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THE AGE OF THE MORRISON FORMATION

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The Morrison Formation in Utah and Colorado contains many volcanic ash layers and ashy beds, now altered mostly to bentonite, that have yielded isotopic ages. The Brushy Basin Member, at the top of the formation, gives single-crystal, laser-fusion and step-heating, plateau $^{40}Ar/^{39}Ar$ ages on sanidine that range systematically between 148.1 ± 0.5 (1 std. error of mean) at the top of the member to 150.3 ± 0.3 Ma near the bottom. The Tidwell Member, at the base of the Morrison Formation, contains one ash bed about 3 m above the J-5 unconformity that occurs in at least two widely separated sections. This ash has been dated by $^{40}Ar/^{39}Ar$ dating of sanidine and gives ages of 154.75 ± 0.54 Ma (Deino NTM sample, laser-fusion), 154.82 ± 0.58 Ma (Deino RAIN sample, laser-fusion), 154.87 ± 0.52 (Kunk NTM sample, plateau), and 154.8 ± 1.4 Ma (Obradovich NTM sample, laser-fusion). The Morrison Formation, therefore, ranges in age from about 148 to 155 Ma and, based upon fossil evidence appears to be entirely Late Jurassic, including the latest Oxfordian(?), Kimmeridgian, and early Tithonian Ages.

Keywords: Morrison Formation; Isotopic ages; Latest Oxfordian(?); Kimmeridgian; Early Tithonian

INTRODUCTION

One of the significant unresolved problems related to the Morrison Formation is its age, both chronostratigraphically and biostratigraphically. The formation has been labeled as Jurassic, Cretaceous, and Jurassic–Cretaceous over the years (e.g., Emmons and others, 1896; Darton, 1922;

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Simpson, 1926; Stokes, 1944; Imlay, 1952; 1980; Bilbey-Bowman and others, 1986; Hotton, 1986; Kowallis and others, 1986; Kowallis and Heaton, 1987). In one of the most recent papers to address this problem, Kowallis and others (1991) observed that, "Precise ages from the uppermost part of the Brushy Basin Member are still needed to determine if the Jurassic–Cretaceous boundary lies within the uppermost Brushy Basin Member." The authors might also have added that very little is known about the age of the lower members of the Morrison Formation. The age data reported in this paper, in addition to those ages reported earlier in Kowallis and others (1991), and in conjunction with the biostratigraphic information reported by Schudack and others (this volume) and Litwin and others (this volume), provide a solid framework for determining the age, both isotopic and biostratigraphic, of the Morrison Formation.

PREVIOUS AGE ASSIGNMENTS

Table I lists studies reporting isotopic ages from the Morrison Formation (most of the previously published ages came from the Brushy Basin Member), excluding the new ages reported here. These radiometric ages span the Cretaceous–Jurassic boundary according to published time scales (e.g., the Jurassic–Cretaceous boundary is given as 130 Ma by Kennedy and Odin, 1982; 145.6 Ma by Harland and others, 1990; 141.1 Ma by Bralower and others, 1990; and 142 Ma by Obradovich, 1993), and do not resolve longstanding debates concerning the age of the formation (i.e., is the formation Jurassic, Cretaceous, or a bit of both?).

These previously published isotopic ages have helped to better define the age of the formation, but they all have inherent problems. The Rb–Sr age by Lee and Brookins (1978) comes from authigenic clay and thus must be viewed as a minimum age. The K–Ar biotite ages are questionable because biotite is almost universally altered to some extent in bentonites, and potassium in biotite can be redistributed during alteration of the volcanic ash beds without affecting the appearance of the grains. Turner and Fishman (1991) and Christiansen and others (1994) have shown that potassium was quite mobile during alteration of the Brushy Basin Member ash beds. The fission-track data have large errors, include ages on some detrital material, and give several ages that appear to be too young when compared with other methods.

The best set of previously published data are the $^{40}Ar/^{39}Ar$ laser-fusion plagioclase ages (Kowallis and others, 1991), but plagioclase has fairly low

TABLE I Isotopic ages from the Morrison Formation

Reference	*Age ± Error* (1σ)	*Material*	*Method*	*Location & Member* *
Lee and Brookins, 1978	148 ± 9 Ma	Clay	Rb–Sr	New Mexico (BB)
Obradovich, 1984 pers. comm.	134 ± 1.2 Ma	Biotite	K–Ar	Colorado (BB)
Bilbey, 1992	147.2 ± 1.0 Ma	Biotite	K–Ar	Cleveland-Lloyd Q. (BB)
Bilbey, 1992	146.8 ± 1.0 Ma	Biotite	K–Ar	Cleveland-Lloyd Q. (BB)
Bilbey, 1992	135.2 ± 5.5 Ma	Biotite	K–Ar	Dinosaur Natl. Mon. (BB)
Kowallis and others, 1986	99–144 ± 8 Ma	Zircon	Fission Track	Notom, Utah (BB)
Kowallis and Heaton, 1987	142–195 ± 9 Ma	Zircon	Fission Track	Notom, Utah (SW)
Kowallis and Heaton, 1987	157 ± 7 Ma	Zircon	Fission Track	Notom, Utah (T)
Kowallis and Heaton, 1987	145 ± 13 Ma	Apatite	Fission Track	Notom, Utah (BB)
Kowallis and Heaton, 1987	132 ± 10 Ma	Apatite	Fission Track	Notom, Utah (SW)
Kowallis and others, 1991	147.6 ± 0.8 Ma	Plagioclase	Ar–Ar laser-fusion	Montezuma Creek (BB)
Kowallis and others, 1991	147.0 ± 0.6 Ma	Plagioclase	Ar–Ar laser-fusion	Montezuma Creek (BB)
Kowallis and others, 1991	145.2 ± 1.2 Ma	Plagioclase	Ar–Ar laser-fusion	Montezuma Creek (BB)
Kowallis and others, 1991	147.8 ± 0.6 Ma	Plagioclase	Ar–Ar laser-fusion	Montezuma Creek (BB)
Kowallis and others, 1991	149.4 ± 0.7 Ma	Plagioclase	Ar–Ar laser-fusion	Montezuma Creek (BB)
Kowallis and others, 1991	152.9 ± 1.2 Ma	Plagioclase	Ar–Ar laser-fusion	Dinosaur Natl. Mon. (BB)
DeCelles and Burden, 1992	129 ± 14 Ma	Zircon	Fission Track	Central Wyoming (BB?)

* Members are BB = Brushy Basin, SW = Salt Wash, T = Tidwell.

levels of potassium, increasing the errors in these ages. In addition, plagioclase appears to be more susceptible to alteration in the Morrison ash beds than sanidine.

The paleontological data base has also been a source of shifting age assignments for the Morrison Formation. Table II lists significant previously published references related to the biostratigraphic age of the Morrison Formation. We have attempted to compile a list of references that is representative and fairly complete, but we have undoubtedly missed some references because the Morrison literature is quite extensive. These references show that early in this century the formation was thought to be Jurassic, Cretaceous, or Jurassic–Cretaceous; during the mid-1900s the formation was thought to be definitely Jurassic; whereas most recently the age has again been questioned, with some scientists proposing a Jurassic–Cretaceous age.

In addition to the isotopic and paleontological age determinations listed in Tables I and II, a few papers have been published on the paleomagnetic reversal sequence in the Morrison Formation. Steiner and Helsley (1975a,b), Steiner (1980), and Steiner and others (1994) observed that the reversal sequence seen in the Morrison Formation correlates "well with the reversal sequence of about the same age [Kimmeridgian], derived from the oldest observed magnetic anomalies in the sea floor." Swierc and Johnson (1990) examined the reversal pattern in the Morrison and Cloverly formations in the Bighorn Basin of Wyoming and inferred a maximum of 7 million years of deposition for the Morrison Formation during the Late Jurassic. They also estimated a minimum of 15 million years of nondeposition between the Morrison and Cloverly formations. However, the nature and position of the contact between the Morrison and Cloverly formations in Wyoming is problematic and no reliable isotopic ages have been obtained there. One zircon fission-track age of 129 ± 14 Ma has been reported from central Wyoming by DeCelles and Burden (1992) from sediments they believe to be Cloverly Formation, but which have been previously assigned to the Morrison. Until these problems are resolved, a chronologic interpretation of the Wyoming paleomagnetic data will be imprecise.

STRATIGRAPHY

The Morrison Formation in the Colorado Plateau consists largely of interbedded conglomerate, sandstone, mudstone, and altered volcanic ash with relatively small amounts of marlstone, limestone, and claystone. The ash

TABLE II Biostratigraphic age information for the Morrison Formation

Reference	*Age*	*Type of Evidence*
Emmons and others, 1896	Cretaceous–Jurassic	Vertebrates similar to Jurassic forms elsewhere
Marsh, 1896	Jurassic	Dinosaurs are like those of European Jurassic
Logan, 1900	Jurassic	Invertebrates similar to Jurassic Wealden of Europe
Ward, 1900	Jurassic	Cycadeoid flora is like that of the Jurassic
Riggs, 1902	Jurassic	Dinosaurs are like those of European Jurassic
Williston, 1905	Cretaceous	Vertebrates indicate a Cretaceous age
Ward, 1906	Jurassic	Cycads like Jurassic forms
Lull, 1911	Cretaceous	Fauna like that of Cretaceous Arundel Formation, Maryland
Berry, 1915	Cretaceous	Flora similar to Cretaceous Potomac Group
Lee, 1915	Cretaceous	Morrison fauna needed more time to evolve than Jurassic
Lull, 1915	Cretaceous	Dinosaurs similar to African (Tendaguru Fm.) Cretaceous forms
Osborn, 1915	Cretaceous–Jurassic	Kimmeridgian dinosaurs are like Morrison's, but could be Cret.
Stanton, 1915	Cretaceous–Jurassic	Invertebrates inconclusive, but more likely Jurassic
Knowlton, 1916	Cretaceous	Plants argue for a Cretaceous age
Mook, 1916	Cretaceous	Fauna like that of Cretaceous Arundel Formation, Maryland
Schuchert, 1918	Jurassic	Dinosaurs similar to African (Tendaguru Fm.) Jurassic forms
Simpson, 1926	Jurassic	Dinosaurs similar to African (Tendaguru Fm.) Jurassic forms
Schuchert, 1934	Jurassic	Dinosaurs similar to African (Tendaguru Fm.) Jurassic forms
Baker and others, 1936	Jurassic	Evaluation of published fossil & other evidences
Peck and Reker, 1948	Jurassic	Microfossils and mollusks indicate a Jurassic age
Imlay, 1952	Jurassic	Fossil evidence suggests a Kimmeridgian age
Yen, 1952	Jurassic	Molluscan fauna suggests Morrison is pre-Purbeckian
Peck, 1957	Jurassic	Charophytes similar to German Kimmeridgian forms
Brown, 1975	Jurassic	Ginkgophytes from Montana suggest Jurassic age
Galton, 1976	Jurassic	European Jurassic dinosaur similar to Morrison form
Madsen, 1976	Jurassic	Charophytes similar to German Kimmeridgian forms
Galton, 1977	Jurassic	Dinosaurs similar to East African (Tendaguru) forms
Hotton, 1986	Jurassic	Palynology suggests a Kimmeridgian–Oxfordian age
Bakker, 1990	Cretaceous–Jurassic	Youngest Morrison dinosaurs may be Cretaceous
Miller and others, 1991	Cretaceous(?)–Jurassic	Advanced stage of dinosaur evolution
Litwin, this volume	Jurassic	Spores & pollen indicate latest Oxford.(?), Kimm., & early Tith.
Schudack, this volume	Jurassic	Charophytes indicate latest Oxford.(?), Kimm., & early Tith.(?)

was derived from dacites or rhyolites erupted from a continental margin volcanic arc (Christiansen and others, 1994) and has been altered to bentonite throughout most of the depositional basin. Progressing eastward to eastern Colorado, the formation loses much of the conglomerate and sandstone, and gains more limestone and marlstone. Altogether, the Morrison contains nine formally named members on the Colorado Plateau, although only four of these need be considered in this report (Fig. 1). In addition, the formation can be divided into two informal members at Garden Park near Cañon City in eastern Colorado. Peterson (1994) provided paleogeographic reconstructions for the Morrison Formation throughout the southern part of the Western Interior.

The Windy Hill Member at the base of the Morrison in the northern part of the Colorado Plateau is a thin glauconitic grayish-brown sandstone unit containing minor gray mudstone interbeds (Peterson, 1994). No ash beds have been found in this member. It was deposited in shallow marine waters and contains the only known marine beds in the formation.

The overlying Tidwell Member consists largely of gray mudstone interbedded with lesser amounts of brown sandstone and gray limestone. It interfingers with the Windy Hill Member or is the basal member farther south in the central part of the Colorado Plateau. Bentonite beds are rare in the member and only one suitable for radiometric dating was found in the central and northern parts of the Colorado Plateau. The Tidwell consists largely of continental strata deposited on mudflats and locally in stream beds. Because it interfingers with the Windy Hill Member, some of the beds could be of marine origin, as suggested by the recent discovery of dinoflagellates in the Tidwell in the northern part of the Colorado Plateau (R.J. Litwin, oral communication, 1994).

The Salt Wash Member consists predominantly of gray or brown sandstone beds and lesser quantities of red and green mudstone beds. Roughly the upper half of the member consists of pebbly or conglomeratic sandstone, or even conglomerate in much of the northern and western parts of the Colorado Plateau. Bentonitic beds are absent or rare in the Salt Wash Member. The member was deposited by streams that flowed generally eastward from highland source regions west of the Colorado Plateau in western Utah and eastern Nevada (Peterson, 1994). Another local source area was in the ancestral Rocky Mountains in what is now the Wet Mountains and Pikes Peak region west and north of Cañon City (Peterson, 1994).

The Brushy Basin Member consists largely of mudstone and is divided into lower and upper parts (Figs. 1 and 2) based largely upon the dominant type of clay minerals within it. The thin lower part of the member

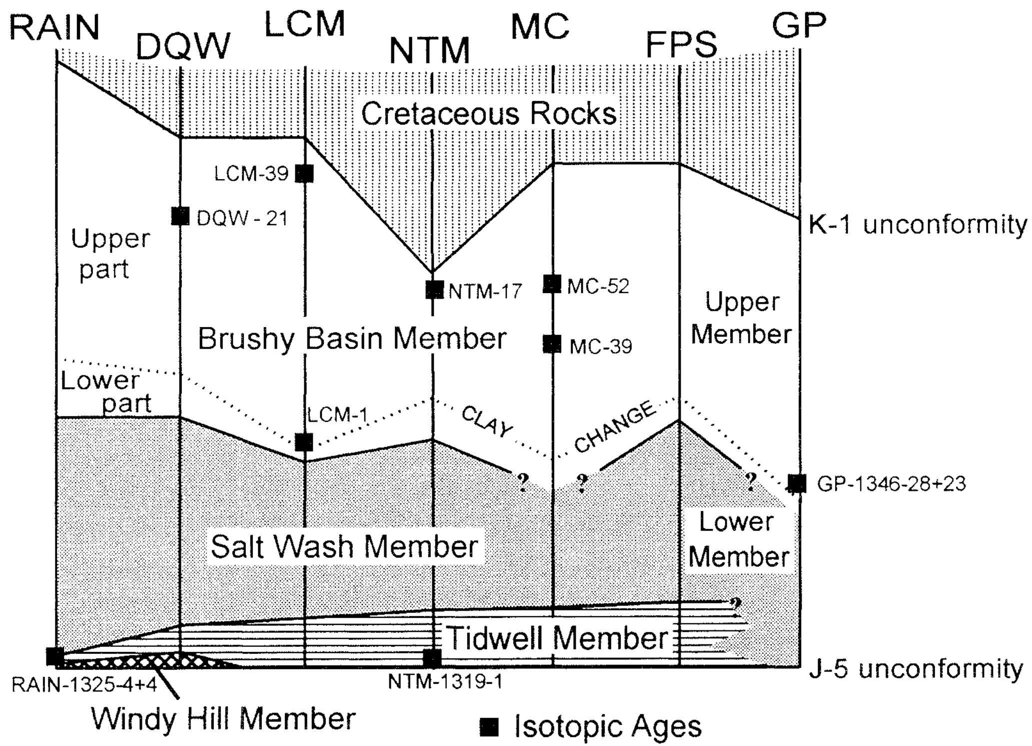

FIGURE 1 Schematic stratigraphic sections of the Morrison Formation at each locality shown on Fig. 3. The base of the figure is the J-5 unconformity. The clay change shown in the lower Brushy Basin Member is a marker horizon that can be traced throughout the study area. The clays below are illitic and non-swelling, while those above are smectitic, swelling clays.

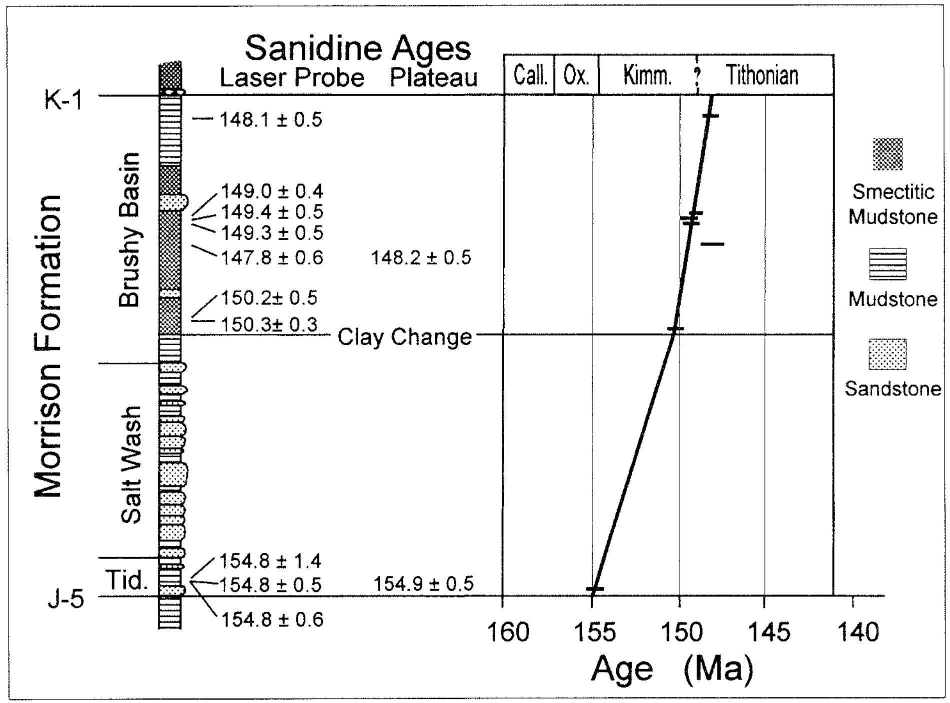

FIGURE 2 Composite stratigraphic section showing the locations of the new sanidine ages reported in this study by both single-crystal (laser probe) and step-heating (plateau) methods. Only one of the samples does not fit on the suggested "best fit" line. The change in slope of the line in the upper Morrison may indicate an increase in sediment accumulation rate. The stage boundaries are from Harland and others (1990) except for the Kimmeridgian–Tithonian boundary that is placed at about 149 Ma based on the ages we have obtained from the upper part of the Morrison Formation, and the Tithonian–Berriasian boundary that is from Bralower and others (1990).

consists of mudstone composed largely of nonswelling illitic clay, tends to be red (although other colors are also present and locally predominate), and locally contains brown to white sandstone beds (Owen and others, 1989). It was deposited in fluvial and overbank floodplain environments on a broad alluvial plain (Turner and Fishman, 1991).

The thick upper part of the Brushy Basin Member consists largely of mudstone, although sandstone beds occur locally, especially at or near the top. The mudstone beds tend to be grayish green with red beds locally significant near the top or throughout the unit on the west side of the Colorado Plateau. The finer-grained fraction consists largely of swelling or smectitic clays (Owen and others, 1989) derived from the alteration of volcanic ash that was carried onto the Colorado Plateau region by winds from a continental margin volcanic arc several hundred kilometers west and southwest of the Plateau region (Turner and Fishman, 1991). This part of the formation contains numerous altered volcanic ash beds. In the east-central part of the Colorado Plateau, the upper part of the Brushy Basin Member was deposited in a large saline alkaline lake that graded laterally into mudflat, fluvial, and overbank floodplain environments (Turner and Fishman, 1991). Freshwater lake deposits occur locally in this interval to the north and east of the saline, alkaline lake deposits and are represented by mudstone and limestone beds containing charophytes, ostracodes, scarce conchostracans, and gastropods.

In eastern Colorado at Garden Park near Cañon City, the Morrison can be divided into two informal members based on the dominant clay mineral in the mudstone beds. The lower member consists largely of mudstone containing nonswelling clay. Other lithologies include uncommon sandstone and scarce thin limestone beds. The member is largely overbank floodplain and lacustrine mudstones with a few fluvial sandstone beds. It was deposited on a broad plain locally traversed by streams that also included extensive overbank floodplain areas, mudflats, and fairly common lakes or ponds.

The upper member in the Garden Park area contains the abundant swelling clays typical of the upper part of the Brushy Basin Member on the Colorado Plateau. This vertical clay mineral change provides one of the best means of correlating the Colorado Plateau Morrison with the eastern Colorado Morrison where formally named members are not recognized (Fig. 1). One of the bentonite beds from low in the upper member, which is well exposed in an open-pit bentonite mine, was selected for isotopic dating. The uppermost part of this member contains several pebbly sandstone beds and interbedded mudstone beds that tend to be nonsmectitic.

Most of the upper member was deposited in lacustrine and mudflat environments although the uppermost beds were deposited by streams and on adjacent overbank floodplains.

Physical correlation of the Morrison Formation and certain strata within it between the Colorado Plateau and eastern Colorado is established by stratigraphic markers. These include the J-5 and K-1 unconformities at the base and top to the formation (Peterson, 1994), a zone of authigenic chert (usually red), called the welded chert (Ogden, 1954) (which is in the Tidwell Member of the Colorado Plateau, the lower part of the lower member near Cañon City, and in the Ralston Creek Formation west of Denver) and the change in dominant clay minerals in about the middle of the formation (see Fig. 1).

SAMPLE LOCALITIES

Since the publication of our earlier paper on the age of the Brushy Basin Member of the Morrison Formation (Kowallis and others, 1991), we have obtained several additional ages, mostly using sanidine grains, from new and old localities. Most of these additional ages come from the Brushy Basin Member, with a few ages from the basal Tidwell Member. The localities from which samples were collected for dating are shown in Fig. 3.

Montezuma Creek, Utah and Notom, Utah

The Montezuma Creek (MC) and Notom (NTM) Utah sections have been described in Kowallis and others (1991). Five separates of plagioclase, all containing a few sanidine crystals, were dated previously by single-crystal $^{40}Ar/^{39}Ar$ laser-probe methods from the MC section (Kowallis and others, 1991) and several fission track ages are available from the NTM section (Kowallis and Heaton, 1987). We chose two additional samples from the middle (MC-39, 51 m above the base of the member) and upper (MC-52, 69.3 m above the base of the member) parts of the Brushy Basin Member in the MC section for dating because they contain abundant sanidine, as well as one sanidine-rich sample from near the top of the Brushy Basin Member (0.5 m below the Cedar Mountain Formation contact and 48.5 m above the base of the member) in the NTM section (NTM-17). Another sanidine-bearing ash was collected from 2.4 m above the base of the Tidwell Member in the Notom section (NTM-1319-1). The other sections are new and will be briefly described here with additional information on location of the sections given in Appendix I.

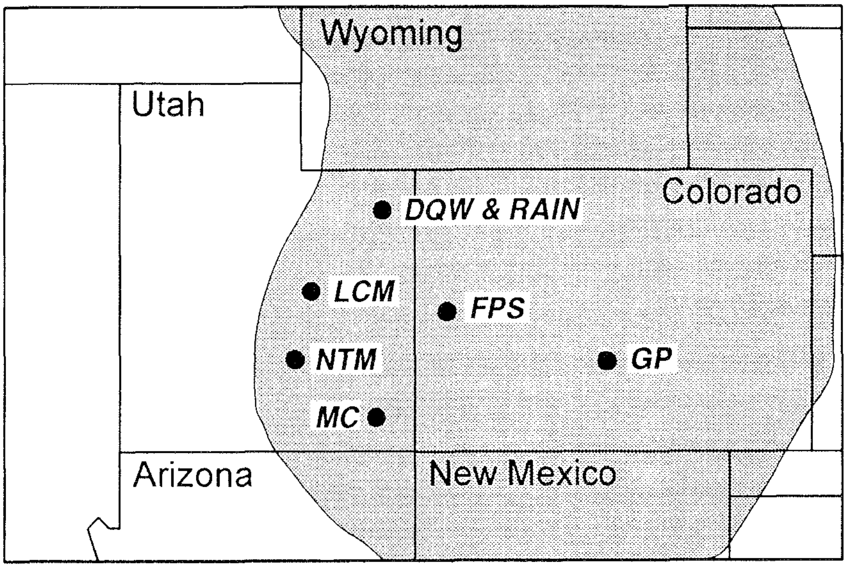

FIGURE 3 Index map showing the locations of sample sections (dots) and the Morrison Formation depositional basin (stippled). Sections are: DQW = Dinosaur Quarry West, FPS = Fruita Paleontological Site, GP = Garden Park, LCM = Little Cedar Mountain, MC = Montezuma Creek, and NTM = Notom.

Little Cedar Mountain, Utah

The Little Cedar Mountain (LCM) section is in Emery County, Utah. There the Brushy Basin Member of the Morrison Formation is about 106 m thick. We collected 39 samples from the Brushy Basin Member; of these, 10 of the samples contained datable (> about 0.2 mm in size), euhedral sanidine grains. The sample nearest the top of the section (LCM-39, 104.5 m above the base of the Brushy Basin Member) and the sample nearest the base (LCM-1, 3.8 m above the base of the member) were selected for dating.

Dinosaur Quarry West, Utah

The Dinosaur Quarry West (DQW) section, Utah is in Dinosaur National Monument near the visitor center. The formation is about 185 m thick at DQW, and the Brushy Basin Member is about 98 m thick. Ages reported by Kowallis and others (1991) and Bilbey (1992) were obtained from samples collected less than 1 km from the DQW section. From the Brushy Basin Member in this section, 26 samples of altered ash were collected; 10

contained datable quantities of sanidine and several contained abundant biotite. Three samples were chosen for dating from this section: biotite from DQW-5 16.5 m above the base of the Brushy Basin Member and 4.5 m above the clay change (see Fig. 1), sanidine from DQW-17 48.3 m above the base of the member and 36.3 m above the clay change, and sanidine from DQW-21 55.4 m above the base of the member and immediately below the main dinosaur quarry sandstone.

Rainbow Draw, Utah

Also within Dinosaur National Monument is the Rainbow Draw (RAIN) section. We collected four samples from this section and found datable plagioclase in one waxy green ash bed (RAIN-1) immediately below a darker organic-rich layer that has been quarried for microvertebrates from the Brushy Basin Member (see Engelmann and others, 1989). Datable sanidine was found in another bentonite (RAIN-1325-4+4) from the Tidwell Member 2.7 m above the base of the formation. This bentonite appears to be the same ash bed from which we collected sample NTM-1319-1. We base this conclusion on the following observations: (1) the four ages from the two sample localities are identical within analytical precision [154.84 ± 0.29 from NTM (Deino), 154.90 ± 0.32 from RAIN (Deino), 154.87 ± 0.52 from NTM (Kunk), and 154.8 ± 1.4 from NTM (Obradovich)]; (2) NTM-1319-1 and RAIN-1325-4+4 have similar phenocryst assemblages – sanidine > quartz > biotite > zircon > apatite; plagioclase is absent; (3) sanidine and apatite compositions are similar (see Figs. 4 and 5); (4) major and trace element compositions were strongly perturbed during alteration to clay minerals, but are compatible with the samples coming from a single eruption (for example, both have high concentration of Nb, as compared to altered ash in the Brushy Basin Member); and (5) the samples come from approximately the same stratigraphic level (NTM-1319-1 is from 2.4 m above the base of the Morrison Formation and RAIN-1325-4+4 comes from 2.7 m above the base) in an interval of the Morrison Formation that has very few other know ash beds.

Fruita Paleontological Site, Colorado

At the Fruita Paleontological Site one sample (FPS-1) was collected by Dr. James Kirkland from the level of the main microvertebrate quarry of Callison *et al.* (1986). At this locality, the Morrison Formation is about 180 m thick; the Tidwell Member comprises about 23 m, the Salt Wash

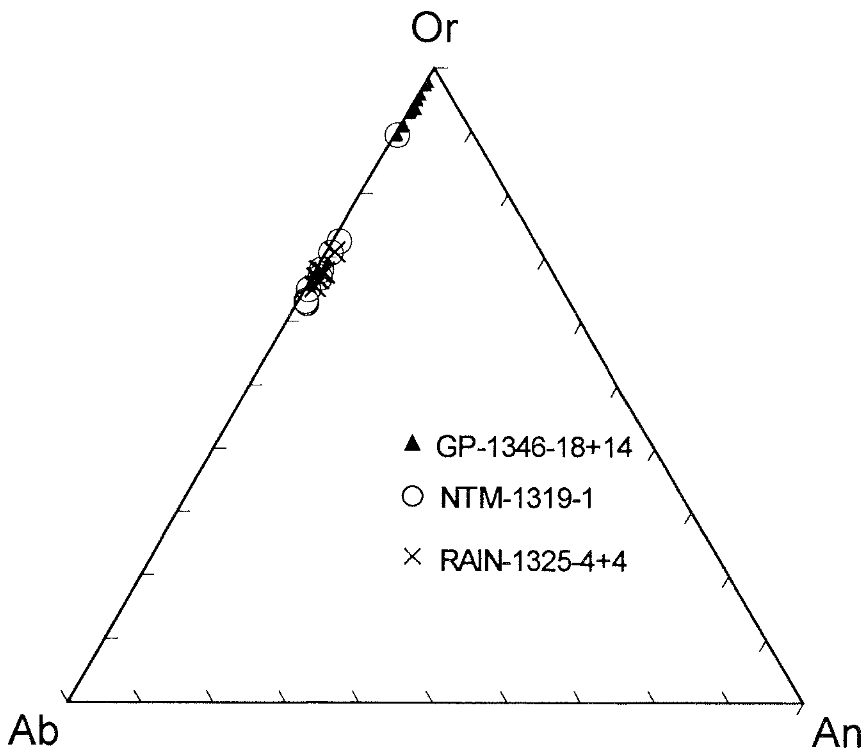

FIGURE 4 Feldspar compositions from Tidwell Member ash bed at two locations, Notom and Rainbow Valley. Also, included is a sample from Garden Park that we thought might be the same ash as at the other two localities, but it only had detrital microcline.

Member about 73 m, and the Brushy Basin Member about 84 m. FPS-1 comes from about 13.7 m above the base of the Brushy Basin Member or 4.0 m above the change in clay minerals (CC in Figs. 1 and 2). This sample contains abundant plagioclase, but, unfortunately, the grains did not produce enough gas during fusion to obtain an age.

Garden Park, Colorado

The Garden Park (GP) section, Colorado and the locations of the two samples collected for dating from this section (GP-1346-28+23 from the Brushy Basin Member and GP-1346-18+14 from the Tidwell Member) are described above in the section on stratigraphy. GP-1346-18+14 from the Tidwell Member was thought to perhaps be the same ash bed found at the NTM and RAIN sections, but it contained mostly rounded detrital grains

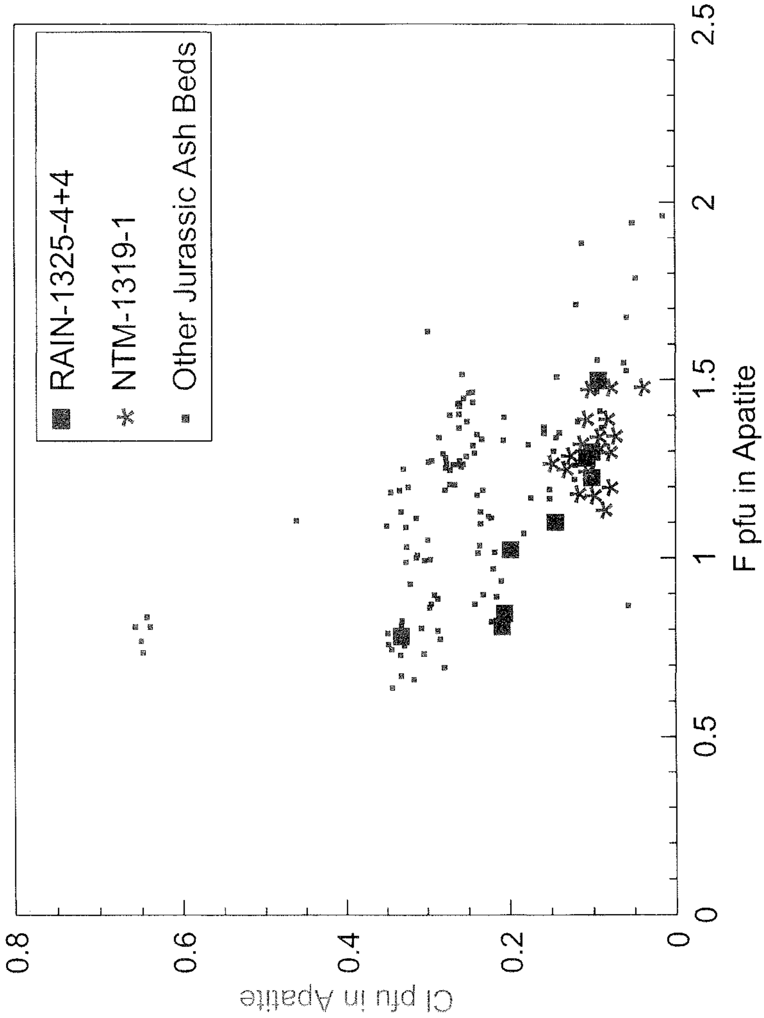

FIGURE 5 Apatite F and Cl compositions from Tidwell Member ash bed at Notom and Rainbow Valley. The data are shown as atoms per formula unit (pfu).

and no primary phenocrysts for dating. In addition, the few feldspars that were found are high potassium orthoclase/microcline grains, probably derived from older plutonic or metamorphic rocks, and quite different from the sanidine compositions from the other two samples (Fig. 4).

ISOTOPIC DATING

Most of the samples were dated at the Berkeley Geochronology Center by single-crystal $^{40}Ar-^{39}Ar$ total fusion of individual sanidine grains using a laser probe. A few additional samples were dated by $^{40}Ar/^{39}Ar$ step-heating methods at the US Geological Survey laboratory in Reston, Virginia. One sample from the Tidwell Member was dated by single-crystal $^{40}Ar-^{39}Ar$ total fusion at the US Geological Survey laboratory in Reston. We report on each type of analysis separately below.

Single-Crystal $^{40}Ar/^{39}Ar$ Laser-Fusion Ages

The procedures used to obtain single-crystal $^{40}Ar-^{39}Ar$ laser-fusion ages at the Berkeley Geochronology Center have been described in detail in Deino and Potts (1990), Deino and others (1990), Chesner and others (1991), and Kowallis and others (1995). Table III lists the single-crystal ages and the weighted mean average ages for each of the mineral separates that were analyzed. Sample NTM-1319-1 was also dated at the US Geological Survey laboratory in Reston and the results are reported in Table IV.

The ages all fit into a consistent stratigraphic framework (Fig. 2) with the exception of MC-39 with a weighted mean age of 147.82 ± 0.63 Ma (1σ), which is about 1 Ma too young. This sample also has the greatest variability of single-crystal ages with a range of over 4 Ma (see Table III), which may indicate a greater degree of alteration than the other samples.

Bulk $^{40}Ar/^{39}Ar$ Step-Heating Ages

High-precision $^{40}Ar/^{39}Ar$ age-spectrum dating of two sanidine separates (MC-39 and NTM-1319-1) was preformed using a low-blank, double-vacuum resistance furnace similar in design to that described by Staudacher and others (1978) for step-heating. Additional details of the methodology used in data collection and reduction can be found in Wintsch and others (1991), Haugerud and Kunk (1988), and Kowallis and others (in press). The plateau age for NTM-1319-1 is 154.87 ± 0.52 Ma (1σ) and is

TABLE III Single-crystal $^{40}Ar/^{39}Ar$ Laser Probe Analytical Data (Deino)

Lab ID#	$J \pm 1\sigma$ ($\times 10^{-2}$)	Ca/K	$^{36}Ar/^{39}Ar$ $\pm 1\sigma$	$^{40}Ar^{*}/^{39}Ar$	$\%^{40}Ar^{*}$	*Age ± Error* (Ma)
Sample DQW-21						
6068/2C-07	1.067 ± 0.003	0.0267	0.00024	8.021	99.1	148.14 ± 0.60
6068/2B-03	1.067 ± 0.003	0.0295	0.00066	8.025	97.6	148.22 ± 0.55
6068/2B-11	1.067 ± 0.003	0.0285	0.00023	8.038	99.2	148.45 ± 0.54
6068/2C-05	1.067 ± 0.003	0.0342	0.00024	8.043	99.1	148.53 ± 0.56
6068/2C-01	1.067 ± 0.003	0.0217	0.00037	8.049	98.7	148.64 ± 0.58
6068/2B-09	1.067 ± 0.003	0.0284	0.00019	8.057	99.3	148.79 ± 0.52
6068/2B-01	1.067 ± 0.003	0.0257	0.00018	8.064	99.3	148.91 ± 0.52
6068/2B-08	1.067 ± 0.003	0.0274	0.00034	8.065	98.8	148.92 ± 0.52
6068/2B-04	1.067 ± 0.003	0.0287	0.00032	8.067	98.9	148.97 ± 0.54
6068/2C-03	1.067 ± 0.003	0.0277	0.00012	8.071	99.6	149.03 ± 0.56
6068/2B-10	1.067 ± 0.003	0.0223	0.00022	8.071	99.2	149.04 ± 0.55
6068/2B-02	1.067 ± 0.003	0.0278	0.00047	8.071	98.3	149.04 ± 0.53
6068/2C-06	1.067 ± 0.003	0.0301	0.00011	8.082	99.6	149.23 ± 0.59
6068/2C-02	1.067 ± 0.003	0.0245	0.00013	8.095	99.5	149.46 ± 0.57
6068/2C-04	1.067 ± 0.003	0.0271	0.00015	8.104	99.5	149.62 ± 0.55
6068/2B-07	1.067 ± 0.003	0.0279	0.00017	8.105	99.4	149.64 ± 0.56
6068/2B-06	1.067 ± 0.003	0.0243	0.00022	8.107	99.2	149.97 ± 0.53
		Weighted Average, 1σ error without error in J =				148.97 ± 0.12
		1σ error with error in J =				± 0.42
Sample GP-1346-28+23						
7738/1-23	1.674 ± 0.001	0.0026	0.00010	5.165	99.4	149.61 ± 0.34
7738/1-32	1.674 ± 0.001	—	0.00005	5.173	99.7	149.83 ± 0.34
7738/1-37	1.674 ± 0.001	0.0041	0.00005	5.174	99.7	149.84 ± 0.35
7738/1-06	1.674 ± 0.001	—	0.00010	5.185	99.4	150.16 ± 0.37
7738/1-17	1.674 ± 0.001	0.0002	0.00000	5.204	100.0	150.70 ± 0.32
7738/1-25	1.674 ± 0.001	0.0031	0.00027	5.221	98.5	151.16 ± 0.48
7738/1-18	1.674 ± 0.001	—	0.00008	5.226	99.6	151.32 ± 0.34
		Weighted Average, 1σ error without error in J =				150.33 ± 0.26
		1σ error with error in J =				± 0.27
Sample GP-1346-28+23, inferred contaminants						
7738/1-16	1.674 ± 0.001	—	0.00005	5.328	99.7	154.14 ± 0.34
7738/1-27	1.674 ± 0.001	0.0115	0.00005	5.717	99.7	164.88 ± 0.38
7738/1-11	1.674 ± 0.001	—	0.00006	6.397	99.7	183.52 ± 0.44
7738/1-09	1.674 ± 0.001	0.2189	0.00010	6.493	99.7	186.15 ± 0.42
7738/1-12	1.674 ± 0.001	0.0140	0.00008	6.499	99.6	186.31 ± 0.40
7738/1-30	1.674 ± 0.001	—	0.00004	6.648	99.8	190.37 ± 0.42
7738/1-02	1.674 ± 0.001	—	0.00006	6.650	99.7	190.42 ± 0.41
7738/1-14	1.674 ± 0.001	—	0.00008	17.442	99.9	462.15 ± 0.91
7738/1-15	1.674 ± 0.001	—	0.00012	20.808	99.8	539.17 ± 1.03
7738/1-26	1.674 ± 0.001	—	0.00020	21.917	99.7	563.84 ± 1.07
7738/1-28	1.674 ± 0.001	—	0.00005	27.131	99.9	675.51 ± 1.25
7738/1-01	1.674 ± 0.001	—	0.00002	31.479	100.0	763.62 ± 1.42
7738/1-35	1.674 ± 0.001	—	0.00005	34.937	100.0	830.75 ± 1.50
7738/1-24	1.674 ± 0.001	—	0.00063	50.630	99.6	1107.44 ± 1.85
7738/1-10	1.674 ± 0.001	—	0.00008	58.961	100.0	1238.74 ± 2.04
7738/1-19	1.674 ± 0.001	—	0.00009	59.568	100.0	1247.93 ± 2.01
Sample LCM-1						
5048-02	3.816 ± 0.013	0.0211	0.00003	2.269	99.7	149.78 ± 0.55
5048-01	3.816 ± 0.013	0.0179	0.00007	2.270	99.2	149.84 ± 0.59

TABLE III (*Continued*)

Lab ID #	$J \pm 1\sigma$ ($\times 10^{-2}$)	Ca/K	$^{36}Ar/^{39}Ar$ $\pm 1\sigma$	$^{40}Ar^{*}/^{39}Ar$	$\%^{40}Ar^{*}$	*Age* $\pm$ *Error* (Ma)
5048/2C-07	3.816 ± 0.013	0.0102	0.00002	2.276	99.8	150.22 ± 0.60
5048-10	3.816 ± 0.013	0.0199	0.00003	2.276	99.6	150.23 ± 0.55
5048B-01	3.816 ± 0.013	0.0137	0.00002	2.276	99.8	150.25 ± 0.55
5048B-04	3.816 ± 0.013	0.0115	0.00003	2.277	99.7	150.31 ± 0.56
5048-05	3.816 ± 0.013	0.0170	0.00002	2.280	99.8	150.50 ± 0.55
		Weighted Average, 1σ error without error in J = 150.18 ± 0.11				
		1σ error with error in J = ± 0.50				
Sample LCM-39						
5042-03	3.801 ± 0.013	0.0139	0.00013	2.237	98.3	147.21 ± 0.69
5042-06	3.801 ± 0.013	0.0315	0.00007	2.239	99.2	147.37 ± 0.59
5042/2C-05	3.801 ± 0.013	0.0428	0.00035	2.246	95.6	147.79 ± 0.67
5042-01	3.801 ± 0.013	0.0120	0.00010	2.252	98.7	148.16 ± 0.63
5042-04	3.801 ± 0.013	0.0119	0.00007	2.253	99.1	148.22 ± 0.56
5042/2C-04	3.801 ± 0.013	0.0453	0.00007	2.254	99.2	148.30 ± 0.68
5042/2C-02	3.801 ± 0.013	0.0009	0.00009	2.254	98.9	148.33 ± 0.65
5042/2C-01	3.801 ± 0.013	0.0012	0.00003	2.257	99.6	148.50 ± 0.62
5042-07	3.801 ± 0.013	0.0501	0.00010	2.258	98.8	148.55 ± 0.62
		Weighted Average, 1σ error without error in J = 148.07 ± 0.17				
		1σ error with error in J = ± 0.51				
Sample MC-39						
5044-03	3.823 ± 0.013	0.0253	0.00010	2.202	98.8	145.81 ± 0.54
5044-01	3.823 ± 0.013	0.0383	0.00007	2.203	99.2	145.87 ± 0.53
5044-05	3.823 ± 0.013	0.0256	0.00008	2.205	99.0	146.04 ± 0.56
5044-04	3.823 ± 0.013	0.0268	0.00008	2.206	99.0	146.09 ± 0.56
5044-02	3.823 ± 0.013	0.0270	0.00004	2.225	99.5	147.27 ± 0.56
5044/2C-03	3.823 ± 0.013	0.0537	0.00007	2.231	99.2	147.66 ± 0.62
5044/2C-01	3.823 ± 0.013	0.0260	0.00005	2.241	99.4	148.28 ± 0.59
5044/2C-02	3.823 ± 0.013	0.0267	0.00003	2.249	99.7	148.81 ± 0.61
5044-06	3.823 ± 0.013	0.0266	0.00004	2.250	99.5	148.85 ± 0.54
5044-10	3.823 ± 0.013	0.0252	0.00003	2.252	99.6	148.97 ± 0.54
5044-09	3.823 ± 0.013	0.0313	0.00006	2.252	99.2	148.98 ± 0.57
5044/2C-05	3.823 ± 0.013	0.0312	0.00003	2.256	99.7	149.27 ± 0.63
5044-08	3.823 ± 0.013	0.0333	0.00008	2.263	99.0	149.72 ± 0.65
5044-07	3.823 ± 0.013	0.0342	0.00006	2.269	99.3	150.05 ± 0.60
		Weighted Average, 1σ error without error in J = 147.82 ± 0.42				
		1σ error with error in J = ± 0.63				
Sample MC-52						
5046-02	3.832 ± 0.013	0.0426	0.00004	2.240	99.5	148.55 ± 0.55
5046-10	3.832 ± 0.013	0.0601	0.00005	2.241	99.5	148.63 ± 0.58
5046-05	3.832 ± 0.013	0.0289	0.00005	2.246	99.4	148.94 ± 0.58
5046-01	3.832 ± 0.013	0.0246	0.00004	2.251	99.6	149.26 ± 0.57
5046-09	3.832 ± 0.013	0.0297	0.00004	2.251	99.5	149.27 ± 0.58
5046-06	3.832 ± 0.013	0.0265	0.00007	2.256	99.2	149.55 ± 0.56
5046B-02	3.832 ± 0.013	0.0667	0.00005	2.260	99.5	149.86 ± 0.60
5046B-05	3.832 ± 0.013	0.0450	0.00013	2.265	98.4	150.18 ± 0.58
5046B-04	3.832 ± 0.013	0.0304	0.00002	2.270	99.7	150.47 ± 0.59
		Weighted Average, 1σ error without error in J = 149.39 ± 0.23				
		1σ error with error in J = ± 0.53				

TABLE III (*Continued*)

Lab ID #	$J \pm 1\sigma$ ($\times 10^{-2}$)	Ca/K	$^{36}Ar/^{39}Ar \pm 1\sigma$	$^{40}Ar^{*}/^{39}Ar$	$\%^{40}Ar^{*}$	*Age ± Error* (Ma)
Sample NTM-17						
5058B-02	3.824 ± 0.013	0.0794	0.00016	2.250	98.1	148.91 ± 0.80
5058B-03	3.824 ± 0.013	0.0957	0.00009	2.251	99.0	148.95 ± 0.57
5058/2-08	3.824 ± 0.013	0.0540	0.00006	2.258	99.4	149.41 ± 0.67
5058/2-03	3.824 ± 0.013	0.0673	0.00007	2.258	99.2	149.43 ± 0.73
5058B-05	3.824 ± 0.013	0.1670	0.00009	2.262	99.1	149.65 ± 0.67
5058/2-05	3.824 ± 0.013	0.3532	0.00011	2.269	99.2	150.10 ± 0.81
Weighted Average, 1σ error without error in $J = 149.29 \pm 0.19$						
1σ error with error in $J = \pm 0.52$						
Sample NTM-1319-1						
5056/2-08	3.793 ± 0.013	0.0165	0.00005	2.351	99.4	154.12 ± 0.66
5056/2-05	3.793 ± 0.013	0.0145	0.00003	2.354	99.7	154.25 ± 0.68
5056/2-06	3.793 ± 0.013	0.0192	0.00002	2.356	99.7	154.39 ± 0.68
5056/2-07	3.793 ± 0.013	0.0131	0.00006	2.356	99.3	154.40 ± 0.70
5056/2-04	3.793 ± 0.013	0.0133	0.00005	2.362	99.4	154.79 ± 0.71
5056/2-03	3.793 ± 0.013	0.0146	0.00003	2.364	99.6	154.91 ± 0.71
5056/2-01	3.793 ± 0.013	0.0162	0.00003	2.368	99.7	155.13 ± 0.84
5056/2-09	3.793 ± 0.013	0.0160	0.00001	2.369	99.8	155.19 ± 0.69
5056/2-10	3.793 ± 0.013	0.0103	0.00000	2.371	100.0	155.32 ± 0.80
5056/2-02	3.793 ± 0.013	0.0146	0.00002	2.375	99.8	155.58 ± 0.68
Weighted Average, 1σ error without error in $J = 154.75 \pm 0.18$						
1σ error with error in $J = \pm 0.54$						
Sample RAIN-1325-4+4						
5064/2-04	3.811 ± 0.013	0.0090	0.00014	2.344	98.3	154.37 ± 0.80
5064B-08	3.811 ± 0.013	0.0179	0.00011	2.351	98.7	154.79 ± 0.71
5064/2-03	3.811 ± 0.013	0.0052	0.00011	2.360	98.6	155.35 ± 0.96
5064/2-01	3.811 ± 0.013	0.0089	0.00004	2.361	99.6	155.43 ± 1.29
Weighted Average, 1σ error without error in $J = 154.82 \pm 0.30$						
1σ error with error in $J = \pm 0.58$						

Notes: Errors in age quoted for individual runs are 1σ analytical uncertainty. Weighted averages are calculated using the inverse variance as the weighting factor (Taylor, 1982), while errors in the weighted averages are 1σ standard error of the mean (Samson and Alexander, 1987). Ca/K is calculated from $^{37}Ar/^{39}Ar$ using a multiplier of 1.96; where no entries appear for Ca/K, ^{37}Ar was below the level of detection. $^{40}Ar^{*}$ refers to radiogenic argon. $\lambda = 5.543 \times 10^{-10}\,y^{-1}$. Isotopic interference corrections for sample DQW-21: $(^{36}Ar/^{37}Ar)_{Ca} = (2.64 \pm 0.02) \times 10^{-4}$, $(^{39}Ar/^{37}Ar)_{Ca} = (6.7 \pm 0.4) \times 10^{-4}$, $(^{40}Ar/^{39}Ar)_{K} = (8.4 \pm 0.2) \times 10^{-3}$; for sample GP-1346-28 ± 23: $(^{36}Ar/^{37}Ar)_{Ca} = (2.64 \pm 0.02) \times 10^{-4}$, $(^{39}Ar/^{37}Ar)_{Ca} = (6.7 \pm 0.4) \times 10^{-4}$, $(^{40}Ar/^{39}Ar)_{K} = (7 \pm 3) \times 10^{-4}$; for all other samples: $(^{36}Ar/^{37}Ar)_{Ca} = (2.58 \pm 0.06) \times 10^{-4}$, $(^{39}Ar/^{37}Ar)_{Ca} = (6.7 \pm 0.3) \times 10^{-4}$, $(^{40}Ar/^{39}Ar)_{K} = (2.35 \pm 0.04) \times 10^{-2}$.

TABLE IV Single-crystal $^{40}Ar/^{39}Ar$ Analytical Data for NTM-1319-1 (Obradovich)

Lab ID #	$J \pm 1\sigma$ ($\times 10^{-2}$)	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar^{*}/^{39}Ar$	$\%^{40}Ar^{*}$	*Age ± Error* (Ma)
90Z0943	0.886 ± 0.004	0.016258	0.000563	10.1796	98.13	155.8 ± 1.1
90Z0944	0.886 ± 0.004	0.011097	0.000029	10.0973	99.64	154.6 ± 0.9
90Z0945	0.886 ± 0.004	0.011331	0.000104	10.0671	99.42	154.1 ± 0.9
Average Age with 1σ error in $J = 154.8 \pm 1.4$						

Notes: Isotopic interference corrections: $(^{36}Ar/^{37}Ar)_{Ca} = 0.000251$, $(^{39}Ar/^{37}Ar)_{Ca} = 0.000671$, $(^{40}Ar/^{39}Ar)_{K} = 0.0285$. MMhb-1 monitor age = 520.4 Ma.

indistinguishable from the single crystal ages on this same ash bed (see Fig. 6 and Tables III–V). MC-39 is the sample that gave a mean single-crystal age that was stratigraphically too young. It gives plateau ages of 148.21 or 148.63 ± 0.50 Ma (1σ) depending on the temperature steps used in calculating the age. Both of these ages are statistically indistinguishable from the laser-fusion mean age at the 95% confidence level, but are somewhat closer to fitting in with the rest of the stratigraphic framework (Fig. 2).

TABLE V $^{40}Ar/^{39}Ar$ Age Spectrum Data (Kunk)

T (°C)	% ^{39}Ar *of Total*	$^{40}Ar_R/^{39}Ar_K$ †	*Apparent* K/Ca ‡	*Apparent* K/Cl	*Radiogenic Yield* (%)	$^{39}Ar_K$ § ($\times 10^{-12}$ moles)	*Apparent Age* ¶ ± *Precision* (Ma)
Sample MC-39		$J = 0.007422 \pm 0.25\%$				Sample wt. = 0.2512 g	
1075	9.3	11.549	15.99	—	99.9	1.649	148.37 ± 0.21
1120	8.1	11.511	11.42	—	99.7	1.425	147.89 ± 0.26
1150	8.2	11.517	20.50	—	99.7	1.443	147.97 ± 0.19
1180	8.8	11.503	7.60	—	99.6	1.549	147.79 ± 0.44
1220	10.7	11.549	16.06	—	100.0	1.899	148.36 ± 0.13
1260	12.3	11.519	13.55	—	99.7	2.172	147.99 ± 0.31
1300	13.4	11.559	0.00	—	99.8	2.369	148.49 ± 0.23
1350	17.5	11.590	164.85	—	100.0	3.093	148.87 ± 0.09
1450	11.8	11.623	370.61	—	99.9	2.085	149.27 ± 0.29
Total Gas		K/Ca = 80.7				Age	148.41 ± ????
Plateau Age (70.7% of gas on plateau, steps 1075–1300°C)							148.21 ± 0.50
Plateau Age (53.9% of gas on plateau, steps 1220–1350°C)							148.63 ± 0.50
Sample NTM-1319-1		$J = 0.007424 \pm 0.25\%$				Sample wt. = 0.1914 g	
1075	9.4	12.208	39.96	—	100.0	2.128	156.51 ± 0.22
1120	8.0	12.095	81.47	—	99.8	1.816	155.12 ± 0.39
1150	8.2	12.095	636.27	—	99.9	1.851	155.12 ± 0.12
1180	8.6	12.066	17.34	—	99.8	1.944	154.77 ± 0.05
1220	10.6	12.071	0.00	—	99.8	2.396	154.83 ± 0.24
1260	11.7	12.091	23.78	—	99.9	2.653	155.07 ± 0.17
1300	12.1	12.093	0.00	—	99.7	2.744	155.09 ± 0.35
1350	19.1	12.197	87.31	—	100.0	4.326	156.38 ± 0.24
1450	12.2	12.411	105.74	—	99.8	2.747	159.00 ± 0.35
Total Gas		K/Ca = 96.2				Age	155.89 ± ????
Plateau Age (59.3% of gas on plateau, steps 1120–1300°C)							154.87 ± 0.52

† This ratio has been corrected for mass discrimination, atmospheric argon, and the production of interfering isotopes during irradiation using the values reported by Dalrymple and others (1981) for $(^{36}Ar/^{37}Ar)_{Ca}$, $(^{39}Ar/^{37}Ar)_{Ca}$, and $(^{40}Ar/^{39}Ar)_K$.

‡ Apparent K/Ca ratios were calculated using the equation given in Fleck, Sutter, and Elliot (1977).

§ ^{39}Ar concentrations were calculated using the measured sensitivity of the mass spectrometer and have a precision of about 5%.

¶ Comparisons between steps for the determination of the existence of an age plateau were done using the larger of: the calculated uncertainty from the analyses or, the reproducibility limit of the mass spectrometer as determined by replicate measurements of FCT-3. During the period of time in which these samples were analyzed the reproducibility limit was 0.15%.

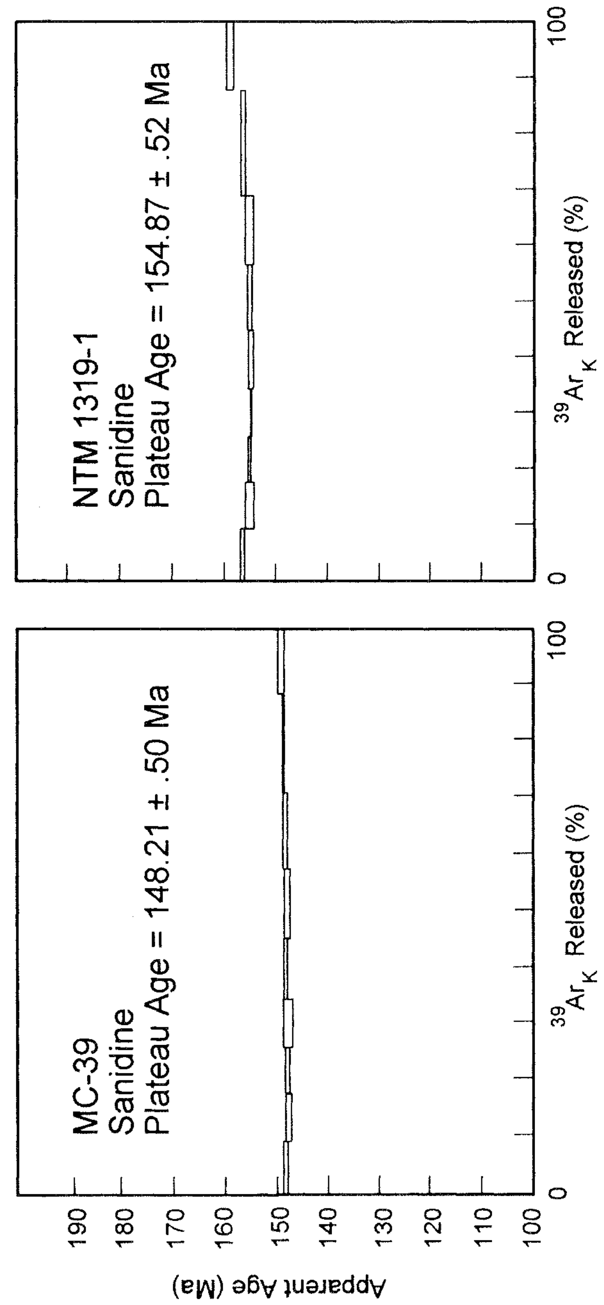

FIGURE 6 $^{40}Ar/^{39}Ar$ age spectra for MC-39 and NTM-1319-1.

DISCUSSION

Some idea of the maximum possible age range of the Morrison Formation and its bounding unconformities can be obtained from the ages of rocks just below and just above the formation. The available biostratigraphic age information on rocks that enclose the Morrison indicates that the maximum time span represented by the Morrison Formation and the bounding J-5 and K-1 unconformities ranges from latest Oxfordian to possibly Barremian.

The youngest unit below the Morrison is the Oxfordian age Redwater Shale Member, which is included in either the Sundance or Stump formations of eastern or western Wyoming, respectively. Most of this unit is well dated by ammonites and ranges through the entire early and middle Oxfordian according to Imlay (1980) and Callomon (1984). The undated uppermost beds of the Redwater Shale, above the highest fossil collections, could extend into the earliest part of the late Oxfordian. Allowing some time for formation of the J-5 unconformity at the top of the Redwater Shale, the base of the Morrison should be latest Oxfordian at the oldest. Preliminary examination of trace-fossil assemblages across the Redwater–Windy Hill contact at Dinosaur National Monument, Utah, suggests continuous deposition. Either there is no unconformity between these units there or the J-5 unconformity is stratigraphically lower than has been thought (S.T. Hasiotis and T.M. Demko, oral communication, 1994). This problem is currently being investigated.

The oldest rocks above the Morrison Formation are included in the Burro Canyon and Cedar Mountain formations, which appear to be correlative units, at least in part (Aubrey, this volume), in the eastern and western parts of the Colorado Plateau, respectively. Palynomorphs recovered from the uppermost part of the Burro Canyon Formation indicate "an Aptian–early Albian age, with the remote possibility of a late Barremian age" according to Tschudy and others (1984, p. 19). Palynomorphs recovered from the uppermost part of the Cedar Mountain Formation indicate that it is "clearly of late or latest Albian age" (Tschudy and others, 1984, p. 11). The lower parts of both formations have not been well dated, but a small dinosaur fauna recovered from the lower beds of the Cedar Mountain Formation may suggest a Barremian age (Kirkland, 1992). Thus, the dinosaurs and palynomorphs indicate that the Cedar Mountain and Burro Canyon formations above the K-1 unconformity are about Barremian to Albian in age. Accordingly, the Morrison Formation is probably older than Barremian.

The results of our current dating efforts allow us to more confidently place the Morrison Formation in its proper time-stratigraphic position (see Fig. 2). The ages from the Tidwell Member suggest that deposition of the Morrison Formation began around 155 Ma, which is close to the Oxfordian–Kimmeridgian boundary that Harland and others (1990) place at 154.7 Ma. According to Schudack and others (this volume), Oxfordian(?) fossils were found just above the level of the dated bentonite bed in the Tidwell Member near Grand Junction, Colorado and Kimmeridgian charophytes and palynomorphs were recovered from higher strata in the Tidwell (Litwin and others, this volume; Schudack and others, this volume). The new ages reported here are the most precise isotopic age data yet published from latest Oxfordian(?) to early Kimmeridgian-age sedimentary rocks. Consequently, these new data suggest that the hiatus at the J-5 unconformity is probably on the order of 1 Ma in duration.

Sanidine ages from the Brushy Basin Member range from 150.33 ± 0.27 Ma (1 std. error of mean) to 147.82 ± 0.63 Ma; they suggest a Kimmeridgian–Tithonian age for this member based on the time scales of Obradovich (1993), Bralower and others (1990), or Harland and others (1990). The paleontological data reported in this volume by Litwin and others and Schudack and others indicate that the Brushy Basin Member is Kimmeridgian to perhaps early Tithonian in age. We conclude that deposition of the Morrison Formation ended before the end of the Jurassic, and that the formation is entirely Late Jurassic in age. The hiatus at the K-1 unconformity is approximately 20 Ma in duration and includes part of the Tithonian, the entire Berriasian, Valanginian, and Hauterivian, and part or all of the Barremian Ages.

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APPENDIX I

Location of measured sections and isotopically dated samples.

Dinosaur Quarry West Section

About 0.6 km west of the Carnegie Quarry Building at Dinosaur National Monument along the west side of a small canyon locally known as Douglas Draw.

SE¼ NE¼ SE¼ sec. 27, T 4 S, R 23 E, Uintah Co., Utah.

Top of measured section at 40° 26′ 20″ North Latitude, 109° 17′ 40″ West Longitude.

Fruita Paleontological Site Section

Sample collected on the northeast side of a small hill locally known as Al Look hill.

SE¼ SE¼ SW¼ sec. 13, T 1 N, R 3 W, Mesa Co., Colorado.

39° 09′ 00″ North Latitude, 108° 46′ 06″ West Longitude.

Section measured by J.I. Kirkland (oral communication, 1993), modified after a partial section measured by F. Peterson (unpublished data).

Garden Park Section

Sample came from artificial cuts in a bentonite mine on the north side of a small west-draining tributary to Fourmile Creek.

N½ NE¼ NW¼, E½ SE¼ NW¼, SW¼ SW¼ NE¼, NW¼ NW¼ SE¼ sec. 26, T 17 S, R 70 W, Fremont Co., Colorado.

The bentonite mine is at 38° 32′ 39″ North Latitude, 105° 11′ 52″ West Longitude.

Little Cedar Mountain Section

In a slight reentrant on the south side of Little Cedar Mountain.

NW¼ NW¼ SE¼, SW¼ SW¼ NE¼, SE¼ SE¼ NW¼ sec. 5, T 19 S, R 10 E, Emery Co., Utah.

Top of measured section at 39° 12′ 02″ North Latitude, 110° 49′ 25″ West Longitude.

Montezuma Creek Section

At the head of a small tributary draw to Montezuma Creek.

W½ SE¼, SW¼ NE¼ sec. 7, T 40 S, R 24 E, San Juan Co., Utah.

Top of measured section at 37° 19′ 15″ North Latitude, 109° 26′ 26″ West Longitude.

Notom Section

On the east side of a small north-draining draw that is a tributary to the Fremont River.

SW¼ SE¼ sec. 24, T 29 S, R 7 E, Wayne Co., Utah.

Top of measured section at 38° 16′ 44″ North Latitude, 111° 07′ 35″ West Longitude.

Partly from a section measured by Petersen and Roylance (1982, section A).

Rainbow Draw Section

In the head of a small tributary canyon to Rainbow Draw.

SE¼ SE¼ NW¼, NE¼ NE¼ SW¼ sec. 14 and NW¼ SE¼ SE¼, E½ SW¼ SE¼ sec. 23, T 3 S, R 24 E, Uintah Co., Utah.

Top of measured section at 40° 33′ 30″ North Latitude, 109° 11′ 36″ West Longitude.