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HISTORY, SEDIMENTOLOGY, AND TAPHONOMY OF FELCH QUARRY 1 AND ASSOCIATED SANDBODIES, MORRISON FORMATION, GARDEN PARK, COLORADO

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Felch Quarry 1, north of Cañon City, Colorado, has produced the largest number of vertebrate type specimens of any single Morrison Formation dinosaur locality. The site was first quarried in 1877, and has produced ten vertebrate holotypes, including the dinosaurs *Allosaurus fragilis*, *Ceratosaurus nasicornis*, *Diplodocus longus*, *Haplocanthosaurus priscus*, and *Stegosaurus stenops*. The bones were found in two coarse-grained, arkosic sandstones separated by a fine-grained mudstone. The sandstones are part of a large, broadly lenticular sandstone body trending towards the southwest (about 210°). The quarry is in the upper of 4 lenticular sandstone bodies that had paleocurrent flows to the southeast and to the southwest. All the sandstones were deposited by laterally shifting streams with moderate sinuosity as shown by the geometry of crossbeds and very large-scale inclined stratification dipping toward the margins of the sandbodies. The bones in Quarry 1 accumulated in a basal channel lag and at the base of a channel scour that was covered by a point bar. Based on the degree of skeletal disarticulation, the site is the result of attritional and noncatastrophic mass mortality.

Keywords: Felch Quarry; Morrison Formation; Sedimentology; Attritional accumulation; Noncatastrophic mass mortality

INTRODUCTION

One of the most historically important dinosaur localities in the Morrison Formation is Felch Quarry 1 on the south end of Garden Park, 11 km north of Cañon City, Colorado (Fig. 1). Located about 48 m above the

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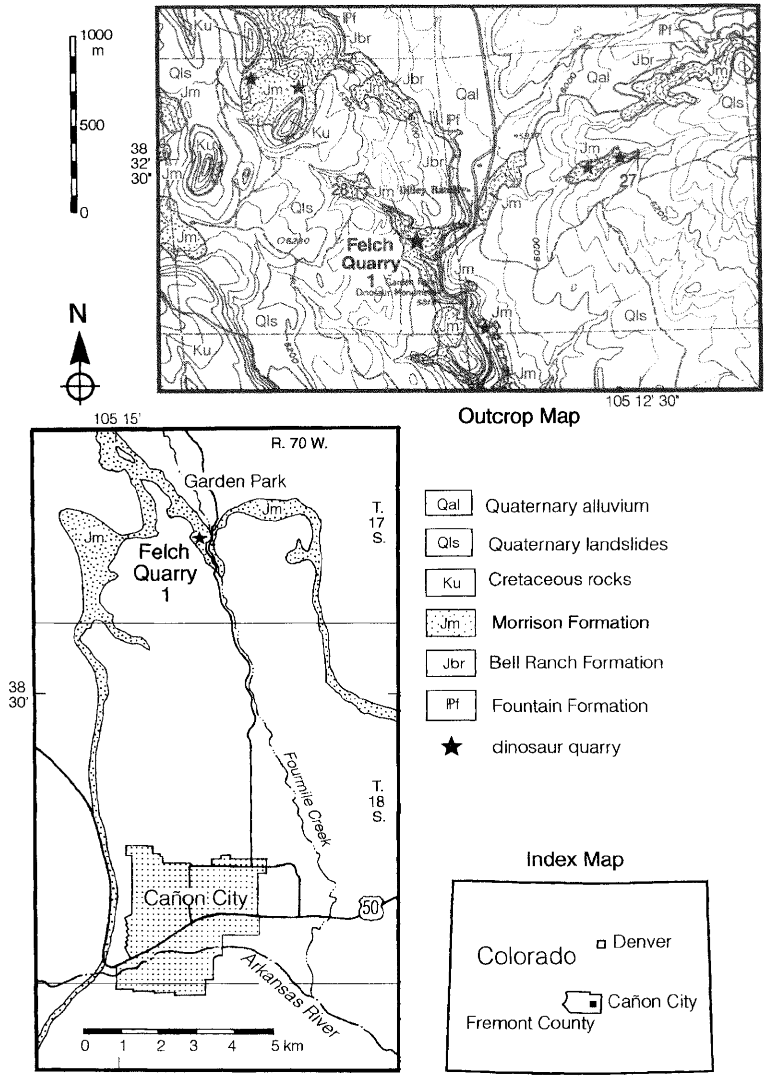


FIGURE 1 Location map of the Felch Quarries 1 and 2, plotted on the surfical geologic map of the Garden Park dinosaur area (Evanoff and Kuntz, 1987).

base of the Morrison, the quarry has produced ten vertebrate holotypes, including eight dinosaurs (three are now considered *nomen dubium*). Dinosaur species diversity is high ($n = 13$), making this one of the most species-rich quarry the Morrison.

Some of the best-known specimens of dinosaur skulls and skeletons came from this quarry, and are currently on display at the National Museum of Natural History. These include the holotypes of *Stegosaurus stenops* and *Ceratosaurus nasicornis*, the paratype skeleton of *Allosaurus fragilis*, and the skull of *Diplodocus longus*. Other holotypes include the dinosaurs *Haplocanthosaurus priscus*, *H. utterbackii*, "*Morosaurus*" *agilis*, *Labrosaurus ferox*, the fish *Ceratodus guntheri*, and the pantothere *Kepolestes coloradensis*.

Mass accumulations of dinosaurs in bone beds are common in the Morrison Formation (Dodson *et al.*, 1980). Similar to the quarry sandstone at Dinosaur National Monument, Felch Quarry 1 is in the base of a broadly lenticular sandstone body, and represents the accumulation of bones in an ancient river channel. The distribution of bones, geometry of the surrounding sandstone body, and the internal stratification within the sandstones give clues to the origin of the bone accumulation.

HISTORY OF STUDIES

The site that was to become Felch Quarry 1 was discovered by Henry Felch in 1869 or 1870 (Schuchert and LeVene, 1940). Henry was the brother of Marshall P. Felch, who was to work the quarry for Othniel C. Marsh of Yale University. Marsh, however, did not learn of the discovery until 1877 when he sent one of his collectors, Benjamin Mudge, to investigate Denver newspaper accounts of large bones being found near Cañon City. Mudge discovered that these bones were being collected for Philadelphia paleontologist Edward D. Cope. Fortunately for Marsh, Mudge soon met a man who knew of other bone localities (Mudge, August 12, 1877, letter to Marsh). On August 18, 1877, Mudge began excavating one of these sites that would become the Felch Quarry.

The bones at this site were in a yellow sandstone (see below) above a cliff formed on the north side of an arroyo feeding into Four Mile Creek (also known as Oil Creek). By late August, 1877, Mudge, Felch and Walter Weld were excavating and shipping various large bones and vertebrae to Marsh (Mudge, letters to Marsh, August 17–October 7, 1877). Many of the bones excavated were near the ground surface and were in poor condition. Mudge wrote to Marsh asking for the assistance of another of Marsh's collectors, Samuel W. Williston, to draw the bones they were not able to save. Once Williston arrived in Cañon City in September, 1877, he, Mudge, and Felch expanded the quarry along the cliff face. They soon uncovered numerous bones but were able to salvage only a portion of them because the bones were so deeply weathered. Frustrated at the poor recovery, Williston encased some of the bones in paper and flour paste bandages (Williston, September 26, 1877, letter to Marsh). Mudge departed for home in early October. Left alone, Williston was impatient with quarry work and spent time prospecting for new sites (Williston, September 26, 1877, letter to Marsh). Nothing significant was found and he joined Arthur Lakes at Morrison, Colorado (Williston, October 27, 1877, letter to Marsh). Although only a few months were spent excavating at the Felch Quarry, Marsh named *Diplodocus longus* and *Allosaurus fragilis* from material collected (Marsh, 1878; 1879).

It was several more years before work was renewed at the quarry. On March 30, 1882, Marsh wrote Felch about the possibility of Felch collecting for him in Garden Park. In reply, Felch recommended that the old quarry be reopened (Felch, April 22, 1882, letter to Marsh). Felch immediately began excavating some of the bones uncovered in 1877, but it was a year before Marsh hired Felch full time. By 1879, Marsh had accepted the position of Vertebrate Paleontologist for the US Geological Survey that gave him access to a considerable amount of support money for his field crews and laboratory technicians. With this money, Marsh was able to hire Felch to excavate the quarry for the next five years. The results were considerably better than in 1877, with over 270 crates of fossils shipped to Marsh.

A second, smaller quarry (Felch Quarry 2) was opened in 1883 across the arroyo from the main quarry (Fig. 1), but most of the collecting there was not done until 1888. The specimens from Quarry 2 were destroyed in December, 1888, by George Bronson who was feuding with Felch's oldest son (Felch, February 10, 1891, letter to Marsh). The quality and number of specimens was less than Felch had originally anticipated (Felch, November 23, 1888, letter to Marsh) and little additional work was done the following year.

Initially at Quarry 1, Felch excavated each bone as he was taught by Mudge and Williston. As each bone was exposed, it was covered with cloth pasted to the surface (Felch, October 19, 1883, letter to Marsh). Despite this precaution, many bones were lost or damaged the first year, and the fragments were thrown over the edge of the quarry. Marsh became concerned about the loss of material and had Felch recover the fragments that had been thrown into the spoils pile (Felch, March 12, 1884, reply letter to Marsh). Felch began to use a sodium silicate solution as a hardener at Marsh's suggestion (Felch, October 30, 1883, letter to Marsh), and gum arabic the following year. He also began removing the bones in blocks of sandstone. These blocks and their bones, which Felch had exposed on the surface, were drawn to show how the blocks fitted back together for preparation (Felch, October 25, 1883, letter to Marsh).

Felch continued to work the quarry for Marsh on a year by year basis. However, on October 1, 1887, Felch wrote to Marsh that he "had come to the conclusion that our old quarry, that has produced so many good – & indifferent specimens – is about 'petered out.'" Nevertheless, Felch continued working the quarry for another year (letters to Marsh). Surprisingly, John Hatcher, of the Carnegie Museum of Natural History, was to quote Felch years later as claiming that the amount of bone left in the quarry was still high (Hatcher, May 9, 1900, letter to Holland).

John Hatcher, who had been another of Marsh's collectors, reopened the quarry twelve years later for the Carnegie Museum of Natural History. Hatcher sent William Utterback to reopen Felch's Quarry 1 in November 1900. Utterback interviewed M.P. Felch and two other men who had worked the quarry and was able to concentrate on what was supposed to be the main bone deposit (Utterback, November 17, 1990, letter to Hatcher). Utterback and a small crew of local men worked less than a year with modest results. The most important specimens were two partial sauropod skeletons Hatcher (1903a,b) named *Haplocanthosaurus priscus* and *H. utterbackii.*

The earliest interpretation of the origin of the bone bed was by M.P. Felch in his letters to Marsh. By 1883, Felch recognized that the deposits were fluvial, and in 1887 suggested the animals had been trapped in a "mire hole" (Felch October 1, 1887, letter to Marsh). Hatcher (1901, p. 335) elaborated on this idea, and suggested the stream had cut into impermeable clay and that the resulting "bog or bed of quicksand" at the bottom of the stream had trapped the animals. Felch drew sketches of the stratigraphic sequence in the quarry, but Mook (1916, pp. 116–118) was the first to publish the sequence and draw a diagrammatic cross section through the quarry. Mook also interpreted the bone accumulation to be within a stream. Brady (1967, 1969) interpreted the lenticular sandstone bodies in the Garden Park area to have been deposited by small, high-sinuosity streams, on the basis of the size and discontinuity of the sandstone bodies and the mud to sand ratio of the Morrison Formation. Donovan and Sweet (in Sweet, 1981, pp. 199–204) recognized lateral accretion stratification (epsilon cross beds) in the sandstone body directly below the quarry. Lateral accretion deposits are typical (though not diagnostic) of meandering streams (Jackson, 1978; Bridge, 1985).

STRATIGRAPHIC SETTING

Felch Quarry 1 lies 47.9 m above the J5 unconformity (Fred Peterson, personal communication, 1992) and is 2.2 m below the change from greenish gray non-smectitic to purplish gray smectitic clays separating the lower and middle Morrison (Fig. 2). The quarry is within the upper portion of a 16-meter thick interval containing four thick sandstone bodies bounded by mudstones and thin limestones. This interval represents the uppermost of four similar intervals characterized, from bottom to top, by basal thin gray limestones, calcareous mudstones, thin sheet and thick lenticular sandstones, and calcareous mudstones capped by thin limestones at the base of the overlying interval (Fig. 2). Scattered within the calcareous mudstones are thin reddish mudstones containing rhizoliths. The limestones and thin reddish mudstones are widespread and can be used as stratigraphic markers. Multiple thick sandstones occur only in the upper interval. The limestones and calcareous mudstones of the upper interval contain charophyte öogonia, ostracodes, freshwater gastropods, scattered small bones, and rare eggshell fragments (Fig. 2). The freshwater gastropods include taxa (Valvatidae and Viviparidae?) whose modern relatives prefer permanent water bodies (see also Evanoff and others, this volume). The thick sandstone bodies (sandbodies) are labeled from 1 to 4, based on the position of their tops relative to the lower limestone of the upper interval (Fig. 3). The positions, trends, maximum thicknesses, and estimated widths of the thick sandbodies are given in Table I.

SEDIMENTOLOGY OF THE MAJOR SANDBODIES

The sandbodies range in shape from ribbons to sheets (width/thickness of 11–19, Table I). They have low sinuosities and trend southeast and southwest (azimuths ranging from 150° to 210°). The sandstones are composed of arkosic, fine to very fine sand, with coarse sand and granule

TABLE I Features of the thick, lenticular sandstone bodies near the Felch quarries

	*Stratigraphic position**	*Trend*	*Maximum thickness*	*Estimated width*	*Width/thickness*
Sandbody 1	4.6 m	150°	1.8 m	Unknown	—
Sandbody 2	9.3 m	160°	4.2 m	45 m	10.7
Sandbody 3	9.6 m	210°	2.1 m	Unknown	—
Sandbody 4	12.4 m	210°	3.9 m	75 m	19.2

* Measured from the base of the lower limestone in interval 4.

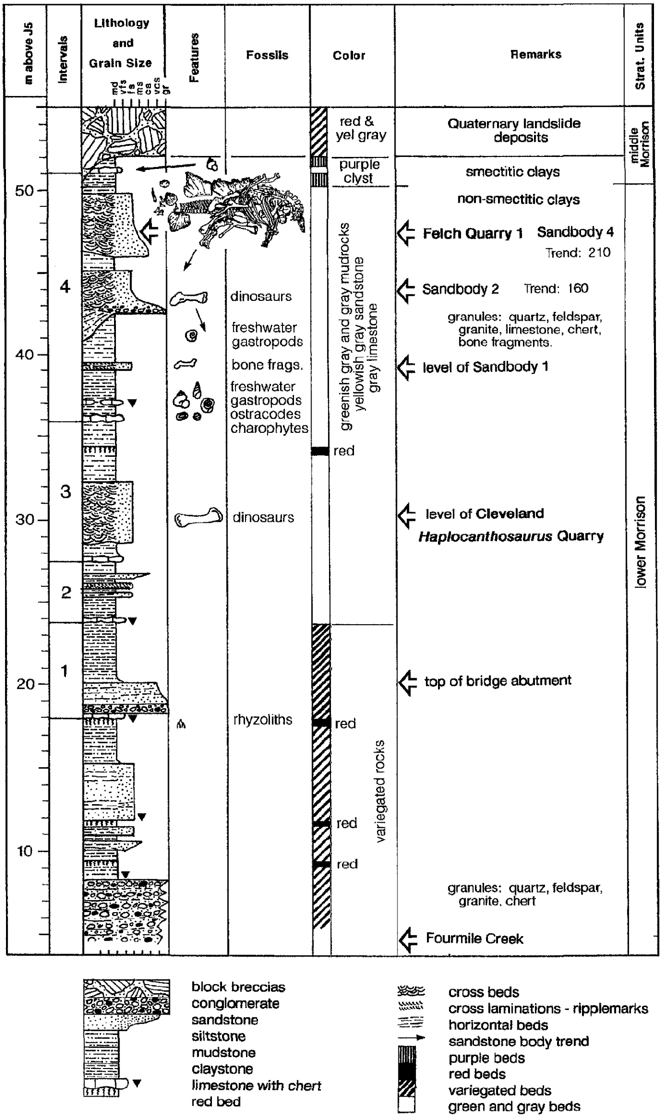


FIGURE 2 Stratigraphic sequence from near the base of the Morrison Formation along Fourmile Creek to the landslide breccias above Felch Quarry 1. Numbered intervals refer to subunits bounded by thin gray lacustrine limestones. Lithologies through interval 3 (35.8 m level) are modified from Brady (1967); positions above the J5 unconformity from Peterson (personal communication, 1992). This section was measured in the E½, NE¼, SE¼, sec. 28, T. 17 S., R. 70 W.

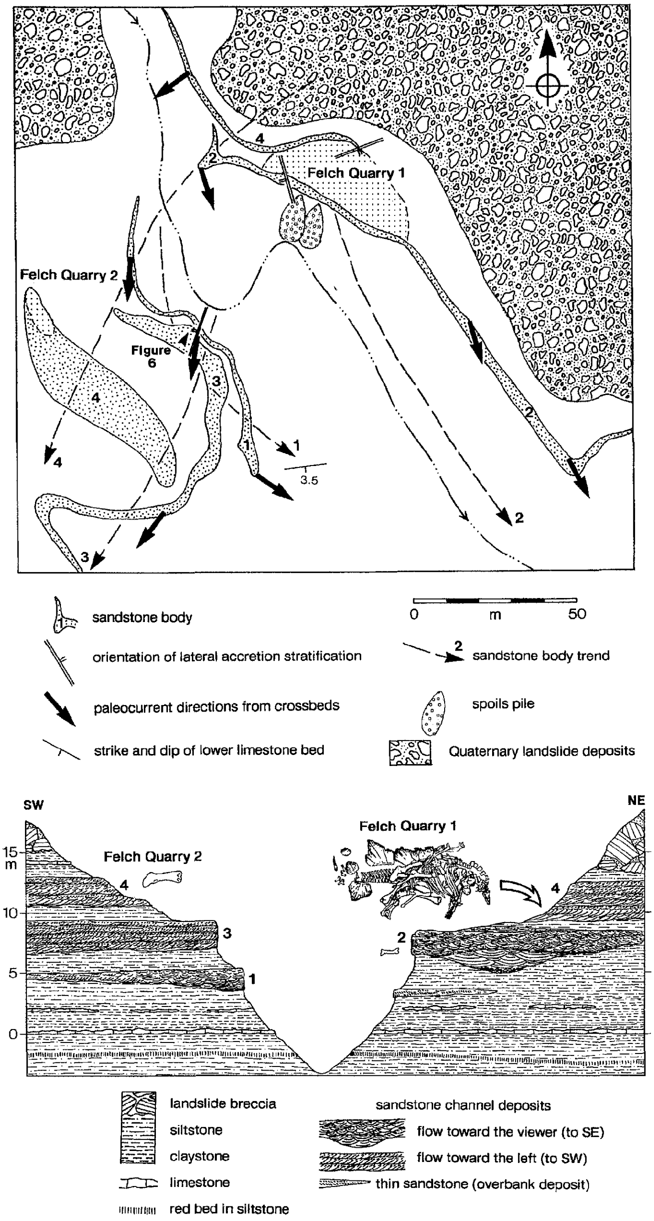


FIGURE 3 Generalized map and cross section in the vicinity of Felch quarries 1 and 2. See Fig. 1 for the location of this map.

conglomerates near the base of each unit. The basal conglomerates include Paleozoic limestone, Proterozoic granite, mudstone rip-up clasts, and scattered dinosaur bones. The granite and limestone clasts were derived from Proterozoic and Paleozoic rocks now exposed to the north on the margins of Garden Park.

Stratification in the sandstone bodies include small- to large-scale (5 cm–1 m thick) trough and tabular crossbed sets, and crescentic ripples with their associated small-scale cross-lamination sets (Fig. 4). The top surfaces of the cross-laminated slabs show well-formed rib and furrow patterns. The dispersion of paleocurrent directions indicated by the crossbeds is relatively low (vector magnitudes ranging from 85% to 99% determined from 85 measurements from eight locations) and indicate original flow directions (Fig. 3). The crossbeds are arranged in packages of upward-thinning sets separated by intervals of stacked ripples (Fig. 5). These packages are gently inclined toward the margins of the sandbodies, are highly oblique to perpendicular to the paleocurrent directions, and, therefore, represent lateral accretion deposits.

Deep scours locally occur at the base of the sandbodies and are filled with very thick (> 1 m) crossbed sets inclined parallel to the original stream flow, as indicated by smaller trough crossbed sets. Lateral to the lenticular sandbodies are widespread, lobate sheets of thin sandstone that locally contain abundant cross-lamination sets with paleocurrent directions oriented oblique or perpendicular to the thick sandbodies. Bone fragments can be common clasts in some of these sheets near the thick sandstone bodies.

Sandbody 2, situated just below Felch Quarry 1, is the best exposed of the four sandstone bodies (Fig. 6). This sandbody trends to the southeast (160°), paralleling the modern arroyo. The lowest feature of this sandbody is a large prominent scour directly below the quarry. The fill within this scour contains very-large-scale cross stratification that is inclined toward the southeast, parallel to the paleocurrent directions shown by medium-scale cross beds within this fill. Overlying this scour-fill is a sequence of stacked, gently dipping lateral accretion deposits. The lateral accretion deposits in Sandbody 2 are inclined from the west to southwest, indicating the southwestward migration of a point-bar. The upper lateral accretion deposits thin over the older scour-fill deposit (Fig. 6). The final sand-filled scour of the stream is preserved only on a point just northwest of the Felch quarry (Fig. 6).

The broad lenticular sandbodies represent the channel deposits of laterally migrating streams with moderate sinuosities, as indicated by the strikes

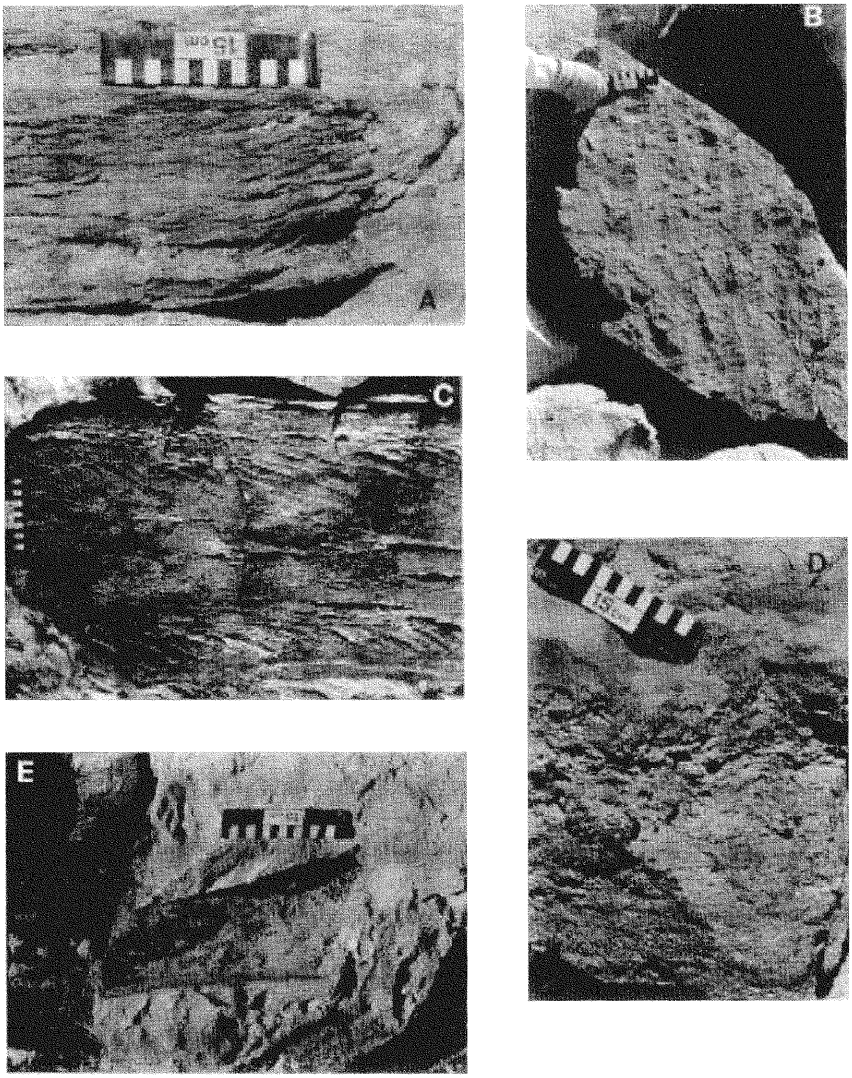


FIGURE 4 Photographs of common small-to-medium-scale sedimentary structures in the broadly lenticular thick sandstone bodies in the vicinity of the Felch quarries. (A) Stacked sets of cross lamination, with original flow to the left. (B) Rib and furrow structures on the top of a slab with abundant cross lamination formed by lunate ripples. Original flow was toward the top of the photograph. (C) Thinning upward sets of thin tabular crossbeding separated by a bed containing climbing cross lamination. Thin refers to sets < 10 cm thick; medium refers to sets between 10 and 50 cm thick; thick refers to sets 50 cm–1 m thick; very thick refers to sets > 1 m thick. (D) Basal conglomerate of Sandbody 2. The scale is on the upper surface of the conglomerate. (E) Mold of a portion of a dinosaur limb bone in Sandbody 3.

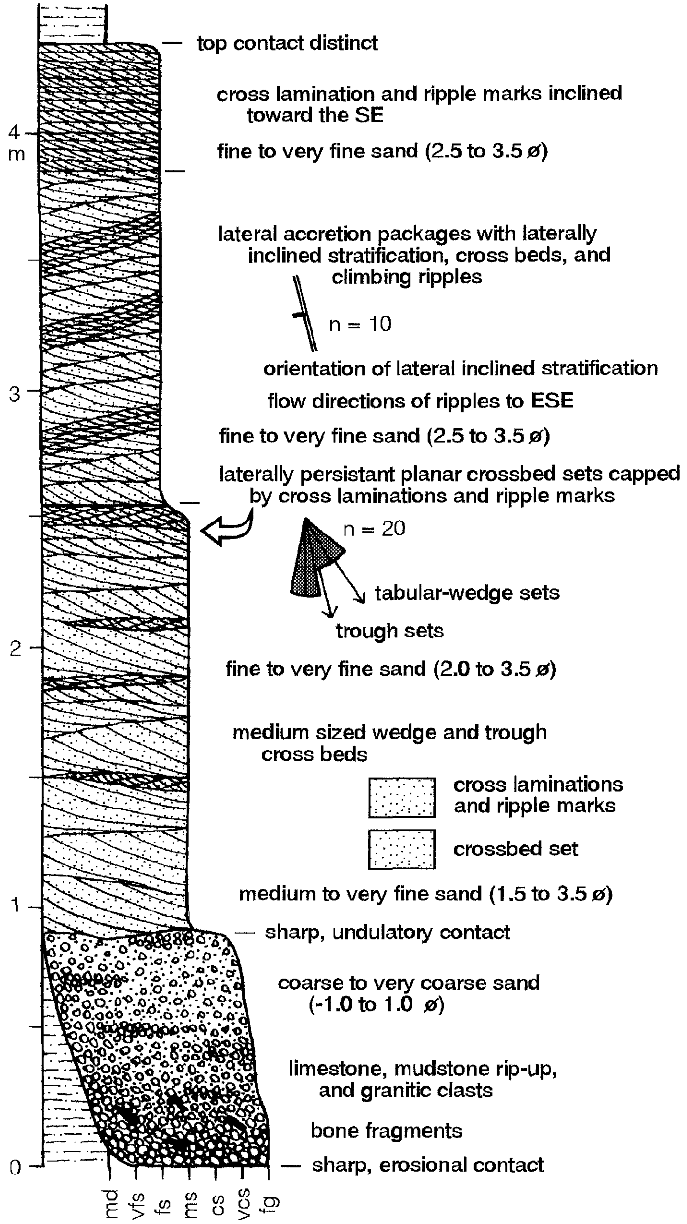


FIGURE 5 Stratigraphic sequence of sedimentary structures through Sandbody 2 downstream of the large basal scour. See Fig. 6 for location of the measured sequence.

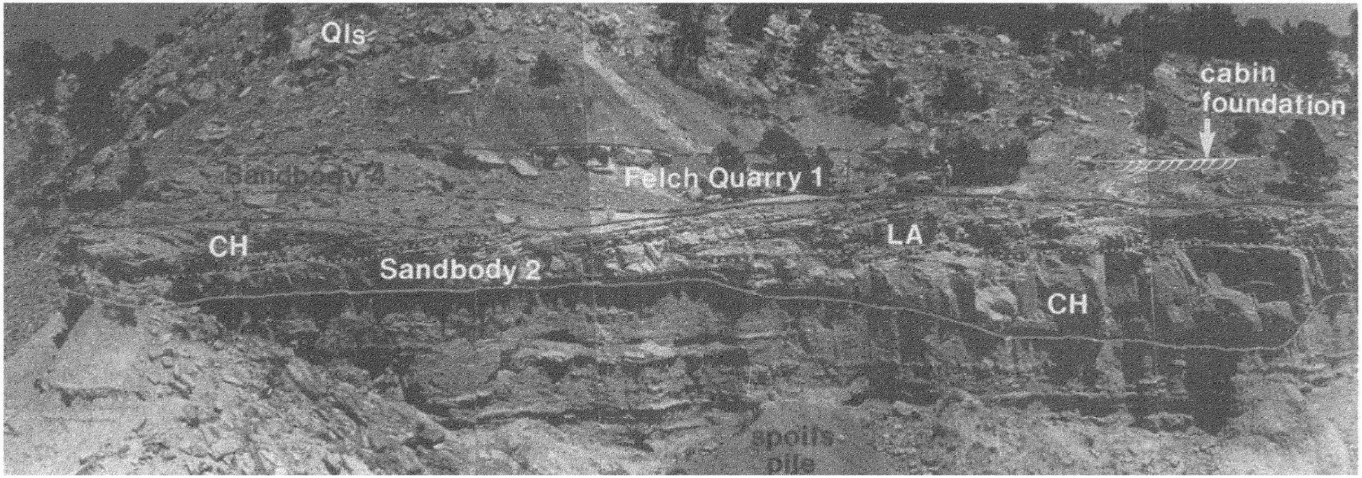

Qls
cabin
foundation
Sandbody 4
Felch Quarry 1
LA
CH
Sandbody 2
CH
spoils
pile

FIGURE 6-L

FIGURE 6-R

FIGURE 6 Panorama showing Felch Quarry 1 and Sandbody 2 below the quarry. CH refers to scour fills at the base and top of Sandbody 2; LA refers to stacked lateral accretion deposits, numbered in stratigraphic order. This photo was taken in July of 1992 from the top of Sandbody 3, and the view is nearly identical with that of I.C. Russell's 1888 photograph (Fig. 7). The location of the panorama is shown in Fig. 3.

of the inclined lateral accretion deposits. Articulated unionid clam shells locally occur in the sandstones, indicating that the clams lived in the streams and the streams were perennial. The widespread thin sheets lateral to the thicker sandbodies are splay deposits derived from the channels. The thick scour-fill in Sandbody 2 below Felch Quarry 1 was a large scour that was filled by a sand bar prograding downstream into the scour.

The relations between Sandbodies 2 and 3 are somewhat problematic. The top of Sandbody 3 is only 0.3 m above the top of Sandbody 2, and the trends of the two sandbodies are separated by 50°. Sandbody 3 has paleocurrents trending to the southwest (210°) and has lateral accretion deposits that show channel migration to the northwest. However, no evidence exists that Sandbody 3 occurs on the northeast side the arroyo, because no southwestern trending scour cuts Sandbody 2. These relations suggest that Sandbody 3 resulted from a major southwestern avulsion of the stream that deposited Sandbody 2, with subsequent development of point bars along the new channel.

SEDIMENTOLOGY OF FELCH QUARRY 1

Felch Quarries 1 and 2 occur in the uppermost thick, broadly lenticular sandstone body (Sandbody 4). Much of the hillside above Felch Quarry 1 has slumped into the quarry, covering the bone-bearing units. Thus, our sedimentological interpretation of Felch Quarry 1 is based upon Felch's letters to Marsh, historic photographs of the quarries (Fig. 7), and our limited field observations.

Felch repeatedly reported to Marsh (e.g., February 11, 1886 letter) that the bones occurred in two distinct layers at the base of Sandbody 4. The lower bed is a well-cemented, conglomeratic sandstone containing large bones, abraded bone fragments, small bones, and solitary teeth. This lower conglomeratic sandstone is separated from the upper bone-bearing sandstone by a thin mudstone. The upper bone-bearing unit is a less well-cemented sandstone that was, according to Felch, thickest along a northeast-trending trough and contained most of the articulated skeletons (Fig. 8). Many of the bones extended from the upper part of the lower conglomeratic sandstone, up through the overlying thin mudstone, and into the base of the upper sandstone. The total thickness of the bone bearing deposits ranged from 0.6 m on the margins to 1.8 m in the central trough.

Above the bone-bearing lower sandstones are less-fossiliferous sandstones that are still exposed in the rear cut of the quarry. These sandstones

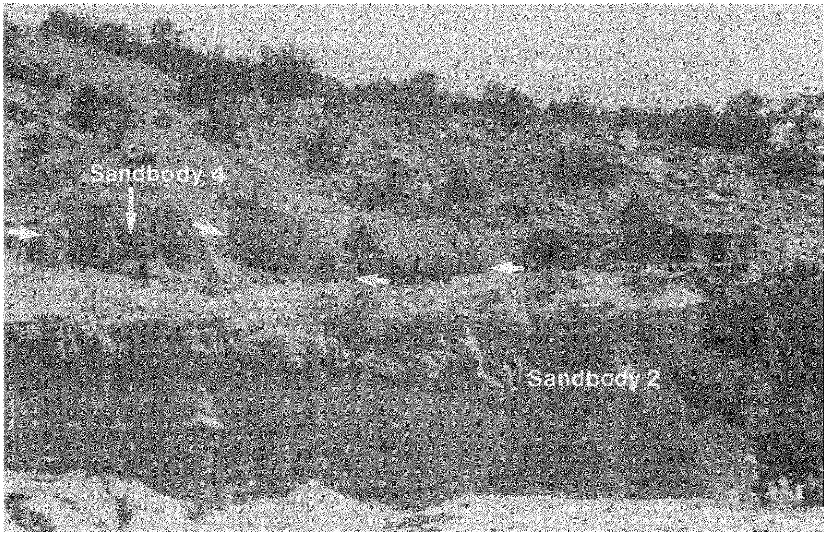
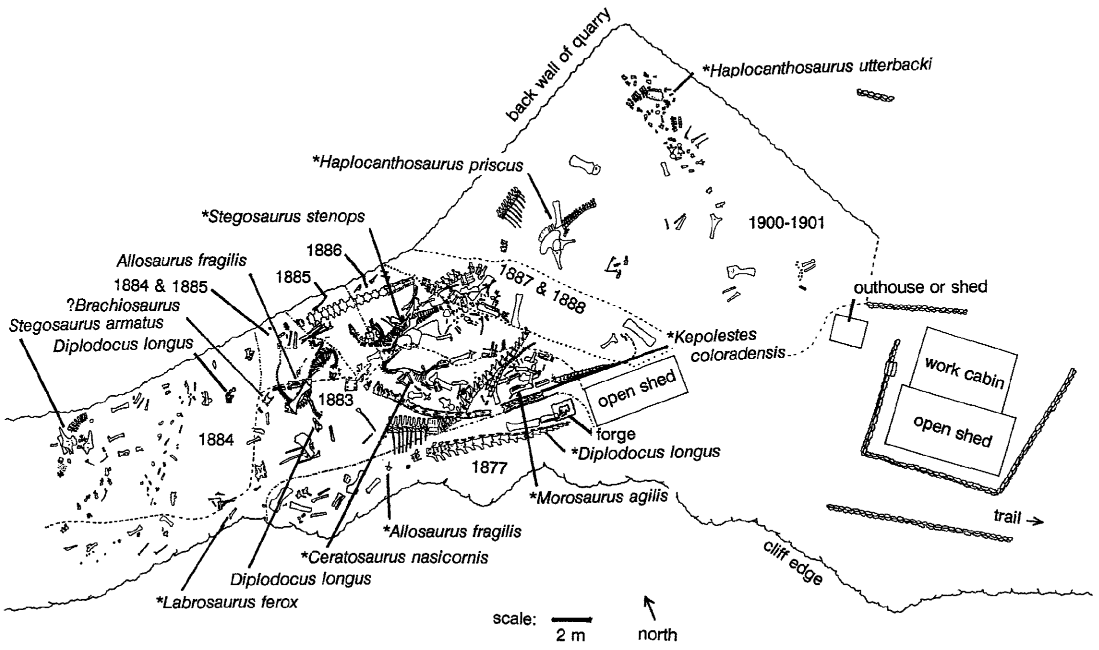


FIGURE 7 Felch Quarry 1 as it appeared in July of 1888. Arrows point to the bounding surface of the large southeastward inclined wedges of sandstone above the bone-bearing unit. Photograph by I.C. Russell of the US Geological Survey.

contain scattered trough-crossbed sets showing paleocurrent flow to the southwest. The troughs are within larger wedge-shaped packages of sandstone with bounding surfaces inclined to the southeast. These inclined wedges are well shown on the back wall in the 1888 photograph of the active quarry (Fig. 7). Felch's sketch of the quarry made on December 2, 1883, shows a *Dryosaurus* specimen from these wedge-shaped packages. These upper sandstones are 2.4 m thick within the quarry, and represent lateral accretion deposits of a southeastward-migrating point bar.

The geometry of the bone-bearing and overlying sandstones indicate the bones accumulated as: (1) a basal lag within the channel (for the basal conglomerate sandstone), and (2) in a deep scour at the apex of a southeastward-migrating point bar (for the upper bone-bearing sandstone). The thin mudstone separating the two fossiliferous beds represented quiet-water deposition of mud in a deeper part of a stream channel during a hiatus of active stream flow. The skeletons accumulated in this mud hole, and were later buried by sands as stream flow resumed and the point bar migrated over the deep scour. The increased thickness of the upper bone bed reflects (1) the original scour geometry of the pool, and (2) the increased deposition of sand around the skeletons that acted as sediment traps on the floor of the channel.



Felch Quarry 1

FIGURE 8 Map showing bone distribution at Felch Quarry 1. Holotypes (*), important specimens and skulls are noted; location of *Kepolestes* approximate, and is inferred from Felch's letters. Large blank areas mostly contained fragmented bones or isolated elements whose distribution was not recorded by either Felch or Utterback.

TAPHONOMY OF THE FELCH QUARRY

Our conclusions on the taphonomy of the Felch Quarry are based upon published and unpublished material. The unpublished records include the letters of Benjamin Mudge, Samuel Williston, Fredrick Brown, and Marshall P. Felch to Marsh, and of Utterback to Hatcher, the quarry maps made by Felch during the course of his excavations, the accession records at the Peabody Museum, Yale University, the recently completed dinosaur bone inventory at National Museum of Natural History, and on going studies of the Felch Quarry dinosaurs by one of us (Carpenter). Published descriptions of specimens from the quarry include Marsh (1896), Hatcher (1903b) and Gilmore (1914, 1920). The quarry map (Fig. 8) is compiled from the letters, diagrams and maps made by Felch, and the map published by Hatcher (1903b). The distribution of the bones is a "best fit" of these data because the maps of Felch and Hatcher did not reflect the actual shape of the quarry. This fit was achieved by matching certain landmarks on the maps (e.g., front edge of the quarry, location of the forge, etc.) with a outline map of the quarry made with Brunton compass and tape. As a result, azimuth interpretations of bone orientation from the map must be used with caution.

During the excavation of Quarry 1, Felch made several observations that we would today interpret as taphonomic. For example, Felch wrote to Marsh (September 14, 1887), "One thing seems strange in regard to the skeleton of the carnivore is – that though we find plenty of leg bones – one coracoid – lots of hollow foot bones, ribs & c.[sic] we find but very few vertebrae either caudal or dorsal that belong to it..." Today, we understand that the absence of vertebrae in an active channel is caused by their transport by flowing water (e.g., Voorhies, 1969; Hanson, 1980). Later in the letter, Felch wrote: "... as we go on east – we have to leave that deep depression which runs diagonally... and in which all of our best specimens have came from – and in this ground the bones though plenty in places are badly broken and worn – the strata in which they lay is thin – full of rocks and pebbles... and the whole appearance goes to show – these were out of the *mire hole* – where so many animals got stuck – and what we have now is but stray and scattered fragments brought in by the wash and drift" (Felch to Marsh, October 1, 1887).

The earliest published taphonomic account was Gilmore's (1914) discussion about how the holotype of *Stegosaurus stenops* at Felch Quarry 1 was preserved. His interpretation differed from the quicksand interpretation of Felch in his letters to Marsh and by Hatcher (1901). He thought the carcass had been stranded on a river bar during wanning water flow. The plates of the back drooped where they snagged on the river bed and were forced under the body. The carcass then came to rest and decomposition continued on the upper, or right side of the body. Currents moved some of the bones piling them against the pelvis.

Specimen counts are based in part on catalogued specimens and some of these may actually belong to the same individual. The dinosaur fauna at the Felch Quarry is dominated by the sauropod *Haplocanthosaurus priscus* (specimens $n = 18$), which is very rare outside the Cañon City area. Other sauropods include *Diplodocus longus* ($n = 15$), *Apatosaurus* cf. *A. excelsus* ($n = 8$), and *Brachiosaurus* sp. ($n = 3$). Carnivores are common ($n = 15$) and include *Allosaurus fragilis* ($n = 9$), *Ceratosaurus nasicornis* ($n = 3$), *Coelurus fragilis* ($n = 2$), and *Elaphrosaurus* sp. ($n = 1$). Ornithopods are not common, but include ?*Camptosaurus* sp. ($n = 3$), *Othnielia rex* ($n = 3$), and *Dryosaurus altus* ($n = 1$). Stegosaurs are very common as specimens ($n = 13$) but much of this material may have come from only a few individuals. Only one each of *Stegosaurus armatus* and *Stegosaurus stenops* have been positively identified. Other taxa from the quarry include the lungfish *Ceratodus guntheri* ($n = 4$), the turtle *Gyptops* cf. *G. plicatus* ($n = 3?$), crocodiles *Eutretauranosuchus* ($n = 1$) and *Goniopholis* sp. ($n = 3$), and the mammals *Kepolestes coloradensis* ($n = 1$) and *Docodon* sp. ($n = 2$). No other fishes, amphibians, lizards, or pterosaurs are known, possibly because of the coarse-grain size of the bone bearing horizons. Elsewhere, these taxa are known where the surrounding matrix is fine grained (Dodson *et al.*, 1980).

Specimens at the quarry range from very small to very large, and from isolated bones to almost complete skeletons. Felch reported that water worn bone was common in the quarry, especially in the lower conglomeratic sandstone and in blank areas of the quarry map (Fig. 8). None of these specimens were saved, although examples of abraded bone pebbles were found in the matrix adhering to the disarticulated *Brachiosaurus* skull (Carpenter and Tidwell, this volume). These unidentifiable fragments of larger bones range in size from 3 mm to more than 300 mm. Some of the bone pebbles are well rounded indicating substantial transport, or several cycles of transport, deposition and exhumation (Wood *et al.*, 1988). Solitary whole bones are also common at the quarry and these range in size from the small dentary of *Kepolestes coloradensis*, 15.8 mm long, to a sauropod femur almost 1820 mm long. Almost all of these solitary bones show little transport abrasion, suggesting that they may belong to disarticulated skeletons in the quarry.

Strings of articulated vertebrae are also common ($n = 16$). These include cervicals, dorsals with ribs, and caudals with chevrons. Most of these strings of vertebrae occur on the eastern and western sides of the quarry. Also present are articulated upper and lower portions of limbs ($n = 5$) in the eastern part of the quarry. Disarticulated skeletons occur, especially in the western portion of the quarry. These include an *Allosaurus fragilis* skeleton mentioned earlier (USNM 8423), *Stegosaurus armatus* with skull (USNM 4936), and *Haplocanthosaurus* (CMNH 572). Articulated skeletons with skulls include those of *Allosaurus fragilis* (USNM 4734), *Ceratosaurus nasicornis* (USNM 4735), and *Stegosaurus stenops* (USNM 4934). These occur close together in the central section of the quarry.

Several isolated dinosaur skulls are also known from the quarry. These include two of *Diplodocus longus* (USNM 2672), including one with a string of several vertebrae attached (USNM 2673), a *Brachiosaurus* sp. (Carpenter and Tidwell, this volume), and "*Morosaurus*" *agilis* (possibly *Haplocanthosaurus*, Carpenter and Tidwell, this volume) with three cervicals. The total number of skulls from the quarry, including those associated with skeletons, is eight. This high number is second only to the quarry sandstone at Dinosaur National Monument, where 14 skulls are known.

Some of the isolated bones in the quarry suggest a relatively long accumulation time where complete disarticulation of the carcasses occurred in the channel. Many of these bones apparently belong to the same individual (e.g., the disarticulated *Brachiosaurus* skull; see Carpenter and Tidwell, this volume). The quarry also has skeletons in various stages of disarticulation, including nearly complete skeletons (*Allosaurus*, *Ceratosaurus* and *Stegosaurus*), partially articulated but with other bones nearby (*Stegosaurus*, *Allosaurus*, *Apatosaurus*, *Diplodocus*), and mostly disarticulated but with vertebrae or limb segments still in articulation (e.g., *Haplocanthosaurus* tail and pelvis, and dorsals and ribs; *Diplodocus* right hind leg). These groups are artificial because the degree of articulation or disarticulation within each varies considerably. Actually, they form a continuous spectrum of disarticulation implying that timing of death of the individuals was not the same. These specimens provide a clue to the cause and timing of death of the individuals.

MASS DEATH ASSEMBLAGES AND FELCH QUARRY 1

Typically, bone beds in the fossil record have been divided into attritional and catastrophic accumulations (e.g., Kurtén, 1953; Voorhies, 1969;

Shipman, 1981; Rogers, 1990; Fiorillo, 1991). By the criteria by which these are defined, the Felch Quarry is both attritional and catastrophic in origin. This categorization, however, is unsatisfactory because of the wide range of disarticulation of the skeletons. A more refined classification of mass accumulations has been presented briefly elsewhere (Carpenter, 1988) and is elaborated here to explain Felch Quarry 1.

Attritional bone beds are believed to represent the normal "background" death in a community due to old age, predation, etc. (Voorhies, 1969). With attritional mortality, the age and sex of an individual can impart a strong survival advantage (Corfield, 1973; Crowe and Liversidge, 1977). Life survivorship curves show that juveniles and older adults numerically dominate the assemblage while the more fit prime-age adults are under-represented (Kurtén, 1953; Klein, 1981; Shipman, 1981). In addition, an attritional accumulation will most likely contain several taxa because no one species is expected to contribute all of the carcasses. This is because predation, old age, illness, etc. will affect individuals of all species in the area.

Catastrophic mass mortality is here defined as the "sudden" death of numerous individuals within a very brief span of time measured in second or minutes, or at most a few hours. The killing agent is external to the animals, thus it acts from the outside upon the individuals (rather than from within such as a disease). The agent is generally nonselective about the species affected, or to the age, health, gender or social ranking of the animals. Death occurs so rapidly that it may literally drop the animals in their tracks. By this definition, catastrophic mass mortality rarely occurs over a time span greater than a few minutes or few hours, otherwise the victims could flee the killing agent.

A recent example of catastrophic mass mortality is the death of 1,700 villagers and 3,000 cattle in Cameroon by a carbon dioxide cloud (Stager, 1987). An example in the fossil record is that of an ash fall in Nebraska during the Miocene (Voorhies, 1985). Birds, horses and camels at the base of the ash bed indicate immediate death, while the occurrence of rhinoceroses a little higher in the ash indicates a slightly later death. Grass seeds in the throat region of some rhinos show that many were feeding at the time of death. Some juvenile rhinos were apparently feeding or seeking shelter next to their mothers at the time of death.

Catastrophic mass mortality frequently cuts across all age and sexual groups resulting in a "snapshot" of the living population as reflected by the victims. Thus, if the 1,700 villagers killed in Cameroon are categorized by age and sex, then the results would replicate the age and sex groups of the population before the eruption of the gas cloud.

Noncatastrophic mass mortality occurs over the span of hours, days, weeks, or months. The killing agent may be external (e.g., drowning while fording a river) or internal (e.g., disease and starvation). The killing agent is selective about the species affected, their age, health, gender, and social ranking of the individuals. Other killing agents include malnutrition due to over population (Ferrar and Kerr, 1971), exhaustion, starvation and disease (Crowe and Liversidge, 1977), and parasitic infestation (Melton and Melton, 1982). Because death occurs over a span of time, carcass production also occurs over a span of time, but at a much higher rate than attritional mortality.

An example of noncatastrophic mass mortality is the mass death of migratory species of mammals, such as the wildebeest, which drown while crossing rivers during the migratory season. Such deaths occur over the span of hours (i.e., the time it takes the herd to cross over the river), with young and females drowning most frequently (Sinclair, 1977). Another example is death during a drought. An individual's fitness at the time of the drought is the key factor in its survivability (Hillman and Hillman, 1977; Foster, 1965), and even the age and gender of an individual can impart a strong survival advantage (Corfield, 1973; Crowe and Liversidge, 1977). This differential survivorship results in the bone assemblage not mirroring the living population in the number of individuals per age category. For this reason, drought assemblages can not be considered a result of catastrophic mortality, contrary to Shipman (1975).

Furthermore, because noncatastrophic mass mortality occurs over a considerable span of time, months in the case of droughts, a wide range of skeletal disarticulation may be evident. This is certainly true at Felch Quarry 1. In addition, some of the isolated elements (e.g., the *Kepolestes* dentary) show that this mortality is superimposed upon attritional accumulation.

The noncatastrophic mass mortality at Felch Quarry 1 most likely occurred over a considerable amount of time, possibly months, because skeletons in the channel range from almost completely articulated to completely disarticulated, but not widely scattered. This spectrum of disarticulation is similar to drought killed cattle shown in Kirtley and Kirtley (1985). Therefore, the most probable killing agent of the dinosaurs is a severe drought (see Carpenter, 1987, for a discussion of Mesozoic droughts; see also Shipman, 1975). As has been demonstrated by Demko (this volume), the strong seasonality evidenced in the sediments of the Morrison Formation indicate that conditions were in fact present for droughts (see also Carpenter, this volume). Russell and others (1980) invokes droughts as the killing agent for many of the Late Jurassic dinosaurs at Tendaguru, Tanzania, as did Rogers (1990) for monospecific bone beds in the Upper Cretaceous of Montana.

DISCUSSIONS AND CONCLUSIONS

The two Felch quarries were deposited in the uppermost of four thick lenticular sandstone bodies within a 16-m thick interval bounded by thin limestones and thick mudrocks. The sandstone bodies were deposited by moderate sinuosity, laterally migrating streams that flowed to the southeast and southwest. The sandbodies are lenticular, despite the presence of lateral-accretion structures, because the streams avulsed before a widespread sheet could form. One such avulsion is recorded by the stratigraphic positions and areal distributions of sandbodies 2 and 3. The alternation of lacustrine limestones and channel-belt sandstones within the sequence may reflect long-term channel migration in and out of the study area, with the limestones representing flood basin ponds far from the active channel belt. The streams and ponds were typically perennial, as indicated by their associated nonmarine mollusks which now inhabit perennial waters.

Felch Quarry 1 occurs near the base of the upper, broadly lenticular sandstone that was deposited by a southwestward flowing stream. Scattered bones of various sizes were deposited in the basal gravelly lags of the channel, while the articulated skeletons accumulated in a large scour that was filled by a sandy bar. The basal lags and the skeleton-bearing sandstone are separated by a thin mudstone, suggesting a short time interval when stream flow was highly reduced, probably during a drought. The skeleton-bearing deposit was subsequently buried by a point bar that migrated to the southeast after the return of normal fluvial conditions.

The initial production of Felch Quarry 1 bone bed is due to attritional accumulation of bones in a channel at the outer bend of a point bar. This accumulation was enhanced over a span of time, perhaps months, as the result of a prolonged drought causing the death of many dinosaurs. The evidence for this is the wide spectrum of disarticulation of the dinosaur carcasses which is similar to that seen among extant drought mortality victims (see Kirtley and Kirtley, 1985). Those dinosaurs that died early in the drought underwent considerable disarticulation, and water transport scattered and intermingled the bones. The under representation of certain bones from the bone bed (e.g., distal tail vertebrae) is most probably due to the hydrodynamic ease by which some bones are transported (Voorhies, 1969; Behrensmeyer, 1975).

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References

Brady, L.L. (1967) *Stratigraphy and petrology of the Morrison Formation (Jurassic) in the vicinity of Canon City, Colorado* [M.S. thesis]. Manhattan, Kansas: Kansas State University, 111 pp.

Brady, L.L. (1969) Stratigraphy and petrology of the Morrison Formation (Jurassic) of the Canon city, Colorado, area. *Jour. Sed. Pet.*, **39**, 632–648.

Behrensmeyer, A.K. (1975) The taphonomy and paleoecology of Plio-Pleistocene vertebrate assemblages east of Lake Rudolf, Kenya. *Bull. Mus. Comp. Zool.*, **146**, 473–578.

Bridge, J.S. (1985) Paleochannel patterns inferred from alluvial deposits: a critical evaluation. *J. Sediment. Petr.*, **55**, 579–589.

Carpenter, K. (1987) Paleoecological significance of droughts during the Late Cretaceous of the Western Interior. In Currie and E. Koster (Eds.) Fourth Symposium on Mesozoic Terrestrial Ecosystems Short Papers. *Occasional Papers of the Tyrrell Museum of Palaeontology*, **3**, 42–47.

Carpenter, K. (1988) Dinosaur bone beds and mass mortality: implications for the K-T Extinction. Global Catastrophes in Earth History: an interdisciplinary conference on impacts, volcanism and mass mortality. *Lunar Planet. Inst. Contr.*, **673**, 24–25.

Corfield, T. (1973) Elephant mortality in Tsavo National Park, Kenya. *East Afr. J. Wildlife*, **11**, 339–368.

Crowe, T. and R. Liversidge (1977) Disproportionate mortality of males in a population of springbok (Artiodactyla: Bovidae). *Zool. Afr.*, **122**, 469–473.

Dodson, P., A.K. Behrensmeyer, R.T. Bakker and J.S. McIntosh (1980) Taphonomy and paleoecology of the dinosaur beds of the Morrison Formation. *Paleobiology*, **6**, 208–232.

Evanoff, E. and D.W. Kuntz (1987) The Geological Advisory Group – a partnership for managing geologic features on public lands. *Nat. Areas J.*, **7**, 179–193.

Ferrar, A. and M. Kerr (1971) A population crash of the reedbuck *Redunca arundinum* (Boddaert) in Kyle National Park, Rhodesia. *Arnoldia*, **5**, 1–19.

Fiorillo, A. (1991) Taphonomy and depositional setting of Careless Creek Quarry (Judith River Formation), Wheatland County, Montana. *Palaeogeogr., Palaeocl., Palaeoecol.*, **81**, 281–311.

Foster, J. (1965) Mortality and ageing of black rhinoceros in East Tsavo Park, Kenya. *East Afr. J. Wildlife*, **3**, 118–119.

Gilmore, C. (1914) Osteology of the armored Dinosauria in the United States Museum, with special reference to *Stegosaurus. U.S. Nat'l Mus. Bull.*, **89**, 1–25.

Gilmore, C. (1920) Osteology of the carnivorous Dinosauria in the United States National Museum, with special reference to the genera *Antrodemus* (*Allosaurus*) and *Ceratosaurus. U.S. Nat'l Mus. Bull.*, **110**, 1–154.

Hanson, C. (1980) Fluvial taphonomic processes: models and experiments. In Behrensmeyer, A. and A. Hill (Eds.) *Fossils in the Making.* Chicago: Univ. Chicago Press, pp. 156–181.

Hatcher, J.B. (1901) The Jurassic dinosaur deposits near Canyon City, Colorado. *Ann. Carnegie Mus.*, **1**, 327–341.

Hatcher, J.B. (1903a) A new sauropod dinosaur from the Jurassic of Colorado. *Proc. Biol. Soc. Washington*, **16**, 1–2.

Hatcher, J.B. (1903b) Osteology of *Haplocanthosaurus*, with description of a new species, and remarks *on* the probable habits of the Sauropoda and the age and origins of the *Atlantosaurus* beds. *Mem. Carnegie Mus.*, **2**, 1–72.

Hillman, J. and A. Hillman (1977) Mortality of wildlife in Nairobi National Park during the drought of 1973–1974. *East Afr. J. Wildlife*, **15**, 1–18.

Jackson, R.G., II (1978) Preliminary evaluation of lithofacies models for meandering alluvial streams, In Miall, A.D. (Ed.) *Fluvial Sedimentology. Canad. Soc. Petr. Geol. Mem.*, **5**, 543–576.

Kirtley, M. and A. Kirtley (1985) Senegambia – a now and future nation. *Nat'l Geogr.*, **168**, 224–251.

Klein, R. (1981) Ungulate mortality and sedimentary facies in the Late Tertiary Varswater Formation, Langebaanweg, South Africa. *Ann. South Afr. Mus.*, **84**, 233–254.

Kurtén, B. (1953) On the variation and population dynamics of fossil and recent mammal populations. *Acta Zool. Fennica*, **76**, 1–122.

Marsh, O.C. (1878) Principle characters of American Jurassic dinosaurs, Part I. *Amer. J. Sci.*, **116**, 411–416.

Marsh, O.C. (1879) Principle characters of American Jurassic dinosaurs, Part II. *Amer. J. Sci.*, **117**, 86–92.

Marsh, O.C. (1896) The dinosaurs of North America. *U.S. Geol. Surv., 16th Ann. Rep.*, 133–244.

Melton, D. and C. Melton (1982) Condition and mortality of waterbuck (*Kobus ellipsisprymnus*) in the Umfolozoi Game Reserve. *Afr. J. Ecol.*, **20**, 89–103.

Mook, C.C. (1916) Study of the Morrison Formation. *Ann. New York Acad. Sci.*, **27**, 39–191.

Rogers, R. (1990) Taphonomy of three dinosaur bone beds in the Upper Cretaceous Two Medicine Formation of northwestern Montana: evidence for drought-related mortality. *Palaios*, **5**, 394–413.

Russell, D., P. Béland, and J.S. McIntosh (1980) Paleoecology of the dinosaurs of Tendaguru (Tanzania). *Mém. Soc. géol. France*, **139**, 169–175.

Schuchert, C. and C. LeVene (1940) *O.C. Marsh, Pioneer in Paleontology.* New Have, Connecticut: Yale University Press, 541 pp.

Sinclair, A. (1977) *The African Buffalo.* Chicago: University of Chicago Press, 355 pp.

Shipman, P. (1975) Implications of drought for vertebrate fossil assemblages. *Nature*, **257**, 667–668.

Shipman, P. (1981) *Life History of a Fossil.* Cambridge, Massachusetts: Harvard University Press, 222 pp.

Stager, C. (1987) Silent death from Cameroon's killer lake. *Nat'l Geogr.*, **172**, 404–420.

Sweet, R.G. (1981) *A sedimentary analysis of the Upper Jurassic Morrison Formation as it is exposed in the vicinity of Canon City, Colorado* [M.S. thesis]. Stillwater, Oklahoma: Oklahoma State University, 210 pp.

Voorhies, M.R. (1969) Taphonomy and population dynamics of an early Pliocene vertebrate fauna, Knox County, Nebraska. *Contr. Geol. Univ. Wyoming, Spec. Paper*, **1**, 1–19.

Voorhies, M.R. (1985) A Miocene rhinoceros herd buried in volcanic ash. *National Geographic Society Research Reports*, **19**, 671–688.

Wood, J., R. Thomas, and J. Visser (1988) Fluvial processes and vertebrate taphonomy: the Upper Cretaceous Judith River Formation, South-central Dinosaur Provincial Park, Alberta, Canada. *Palaeogeogr., Palaeocl., Palaeoecol.*, **66**, 127–143.