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A U/Pb age for the Mygatt-Moore Quarry, Upper Jurassic Morrison Formation, Mesa County, Colorado

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Key words: Morrison Formation, U/Pb dating, CA-TIMS, dinosaurs, North American Jurassic.

Abstract. Mygatt-Moore Quarry in the Brushy Basin Member of the Upper Jurassic Morrison Formation is one of the more important large dinosaur quarries in the formation, yielding fossils of sauropod dinosaurs including *Apatosaurus*, *Camarasaurus*, and an indeterminate diplodocine (cf. *Diplodocus* or *Barosaurus*), the theropod dinosaurs *Allosaurus* and *Ceratosaurus*, and the ornithischians *Othnielosaurus* and *Mymoorapelta*. Fossil wood and carbonized plants are known from the deposit, and carbonized dinosaur skin has also been discovered.

We report here on a new U/Pb radiometric age for the Mygatt-Moore Quarry, from a smectitic mudstone collected at the quarry horizon. We isolated zircons using an ultrasonic separation technique and standard heavy liquid and magnetic methods, analyzed single zircons using a chemical abrasion method (CA-TIMS). The age determined for this dinosaur quarry, 152.18 ±0.29 Ma, places the quarry at the boundary between the Kimmeridgian and Tithonian stages of the Late Jurassic Period. This age can now be used to place the quarry into stratigraphic position with respect to other dated horizons in the Morrison Formation and other rock units worldwide. We will also use this age along with other ages to create a radiometrically based stratigraphic framework for the Morrison Formation.

INTRODUCTION

The Morrison Formation is an Upper Jurassic terrestrial rock unit that originally covered at least ~1,000,000 km^2 of what is now the western United States. The formation is well known for its fossil flora and fauna, especially the remains of dinosaurs (Dodson *et al*., 1980; Russell, 1989; Foster, 2003). Dinosaur quarries in the Morrison Formation number in the hundreds, and include quarries that yield a few bones of one individual and others with 10,000 bones of multiple individuals and species. The Mygatt-Moore Quarry is one of the larger quarries and was discovered in 1981, by J.D. and Vanetta Moore and Pete and Marilyn Mygatt (Armstrong, Perry, 1985; Mygatt, 1991; Kirkland, Armstrong, 1992). It is approximately 2.5 km from the Utah-Colorado state line in far western Mesa County, Colorado, about 27 km west of the town of Fruita (Fig. 1A).

As part of a long-term project to date the Morrison Formation, we collected a sample of smectitic mudstone from the bone-bearing horizon at the Mygatt-Moore Quarry in 2011. We used new mineral separation and analytical techniques designed to allow isolation and U/Pb dating of small, ashfall zircons to determine an age for the quarry. This age can then be used to place the quarry into stratigraphic position with respect to other dated horizons in the Morrison Formation and other rock units worldwide.

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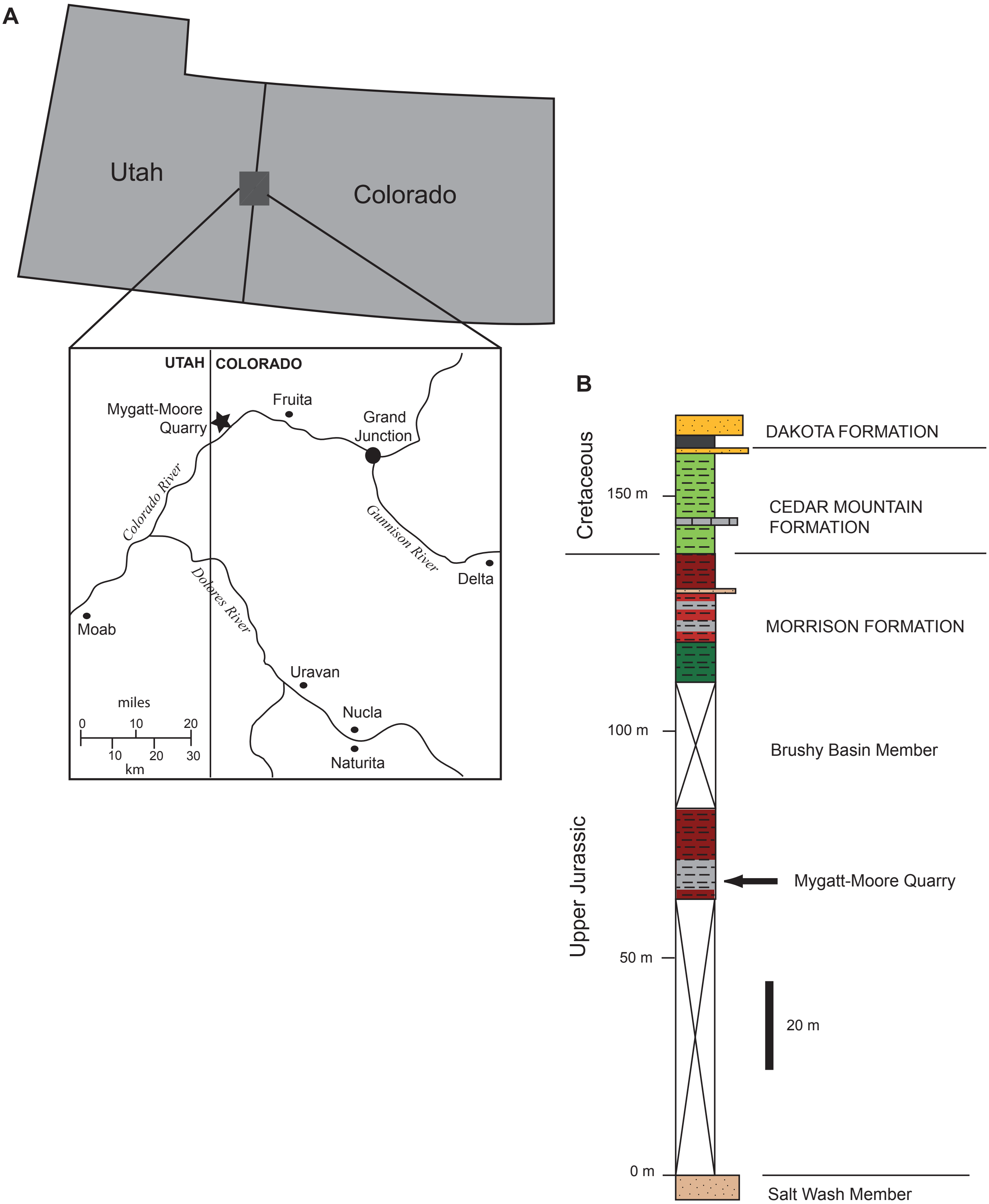

Fig. 1. A. Location of Mygatt-Moore Quarry in western Colorado. B. Stratigraphic section of the Brushy Basin Member of the Morrison Formation showing position of the Mygatt-Moore Quarry (from Foster, Hunt-Foster, 2011)

MYGATT-MOORE QUARRY

The Morrison Formation is exposed over a vast depositional area. In the Colorado Plateau region it has been divided into many different members, although these distinctions break down outside of the Colorado Plateau region (Peterson, Turner-Peterson, 1987). In west-central Colorado, the formation consists of the basal Tidwell Member, the Salt Wash Member, and the upper Brushy Basin Member. The top of the Salt Wash Member in the vicinity of the Mygatt-Moore Quarry is formed by the top of one of several tan, laterally continuous channel sandstones that can be traced across the valley. The Brushy Basin Member consists of approximately 100–140 m of gray, maroon, and greenish-gray claystone with numerous channel sandstones and thin splay sandstones and a few, thin freshwater limestone beds. The Mygatt-Moore Quarry is approximately 64 m above the local base of the Brushy Basin Member of the Morrison Formation, in a section in which the member is 135 m thick. This puts the quarry near the top of the lower half of the Brushy Basin Member (47% of the way up in the member section), at a level close to that illustrated by Turner and Peterson (1999) (Fig. 1B). A horizon with numerous fish fossils above the quarry (Kirkland, 1998) serves as a local marker bed which can be traced more than 500 m to the east of the quarry. The main quarry layer itself is a smectitic mudstone with a significant percentage of silt-sized grains, clay balls (some containing silt clasts themselves), and an abundance of carbonized plant debris and wood fragments.

Nearly 2400 bones have been mapped and collected over the 30 years of work at the Mygatt-Moore Quarry. The fauna of the quarry is dominated by sauropod dinosaurs and the theropod *Allosaurus fragilis*. By number of elements, the most abundant vertebrate taxa are indeterminate sauropods and *Apatosaurus louisae*, followed by *Allosaurus* and the ankylosaur *Mymoorapelta*. All other dinosaur taxa are rare and include *Camarasaurus*, *Ceratosaurus*, *Othnielosaurus*, and an indeterminate diplodocine (cf. *Diplodocus* or *Barosaurus*). One crocodylomorph vertebra and indeterminate small reptiles are also present but are very rare. Although fragmentary bones are most abundant, teeth, vertebrae, and ribs are well represented. Carbonized dinosaur skin has also been discovered in the Mygatt-Moore Quarry (Foster, Hunt-Foster, 2011). The fauna includes, by minimum number of individuals of dinosaurs and other vertebrates, 4 juveniles, one sub-adult, and 17 adult-sized animals. Such a distribution with many adults, fewest number of subadults, and moderate representation of juveniles is suggestive of an attritional mortality assemblage with delayed burial (Eberth *et al*., 2007).

The total sample to date curated in the Museum of Western Colorado collections, including taxonomically unidentifiable material, consists of nearly 1900 elements. The main bone layer is approximately 1 m thick, and the occurrence of bones within this interval is concentrated in the basal 33 cm. The quarry map shows a random orientation, with many broken and fragmentary bones but also a large number that are fairly well preserved and complete. The mapped bones collected from the Mygatt-Moore Quarry show a pattern of disarticulation and only slight association. Of the entire mapped sample, only 8 bones are in articulation with at least one other bone. Approximately 4% of the bones from the quarry have some indication of tooth marks from carnivorous dinosaurs, and more than 400 shed theropod teeth have been found in the deposit.

Based on these data, the Mygatt-Moore Quarry main quarry layer ("bone layer") may represent a near-perennial or ephemeral pond similar to a wooded, vernal pool. The area was surrounded by plants including horsetails, ferns, many types of conifers, ginkgoes, cycadophytes, relatives of quillworts and clubmosses, and the wet-adapted *Czekanowskia* (Tidwell *et al*., 1998; Hotton, Baghai-Riding, 2010). The unit geometry and lithology indicate that it was not a river channel and was likely some type of overbank deposit. The presence of many bone fragments (almost a "background" of small, nearly rounded fragments), calcium carbonate "pebbles", and small clay balls indicates that a significant portion of the material was washed in (Hunt-Foster, Foster, 2014), probably during flooding of a nearby channel. The total lack of fish and turtle material from the main quarry layer, and the extreme paucity of neosuchian material, suggests that permanent water was probably not present at the site. The high degree of corrosion (or bone spalling and "rot") on the fossil bones is also likely indicative of acidic conditions in the surrounding mud at the time, although the effects of low pH on bones can be quite variable even between samples in the same area. Preservation of dinosaur skin, not just as impressions in matrix, but more often carbonized, suggests occasional dysoxia in the mud of the deposit. The presence of trampled bones suggests that living animals frequented the deposit area, stepping on bone already in the mud during times of low (or no) water. The frequent presence of carnivorous dinosaurs is indicated by the abundance of *Allosaurus* bones, the abundance of shed theropod teeth, and the moderate amount of tooth marks on bones. The extremely high rate of disarticulation compared with other large quarries in the Morrison Formation may also be in part due to scattering by scavenging theropods.

U/PB DATING METHODS

J. Foster collected the sample for radiometric dating from the bone-bearing horizon at Mygatt-Moore Quarry. The sample collected was a smectitic mudstone and not a discrete ash bed. All aspects of the U/Pb dating were done at the University of Wyoming Geochronology Laboratory, under the supervision of K. Chamberlain.

In order to isolate zircons from smectitic mudstone, we used an ultrasonic probe to deflocculate the clays. The ultrasonic method of zircon separation avoids the need to subject the sample to deflocculating chemicals and adequately isolates the zircons from the electrostatic grip of clays. A small amount of the sample was first ground in a heavy-duty blender with water in a ratio of approximately 1 part rock to 5 parts water. Approximately 500 ml of this mud slurry was added to a 5000 ml pitcher and subjected to continuous ultrasonic disruption for 45 minutes while it was continuously stirred by a magnetic stirring bar. This “Phase I separation” breaks up the flocculated clay particles and allows the very small, heavy grains to fall to the bottom (Trujillo, 2003). In Phase II separation, the sample was ultrasonically disrupted in short (3 second) bursts for between 8 and 12 hours. Water was allowed to flow through the pitchers, carrying away the floating clay particles and leaving behind the heavier grains. After Phase II separation, the heavier grains were washed by manually decanting water in increasingly short intervals to remove as much of the remaining clay as possible. The resulting concentrate was dried using acetone. Multiple batches were processed this way to concentrate enough heavy grains; standard heavy liquid and magnetic separation techniques were used to further concentrate the zircons. Next, the resulting heavy mineral separation was hand-picked under a binocular microscope. Only zircons with specific morphologies typical of ash-fall zircons were chosen for U/Pb dates. Characteristics interpreted to indicate ash-fall zircons include elongate tips, longitudinal bubble trails and transverse channels (Fig. 2). These characteristics have been found empirically to correlate with the youngest zircons in ashes and may reflect volatile-rich, low pressure and low temperature crystal growth within the magma chamber just prior to eruption. Selected zircons were annealed at 850°C for 48 hours, then dissolved in two steps, modified from the chemical abrasion method of Mattinson (2005). The first step used concentrated HF (hydrofluoric acid) and HNO_3

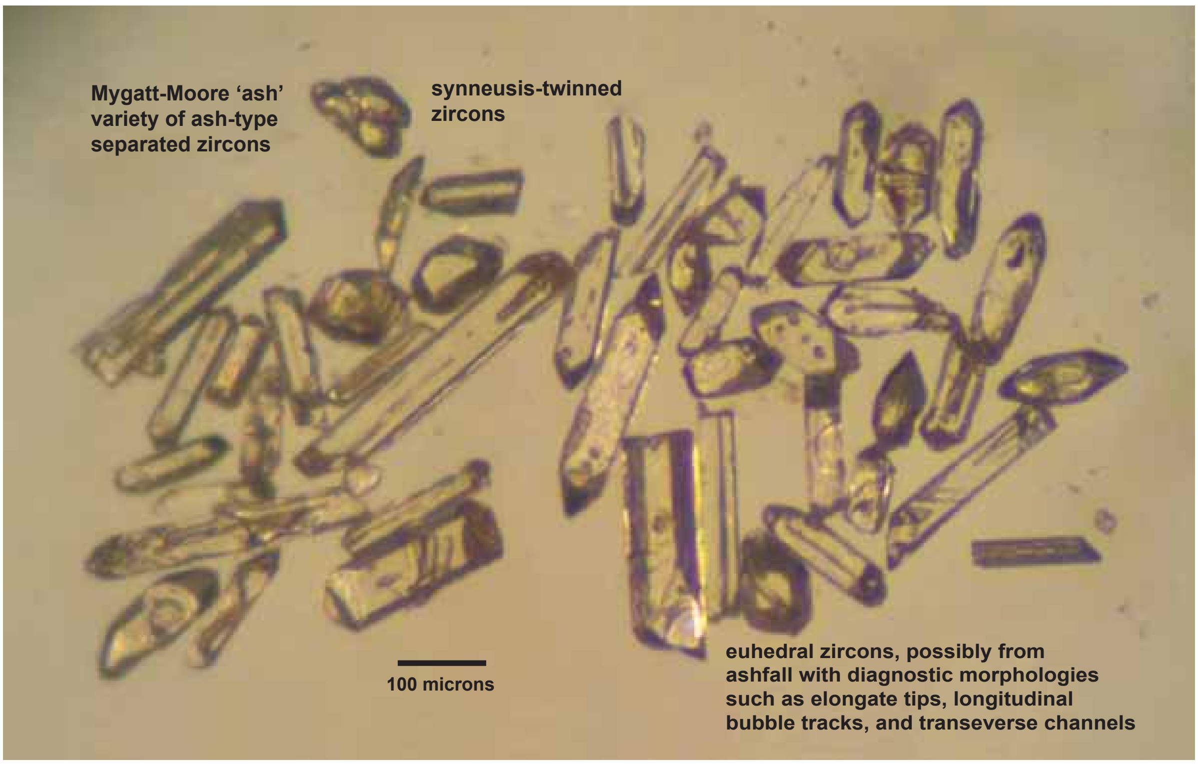

Fig. 2. Zircon morphologies separated from the Mygatt-Moore sample, showing characteristics typical of ash-fall zircons including elongate tips, longitudinal bubble trails and transverse channels. Only grains from the ash-fall type sub-population were processed for U/Pb dates

Table 1

CA-TIMS U/Pb zircon data for Mygatt-Moore Quarry

Sam-ple	Weight	U	sample Pb		cPb	Pb*	Th	^{206}Pb	^{208}Pb	Corrected atomic ratios ^{206}Pb/^{238}U		^{207}Pb/^{235}U		^{207}Pb/^{206}Pb		206/238	err	207/235	207/206	Rho
	[µg]	[ppm]	[ppm]	[pg]	[pg]	Pbc	U	^{204}Pb	^{206}Pb	[rad.]	%err	[rad.]	%err	[rad.]	%err	Age [Ma]		Age [Ma]	Age [Ma]	
Mygatt-Moore		152.18 ±0.29 Ma 95% confidence (MSWD 0.56), 4 points																		
sA	1.30	76.4	2.6	3	0.9	3.7	2.02	181	0.63	0.02378	(0.74)	0.1575	(8.1)	0.0480	(7.5)	151.52	±1.12	148.48	100.10	0.81
sB*	2.64	31.5	2.6	7	6.8	0.4	0.28	38	0.56	0.02537	(2.35)	0.2530	(18.6)	0.0723	(16.6)	161.51	±3.80	229.03	995.36	0.88
sD	2.43	193.3	6.8	16	0.6	26.9	1.95	1194	0.65	0.02390	(0.21)	0.1698	(1.07)	0.0515	(0.97)	152.24	±0.31	159.24	264.71	0.54
sF	0.61	141.0	4.2	3	2.7	0.9	1.29	67	0.39	0.02394	(2.17)	0.1540	(26.98)	0.0467	(25.05)	152.48	±3.31	145.42	31.73	0.90
sG	1.08	107.4	3.0	3	4.2	0.7	0.81	61	0.25	0.02378	(2.39)	0.1535	(29.40)	0.0468	(27.30)	151.50	±3.62	145.02	40.38	0.89

Notes: sample: s_=single grain; * excluded from weighted mean calculations.

Weight: represents estimated weight after first step of CA-TIMS zircon dissolution and is only approximate. U and Pb concentrations are based on this weight and are useful for internal comparisons only. Picograms (pg) sample and common Pb from the second dissolution step are measured directly, however and are accurate

sample Pb: sample Pb (radiogenic + initial) corrected for laboratory blank

cPb: total common Pb. All was assigned to laboratory blank unless greater than 3 pg.

Pb*/Pbc: radiogenic Pb to total common Pb (blank + initial)

Corrected atomic ratios: ^{206}Pb/^{204}Pb corrected for mass discrimination and tracer, all others corrected for blank, mass discrimination, tracer and initial Pb, values in parentheses are 2 sigma errors in percent.

Rho: ^{206}Pb/^{238}U vs ^{207}Pb/^{235}U error correlation coefficient

Zircon dissolution and chemistry were adapted from methods developed by Krogh (1973), Parrish et al. (1987) and Mattinson (2005). All zircons were chemically abraded (CA-TIMS). Final dissolutions were spiked with a mixed ^{205}Pb/^{233}U/^{235}U tracer (ET535). Pb and UO2 from zircons were loaded onto single rhenium filaments with silica gel without any ion exchange cleanup; isotopic compositions were measured in single Daly-photomultiplier mode on a Micromass Sector 54 mass spectrometer at the University of Wyoming. Mass discrimination for Pb was 0.220 ±0.10 %/amu for Daly analyses based on replicate analyses of NIST SRM 981. U fractionation was determined internally during each run. Procedural blanks ranged from 3 to 0.7 pg Pb during the course of the study. U blanks were consistently less than 0.2 pg. Isotopic composition of the Pb blank was measured as 18.463 ±0.84, 15.686 ±0.47, and 38.226 ±1.2 for 206/204, 207/204 and 208/204, respectively.

Concordia coordinates, intercepts, and uncertainties were calculated using MacPBDAT and ISOPLOT programs (based on Ludwig 1988, 1991); initial Pb isotopic compositions for zircon were estimated by Stacey and Kramers (1975) model. The decay constants used by MacPBDAT are those recommended by the I.U.G.S. Subcommission on Geochronology (Steiger, Jäger, 1977): 0.155125×10^{-9}/yr for ^{238}U, 0.98485×10^{-9}/yr for ^{235}U and present-day ^{238}U/^{235}U = 137.88.

(nitric acid) for 12 hours at 180°C. This removed the most metamict domains and surficial Pb. After rinsing and discarding the leachate, individual grains were spiked with a ^{205}Pb-^{233}U-^{235}U tracer (ET535) and completely dissolved in HF and HNO_3 at 240°C for 30 hours. The solutions were converted to chlorides and evaporated with 0.05N H_3PO_4 in preparation for thermal ionization mass spectrometry. See Table 1 for more details.

RESULTS

Based on CA-TIMS analysis of single zircons, an age of 152.18 ±0.29 Ma is proposed for the horizon that includes the Mygatt-Moore Quarry (Fig. 3). This is the weighted mean of four ^{206}Pb/^{238}U dates with uncertainty at 95% confidence interval (Fig. 4).

With regards to precision versus age uncertainty, the complete age report is 152.18 ± 0.29/0.32/0.49 Ma for 95% confidence limits on ^{206}Pb/^{238}U dates for internal precision/including tracer uncertainty/plus uncertainty in ^{238}U decay rate. The first precision can be used in comparing U/Pb dates using ET535 spike, the second for U/Pb dates that used a different tracer, and the third for comparison to fully regressed 95% confidence limits by other methods, such as ^{40}Ar/^{39}Ar. Note however, that when comparing to ^{40}Ar/^{39}Ar dates, the uncertainty on the ^{40}K-^{40}Ar decay rate must also be propagated in the ^{40}Ar/^{39}Ar dates.

SUMMARY AND CONCLUSIONS

Over the last hundred years, the Morrison Formation has been variously interpreted to be entirely Jurassic in age, entirely Cretaceous in age, or deposited during both periods (Kowallis *et al*., 1998). The most recent published radiometric ages prior to this, from ^{40}Ar/^{39}Ar on sanidine, support an age for the entire formation of Late Jurassic (Kowallis *et al*., 1998).

This new U/Pb age of 152.18 ±0.29 Ma for the Mygatt-Moore Quarry in the Morrison Formation of western Colorado agrees in general with these ^{40}Ar/^{39}Ar dates and places this portion of the formation squarely within the Late Jurassic. Using the timescale of Ogg *et al*. (2012), the boundary between the Kimmeridgian and Tithonian stages is currently set at 152.1 Ma. Mygatt-Moore Quarry therefore straddles this stage boundary.

Our new age for this quarry is part of an ongoing, long-term project to date the Morrison Formation (*e.g*., Trujillo, Chamberlain, 2013; Trujillo *et al*., 2014). By focusing on fossil-bearing localities, we can give ages to specific components of the fauna and flora while gaining more data for general stratigraphic correlations. In addition to quarries in Utah, Colorado, and southeastern Wyoming, we also plan to include quarries in eastern and northern parts of the Morrison Formation to increase our understanding of how those areas fit into the geochronological picture of the Morrison Formation.

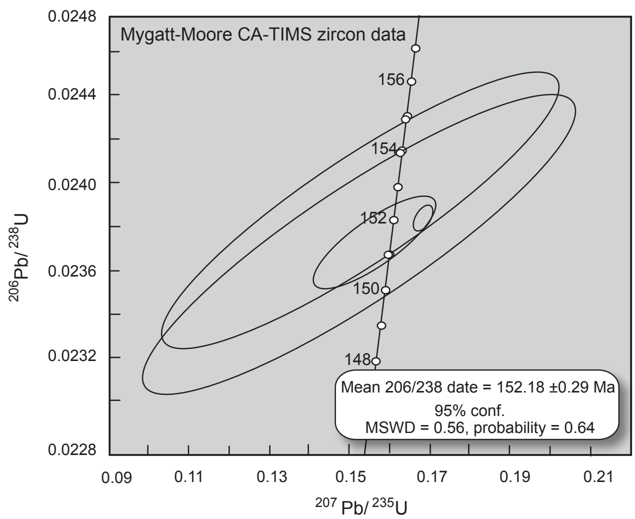

Fig. 3. Concordia plot of single grain, chemical abrasion, isotope dilution, thermal ionization mass spectrometric U/Pb analyses of zircon from Mygatt-Moore Quarry

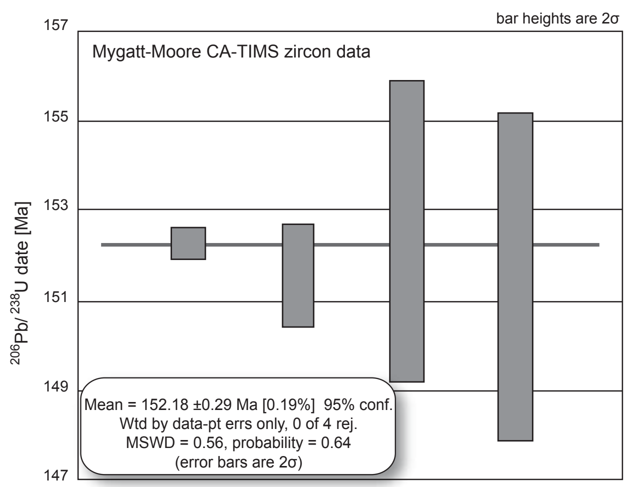

Fig. 4. Weighted mean plot of 4 single zircon CA-ID-TIMS ^{206}Pb/^{238}U dates from the Mygatt-Moore sample

The stratigraphic position of the Mygatt-Moore Quarry within the Brushy Basin member as determined for this study (J.R. Foster, unpublished data) is slightly higher than that indicated in Turner and Peterson (1999; new level is close to CO-57 on their figure 7 column). This level, nearly 73% of the way up from the base of the formation, might have been expected to yield an age around 150-151 Ma, based on recalibrations of the $^{40}Ar/^{39}Ar$ ages listed on the right of their figure 7 (Turner, Peterson, 1999, p. 86; based on Kowallis *et al*., 1998; recalibrations from Trujillo, unpublished). That the Mygatt-Moore Quarry age is at least a million years older than might have been expected indicates that vertebrate species so far endemic to western Colorado (or, even more restrictedly, are found only at the Mygatt-Moore Quarry) such as the polecanthine ankylosaurs *Mymoorapelta maysi* and the fish *Morrolepis schaefferi* and *"Hulettia" hawesi* appeared earlier than previously realized. Considering the age of 152.2 Ma for Mygatt-Moore Quarry near the middle of the Brushy Basin reported here, recalibrated ages of ~152 Ma for near the base of the Brushy Basin Member in Turner and Peterson (1999, their figure 7; recalibration from Trujillo, unpublished) may prove too young, and characteristically "lower Morrison" taxa such as the sauropod *Haplocanthosaurus* (see Foster, Wedel, this volume), generally restricted to the Salt Wash and lower Brushy Basin members and equivalents, may similarly be significantly older than previously realized. It is important to note, however, that the age for the base of the Tithonian has increased (Ogg *et al*., 2012), so that although much of the Morrison Formation may be older than expected previously, a significant portion of the formation's upper level still appears to be Tithonian in age.

The Morrison Formation is one of the most important fossil-bearing rock units in the world, and many researchers have attempted correlations within the formation as well comparisons of the floras and fauna of the Morrison Formation with other Upper Jurassic rock units worldwide. Because of the terrestrial nature and lithologic variability of the Morrison Formation, however, long-distance correlations within the formation are problematic. Radiometric ages are the best method to correlate across the depositional area of the Morrison Formation, and they are also the best way to compare the flora and fauna of the Morrison Formation with others in distant places. This new age for the Mygatt-Moore Quarry will be used along with other newly completed and planned ages to create a radiometrically based stratigraphic framework for this important formation.

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