The Upper Cretaceous Vernal Delta of Utah—Depositional or Paleotectonic Feature?

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A conspicuous seaward bulge of the middle to late Turonian shoreline of the Cretaceous seaway in northeastern Utah and southwestern Wyoming has been identified by previous authors as the Vernal delta. Strata of the Frontier Formation and the Ferron Sandstone Member of the Mancos Shale that form the Vernal delta consist largely of fluviodeltaic facies. The delta, however, is not recognizable as a locus of Turonian sedimentation; there is no substantial isopach thickness associated with it. The Vernal delta was apparently a large feature, encompassing an area of at least 6250 mi^2 (16,250 km^2). Comparison between the depositional setting and paleogeography of northeastern Utah during the Late Cretaceous and a structurally similar present-day area on the east flank of the Andes in Colombia suggests that a feature the supposed size of the Vernal delta could not have been produced by a single river. Strata of the Vernal delta overlie the ancestral Uinta Mountain uplift, an area where Cenomanian marine shale was entirely removed by what appears to have been submarine erosion during early Turonian time. When the shoreline prograded eastward across this area during middle Turonian time, the sediment load caused the area to subside, but at a rate slower than rates of subsidence to the north and south. We hypothesize that this differential subsidence is the cause of the shoreline bulge. Although it includes deltaic facies, the Vernal delta was probably not an actual delta, but a feature produced primarily as the result of gentle tectonic movement of the ancestral Uinta Mountain uplift.

INTRODUCTION

Deltas have long been recognized as important depositional features in the stratigraphic record (Gilbert, 1885; Barrell, 1912). It has only been within the last 10–20 years, however, that a substantial body of information describing the diagnostic features of deltas has been available. This information has come primarily from studies of modern deltas, particularly that of the Mississippi River (see Wright, 1978, for a succinct description of the properties of deltas). The recognition and mapping of ancient deltas is an important matter for energy geologists inasmuch as they contain disproportionately large quantities of both oil and gas (Rainwater, 1975) and coal (Galloway and Hobday, 1983).

The substantial volume of information that exists regarding depositional processes, characteristics, and sediments of modern deltas facilitates recognizing deltaic facies in the stratigraphic record. But what are the criteria by which the outlines of ancient deltas can be distinguished and mapped? Moore and Asquith (1971) define a delta as "the subaerial and submerged contiguous sediment mass deposited in a body of water (ocean or lake) primarily by the action of a river." This is a broad definition; it avoids any statement about shape or size. Galloway and Hobday (1983) note that several important corollaries are implicit in this broad definition: (1) deltas are progradational (see also Wright, 1978); (2) the bulk of the sediments in a delta are delivered at one or more point sources, these being the mouth or mouths of the river; (3) delta systems develop around the margins of large basins; and (4) a delta system typically defines a locus of deposition. Defining an ancient delta in the subsurface usually requires, in practice, meeting two conditions: (1) Is there a recognizable shoreline bulge? (i.e., is there evidence of more rapid rates of progradation at the site of the delta than in adjacent areas?); and (2) If present, is the bulge associated with a greater isopach thickness? (i.e., is there a recognizable locus of deposition?)

A large number of authors have recognized deltaic deposits within strata that accumulated along the western margin of the interior Cretaceous seaway of western North America. In Utah and Wyoming, deltaic facies have been recognized and described by Katich (1953), Hale and Van de Graaff (1964), Maione (1971), Hale (1972), Thomaidis (1973), Cotter (1975), De Chadenedes (1975), Peterson and Ryder (1975), Myers (1977), Uresk (1979), Balsley (1980), Winn and Smithwick (1980), Ryer (1981), Lawrence (1982), and Fouche et al. (1983) among others. Few of these authors, however, have attempted to areally define the deltas in which the strata they studied were deposited. Among these few are Hale and Van de Graaff (1964) and Hale (1972), who defined and mapped two contemporaneous deltas of middle to late Turonian age in Utah and southern Wyoming (Figure 1). The northern of these, the Vernal delta, is the subject of this paper.

THE VERNAL DELTA

The Vernal delta, as described by Hale and Van de Graaff (1964), includes predominantly sandy strata of the Ferron Sandstone Member of the Mancos Shale in central and east-central Utah and the Frontier Formation in northern Utah and southwestern Wyoming. It is worth noting that initially the Vernal delta was not fully acknowledged in the literature. Hale and Van de Graaff (1964, p. 129) initially described it as "an eastward bulging deltalike feature" that they "somewhat arbitrarily termed the 'Vernal delta'." Hale (1972) was less hesitant in his naming of the Last Chance delta farther to the south in central Utah. He made no mention of the Vernal delta, however, in his 1972 paper.

It was not until 4 years later that Cotter (1976) elevated the hypothetical Vernal delta of Hale and Van de Graaff (1964) to a fully recognized feature, seeing in the autocyclic shifting of the delta a means of explaining some of the depositional features that he had observed in the lower part of the Ferron Sandstone Member on the flanks of the San Rafael Swell. Cotter did not, himself, study deposits of the Vernal delta, having restricted his studies to outcrops of the Ferron Sandstone Member in east-central Utah.

The sandy strata of the Vernal delta are underlain by offshore marine shale of the Tununk Shale Member of the Mancos Shale and its equivalents (Figure 2). These shales were deposited at the transgressive maximum of the Greenhorn cycle of Kauffman (1977), during which the shoreline of the Cretaceous seaway encroached westward nearly to the edge of the Sevier orogenic belt (Armstrong, 1968).

The regressive phase of the Greenhorn cycle, which culminated in deposition of the Vernal delta, is recognizable throughout the Western Interior of North America. In the area of this study, it is represented by the lower part of the Funk Valley Formation (Fouch et al., 1983), the Ferron Sandstone Member (Ryer and McPhillips, 1983), and the Frontier Formation (Hale, 1960; Ryer, 1977; Myers, 1977; Merewether, 1983; Merewether et al., 1983). Hancock (1975) and Hancock and Kauffman (1979) presented evidence that this middle to late Turonian regression can be recognized worldwide and attributed it to eustatic lowering of sea level.

The Vernal delta was bounded on the south by an embayment of the shoreline that existed in east-central Utah (Ryer and McPhillips, 1983). The easternmost position of the strand, as identified by the limit of coal-bearing rocks in the Ferron Sandstone Member and the Frontier Formation, defines a northeast-trending shoreline extending from the vicinity of Price, Utah, at the western edge of the Book Cliffs, through the Uinta basin, to the area of Vernal and Dinosaur National Monument, near the Utah–Colorado state line (Figure 3). From this area, the shoreline is believed to have trended northwestward (McGookey et al., 1972), although reconstruction of the northern edge of the delta is sketchy, mainly because of the lack of outcrop control on the thrusted northern flank of the Uinta Mountains. Thus defined, the Vernal delta covered an area that today includes much of the Uinta basin, the western part of the Uinta Mountains, and the southernmost part of the greater Green River basin. If the delta plain of the Vernal delta is considered to extend from the shoreline described above westward to the limits of the underlying marine shale, it covered an area of about 12,000 mi^2 (31,200 km^2).

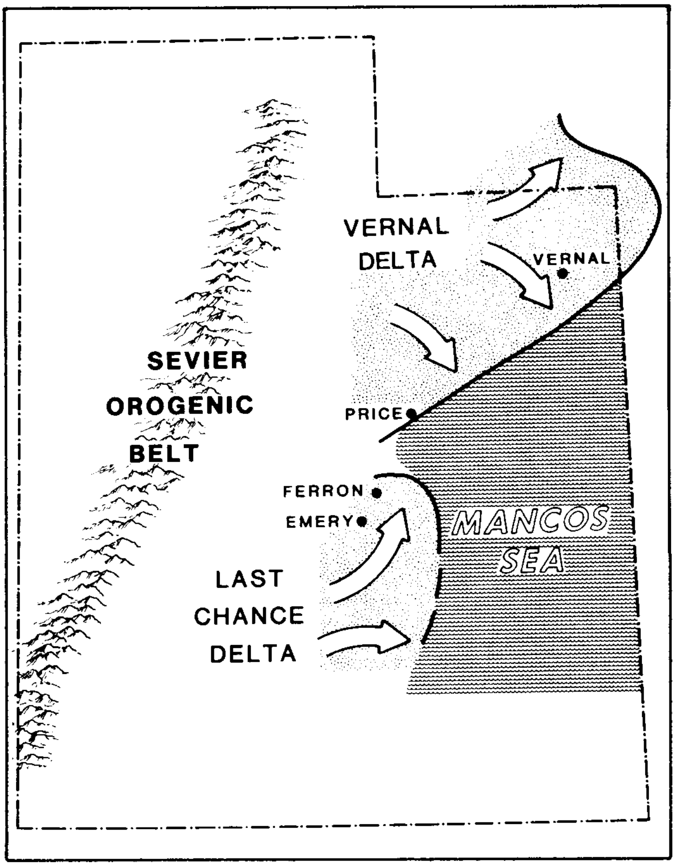

Figure 1—The Upper Cretaceous Vernal and Last Chance deltas. Arrows indicate inferred directions of sediment transport. Modified from Cotter (1976), who based his figure on paleogeographic maps by Hale (1972) and Hale and Van de Graaff (1964). Used with permission of the Department of Geology, Brigham Young University and the Utah Geological Association.

The strata of the Vernal delta constitute a clastic wedge that thins and interfingers eastward into marine shale. The properties of these rocks are best known from outcrops of the Frontier Formation along the south flank of the Uinta Mountains. The Frontier consists primarily of nonmarine rocks in the western part of this outcrop belt. Walton (1944) identified an area of extensive interfingering between the upper part of the Frontier Formation and the Mancos Shale in the Tabiona area. The older, lower part of the wedge extends eastward to Vernal (Figure 4), where substantial quantities of coal have been mined from the Frontier Formation (Doelling and Graham, 1972). Brackish water and fluvial beds disappear eastward in Dinosaur National Park (Maione, 1971) and only platy marine sandstone is present at Blue Mountain, just east of the Utah–Colorado border (Cobban and Reeside, 1952). The facies and depositional features described by these authors are entirely compatible with a deltaic origin for the Turonian portion of the Frontier Formation.

The isopach map in Figure 5, which incorporates selected data both from published outcrop studies and analysis of electric logs, shows the combined thicknesses of predominantly sandy delta front, delta plain and alluvial plain strata that compose the Vernal delta. The delta is best distinguished on the basis of the 100-ft (30-m) isopachous line. Outcrop data from east-central and northeastern Utah indicate that this line approximates the seaward limit of coal-bearing strata; uncertainty exists regarding the position of the shoreline on the northern flank of the delta. Although recognizable as a seaward bulge of the shoreline, the Vernal delta did not coincide with a major locus of sediment accumulation.

It is important to keep in mind that Figure 5 is a facies isopach map; the form of the Vernal delta would certainly be less distinct and might even disappear entirely if time-equivalent marine shale deposited to the east of the sandy deltaic facies was included in the isopached interval. Unfortunately, the detailed biostratigraphic or chronostratigraphic information required to construct such a map does not presently exist.

The absence of a pronounced depocenter associated with the Vernal delta is surprising, considering the supposed tremendous size of the feature. Although the existence of a shoreline bulge constitutes evidence that the Vernal delta is truly a delta, the absence of a well-defined depocenter associated with it contradicts one of the basic properties of deltaic sedimentation and casts doubt on the validity of the deltaic interpretation.

A Question of Size

As noted earlier, the Vernal delta was a very large feature that extended as much as 115 mi (185 km) in the dip direction and about 130 mi (210 km) in the strike direction and that formed a delta plain that covered an area of approximately 12,000 mi^2 (31,200 km^2). Even if the area of the Vernal delta is more conservatively measured as that part of the regressive wedge contained within the shoreline bulge itself and limited on the seaward side by the 100-ft (30-m) isopachous line (as in Figure 5), it would still have had an area of approximately 6250 mi^2 (16,250 km^2).

Is it possible that a single river draining eastward from the Sevier orogenic belt into what is now northeastern Utah and southwestern Wyoming could have produced a feature as large as the Vernal delta? A useful comparison can be made with the rivers that exist today on the eastern flank of the Andes in South America. Figure 6 pictures the approximate situation that would exist in South America if eustatic sea level were to rise about 1600 ft (500 m), as it did in the Cretaceous. Such a sea level rise would flood much of South America, producing an epeiric seaway strikingly similar to that which occupied the Western Interior of North America during Cretaceous time (compare witn paleogeographic maps by Williams and Stelck, 1975). A Cretaceous sea level rise of about 1700 ft (510 m) was calculated by Hays and Pitman (1973), although Pitman (1978) later revised the figure downward to about 1150 ft (345 m) above present sea level. Hancock and Kauffman (1979) speculated that Cretaceous sea level may have reached as much as 2100 ft (630 m) above its present level.

Even allowing for differences in latitude, climate, and types of vegetation, the rivers that flowed eastward from the Sevier orogenic belt during Cretaceous time could not, we believe, have been too much different than those that now occupy the eastern flank of the Andes. In Figure 7, the Vernal and Last Chance deltas are superimposed on portions of Colombia, Ecuador, and Peru. This location was chosen because the curve of the Andean mountain chain that occurs just south of the Colombia–Ecuador border is strikingly similar to the curve of the Sevier orogenic belt associated with the Grand Canyon Bight in northernmost Arizona (Stokes and Heylmun, 1963; Moir, 1974). If the spacings of Cretaceous rivers in northern Utah and southwestern Wyoming in fact resembled those of the rivers that today exist on the east flank of the Andes, it seems highly unlikely that the Vernal delta could have been formed by just one river. But if the feature was formed by more than one contemporaneous river, can it be considered a delta? More importantly, why should such a large delta exist when the paleogeography reconstructed for the area indicates that it should have included numerous small rivers whose headwaters lay no more than about 250 mi (400 km) to the west? A possible answer lies in the paleotectonic setting of the Vernal delta.

THE UNCONFORMITY AT THE BASE OF THE FRONTIER

An unconformity lies at the base of the Frontier Formation in the vicinity of the Uinta Mountains (Figure 8). On the northern flank of the Uintas at Flaming Gorge (Kinney, 1955), along the southern flank of the Uinta Mountains (Walton, 1944; Cobban and Reeside, 1952), and eastward into Colorado (Reeside, 1955; Weimer, 1962; Sharp, 1963), the lower marine shale unit of the Frontier, which contains fossils of middle Turonian age, unconformably overlies the upper Albian Mowry Shale. Merewether et al. (1983) have demonstrated that this unconformity extends throughout much of south-central Wyoming. There the time span of the unconformity is much less, however, and it is more difficult to recognize. The westward extent of the unconformity is unknown. It is possible, as speculated by Merewether (1983; see also Merewether et al., 1984), that the rapid eastward disappearance of the Chalk Creek and Coalville Members of the Frontier Formation between the Overthrust Belt and the southern part of the Moxa Arch may be the result of bevelling of these units against the unconformity (as indicated in Figure 2). Similarly, the southward extent of the unconformity within the Uinta basin remains unknown. The absence of the distinctive zone of *Pycnodonte newberryi* and the presence of a bed of chert pebble conglomerate at the top of the Dakota Sandstone in the vicinity of the San Rafael Swell of east-central Utah (Katich, 1954) indicate that it extends that far to the south, although the time span represented by the unconformity in this area is certainly small compared to that in the area of the Uinta Mountains.

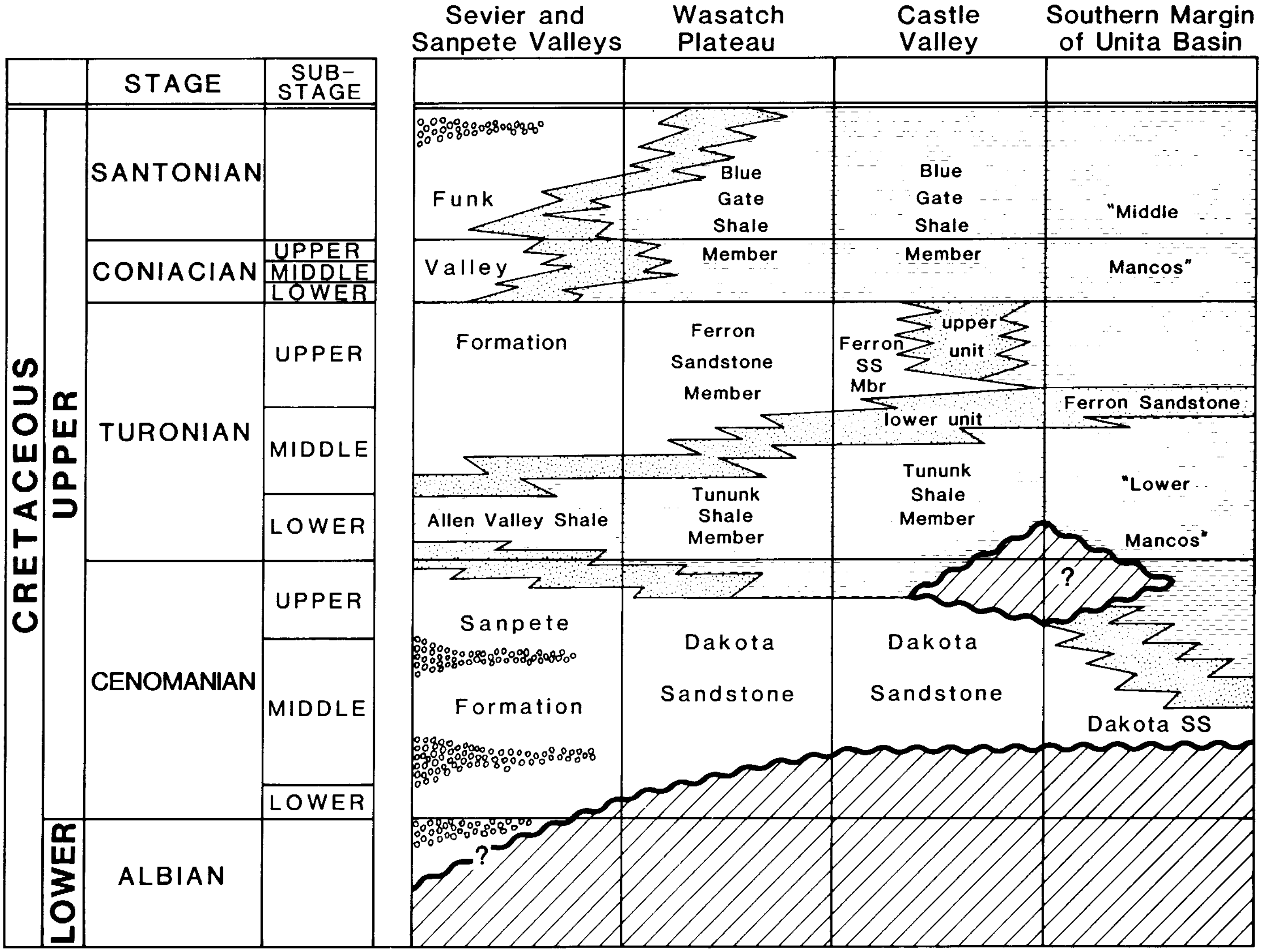

Figure 2—Correlation diagram showing stratigraphic positions and ages of units contained in and associated with the Vernal delta. Coniacian age units in the Coalville area are highly generalized.

Weimer (1962) and, more recently, Merewether (1983) utilized subsurface data from areas adjacent to the eastern end of the Uinta Mountains to demonstrate that the unconformity between the Frontier Formation and the underlying Mowry Shale is angular and that as much as 300 ft (90 m) of Cenomanian (Belle Fourche age) marine shale had been uplifted and eroded prior to Frontier deposition. Weimer (1962, p. 129) postulated that this erosion was the result of gentle upwarping of an "embryonic Uinta Mountain uplift." An isopach map (Figure 9) of the thickness of the marine shale unit that underlies the regressive wedge of the Vernal delta delineates this ancestral Uinta uplift. Such an isopach map is made possible by the fact that the contact between the highly siliceous Mowry Shale and the overlying nonsiliceous Frontier shale is relatively easy to recognize both in outcrop (Figure 4) and on electrical logs (Figure 8). Although there can be little doubt that the erosion of Cenomanian shale resulted from crustal upwarping, the agent or agents of erosion remain unclear. Nowhere has evidence of subaerial erosion or weathering on this surface been found. Very low relief on the erosional surface and an absence of fluvial strata, soils, and transgressive lags suggest that the unconformity was of submarine origin.

A likely scenario (Figure 10) is that the upwarping of the ancestral Uinta uplift occurred during early Turonian time when the shoreline of the Cretaceous seaway lay far to the west. The upwarp produced an east-west-trending shoal area where Cenomanian marine shale was gradually stripped as it was elevated to water depths where wave-induced currents were capable of regularly working the bottom. The absence of any sandy deposits on the surface of the unconformity apparently indicates that the shoal must have been separated from the contemporaneous shoreline by an area of deeper water, precluding introduction of sand to the shoal. This area of deeper water probably coincided with the area of pronounced thickening of the marine shale section evident in Figure 9. This greater isopach thickness marks the

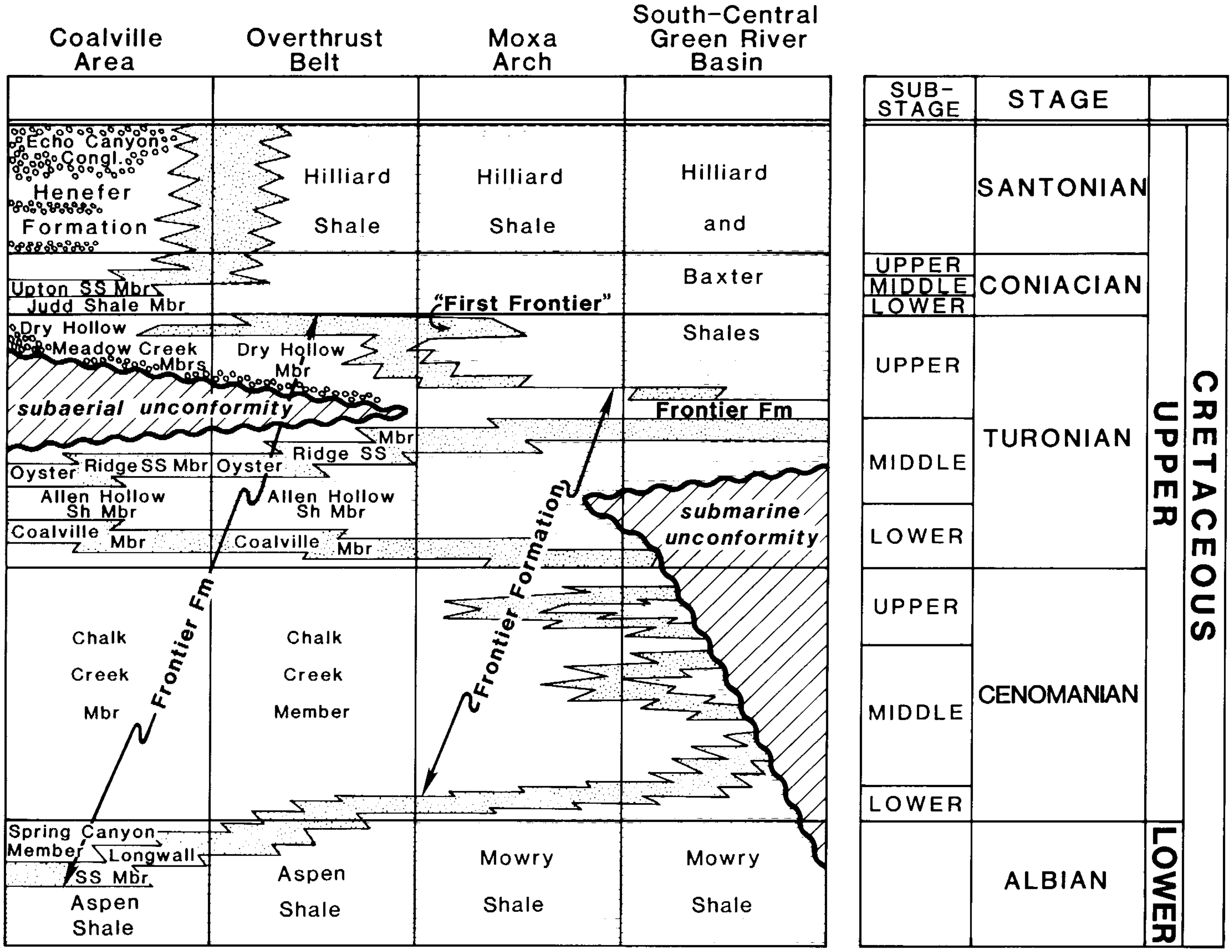

Figure 2—(continued).

eastern edge of the foreland basin that developed immediately to the east of the Sevier orogenic belt. Thinning of the shale to the west of the isopach thickness is the result of a facies change to shoreline and nonmarine facies.

PALEOTECTONIC CONTROL OF THE VERNAL DELTA

If the unconformity at the base of the Frontier developed as described above, a quite different explanation for the origin of the feature known as the Vernal delta becomes possible. A comparison of Figures 5 and 9 indicates that strata of the Vernal delta immediately overlie the ancestral Uinta uplift. The superposition of these two features strongly suggests that they share a common causal mechanism, this mechanism possibly being gentle tectonic upwarping during Cretaceous time of the area overlying the present-day Uinta Mountains.

By way of explanation, we continue the scenario begun in the preceding section as follows. Immediately after the transgressive maximum of the Greenhorn cycle in early middle Turonian time, the shoreline of the interior Cretaceous seaway began to shift eastward. The regression was the result of two factors: eustatic lowering of sea level and an abundant supply of clastic sediment delivered by the numerous small rivers that drained the Sevier orogenic belt. Having gradually prograded eastward across the subsiding foreland basin, the shoreline encountered the area of the ancestral Uinta uplift. The arching of this structure had decreased by this time, and it was no longer an area of uplift and erosion. The change from erosion to deposition, in fact, was probably the result of crustal loading by the weight of sediments in the eastward-extending clastic wedge (Jordan, 1981). Nonetheless, the ancestral Uinta uplift remained

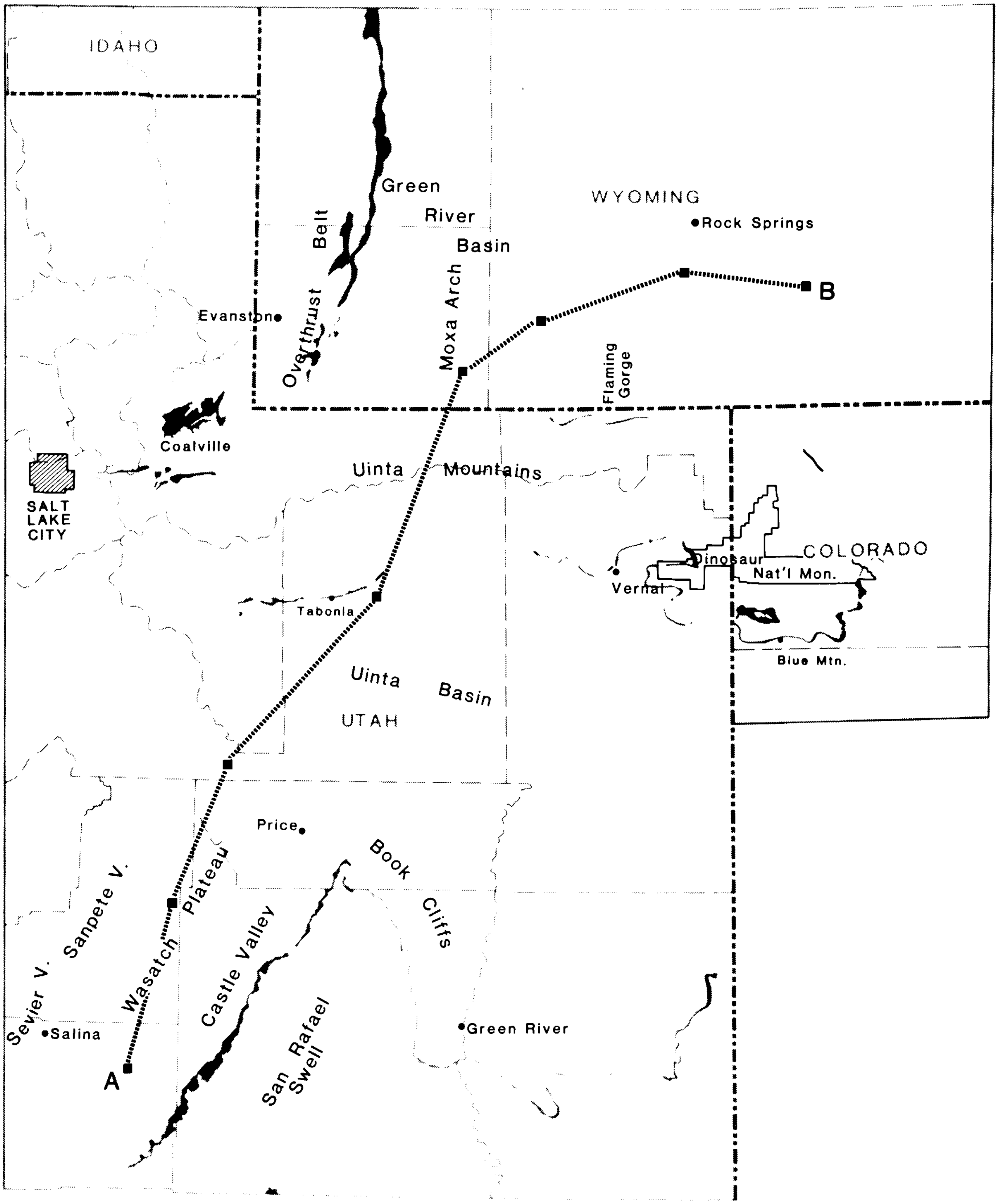

Figure 3—Map showing the location of the study area and identifying the localities and geographic features referred to in the text. The location of stratigraphic cross section A–B in Figure 8 is indicated.

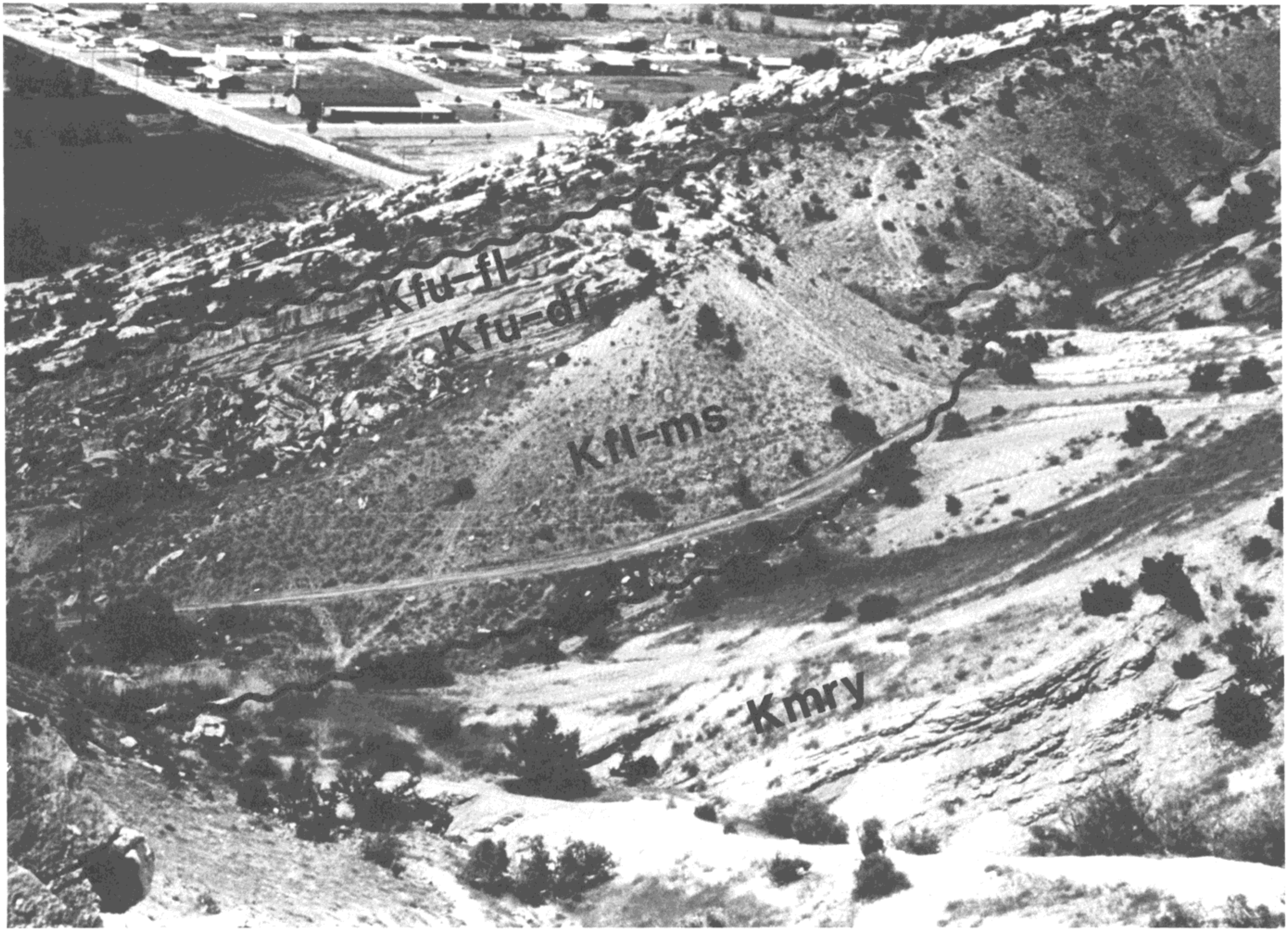

Figure 4—Exposures of the Mowry Shale and the Frontier Formation near Vernal, Utah. Light-colored, siliceous shale of the Mowry (Kmry) is unconformably overlain by drab marine shale of the lower part of the Frontier (Kfl-ms). Flat-bedded delta front sandstone of the upper part of the Frontier (Kfu-df) forms the prominent ledge; it is erosionally overlain by more massive fluvial sandstone deposited by a meandering channel (Kfu-fl). The uppermost, coal-bearing strata of the Frontier do not appear in this photo.

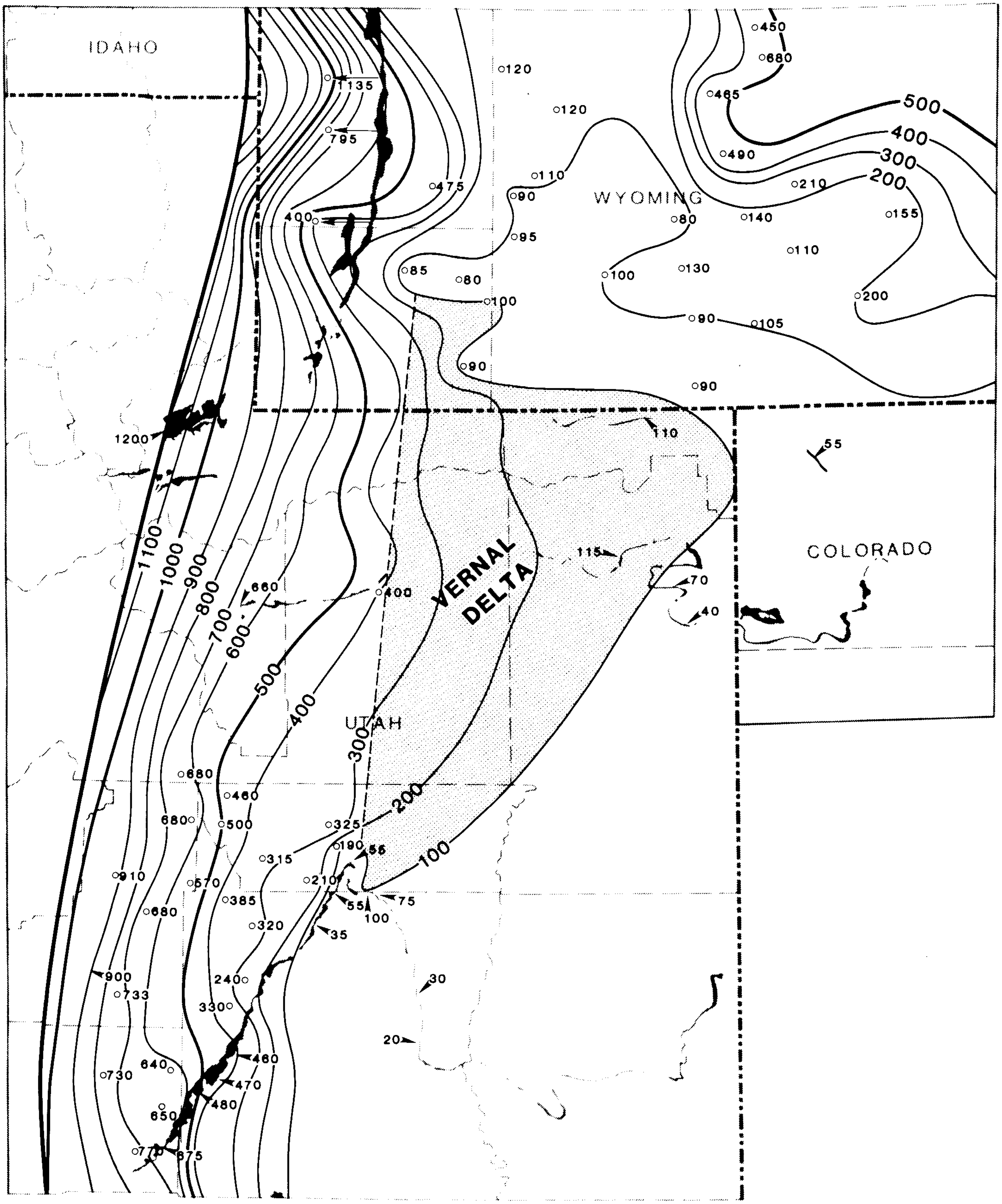

Figure 5—Isopach map (contour interval in feet) of predominantly sandy strata that compose the Turonian–Coniacian clastic wedge: the Ferron Sandstone Member; the upper part of the Frontier Formation; and in the Overthrust Belt, the Oyster Ridge, Dry Hollow, and Meadow Creek members of the Frontier. Shading indicates the area, conservatively defined, of the deltaic plain of the Vernal delta at the peak of regression. The heavy line that truncates the isopachous lines marks the western limit of the marine shale of the Niobrara cycle; the Turonian–Coniacian clastic wedge cannot be distinguished west of this line.

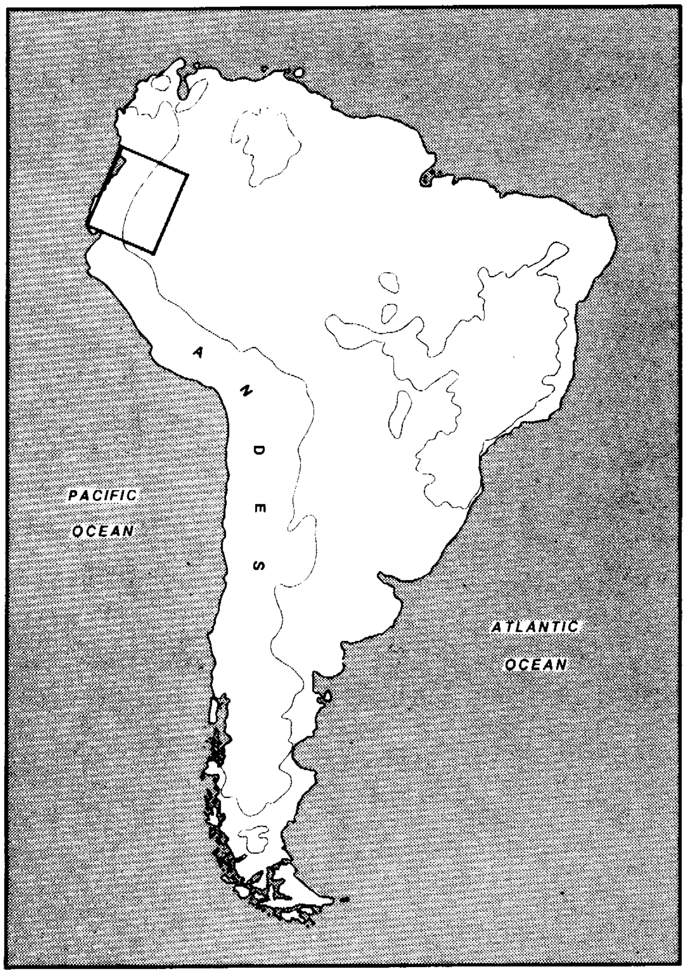

Figure 6—Shading indicates approximate area of South America that would be flooded by a 1650 ft (500 m) rise in sea level. No attempt has been made to compensate for subsidence that would result from isostatic loading by water. The hypothetical shoreline is approximately the present-day 1650 ft (500 m) contour. The shoreline position has been smoothed across valleys to simulate the effects of fluvial aggradation during sea level rise. Box indicates the location of Figure 7.

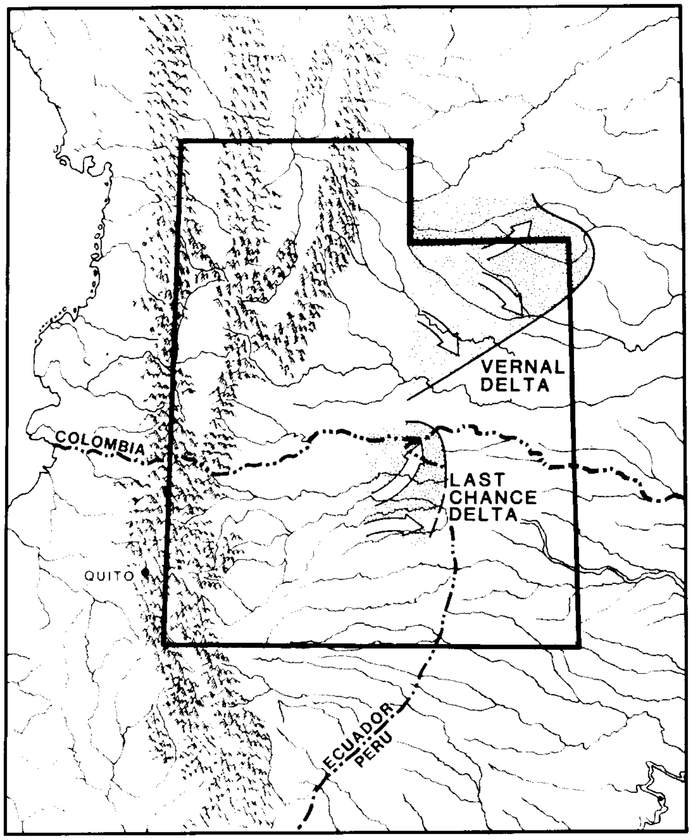

Figure 7—The Vernal and Last Chance deltas superimposed on the eastern flank of the Andes. The Cretaceous Sevier orogenic belt is made to coincide with the location of the Andes. The outline of Utah is added to aid in orientation.

slightly positive relative to adjacent areas; it subsided less rapidly than did areas to the north and south, as evidenced by thinning (possibly reflecting an onlapping relationship) of the marine shale unit of the Frontier in the vicinity of the uplift (Figures 8 and 9). As the shoreline encroached eastward onto the ancestral Uinta uplift, the shoreline began to bulge seaward. The bulge continued to grow as progradation continued, reaching the eastern edge of the ancestral Uinta uplift before being transgressed by the sea in late Turonian–early Coniacian time.

The transgression that marked the demise of the Vernal delta, and that marked the beginning of the Niobrara transgressive–regressive cycle (Kauffman, 1977), was primarily the result of rising sea level. The initial westward transgression of the sea across the Vernal delta was rapid. It was followed by a period of gradual transgression characterized by extensive interfingering between deltaic and offshore marine deposits (Figures 2 and 8). Outcrop data from east-central (Ryer, 1981) and northeastern Utah (Walton, 1944) indicate that the position of the shoreline at the time this interfingering occurred approximately coincides with the 400-ft (120-m) isopachous line on Figure 5. The form of the Vernal delta is not recognizable on the basis of this line, indicating that the feature had ceased to exist by late Turonian time. Only strata in the lower part of the Turonian–Coniacian clastic wedge contribute to the Vernal delta.

The Vernal delta, we believe, owes its origin to the slower rates of basin subsidence that prevailed in the vicinity of the ancestral Uinta uplift during middle Turonian time. A given volume of sandy sediment will produce a blanket that is thinner but more extensive in an area of slower subsidence. In the case of the ancestral Uinta uplift, predominantly sandy sediment delivered eastward by rivers from the Sevier orogenic belt produced a thinner but more widespread clastic wedge within the area of more gradual subsidence associated with the uplift. It must be noted that this conclusion is not borne out by the isopach map of the clastic wedge presented in Figure 5. This map, however, isopachs the entire clastic wedge rather than just its lower part, and as noted above, the Vernal delta is recognizable only in this part. Until such

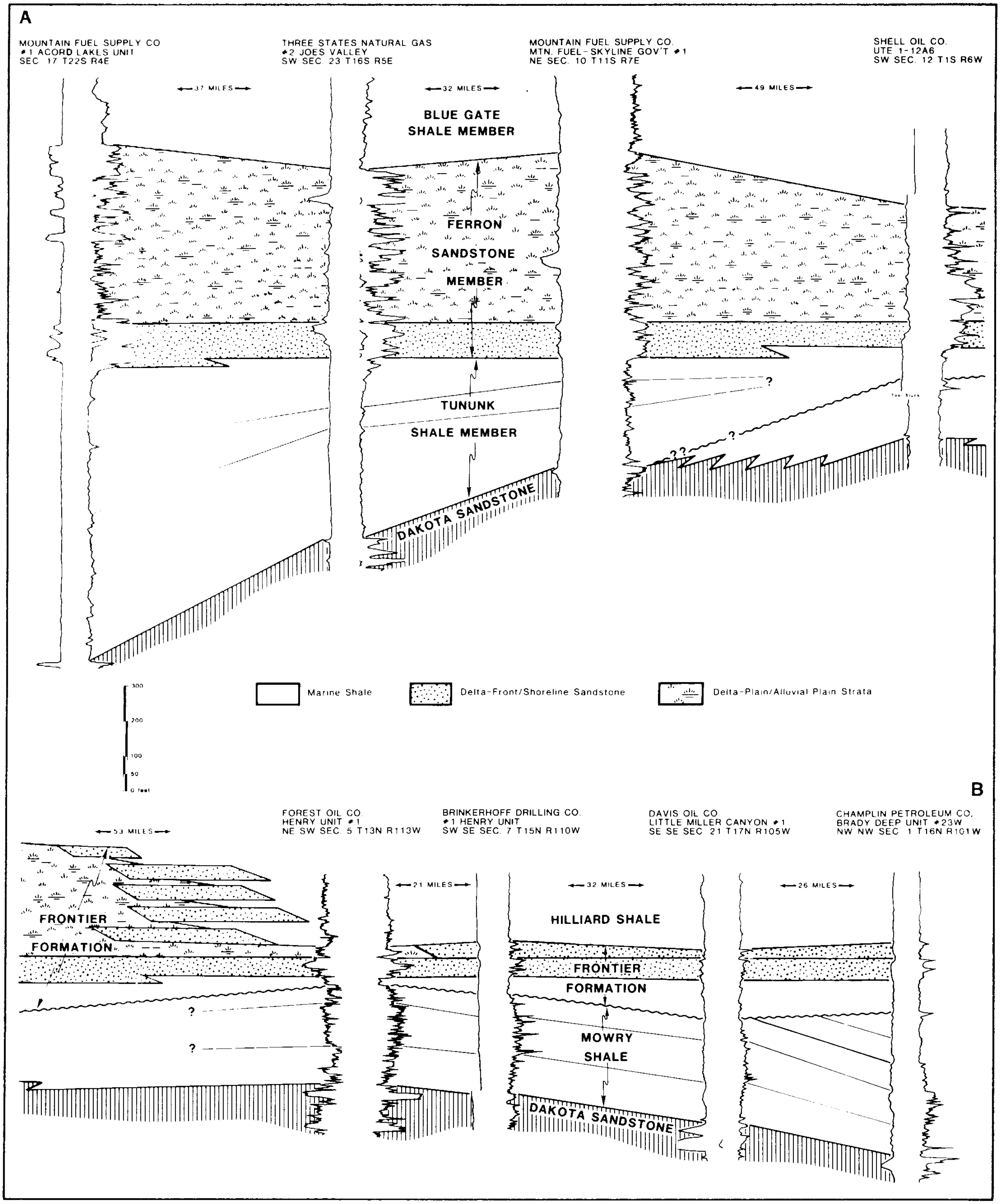

Figure 8—Electric log cross section showing the stratigraphic relationships, including interpreted relationships across the present-day Uinta Mountains, between units in and associated with the Turonian–Coniacian clastic wedge in Utah and Wyoming. The location of the cross section is shown in Figure 3.

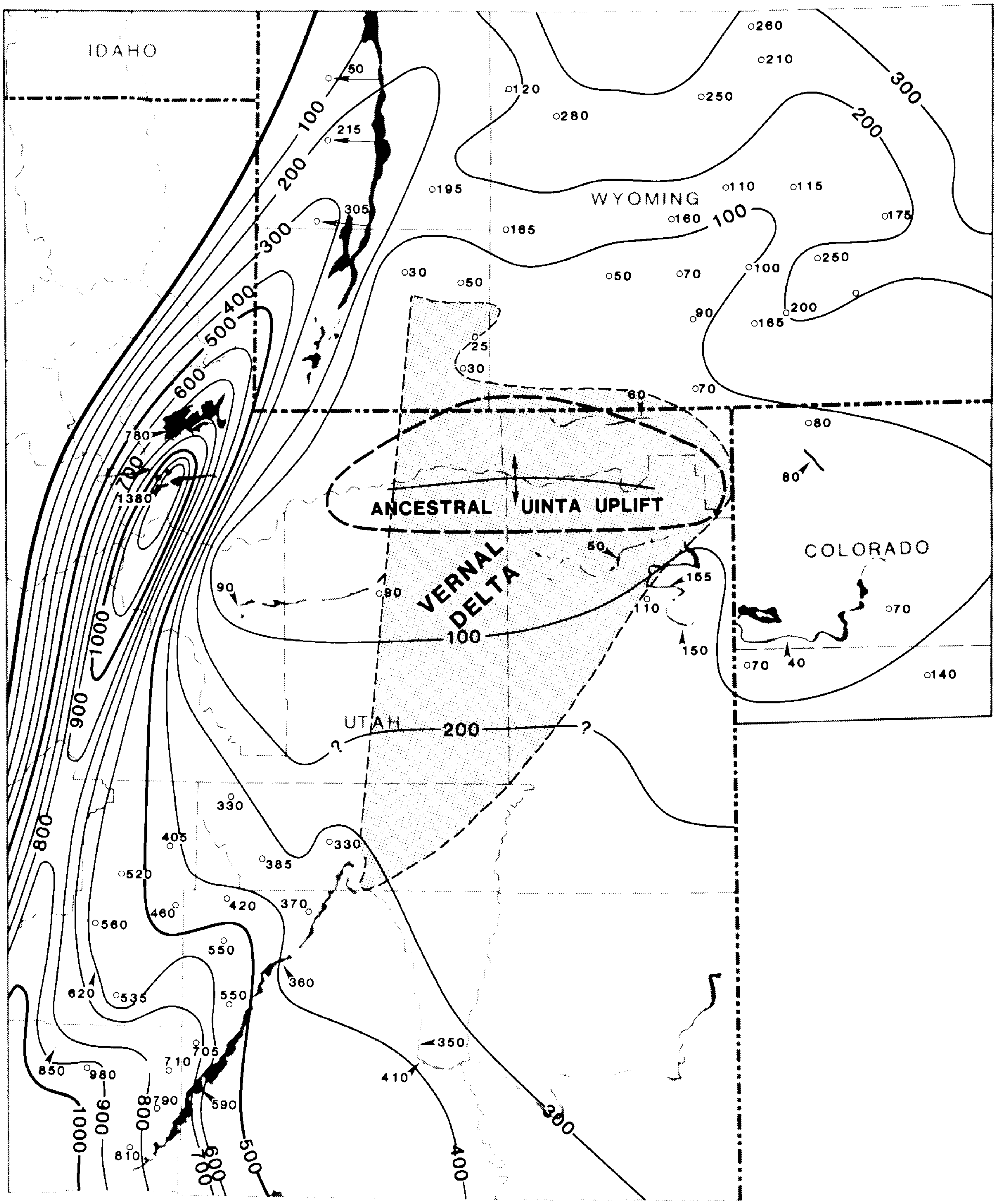

Figure 9—Isopach map of the Upper Cretaceous marine shale interval that underlies the Turonian–Coniacian clastic wedge: the Tununk Shale Member, the "lower Mancos" shale, the lower shale unit of the Frontier, and the Allen Hollow Shale Member of the Frontier. The ancestral Uinta uplift coincides with an area of pronounced thinning of this shale interval. The shaded area, as in Figure 5, is the deltaic plain of the Vernal delta.

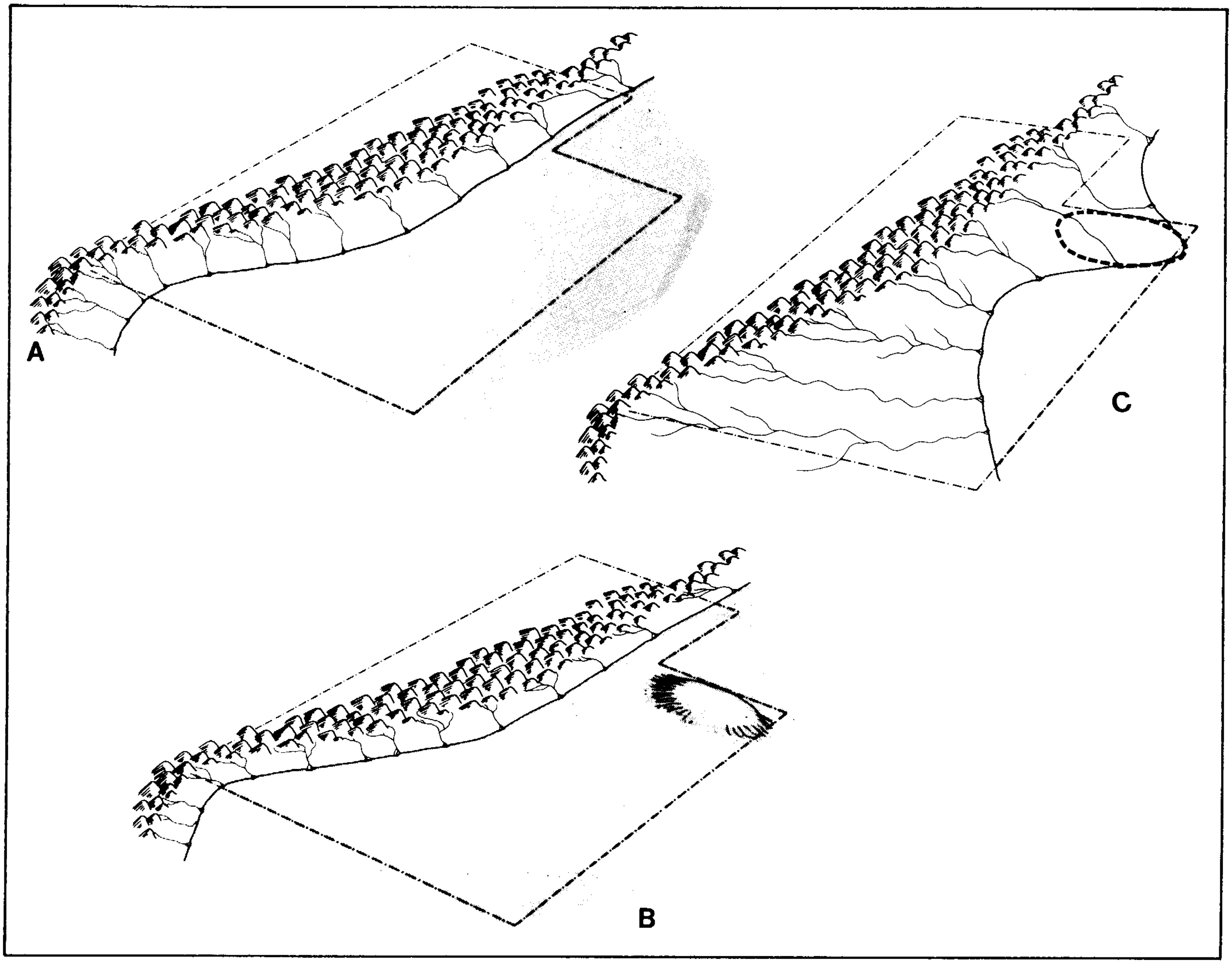

Figure 10—Diagrammatic representation of the formation of the Vernal delta. A. The Greenhorn transgression, which reached its peak in early Turonian time, caused the Cretaceous epeiric sea to encroach nearly to the edge of the Sevier orogenic belt. B. Upwarping of the ancestral Uinta uplift, possibly as a result of eastward compression associated with the Sevier orogeny, led to erosion of previously deposited marine shale. Erosion may have been entirely submarine; alternatively, the surface of the uplift may have risen above sea level. In either case, the presence of deeper water between the shoreline and the uplift apparently precluded introduction of sand to the area of the uplift. C. Eastward progradation of the shoreline during middle Turonian time and subsequent loading of the crust resulted in subsidence of the ancestral Uinta uplift, but at a somewhat slower rate than in adjacent areas. The shallower and more slowly subsiding area accumulated a thinner layer of the sediment than did areas to the north and south. The result was the eastward bulge of the shoreline identified as the Vernal delta.

time as sufficient data exist to facilitate mapping of the lower part of the Turonian–Coniacian clastic wedge throughout the study area, the proposed relationship between rates of subsidence and the thickness and lateral extent of this part of the wedge must remain hypothetical.

Although presently unprovable, the hypothesis that the Vernal delta owes its origin to the ancestral Uinta uplift satisfactorily explains the superposition of these two features. It accounts for the absence of a pronounced depocenter associated with the "delta" and is entirely compatible with more than one river supplying sediment to the shoreline bulge. Despite the fact that the Vernal delta may consist largely or even predominantly of deltaic sediments, it was probably not an actual delta, but rather a feature that was primarily attributable to its tectonic setting.

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