Lacustrine to fluvial floodplain deposition in the Eocene Bridger Formation

H.P. Buchheim a,*, L.R. Brand a, H.T. Goodwin b

a Department of Natural Sciences, Loma Linda University, Loma Linda, CA 92350, USA
b Department of Biology, Andrews University, Berrien Springs, MI 49104, USA

Received 19 August 1999; accepted for publication 5 April 2000

Abstract

The depositional systems and sedimentology of lithofacies sequences in the Bridger Formation (unit B) are described. A lithofacies association is determined and includes from base to top: limestone, claystone, thin bedded sandstone and siltstone, and a cross-bedded sandstone facies. The limestone facies is generally composed of a dense resistant limestone that may contain fossil plant impressions, tufa and/or stromatolites, gastropods, bivalves, and other fossils. The claystone facies contains abundant fossil turtles, fish, crocodiles, gastropods and plants. Desiccation cracks, plant roots and soil features are lacking. Extremely abundant turtles may occur in this facies, sometimes associated with abundant coalified plant fragments. The thin bedded sandstone and siltstone facies is composed of silty clay to medium sand. At a few localities it grades laterally into medium- to coarse-grained sandstone channels up to 3 m thick. Fossil turtles are present, but are much less abundant than in the claystone facies. The cross-bedded sandstone facies is composed of thick, laterally extensive channel sands associated laterally with silty claystone beds. The facies association is interpreted as a shallowing upward sequence. It started with a basal limestone facies, deposited in a widespread, shallow, carbonate-precipitating lake. The lake was rapidly filled by episodic volcaniclastic deposition, delivered via air-fall and/or prograding fluvial–deltaic systems. Deltaic deposition may have been similar to the infilling of the northern portion of Lake Turkana in Africa by the Omo River Delta. The claystone facies is interpreted as a short-lived fluvial–lacustrine system that prograded out over the limestone facies and/or was deposited as air-fall ash into the entire lake. The sharp upper contact of the limestone facies with the claystone facies suggests that an abrupt paleoenvironmental change may have taken place with a large influx of volcaniclastics. An organic-rich unit, the organic turtle bed within the Black Mountain turtle layer (a claystone facies), contains abundant plant material and turtles and is interpreted as representing an episodic depositional event, probably storm related. As volcaniclastic deposition continued to dominate the system, the thin bedded sandstone and siltstone facies sequence was deposited. It is interpreted as distributary and crevasse splay sheet sands uniformly deposited (laterally correlative) over large areas. This depositional system was ultimately replaced by a well-established, fluvial floodplain environment with large fluvial channels representing major meandering rivers. Development of the succeeding lake system occurred when siliciclastic deposition significantly slowed relative to the rate of basin subsidence. Deposition in the Bridger Formation, unit B, suggests a delicate balance between a closely interacting lacustrine and fluvial system. Although fluvial processes and elastic sedimentation dominated depositional patterns, lacustrine depositional regimes frequently returned. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Bridger Formation; Eocene; fluvial–lacustrine; lithofacies; paleoenvironment

* Corresponding author. Tel.: +1-909-558-4530; fax: +1-909-558-0259.
E-mail address: pbuchheim@ns.llu.edu (H.P. Buchheim)

0031-0182/00 - see front matter © 2000 Elsevier Science B.V. All rights reserved.
PII: S0031-0182(00)00112-7
1. Introduction

The Eocene Bridger Formation of southwestern Wyoming occupies the intermontane Green River Basin. It is generally interpreted as flood plain sediments around the margins of the basin as the last of the Green River Formation was deposited. The Bridger Formation then widened and finally filled the basin as Lake Gosierie shrank (Bradley, 1964). The Bridger Formation is well known for an abundance of fossil turtles and mammals. Extensive investigation has been directed toward understanding the Bridgerian mammal sequences (Matthew, 1910; West, 1970; Gazin, 1976; Gunnel1996). Less work has been done on fossil turtles, especially as they relate to the depositional environments and systems, because they offer little biostratigraphic information. This study focused on depositional systems and sedimentology of selected units in the Bridger Formation to understand better the taphonomy and deposition of sedimentary beds containing abundant turtle fossils. This investigation broadened our understanding of depositional sequences, lithofacies associations, and paleogeography of the Bridger Formation, unit B, and the dynamic interactions within the fluvial-lacustrine system of the Bridger Formation. This has provided a sedimentological framework and foundation for better understanding the distribution of fossil turtles and the Bridger Formation limestones.

2. Previous work

Early work by Sinclair (1906) and Johannsen (1914) described the volcanic sediments of the Bridger Formation, and their petrology. Koenig (1960) described both fluvial and lacustrine sediment types in the Bridger, and the monographic work of Bradley (1964) laid the foundation for future study of this formation. His detailed stratigraphic sections describe the varied lithologies, that are dominated by volcanics including mudstone, claystone, and sandstone.

Previous workers have agreed that most sediment in the Bridger Formation is of volcanic origin (Sinclair, 1910; Koenig, 1960; Bradley, 1964; Gustav, 1974; West, 1976). Bradley (1964) describes devitrified glassy volcanic rock, and he says that "the large areal extent and the continuity of crossbedded lenses of these andesite tuves suggest that the ash falls choked the drainage channels and caused the overloaded streams to wander widely in the newly fallen ash until their former gradients were reestablished". Gustav (1974) describes the abundant presence of biotite and glass shards indicative of the volcaniclastic origin of the Bridger Formation, although these are not so common in the more altered fine sediments. The bulk of these largely tuveous sediments are floodplain deposits, with associated channel sandstones, thin continuous beds of lignitic or coaly deposits in some areas, and deltaic and lacustrine sandstone and siltstone (Koenig, 1960; Bradley, 1964; Gustav, 1974).

Most of the volcanic material in the Bridger apparently came from the Absaroka volcanic field 280 km to the north (Bradley, 1964), but Evans and Rosetti (1992) presented evidence that the tuveous sediment in composition from the rest of the Bridger volcanics, and may have come from the Challis volcanic field of Idaho. Although the Absaroka volcanic field is quite far from the southern part of the Green River Basin, it is the only documented source to date for most of the tuveous sediments. Isolated Bridger outcrops near the Wind River Mountains, nearer to the Absarokas, have typical Bridger depositional characteristics and fossils, but are whitish, clearly tuveous sediments, supporting the hypothesis that the Bridger sediments came from that source.

Roehler (1992) described the mineralogy and petrology of the Washakie Formation in the Washakie Basin, that he correlated with the Bridger Formation in the Green River Basin. X-ray diffraction (XRD) analysis of Washakie sediments revealed illite, montmorillonite, magnesium smectite, potassium feldspar, analcime, clinoptilolite, and mordenite. These mineral grains are only slightly rounded. Roehler (1992) suggested these indicate a short transport distance before deposition. However, he concluded that the source area is outside of the greater Green River Basin, as suggested by previous workers (see above).

Roehler (1992) described the carbonates primarily as limestones, but did not provide XRD

Koenig (1960) claimed that limestones are not common in Bridger B. However, several others have concluded that after Lake Gosiute regressed, exposing the fluvial plain, the lake again expanded at intervals to form a shallow lake occupying very wide areas in the basin and depositing limestones (Sinclair, 1906; Gustav, 1974; West, 1976; Sullivan, 1980; Gunnell and Bartels, 1990). Gustav (1974) indicated that this transgression with limestone deposition, and regression, was a cyclic process, occurring several times during Bridger B time. Some have concluded that, within these limestones, only the Sage Creek white layer (or Sage Creek limestone; Evano et al., 1998) can be mapped across the entire basin, whereas others are only local in extent (West, 1976; Roehler, 1992). More recent work documented seven limestones and several other beds in Bridger B that can be mapped across the entire basin (Brand, 1997; Evano et al., 1998). Some other limestones are more local in extent (Brand and Evano, unpublished data).

Outside of conclusions concerning depositional environments for the deposition of the Bridger Formation, no attempt has been made to understand the cyclic nature of the facies or to erect a facies association scheme. This method has been described in detail by Miall (1990) and is a profitable approach to understanding better and modelling a depositional system. This research is the first effort to approach a study of the Bridger Formation using the facies analysis method.

3. Methods

In association with research on the fossil turtles (Brand et al., 2000), vertical sections through upper middle Bridger B sediments (Fig. 1) were measured at 23 localities (Fig. 2), using a Jacob’s staff and Abney level (Brand, 1995). Sediments were analyzed in the field, and hand samples from some sections were cut, polished, and examined. All samples were examined for sedimentary structures, including root structures, mud cracks, and bioturbation. The sections were correlated, and then detailed high-resolution stratigraphic correlations were made in the turtle-rich sediments above two limestones (Lower turtle layer and Black Mountain turtle layer). Lateral variations in the facies within these two intervals were studied by walking each of them for 3–4 km and documenting changes in thickness and lithology. The limestones and other marker beds were mapped over the entire basin to document their lateral extent (Evano et al., 1998). XRD mineralogic analysis was conducted by The Mineral Lab in Lakewood, CO.

4. Stratigraphy

Bridger B contains a series of widespread limestones. The sedimentary units above several of the
Fig. 2. Geologic map of two Bridger Formation limestones, the Black Mountain turtle layer and Golden bench limestone. Inset shows detail in the Devil's Playground area at the foot of Black Mountain, including the Lower turtle layer. Note the extensive distribution of the limestones, with their associated claystone units. Mapping of the limestones on the west side of the basin was done partly by Emmett Evans.
limestones (Fig. 3) form a cyclic sequence that we are describing here as a lithofacies association. This association was most intensively studied at the Black Mountain turtle layer interval. The series of lithofacies in this interval can be correlated over the entire basin (Fig. 4). There are variations in the thickness and in the lithology of each facies across this distance. Detailed field mapping of the limestone and associated lithofacies of the Lower turtle layer limestone and Black Mountain turtle layer in the Devil’s Playground area demonstrates the lateral facies variation that occurs and the lateral continuity of the limestone facies and overlying claystone facies (Fig. 5).

5. Lithofacies

Table 1 describes the characteristics of the most common lithofacies. The lithofacies are repetitive
in nature and are described as a lithofacies association. The lithofacies association includes (from bottom to top: Fig. 6) limestone, claystone, thin bedded sandstone–siltstone, and cross-bedded sandstone facies. Not all the features discussed below occur in every lithofacies sequence. For example, the limestone facies does not always contain stromatolites or tufa, and, at some intervals, turtles are not abundant in the claystone facies. Fig. 3 illustrates the lithofacies association.

5.1. Limestone facies

The limestone facies (Figs. 6 and 7A) is generally composed of a dense resistant limestone, (e.g. limestone underlying the Black Mountain turtle layer) exhibiting varying degrees of diagenesis. In some areas it is silicified. However, most frequently it is a thin to thick bedded calcimicrite, and contains stromatolites and tufa (Fig. 7G) at some locations. Tufa and/or stromatolites usually are 2–20 cm thick, in some cases coating turtle carapaces and other fossils, but occasionally they form mounds up to 1 m high. The limestone facies is represented by a laminated calcimicrite (oil shale) in at least one of the ‘limestone facies’ units (just above Bridger B at Black Mountain), similar to those of the Green River Formation. Fossil plant impressions occasionally occur in the limestone facies.

The limestone lithofacies varies in thickness throughout the basin, and also varies in character, suggesting differences between the successive lakes. Some of the prominent, bench-forming limestones form the upper unit in a sequence of two or three limestones (especially in the eastern part of the basin), separated by a few meters of mudstone. The limestone underlying the Black Mountain turtle layer is best developed in the Black Mountain area where it is about 1 m thick, and at some locations contains tufa and stromatolites. It thins to the north and south. Northward, this unit becomes more siliciclastic-rich, grading into a calcareous claystone.

The limestone facies forms widespread marker beds. Fig. 4 demonstrates the widespread consistent character of the limestone facies. The Golden bench limestone is an excellent example of the facies, which was mapped throughout the basin as a continuous unit (Fig. 2), generally 1 m or more thick. It contains plant fragments including Sequoia, palm, and fern (Brand et al., 2000). At some localities these plants, and other fossils that appear to be strands of algae, are coated with a thin layer (<1 mm) of tufa (Fig. 7H).

At the base of Bridger B, the Lyman limestone contains abundant ostracods in the northern part of the basin, and becomes a Goniobasis (a gastropod) and bivalve coquina in the eastern portion (Fig. 7I), continuing southward to Utah (north of the Uinta Mountains). Roehler (1992) reported varying densities of ostracods, ‘algal heads’ (tufa and stromatolites), gastropods, pelecypods, and root fillings in similar limestones of the Washakie Formation.

5.2. Claystone facies

The claystone facies is exemplified by the Black Mountain turtle layer (Fig. 6, Figs. 6 and 7A–E), which is basin-wide in extent (Fig. 2) and contains the most abundant fossil turtles (Brand et al., 2000). It consists of varying amounts of silt and clay. Turtles, gar, crocodilians, and gastropods are common fossils. This unit exhibits soft-sediment deformation structures (Fig. 7C) in the form of displaced and deformed intraclasts of clay, soft-sediment flaw structures, and associated displaced turtle bone fragments. Mudcracks, plant roots, and evidence of a soil profile or desiccation sur-
Fig. 6. Photograph showing the lithofacies association at locality NR-28. LS: limestone facies; CS: claystone facies; TBS/S: thin bedded sandstone–siltstone facies; CBS: cross-bedded sandstone facies; BMtl: Black Mountain turtle layer; MSwl: Meadow Springs white layer.

faces are absent. Bioturbation is rare, but there is scattered bioturbation at some localities (Fig. 7D). A thin (5–10 cm), dark gray to brick red, unit composed of clay with abundant coalified plant fragments, abundant turtles, and other organic fragments occurs within the Black Mountain turtle layer. No root bioturbation is seen associated with this 'organic turtle bed'. Several 1–2 cm thick beds of organic-rich, laminated shale occur within the claystone facies in the area of Black Mountain and can be traced laterally over a large area (Fig. 7E). The sharp boundaries of the laminated shale units, like the organic turtle bed, have not been disrupted by bioturbation. This supports the interpretation that bioturbation is rare in the claystone facies. The claystone facies contains scattered sandstone channels, but the number of channels is surprisingly small. Other sandstone channels that are part of the thin bedded sandstone and siltstone facies have in some cases cut into the claystone facies a few tens of centimeters.

Fig. 5. Correlation of the Lower turtle layer limestone, claystone, and associated sandstone facies over a 1.5 km² area, and accompanying depositional model. Note that the tufa unit 'climbs' through the section. At section B, the tufa sits directly on the limestone and gradually rises to over 1 m above the limestone at section E. The sequence of events is as follows. Time 1: shallow, alkaline lake and deposition of calcium carbonate. Time 2: 'shoestring' sand extends out into the lake as period of rapid deposition of volcaniclastics begins. Time 3: siliciclastic deposition subsides and clear lake waters favor continued deposition of limestone and associated tufa and stromatolites that 'colonize' fluvial–deltaic channel and overbank facies. Time 4: another period of volcaniclastic deposition that overwhelms carbonate deposition and largely replaces lacustrine deposition with fluvial deposition. Time 5: large-scale meandering channels of the fluvial floodplain dominate deposition in the basin, concluding the depositional cycle. Note that the panels are a depositional model, not cross-sections.
Table 1
Descriptions of lithofacies in the lithofacies association. These descriptions are typical, but not all of these features occur in every lithofacies unit.

<table>
<thead>
<tr>
<th>Limestone</th>
<th>Claystone</th>
<th>Thin bedded sandstone-siltstone</th>
<th>Cross-bedded sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Color</strong></td>
<td>White</td>
<td>Greenish gray</td>
<td>Greenish gray</td>
</tr>
<tr>
<td><strong>Organic carbon</strong></td>
<td>Low to none</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>0.15-1.00 m, thickness may vary</td>
<td>Silty claystone &gt; 3 m sandstone</td>
<td>Silty claystone &gt; 3 m sandstone</td>
</tr>
<tr>
<td><strong>Sedimentary structures</strong></td>
<td>No preserved structures</td>
<td>Abundant soft sediment deformation; contains several 1-2 cm thick shale horizons, scattered bioturbation at some locations</td>
<td>Abundant soft sediment deformation; contains several 1-2 cm thick shale horizons, scattered bioturbation at some locations</td>
</tr>
<tr>
<td><strong>Grain size</strong></td>
<td>Micritic</td>
<td>Clay and silt size</td>
<td>Clay and silt size</td>
</tr>
<tr>
<td><strong>Mineralogy</strong></td>
<td>Calcimicrite with varying amounts of siliciclastics</td>
<td>Clay minerals (altered from volcaniclastic)</td>
<td>Volcaniclastic</td>
</tr>
<tr>
<td><strong>Paleontology</strong></td>
<td>May contain ostracods, molluscs, Stromatolites or tufa, and plant impressions</td>
<td>Abundant fossil turtles; some gastropods, fish, crocodile, mammal, and plant remains</td>
<td>Abundant fossil turtles</td>
</tr>
<tr>
<td><strong>Other notes</strong></td>
<td>The limestone that forms the bench below the Black Mountain turtle layer forms a dense resistant unit at Black Mountain; increasing content of siliciclastics toward the west and north where it grades into a calcareous siltstone.</td>
<td>None observed in silty claystones; occasional cross-bedding observed in sandstones</td>
<td>None observed in silty claystones; occasional cross-bedding observed in sandstones</td>
</tr>
</tbody>
</table>
Fig. 7. Examples of lithofacies or associated lithotypes that occur in the lithofacies association. (A) Limestone facies (resistant ledge with the overlying claystone facies). (B) Polished slab of the claystone facies with fossil turtle shell fragments at the base; note that very little structure is present. (C) Claystone facies showing soft-sediment deformation features including very angular clasts with sharp ends and irregular margins. (D) Bioturbation features in claystone facies. (E) Thin organic-rich shale unit within the claystone that was highly disrupted by hydroplastic flow. (F) An example of the cross-bedded sandstone facies, with clay pebbles. (G) Tufa-stromatolite from the claystone facies. (H) Tufa-coated algae from the Golden bench limestone. (I) Goniothalamus in the Lyman limestone.

The claystone facies in the Bridger Formation (Black Mountain turtle layer) is dominated by clays (~50%), with lesser amounts of quartz (~20%), feldspars (~25%), and less than 5% clinoptilolite in two of six samples analyzed (Table 2). The mineralogical composition of clays
Fig. 8. Depositional model illustrating the sequence of events that resulted in deposition of the limestone, claystone, thin bedded sandstone, and sandstone lithofacies association. Time 1: nearly basin-wide, shallow alkaline lake where limestone deposition predominated. Time 2: active phase of volcaniclastic deposition dominated with associated mass mortality of turtle faunas. Extensive ‘shoestring’ sands prograded rapidly into the shallow lake basin. Overbank deposition and ash-fall deposition resulted in the deposition of lacustrine claystone facies. Time 3: fluvial floodplain deposition dominated the depositional regime and thick sequences of coarse-grained fluvial sequences were deposited. Time 4: reinitiating of shallow lacustrine limestone deposition began as volcanic activity ceased and basin subsidence continued. See text for more details. Drawings not to scale, but represent several kilometers laterally.

in the time-equivalent Washakie Formation (Roehler, 1992) [mapped as Bridger Formation by Bradley (1964)] is similar, with illite, montmorillonite, and magnesium smectite and varying amounts of potassium feldspar, analcime, clinoptilolite, and mordenite.
5.3. Thin bedded sandstone and siltstone facies

The thin bedded sandstone and siltstone facies (Fig. 6) is composed of silt or silty claystone and fine to medium sand. It occurs over extensive areas. Two to three laterally extensive fine- to medium-grained gray sandstone units (generally less than 1 m thick) were observed in many sections measured. They can be correlated over large distances exceeding 20 km. In the north they grade laterally into medium- to course-grained sandstone channels up to 3 m thick. No small-scale sedimentary structures were observed in the bedded sandstones, but cross-beds and grading occur in the channels. In the Black Mountain area a channel system associated with this facies was traced and
Table 2

Percentage XRD peak height (approx. mineral percentage) in a sample of the limestone underlying the Black Mountain turtle layer, and in six samples of the claystone facies of the Black Mountain turtle layer, from four localities. At locality DP-11, claystone samples were taken from below, within, and above the organic turtle layer (otl). Locality BKD-8 was at the western edge of the study area.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Claystone</th>
<th>Limestone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DP-4</td>
<td>DP-11 below otl</td>
</tr>
<tr>
<td>Quartz</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Plagioclase feldspar</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>K-feldspar</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Muscovite</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>Smectite</td>
<td>36</td>
<td>30</td>
</tr>
<tr>
<td>Chamosite</td>
<td>&lt;3</td>
<td></td>
</tr>
<tr>
<td>Chlinoamphibole</td>
<td>&lt;3</td>
<td></td>
</tr>
<tr>
<td>Hematite</td>
<td>&lt;3</td>
<td></td>
</tr>
<tr>
<td>Magnetite</td>
<td>&lt;5</td>
<td></td>
</tr>
<tr>
<td>Calcite</td>
<td>&lt;5</td>
<td></td>
</tr>
<tr>
<td>Unidentified</td>
<td>&lt;5</td>
<td></td>
</tr>
</tbody>
</table>

The primary focus of this study was the Black Mountain turtle layer and associated facies. The study of these limestones has been interpreted as local in extent (Roehler, 1992), but it is now evident that a number of them are basin-wide (Fig. 2) (Evano et al., 1998). The cross-bedded sandstone facies (Figs. 6 and 7F) is composed of thick sandstone channels associated laterally with typical Bridger silt claystone beds. The channels are generally 4-6 m thick, but may exceed 10 m in thickness, and are laterally extensive. They are generally coarse grained, often with clay rip-up clasts, and contain large channel cross-beds. This unit was not studied in detail because it contained few turtle remains.

6. Deposition of lithofacies association

The distinctive fluvial character of the Bridger Formation has been well established (Sinclair, 1906; Bradley, 1964; Gustav, 1974; West, 1976). The limestones represent a lacustrine facies (Sinclair, 1906; Gustav, 1974; West, 1976; Sullivan, 1980; Gunnell and Bartels, 1990) that has also played a significant role in the paleoenvironmental history of the basin (Brand et al., 1993). The limestones are interpreted as basin-wide occurrence of many of these limestones. These lakes have been interpreted as shallow (Sinclair, 1906; Gustav, 1974; West, 1976; Sullivan, 1980; Gunnell and Bartels, 1990; Murphey, 1995). This interpretation is supported by the observation that the limestones do not grade laterally into deeper water facies such as laminated calcimicrite. This suggests that the topographic gradient on the lake bottom was extremely low and that the lake was basically flat-bottomed. Associated stromatolites, tufa, ostracods, bivalves, and gastropods (not all necessarily occurring in every limestone unit) support a shallow, fresh water lake interpretation.

Fresh water conditions are also suggested by several other lines of evidence. The abundant

...
occurrence of the gastropod *Goniobasis* is well known to be associated with fresh water (Surdam and Stanley, 1979). The calcitic composition of the limestones also indicates fresh water conditions, as in the associated Green River Formation, compared with hypersaline–alkaline conditions where dolomite is the dominant carbonate phase (Eugster and Hardie, 1975; Surdam and Stanley, 1979; Buchheim and Surdam, 1981; Buchheim and Eugster, 1998). The presence of fossil fish remains in the claystones implies fresh water, as has been demonstrated in the Green River Formation lacustrine facies (Buchheim and Surdam, 1981; Buchheim, 1994). The ash in the claystone has been altered primarily to clays (smectite, montmorillonite, illite), and this also indicates a fresh water environment. If conditions had been hypersaline and alkaline the ash would have been altered to various zeolites and even authigenic feldspar (Surdam and Sheppard, 1978; Surdam and Stanley, 1979; Buchheim, 1994). The presence of small amounts of zeolites, such as clinoptilolite (less than 5%), suggests that conditions may have at times become slightly brackish during deposition of the claystone.

The lake was best developed in the southern part of the Bridger Basin during Black Mountain turtle layer time, especially in the Black Mountain area. This trend is consistent with that reported by Surdam and Stanley (1979) for the Laney Member of the Green River Formation, where they interpreted the basin as subsiding more rapidly in the south, near the Uinta Mountains. Continuing subsidence along the Uinta Mountains and progradation of fluvial facies from the north resulted in deposition of lake facies over a longer period of time in the southern part of the Green River Basin. One well-laminated (oil shale) calcimicrite occurs on Black Mountain in lower Bridger C, suggesting a short-lived, but relatively deeper lake later in Bridger time.

Siliciclastic deposition diluted an otherwise clear lake in the northern part of the basin, as indicated by the gradual lateral facies change in the limestone facies associated with the Black Mountain turtle layer. These clastics are either air-fall ash, fluvial–deltaic, or a combination thereof. The volcanioclastic composition of most of the elastic sediments of the Bridger Formation is well documented (Sinclair, 1906; Bradley, 1964; Gustav, 1974; Roehler, 1992).

The claystone facies is interpreted as a fluvial–lacustrine system that prograded out over the limestone facies and/or was deposited as air-fall ash into the entire lake over a short period of time. The sharp upper contact of the limestone facies with the claystone facies suggests that an abrupt paleoenvironmental change may have taken place with a sudden influx of volcanioclastics from major eruptions north of the basin. The claystone facies is only a few meters thick and its mineralogic composition is consistent with an ash that was altered largely to clay minerals. Several factors suggest that the claystone facies is lacustrine: (1) the sediment is primarily clay-size, and is associated with gastropods, gar, crocodilians, and pond turtles; (2) there are few channels in the claystone facies; (3) the claystones cover very wide areas (Fig. 2); (4) there are continuous organic-rich units of wide lateral extent, unbroken except by small amounts of zeolites, such as clinoptilolite; (5) the presence of clinoptilolite that forms in alkaline lakes (Surdam and Sheppard, 1978). In some localities the claystone is fluvial–lacustrine, as indicated by a close association with crevasse splay, overbank, and fluvial–deltaic channels. The lack of mudcracks, soil brecciation, and other subaerial features suggest that this facies was not subaerial.

An organic-rich unit, the organic turtle layer, within the claystone facies of the Black Mountain turtle layer contains the most abundant turtles recorded in the Bridger Formation. The organic component appears to be fragments of wood and plants that accumulated over a large area centered around Black Mountain. In addition, two laminated organic-rich shales (<1 cm thick) occur within this unit, suggesting lake deposition. This unit contains no discernible primary sedimentary structures. However, intrastratal hydroplastic-flow structures that include squeezed intraclasts, fluidization features, and poor ‘sorting’ that are inconsistent with normal hydrodynamic sorting (Fig. 7C) are common. Such structures occur commonly in sediments composed largely of clay and were also described from the lacustrine facies of the Green River Formation (Buchheim, 1982). No
Fluvial deposition with floodplain ponding resulted in the deposition of the thin bedded sandstone and siltstone facies, eventually filling in the shallow lake. This facies is gradational with the claystone facies and represents distributary and crevasse splay sheet sands uniformly deposited (laterally correlative) over large areas. They are associated laterally with small channels 1–3 m deep. The terminal parts of these channels represent deltaic shoestring sands that prograded large distances out into a very shallow lake (Fig. 8).

Northward, these sands thicken from a few centimeters to over 1 m, suggesting progradation from that direction. Modern examples of delta channels that prograde large distances as straight channels include Lake Turkana in the African Rift Valley and Salton Sea in California (Fig. 9). The Lake Turkana delta filled a large area of the lake over a short period of time (Johnson et al., 1987). From 1965 to 1994 the Omo River delta increased in area by approximately 400% to 1800 km$^2$ (Fig. 9). This occurred when sedimentation rates were extremely high, resulting from deforestation around Lake Turkana. It appears that the Bridger lakes were shallower than Lake Turkana, and consequently would have required even less sediment to fill them rapidly. During Bridger time, very high rates of sedimentation may have been caused by episodes of volcanism similar to those in Central Oregon in the Miocene–Pliocene (Smith, 1987). The basin probably would have remained a shallow lake through more of Bridger B time if there had not been these episodes of high-sediment-load input from volcanic sources to the north.

Fig. 9. A high rate of sedimentation from 1973 (A) to 1989 (B) resulted in the infilling of 985 km$^2$ and extension of the Omo River delta over 15 km into Lake Turkana in Kenya and Ethiopia. Of particular interest is the long extension ('shoestring sand') of the delta out into the lake, depositing fluvial–deltaic sediments within a lake facies. This is analogous to the paleoenvironmental context during deposition of the Black Mountain turtle layer. The delta on the southern margin of Salton Sea, California, provides a similar analogue (C). The delta finger is about 3 km long. Figures (A) and (B) of Lake Turkana are from www.usgs.gov/Earthshots for Earthshots, fourth ed., 14 February 1999, from the EROS Data Center of the U.S. Geological Survey, a bureau of the U.S. Department of the Interior. Figure (C) taken by the authors.
Evidence that ‘fluvial’ channels extended significant distances into the lake (‘shoestring’ sands) and formed prograding deltas include the following: (1) Lateral facies changes from fluvial channel to lacustrine clays. Overbank flooding into floodplain ephemeral lakes could also result in a similar sequence. However, the observation that the actual channels are rare and isolated with lake sediments between them argues for the first hypothesis. (2) The claystone facies is basin-wide and laterally continuous. It contains gastropods and gar. (3) Tufa and stromatolites ‘colonized’ fluvial channel facies (Fig. 5) that were apparently abandoned for periods of time, allowing lake tufa to encrust previously deposited prograding channels. Stromatolites and tufa are indicative of shallow-water lake deposition in the Green River Formation (Surdam and Stanley, 1979). The tufa layer varies in distance above the basal limestone, in places rising over lenses that seem to represent the ‘fluvial’ shoestring sand bodies. The relationship of the sand bodies with the tufa and stromatolites is interpreted as an initial ‘delta’ or channel sand that rapidly prograded out into the shallow lake (Fig. 8, times 1 and 2). The stromatolites reestablished growth during a period of low siliciclastic deposition (part of time 2). Siliciclastic deposition of additional prograding channels buried the stromatolites and previously deposited siliciclastics. In some cases they also eroded the older deposits.

Deposition of the cross-bedded sandstone facies occurs between times 2 and 3 (Fig. 8) on a well-established fluvial floodplain environment. Large fluvial channels represent major meandering rivers. Channel lags with pebbles and wood fragments are consistent with this interpretation. The cross-bedded sandstone facies concludes the lithofacies association. This sequence repeated itself as subsidence rates exceeded depositional rates and much of the basin was again invaded by a subsequent shallow lake (time 4).

7. Conclusions

A lithofacies assemblage consisting of lacustrine to fluvial facies was deposited in a shallowing upward lake system that evolved into a fluvial floodplain. This sequence was repeated numerous times during Bridger deposition, and is well illustrated by the Black Mountain turtle layer sequence. The limestone facies was deposited during the initial phase of the sequence in a relatively clear lake that occupied a large part of the basin. The lake was shallow because of a very low topographic gradient within the basin and a relatively low evaporation/precipitation ratio or a low breech point so that an open-hydrologic system existed. Episodic deposition of volaniclastic sediments brought this stage to an abrupt end. However, a lake dominated by siliciclastic deposition continued until it was filled by a southward prograding deltaic–fluvial system that eventually evolved into a classic floodplain with meandering rivers.

It is not clear whether the initial limestone-depositing phase was brought to an end by a high influx of volcanoclastic (primarily air-fall ash), or from the rate of deposition of clastics exceeding the subsidence rate, or a combination of the above. The lake water was fresh to slightly brackish, as indicated by fossils and clay mineralogy.

It is likely that variations in volcanic input along with a constant rate of subsidence resulted in the lithofacies association described here. When sediment supply decreased compared with subsidence rate (accommodation to sediment supply ratio), shallow, clear, limestone-depositing lakes developed. When sediment supply was at its highest, a fluvial floodplain system developed.

Deposition of Bridger unit B suggests a delicate balance between closely interacting lacustrine and fluvial systems. Although fluvial processes and clastic sedimentation dominated depositional patterns, the balance favored returning to the lake system that long dominated deposition within the Green River Basin. There is much to learn about this interaction, its effect on life in the system, and the relationships between sediment supply, basin subsidence, and the effect of tectonics and related volcanoclastic contribution. The recent mapping of numerous basin-wide marker beds (Brand, 1997; Evano et al., 1998) will facilitate continued paleo-geographic study of the Bridger Formation.
Acknowledgements

We thank the many undergraduate and graduate field assistants who assisted in the field work, including Meredith Church, Judy Holbert, Karen Koptizke, Mark Loewen, Brett Malas, Matthew Niemeyer, Aimee Wyrick, and Sam Yamamoto. We thank Bob Cushman for reading the manuscript, and Emmett Evano for his contribution to mapping the marker beds. Research funds supporting this research were provided by the Department of Natural Sciences, Loma Linda University. The field work was done under BLM paleontological resource permits. Thanks to Greg Gunnell and Anna Behrensmeyer for their helpful comments on an earlier draft of this manuscript.

References


Sundram, R.C., Slepicka, R.A., 1978. Zoolithes in saline alkaline-

