CONTROLS ON THE GEOMETRY OF INCISED VALLEYS IN THE BASAL QUARTZ UNIT (LOWER CRETACEOUS), WESTERN CANADA SEDIMENTARY BASIN

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ABSTRACT: **In southern Alberta, multiple episodes of fluvial erosion occurred during Lower Mannville, Basal Quartz time (Early Cretaceous), creating a series of incised-valley systems. This study examines two of these valley networks, in order to illustrate the geomorphic and genetic complexity of incised-valley systems. Both valley networks are filled by a transgressive succession of fluvial to estuarine deposits. Isopach mapping of these deposits over an area of approximately 10,000 km^2 in southern Alberta shows that both systems are dendritic to rectilinear in character, with the trunk valley flowing from south to north along the length of the Western Canada Sedimentary Basin. These systems were fed from the west, south, and east by a network of tributaries. Eustatic sea-level changes may have played a role in initiating river incision, but regional tectonic movements had an important influence on the history of accommodation change. The periods of erosion appear to have been relatively brief because the valleys are narrow, although confinement within cohesive, mudstone-rich paleosols of the underlying incised-valley deposits may have slowed valley widening. A relatively wet paleoclimate may also have contributed to the formation of narrow valleys by favoring the existence of single-channel rivers. The general morphology of the Alberta foreland basin, together with the distribution of unfilled relief associated with a preceding valley system and/or of less resistant, slightly older deposits, determined the location of the trunk valleys. Uplift of the Bow Island Arch (Sweetgrass Arch) to the east may have been responsible for a shift in the valley headwaters between the formation of the two valley systems. Synerosional block faulting in response to flexural loading had a significant influence on the geometry of the valley network through its control on the location and geometry of major tributary valleys. The trunk valley is also significantly narrower and more deeply incised where it crosses the most pronounced uplifted block. Enhanced erosion at tributary junctions and valley bends produced localized areas (ca. 2–3 km in diameter) where the valley fill is up to five times thicker and considerably coarser grained than the adjacent valley deposits. Such localized scour fills represent prime petroleum-exploration targets.**

INTRODUCTION

Incised valleys have been a topic of considerable interest in recent years, in part because of their importance as indicators of sequence boundaries, and also because of the significant quantities of hydrocarbons that have been discovered within them. Numerous papers have described the nature of the valley-fill deposits, but few have discussed the geometric nature of the valleys themselves (i.e., the ''container'' that holds the sediments; cf. Dalrymple et al. 1994, p. 6). If valley-form geometry is discussed, it is generally considered using only two-dimensional cross sections or simplified maps of small areas. Reconstructions of ancient valley systems, complete with a network of tributaries, over large areas are uncommon (e.g., Siever 1951; Pepper et al. 1954; Suter et al. 1987; Rosenthal 1988; Colman et al. 1992; O'Byrne and Flint 1995; Sherwin 1996; Zaitlin et al. 2002), and such studies have rarely analyzed the factors that controlled the morphology of the valley network. Outcrop studies generally cannot examine entire valley networks because of limited exposure. Subsurface studies are not restricted in this way, but they are either of limited geographic extent (so-called ''pool studies''), or, if of larger areal coverage, lack the density necessary to accurately delineate the smaller tributary valleys. However, accurate knowledge of the three-dimensional valley form is important for a full understanding of the valley-filling deposits. For example, narrow valleys offer less total accommodation space than wide valleys with the same depth of incision. Therefore, all else being equal (e.g., the rate of base-level rise and the rates of fluvial and marine sediment input), narrow valleys will contain a higher proportion of fluvial sediments and fewer estuarine deposits than wide valleys. In addition, knowledge of the geometry of the valley is essential for the prediction and development of petroleum reservoirs and ground-water aquifers.

For these reasons, we have reconstructed the three-dimensional geometry of two subsurface valley networks in a 100 km by 120 km portion of the densely drilled ''BAT'' (Bantry–Alderson–Taber) unit, which forms part of the ''Basal Quartz,'' an informal stratigraphic unit of Lower Cretaceous age in southern Alberta (Fig. 1; Zaitlin et al. 1999, 2002). We then examine the various factors (eustasy, local and regional tectonics, climate, substrate, and inherent fluvial processes) that may have influenced the geometry of the valley system with its network of tributaries. In this, we draw on a considerable body of previous work on the geomorphology of modern valleys (e.g., Howard 1967; Schumm and Ethridge 1994; Best and Ashworth 1997; Holbrook and Schumm 1999; Schumm et al. 2000). Our broader objectives are to demonstrate that ancient incised valleys represent the complex response of fluvial systems to many variables, and that a complete understanding of any incised-valley deposit can be gained only when the full context is known.

GEOLOGIC SETTING

The study area is located in south-central Alberta, from Townships (T) 6 to 18 and Ranges (R) 11W4 to 22W4, covering a total area of approximately 10,000 km^2 (Fig. 1). The BAT unit, which forms the subject of this study, lies within the Taber–Cutbank valley system (an extension of the Cutbank valley in Montana; Dolson and Piombino 1994), a major northwest-draining system (Fig. 1) incised into Mississippian and Jurassic deposits (Zaitlin et al. 1999, 2002; Lukie et al. 2002).

Multiple relative sea-level oscillations between Late Jurassic and Early Cretaceous time (ca. 135–115 Ma) led to the erosion and infilling of a complex series of nested valley systems (Figs. 2, 3), collectively known as the Basal Quartz. According to Zaitlin et al. (1999, 2002) and Arnott et al. (2000), the Basal Quartz consists of four mineralogically distinct, unconformity-bounded units, namely the A-sandstones, Horsefly, Bantry–Alderson–Taber (BAT), and Ellerslie units. The thickness of the Basal Quartz deposits within the study area reaches 76 m, and the thickness of the BAT reaches 45 m. The geometry of the various erosion surfaces within the Basal Quartz shows a progression from the relatively flat and laterally extensive surface beneath the oldest unit, the A-sandstones, which is preserved only as erosional remnants (Figs. 1, 3), through the broad, flat-floored valleys of the Horsefly unit, to the deeply incised and narrow valleys of the BAT unit (Ardies 1999; Lukie 1999; Zaitlin et al. 1999, 2002). Because the maximum depth of incision occurs within the BAT unit in the study area (Fig. 3B), the A-sandstones and Horsefly unit may represent the falling-stage systems tract of a second-order sequence. The deposits constituting these two units are entirely fluvial in the study area (Ardies 1999;

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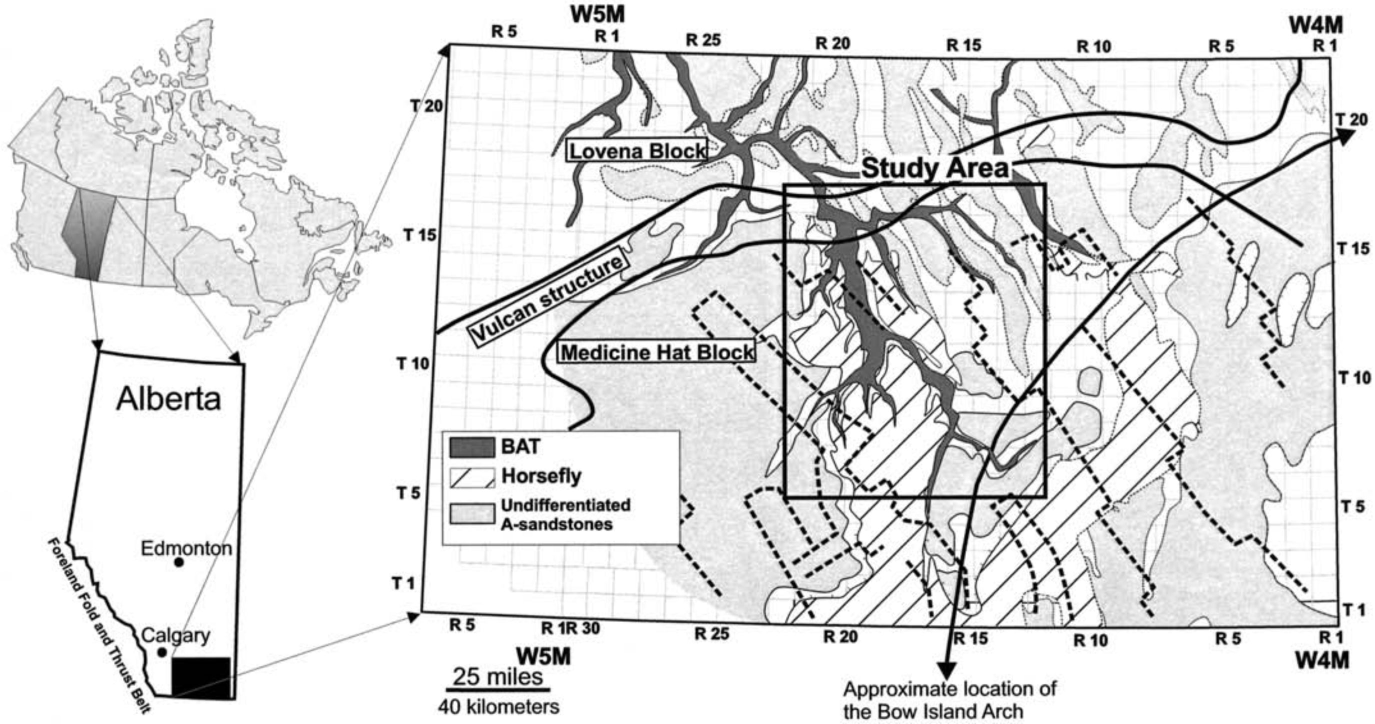


FIG. 1.—Location map showing the distribution of the component parts of the Basal Quartz (A-sandstones, Horsefly, and BAT units) in southern Alberta (after Zaitlin et al. 2002); the Township and Range grid is visible in areas where the Basal Quartz is not present. This map was constructed using approximately one well per section (1.6 km × 1.6 km). As a result, the distributions of the units are somewhat simplified. Note that the A-sandstones have a sheet-like distribution that has been dissected by later fluvial incision, whereas the Horsefly and BAT units occupy progressively narrower, NNW-trending valleys. Boundaries of basement elements (heavy solid lines) and suspected faults (dashed lines) from Ross et al. (1997).

Zaitlin et al. 1999; Lukie et al. 2002), whereas the BAT and overlying Ellerslie units contain both fluvial and estuarine facies (see more below), especially in more northerly locations, which were closer to the sea. The maximum transgression of the second-order sequence occurred during deposition of the Ostracod Member (Fig. 3) (Banerjee and Kidwell 1991; Cant 1996; Cant and Abrahamson 1996).

The encroaching thrust belt of the Cordilleran orogen had initiated formation of the Alberta foreland basin prior to Basal Quartz time (Cant and Abrahamson 1996). Temporal variations in the magnitude of the load led to intermittent subsidence and uplift of the basin, as well as intermittent movement of the Swift Current Platform and Bow Island Arch (the northern extension of the Sweetgrass Arch; Fig. 1), which lay to the east of the study area (Christopher 1984; Arnott 1988; Cant and Stockmal 1989; Leckie and Smith 1992). These tectonic features were partially responsible for constraining the location and orientation of the axial drainage system of the Taber–Cutbank valley.

Precambrian basement in southern Alberta consists of two Archean crustal domains, the Medicine Hat Block in the south, on which the study area lies, and the Loverna Block to the north (Fig. 1; Ross et al. 1997; Ross and Eaton 1999). They are separated by the Vulcan structure, a geophysical lineament that marks the Paleoproterozoic suture between the two domains (Eaton et al. 1999). The location of this structure also marks a significant change in the flexural response of the basin, from a low rate of creation of accommodation (i.e., relative stability) in the south, to a higher rate of subsidence in the north (Zaitlin et al. 2002). Within the study area, the dominant structural grain of the Precambrian basement is oriented southeast–northwest, with a subsidiary northeast–southwest trend (Fig. 1).

METHODOLOGY

Approximately 1,150 petrophysical well logs were examined in this study (Fig. 4), of which nearly 500 were used to construct a grid of cross sections to determine the distribution and stratigraphic relationships among the various units (Ardies 1999). Approximately one hundred cores (Fig. 4) were examined and logged to determine the stratigraphic subdivisions and depositional environments. Grain size and composition, sedimentary structures, trace fossils, bed and bedset thicknesses, nature of contacts, and cement type were recorded on a centimeter scale.

Isopach maps, structural-contour maps, and cross sections of various Basal Quartz units were constructed from the well-log data. The top of the Upper Mannville was used as a datum for the cross sections, because it is easily distinguishable on logs and regionally extensive. The Ostracod Member is a superior datum because of its closer proximity to the study interval (Figs. 2, 3); however, it has been removed in many places by later channel erosion and thus could be used only locally.

SEDIMENTOLOGY AND STRATIGRAPHY OF THE BAT UNIT

Although the goal of this paper is to discuss the geomorphology of the erosion surface that defines the BAT valley system, we first provide a brief description of the valley-fill deposits; the reader is referred to Ardies (1999) for more detail. In the cores, twelve facies were distinguished, ranging from conglomerate, through a variety of sandstone-dominated and heterolithic deposits, to mudstone-dominated sediments. These facies in turn occur in five environmentally significant facies associations (FA; Table 1; Figs. 5, 6, 7).

FA1 is erosionally based and fines upward, with a composition (from bottom to top) of conglomerate, pebble-rich sandstone, cross-bedded sandstone and/or massive sandstone, and interbedded sandstone, siltstone, and mudstone, with subordinate current- and wave-rippled sandstone (Figs. 5, 6). The absence of marine attributes (i.e., double mudstone drapes, bidirectional cross lamination, and trace fossils) indicates that FA1 represents fluvial channel deposits. FA2 also has an erosional base (Fig. 7), fines

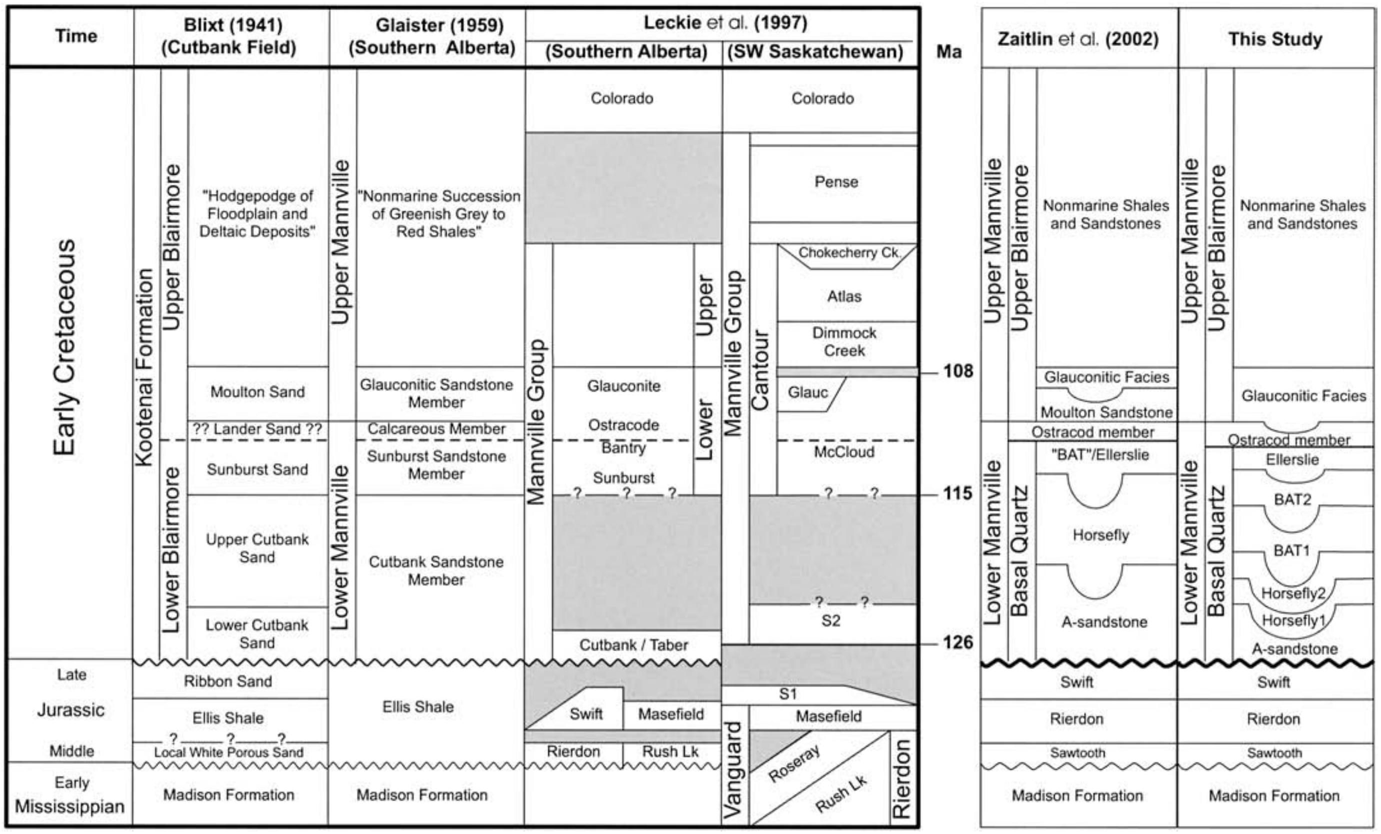


FIG. 2.—Stratigraphic subdivision of the study area and adjacent regions (Cutbank Field, Montana, and southwest Saskatchewan) showing the evolution of terminology and unit correlations. The Horsefly unit is divisible into two unconformity-bounded sequences (Horsefly 1 and Horsefly 2; Ardies 1999; Arnott et al. 2000; Lukie et al. 2002; Zaitlin et al. 2002), but this differentiation is not discussed in the text. Absolute ages from Leckie et al. (1997).

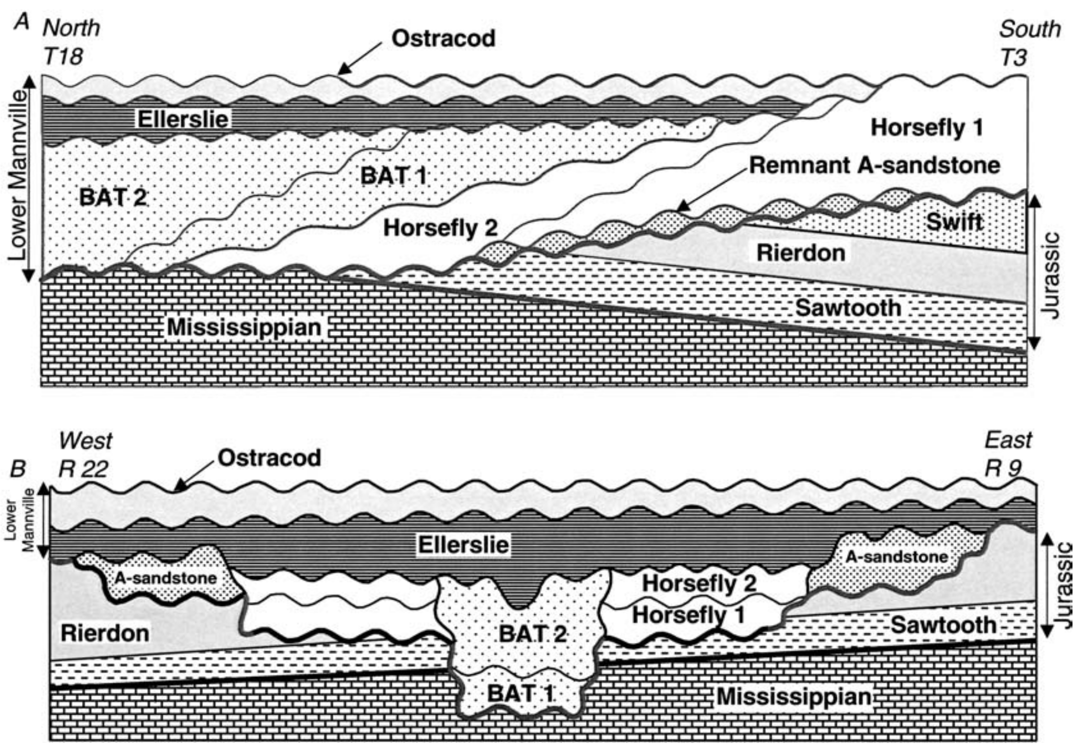


FIG. 3.—Schematic sections showing the stratigraphy in the study area (see also Figs. 1, 2). Section A runs north–south through Ranges (R) 18–19, whereas section B passes east–west approximately through Township (T) 12. The line weight of unit-bounding unconformities is proportional to the time gap.

TABLE 1.—*Descriptions of facies associations (FA) recognized in the study area.*

FA	Unit Thickness	Lithology	Grain Size	Sedimentary Structures	Internal Organization	Inferred Origin
1	0.4–6 m	Quartz-chert arenite and minor conglomerate with various intraformational and extraformational clasts	Fine- to coarse-grained sandstone and conglomerate	Structureless sandstone, low- to high-angle cross bedding, rare imbrication, soft-sediment deformation	Several decimeter- to meter-scale upward-fining successions; multiple scours	Fluvial channel
2	0.5–5 m	Quartz-chert arenite and minor conglomerate with various intraformational and extraformational clasts	Fine-grained to coarse-grained sandstone and conglomerate	Cross bedding, soft-sediment deformation, syneresis cracks, restricted trace-fossil assemblage (*Skolithos, Planolites, Thalassinoides,* and *Cylindrichnus*; fugichnia), paired mudstone drapes, sigmoidal cross bedding, flaser bedding, current ripples	Numerous decimeter- to meter-scale fining-up successions	Tidal-fluvial channel and/or distributary channel
3	0.1–9 m (local, anomalous thicknesses of 12 m and 18 m)	Mudstones with subordinate amounts of quartz-chert arenite	Dominantly mudstone with subordinate coarse- to fine-grained sandstone	Cross bedding, soft-sediment deformation, rare syneresis cracks, rare trace fossils, flaser bedding, thin mudstone clast lags, rare horizontal lamination, root traces, gleyed surfaces, non-oriented slickensides, granular (ped) structure, color mottling, horizontal stratification, current and wave ripples	Interbedded sandstone and mudstone with no preferred vertical grain-size trend; root traces most abundant near top of succession	Overbank floodplain and/or salt marsh
4	0.5–8 m	Variably bedded sandstones, siltstones, and mudstones	Fine-grained to coarse-grained sandstone and conglomerate	Cross bedding, soft-sediment deformation, current and wave ripples, abundant syneresis cracks, stressed (limited-diversity) trace-fossil suite (i.e., *Teichichnus, Planolites,* and *Skolithos*; fugichnia), HCS, SCS, paired mudstone drapes, sigmoidal cross beds, flaser bedding	Numerous, decimeter-scale, upward-coarsening successions, composed of normally graded beds	Bay-head (estuarine) delta
5	0.7–9 m	Variably bedded sandstones, siltstones, and mudstones	Coarse-grained sandstones to mudstones	Wave ripples, syneresis cracks, brackish-water trace-fossil suite (moderate diversity) (i.e., *Teichichnus, Planolites, Skolithos, Palaeophycus, Chondrites, Asterosoma, Diplocraterion, Cylindrichnus, Thalassinoides, Rosselia,* and *Terebellina*; fugichnia), horizontal lamination, soft-sediment deformation, small-scale faulting	Heterolithic to mudstone dominated, with no preferred vertical grain-size trend	Interdistributary bay/central basin

upward, and contains a suite of facies similar to that of FA1. However, FA2 contains variable amounts of bioturbation (*Skolithos, Planolites, Thalassinoides,* and *Cylindrichnus*), double-mudstone drapes, and syneresis cracks, and is finer-grained than FA1 (Table 1). Consequently, FA2 is interpreted as tidal–fluvial channel deposits.

FA3 varies from heterolithic to mudstone dominated (Fig. 6) and contains a diverse suite of sedimentary structures (Table 1). The presence of root traces, gleyed surfaces, slickenslides, angular peds, color mottling, and rare immature soil horizons and carbonate concretions indicates that these deposits represent pedogenically altered overbank deposits. The greenish-black to grayish-black color of these paleosols suggests that they were deposited in relatively wet floodplain and/or salt-marsh environments. FA4 consists of irregular, meter-scale, upward-coarsening successions (Fig. 7), composed of centimeter- to decimeter-scale upward-fining beds that contain soft-sediment deformation features and a low-diversity trace-fossil suite (i.e., *Teichichnus, Planolites,* and *Skolithos*; Table 1). As a result, FA4 is believed to have accumulated in an estuarine bayhead–delta environment (cf. Zaitlin et al. 1994; Nichol et al. 1997). FA5 is heterolithic but more mudstone rich than FA4 (Fig. 7) and contains a greater abundance and higher diversity of trace fossils. Syneresis cracks are moderately abundant, but pedogenic features such as those typifying FA3 are absent. Judging by these features, FA5 is interpreted as interdistributary bay and/or estuarine central-basin deposits (cf. Zaitlin et al. 1994; Nichol et al. 1997).

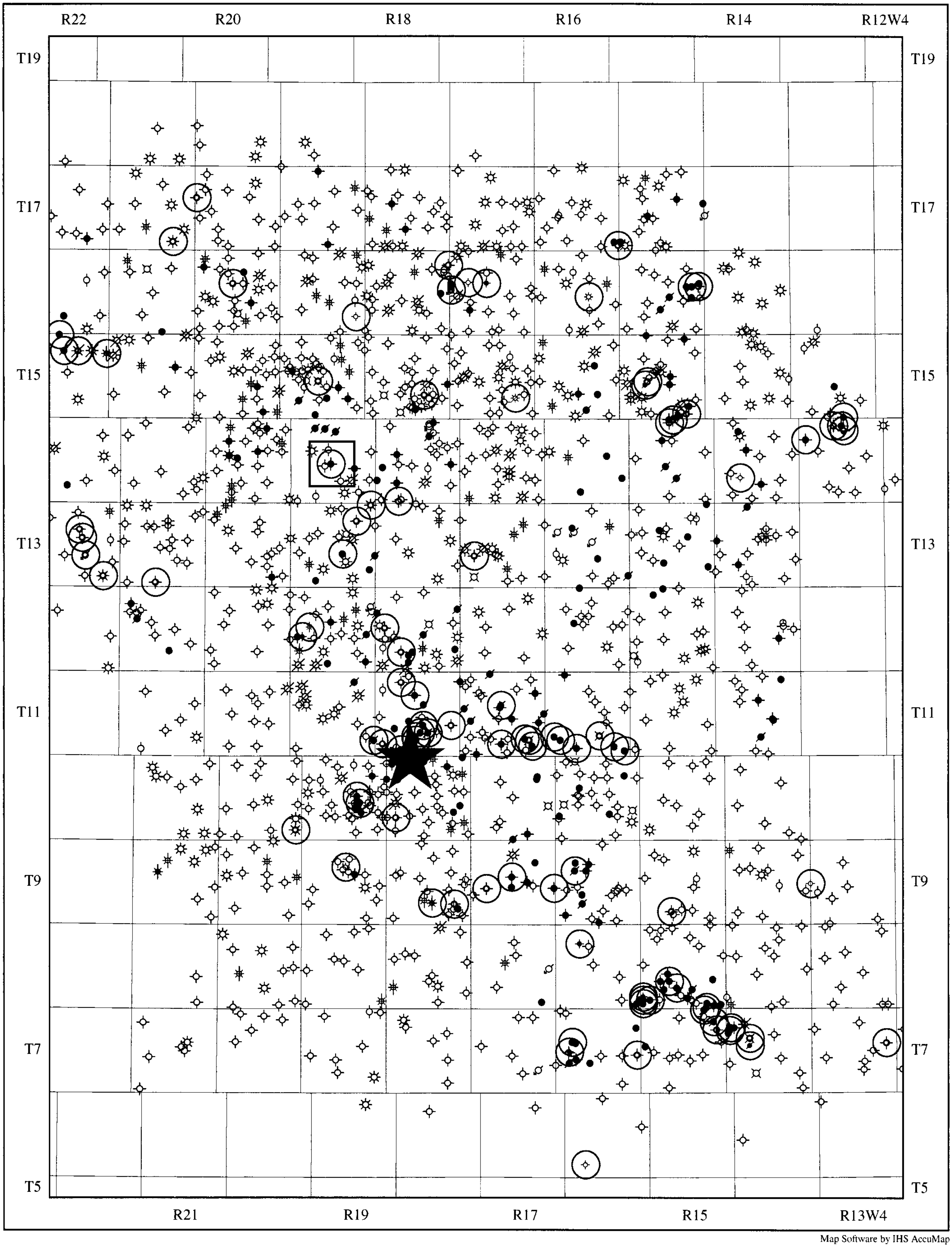
These facies associations show a predictable vertical and longitudinal organization within the BAT. Cores and well logs show that the BAT consists of two large-scale, upward-fining successions. Locally, these occur stacked on each other (Fig. 6), but, more commonly, the lower succession (BAT1) is absent (Fig. 5). Each of these successions is generally 4–30 m thick and begins with an erosional base that is overlain by fluvial–channel deposits (FA1). These sandstone to conglomeratic sediments range in thickness from 0.4 to 6 m (Figs. 5, 6) and consist of one or more amalgamated channels. The intraformational, angular mudstone pebbles that occur at the base of these channels imply that overbank environments were widespread, but only rarely are mudstones of FA3 preserved in the lower part of each large-scale succession. Because the channel deposits display well developed upward-fining trends and were originally bordered by floodplain sediments, we suggest that the BAT rivers meandered (cf. Walker and Cant 1984).

In many places, these fluvial deposits pass upward into overbank mudstones containing pedogenic features (FA3; Fig. 6). Elsewhere, they are overlain erosionally by the deposits of tidal-fluvial channels (FA2) that range in thickness from 0.5 to 5 m. In the southern part of the study area, overbank deposits of FA3 also overlie the tidal–fluvial sediments in both of the upward-fining successions. However, in more northern locations, and especially in the upper succession (BAT2), the tidal–fluvial channel deposits are overlain by 0.7 to 9 m of grayish-black mudstones of FA5 (central-basin sediments; Fig. 7) and/or the more heterolithic, upward-coarsening deposits of FA4 (bayhead–delta sediments), indicating a northward transition to more distal estuarine conditions.

The vertical succession of depositional environments within each of the two BAT successions (fluvial sediments at the base, passing upward into progressively more distal, estuarine deposits at the top) is transgressive in character. In many of the wells where the two successions are stacked on each other, extraformational, conglomeratic fluvial deposits at the base of BAT2 erosionally overlie tidal–fluvial or muddy central-basin estuarine sediments of BAT1, implying a significant basinward shift of facies. Mapping also shows that the two successions are traceable regionally (Figs. 8, 9). Thus, the BAT1 and BAT2 successions represent two separate, unconformity-bounded sequences.

GEOMETRY OF THE BAT VALLEYS

Figures 8 and 9 show isopach maps for the BAT1 and BAT2 sequences, respectively. The distribution of the BAT1 sequence has been influenced by erosion at the base of the BAT2 sequence, especially north of T12, where BAT1 is absent for this reason. Both sequences are locally eroded by narrow valleys of Upper Mannville age, but this is of limited extent. Thus, the isopach distributions are controlled mainly by the topography on the basal erosion surface of each sequence. This is indicated by the significant truncation of underlying units (the Horsefly unit is completely removed over large areas and the BAT also erodes into the underlying Jurassic and Mississippian units; Figs. 3, 10), and by the valley-form geometry of the base of the BAT in stratigraphic cross sections. Later modification of the basal erosion surfaces by tidal scour during transgression appears to have been negligible, because fluvial–channel deposits occupy the bottom of the valleys throughout the study area, and tidal–fluvial channels are only locally in contact with the valley walls. Thus, the area where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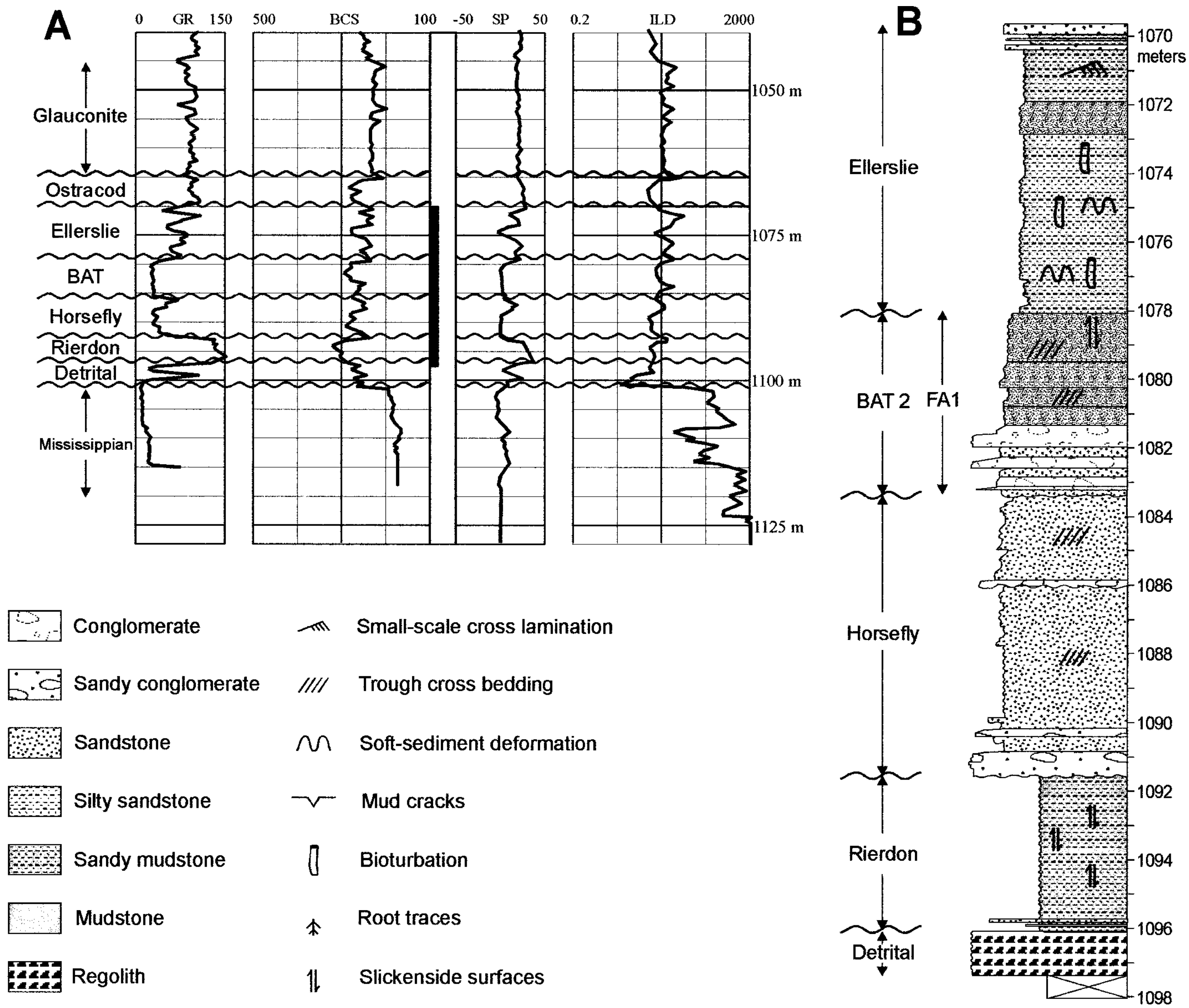

FIG. 5.—**A)** Well logs and **B)** lithic log of well NCE Turin 15-32-10-18W4 (2129–2153 m; see Fig. 4 for location) showing typical stratigraphic succession in the study area: the ''Detrital'' unit regolith (Mississippian to Jurassic), Rierdon Shale (Jurassic), Horsefly unit (braided and/or coarse-grained meandering fluvial sandstones), BAT unit (coarse-grained meandering fluvial sandstones), Ellerslie Formation, and Ostracod Member. The sequence boundary at the base of the BAT2 sequence is overlain by fluvial conglomerates and cross-bedded, medium-grained sandstones (FA1). Point-bar top and overbank deposits have been removed at the combined sequence boundary and flooding surface at the base of the Ellerslie. In A: GR = gamma ray log; BCS = sonic log; SP = spontaneous potential log; and ILD = resistivity log.

each sequence is absent generally corresponds to the interfluves, whereas the deposits occupy a complex network of fluvially eroded valleys with a clearly defined hierarchy of tributaries. Indeed, the presence of tributaries is strong evidence that these deposits represent an incised fluvial system (cf. Posamentier 2001). The convergence of tributaries clearly indicates that the paleoflow was to the north–northwest in both sequences.

BAT1 Valley System

The isopach map for BAT1 (Fig. 8) shows that this valley system extends northwestward from the southeastern corner of the study area to T13, where it is truncated by BAT2 incision. The mean width of the gently sinuous trunk valley (as measured between the zero-isopach contours, perpendicular to the local trend of the valley) is approximately 2.5 km in the south (T7) and decreases abruptly to approximately 1.5 km in T10. In the area from T10 to T13, tributaries join the trunk valley at angles of 70° to 120°, as measured relative to the upstream portion of the trunk valley, forming a rectangular pattern (*sensu* Howard 1967). A more dendritic pattern of tributaries, with tributary-junction angles 30° to 60°, exists in T7 to T9. Tributaries in the rectangular region are short (less than 10 km long) and deep (8–22 m thick), whereas those in the south are up to 14 m thick, are slightly sinuous, and reach 18 km in length. All of the preserved tributaries in the

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FIG. 4.—Map showing well and core (circled wells) control for the study. The star (15-32-10-18W4) indicates the location of the core shown in Figure 5; the box (16-16-14-19W4) shows the location of the core shown in Figure 7.

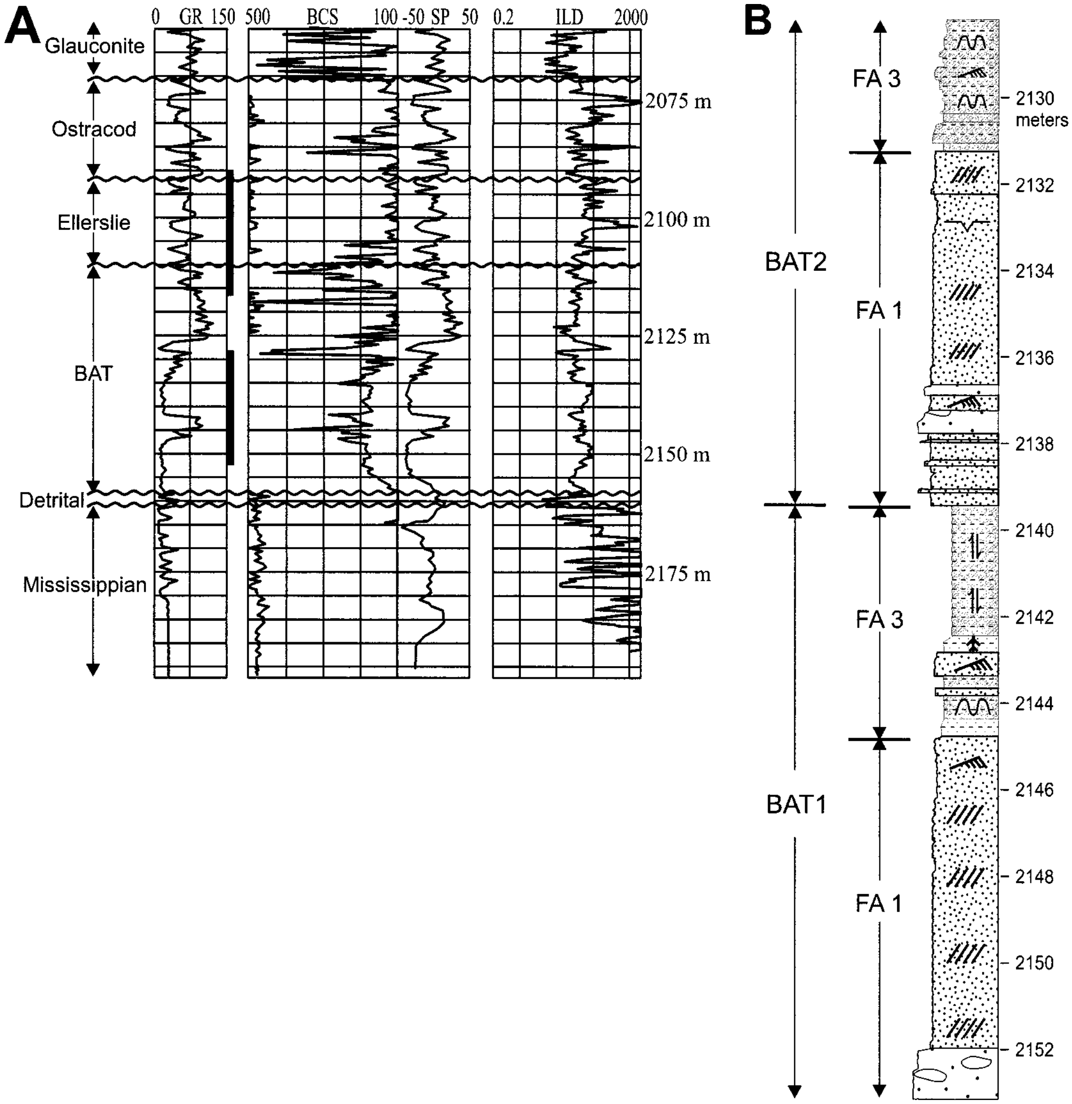

FIG. 6.—**A)** Well logs and **B)** lithic log of well CdnOxy et al. Crossfield 6-11-26-28W4 (2129–2153 m) showing superposition of the two BAT sequences (BAT1 and BAT2). Although this well lies to the north of the Vulcan structure, well logs show that a similar succession occurs in the study area; unfortunately, core is not available. Both BAT sequences begin with conglomeratic sediments and pass upward into medium-grained, cross-bedded, point-bar sandstones (FA1), which are in turn overlain by overbank mudstones with pedogenic features (FA3). D-N = density-neutron log. See Fig. 5 for other abbreviations and legend.

BAT1 valley are first-order streams (*sensu* Strahler 1954; Strahler 1981, p. 408–409), making the trunk valley a second-order stream (Fig. 8). Anomalously thick deposits occur where many of the tributaries join the trunk valley, some of the most notable occurring in T9 R16 and T11–T12 R18 (Fig. 8), and also where the trunk valley is curved (e.g., T11, R17). These isolated pods are typically ca. 8 km² in area and are two to five times thicker than the adjacent valley segments, locally reaching more than 25 m in thickness. Petrographic data and well-log signatures indicate that these anomalously thick deposits are part of the BAT1 unit and are not older Horsefly sediments (Ardies 1999).

BAT2 Valley System

The BAT2 valley system (Fig. 9) is more completely preserved than the BAT1 valley and extends beyond the northern limit of the study area for a distance of at least 225 km (Zaitlin et al. 2002). The portion within the study area displays a well-defined dendritic pattern (Fig. 9). The width of the trunk valley expands from approximately 2 km in the south (T7) to a maximum of 17 km in the northern portion of the study area (T15) but then decreases abruptly to less than 4 km in T16 and 6 km in T17 (Figs. 9, 11). Along most of its length, the thickness of the valley deposits averages 17 m; however, the valley-fill thickness increases abruptly to 45 m in T17 (Figs. 11, 12).

A complex network of tributary valleys joins the trunk valley from the east, south, and west, with those entering from the east being longer, on average, than those entering from the south and west (Fig. 9). Up to four valley orders can be recognized. The first-order tributaries are generally less than 10 m thick, straight, and up to 17 km long. The second-order valley segments range in length from 3 to 18 km and are also relatively straight and about 9 m thick, whereas the third-order segments range from 6 to 55 km in length, with average axial thicknesses of 10–15 m. The single fourth-order valley starts in T14 and extends for 55 km to the north edge of the study area.

The two main, second-order tributary systems in the southwest (T7–T10 R18–R21; up to 40 km long) are particularly notable for their straightness and common southwest–northeast orientation (Fig. 9). Each of them is

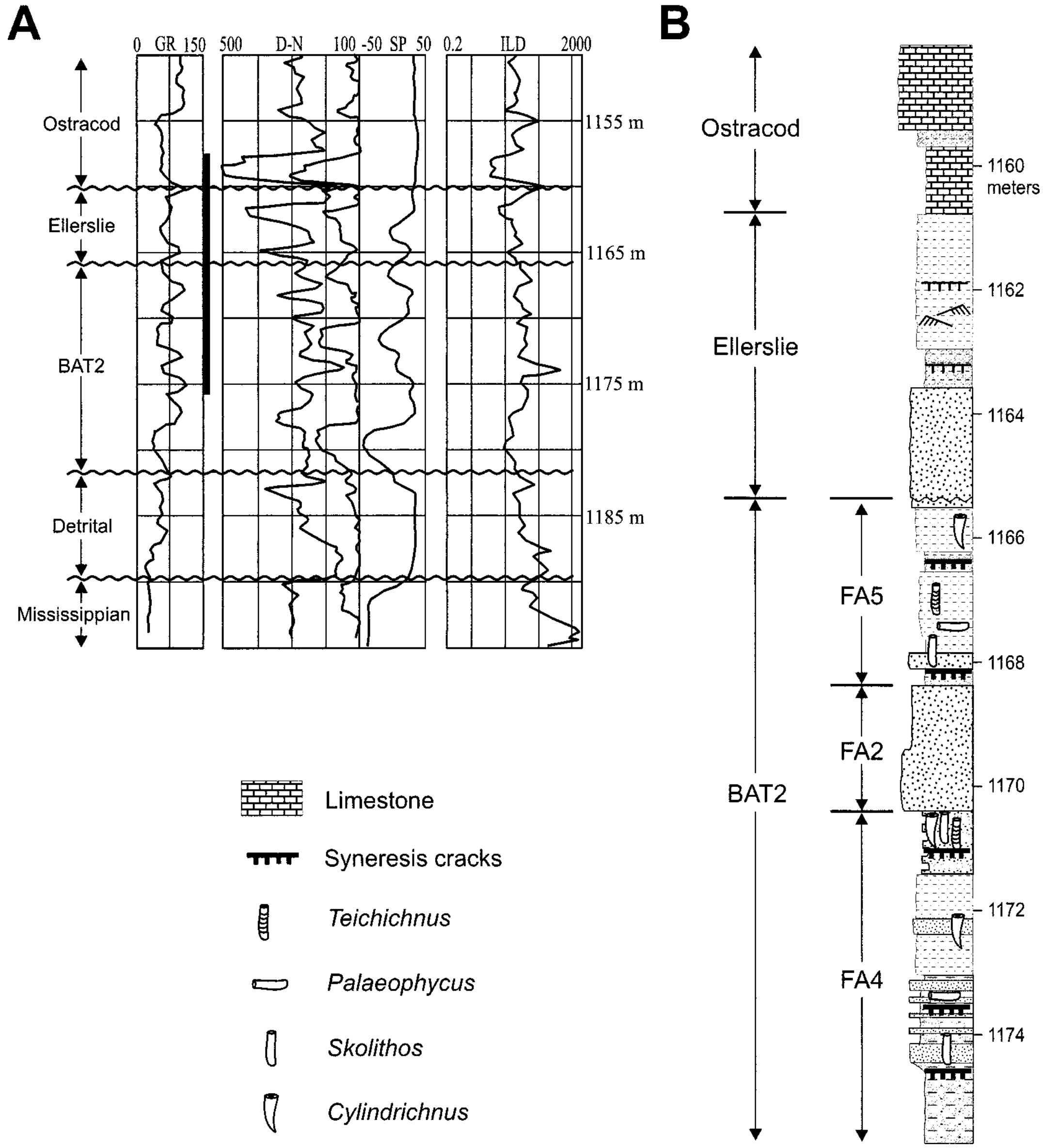

FIG. 7.—**A)** Well logs and **B)** lithic log of well Cabre et al. Little Bow 16-16-14-19W4 (1158–1176 m; see Fig. 4 for location) showing the upper, estuarine-dominated portion of the BAT2 sequence that characterizes the northern part of the study area. The presence of medium- to fine-grained, tidal–fluvial (distributary?) channel sandstones (FA2) overlying the upward-coarsening succession of interbedded fine to very fine sandstones and mudstones (FA4) implies progradation of the estuarine bayhead delta. The presence above this of FA5 (interdistributary bay or estuarine central-basin deposits) suggests renewed transgression. D-N = density-neutron log. See Fig. 5 for other abbreviations and additional legend.

characterized by a dendritic to rectangular drainage pattern with tributary-junction angles ranging from 30° to 80°. The two largest tributary systems in the northeast (T14–T16 R13–R18; > 60 km in combined length of second- and third-order segments) are also relatively straight, but are not parallel to the southwestern tributaries, having an east–west orientation rather than a SW–NE trend. Most of the first-order tributaries to the two large eastern valleys show a dendritic pattern (junction angles 30° to 70°). However, the tributaries on the north side of the northernmost of these valleys (i.e., in T16–T17) display a trellis pattern (Fig. 9), as indicated by the presence of many short, straight tributaries that join the third-order valley with junction angles between 50° and 110°.

It is also noteworthy that the trunk valley displays several abrupt changes in orientation; notable ''kinks'' are commonly associated with the junction of large tributaries, as at T9 R18 and T11 R18, whereas a less pronounced bend is present at T11–T12 R18–R19. These and other bends in both the trunk and tributary valleys (Fig. 9, diamonds) are commonly characterized by isolated areas with thicknesses that are two to five times greater than those of the adjacent valley segments. Similar isolated ''thicks'' also occur at many places where a tributary joins a higher-order valley (Figs. 9, squares; Fig. 13). Both types of isolated pods are typically ca. 5 km^2 in area. Cores and well logs show that these pods consist of BAT2 sediments and are not isolated remnants of older units. The sediments within these pods are thicker and contain a higher proportion of fluvial–channel sandstone (i.e., overbank fines are thin or absent) than the adjacent, more shallowly incised portions of the valley. In addition, the fluvial sandstones within the pods are, on average, coarser grained (medium to coarse sandstone versus fine to medium sandstone) and better sorted (moderately to well sorted versus moderately sorted) than those in adjacent areas.

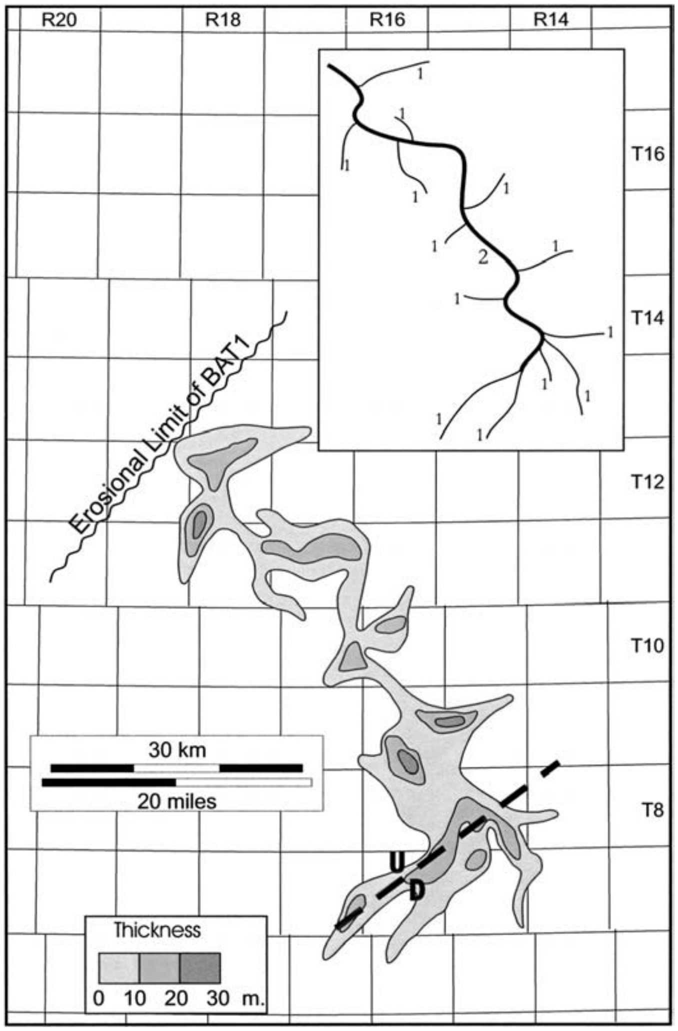

FIG. 8.—Isopach map of the BAT1 sequence. Contours (10-m interval; legend lower left) represent valley-fill thickness, which is a surrogate for depth of incision. Dashed line indicates fault; U = upthrown side; D = downdropped side. Inset map provides a simplified sketch of the valley pattern showing the inferred stream orders for the various valleys.

CONTROLS ON VALLEY FORM

Introduction

The two incised-valley networks described above resemble many modern fluvial systems (cf. Zernitz 1932; Melton 1959; Howard 1967) and represent the integrated response of the BAT rivers to such factors as base-level (sea-level) change, regional and local structural movements, climate, and the nature of the substrate (cf. Schumm 1981, 1993; Starkel 1991; Miall 1996; Shanley and McCabe 1998; Holbrook and Schumm 1999; Blum and Törnqvist 2000). The inherent behavior of the rivers themselves may also have exerted an important influence on the shape of the valley (Schumm and Ethridge 1994). Below, we consider the effects that each of these variables had on the geometry of the valleys.

Relative Sea-Level Changes

Comparison of the local sea-level (RSL) curve (Fig. 14) with the global eustatic sea-level curves of Haq et al. (1988), Jacquin and de Graciansky (1998), and Jacquin et al. (1998) indicates general agreement at the second-order level: the eustatic fall from the Late Jurassic to the late Berriasian corresponds with the transition from marine sedimentation in the Jurassic to fluvially dominated sedimentation in the Lower Mannville and the associated formation of the sub-Cretaceous unconformity. The subsequent eustatic sea-level rise from the Valanginian to the Aptian in turn corresponds with the long-term transgression from the fluvially dominated older portions of the Basal Quartz (i.e., the A-sandstones and Horsefly units) to the marine deposits of the Ostracod Member (Leckie and Smith 1992; Cant and Abrahamson 1996). The smaller-scale oscillations, which are required to explain the multiple incised-valley sequences constituting the Basal Quartz (Figs. 1, 2, 3), may correspond to the many small excursions shown on the global curve, but the relative elevation of the various lowstands and the amplitude of the oscillations do not appear to be consistent with the global curve (Fig. 14). Specifically, the younger, BAT2 valley is incised more deeply than either of the A-sandstones or Horsefly valleys in the study area, a pattern that is inconsistent with the global sea-level curve. This implies that regional-scale tectonic movements were superimposed on the eustatic sea-level signal. Furthermore, the fact that the BAT2 valley extends more than 200 km farther northward (i.e., the study area lay at least this far from the contemporaneous BAT2 shoreline; Zaitlin et al. 2002) argues against a fall of sea level as the main cause of incision (Leeder and Stewart 1996). However, the lack of precise control on the age of the various Basal Quartz valleys makes it impossible to ascertain the extent to which tectonic movements decoupled the history of valley incision and filling from global sea-level changes.

Although the primary influence of the RSL falls was to determine the timing of valley formation, the duration of the lowstands may have been responsible for the different width:depth ratios of the various Basal Quartz valleys. As noted by Schumm and Ethridge (1994; see also Leeder and Stewart 1996), downward incision takes place much more rapidly than lateral widening (excision), because channel-bottom scour is more effective than hillside erosion. Thus, narrow valleys, such as those that characterize the BAT, may indicate shorter-duration lowstands than those responsible for the wider valleys in the underlying Horsefly unit (Fig. 1).

Regional Tectonics and Local Faulting

As discussed above, regional tectonic movements might have contributed to the cyclic changes in accommodation that caused the multiple episodes of valley incision and filling during Basal Quartz time. This is consistent with a growing body of work in Canada and the U.S. showing that structural activity influenced sedimentation throughout the Cretaceous (Catuneanu et al. 1997; Donaldson et al. 1999; Zaitlin et al. 1999, 2002; Holbrook 2000; Lukie et al. 2002). Given this, it is possible that structural activity might also have influenced the geomorphology of the valley network (cf. Schumm et al. 2000).

At the largest scale, the BAT valleys trend sub-parallel to the axis of the Alberta foreland basin. In addition, the Basal Quartz onlaps the flank of the Bow Island Arch (Fig. 1), indicating that the Arch was a positive topographic feature at that time. Thus, the large-scale tectonic setting had a fundamental control on the location and orientation of the valleys. Contemporaneous tectonic movement of the Arch is also suggested by the westward shift of the headwaters of the rivers from BAT1 to BAT2 time (compare Figs. 8 and 9), indicating that the foreland basin subsided and/or the Bow Island Arch rose slightly between the formation of these two sequences. In addition, the eastern tributaries of the BAT2 system show a radial drainage pattern (i.e., eastward in T9–T12; northward in T13–T14; Fig. 9) that appears to define the northern end of the topographically elevated Arch.

At a smaller scale, detailed well-log correlations using marker horizons in the underlying Mississippian and overlying Ostracod units show that faults with offsets of up to 20 m cut the Basal Quartz (Figs. 8, 9, 12, 13, 15). Many of these faults are aligned with straight tributary valleys or are coincident with sharp bends (''kinks'') in the trunk BAT2 valley and/or

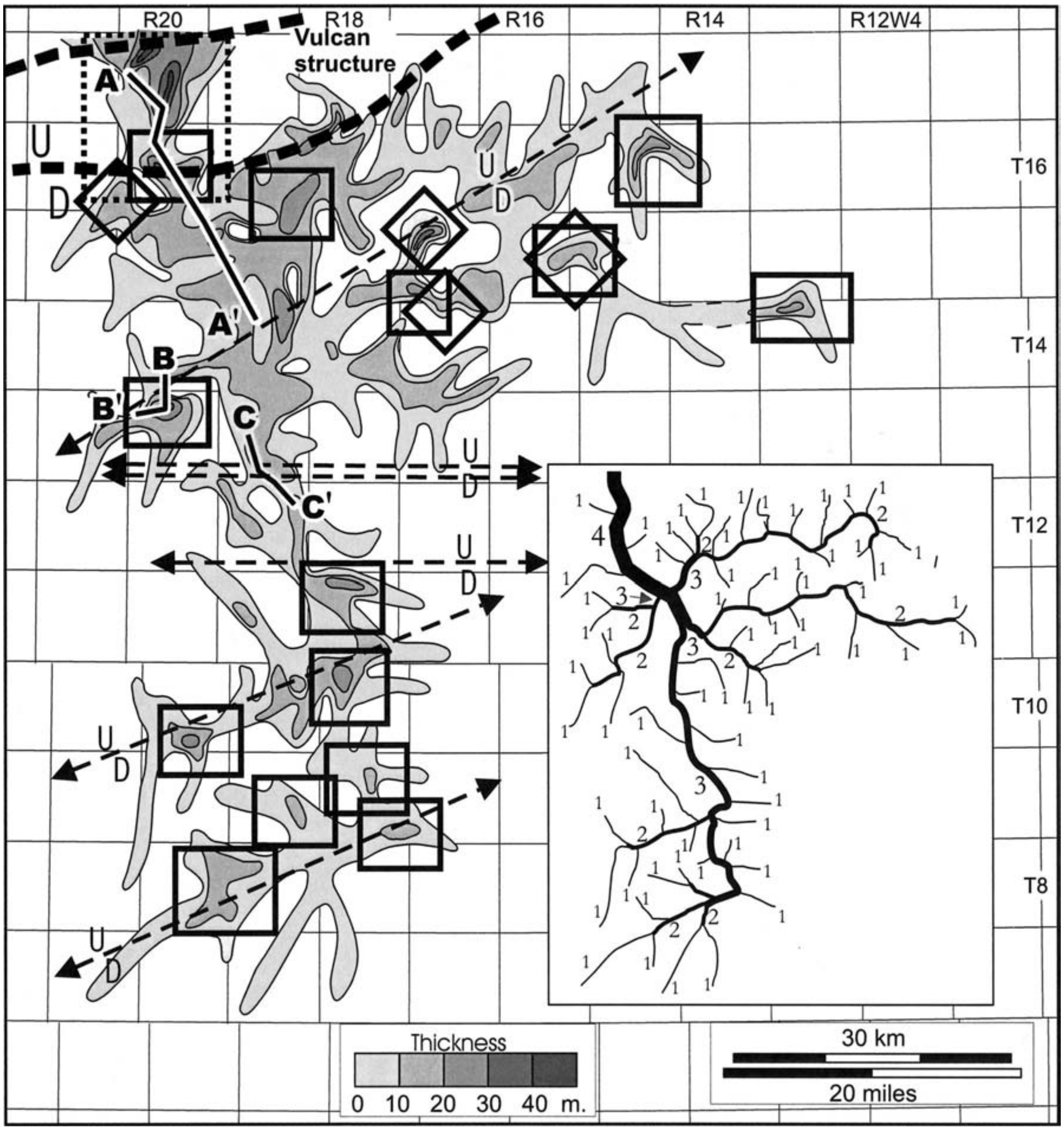

FIG. 9.—Isopach map of the BAT2 sequence. Contours (10-m interval; legend at bottom) represent valley-fill thickness. Boxes (□) denote areas of anomalously deep scouring at tributary junctions; diamonds (◇) indicate locations of possible valley-bend scours. Dashed lines indicate faults; U = upthrown side; D = downdropped side. Inset map provides a simplified sketch of the valley pattern showing inferred stream orders. Dashed box (T16–T17 R20) outlines deep scouring at a constriction that is interpreted to be a paleo-water gap (see text for details). Heavy dashed lines indicate the approximate location of the Vulcan structure as indicated by crustal-scale geophysical data (Ross et al. 1990; Eaton et al. 1999). Relative movement across the Vulcan structure is inferred from observations discussed in the text. Locations of cross sections in Figs. 12 (A–A′), 13 (B–B′), and 15 (C–C′) are shown by heavy lines.

with abrupt changes in valley-fill thickness (Figs. 8, 9). Such associations indicate that syndepositional movement of these faults caused sufficient surface relief to influence the path of the rivers (cf. Fig. 15).

The most prominent example of inferred fault control on valley geometry and the nature of the valley-fill deposits occurs in the northern part of the BAT2 system (Fig. 9, T14–T17). Here, the two longest tributaries flow parallel to each other for more than 50 km. They are fed from the south by a dendritic pattern of long, straight tributaries, whereas those entering from the north are short and exhibit a trellis pattern. The trunk valley itself is broad (approx. 17 km) and relatively shallow (average 17 m) in Townships 14 and 15, but it narrows abruptly to less than 6 km in T16 and 17 and increases in depth to as much as 45 m (Figs. 9, 11). The deposits within this narrow, deep section are composed mostly of well-sorted, coarse-grained sandstone, with much less overbank fine material than in the valley fill to the south (Fig. 12).

All of these features are interpreted to indicate that the area in T16–T17 was uplifted relative to the area to the south, along one or more subparallel, approximately east–west faults. Thus, the large northeastern tributaries are interpreted to have flowed along the length of asymmetric structural lows: the northern flanks of these depressions were steeper, producing the short, straight, first-order tributaries, whereas the more gently dipping southern flanks developed longer tributaries (Fig. 9). The narrow, deep incision in the trunk valley in T16–T17 is interpreted as a paleo-water gap (cf. Strahler 1981; Kinnebrew 1988) that formed where the main river cut through the

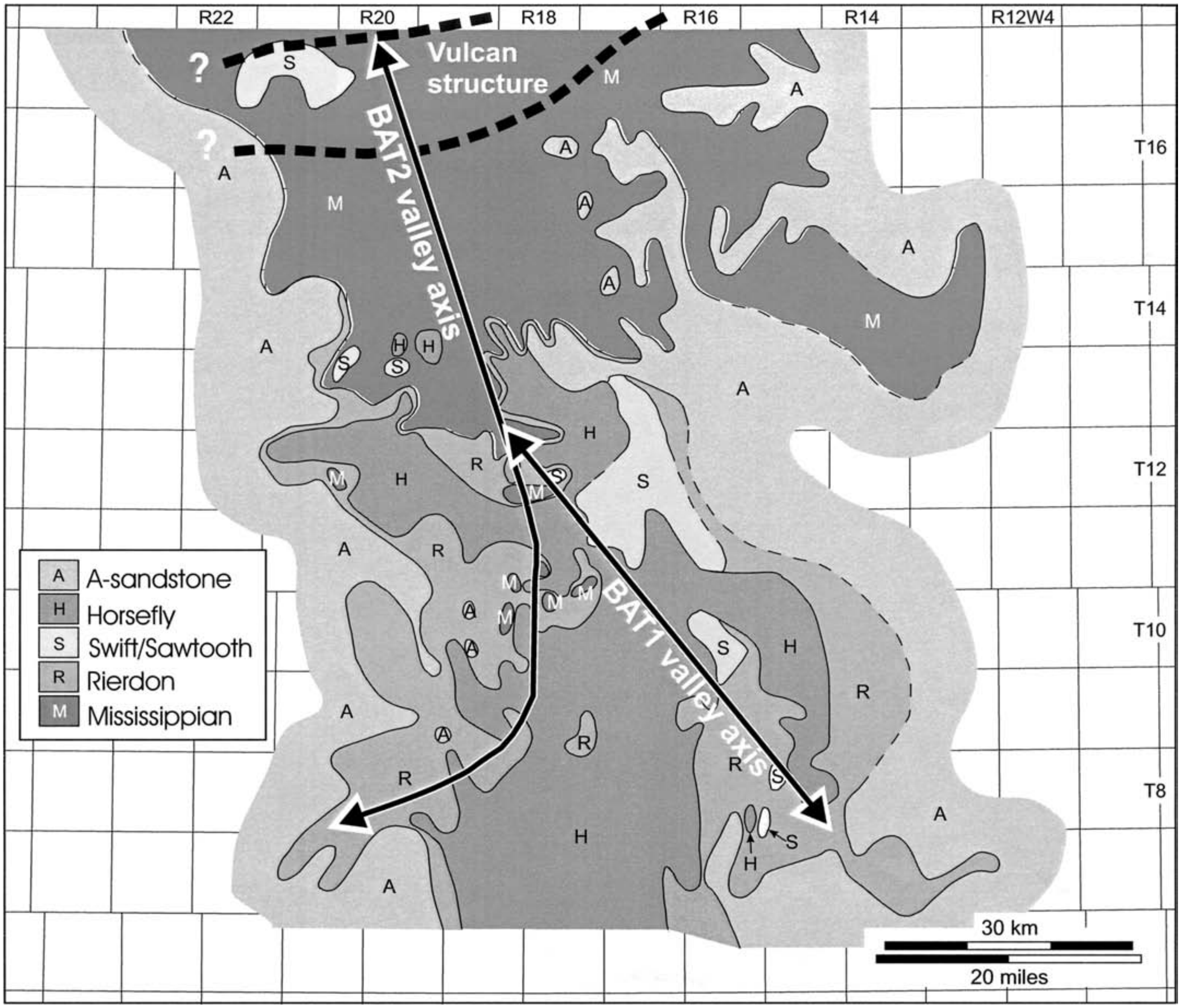

FIG. 10.—Subcrop map beneath the BAT unit. See Figure 2 for table of stratigraphic units. In the southern part of the study area, note how the axes of the BAT valleys overlie the Horsefly unit, which is the next older component of the Basal Quartz. The Horsefly is absent in the area north of T12 because of erosion during BAT time.

uplifted region. This uplift was presumably synchronous with valley incision because the course of the river was not deflected. However, the ongoing uplift of the underlying resistant Mississippian carbonates (Fig. 10) inhibited lateral erosion, which in turn produced higher current speeds and led to significantly deeper incision than elsewhere along the valley (cf. Kinnebrew 1988; Schumm 1993). This also promoted the accumulation of coarser-grained channel deposits and restricted the deposition of overbank fines. Similar responses to ongoing uplift have been documented along the Tallahala and Bogue creeks in Mississippi (Holbrook and Schumm 1999).

There have been few systematic studies of faulting within the Cretaceous section in southern Alberta, but recent work by Ross et al. (1990), Wright et al. (1994), Lemieux (1999), and Ross and Eaton (1999) indicates that northwest–southeast trending normal faults (extending to the basement) are present in response to flexure of the foreland basin. However, such faults cannot explain the NE–SW and E–W oriented structures documented here (Figs. 8, 9). Instead, the faults offsetting the BAT have orientations that are similar to the grain of the large-scale basement tectonic elements (Fig. 1). Specifically, the structures that control the location and orientation of the northeastern tributary network and the constriction of the trunk valley are coincident with and/or closely parallel the southern margin of the Vulcan structure (Fig. 1). This feature and related basement structures appear to have remained weak zones that moved in response to differential loading of the western margin of the North American craton.

Substrate

Substrate composition has been shown to have a substantial control on the location and spatial pattern of fluvial erosion (e.g., Melton 1959; Schumm 1981; Törnqvist 1993; Schumm and Ethridge 1994). For example, preferential erosion and incision into less cohesive substrates has been documented by Törnqvist (1993), areas of uniform substrate lithology and slope favor the development of dendritic drainage patterns (Martin 1966), areas with faulted or fractured bedrock have rectangular drainage patterns

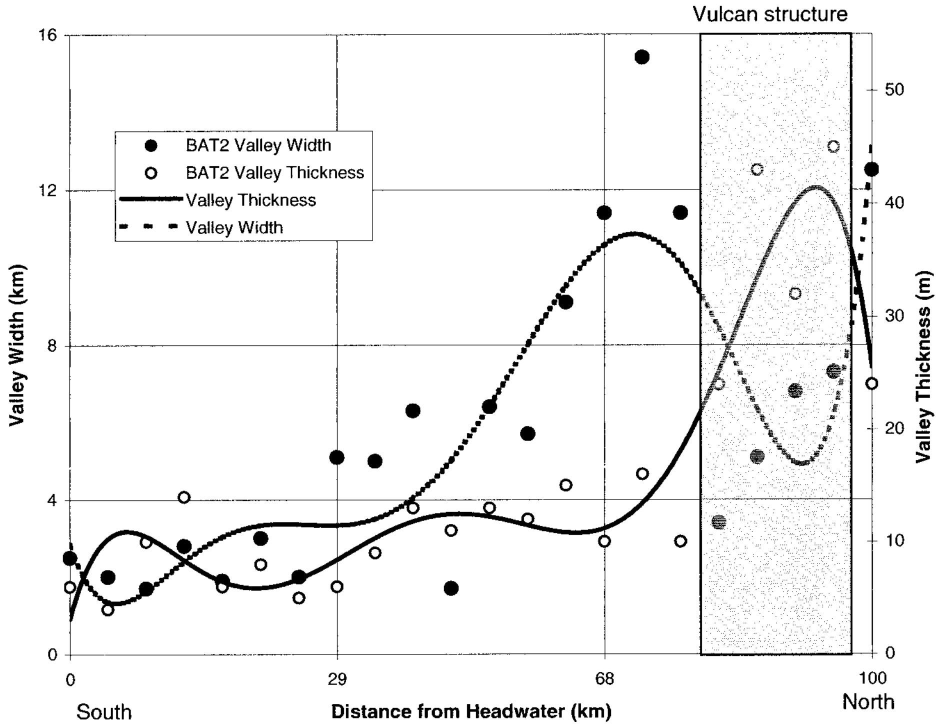

FIG. 11.—Plot of valley-fill thickness and width against distance along the BAT2 trunk valley (Fig. 9). Smooth curves have been fitted to the data using the least-squares technique, to illustrate how thickness (i.e., depth of incision) is inversely proportional to valley width. The anomalously deep and narrow valley at about 90 km (shaded zone) is interpreted as a paleo-water gap where the river has cut through resistant, uplifted Mississippian rocks. The wide, shallowly incised segment from 60 to 75 km occupies the region of greater subsidence to the south of the Vulcan structure.

(Thussu 1999), and a resistant substrate inhibits lateral erosion and leads to the development of deeper incision as noted above.

The substrate to the BAT valley system is complex (Fig. 10), including units ranging in age and rock type from resistant Mississippian carbonates, through moderately lithified Jurassic sandstones and shales, to relatively young and potentially poorly cemented (at the time of BAT deposition) Horsefly sandstones and mudstones. It is tempting to suggest that substrate influenced the location of the BAT1 and BAT2 valleys, given that the axes of the two valleys directly overlie the relatively young and weakly lithified Horsefly deposits in the southern portion of the study area and their inferred

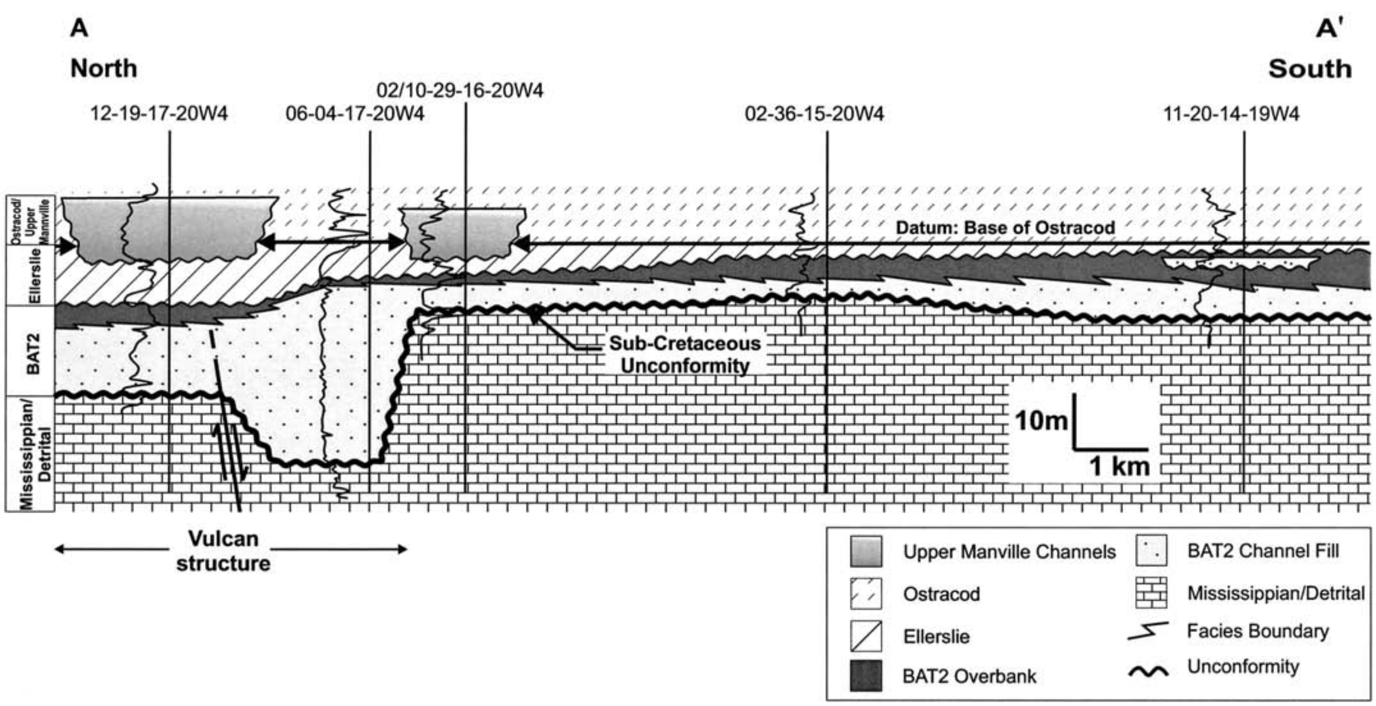

FIG. 12.—Along-valley section (N–S) showing anomalous thickening of the BAT2 in Township 17, where the valley narrows as it crosses the Vulcan structure through a paleo-water gap (cf. Figs. 1, 9, 11). All log traces are gamma-ray curves. Note the blocky, sandstone-rich character of the BAT2 at this location, as shown by the consistent leftward deflection of the log in well 06-04-17-20W4; adjacent thinner, but wider, sections of the valley contain higher proportions of shale. See Figure 9 for location.

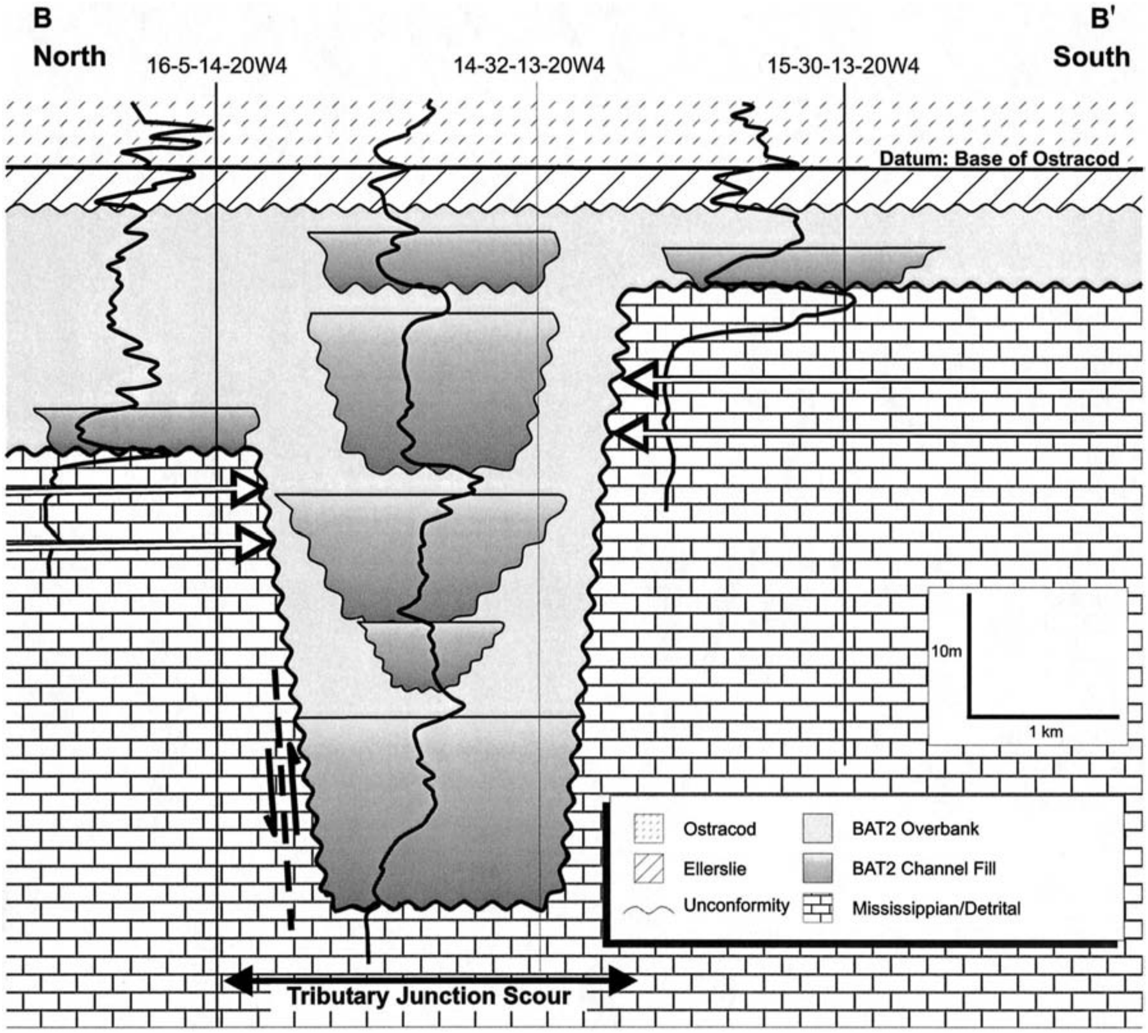

FIG. 13.—Along-valley section through a tributary-junction scour (TJS; well 14-32-13-20W4) in the BAT2 sequence, showing significant thickening and higher sandstone percentage as indicated by greater leftward shift of the gamma-ray curve relative to those in adjacent wells. In core, the sediments in the TJS are structureless, coarse-grained, well-sorted sandstones. See text for additional discussion and Figure 9 for location. The arrows in the Mississippian show truncated horizons indicating substantial incision.

extension in the area north of T12 (Figs. 1, 10). However, the location of the BAT valleys may have been influenced by the pattern of regional subsidence/uplift, as discussed above, and/or they may simply occupy unfilled topographic relief that was created during the formation of the older Horsefly valleys. If so, tectonic factors, including faulting, may have had a greater control on valley location than substrate.

Locally, however, the details of the tributary networks may show some influence of substrate. For example, the dendritic pattern of the southern tributary network of BAT2 is developed by erosion into the relatively homogeneous Rierdon Shale (Figs. 9, 10), whereas a more rectilinear pattern exists in areas with brittle Mississippian carbonates at, or close to, the surface. There is also the suggestion that the drainage density (total length of valleys per unit area; Howard 1992) of first-order streams in the BAT2 systems is less in the northeast than it is in the south (Fig. 9). This may be related to the higher infiltration capacity of the underlying A-sandstones and Mississippian carbonates in this area, relative to the Rierdon Shale in the south.

Finally, the Horsefly unit, which underlies large parts of the BAT valley system, is capped by a succession of paleosols up to 9 m thick (Ardies 1999). These deposits, which are widely preserved outside the axis of the BAT valleys, would have been relatively resistant to erosion because of the syndepositional compaction that occurs in response to periodic drying (Nadon and Issler 1997). The erosional resistance of these mudstones may have contributed to the narrow nature of the valleys.

Climate

Much recent research has focused on climate as an important but understudied factor influencing fluvial erosion and sedimentation (Miall 1996; Jones et al. 1999; Blum and Törnqvist 2000). The available floral data (Upchurch and Wolfe 1993) suggest that climate remained constant throughout the entire Early Cretaceous. However, the paleosols within the Horsefly and BAT units indicate otherwise. The paleosols in the Horsefly unit consist mainly of red paleosols with incipient caliche, limited root traces, and only rare carbonaceous debris (Lukie 1999; Arnott et al. 2000; Lukie et al. 2002). Greenish gleysols are present only locally. By comparison, paleosols throughout the two BAT sequences are dark colored (low chromas; gray-green to dark green), and contain abundant root traces and significant amounts of preserved organic debris including large pieces of carbonized wood. These paleosols have been interpreted to be gleysols

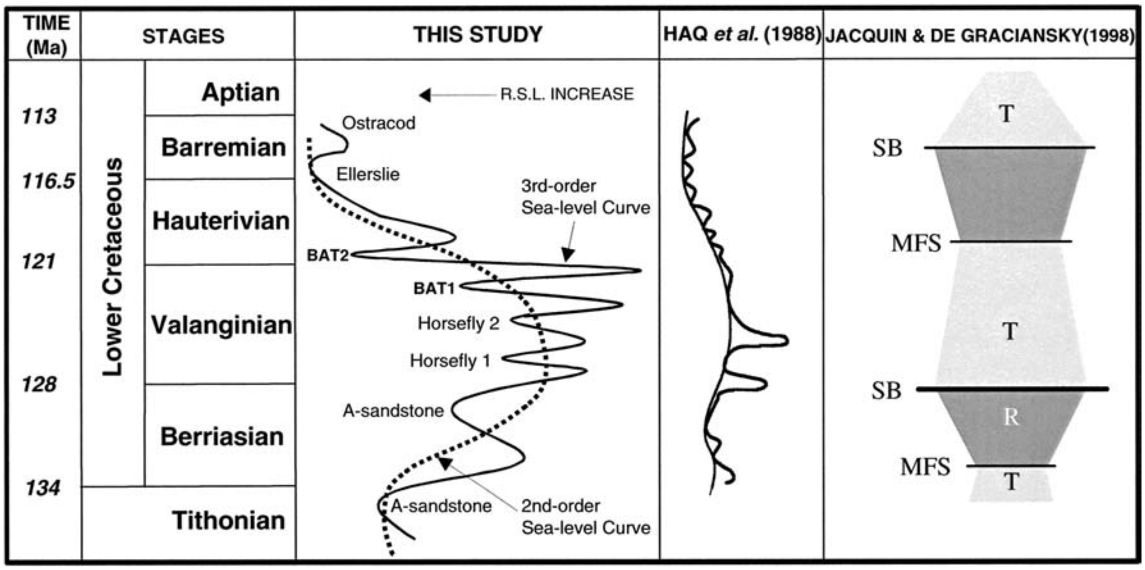

FIG. 14.—Comparison of the global eustatic sea-level curve (Haq et al. 1988) and the transgressive–regressive cyclicity of European basins (Jacquin and de Graciansky 1998) with the relative sea-level curve for the study area (Ardies 1999; Lukie 1999). The latter curve is poorly constrained temporally because of the absence of age-diagnostic fossils or other datable material in the fluvially dominated deposits of the Lower Mannville. Each of the high-frequency oscillations on the local, third-order curve has been drawn to represent a known episode of valley incision, including at least two in each of the A-sandstones and Horsefly units (Ardies 1999; Zaitlin et al. 2002). The relative depth of each lowstand is constrained by the depth of the valley, and the relative duration of each cycle is constrained by the valley width (the wider Horsefly valleys presumably taking longer to form than the narrow BAT valleys) (cf. Schumm and Ethridge 1994). Time scale from Haq et al. (1988).

(*sensu* Mack et al. 1993). Reddish paleosols are rare in BAT facies (Ardies 1999). This difference suggests that, overall, the Horsefly paleosols accumulated under conditions with a lower water table than did BAT paleosols. While factors such as the proximity to a river and/or the grain size and permeability of the sediment can have a significant influence on the level of the local water table (Kraus and Wells 1999), they cannot account for the consistent difference in the paleosols between the two units throughout their entire vertical and spatial extent. Therefore, we infer that there was a change in climate between the two units, the Horsefly having formed under drier conditions than the BAT.

It is perhaps significant that the marked change in valley morphology (from broad, flat-bottomed valleys in the Horsefly to the narrow BAT systems) occurred at the same time as the inferred climate change. Above, it was argued that this might reflect different durations of the lowstands, the BAT valleys having formed in a shorter time than the Horsefly valleys. It is also possible, however, that the drier climates that characterized the Horsefly favoured a more braided fluvial style, while the wetter conditions during BAT time led to the development of meandering rivers. Specifically, drier climates tend to be characterized by more variable discharges and smaller amounts of channel-margin vegetation (and hence lower bank stability), all of which favor the formation of braided rivers (Smith 1976; Baker 1978; Schumm et al. 1987). Such rivers might in turn have promoted the erosion of wider valleys than were produced by the meandering rivers that characterized the BAT.

Autogenic Factors

Schumm and Ethridge (1994) noted that valley floors are rarely flat, because of localized concentrations of energy that cause deeper scour. They identified three situations where this scour can occur: at constrictions in the valley, at the junction of tributaries with the main valley, and on the outside of channel or valley bends. All three situations are observed in the BAT valleys (Figs. 8, 9). The first of these has been discussed already and is represented by the deep scour in the trunk valley in T16–T17, where the river is interpreted to have incised through a contemporaneous uplift composed of Mississippian carbonates. Because this situation was created by externally imposed factors (i.e., fault movement and substrate consistency), it is considered allogenic in nature. By contrast, all river and valley systems contain tributary junctions and some degree of sinuosity; hence, the scours that occur at these locations are to some degree autogenic in origin.

Tributary-junction scours (TJS) and valley-bend scours (VBS) are present in several places in the BAT1 and BAT2 valley systems (Figs. 8, 9). TJS have been described from several modern fluvial systems (Bristow et al. 1993; Best and Ashworth 1997; see Cowan 1991 for an ancient example) and have a maximum water depth up to five times greater than that in nearby areas, because of the focusing of hydraulic energy at the confluence. The localized isopach thicks at such locations in the BAT valleys, with their higher proportion of coarser-grained sandstone, are precisely what would be expected, judging from the modern examples. VBS have been noted by several workers (e.g., Jackson 1976; Bridge 1985; see Pepper et al. 1954 for an ancient example) and originate because of the acceleration of flow around the outside of the bend. They have not been studied systematically, but they are probably not as deep as TJS (Best, personal communication 2001). Because sediment deposition in both TJS and VBS occur under conditions of higher-than-normal energy, the deposits within them make ideal petroleum-exploration targets.

SUMMARY AND CONCLUSION

The BAT unit contains two overall fining-up successions (BAT1 and BAT2) separated by a significant sequence boundary. Each sequence occupies a narrow (1–17 km wide), deeply incised (up to 45 m), northward-flowing, fluvial valley system that is characterized by a dendritic to rectangular drainage pattern. Each sequence begins with a multistory, channel conglomerate to sandstone succession, which was deposited by meandering fluvial and tidal–fluvial estuarine systems. These deposits are capped by a mudstone-dominated succession of terrestrial overbank to estuarine central-basin deposits.

The narrow nature of the valleys might be related to the short duration of the relative sea-level falls, which did not allow time for widening (excision) by hillside processes. The abundance of root traces and carbonaceous debris in the BAT suggests that a humid climate existed at this time,

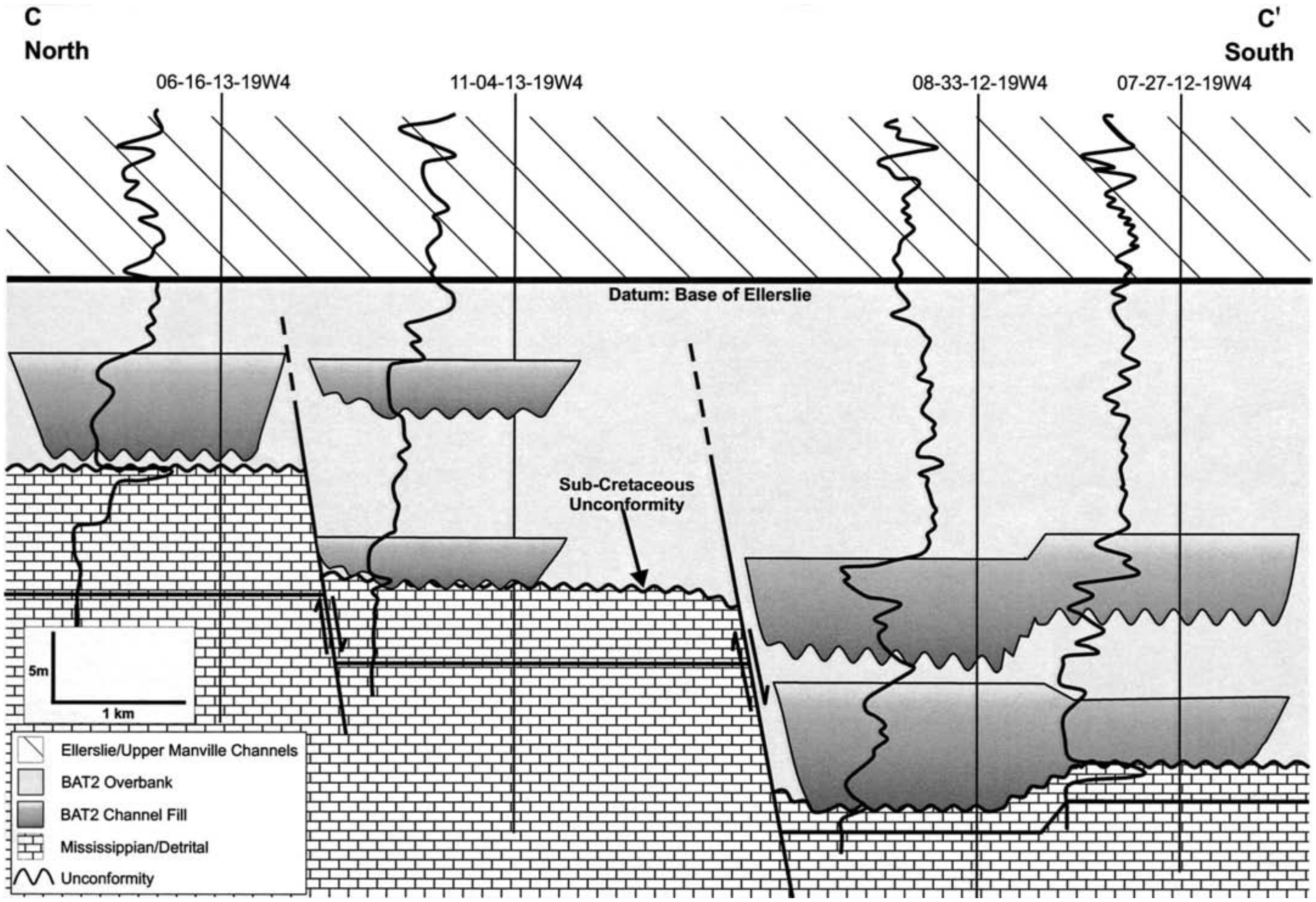

FIG. 15.—Penecontemporaneous local faulting during deposition of the BAT2 sequence; note offset of markers in the Mississippian succession. All log traces are gamma-ray curves. The higher proportion of channel deposits above the lowest fault block presumably occurs because the river preferentially flowed in the area of greatest local subsidence. See Figure 9 for line of section.

which favored the development of meandering rivers. This, together with the cohesion of the mudstone paleosols of the Horsefly unit into which the valleys were cut throughout much of the area, also promoted the development of narrow valleys.

The timing of valley incision may have been controlled by third-order eustatic, sea-level falls, but tectonic uplift appears to have played a major role in determining the depth of incision; the influence of tectonic movements on the timing of incision cannot be determined because of poor temporal control. The position and orientation of the trunk valley may have been determined by unfilled topographic relief associated with the preceding Horsefly valley system, the location of which was in turn controlled by regional foreland-basin subsidence, coupled with uplift of the Bow Island Arch to the east of the valley systems. Contemporaneous tectonic movement is implied by the westward shift of the valley headwaters between BAT1 and BAT2 times. The differential resistance to erosion of the substrate may also have influenced valley position, because the valley overlies the youngest and probably least lithified of the underlying units.

Contemporaneous faulting, related to thrust-induced loading and reactivation of basement structures, appears also to have had a major influence on the location and geometry of the BAT valley system. These faults, which are oriented NE–SW and E–W, determined the location and geometry of the two largest tributary systems. An anomalously thick and coarse-grained valley-fill succession accumulated where the trunk river cut through the constriction created by the largest uplifted block. Smaller faults also lead to the development of a quasi-rectangular valley pattern and abrupt changes in valley-fill thickness. Isolated, thick sandstone pods also occur at tributary junctions and the outside of valley bends, where fluvial energy is concentrated and scour is most pronounced. These features, which are up to five times thicker than adjacent valley-fill deposits, host well-sorted, coarse-grained sandstones that constitute ideal hydrocarbon reservoirs.

This study illustrates that the form of paleovalley systems is controlled by a complex interplay of many autogenic and allogenic factors, in the same way that modern river systems respond to a multitude of influences. Thus, such valley systems represent a significant source of information on the geological history of a region. Full understanding of the valley-system geometry is essential to the development of an effective hydrocarbon exploration strategy.

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