The dinosaur-bearing rocks of Aniakchak National Monument and Preserve: A fossil resource of global interest

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ABSTRACT

The first discovery of any dinosaur remains in a US National Park Service unit in Alaska occurred in 2001 in Aniakchak National Monument and Preserve. The record consisted of the track of a pes impression, or track made by the foot of a hadrosaur (duck-billed dinosaur) and an associated manus impression, or track made by a hand. Subsequent work has shown the original track discovery was not unique, and that the coastal exposures of the Cretaceous Chignik Formation in Aniakchak National Monument and Preserve contain a remarkable number of tracks. Further, because of the limited faulting, the several hundred meters of section found along this coastal set of exposures provide a remarkably complete look at an ancient high-latitude dinosaurian ecosystem and are of outstanding universal value.

INTRODUCTION

Though the first technical description of Alaskan dinosaurs came from discoveries in northern Alaska (Roehler and Stricker, 1984), the first dinosaur discovery in any Alaska US National Park Service (NPS) unit occurred in 2001, in a very remote park along the southern edge of the Alaska Peninsula, Aniakchak National Monument and Preserve (ANIA; Figure 1). The dinosaur record was found in an approximately 2-kilometer-long coastal exposure of the Late Cretaceous Chignik Formation (Fiorillo and Parrish 2004). Exceptional additional discoveries followed. This subsequent multidisciplinary research has quantified climatic parameters, identified ancient dinosaurian biodiversity, and recognized multiple environments containing different dinosaur demographic profiles that shed light on dinosaur paleobiology (Fiorillo et al. 2019, 2022).

FIGURE 1. General map of Alaska showing the location of Aniakchak National Park and Preserve (ANIA), Denali National Park and Preserve (DENA), and Chignik Bay.

ANIA is located on the Alaska Peninsula (Figure 1) in an area that is remote even by Alaskan standards. This region of southwest Alaska was nicknamed the "Cradle of Storms" by the Jesuit priest Bernard Hubbard (Hubbard 1935). Hubbard was one of the first geologists to explore the Alaska Peninsula and was also the first to lead a scientific expedition into what later became the park. ANIA comprises approximately 2,400 square kilometers, and with an average number of registered visitors reaching only slightly more than 100 people per year, it is one of the least-visited parks within the National Park System.

The park was established in 1978 because of the nearly 10-kilometer-wide Aniakchak Caldera, a deep, roughly circular feature with walls hundreds of meters high because of the collapse of a magma chamber. Remarkably, this large feature, which is easily seen in satellite images, was only named

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in 1922, and even then its description was accomplished not by field sighting but instead by careful plotting of field survey data in an office (Smith 1925). The caldera was created approximately 3,500 years ago when an eruption caused the collapse of the chamber (Begét et al. 1992; Ringsmuth 2007).

In addition to this remarkable volcanic feature in ANIA, sedimentary rocks ranging in age from the Late Jurassic (Naknek Formation) to Eocene (Tolstoi Formation) can be found there (Detterman et al. 1981; Wilson et al. 1999). It is within the Upper Cretaceous Chignik Formation that a robust and growing record of dinosaurs has been reported (Fiorillo and Parrish 2004; Fiorillo et al. 2018, 2019, 2023).

BRIEF HISTORY OF THE FIRST DINOSAUR DISCOVERY IN ANIA

The initial discovery of a dinosaur footprint resulted from an inventory and monitoring program initiated by the NPS Alaska Region in 2000. The parks to be explored in the first phase of this program were ANIA, Katmai National Park and Preserve (KATM), Kenai Fjords National Park (KEFJ), and Lake Clark National Park and Preserve (LACL). A second phase included Denali National Park and Preserve (DENA), Wrangell-St. Elias National Park and Preserve (WRST), and Yukon-Charley Rivers National Preserve (YUCH). The results of these surveys yielded documentation of a variety of fossils that included marine invertebrates, plants, dinosaur footprints, fish traces, and invertebrate trace fossils.

Based on the results of the initial research-based survey, through meetings between NPS resource managers and paleontological partners (specifically the authors of the present paper, ARF and TH) it was deemed that the most efficient approach for ANIA would be a multi-day trip down the Aniakchak River, starting within the caldera and ending on the coast of the park. The float trip down the river occurred in 2001. From the beginning of the float trip fossils were recorded in field notes, including plant remains interbedded with volcanic rocks in the caldera, continuing all the way to the coast. The discovery of dinosaur tracks occurred during the last three hours of the trip, and the recognition of the significance of the discovery was immediate. Photographs were taken at that time, and upon return to park headquarters in King Salmon, Alaska, discussions took place between the two authors regarding next steps. A second NPS team scheduled for a fish survey was tutored on how to make a latex mold of a footprint, and in September 2001 that team successfully made a mold, which was sent to ARF. From the mold a cast was made, and laser scanned. The cooperative efforts resulted in the successful documentation of this first discovery (Fiorillo and Parrish 2004).

THE CRETACEOUS CHIGNIK FORMATION OF ANIA

The rocks that now comprise the Chignik Formation were originally of interest due to the common occurrence of coal seams in the rock unit, specifically in exposures along the Chignik River on the Gulf of Alaska side of the Alaska Peninsula (Dall 1896). Stanton and Martin (1905) added to this growing geologic awareness of these rocks by providing lists of fossil plants and marine invertebrates, as well as correlating this unit with other Cretaceous units throughout the region.

The rock unit was later named by Atwood (1911) for rocks exposed in the vicinity of Chignik Bay, southwest of what is now ANIA. The formation is several hundred meters thick in the area of Chignik Bay, but varies outside the type area, thinning rapidly to the northeast and southwest (Detterman et al. 1996). The rock unit is a cyclic sequence of predominately shallow marine to nearshore marine environments in the lower part and predominately continental environments in the upper part of the section (Detterman 1978; Detterman et al. 1996). Based on the presence of specific marine bivalves and ammonites, the age of the Chignik Formation is late Campanian to early Maastrichtian (Detterman et al. 1996), approximately 72 million years ago.

The Chignik Formation is part of the Peninsular Terrane, the tectonic block that collided with the rest of the accreting Alaska region, and the block includes much of southwestern Alaska. The paleogeographic position of this terrane at the time the Chignik Formation was being deposited was at approximately the current modern latitude (Hillhouse and Coe 1994; Lawver et al. 2002).

The depositional environments preserved within the Chignik Formation are varied (Figure 2). The section shows limited faulting and displacement of the sedimentary sequences through the approximately 300 meters that have been examined in detail; or, in other creative words, the individual layers read like the pages in a book of geologic history of the cliffs. In the lowermost part of the exposures the sandstones and sedimentary structures suggest that the depositional setting was marine (Fiorillo and Parrish 2004; Fiorillo et al. 2019). Brackish water indicators include the mineral jarosite, as well as biogenic indicators such as *Teredolites*-bored coalified wood, and abundant vertical and subvertical burrows (Fiorillo et al. 2019). Within the stratigraphic section containing the multitude of dinosaur footprints, the sedimentary setting appears to represent coastal or terrestrial environments (Fiorillo and Parrish 2004; Fiorillo et al. 2019). More specifically, the environments containing abundant dinosaur footprints are coastal tidal flat, deltaic, and terrestrial overbank deposits (Fiorillo et al. 2019).

PALEONTOLOGY OF THE CHIGNIK FORMATION IN ANIA AND ITS IMPORTANCE

Fossil leaves are abundant throughout exposures of the Chignik Formation along the Alaska Peninsula, as are carbonized fossil wood. Hollick (1930) identified 49 angiosperm leaf forms from this rock unit in the vicinity of Chignik Bay, and while the taxonomy of his identifications has gone through various revisions, his 1930 monograph remains the standard for plants from this rock unit. Carbonized fossil wood and a variety of types of fossil leaves are also abundant within ANIA (Fiorillo et al. 2018, 2019, 2022). At least 12 distinct leaf forms were found, including cf. *Metasequoia*, *Quereuxia*,

FIGURE 2. Example of the sandstones and siltstones of the coastal Chignik Formation at ANIA. In general, from oldest to youngest, the rocks represent marine, brackish water, coastal, and fluvial environments (Fiorillo et al. 2019). The snow-capped peaks in the background are the Aniakchak Caldera.

Nilssonia, a selaginellid moss, *Equisetites*, and eight different angiosperms (Fiorillo et al. 2022). The fossil pollen record within this rock unit in ANIA is sparse, but it includes an angiosperm taxon (*Triporopollenites*), a conifer taxon (*Taxodiaceaepollenites*), a variety of fern spores (e.g., *Deltoidospora*, *Dictyophyllidites*, *Osmundacidites*, *Cicatricosisporites*) and clubmoss and spikemoss spores (*Lycopodiumsporites*, *Acanthotriletes*; Fiorillo 2018).

Also within ANIA are several stratigraphic horizons where fossil leaves, upright trees (Figure 3), and dinosaur footprints are found together. The preserved sections of trunks are generally less than 1 m in height and less than 20 centimeters in diameter, but clearly have been compressed laterally (Fiorillo 2018; Fiorillo et al. 2018, 2019). Most of the tree bases can be traced into the associated root systems that spread along the base of the bed, although extensions of the root systems are not always visible in the underlying siltstone. The spacing between these trunks ranges from 1 to 6 meters. Thin laminae of carbonaceous shale occur laterally between some of the upright trees; these layers contain angiosperm leaves. For all these leaf horizons there is evidence of multiple types of herbivorous insect damage (Figure 4 shows fossil leaf damage), including traces that are like those left by leaf miners on modern leaves.

FIGURE 3. Upright carbonized fossil tree trunk (yellow arrows), with a rock hammer for scale.

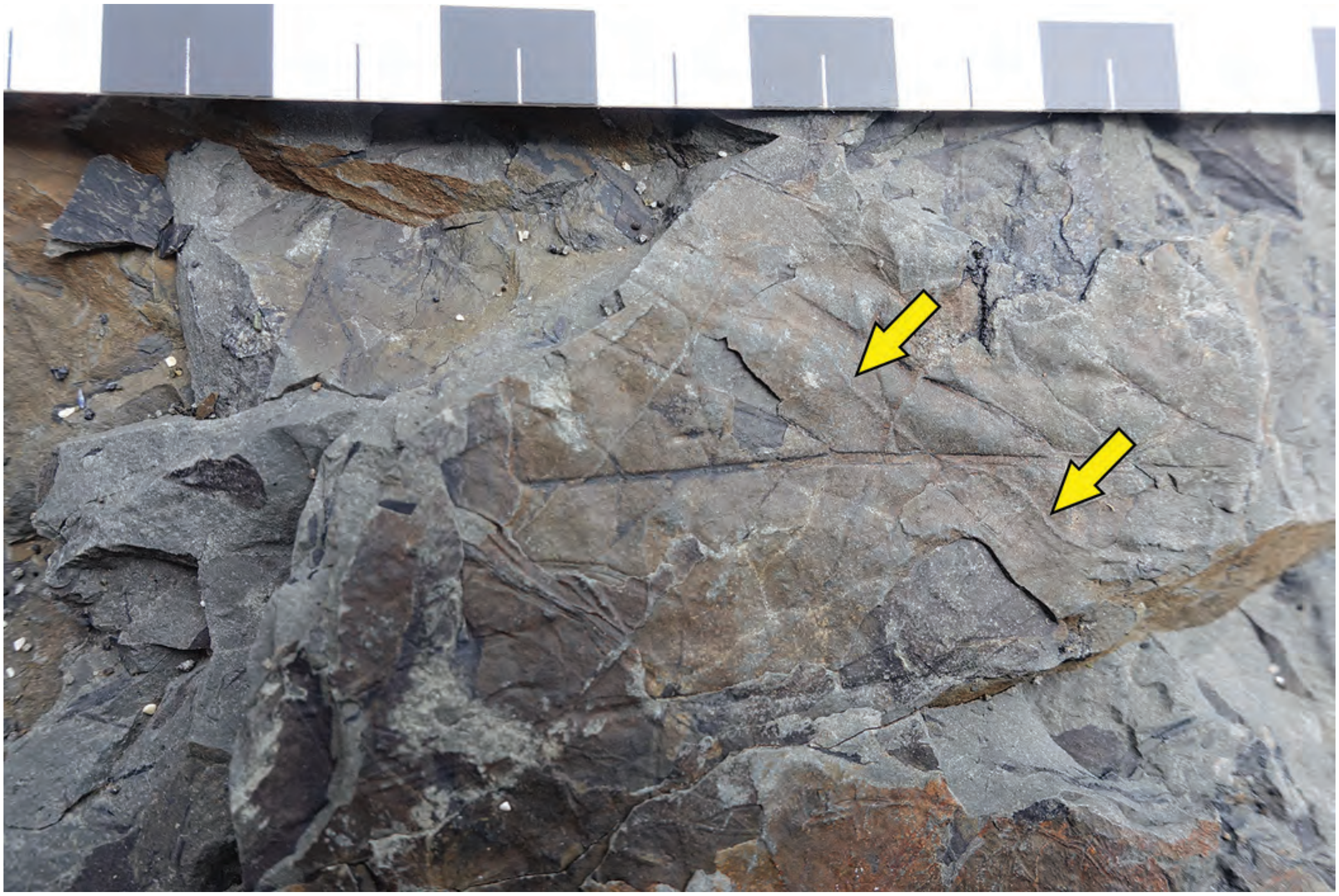
Hadrosaurs, or duck-billed dinosaurs, are the makers of the most frequently encountered dinosaur tracks in the Chignik Formation of ANIA (Figure 5). Based on track morphology, Fiorillo et al. (2019) reported that approximately 94% of the tracks found were attributable to the ichnogenus *Hadrosauropodus*. Most of the tracks are pes (foot) tracks, while manus (hand) tracks are uncommon. The size range of hadrosaur tracks included those attributable to juveniles, sub-adults, and full-sized adults (Fiorillo et al. 2019), suggesting that these animals were living and breeding in the region at the time. Furthermore, the interdisciplinary nature of the paleontological and sedimentological work done in ANIA fine-tunes the paleobiologic understanding of these extinct animals, indicating that hadrosaurs seemed to thrive in coastal and delta plain conditions (Fiorillo et al. 2019; Figure 6).

Though far less common, tracks attributed to the ichnogenus *Tetrapodosaurus*—made by the four-legged, armored dinosaurs, or ankylosaurs, as well as bipedal predatory dinosaurs, or non-avian theropods—also occur in ANIA (Fiorillo et al. 2019). While the non-avian theropod track reported by Fiorillo et al. (2019) corresponded with a tyrannosaur approximately 4.5–5 meters in body length, subsequent work in the park discovered a larger tyrannosaur track attributed to the ichnogenus *Tyrannosauripus*, one that would correspond to a body length almost 60% larger; that is, a track made by an animal with a body length of approximately 8 meters (Fiorillo et al. 2023). There are also two types of tracks attributable to avian dinosaurs: the ichnogenera *Aquatilavipes* and *Magnoavipes* (Fiorillo et al. 2019), respectively a shorebird-like track, made by a bird like a modern willet (*Catoptrophrorus semipalatus*), and crane-like tracks, like tracks made by modern sandhill cranes (*Antigone canadensis*) or common cranes (*Grus grus*).

In addition to these paleontological studies that focused on plants and vertebrate animals, other studies have examined paleoclimatic parameters, specifically Mean Annual Temperature (MAT) and Mean Annual Precipitation (MAP), that are recorded within these rocks. For example, Upchurch et al. (2015) calculated a MAT of approximately 13°C

▼ **FIGURE 4.** Angiosperm leaf with insect damage (yellow arrows). The scale bar is in centimeters.

▼▼ **FIGURE 5.** Representative hadrosaur footprint from ANIA. The scale bar is in centimeters. Note the three large rounded toes. From Fiorillo et al. 2018.



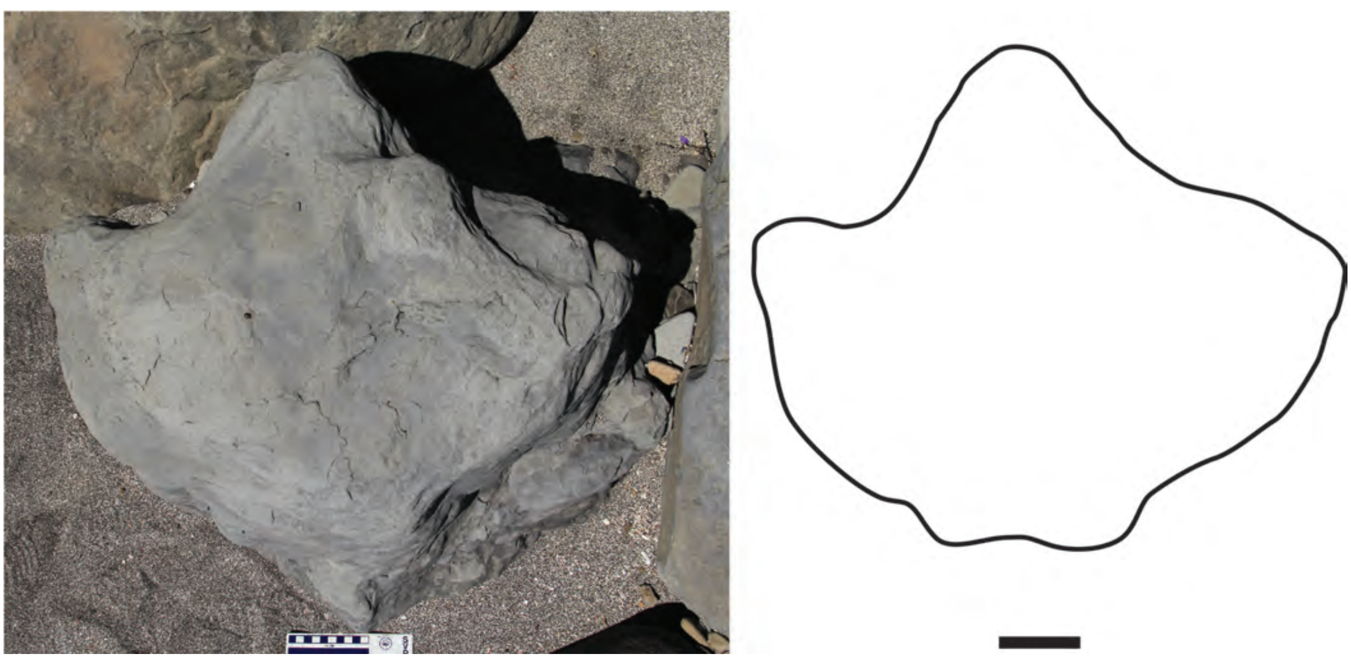


FIGURE 6. Reconstruction of hadrosaurs in rain, illustrating that the Chignik Formation had ample rainfall. Artwork by Masato Hattori.

for the Chignik Formation based on their work on leaf margin analysis—a value slightly cooler than that of modern-day San Francisco, California. In another study, wood fragments from the Chignik Formation were measured for their carbon isotopic composition, and δ13C was used to calculate an average MAP value of 1,090 millimeters per year (Fiorillo et al. 2022), an annual precipitation like that of modern Galveston, Texas. This latter study compared paleoclimate conditions of correlative Cretaceous rocks of northern Alaska that were deposited at approximately 71°–85° N paleolatitude, approximately 1,500 kilometers from ANIA, and those of the Chignik Formation of ANIA, which were deposited at a paleolatitude of approximately 57° N. This comparison demonstrated there was some variation in both MAT (approximately 5–13°C) and MAP (approximately 661–1,250 millimeters per year) across the region, and precipitation likely played a more direct role in determining the distribution of specific types of herbivorous dinosaurs (Fiorillo et al. 2022).

THE IMPORTANCE OF THE COASTAL CLIFFS OF ANIA

> *Given the abundance of important fossil-bearing rocks in these and other parks, there are likely many more exciting dinosaur discoveries waiting throughout Aniakchak and the larger Alaska Region* (Ringsmuth 2007).

While more paleontological and sedimentological work remains to be done in ANIA, the subsequent published work of over a dozen studies shows that Ringsmuth's far-sighted statement, quoted above, has rung true. In addition to the historic importance of ANIA being the Alaskan NPS park unit with the first dinosaur record, we can now place the known ANIA dinosaur track record within the context of other NPS units within Alaska, as well as within the context of other reconnaissance studies of the other exposures of the Chignik Formation along the Alaska Peninsula.

There are three NPS units in Alaska that have published dinosaur records: ANIA; DENA (Fiorillo et al. 2007, 2009, 2011, 2014, 2015; Fiorillo and Adams 2012; Tomsich et al. 2014; Fiorillo and Tykoski 2016); and WRST (Fiorillo et al. 2012). Collectively, these parks have made major contributions to the greater global understanding of dinosaurs and their environments in the higher latitudes, a concept that challenges the classic stereotype of dinosaurs as tropical or subtropical animals. In addition, with societal concerns surrounding a modern warming planet, and with the effects of such warming being most prominently expressed in the high latitudes, these paleontological contributions have also provided baseline data for insights into the dynamics of ancient warm high-latitude environments.

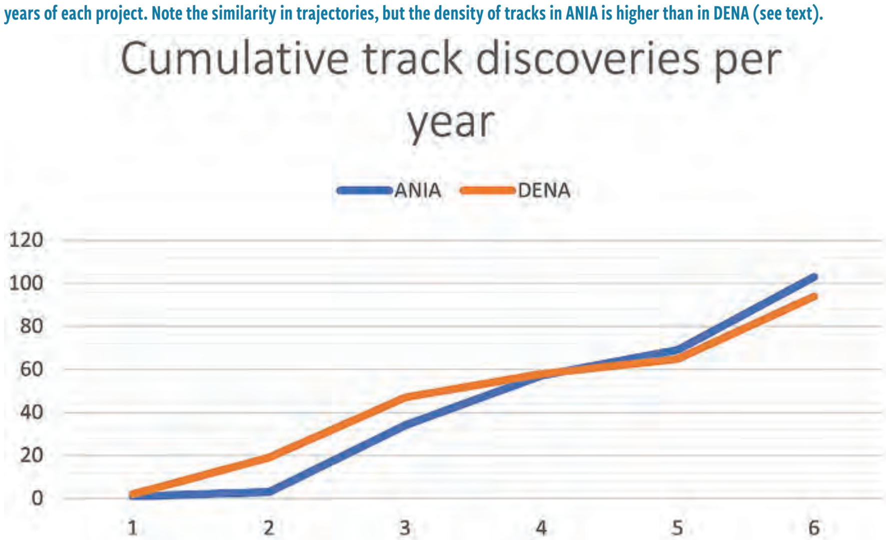
Of these park units, WRST, has a very limited dinosaur record and though these discoveries have offered insights on the geologic history within the park, WRST will not be considered further here. Rather, given that DENA is recognized as one of the most iconic national parks in Alaska, and contains a robust fossil record, our discussion now shifts to comparing ANIA to its more famous neighbor.

The lead author of the present paper (ARF) had the good fortune of playing a role in the dinosaur discoveries within both ANIA and DENA. The tallying of dinosaur discoveries in both parks comes from ARF's field notes. Copies of these notes are on file at the NPS Alaska Region archives in Anchorage.

Figure 7 is a graph that shows the cumulative number of dinosaur tracksites discovered per year in both ANIA and DENA. As mentioned above, the first track found in ANIA was in 2001, and was followed by additional survey work in 2002. After a long hiatus, work in ANIA resumed in 2016. The first dinosaur track found in DENA was in 2005, and work continued for several years after. Examination of the graph shows that the rate of discovery in both park units was comparable, with slightly more tracks found in ANIA over the first six years of investigation in either park.

But what is of particular interest in this comparison is the length of the transects over which these discoveries occurred. In ANIA, the length of the outcrop exposure, or transect, is slightly less than 2 kilometers. In contrast, the length of

FIGURE 7. Graph showing the cumulative growth of dinosaur track discoveries in ANIA and DENA, through the respective first six years of each project. Note the similarity in trajectories, but the density of tracks in ANIA is higher than in DENA (see text).



the transect over which the DENA discoveries were made was slightly longer than 45 kilometers. By this comparison, ANIA has a higher density of tracks than its better-known neighbor.

It is tempting to ask, then, if the Chignik Formation is a rock unit where dinosaur tracks are just more abundant. ARF expanded the study of the Chignik Formation in 2018 and 2019 to investigate its cliff exposures in the vicinity of the village of Chignik Bay, approximately 70 kilometers to the southwest of ANIA (Figure 1). During those two field seasons, the reconnaissance team found one dinosaur footprint while traversing approximately 1.75 kilometers, a distance slightly less than the distance traversed in ANIA. This suggests that the dinosaur track density in ANIA is unique. Further, we suggest that such a resource within ANIA is deserving of additional recognition beyond its inclusion within an NPS unit.

Such a complete combination of insights within one nearly complete sequence of rocks in ANIA is unique and so exceptional as to transcend geographic and cultural boundaries. Because of such important paleontological resources, one option for recognition might be the National Natural Landmark designation through the National Park Service, as that program encourages the conservation of sites that contain outstanding biological and geological resources. Examples within NPS known for paleontological resources are Hagerman Fossil Beds National Monument and the Hagerman Fauna Sites, recognized as the world's richest terrestrial Upper Pliocene deposits. Similarly, John Day Fossil Beds are globally famous for the various fossil biotas preserved there that document paleoclimate change. Further examples include such important sites as Indian Springs Trace Fossil Site, famous for its invertebrate trace fossils, and the Morrison-Golden Fossil Areas, famous for its dinosaur bones and tracks. A second option is UNESCO's Global Geopark designation, which is determined by the national and international significance of the relevant scientific research. Precedent for a paleontological resource for this program is the Zigong UNESCO Global Geopark in China, which includes an abundance of Jurassic dinosaur remains. Finally, we suggest that the ANIA coastal cliffs are on a par with those of the Joggins Fossil Cliffs in eastern Canada, which have been recognized by the World Heritage Committee as possessing the requisite "outstanding universal value" for a World Heritage Site. Joggins is recognized as having the most comprehensive rocks, dating back 318 to 303 million years, containing a complete fossil record of terrestrial life of that time. As such, it is also listed by the International Union of Geological Sciences as a geological heritage site for being a key place with a substantial contribution to the development of geological sciences through history. The case has been made here that the coastal cliffs of ANIA have historical significance as the park where the first discovery of dinosaurs was ever made within the vast national parks of the NPS Alaska Region and established the widespread nature of dinosaurs in northwestern North America (Fiorillo and Parrish 2004), as well as uniquely contributing to understanding iconic Cretaceous dinosaurs and their ecosystems, particularly in ancient high latitudes. As such, ANIA should stand out as a true global paleontological treasure.

SUMMARY

The first discovery of any dinosaur remains in a US National Park Service unit in Alaska occurred in 2001 in ANIA. Subsequent work has shown that the dinosaur record within the coastal exposure of the park is remarkable. Further, there are additional components of the fossil record of ANIA, such as an abundance of fossil plants and evidence of insect herbivory on fossil leaves, as well as integration of these fossils in reconstructing paleoclimatic parameters such as MAT and MAP. Taken together, there is a remarkably complex ecosystem preserved in these rocks, with evidence of small herbivores (insects) eating leaves, to multiple woodlands with tree spacings, to large herbivorous dinosaurs, predatory dinosaurs, and multiple types of birds flying overhead. Combined with fine-scale stratigraphic understanding of the environments preserved within these rocks, this coastal set of exposures within ANIA is a remarkably complete look at an ancient, high-latitude, dinosaurian ecosystem. Arguably this is one of the best exposures in the world for understanding this slice of geologic time, and very much deserves additional, special recognition as a unique paleontological resource.

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