Biostratigraphy of nonmarine Miocene gastropods from the Barstow Formation of California

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Introduction

The Barstow Formation comprises a concave belt of alluvial and lacustrine sediment, extending for 83 km between the Gravel Hills on the west and the Cronese Basin on the east in the Mojave Desert of California (Woodburne et al., 1990). The formation is best known for its fossil rich outcrops located within the Mud Hills, approximately 10 miles north of Barstow, California (Figure 1). Besides an abundance of vertebrate fossils, the Barstow Formation has yielded a considerable number of Miocene gastropods (Taylor, 1954; Plyley et al., 2013; Abersek et al., 2016).

The earliest work on gastropods from the Barstow Formation was by Dwight Taylor who attended Webb School of California, a secondary school in Claremont, California, in the late 1940s. He worked closely with Raymond Alf, a paleontologist/science teacher who eventually founded the museum that bears his name on the Webb campus. Shortly after completing his undergraduate degree, Taylor (1954) published his study of Barstow Formation gastropods, describing eight species from seven localities, four of which were new.

Beginning in the early 1990s, crews from the Raymond M. Alf Museum of Paleontology (RAM) have made significant collections of gastropods from the Barstow Formation. These collections were briefly described by Plyley et al. (2013) and compared to gastropods from the Temblor Formation of central California. Soon thereafter, description of gastropods from the Lake Bed locality (locality 3 of Taylor, 1954) and the geologic setting and paleoecology of the site, were provided by Abersek et al. (2016). However, the remainder of the RAM gastropod collection from the Barstow Formation has not been described. Also, in contrast to detailed biostratigraphic studies of the mammalian fauna of the Barstow Formation (Woodburne et al., 1990; Pagnac, 2009), a biostratigraphic analysis of gastropods from the formation has yet to appear.

Here, we document the lithostratigraphic position of RAM gastropods from the Lake Bed site (Abersek et al., 2016) and hundreds of other specimens from six RAM additional localities in the Barstow Formation. Based on these data, we provide the first biostratigraphic analysis of gastropods from the Barstow Formation. Detailed description of the entire RAM Barstow Formation mollusk collection will appear soon (Lofgren et al., in preparation).

Materials and methods

Gastropods in the RAM collections are from seven localities in the Barstow Formation: the Lake Bed (RAM V200025), Slug Bed (RAM V200515, RAM V94183), Chert Ridge Quarry (RAM V201202), Snail Farm (RAM V201201), *Helminthoglypta alfi* Type Locality (RAM V200114), Quarry 5 (RAM I99015), and the Bird Bone Bed (RAM V98004). The RAM collection has representatives of all eight of the gastropod species described by Taylor (1954) and one unnamed new taxon. Significant efforts to identify the RAM gastropod collection began with Plyley et al. (2013). A description of all nine species was presented by Abersek et al. (2016) based on specimens from the Lake Bed locality. Specimens from the other six localities were identified using the figures and descriptions provided in Abersek et al. (2016).
Measurements of the stratigraphic sections discussed in the text or shown in Figure 2 were compiled thusly: V98004 and Easter Quarry sections, November 2010, by D. L. Lofgren and P. Liskanich; Lake Bed section, November 2015, by D. L. Lofgren, W. F. Abersek, and M. Fassler; Chert Ridge Quarry (and Snail Ridge), Slug Bed, *Hemicyon* Tuff, and Unnamed Faulted sections,

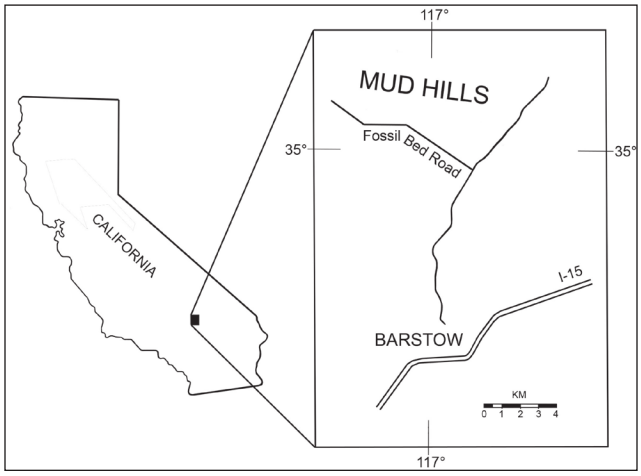

Figure 1. Location of the Barstow Formation within the Mud Hills, Mojave Desert, California (adapted from Steinen 1966).

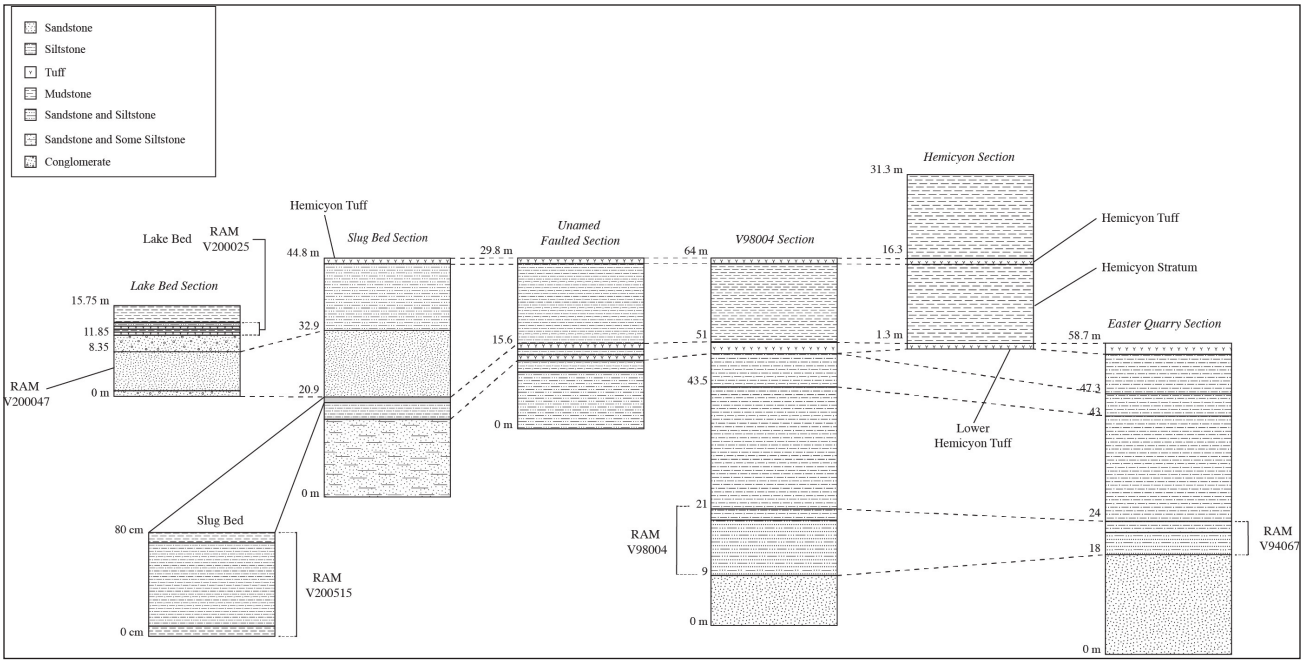

Figure 2. Correlation of stratigraphic sections from the upper member of the Barstow Formation showing lateral relationships between major gastropod-bearing sites and the *Hemicyon* Tuff along Fullers Earth Canyon and outcrops to the east (SE 1/4 section 15 and SW 1/4 Section 14, township 11 north, range 2 west); Easter Quarry Section about 1.8 km east of Lake Bed Section, strata thicknesses in meters, except for Slug Bed locality (V200515) detail which is in centimeters.

October 2016, by W. F. Abersek and D. L. Lofgren. Figure 2 includes standard rock textures provided by the United States Geological Survey. A standard Jacob's staff was used to measure all stratigraphic sections in meters. General geographic locations for RAM gastropod localities are given in Figure 2 or in text; GPS coordinates available to qualified investigators by request.

RAM Barstow Formation gastropod localities

Abersek et al. (2016) and Taylor (1954) identified eight mollusk species from the Barstow Formation, two of which are conically spiraled (*Lymnaea mohaveana* and *Lymnaea megasoma*) and five of which are discoidally spiraled (*Helminthoglypta alfi*, *Menetus micromphalus*, *Planorbula mojavensis*, *Pristiloma chersinellum*, and *Vallonia cyclophorella*). The other species is the 'slug' *Craterarion pachyostracon*. Abersek et al. (2016) also identified an unnamed discoidal gastropod and described it as "species indeterminate," although it bears some similarity to *Helminthoglypta alfi*.

Of the seven Barstow localities where RAM crews recovered gastropods, the Lake Bed locality (RAM locality V200025) has the most diverse number of species (Figure 3) and its most common is the aquatic species *Lymnaea mohaveana* (Abersek et al., 2016). The Lake Bed is also the type locality of *Lymnaea mohaveana*, *Craterarion pachyostracon*, and *Menetus micromphalus* (Taylor, 1954), and the only locality where "species indeterminate" has been found (Abersek et al., 2016). *Craterarion pachyostracon* is extremely common at the Slug Bed (RAM localities V200515 and V94183) (Figure 3), but this site was as yet undiscovered when Taylor (1954) completed his study of Barstow Formation gastropods.

The seven RAM localities that yield gastropods are described below. The Lake Bed, the Slug Bed, and the Bird Bone Bed (RAM locality V98004) are shown in their stratigraphic positions in relation to one another and to the *Hemicyon* Tuff (Figure 2). The four others are discussed in relation to their stratigraphic position compared to the Skyline or Oreodont tuffs. All RAM sites are in the upper member of the Barstow Formation except for Quarry 5, which is in the middle member.

Lake Bed, RAM Locality V200025 (locality 3 of Taylor, 1954). The Lake Bed is composed of 40-50 cm of brown mudstone with thin beds of siltstone located between two 4 cm thick tuffaceous marls (Abersek et al., 2016). Fossil mammals and gastropods are both abundant in the Lake Bed and all of the nine known gastropod taxa from the Barstow Formation are present at the site (Figure 3) (Abersek et al., 2016). A 15.75 m thick section encompasses the Lake Bed which is in an arroyo referred to as Bird Canyon (see map in Lindsay, 1972: fig. 1). Based on approximate stratigraphic position, the Lake Bed locality is certainly stratigraphically below the *Hemicyon* Tuff (equals *Hemicyon* Tuff of Woodburne et al., 1990, which overlies the *Hemicyon* stratum containing abundant mammals). But the top of the Lake Bed section is faulted just above the locality, so the available outcrop does not preserve the relative stratigraphic positions of the Lake Bed and *Hemicyon* Tuff (Figure 2). Lindsay (1972) estimated that the Lake Bed was about 10 m below the *Hemicyon* Tuff and this seems to be reasonable based on

extrapolated lithostratigraphic correlations from the Slug Bed section (Figure 2). The base of the Lake Bed section is also faulted so that highly disturbed remnants of Slug Bed sediment occur on the fault scarp in Bird Canyon.

Slug Bed, RAM Locality V200515 and V94183. The Slug Bed is composed of about 80 cm of siltstone and mudstone (Figure 2) in which specimens of the slug *Craterarion pachyostracon* abound. A few specimens of *C. pachyostracon* were also recovered from the Lake Bed (Figure 3), but this rare taxon has not been reported elsewhere in North America. Unlike most other gastropod bearing sites in the Barstow Formation, specimens of species other than *C. pachyostracon* at the Slug Bed are very fragile and are destroyed as they erode. Thus, only one adult specimen of *Lymnaea mohaveana* has been recovered, except for a possible crushed specimen of *Helminthoglypta alfi* (Figure 3).

Many small elements of mammals occur in the Slug Bed, the most common of which are isolated teeth or jaw fragments of a beaver identified by Lindsay (1972) as *Monosaulux pansus*. The 44.8 m Slug Bed section indicates that the *Hemicyon* Tuff is about 23 m above the Slug Bed (Figure 2). Also, extrapolating strata from the V98004 section and Unnamed Faulted section between the V98004 and Slug Bed sections, the Slug Bed appears to be approximately laterally equivalent to the Lower *Hemicyon* Tuff (Figure 2). The throw of the fault between the Slug Bed section and the Unnamed Faulted section is about 29 m, but stratigraphic units can be easily traced across this fault because of excellent exposures. Similarly, there is another fault between the Unnamed Faulted section and the V98004 section, but the Lower *Hemicyon* Tuff and *Hemicyon* Tuff are laterally traceable across the fault (Figure 2).

RAM Locality V98004, Bird Bone Bed. The V98004 section is 64 m thick and encompasses the Lower *Hemicyon* Tuff, *Hemicyon* Tuff, and RAM locality V98004, which is composed of 12 m of mostly siltstone (Figure 2) that has yielded a rich mammalian fauna (Lofgren et al, 2014). The V98004 stratigraphic interval yielded the holotype of *Megahippus mckennai* (Tedford and Alf, 1962) and an M2 of the proboscidean *Gomphotherium*, the oldest known record of this taxon from the Barstow Formation (Lofgren et al., 2010; Lofgren et al., 2012). The site is also notable for its large concentration of small vertebrate bones in a 10 cm thick siltstone lens (one meter in width), of which over 50% are avian elements (Lofgren et al., 2014). Three specimens of *Helminthoglypta alfi* were also recovered from this siltstone lens (Figure 3).

The two tuffs and other strata from the V98004 section can be traced to the east across a couple of minor faults to the *Hemicyon* Stratum and Easter Quarry sections, which contain the Frick Quarry sites of the same names. Specimens from Easter Quarry and the *Hemicyon* Stratum (often called *Hemicyon* Quarry) are housed at the American Museum of Natural History in New York. The fossil rich *Hemicyon* Stratum occurs high in the 15 m interval of strata between the Lower *Hemicyon* Tuff and *Hemicyon* Tuff, but this same interval in the V98004 section is not significantly fossiliferous. Also, 6 m of the Easter Quarry section are laterally equivalent to strata that comprise RAM locality V98004 (Figure 2) and the two

	Lake Bed V200025	Slug Bed V200515	Chert Ridge Quarry V201202	Snail Farm V201201	*H. alfi* Type Locality V200114	Quarry 5 I99015	Bird Bone Bed V98004
Lymnaea mohaveana	321	1					
Lymnaea megasoma	15		4				
Craterarion pachyostracon	5	Approx. 5000					
Helminthoglypta alfi	3	1			144		3
Menetus micromphalus	3		1		2		
Planorbula mojavensis	14		122	72	1	1	
Pristiloma chersinellum	41						
Vallonia cyclophorella	2				1		
Species Indeterminate	3						

Figure 3. Number of specimens per gastropod taxon recovered from the seven RAM localities. Stratigraphic position of sites shown in Figure 2 or discussed in text.

intervals have a similar concentration of well preserved, black-gray fossils. The 6 m interval in the Easter Quarry section is known as RAM locality V94067 (Lofgren et al., 2014) and the Frick Easter Quarry is located in the upper part of this 6 m interval.

Chert Ridge Quarry, RAM Locality V201202 (SE ¼, Section 9, Township 11 north, Range 2 west). Chert Ridge Quarry is another Frick quarry, but actually is three quarries spaced about 200 meters laterally that were centered on excavation of a bone rich tuffaceous siltstone. The middle quarry produces 95% of the gastropod specimens found by RAM crews. Measuring up from the Skyline Tuff (50 cm thick and well exposed in this area), RAM locality V201202 is about 39 m above the Skyline Tuff. The *Hemicyon* Tuff is mapped in this vicinity (Woodburne et al., 1990), but a number of tuffs were found above the Skyline Tuff and we could not distinguish which was the *Hemicyon* Tuff. Chert Ridge Quarry (V201202) yielded more than one hundred gastropods, over 90% of which were *Planorbula mojavensis* (Figure 3). Four specimens of *Lymnaea megasoma* and a single specimen of *Menetus micromphalus* were also recovered.

Snail Farm, RAM Locality V201201 (SE ¼, Section 9, Township 11 north, Range 2 west). This site is about 200 m east of Chert Ridge Quarry (V201202) and is in a tuffaceous siltstone that is approximately stratigraphically equivalent to the one represented by V201202. Seventy two specimens of *Planorbula mojavensis* were collected from the Snail Farm (V201201), but no other species were found.

Helminthoglypta alfi Type Locality, RAM Locality V200114 (locality 1 of Taylor, 1954) (NW ¼, Section 24, Township 11 north, Range 2 west). This site is within Rainbow Basin and is stratigraphically equivalent to the type locality of *Dyseohyus fricki*, a species of peccary described by Stock (1937) and Woodburne (1969). Raymond Alf and his student Bill Webb found the skull and jaw fragments of this peccary in 1936 and donated them to Stock at the California Institute of Technology (Lofgren and Anand, 2010). The type locality of *H. alfi* is about 105 m above the Skyline Tuff. The *Hemicyon* Tuff does not extend into Rainbow Basin (Woodburne et al., 1990), so determining the stratigraphic position of V200114 relative to the *Hemicyon* Tuff is not possible. Taylor (1954) only recovered *H. alfi* from this site, but RAM crews have collected two specimens of *Menetus micromphalus*, and one each of *Planorbula mojavensis* and *Vallonia cyclophorella* (Figure 3). However, the site is indeed dominated by *H. alfi* as 144 specimens are present in the RAM collections.

Quarry 5, RAM Locality I99015 and V94026 (NE ¼, Section 23, Township 11 north, Range 2 west). Quarry 5 represents a channel lag deposit about 10 m above the Oreodont Tuff, based on mapping by Woodburne et al. (1990). This channel fill contains a high concentration of bone (elements often water worn) and was discovered and excavated by Ray Alf and Webb students for over two decades (Lofgren and Anand, 2010). Only *Planorbula mojavensis* is known from the site; this record is based on a single specimen, the only gastropod in the RAM collections from the middle member of the Barstow Formation.

Gastropod biostratigraphy and discussion

The stratigraphic ranges of the nine gastropod species from seven RAM localities are shown in Figure 4. All of the species occur in the upper member of the Barstow Formation in outcrops stratigraphically between the Skyline Tuff and the *Hemicyon* Tuff (Figure 2 and 4). These taxa comprise an upper member interval characterized by the co-occurrence of *Lymnaea mohaveana*, *Lymnaea megasoma*, *Helminthoglypta alfi*, *Menetus micromphalus*, *Planorbula mojavensis*, *Pristiloma chersinellum*, *Vallonia cyclophorella*, and *Craterarion pachyostracon*. Although little is currently known about the gastropod assemblages of the middle or Owl Conglomerate members of the Barstow Formation, and upper member gastropod zone could be loosely defined as those taxa that occur between the Skyline Tuff and *Hemicyon* Tuff (Figure 4). Thus, it would be equivalent to the lower half (interval between the Dated Tuff and *Hemicyon* Tuff) of the *Megahippus mckennai*/*Merycodus necatu*s Interval Zone of Pagnac (2009: fig. 3) of the Ba 2 biochron, a biostratigraphic zonation based on mammalian megafauna (Tedford et al., 2004). The geochronology of this gastropod "zone" would span a little less than 1.0 Ma, as although the Skyline Tuff has not been dated, the Dated Tuff in Rainbow Basin (only 18 m above Skyline Tuff) is about 14.8 Ma and the *Hemicyon* Tuff is about 14.0 Ma (Woodburne et al., 1990).

The only gastropod recovered from the middle member in the RAM collections is a specimen of *Planorbula mojavensis* from Quarry 5, a site about 10 m above the Oreodont Tuff (Figure 4). Thus, definition of a gastropod zone for the middle member is not possible and it is not known if taxa from the "upper member zone" occur lower in the section, except for *P. mojavensis*. The Oreodont Tuff has been dated at 15.9 Ma (Woodburne et al., 1990) and all that can be determined thus far is that the geochronologic range of *P. mojavensis* spans about 2 Ma (15.9 Ma to 14.0 Ma) based on its occurrence in both the upper and middle members of the Barstow Formation.

The middle member is similar to the upper member in that both are highly fossiliferous at certain outcrops and have yielded a very large number of fossil vertebrates, mainly mammals. However, even after extensive prospecting of outcrops of the middle member in the Rainbow Basin and Coon Canyon areas for more than two decades by RAM crews, only the single specimen of *Planorbula mojavensis* was found. The reason for this is not clear, but may be related to depositional setting.

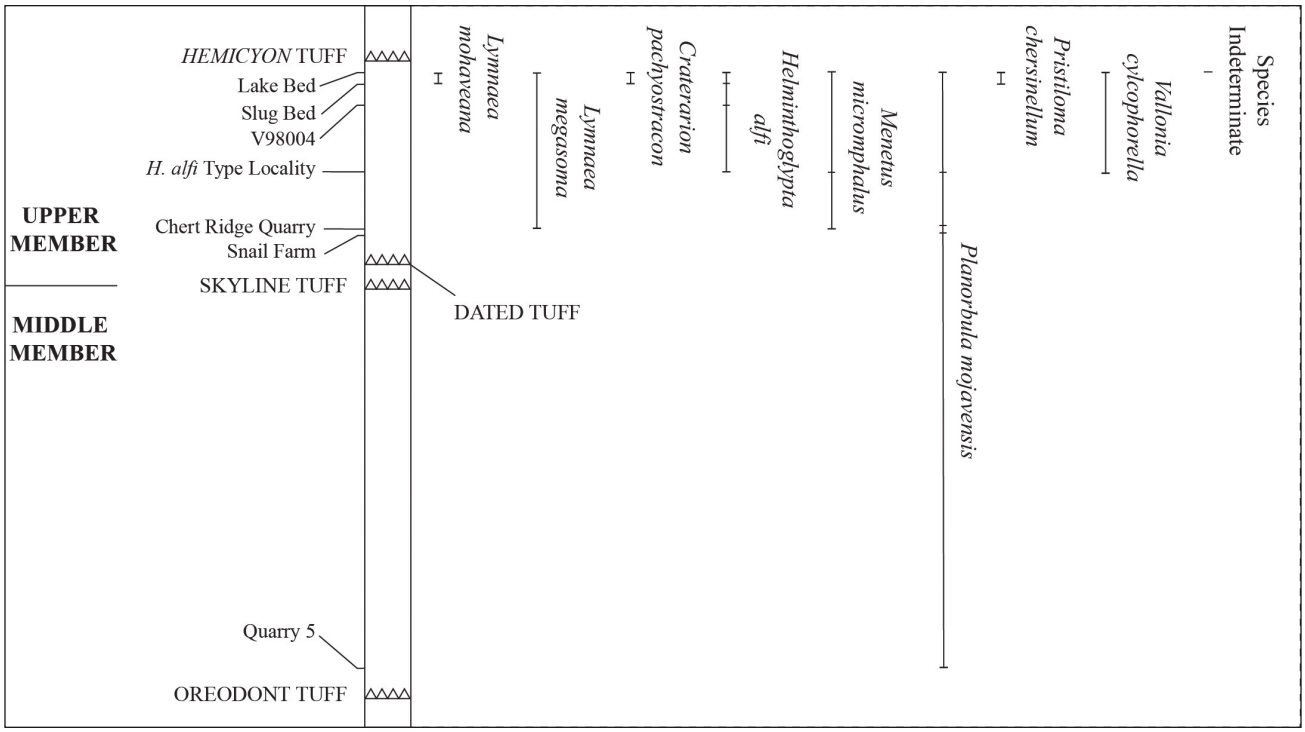

Figure 4. Stratigraphic ranges of gastropods based on taxa recovered from seven RAM localities that occur in either the middle or upper members of the Barstow Formation Isotopic dates of the *Hemicyon* Tuff and Oreodont Tuff are about 14.0 Ma and 15.8 Ma respectively (Woodburne et al., 1990). Only a single specimen of Planorbula mojavensis is known from the middle member.

The upper member is composed mostly of lacustrine sediments, with minor coarse grained clastic beds (Woodburne at al., 1990) and all the RAM sites in the upper member appear to represent lacustrine deposits. The middle member between the Oreodont and Skyline tuffs in the Rainbow Loop area is composed mainly of alluvial and conglomeratic sandstone (Woodburne et al., 1990), and between Rainbow Basin and Coon Canyon some of the vertebrate bearing units are clearly channel fill deposits containing abundant bone (Quarry 5, for example). Thus, the difference in the number of gastropods recovered from the two members may be related to their differences in depositional setting.

Mammalian faunal differences are significant between the middle and upper members of the Barstow Formation (Pagnac, 2009: fig. 3). One explanation is that about 15 million years ago, shrubs and deciduous hardwoods were replaced by tougher foliage as the result of climatic warming and a decrease in precipitation, so mammals with teeth adapted to soft vegetation disappeared from the Barstow region (Pagnac and Reynolds, 2006). It would be interesting to test this hypothesis by contrasting gastropods from the middle and upper members to see if these gastropod assemblages differ significantly. Climatic differences that apparently affected the Barstow Formation mammalian assemblage about 15 Ma may have had little effect or a major effect on invertebrate assemblages. This can't be addressed based on the RAM collections, as the RAM biostratigraphic record of gastropods is almost entirely limited to the upper member of the formation. We recommend that this study be extended to the collections of other institutions that have a significant number of well documented Barstow Formation gastropods to address this issue.

This is the third paper in a series concerning gastropod paleontology of the Barstow Formation based on RAM collections (Plyley et al., 2013; Abersek et al., 2016). In the future, RAM field crews will be concentrating on recovery of gastropods and other invertebrates from the middle member of the Barstow Formation.

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