidirectional flow structures or calcareous cement, and with underlying, overlying, and/or laterally adjacent facies typically fine-grained lacustrine. Poor-quality exposure limits detailed observations.	Lacustrine, high energy littoral, undifferentiated	SA
Sandbody, very poorly exposed. Lacking in diagnostic internal structures. Overlying, underlying, and lateral facies of uncertain or mixed fluvial-lacustrine interpretation.	Undifferentiated high energy clastic depositional setting	S
Mudstone (claystone ± siltstone ± v.f. sandstone laminae), gray, laminated. Interbedded with thin, rippled, fine-grained sandstones of overbank sheetflood (?crevasse) origin, and limited bio/pedoturbation.	Floodplain, levee	FTleve
Claystone, brown or gray, limited bio/pedoturbation, thinly horizontally laminated. Onlaps fluvial channel sandstones.	Floodplain, fluvial channel abandonment	FTchab
Mudstone, gray or greenish, bio/pedoturbated, blocky peds. Associated with thin coaly caps.	Floodplain, waterlogged paleosol (Gleysol)	FTpagl
Mudstone, red, brown, purple, or mottled (gray or green and ochre), bio/pedoturbated, with differentiated (e.g. clay rich, platy, blocky ped) horizons but depleted in Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}. Associated with fluvial and sheetflood facies.	Floodplain, paleosol (?Ultisol)	FTpaul
Mudstone, red, brown, and or purple ± mottle, with evidence of bio/pedoturbation. Poor-quality exposure limits detailed observations.	Floodplain, undifferentiated or poorly developed, reddish paleosol	FTpar
Mudstone (claystone ± siltstone ± v.f. sandstone laminae), laminated, limited bio/pedoturbation. Red or gray colored. Associated with fluvial and sheetflood sandstones.	Floodplain, interfluve	FTinch
Mudstone, red or gray colored. Poor-quality exposure limits detailed observations, but associated laterally and vertically with fluvial or sheetflood sandstones or floodplain fines.	Floodplain, undifferentiated	FT
Claystone, shaly, gray, greenish or blueish, or dark gray, laminated to massive, limited bioturbation ± few fossils. Associated with overlying and/or underlying lacustrine carbonates.	Marginal lacustrine, lagoonal	FAlagn
Mudstone, gray, greenish or bluish, laminated to massive, calcareous, with limited bioturbation. Interbedded with lacustrine sandstones of shoal or simple bar origin.	Lacustrine, quiet water, littoral, intershoal	FAnrsh
Siltstone and very-fine-grained sandstone, gray, poorly sorted, ± mudstone pebbles, ± calcareous and ± ptygmatic fracturing. Interbedded with offshore mudstones, carbonates, and/or oil shales.	Lacustrine, distal fan, turbidite	FAdfan
Mudstone, calcareous, gray (greenish/bluish), laminated and/or bioturbated. Associated with lacustrine carbonates.	Lacustrine, quiet water, profundal (offshore, or nearshore embayment)	FAprof
Mudstone, gray (greenish/bluish), typically calcareous. Poor-quality exposure limits detailed observations, but interbedded with lacustrine carbonates.	Lacustrine, quiet water, undifferentiated	FA
Mudstone, usually gray, very poorly exposed. Lacking in diagnostic internal structures. Overlying, underlying, and lateral facies of uncertain or mixed fluvial-lacustrine interpretation.	Undifferentiated low energy clastic depositional setting	F
Limestone, irregularly laminated, occasionally brecciated (algal mats).	Lacustrine, marginal mud flat	LOmmat
Limestone, irregularly laminated, domal (algal stromatolites).	Lacustrine, quiet water < 10 m water depth	LOstrm
Limestone, coquina, granule and coarser grain sizes of gastropod, bivalve, ostracode, and algal hash. Horizontally bedded. Associated with finer-grained lacustrine carbonates.	Lacustrine, beach, shoreface	LXbeac
Limestone, grainstone, coarse and medium-grained, coated (oolitic oroncolitic) grains with typically ostracode nuclei, ostracode hash, variable other shell hash. Massively bedded, rarely wave rippled or hummocky/swaly cross-stratified. Associated with finer-grained lacustrine carbonates and clastics, and occasionally with fluvial (truncating) and floodplain facies.	Lacustrine, shoal, bar, or barrier	LXbarn
Limestone, sparry calcite cemented, sandy (very-fine-grained), with bidirectional flow indicators. Passes up or laterally into coarser-grained clastics or carbonates.	Lacustrine, quiet water, littoral intershoal	LXmarsh
Limestone, sparry calcite cemented, sandy (very-fine-grained). Massive bedding or poor exposure inhibits observation of diagnostic features, but beds pass up or laterally into coarser grained clastics or carbonates.	Lacustrine, littoral, undifferentiated	LX
Limestone, micritic, variably kerogenous, gray to brown, massive, restricted diversity of fossils—often of terrestrial gastropods. Hydrous pyrolysis of samples indicates terrigenous kerogens present. Rare roots or bioturbation. Interbedded with coarse-grained carbonates.	Lacustrine, quiet water, poorly oxygenated, lagoonal or resticted embayment	LMlagn
Limestone, micritic, often fissile. Gray colored, but weathers yellow. Massive bedding, bioturbation, or poor-quality exposure inhibit observation of diagnostic features	Lacustrine, quiet water (oxygenated), undifferentiated	LM
Oil shale: organic rich, dolomitic limestone, micritic, gray, dark gray, black, or purple, variably kerogenous. Massive, can be bioturbated, or with vertebrate (including fish) and invertebrate fossils. Hydrous pyrolysis of samples shows minimal evidence of terrestrially derived kerogens.	Lacustrine, profundal	OLMprof
Coal, black.	Marsh or swamp	Oswmp

→

FIG. 6.—Examples of major lithofacies associations. **A**) Dolomitic oil shale encased in coarse-grained strata, M2 at S10, with part of meter stick for scale. The succession is interpreted to pass up from alluvial sheetflood sands to sandy (increasingly ostracodal upward), wave-rippled and small-scale hummocky lacustrine-bar sands that fine upward to a purple-black profundal oil shale and dark gray, profundal lacustrine mudstone. The latter are truncated by fluvial sandstone. **B**) The same profundal oil shale (M2) and underlying lacustrine-bar sandstone, ~ 1 km farther east at S11. Here they are encased in fines: capping gray mudstone of likely floodplain origin and underlying



fine-grained dark gray profundal mudstone. **C, D**) Photo and line drawing of the truncation of a carbonate grainstone by a lenticular micrite that is laterally extensive to the right (east), M6 between S2 and S12, junction of Nine Mile and Argyle Canyons. The grainstone is interpreted to be a littoral bar or shoal that has been cut by a distributary channel, subsequently abandoned and infilled with micrite in a lagoonal setting, A second, overlying littoral bar is also truncated, with its carbonate grains reworked and redeposited as part of a fluvial deposit. **E**) Coarsening-upward, micritic to ostracodal and oncoidal grainstone bed. This is marker bed M1, near S2B. Lens cap (50 mm diameter) for scale. **F**) Compound paleosols comprising lower immature (banded) paleosol and upper highly mature, brownish-red (mottled bluish gray) paleosol, which itself is composite, U2 at S11. Meter stick for scale. **G, H**) Photo and line drawing of stacked fine-grained channels in U1 at S2. The upper fine-grained interval contains inclined (heterolithic) and crosscutting sets. Underlying strata contain laterally persistent and parallel, decimeter-scale heteroliths which are themselves underlain by lacustrine carbonate.

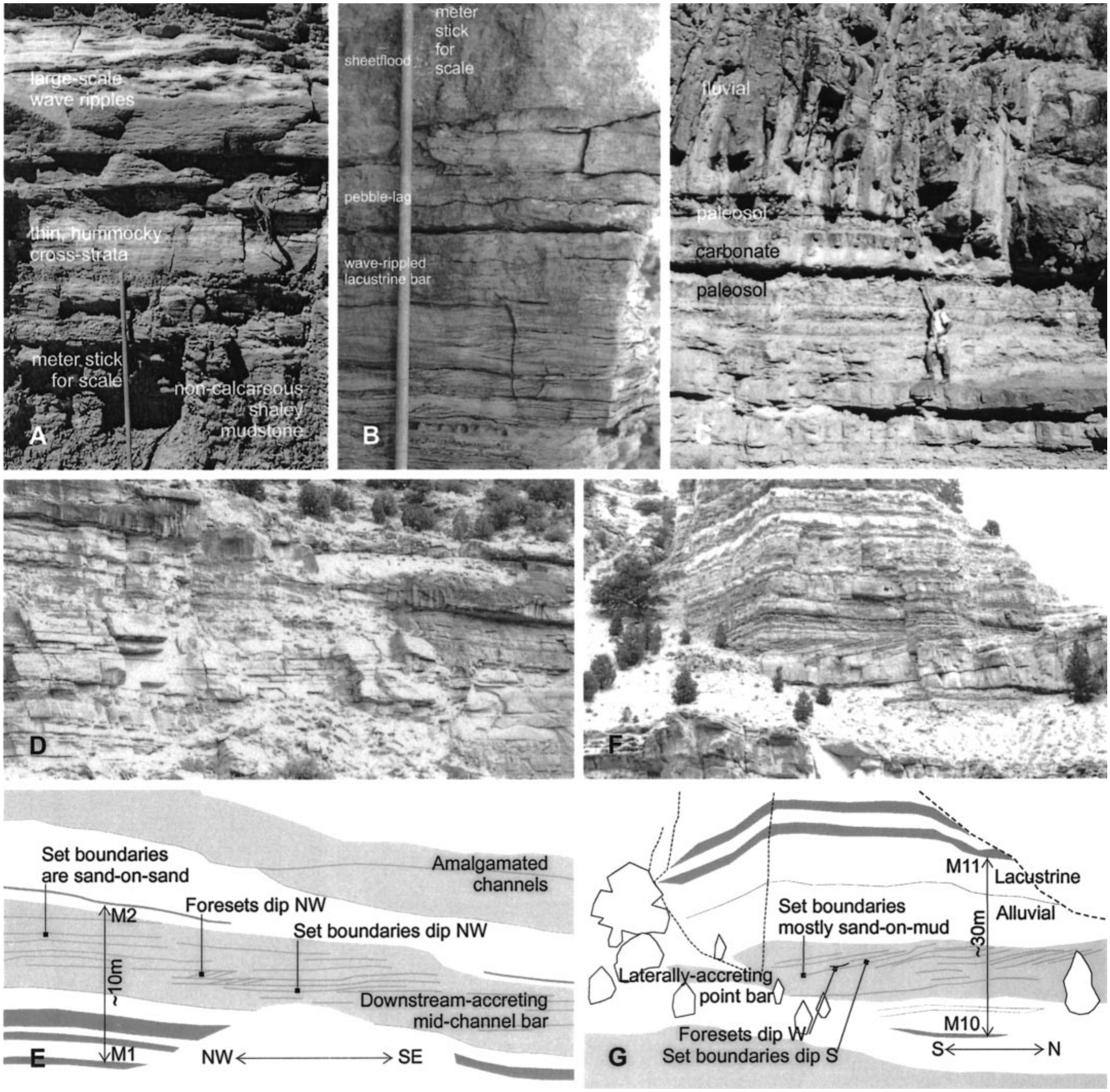


FIG. 7.—Examples of major lithofacies associations. **A**) Calcareous, siliciclastic, coarsening-upward succession from U3, S11. Upsection, swaly, occasionally hummocky cross-strata pass upward into large-scale symmetrical ripples. Part of meter stick for scale. **B**) Fine-grained, calcareous sandstone with wave ripples and pebble lags, erosionally overlain by vaguely parallel laminated, noncalcareous sandstone in U6, S2. Part of meter stick for scale. **C**) Lenticular sandstone truncating two paleosols that enclose a meter-thick carbonate grainstone (M4) between S12 and S3. Person for scale. **D, E**) Photo and line drawing of a 5-m-thick sandstone, located between S1 and S2, that has an overall lenticular cross section and can be mapped out as a low-sinuosity ribbon. Foresets and set boundaries have similar dip directions and are located well away from the mapped channel margin. The channel has cut down through strata interpreted as Gleysols and clastic littoral shoals and is enclosed between lacustrine carbonate markers (M1 and M2). **F, G**) Photo and line drawing from U10, adjacent to S3. Set boundaries and cross-strata foresets in this lenticular sandstone have divergent dip directions.

latter two deposits is likely for each occurrence depends on the geometry of the sandstone relative to its source fluvial channel, which usually cannot be adequately mapped out).

Siltstone that onlaps and drapes sigmoidal fluvial sandbody tops may be locally truncated by coarse-grained, lenticular sandbodies. These fines are interpreted to be from an epilittoral environment accessible to fluvial invasion (e.g., embayment, lagoon). In contrast, laminated mudstone that onlaps and drapes fluvial sandbodies within a succession devoid of lacustrine indicators is interpreted as a channel-abandonment deposit. For laterally extensive, massive or laminated gray mudstone, which is usually one of

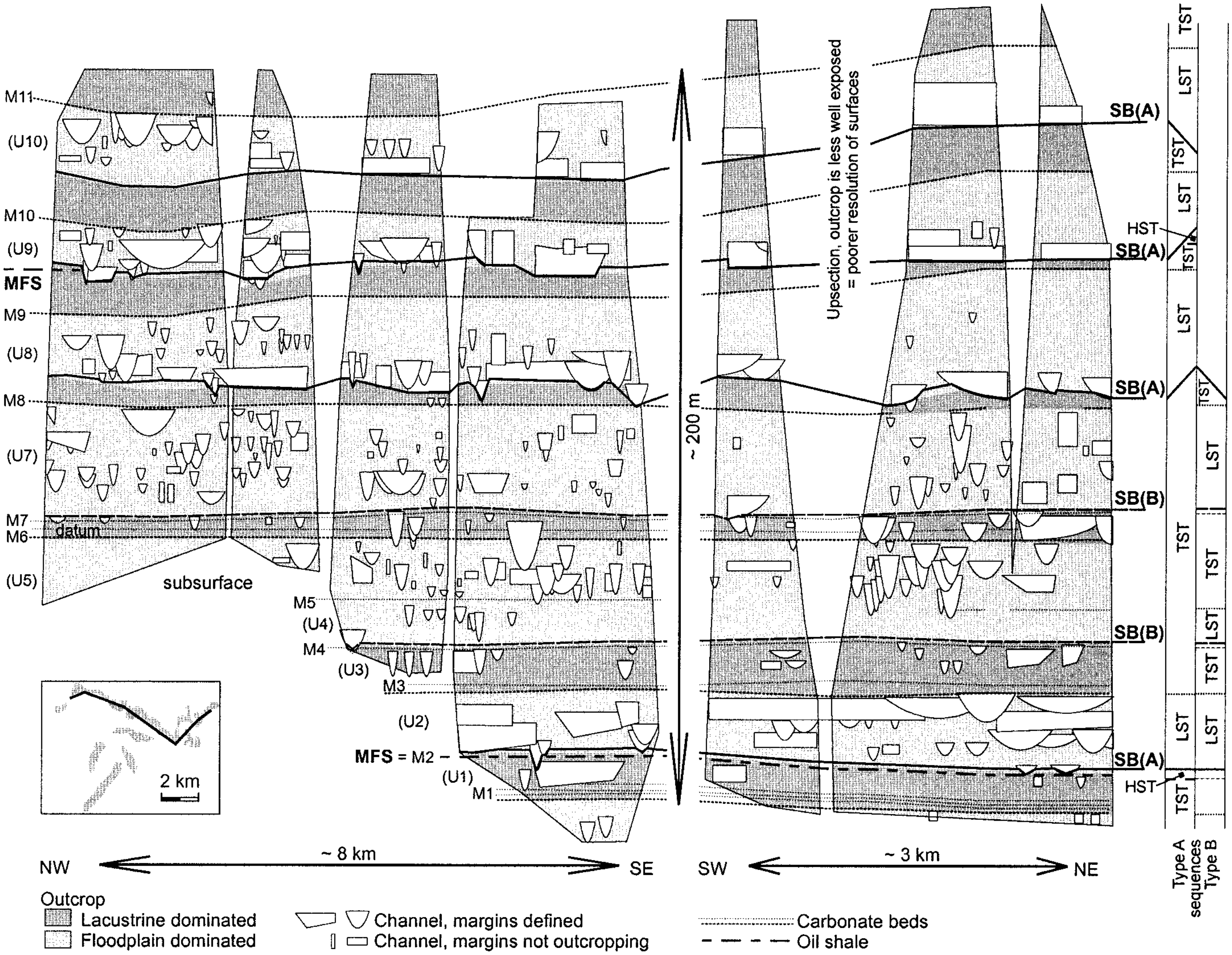


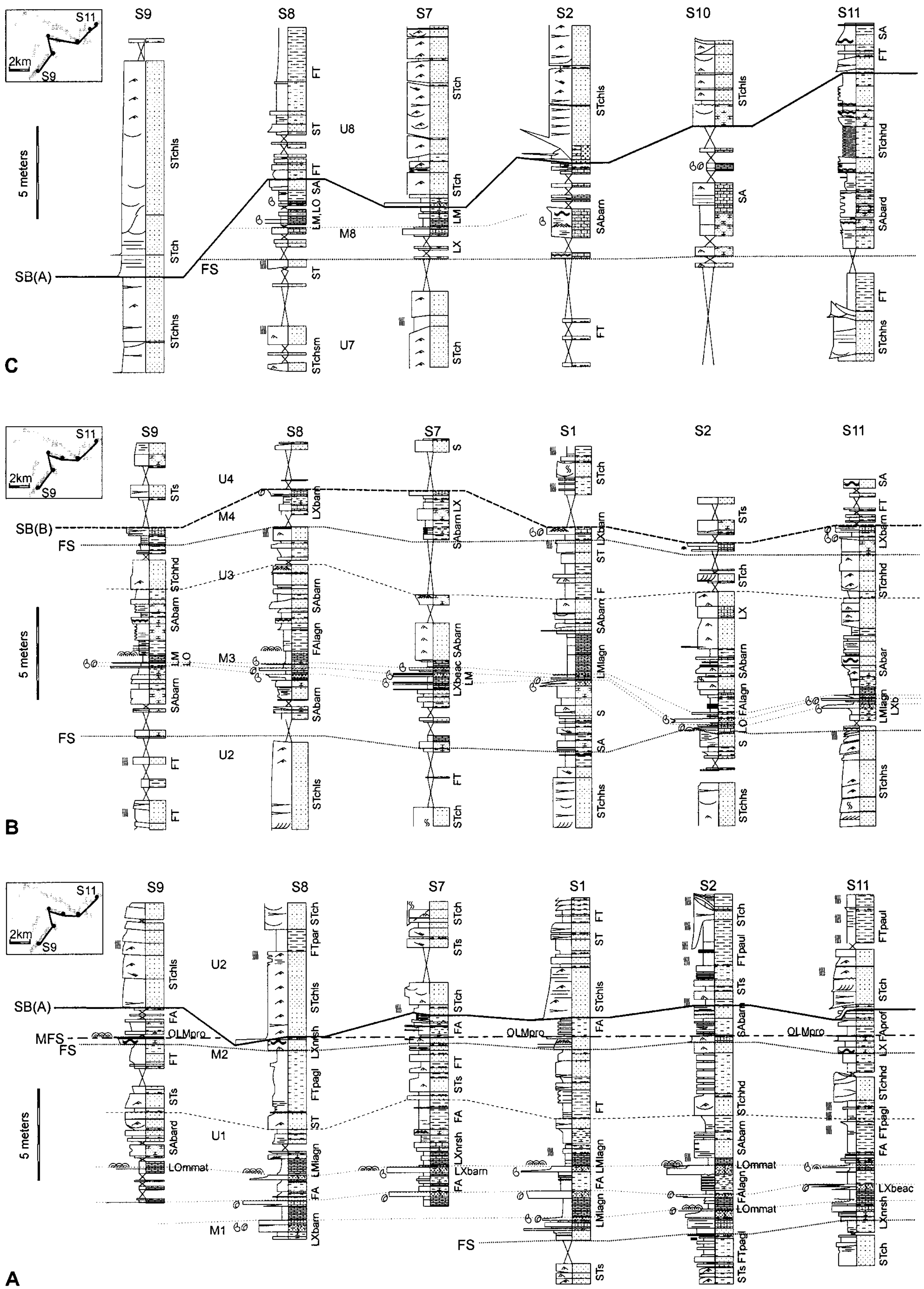
FIG. 8.—W–E section crossing the entire study area, showing the distribution of generalized facies associations, and with major bounding surfaces added. M1 to M11 indicate the carbonate marker beds used for correlation across the field area, and subdivide the succession into ten units, U1 to U10. MFS = maximum flooding surface, SB(A) = type A sequence boundary, SB(B) = type B sequence boundary, LST = lowstand systems tract, TST = transgressive systems tract, HST = highstand systems tract.

the most poorly exposed lithotypes, a lacustrine interpretation is best indicated where there is an increased uranium ratio in the SGR data (Keighley et al. 2002, and Fig. 4), and a littoral interpretation is preferred where hydrous pyrolysis of the fines by Ruble (personal communication 1999) has indicated a mixed terrestrial–algal signature. In other cases, the nature of overlying and underlying beds has to direct the interpretation. Where both overlying and underlying beds are interpreted as lacustrine, and the mudstone lacks evidence of oxidation, pedogenic features, inclined heteroliths, or other features indicative of alluvial deposition, there is no reason to infer an intervening phase of terrestrial deposition. Likewise, where overlying beds are interpreted as deltaic and underlying beds as lacustrine, a lack of features suggesting emergence in the mudstone, or in parallel-bedded fine-grained heteroliths (Fig. 7G, H), would result in an interpretation of a quiet, littoral environment.

Coarser-Grained Clastic Deposits

Medium- to fine-grained, variably carbonate-cemented sandstone constitutes 25–45% of the vertical section. Coarse-grained sandstone and intraformational conglomerate are rare. Coarsening-upward sheet sandbodies that lack internal erosion surfaces and contain wave ripples, synaeresis or diastasis cracks, and swaly or rare hummocky cross-strata are interpreted as lacustrine shoals (Fig. 7A) or, if associated with unidirectional ripples and cross-strata, delta-mouth bars. Where the tops are wave rippled they are considered (nearly) emergent barforms. Such sandbodies usually contain a carbonate cement. A lacustrine origin is also inferred where adjacent carbonate lithofacies are present. In sand-on-sand contacts there is commonly an abrupt loss of carbonate cement upward into an alluvial sandstone (Fig. 7B).

Lenticular sandbodies, particularly those that truncate paleosols, are interpreted as fluvial channel deposits (Fig. 7C). Reliable identification of fluvial channel planform (braided versus singular, straight versus sinuous) is dependent on the identification of component bedforms such as channel bars or sandwaves (e.g., Miall 1988; Keighley and Pickerill 1996). Mid-channel bars are identified where sets of trough or planar cross strata pass up into parallel, low-angle cross strata and/or ripple (climbing) cross-laminae, and set boundaries dip in the same direction as the paleocurrent direction (Fig. 7D, E). These downstream-accreting bars are indicative of


S9
S8
S7
S2
S10
S11
2km
5 meters
SB(A)
FS
U8
M8
U7
STchls
STch
STchhs
FT
ST
SA
LM,LO
STchsm
LX
SAbarn
STchhd
SAbard
C
S1
U4
M4
SB(B)
U3
M3
U2
STs
LXbarn
SAbarn
FAlagn
LM
LO
STchd
LXbeac
LMlagn
FAlagn
LXb
B
U1
M2
M1
MFS
OLMpro
FTpar
FTpagl
LXnrsh
LOmmat
LXbarn
FTpaul
FAprof
LXbeac
A

low-sinuosity channel belts with braided channel components. Major braid channels can comprise successive overlapping mid-channel bars so that, in vertical succession, more than one fining-upward set may be encountered. Heterolithic (co-) sets composed of mixed, inclined successions of trough or planar cross-stratified sandstone, low-angle or parallel cross-stratified sandstone, ripple cross-laminated sandstone, and/or parallel-laminated siltstone or mudstone are interpreted as laterally accreting bars (Fig. 7F, G). Lateral accretion surfaces dipping in opposing directions have been identified in laterally adjacent outcrops, providing further indication of high-sinuosity channels.

ARCHITECTURE

Marker Beds

Eleven carbonate beds can be traced laterally across the study area. Designated M1 (= D Marker of Jacob 1969) to M11 (= C2 marker of Jacob 1969), they subdivide the study package into ten units, U1 to U10 (Figs. 5, 8). Some of the carbonate beds have unique lithological characteristics (table 2 in Keighley et al. 2002). At some localities, the carbonate is truncated by overlying fluvial sandbodies (Fig. 7C). Where micritic carbonate is truncated, boulder-size carbonate clasts may be encountered in the truncating sandstone, and indicate prior carbonate lithification (Fouch et al. 1992). Where ostracodal and ooidal grainstone is truncated, reworked individual grains are preserved in the fluvial channel sandstone (i.e., grainstone beds were unlithified prior to reworking).

Lacustrine-Dominated Intervals

Lacustrine-dominated intervals have markers present near the base and, often, the top (Fig. 8). Typically, the intervals include, at the base, three coarse-grained beds of littoral carbonate interbedded with finely crystalline carbonate and mudstone (e.g., Fig. 9A, B). They are characteristically overlain by a coarsening-upward, laterally extensive, clastic shoal (e.g., within U3, Fig. 7A), capped by gray floodplain fines. In places, the fines are cut by fine-grained high-sinuosity and isolated, large, coarser-grained, low-sinuosity fluvial channel fills (Fig. 7D). These subaerial strata are overlain by a flooding surface with overlying finely crystalline carbonate or mudstone interbedded with either a profundal oil shale (Figs. 6A, B, 9A) or a littoral grainstone (Fig. 9B).

Floodplain-Dominated Intervals

Floodplain-dominated intervals are of two types. Both contain gray and red mudstone, including paleosols, interbedded with lenticular sandbodies and rare carbonate grainstone of lacustrine-bar origin (e.g., M5 in Fig. 8). In the first type, the isolated or, rarely, crosscutting sandstone lenses are exclusively of sinuous fluvial channel origin (e.g., U5, U7 in Fig. 8; Fig. 10B). In the second type, lenticular sandbodies are mostly restricted to the upper parts of the floodplain-dominated interval and laterally extensive sandbodies are also encountered (e.g., U2, U8 in Fig. 8; Fig. 10A). The laterally extensive sandbodies mostly comprise amalgamated fluvial sandstone of braid channel origin—channel margin truncations are so common that the identification of individual channel forms and geometries is often not possible. More mature, composite paleosols are confidently identified (Fig. 6F) only in intervals that contain the amalgamated sandbodies. This relationship may be a function of the exposure, because paleosols are best exposed beneath large sandstone outcrops. Gleysols are present at the tops of some floodplain-dominated intervals.

Summary

The 200-m-thick package comprises cyclic alternations of approximately 20-m-thick floodplain-dominated and approximately 10-m-thick lacustrine-dominated intervals (Fig. 8). Apart from one floodplain-dominated interval with extensive sheet-like sandbodies (U2), the lower half of the investigated package contains only disseminated, lenticular fluvial sandbodies; the upper half has much more extensive, sheet-like sandbodies (U8, U9, U10). Contacts between lacustrine-dominated and overlying floodplain-dominated intervals are of two types (Figs. 9, 10). Type A contacts are identified where lacustrine-dominated intervals that include profundal lacustrine facies near their top (M2, oil shale above M9) are abruptly overlain by floodplain-dominated intervals, and/or where the lacustrine–floodplain transition is across an angular unconformity. Sheet sandbodies occur in the floodplain-dominated intervals overlying these contacts (U2, U8, U9, U10). Type B contacts are identified where no angular unconformity is mapped and lacustrine-dominated intervals that lack any distinct profundal facies (U3, U6) pass upward into floodplain-dominated strata with exclusively lenticular sandbodies (U4, U5, U7). Further details can be found in Keighley et al. (2002).

SEQUENCE STRATIGRAPHY OF THE STUDY PACKAGE

Flooding Surfaces and Parasequences

Major flooding surfaces are identified most clearly at the base of lacustrine-dominated intervals where carbonate abruptly overlies a fluvial sandstone or paleosol. The top of the fluvial sandstone can be partly reworked during the transgression. Juxtaposition of a calcareous, often wave-rippled, fine-grained sandstone on noncalcareous sandstone or mudstone with terrestrial affinities is the other common indicator of a flooding surface. Root structures and/or gleysols with rare local, thin ($<$ 1cm) coaly caps (Fig. 9A, section S2) may underlie the contact, indicating a rising watertable in advance of the surface being flooded.

Flooding surfaces, by definition (Van Wagoner et al. 1988), bound parasequences. The lower part of each lacustrine-dominated interval typically contains three carbonate parasequences $<$ 2 m thick. Each parasequence displays a coarsening-upward trend defined by more abundant oncoids, ooids, or fossil material toward the top (Fig. 6E). The parasequence boundaries are indicated by low-energy micrite and thinly laminated shale of lagoonal or interdistributary bay origin (e.g., at M3, Fig. 9B) that sharply overlie high-energy, coarse-grained, coquina or grainstone of littoral or shoreline origin. A carbonate parasequence set is overlain at most localities by a single coarsening-upward clastic succession, 4 to 8 m thick, containing swaly, hummocky, and wave-rippled structures, capped by delta-top floodplain fines and delta-distributary fluvial channels. Minor lake deepening or

←

FIG. 9.—**A**) The succession and sequence stratigraphic interpretation of M1 to middle U2 strata for selected logged sections in a SW–NE transect. This sequence boundary SB(A), generally parallels the underlying flooding surfaces, FS, and maximum flooding surface, MFS. Although a fluvial sandstone may rest directly on the oil shale, the oil shale is truncated and reworked only at a few localities, as at S8, where the oil shale is siltier. **B**) The succession and sequence stratigraphic interpretation of upper U2 to M4 strata for selected logged sections in a SW–NE transect. The flooding surface in S2 is marked by carbonate rip-up clasts erosionally truncating an alluvial sheetflood sandstone, representing a potential ravinement surface with overlying transgressive lag. The overall succession is similar to that shown in Figure 9A. The major differences are that the uppermost flooding surface passes upward not into an oil shale but into carbonate grainstone, and any overlying sandstone is lenticular rather than stacked and sheet-like. **C**) The succession and sequence stratigraphic interpretation of upper U7 to middle U8 strata for selected logged sections in a SW–NE transect. Thin carbonate parasequences can be identified in S8, but they pass laterally into a sandier delta-front succession farther east. Note the sand-on-sand sequence boundary in S9. For key to sedimentary structures, lithologies, and lithofacies codes, see Figure 4 and Table 1.

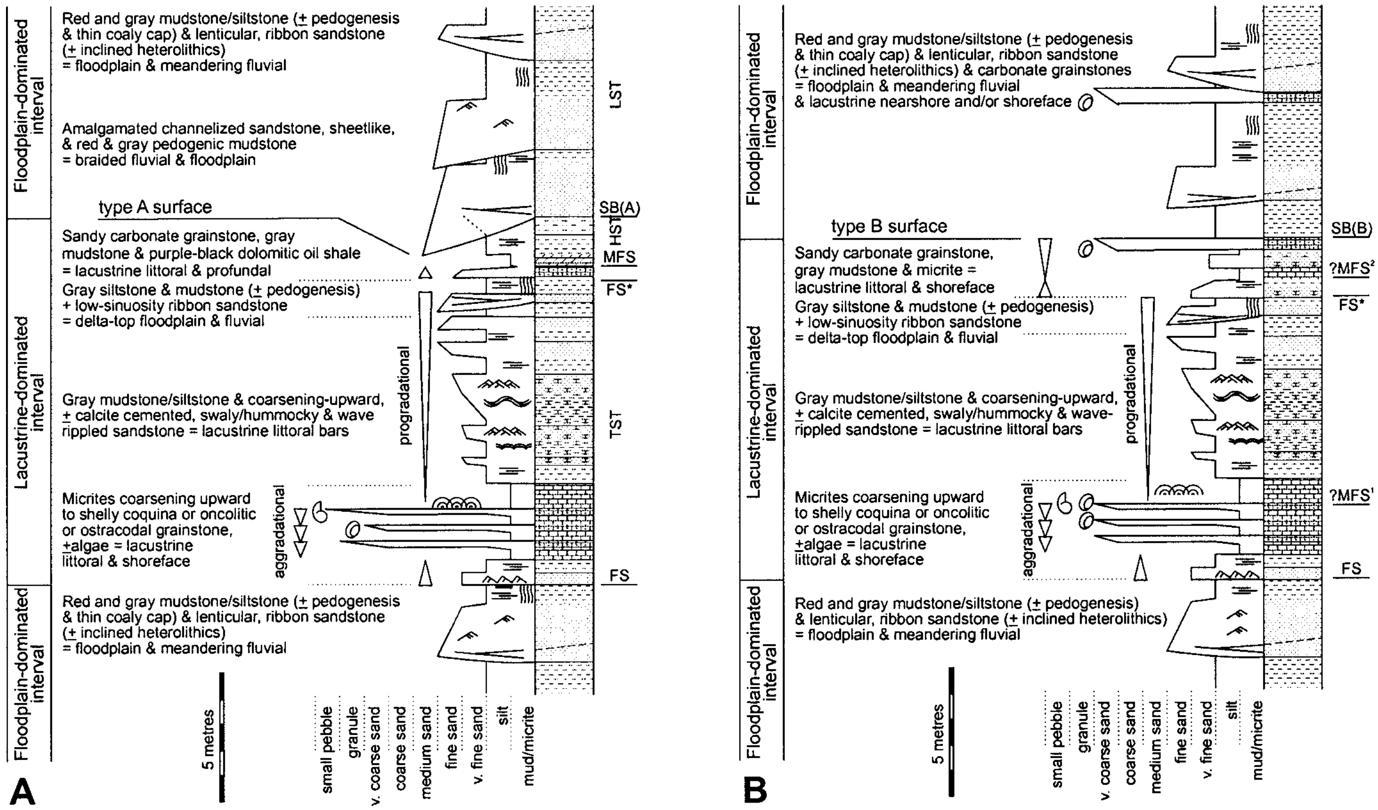


FIG. 10.—Highly generalized lithofacies associations for different successions of floodplain- and lacustrine-dominated intervals, summarizing the sections shown in Figure 9 (see Figure 4 for key). **A**) Succession across a type A surface. **B**) Succession across a type B surface.

autocyclic factors may be responsible for local variability. For example, Figure 9C shows a lateral facies shift in the lacustrine-dominated interval from quiet-water micrite to channelized, inclined heteroliths of fine-grained clastics (in section S11), toward the northwest, along depositional strike. This suggests a delta-front facies association in the vicinity of S11, with an interdistributary embayment to the southwest. These clastic parasequences are bounded on top by a flooding surface except where the clastic succession is truncated by overlying floodplain-dominated strata associated with M8 and M10.

Maximum flooding surfaces are present within oil shale interpreted to be of profundal origin (Fig. 9A). Sets of convex-up cross-lamination immediately underlie the oil shale and may represent small lacustrine hummocks (Fig. 6A, 6B). The sets display a fining up of clastic grain size with progressively fewer ostracode fossils. Collectively, this succession represents a major landward facies dislocation. In the study area, these surfaces are only identified toward the top of intervals, approximately 10 m thick, of lacustrine-dominated strata that are associated with markers M1–M2 and M9.

Sequence Boundaries

Sequence boundaries are interpreted at stratigraphic positions where there is an abrupt basinward shift in facies across a surface that is regionally mappable (Van Wagoner et al. 1988). They correspond to the type A and type B contacts described above. Sequence boundaries are marked by the base of the first channelized fluvial sandstone or the top of the first well-developed paleosol A-horizon above lacustrine-dominated strata. The latter contact is interpreted as an interfluve sequence boundary marking subaerial exposure lateral to areas of fluvial incision (McCarthy and Plint 1998).

Type A Sequence Boundaries.—These contacts are best developed above M2 and M9, where lacustrine successions that include a maximum flooding surface are truncated by laterally extensive, amalgamated fluvial channels (Figs. 8, 9A). The abrupt basinward facies shift and mappable unconformity, which is angular in the case of M9, make these type A surfaces equivalent to Exxon type 1 sequence boundaries in marine strata (Van Wagoner et al. 1988). Variable degrees of incision at these sequence boundaries are considered to have removed underlying strata of the lacustrine-dominated intervals, including maximum flooding surfaces, leading to juxtaposition of the amalgamated fluvial deposits on a variety of subaqueous or subaerial facies. For example, the oil shale associated with M9 is encountered only in the far northwest and is removed by fluvial incision in adjacent sections (Fig. 8). In the study area, erosional relief at these sequence boundaries is not normally greater than 10 m, which is the maximum thickness of a single channel fill, and explains why classic incised-valley geometries (*sensu* Posamentier et al. 1988) are not developed.

Amalgamated fluvial sandbodies also variably truncate lacustrine-dominated intervals associated with markers M8 and M10 to form structurally angular unconformities (Figs. 8, 9C). Oil shale may have been present toward the top of these lacustrine-dominated intervals, but it would have been eroded during the formation of the angular unconformity. Indeed, in the far southwest of the study area, incision has completely removed the lacustrine-dominated interval associated with M8, with the result that the sequence boundary occurs with a sand-on-sand contact (section S9, Fig. 9C). The angular nature of the boundaries associated with M8 and M10 is illustrated by the onlap of succeeding initial flooding surfaces, resulting in the intervening section thickening toward the northeast (Fig. 8).

Type B Sequence Boundaries.—Contacts between the approximately 10-m-thick lacustrine-dominated intervals associated with M3–M4 and M6–M7, and overlying subaerial deposits are less marked evidence for basinward shifts in facies. The subaerial strata include isolated lenticular fluvial channel sandstone beds that only locally incise into the lacustrine-dominated intervals. Any profundal oil shale or micrite that had been deposited would be preserved in the extensive interfluves to these channels, but only littoral deposits are present (e.g., Fig. 9B). The localized fluvial downcutting produces an irregular relief to the boundaries in the cross sections of Figure 9 but does not produce a mappable unconformity at the study-area scale. One interpretation is therefore that these Type B contacts simply record normal progradation during a temporary slowing of lake-level rise with no relative fall in base level.

Our preferred interpretation is that type B surfaces are sequence boundaries because of the following observations. (1) There is a basinward shift in facies, albeit not as pronounced as in type A sequence boundaries. (2) Where channels have not truncated the lacustrine-dominated interval, the tops of some grainstone beds have a distinct orange staining; the color is interpreted as indicating subaerial exposure, equivalent to an interfluve sequence boundary. (3) The subaqueous strata and overlying subaerial strata are of otherwise similar lithofacies and of thickness similar to those encountered across type A sequence boundaries.

Systems Tracts

Systems tracts are contemporaneous, three-dimensional lithofacies assemblages that subdivide a sequence on the basis of their position within the sequence and the type and distribution of the contained parasequence set(s) and bounding surfaces (Van Wagoner et al. 1988). Herein, they have been identified only between type A sequence boundaries.

Lowstand Systems Tracts.—Successions assigned to a lowstand systems tract occur above each of the type A sequence boundaries and are capped by the first significant transgressive surface (Fig. 8). The lowermost 10 to 15 m of these tracts are characterized by amalgamated fluvial channel sandstone and minimal preservation of fines. Above the amalgamated channels, and up to the transgressive surface, there is a shift to more lenticular sandbodies of higher sinuosity. The timing of deposition within this tract of the amalgamated channel sandstone is uncertain because we cannot correlate these deposits to basin-center areas. However, the transition to higher-sinuosity sandbodies is interpreted as a response to reduced fluvial gradient accompanying early base-level rise.

Transgressive Systems Tracts.—These tracts, bounded by the initial transgressive surface below and the maximum flooding surface above, range in approximate thickness from 10 m to 80 m (Fig. 8). Beneath the maximum flooding surface, the succession typically comprises a lacustrine-dominated interval consisting of carbonate parasequences approximately 2 m thick, overlain by a clastic parasequence approximately 5 m thick. The thinnest of these tracts, associated with M9, is contained within a single lacustrine-dominated interval. The thickest of these tracts spans three lacustrine-dominated intervals (M3–M4, M6–M7, and M8) and contains multiple carbonate–clastic parasequences. In the two lower intervals, the carbonate parasequences are thinner than elsewhere and there is no profundal oil shale identified above either clastic parasequence.

Highstand Systems Tracts.—These tracts, being bounded by maximum flooding surfaces and the succeeding sequence boundaries, are not well preserved because of partial or complete truncation by the later sequence boundary. Examples include the highstand systems tract associated with M2, which is of mudstone, quite uniformly 1 to 2 m thick, and rarely truncated. The tract associated with M9 is up to 4 m thick, but the shoaling upward succession is often truncated.

Cyclicity and Stacking Patterns

The average vertical spacing between successive type B sequence boundaries is very regular: 30 m, 27 m, 35 m, 28 m, and 23 m. In contrast, type A sequence boundaries are more common upsection (Fig. 8). Successively upsection, vertical spacing averages 92 m (containing the three lowermost type B sequences), 28 m, and 23 m. Because type B sequence boundaries mark less pronounced basinward facies shifts and hence lower-magnitude falls in lake level than those marked by type A surfaces, then type B sequences represent high-resolution sequences nested within type A sequences which are of lower resolution and typically longer duration.

Within each cycle, the lacustrine-dominated intervals contain carbonate parasequences and an overlying clastic parasequence collectively forming an aggradational-to-progradational set. This stacking pattern is typically associated with a conventional highstand systems tract (van Wagoner et al. 1988), where sediment is increasingly able to fill available accommodation due either to a decreasing rate of base-level rise or increased rate of sediment supply. In type A sequences, however, this stacking pattern occurs stratigraphically below any identified maximum flooding surface, which by definition, should form the basal boundary of the highstand systems tract (Fig. 10A). In the study area, the lack of preserved strata precludes observation of any potentially similar stacking above the maximum flooding surface. In type B sequences, the position of the maximum flooding surface is difficult to determine because of the lack of demonstrably profundal facies, as shown in Figure 10B. If it is placed immediately above the carbonate parasequences (?MFS[1]), the progradational siliciclastic parasequence could represent part of a classical highstand systems tract. Strata overlying the subsequent flooding surface (FS*) could then represent the response to a tectonically raised threshold (as in Fig. 3G). Alternatively, a situation similar to that of Type A sequences would have the surface above the clastic parasequence at ?MFS[2].

DISCUSSION

A major utility of sequence stratigraphy is its predictive potential. Given a robust conceptual sequence-stratigraphic model, there is the possibility to extrapolate the key surfaces and system tracts beyond the area of study and to postulate stratigraphic evolution at the basin scale. The resulting working stratigraphic model for the Uinta Basin (Fig. 11) illustrates our paleogeographic model for a complete type A sequence.

Interpretations of Sequence Stacking

Type A Sequences.—At maximum flooding surfaces, such as within the M2 marker bed, profundal oil shale accumulates over the widest area in a deep, expanded lake and clastic deposition is restricted to the basin margin. If the highstand was not prolonged (balanced-fill lake basins), or if sediment supply was relatively limited as during the sediment-starved period of basin evolution, the coarse clastic component is accommodated in a narrow apron and the available accommodation is underutilized (Fig. 11D). In a sediment-starved situation, increased sediment supply might accompany greater fluvial inputs to the basin during wet climates but would be offset to some degree by smaller areas being prone to erosion (cf. Lambiase 1990). Basin topography also influences apron geometries. Low-gradient basin floors and steep-gradient basin margins promote thick, narrow aprons (the terraces and Gilbert Deltas of Utah's Bonneville Basin are a modern analogue). Unfortunately, the southern margin of the Uinta Basin is not preserved, so no potential apron facies geometries are available for study.

Subsequent lake-level fall exposes the tops and steep marginal slopes of any aprons (Fig. 11E), which, if extensively developed, may act as a local ''shelf.'' Major increase in gradient across the ''shelf edge'' promotes fluvial incision (Schumm 1993) and development of a sequence boundary. An appropriate modern analogue is the ongoing incision of the Provo highstand Weber delta in the Bonneville Basin (Milligan and Lemons 1998). Because the apron sediment is unlikely to be lithified, a store of relatively coarse clastic material is readily available for transport and deposition as subaqueous facies or, if the lake has contracted across the basin floor, as subaerial deposits (Fig. 11F). Sheet-like, low-sinuosity, braided-fluvial deposits, such as the lower U2 floodplain-dominated interval (lowstand sys-

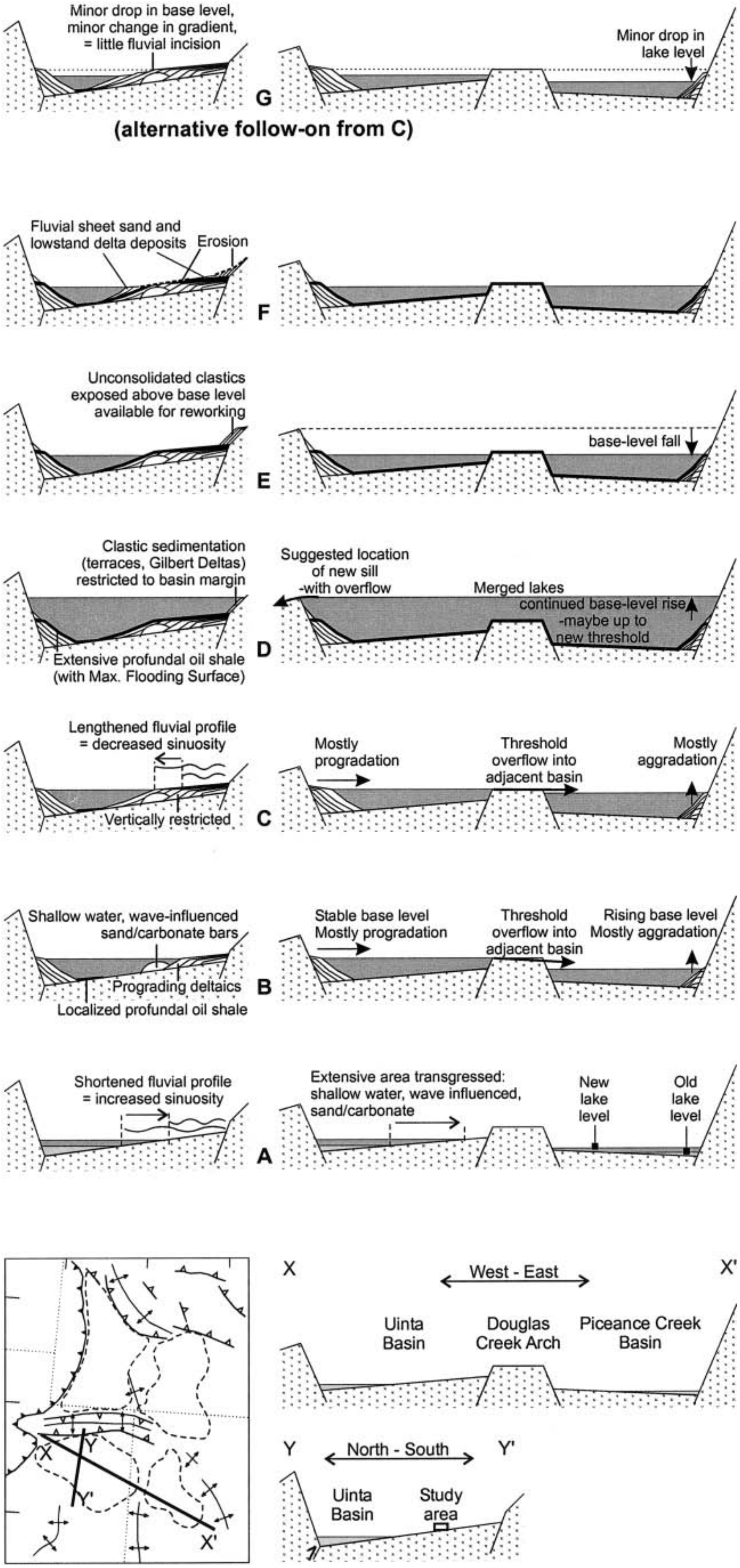


FIG. 11.—Suggested stratigraphic cross sections for the Uinta Basin constructed for various stages of basin fill. The initial situations shown in X–X′ and Y–Y′ illustrate lakes in the Uinta and adjacent Piceance Creek basins at lake lowstand. **A**) Initially, an increased input:output ratio (see Fig. 3) causes the lakes to transgress extensively over the low-gradient basin floor, even with limited relative rise of the base level. Rivers increase in sinuosity. **B**) The Uinta lake reaches threshold and starts to spill into the still-filling Piceance Creek lake. Stable base level promotes progradation in the Uinta lake. **C**) Progradation promotes a straightening of the fluvial planform near the river mouths. **D**) If the two lakes merge and inputs still exceed output, the merged lake can deepen, potentially up to the elevation of the next threshold (here speculated to be west of the Uinta lake). Clastic material no longer reaches much of the lake, which, under deep water, accumulates organic-rich sediment (which lithifies to an oil shale). **E**) A shift to output exceeding input results in a forced regression, exposing recently deposited, likely unconsolidated basin-margin material well above base level. **F**) The basin-margin material will have formed steep basin-margin terraces, with pronounced breaks in gradient. Fluvial systems actively incise through these unconsolidated terraces, reworking them out onto the basin floor as lowstand fluviodeltaics. **G**) In situations where the two lakes never merged, or when the merged lake did not significantly deepen (i.e., situation ''D'' did not occur), subsequent fall in lake level does not expose any major breaks in gradient. Accordingly, little of the previous ''highstand'' deposits are exposed significantly above lake level, so little fluvial incision of them occurs. This situation is considered akin to the formation of type B sequence boundaries. That shown in D, E, and F is considered the model for the formation of type A sequence boundaries.

tems tract), are interpreted as the reworked products of the up-dip incision, deposited on the low-gradient basin floor under the lengthening fluvial profile (Olsen 1990) and subsequent initial relative rise in lake level. Similar deposits in Triassic lacustrine strata of Greenland have also been given a lowstand interpretation by Dam and Surlyk (1992) and Dam et al. (1995). Though accommodation is low, it is now fully utilized. During lowstand and earliest base-level rise, any depressions would be preferentially infilled, because they are most likely to remain below base level (remnant lake or watertable), to produce ramp-like, low-gradient basin floors.

Above the fluvial sheet sandbodies, there is a shift to more lenticular sandbodies of higher sinuosity. This change reflects an increasing rate of base-level rise, higher watertable, and increasing accommodation. Fluvial systems shorten their profile simply by adjusting sinuosity (Fig. 11A), for example, the high-sinuosity fluvial systems encountered in the uppermost part of U2.

Rapid transgression is favored when base-level rise occurs across a low-gradient basin floor. Shallow-water sedimentation, including carbonate grainstone deposition as part of M1 and M3, can occur across a large area of the basin floor (Fig. 11B). If the sill of the basin is at an elevation only slightly above the basin floor, accommodation is limited by the minor base-level rise, and, when threshold is reached, progradation can be widespread. In such situations, fluvial systems adjust by lengthening their profile to produce low-sinuosity channels, as in U1 (Figs. 7D, 11C).

The presence of a maximum flooding surface, as at M2 or M9, capping one of these progradational successions, represents sedimentation in a much larger lake. This might appear contradictory, given that the lake is interpreted to already be at threshold, but a solution is discussed in detail later.

Type B Sequences.—Lacustrine-dominated intervals that are not truncated by type A sequence boundaries still contain thin carbonate parasequences, overlying progradational clastic parasequences, and subsequent flooding surfaces. As previously noted, in type B sequences the location of the maximum flooding surface (and thus recognition of systems tracts in these sequences) is difficult to determine because there is no evidence of demonstrably profundal strata. Two surfaces are candidates (Fig. 10B), but for either, a subsequent drop in lake level, and sequence boundary formation, is unlikely to be marked by large incised valleys. Fluvial channels would adjust to the slight gradient changes by altering their fluvial profile or by minor entrenchment (Schumm 1993) into the underlying shallow-water sediments (Fig. 11G). This is demonstrated in outcrop where isolated, lenticular, single-channel fluvial sandstone truncates down through, and reworks, shallow-water carbonate (Fig. 7C). In this situation, the probable absence of high relief, highstand apron sediments available for erosion, and decreased fluvial inputs potentially driving lake-level fall result in a small proportion of coarse-grained fluvial deposits.

Flooding Surfaces Overlying Progradational Units.—Progradational stacking patterns below maximum flooding surfaces are unusual and differ from most described sequence geometries in marine and nonmarine basins (e.g., Posamentier et al. 1988; Bohacs and Suter 1997). The aggradational-to-progradational stacking pattern, which indicates that the rate of sediment supply is initially equal to and then gradually outpaces accommodation creation, is present in the lower to middle parts of all the studied lacustrine-dominated intervals. Because the study package is contained within the sediment-starved stage of basin fill (Lambiase 1990), this stacking pattern is considered to have been controlled by factors that limited the rate of base-level rise, rather than episodic increases in sediment supply (i.e., the lake was at threshold).

Thin fining-upward units that lie above the progradational unit (above FS* in Fig. 10) indicate that, in each $\sim$ 30 m cycle, the lake then underwent renewed gradual expansion and deepening. In some cases, deposition of littoral grainstone indicates that the expansion and deepening was limited (Fig. 10B). Such gradual but minor expansions of the lake can be explained, for example, by either a tectonic elevation of the sill (Fig. 3F) or tilting of the basin floor that increased the available volume that a lake could fill (Fig. 3Giii).

In other cases, profundal oil shale overlies the threshold-limited progradational units (Fig. 10A). The shale, containing the maximum flooding surface, indicates a lake level significantly higher than the previous threshold. If either sill elevation or basin-floor tilting were the cause, it would require a period of major tectonism always coinciding with progradational stacking—a coupling we cannot explain. Alternatively, a lake level higher than threshold and a maximum flooding surface lying above a progradational parasequence can be achieved if the threshold outflow across a sill (saddle) is into an adjacent basin which contains a lake that does not have a separate threshold at lower elevation. The adjacent lake, being able to fill to the elevation of the common sill, allows the two lakes to merge; the merged lake can continue to deepen, provided that the combined water budget remains positive, until the next lowest sill is encountered (Figs. 3D, 11B–D). Profundal oil shale would form if a positive water budget prevails and the merged lakes are able to deepen considerably. This mechanism also provides our preferred interpretation for the exclusively littoral sediments below a type B sequence boundary: the positive water budget did not prevail much beyond the time of lake merger.

Controls on Cyclicity

Climate.—Following Fouch et al. (1992) and Fouch et al. (1994), the regular, approximately 30-m-thick cycles in the study package may reflect significant rises and falls in lake level associated with wet–dry climate cycles driven by the 100,000 year orbital eccentricity component of Milankovitch cyclicity. The more common occurrence upsection of type A sequences might reflect increasingly prolonged pluvial periods, which permitted larger lakes to form, and supports the increasingly wet climate interpretation proposed for the region in the early–middle Eocene (e.g., Wilf et al. 1998).

Tectonism.—Changes in basin volume, by increased basin-floor subsidence or rise of the sill, may have been a continuing process throughout deposition of the middle Green River Formation, given that the Uinta Basin was still in its early stage of evolution (Fig. 2B, C, D). This background tectonism might also have influenced the observed 30 m cyclicity. If the progradational successions of successive lacustrine-dominated intervals reflect the lake at successive thresholds, then the relative rise of the threshold elevation in the time between two pluvial maxima limits the thickness and volume of sediment that can be deposited during the subsequent highstand (Fig. 3F).

The presence of oil shale has been interpreted by Fouch et al. (1994) to correspond to major reactivation of regional faults on the north flank of the basin. They also noted that rocks associated with these reconfigurations are locally unconformity bounded near the faulted basin margins and associated strata thicken toward the margins. An example in the study area is the reorientation of flooding surfaces above the type A angular sequence boundary associated with M8 (Fig. 8). Thicker sequences are preserved toward the northeast, which suggests basin tilting with greater downthrow toward the Uinta Mountains footwall to the north. Thickening toward the northeast is also noted above M9 and M10. However, cross sections of various orientations (e.g., Fig. 8) show that the sequence boundary above M2 does not form an angular unconformity, nor is there any distinct thickening of the section above the sequence boundary in any direction, unlike the other type A cases. These observations suggest that a phase of increased tectonic activity commenced about midway through deposition of the study package and that the presence of oil shale need not be linked to major tectonic events. Also, successions show gradual facies changes upward into the oil shale (e.g., Fig. 9A), whereas basin-floor tilting would produce instantaneous transgression and changes in lake depths with resulting abrupt facies shifts (Fig. 3G).

Interbasinal Relationships.—Our explanation of progradational stacking patterns below maximum flooding surfaces requires that there be threshold outflow across a sill (saddle) into an adjacent basin. The adjacent basin contains a lake that does not have a separate threshold at lower elevation, thus allowing the lakes to merge during periods of wet climate. We suggest that the middle Green River Formation stratigraphy provides evidence of early episodes of lake merger between the Uinta and Piceance Creek basins across the Douglas Creek Arch (Fig. 1A). Upsection from the study package, the Parachute Creek Member contains numerous beds of oil shale, including the Mahogany Oil Shale, which are correlatable across the two basins (Cashion and Donnell 1974) and mark major merger events. By the time of Mahogany deposition, the Piceance Creek Basin was already beyond the sediment-starved stage and was infilling (Fig 2D, E). An increasingly wet climate and/or a smaller volume to be filled in the Piceance Creek Basin would then explain why, in the Uinta Basin, larger lakes and type A sequences are more common upsection. The increasingly wet climate might also be related to the onset of increased tectonic activity at the northern boundary of the Uinta Basin: higher relief promoting greater precipitation and hence increased runoff and sediment supply. We propose that climate change is a major driving mechanism controlling basin architecture when a basin is classified as underfilled or with balanced fill, and that interbasin topography can influence sequence hierarchy.

ONGOING AND FUTURE WORK

The interpretations suggested in this paper obviously depend on the validity of the models used in extrapolating from the data collected in the 200 m package over a 25 km^2 area of canyons. The same stratal package additionally crops out over several tens of kilometers of Nine Mile Canyon and its tributary canyons farther east, south, and west of the current study area. Increasingly (e.g., Morgan et al. 2002), the package can be correlated northward in the subsurface using well data, and, together with ongoing examination of additional outcrops, our model will be tested further. Key issues to be addressed include the extent and nature of Type B sequence boundaries, the character of more completely preserved highstand systems tracts, and high-resolution tie-in with the sequence stratigraphy in the northeast of the basin (e.g., Borer and McPherson 1998; Borer in Bohacs and Borer 2001).

CONCLUSIONS

(1) Lacustrine basins are subject to a variety of tectonic and climatic controls and influences on sediment supply and thus exhibit a diversity of lithofacies associations both in vertical and lateral succession. In the middle Green River Formation of central Nine Mile Canyon, southwest Uinta Basin, Utah, this diversity is expressed as $\sim$ 20-m-thick fluvial-floodplain lithofacies that are cyclic with $\sim$ 10-m-thick lacustrine and marginal lacustrine strata.

(2) In the study package, all lacustrine-dominated intervals contain carbonate marker beds at their base and occasionally also near their tops. Basal carbonate beds represent aggradational lacustrine parasequences. They are overlain by a progradational lake-margin clastic parasequence formed when the Uinta lake was at threshold and comprising coarsening-upward, often wave-rippled and calcareous sandstone capped by floodplain, often rooted, mudstone crossed by low-sinuosity fluvial sandstone. Except where removed by erosion on overlying sequence boundaries, every lacustrine-dominated interval contains additional lacustrine strata capping the progradational parasequence. Strata may include thin profundal lacustrine oil shale representative of a maximum flooding surface. These lacustrine transgressive systems tracts therefore exhibit parasequence stacking patterns (aggradational to progradational) unlike typical marine sequences (typically retrogradational).

(3) Where preserved, lacustrine strata overlying the progradational parasequence are thin and display an upward shoaling. The strata represent renewed lake deepening following the merging of the Uinta lake with an adjacent lake and the drowning of the original sill between the two. The presence of an oil shale indicates that considerable deepening followed the merger, and overlying shoaling strata form a highstand systems tract. Lake mergers, and any stratal successions suggested to be associated with them, can occur only where the sill between the two marks their mutual threshold elevation.

(4) Lacustrine strata are truncated by the overlying floodplain-dominated interval. Where the truncation is mapped as an angular unconformity, or the facies transition between the two intervals is from the profundal oil shale to floodplain strata, a major drop in base level is implied and a type A sequence boundary is recognized. Such sequence boundaries are overlain by floodplain-dominated intervals that contain extensive, amalgamated fluvial channel sandstone beds that have sheet-like geometries. These amalgamated units of the lowstand systems tract formed during periods of low accommodation by the reworking of highstand lake-margin aprons and deltas following pronounced base-level fall. Overlying sandstone beds, in the upper part of these floodplain-dominated intervals, comprise high-sinuosity fluvial channel deposits with ribbon geometry and represent deposition associated with early base-level rise.

(5) The recurrence of type A sequence boundaries is more common upsection. Furthermore, upsection these boundaries are defined as angular, rather than parallel, unconformities. It is speculated that with time pluvials were more pronounced, permitting deeper merged lakes to form. The climate change may have been partly influenced by greater relief on the uplifting Uinta Mountains, whose uplift also caused tilting of the adjacent basin.

ACKNOWLEDGMENTS

Shell Expro, UK, funded the work and gave permission to publish. Mary Kraus, Kevin Bohacs, Alan Carroll, Keith Shanley, and John Warme provided constructive criticisms of various drafts. Daniel Andersson and Stephen Collins gave invaluable field assistance. Greg Stone (Shell Expro, Lowestoft), Bernard Besly, Brian Glover, Andy O'Beirne and Steve Taylor (Shell Expro, Aberdeen), Craig Morgan (Utah Geological Survey), Logan McMillan (Sego Resources), and leaders and fellow participants of AAPG 1998, NE Uinta Basin, and Bonneville Basin, field trips provided useful discussions and access to data. The spectral gamma ray equipment was borrowed from the Utah Geological Survey. Tim Ruble (CSIRO, Australia) performed the organic geochemistry. Andy and Helene Fry provided logistical assistance, and Nine Mile Canyon landowners gave permission to cross their land.

REFERENCES

Aitken, J.F., and Flint, S.S., 1995, Variable expressions of interfluvial sequence boundaries in the Breathitt Group (Pennsylvanian), eastern Kentucky, USA, *in* Howell, J.A., and Aitken, J.F., eds., High Resolution Sequence Stratigraphy: Innovations and Applications: Geological Society of London, Special Publication 104, p. 193–206.

Andersson, D., 1998, Alluvial–lacustrine facies of the Green River Formation, Trail Canyon, Uinta Basin, east-central Utah, USA: Unpublished Senior Thesis, Stockholm University, 26 p.

Bohacs, K.M., and Borer, J., 2001, Sedimentology, sequence stratigraphy, and basin evolution of the Green River Formation in the Uinta and Washakie Basins: insights for lacustrine hydrocarbon systems: American Association of Petroleum Geologists, Annual Convention, Field Trip 17, Day 1 Guidebook, 46 + 55 p.

Bohacs, K.M., and Suter, J., 1997, Sequence stratigraphic distribution of coaly rocks; fundamental controls and paralic examples: American Association of Petroleum Geologists, Bulletin, v. 81, p. 1612–1639.

Bohacs, K.M., Carroll, A.R., Neal, J.E., and Mankiewicz, P.J., 2000, Lake-basin type, source potential, and hydrocarbon character: an integrated sequence-stratigraphic–geochemical framework, *in* Gierlowski-Kordesch, E., and Kelts, K., eds., Lake Basins Through Space and Time: American Association of Petroleum Geologists, Studies in Geology 46, p. 3–37.

Borer, J., and McPherson, M., 1998, High-resolution stratigraphy of the Green River Formation, Raven Ridge, northeast Uinta Basin: American Association of Petroleum Geologists, Annual Convention, Field Trip 17, Guidebook, 117 p.

Bown, T.M., and Kraus, M.J., 1993, Time-stratigraphic reconstruction and integration of paleopedologic, sedimentologic, and biotic events (Willwood Formation, Lower Eocene, Northwest Wyoming, USA): Palaios, v. 8, p. 68–80.

Boyer, B.W., 1982, Green River laminites: does the playa-lake model really invalidate the stratified lake model?: Geology, v. 10, p. 321–324.

Bradley, W.H., 1964, Geology of the Green River Formation and associated rocks in southwestern Wyoming and adjacent parts of Colorado and Utah: U.S. Geological Survey, Professional Paper P-496-A, 86 p.

BUMP, A.P., 2003, Reactivation, trishear modeling, and folded basement in Laramide uplifts: Implications for the origins of intra-continental faults: GSA Today, v. 13, no. 3, p. 4–10.

CARROLL, A.R., AND BOHACS, K.M., 1999, Stratigraphic classification of ancient lakes: Balancing tectonic and climatic controls: Geology, v. 27, p. 99–102.

CASHION, W.B., 1995, Stratigraphy of the Green River Formation, eastern Uinta Basin, Utah and Colorado—A summary, *in* Averett, W.R., ed., The Green River Formation in Piceance Creek and eastern Uinta basins: Grand Junction Geological Society, Grand Junction Colorado, p. 15–21.

CASHION, W.B., AND DONNELL, J.R., 1974, Revision of the upper part of the Green River Formation, Piceance Creek Basin, Colorado, and eastern Uinta Basin, Utah: U.S. Geological Survey, Bulletin B-1396-G, 9 p.

CASTLE, J.W., 1990, Sedimentation in Eocene Lake Uinta (lower Green River Formation), northeastern Uinta Basin, Utah, *in* Katz, B.J., ed., Lacustrine Basin Exploration—Case Studies and Modern Analogues: American Association of Petroleum Geologists, Memoir 50, p. 243–263.

COLEMAN, J.M., 1969, Brahmaputra River: channel processes and sedimentation: Sedimentary Geology, v. 3, p. 129–239.

CREWS, S.G., AND ETHRIDGE, F.G., 1993, Laramide tectonics and humid alluvial fan sedimentation, NE Uinta uplift, Utah and Wyoming: Journal of Sedimentary Petrology, v. 63, p. 420–436.

CURREY, D.R., ATWOOD, G., AND MABEY, D.R., 1984, Major levels of Great Salt Lake and Lake Bonneville: Utah Geological Survey, Map 73, 1 sheet.

DAM, G., AND SURLYK, F., 1992, Forced regressions in a large wave and storm-dominated anoxic lake, Rhaetian-Sinemurian Kap Stewart Formation, East Greenland: Geology, v. 20, p. 749–752.

DAM, G., SURLYK, F., MATHIESEN, A., AND CHRISTIANSEN, F.G., 1995, Exploration significance of lacustrine forced regressions of the Rhaetian-Sinemurian Kap Stewart Formation, Jameson Land, east Greenland, *in* Steel, R.J., Felt, V.L., Johannssen, E.P., and Mathieu, C., eds., Sequence Stratigraphy on the Northwest European Margin: Norwegian Petroleum Society Conference, 1993, Proceedings, Stavanger, Norsk Petroleums-forening, Special Publication 5, p. 75–96.

DANE, C.H., 1954, Stratigraphic and facies relationships of the upper part of the Green River Formation and lower part of the Uinta Formation in Duchesne, Uintah, and Wasatch counties, Utah: American Association of Petroleum Geologists, Bulletin, v. 38, p. 405–425.

DICKINSON, W.R., KLUTE, M.A., HAYES, M.J., JANECKE, S.U., LUNDIN, E.R., MCKITTRICK, M.A., AND OLIVARES, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America, Bulletin, v. 100, p. 1023–1039.

DYNI, J.R., AND HAWKINS, J.E., 1981, Lacustrine turbidites in the Green River Formation, northwestern Colorado: Geology, v. 9, p. 235–238.

EINSELE, G., AND HINDERER, M., 1997, Terrestrial sediment yield and the lifetimes of reservoirs, lakes, and larger basins: Geologische Rundschau, v. 86, p. 288–310.

EINSELE, G., AND HINDERER, M., 1998, Quantifying denudation and sediment-accumulation systems (open and closed lakes): basic concepts and first results: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 140, p. 7–21.

EUGSTER, H.P., AND SURDAM, R.C., 1973, Depositional environment of the Green River Formation of Wyoming: a preliminary report: Geological Society of America Bulletin, v. 84, p. 1115–1120.

FERBER, C.T., AND WELLS, N.A., 1995, Paleolimnology and taphonomy of some fish deposits in ''Fossil'' and ''Uinta'' Lakes of the Eocene Green River Formation, Utah and Wyoming: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 117, p. 185–210.

FOUCH, T.D., NUCCIO, V.F., ANDERS, D.E., RICE, D.D., PITMAN, J.K., AND MAST, R.F., 1994, Green River (!) petroleum system, Uinta Basin, Utah, USA, *in* Magoon, L.B., and Dow, W.G., eds., The Petroleum System—From Source to Trap: American Association of Petroleum Geologists, Memoir 60, p. 399–421.

FOUCH, T.D., NUCCIO, V.F., OSMOND, J.C., MACMILLAN, L., CASHION, W.B., AND WANDREY, C.J., 1992, Oil and gas in uppermost Cretaceous and Tertiary rock, Uinta Basin, Utah, *in* Fouch, T.D., Nuccio, V.F., and Chidsey, T.C., eds., Hydrocarbon and Mineral Resources of the Uinta Basin, Utah and Colorado: Utah Geological Association, Guidebook 20, p. 9–47.

FRANCZYK, K.J., FOUCH, T.D., JOHNSON, R.C., MOLENAAR, C.M., AND COBBAN, W.A., 1992, Cretaceous and Tertiary paleogeographic reconstructions for the Uinta–Piceance basin study area: U.S. Geological Survey Bulletin B-1787-Q, p. 1–37.

FRANCZYK, K.J., HANLEY, J.H., PITMAN, J.K., AND NICHOLS, D.J., 1991, Paleocene depositional systems in the western Roan Cliffs, Utah, *in* Chidsey, T.C., Jr., ed., Geology of East-Central Utah: Utah Geological Association, Publication 19, p. 111–127.

HANSEN, W.R., 1990, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: alternative interpretation: Discussion: Geological Society of America, Bulletin, v. 102, p. 280–281.

JACOB, A.F., 1969, Delta facies of the Green River Formation (Eocene), Carbon and Duchesne counties, Utah [Ph.D. thesis]: Boulder, University of Colorado, 97 p.

JOHNSON R.C., 1981, Stratigraphic evidence for a deep Eocene Lake Uinta, Piceance Creek Basin, Colorado: Geology, v. 9, p. 55–62.

KEIGHLEY, D., 2000, A preliminary sequence stratigraphy of the Horton Group, southeast Moncton Basin, southeast New Brunswick: interpretation of the Dawson Settlement Member of the Carboniferous Albert Formation, Shell Albert Mines #4 well: New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Mineral Resource Report 2000-4, p. 17–29.

KEIGHLEY, D., AND PICKERILL, R., 1996, The evolution of fluvial systems in the Port Hood Formation (Upper Carboniferous), western Cape Breton Island, eastern Canada: Sedimentary Geology, v. 106, p. 97–144.

KEIGHLEY, D., COLLINS, S., FLINT, S., AND HOWELL, J., 1999, Reservoir-scale distribution of fluvial sandbodies in lacustrine closed basins, and some sequence-stratigraphic implications: Green River Formation, SW Uinta Basin, east-central Utah (abstract): American Association of Petroleum Geologists, Annual Convention, San Antonio, Texas, p. A71.

KEIGHLEY, D., FLINT, S., HOWELL, J., ANDERSSON, D., COLLINS, S., MOSCARIELLO, A., AND STONE, G., 2002, Surface and subsurface correlation of the Green River Formation in central Nine Mile Canyon, SW Uinta basin, Carbon and Duchesne Counties, east-central Utah: Utah Geological Society, Miscellaneous Publication, 02-1, CD-ROM.

KRAUS, M.J., AND BOWN, T.M., 1988, Pedofacies analysis: a new approach to reconstructing ancient fluvial sequences, *in* Reinhardt, J., and Sigleo, W.R., eds., Paleosols and Weathering Through Time: Principles and Applications: Geological Society of America, Special Paper 216, p. 143–152.

LA ROCQUE, A., 1956, Tertiary mollusks of central Utah, *in* Peterson, J.A., ed., Geology and Economic Deposits of East-Central Utah: Intermountain Association of Petroleum Geologists, 7th Annual Field Conference, p. 140–145.

LAMBIASE, J.J., 1990, A model for tectonic control of lacustrine stratigraphic sequences in continental rift basins, *in* Katz, B.J., ed., Lacustrine Basin Exploration—Case Studies and Modern Analogs: American Association of Petroleum Geologists, Memoir 50, p. 265–276.

LAWTON, T.F., 1986, Fluvial systems of the Upper Cretaceous Mesaverde Group and Paleocene North Horn Formation, central Utah: a record of transition from thin-skinned to thick-skinned deformation in the foreland region, *in* Peterson, J.A., ed., Paleotectonics and Sedimentation in the Rocky Mountain Region, United States: American Association of Petroleum Geologists, Memoir 41, p. 423–442.

LIRO, L.M., 1993, Sequence stratigraphy of a lacustrine system: Upper Fort Union Formation (Paleocene), Wind River Basin, Wyoming, U.S.A., *in* Weimer, P., and Posamentier, H.W., eds., Siliciclastic Sequence Stratigraphy: Recent Developments and Applications: American Association of Petroleum Geologists, Memoir 58, p. 317–333.

LUNDELL, L.S., AND SURDAM, R.C., 1975, Playa-lake deposition: Green River Formation, Piceance Creek Basin, Colorado: Geology, v. 3, p. 493–497.

MCCARTHY, P.J., AND PLINT, A.G., 1998, Recognition of interfluve sequence boundaries: integrating paleopedology and sequence stratigraphy: Geology, v. 26, p. 387–390.

MIALL, A.D., 1988, Architectural elements and bounding surfaces in fluvial deposits: anatomy of the Kayenta Formation (Lower Jurassic), southwest Colorado: Sedimentary Geology, v. 55, p. 233–261.

MILLIGAN, M.R., AND CHAN, M.A., 1998, Coarse-grained Gilbert Deltas: facies, sequence stratigraphy and relationships to Pleistocene climate at the eastern margin of Lake Bonneville, northern Utah, *in* Shanley, K.W., and McCabe, P.J., eds., Relative Role of Eustacy, Climate, and Tectonism in Continental Rocks: SEPM, Special Publication 59, p. 177–189.

MILLIGAN, M.R., AND LEMONS, D.R., 1998, A sequence-stratigraphic overview of sandy and gravelly lacustrine deltas deposited along the eastern margin of Late Pleistocene Lake Bonneville, Northern Utah and Southern Idaho, *in* Pitman, J.K., and Carroll, A.R., eds., Modern and Ancient Lake Systems: New Problems and Perspectives: Utah Geological Association, Guidebook 26, p. 105–129.

MORGAN, C.D., CHIDSEY, T.C., JR., MCCLURE, K.P., BERESKIN, S.R., AND MILIND, D.D., 2002, Reservoir characterization of the lower Green River Formation, southwest Uinta Basin, Utah: Utah Geological Survey–U.S. Department of Energy, DOE/BC/15103–4 OSTI, no. 805237, 140 p.

MORRIS, T.H., AND RICHMOND, D.R., 1992, A predictive model of reservoir continuity in fluvial sandstone bodies of a lacustrine deltaic system, Colton Formation, Utah, *in* Fouch, T.D., ed., Hydrocarbon and Mineral Resources of the Uinta Basin, Utah and Colorado: Utah Geological Association, Publication 20, p. 227–236.

OLSEN, P.E., 1990, Tectonic, climatic, and biotic modulation of lacustrine ecosystems—Examples from Newark Supergroup of eastern North America, *in* Katz, B.J., ed., Lacustrine Basin Exploration—Case Studies and Modern Analogs: American Association of Petroleum Geologists, Memoir 50, p. 209–224.

OLSEN, T., 1995, Sequence stratigraphy, alluvial architecture and potential reservoir heterogeneities of fluvial deposits: evidence from outcrop studies in Price Canyon, Utah (Upper Cretaceous and Lower Tertiary), *in* Steel, R.J., Felt, V.L., Johannssen, E.P., and Mathieu, C., eds., Sequence Stratigraphy on the Northwest European Margin: Norwegian Petroleum Society Conference, 1993, Proceedings, Stavanger, Norsk Petroleums-forening, Special Publication 5, p. 75–96.

OVIATT, C.G., MCCOY, W.D., AND NASH, W.P., 1994, Sequence stratigraphy of lacustrine deposits: a Quaternary example from the Bonneville basin, Utah: Geological Society of America, Bulletin, v. 106, p. 133–144.

PICARD, M.D., AND HIGH, L.R., 1968, Sedimentary cycles in the Green River Formation (Eocene), Uinta Basin, Utah: Journal of Sedimentary Petrology, v. 38, p. 378–383.

PICARD, M.D., AND HIGH, L.R., JR., 1972, Paleoenvironmental reconstructions in an area of rapid facies change, Parachute Creek Member of the Green River Formation (Eocene), Uinta Basin, Utah: Geological Society of America, Bulletin, v. 83, p. 2689–2708.

PITMAN, J.K., 1982, Regional stratigraphic and depositional analysis of rock units in the upper Garden Gulch and Parachute Creek Members of the Green River Formation, Piceance Creek basin, Colorado: 15th Oil Shale Symposium, Proceedings, Colorado School of Mines, Golden, p. 79–100.

PITMAN J.K., FOUCH T.D., AND GOLDHABER M.B., 1982, Depositional setting and diagenetic evolution of some Tertiary unconventional reservoir rocks, Uinta Basin, Utah: American Association of Petroleum Geologists, Bulletin, v. 66, p. 1581–1596.

POSAMENTIER, H.W., JERVEY, M.T., AND VAIL, P.R., 1988, Eustatic controls on clastic deposition I—sequence and systems tract models, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea Level Changes: an Integrated Approach: SEPM, Special Publication 42, p. 109–124.

REMY, R., 1992, Stratigraphy of the Eocene part of the Green River Formation in the south-central part of the Uinta basin, Utah: U.S. Geological Survey, Bulletin B-1787-BB, p. 1–69.

Retallack, G.J., 1988, Field recognition of paleosols, *in* Reinhardt, J., and Sigleo, W.R., eds., Paleosols and Weathering Through Geologic Time: Principles and Applications: Geological Society of America, Special Paper 216, p. 1–20.
Roehler, H.W., 1987, Geological investigations of the Vermillion Creek Coal Bed in the Eocene Niland Tongue of the Wasatch Formation, Sweetwater County, Wyoming: paleoenvironments, and sedimentation: U.S. Geological Survey, Professional Paper P-1314-C, p. 27–45.
Roehler, H.W., 1993, Eocene climates, depositional environments, and geography, Greater Green River Basin, Wyoming, Utah, and Colorado: U.S. Geological Survey, Professional Paper P-1506-F, p. 1–74.
Ruble, T.E., and Philp, R.P., 1998, Stratigraphy, depositional environments, and organic geochemistry of source rocks in the Green River Petroleum System, Uinta Basin, Utah, *in* Pitman, J.K., and Carroll, A.R., eds., Modern and Ancient Lake Systems: New Problems and Perspectives: Utah Geological Association, Guidebook 26, p. 289–328.
Ryder, R.T., Fouch, T.D., and Elison, J.H., 1976, Early Tertiary sedimentation in the Western Uinta basin, Utah: Geological Society of America, Bulletin, v. 87, p. 496–512.
Schlische, R.W., and Olsen, P.E., 1990, Quantitative filling model for continental extensional basins with applications to early Mesozoic rifts of Eastern North America: Journal of Geology, v. 98, p. 135–155.
Scholz, C.A., Moore, T.C., Hutchinson, D.R., Golmshtok, A.J., Klitgord, K.D., and Kurotchkin, A.G., 1998, Comparative sequence stratigraphy of low-latitude versus high-latitude lacustrine rift basins: seismic data examples from the East African and Baikal rifts: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 140, p. 401–420.
Schumm, S.A., 1993, River response to baselevel change: implications for sequence stratigraphy: Journal of Geology, v. 101, p. 279–294.
Stanley, K.O., and Collinson, J.W., 1979, Depositional history of Paleocene–Lower Eocene Flagstaff Limestone and coeval rocks, central Utah: American Association of Petroleum Geologists, Bulletin, v. 63, p. 311–323.
Strecker, J.R., Steidtmann, J.R., and Smithson, S.B., 1999, A conceptual tectonostratigraphic model for seismic facies migrations in a fluvio-lacustrine extensional basin: American Association of Petroleum Geologists, Bulletin, v. 83, p. 43–61.
Surdam, R.C., and Stanley, K.O., 1980, Effects of changes in drainage-basin boundaries on sedimentation in Eocene Lakes Gosiute and Uinta of Wyoming, Utah, and Colorado: Geology, v. 8, p. 135–139.
Swain, F.M., 1956, Early Tertiary ostracode zones of Uinta Basin, *in* Peterson, J.A., ed., Geology and Economic Deposits of East-Central Utah: Intermountain Association of Petroleum Geologists, 7th Annual Field Conference, p. 125–139.
Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high resolution correlation of time and facies: American Association of Petroleum Geologists, Methods in Exploration Series 7, 55 p.
Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., and Hardenbol, J., 1988, An overview of the fundamentals of sequence stratigraphy and key definitions, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea Level Changes: an Integrated Approach: SEPM, Special Publication 42, p. 39–45.
Weiss, M.P., 1969, Oncolites, paleoecology and Laramide tectonics, central Utah: American Association of Petroleum Geologists, Bulletin, v. 53, p. 1105–1120.
Wilf, P., Wing, S.L., Greenwood, D.R., and Greenwood, C.L., 1998, Using fossil leaves as paleoprecipitation indicators: an Eocene example: Geology, v. 26, p. 203–206.
Williamson, C.R., and Picard, M.D., 1974, Petrology of carbonate rocks of the Green River Formation: Journal of Sedimentary Petrology, v. 44, p. 738–759.
Witkind, I.J., 1995, Geologic map of the Price 1 x 2 quadrangle, Utah: U.S. Geological Survey, Miscellaneous Information Series, I-2462, 1 sheet.
Wright, V.P., and Marriott, S.B., 1996, A quantitative approach to soil occurrence in alluvial deposits and its application to the Old Red Sandstone of Britain: Geological Society of London, Journal, v. 153, p. 907–913.
Young, R.G., 1995, Stratigraphy of Green River Formation in Piceance Creek Basin, Colorado, *in* Averett, W.R., ed., The Green River Formation in Piceance Creek and Eastern Uinta Basins: Grand Junction Geological Society, Grand Junction Colorado, p. 1–13.

Received 18 April 2002; accepted 1 May 2003.