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REVIEW

Prehistoric earth oven facilities and the pathoecology of Chagas disease in the Lower Pecos Canyonlands

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Abstract

Understanding the endemic region of a disease is part of developing a concept of the disease's natural history and its threat to human health in both ancient and modern times. Chagas disease is caused by the parasite *Trypanosoma cruzi* and has recently been identified as an emergent disease in North America. Ancient endemicity and reemergence has been demonstrated by an examination of a mummy found on the border between Coahuila, Mexico and Texas, USA. This mummified man, who died over 1000 years ago, exhibits the gross pathology of megacolon, which is consistent with Chagas disease. We are now exploring the human behavior that resulted in this parasitic infection. *T. cruzi* infection exists in a sylvatic cycle involving woodrats (*Neotoma* spp.) and triatomine insects (*Triatoma* spp.) in the lower Lower Pecos Canyonlands. The Archaic subsistence strategy may have impacted this life cycle directly through predation on woodrats and through the construction of baking pits. This would have expanded the habitat suitable for both woodrats and triatomine insects. We are proposing that archaeologists develop field methods to test this hypothesis.

Keywords: *Trypanosoma cruzi*, pathoecology, prehistory, Texas, burned rock middens, mummies, woodrats

1. Introduction

Chagas disease was described by Carlos Chagas in 1908 in Brazil (Chagas, 1909). Insects classified as triatomines transmit the parasite to mammals (Figure 1). Triatomines hide during the day, sometimes in the ideal habitats created by the middens left by humans and emerge to feed at night. They suck blood from animals and defecate infectious forms of the parasite on the surface of the skin or the mucosa. The infectious stage of the parasite is able to penetrate the skin of the new host. After a period of acute manifestations of the disease, when cardiac manifestations kill mainly young adults, the disease followed its chronic course. Although many of infected people are asymptomatic, some developed the chronic Chagas disease, when symptoms including cardiac congestion and heart failure may occur. Also, "mega" development of sections of the intestine may occur. It was believed that Chagas disease began to infect humans after domestication of guinea pigs (*Cavia*) and other mammals in the Bolivian altiplans. It was also believed that the disease only spread to other countries after the arrival of Europeans. However, this has been disproven, as discussed below.

Archaeology and pathoecology can expand our knowledge of endemicity and disease transmission (Bryant and Reinhard,

2012; Reinhard, 2008; Reinhard and Bryant, 2008). The history of paleopathology is rich in the documentation of ancient diseases from unexpected places. Paleopathology has extensively modified the conventional wisdom regarding the distribution of tuberculosis, syphilis, hookworms, and other infectious diseases in antiquity. Until relatively recently, paleopathologists believed that Chagas disease became a major human problem after Andean animal domestication and the domiciliation of the Chagas disease cycle. Domiciliation involved association of guinea pigs, dogs, humans, and the insect vectors in cane-walled human habitations (for review see Araújo et al., 2009; Darling and Donoghue, 2014; Ferreira et al., 2011; Guhl et al., 2014; Coimbra, 1988). It had long been believed that Chagas disease only spread across the rest of Latin America during historic times. This notion was refuted by the discovery of Chagas disease in high prevalences in Andean mummies pre-dating animal domestication (Aufderheide et al., 2004; Guhl et al., 2014). Given this discovery, the domiciliation component of our understanding of ancient Chagas disease following animal domestication was invalidated. In the Lower Pecos Canyonlands of Texas (Black, 2013; Hester, 1983, 1989; Shafer, 2013; Turpin, 1995), Chagas paleopathology was diagnosed (Reinhard et al., 2003). Later, Chagas disease was documented in the central plains of Brazil (Fernandes et al., 2008; Lima

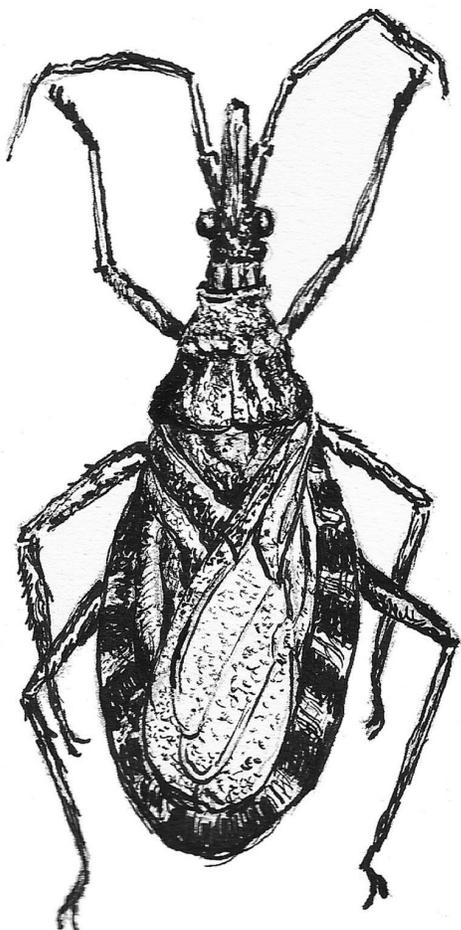


Figure 1. The size of triatomine insects should aid in recovering them. They are approximately about 2.5 cm long. When fragmented, the head and thorax, about 12 mm long in total, should be recoverable. The abdomen would be more susceptible to decomposition due to its thinner, pliable exoskeleton.

et al., 2008). Furthermore, very recent molecular analysis of ancient mummies in Chile indicates that the oldest infections came from wild strains of *Trypanosoma cruzi* related to a bat strain (Guhl et al., 2014). The aforementioned studies revealed that Chagas disease was present outside of the Andes during prehistoric times and did not necessarily involve the domiciled strains common today. The pathoecology of Chagas disease is now believed to have involved sylvatic (wild animal) cycles that humans intruded upon during prehistory. Infection resulted from this fortuitous association.

Recent molecular analysis of six lineages of Chagas disease, and a divergent group, modifies even more our perspective on this disease (Zumaya-Estrada et al., 2012). This analysis, and accompanying molecular clock, suggests that the earliest migrations of humans encountered Chagas disease in North America. The divergent *T. cruzi* group, TcIDOM, is focused among North and Central American strains, and this suggests that transmission in prehistory may have first occurred in North-Central America. However, Zumaya-Estrada and his colleagues have doubts as to how early populations could have supported endemic infection. They write that, “such early settler populations were probably small, dynamic, and inherently unsuitable to sustain transmission of such a genotype. Many questions, therefore, remain unanswered regarding its emergence.” By the analysis of hunter-gatherer lifestyles in Texas where the disease was endemic, we are addressing this question.

Trypanosome infection involves insect vectors known as triatomines. Vectors are animals that transfer infective agents from one host to another. The trypanosomes are transmitted at the site of a triatomine bug bite. Trypanosomes are passed in the feces of the bug and hosts become infected if trypanosomes enter the lesion from the feces left by the triatomine. The feces may also contaminate the eye mucosa of the host to establish infection. As stated by Aufderheide et al. (2004: p. 2035), citing Chagas (1909), “Ingestion of the blood meal causes the vector to defecate. Upon awakening, the victim commonly rubs the itching bite area, pushing the trypanosome-laden feces into the bite wound or onto the conjunctiva. By these methods, the trypanosome gains access to the victim’s blood stream, initiating the acute stage of the disease.” The history of the discovery of the life cycle was summarized by Morel (1999).

People can also be infected by vertical transmission from mother to fetus, or by consuming contaminated food or fluids. The acute form of Chagas disease, which may appear some days after infection, may involve heart symptoms. The more common chronic form, which involves heart or intestinal symptoms, appears years after infection (Dias and Coura, 1997). The severe acute form of the disease is typically associated with ingesting food—liquid or solid—that has been contaminated by triatomine feces laden with *T. cruzi*. There have been several cases described from Brazil in which people have drunk sugar cane juice and açai (*Euterpe oleracea*) juice contaminated with triatomine feces containing the *Trypanosoma* parasite (Nóbrega et al., 2009). The symptoms of Chagas disease usually appear many years after infection; however, in rare cases, acute disease can occur shortly after infection. Acute disease involved the heart, and sudden death may occur in young people. Chronic disease causes heart failure, intestinal megacolon and other problems.

The discovery of a single case of Chagas disease in an ancient hunter-gatherer site on the border of Coahuila and Texas provides a data point that greatly expanded the disease’s known prehistoric natural range (Hanford et al., 2007; Reinhard et al., 2003; Sarkar et al., 2010; Turpin et al., 1986). Reinhard et al. (2003) described a case of megacolon in a partially mummified burial found on the Coahuila-Texas border (Turpin et al., 1986). Megacolon occurs due to lesions of the enteric nervous system caused by degeneration during inflammatory process reducing the muscular activity of intestinal smooth muscle. Peristalsis is disrupted, the muscle loses its tonus, and eventually the intestine fills with partly digested food. In this mummy, the grossly enlarged forms of the ascending, descending, and transverse colons are preserved by abnormally large masses of feces that desiccated. The volume of the feces in the colon of this prehistoric individual was unprecedented in the clinical literature. The burial was dated by radiocarbon analysis to 1150 years ago. It is the oldest confirmed case of the megacolon suggesting Chagas disease outside South America.

Several recent works introduced the *nidus* concept into the pathoecology of ancient parasitism (Reinhard, 2008; Reinhard and Araújo, 2012; Reinhard and Bryant, 2008). Pavlovsky developed the concept that natural nidi of infection are small scale zones driven by larger scale ecosystems. Reinhard and Bryant state that a *nidus* is a geographic or other special area containing parasites, vectors, reservoir hosts, and recipient hosts “that can be used to predict infections based on one’s knowledge of ecological factors related to infection. An individual *nidus* therefore reflects the limits of transmission of a given parasite or pathogen within specific areas of interaction” (2008: 207–208). The professional field archaeologist is a potential expert in identifying nidi due to his/her training in making detailed observations and in documenting the nature and content of archaeological features and strata (Reinhard, 2008; Reinhard

and Bryant, 2008). The emergence of GIS and landscape archaeology has allowed pathoecologists to analyze nidi and to assess the influence of human behavior and environment on the establishment of these infection “hot spots” across large areas. The present study focuses on burned rock middens in the Lower Pecos and proposes methods for data collection to test the hypothesis that these burned rock middens resulted in increased prehistoric exposure to Chagas disease.

The discovery of prehistoric Chagas disease in the Lower Pecos begged explanation. Reinhard and Bryant (2008) suggested that humans created nidi by accumulating the rock and vegetal materials preferred as habitats by the triatomine insects that transmit Chagas disease. Normally, woodrat nests are the habitat for triatomines. By altering the rockshelter environment, humans created alternative habitats for the triatomines in Archaic ‘base camps’. Therefore, human-occupied rockshelters became alternative triatomine nidi for infection (Figure 2).

This web of infection was complicated by the consumption of woodrats, one of the definitive hosts of *T. cruzi* in nature. Reinhard et al. (2007) showed that woodrats were a preferred food in the Lower Pecos. Consumption of woodrats infected with *T. cruzi* would have resulted in human contraction of Chagas disease. GIS documentation of burned rock middens (Koenig, 2012) in the Lower Pecos reveal the potentiality that humans in Archaic times transformed the landscape into a web of nidi for Chagas disease transmission.

Vector borne transmission cycles, like that of Chagas disease,

are restricted to nidi that have overlapping distributions of vectors, hosts, and parasites (Reinhard, 2008). Local infection cycles are dynamic systems. Forces external to them from the ecosystem cause ebbs and flows in the distributions of vectors, hosts, and parasites. Previous explanations of Chagas disease in the Lower Pecos focused on the discovery of an infected individual in a specific place and at a specific time. Here we attempt to link Chagas disease to the influence of Archaic humans who dramatically changed the landscape by creating a remarkable number of nidi across the landscape in the form of cooking features. The areas selected for these cooking features optimized the overlap of triatomine vectors, normal hosts, alternative human hosts, and the trypanosome pathogen.

2. What is a burned rock midden?

“Burned rock midden” (BRM) is an archaeological term. BRMs are the accumulated surviving remains of countless earth ovens, hence they represent earth oven facilities (Black and Thoms, 2014 and Wandsnider, 1997). An individual earth oven is a pit excavated into the ground and fired with wood. Rocks are placed on the wood. As the fire burns down it transfers heat to the rocks. A plant lining called “packing” is placed on the hot rocks. Food to be cooked is placed on the lining and covered with more packing and earth (Black and Thoms, 2014). The food cooks in the oven for periods of time ranging from hours to days. In antiquity, burned rock middens were

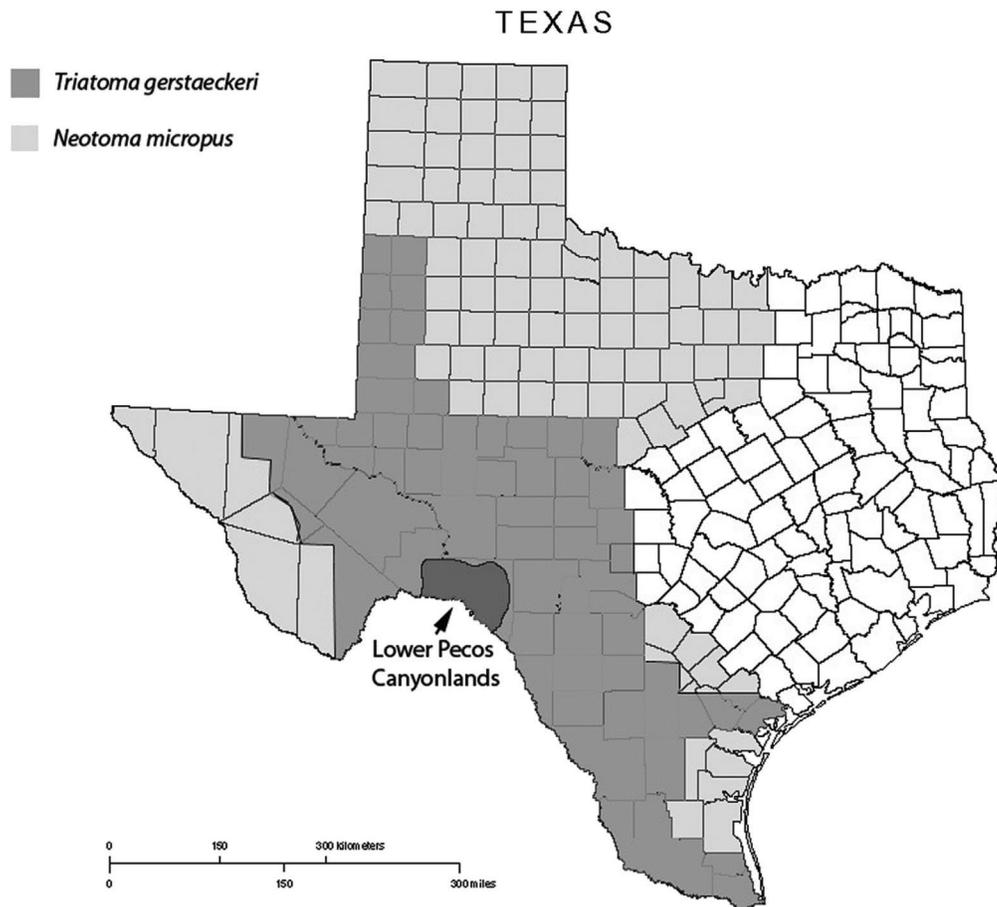


Figure 2. An overlay map of the distribution of *T. gerstaeckeri*, *N. micropus* and the Lower Pecos Canyonlands. *T. gerstaeckeri* is a triatomine insect that is frequent intermediate host and vector for *T. cruzi*. The distribution shown here is adapted from a model distribution by Beard et al. (2003). *N. micropus* is a woodrat that is a common definitive host for *T. cruzi*. The distribution is adapted from Davis and Schmidly (1994). The Lower Pecos Canyonlands, redrawn from Turpin (1995), is one of several cultural areas that falls within the overlap of these two hosts and indicates that prehistoric peoples in the area were at risk of contracting the disease.

enduring landmarks to which people returned for many years. They returned to take advantage of the accumulated rocks to make more earth ovens (Black et al., 1997, Black and Thoms, 2014 and Wandsnider, 1997). For each firing of an earth oven, a large amount of waste was produced in the form of cracked rock, fiber from the cooked plants, ash, and trash from other human activities. The waste concentrated over time into mounds of rock that are seen as archaeological BRMs.

In the Lower Pecos Canyonlands of Texas, USA and Coahuila, Mexico, burned rock middens are the most common type of archaeological site. The artifacts found with them show that they were used for more than cooking. Other foods were prepared and stone tools were manufactured. In rockshelters, there is evidence that burned rock middens were associated with sleeping places as well as general activities (Shafer, 1986).

A few basic resources were needed for earth oven cooking. First, the terrain had to be conducive for digging pits. Secondly, wood had to be available in abundance for firing. Rock had to be present in the area and, of course, food to be cooked was needed. Earth ovens were used to cook agave (*Agave lechuguilla*) hearts and other desert succulent plants. Interestingly, these features occur in the habitats needed by the animals involved in the sylvatic transmission of Chagas disease: woodrats and triatomine bugs.

3. Burned rock middens and triatomine insects

Triatomine bugs are a type of reduviid insect that can carry the parasite *T. cruzi*, which causes Chagas disease. As reviewed by Gaunt and Miles (2000), the habitat preferences for triatomines are rocky areas, rodent nests, and rockshelters.

To date, no burned rock middens have been studied for triatomine infestation. However, studies have been done in modern times of analogous remains. In Guatemala, for example, limestone piles have been studied for triatomines. The analyses show that these rock piles provide a suitable triatomine (*Triatoma dimidiata*) habitat (Monroy et al., 2003). Similarly, brick and tile piles in Mexico make good habitats for triatomines (Walter et al., 2007). Bar and her colleagues found triatomines in rock piles in Argentina (2002). *Triatoma brasiliensis* is found in different habitats in the Brazilian caatinga and cerrado environments (Valença-Barbosa et al., 2014) and *Mepraia* spp. are found in the Pacific coast of northern Chile, in the Atacama desert (Oda et al., 2014), both inhabiting rocks piles, among other different places. However, in the caatinga of Brazil, *T. brasiliensis* prefers wood accumulations to rock piles. Therefore, modern epidemiology shows that accumulations of stones, bricks, and tiles are habitats attractive to triatomines. From this perspective, burn rock middens could have been excellent triatomine habitats. It would be of interest to look in experimental burned rock middens for triatomines to determine if this is so.

Maintaining cactus vegetation also enhances triatomine environment. In the arid caatinga of northeast Brazil, Emperaire and Romaña (2006) showed that where local land owners managed cactus cultivation for livestock, Chagas disease environments increased. The permanent cactus fields presented a reliable habitat for triatomine bugs whose nests proliferated in the protective vegetation provided by dense cactus. This resulted in an increase of triatomine insects.

The analysis of anthropogenic landscape change related to Chagas disease by Ramsey et al. (2012) presents a modern example of ecological connectivity of Chagas disease with human development of the environment. These researchers addressed the basic question of how triatomines become re-established in a Mexican village rapidly after a successful triatomine extermination program. They sampled three environments around the village for triatomines and mammals. Seven

species of rodent were collected, all of which had individuals that were infected. Ramsey et al. (2012) found an ecological connectivity between sylvatic areas, ecotone between sylvatic and domestic areas, and domestic habitats that provided for reservoir species dispersal. They point out that in the modern world, human expansion of domestic environments into sylvatic cycles results in chronic Chagas disease infection. This expansion of domestic activity into sylvatic areas is represented in the Lower Pecos by burned rock middens.

4. Woodrat distribution in the Lower Pecos Canyonlands

The idea that prehistoric humans overlapped the distribution of woodrats is evidenced by the fact that they were an extremely common part of the diet. As reviewed by Reinhard et al., (2003 & 2007), woodrat bones are represented in coprolite and midden studies. Indeed, 18 of 100 coprolites from Hinds Cave had identifiable woodrat bone. The results of coprolite analysis from this rockshelter undoubtedly under represents the importance of woodrats in the diet since the majority of rodent bone (25 of 100) could not be identified to family or genus level. The presence of hair, absence of cooking changes to bone, and presence of entire skeletal elements suggests that the woodrats were eaten nearly whole and were likely undercooked.

Several species of woodrat are found in the Lower Pecos; *Neotoma albigula*, *Neotoma mexicana*, and *Neotoma micropus*. The habitat of *N. albigula* is in association with cholla and prickly pear cactus where they construct above ground dens. *N. micropus* is found in more arid regions where it constructs dens of sticks and cacti. *N. mexicana* is found in the Lower Pecos and prefers rocky areas, rimrocks, and canyon walls (Davis and Schmidly, 1994).

The *N. albigula* has an overlap with the distribution of food resources used by Archaic people who built earth ovens. Stangl et al. (1999) report that a preferred habitat for this species is among agave plants. Thus, the location of earth ovens could have been chosen due to proximity of key food plants, like agave, and key food animals, like woodrats.

5. Spatial analysis of burned rock middens

Burned rock middens occur in three Lower Pecos ecological areas including stream terraces, within rockshelters, and on upland ridges or flatlands (Dering, 1999; Koenig, 2012). Botanical analysis of burned rock midden contents and coprolites show that several plant species were cooked including agave (*A. lechuguilla*), sotol (*Dasylirion* spp.), yucca (*Yucca* spp.), and prickly pear (*Opuntia* spp.) (Riley, 2008, 2010; Sobolik, 1991). These also represent the plant communities preferred by *N. albigula* and *N. micropus* (Davis and Schmidly, 1994). Since triatomines live in woodrat nests, these associations represent nidi for infection. The burned rock middens in rockshelters overlap the environment of *N. mexicana*.

With the exception of burned rock middens in rockshelters, burned rock middens tend to occur away from, but within 3–6 km of, the river canyons. Koenig (2012) clearly showed that most rockshelters contain burned rock middens. Of 878 rockshelters reviewed by Koenig, 571 contain burned rock middens.

The association of burned rock middens in rockshelters represents the establishment of triatomine habitats in Archaic “home bases” (Koenig, 2012). At the core of one settlement pattern, reconstruction is the long-standing argument that the indigenous population used rockshelters differently than open-air sites. The distribution of rockshelters and burned rock middens has been studied by archaeologists for decades. These studies have led to two hypotheses concerning the settlement patterns of prehistoric people. The first hypothesis is that rockshelters were “home bases” for Archaic peoples. This

“home base” hypothesis views open-air sites as temporary camps or logistical processing stations. Analysis of remains from rockshelters containing middens shows that these were habitations associated with cooking. In the “home base” hypothesis, people lived mostly along major river canyons and rockshelters subsisting on the availability of food offered by the river environments. If this hypothesis is valid, we would anticipate that “domiciliation” of the sylvatic life cycle of Chagas disease into rockshelter home bases would have promoted Chagas disease. Unlike the true Andean domiciliation hypothesis, only humans and triatomines would have been associated in rockshelters. Therefore, the more typical infection by triatomine bite while people slept would have been the more common mode of infection. In addition, infection could have occurred by accidental ingestion of insects.

A second hypothesis argues that Archaic people had high mobility and were forced to move frequently by depletion of natural resources (Koenig, 2012). They were always dependent on the water resources of the rivers, but had to move from one place to another along the rivers once resources became overused. Rockshelters were temporary habitations used only when resources near the rockshelters were abundant. The “nomadic forager” hypothesis of Lower Pecos Archaic inhabitants is based on the fact that a lot of energy went into baking desert succulents in earth ovens relative to the caloric yield of the ovens (Dering, 1999). Archaic people could not have resided at earth oven sites because plants and fuel wood would be quickly used up. If this hypothesis is valid, we would expect less infection with Chagas disease within rockshelters because these would be only temporary habitations. The consumption of uncooked insects and woodrats would be the main source of disease.

The analyses and dual hypotheses of land use for Archaic people in the Lower Pecos suggests that the middens established away from the rockshelters were temporarily used by its people. We believe that these rock middens would have expanded the habitat of triatomines in the areas preferred by the woodrats by *N. albigula* and *N. micropus*. The construction of earth oven facilities in canyon rockshelters would have increased the triatomine habitat within human ranges in the ecological area of *N. mexicana*. In essence, human domiciles were established in a large cluster of burned rock midden habitats and amplified sylvatic Chagas disease transmission cycles. Thus, the distribution of burned rock middens would have been a human cultural factor that amplified the transmission potential of Chagas disease to humans.

6. Discussion: anthropogenic and sylvatic considerations

There is a well-known sylvatic cycle in the Lower Pecos region. Studies of wild *Trypanosoma* transmission in the region have been summarized (Reinhard et al., 2003). In Texas, there are seven *Triatoma* species that are naturally infected with *T. cruzi*. These are *Triatoma gerstaeckeri*, *Triatoma indictiva*, *Triatoma lecticularius* (synonym *Triatoma heidemanni*), *Triatoma neotomae*, *Triatoma protracta*, *Triatoma rubida*, and *Triatoma sanguisuga* (Elkins, 1951a, 1951b; Eads et al., 1963; Lent and Wygodzinsky, 1979). All seven Texas species are naturally infected with *T. cruzi* and are vectors of Chagas disease (Davis et al., 1943; DeShazo, 1943; Pippin et al., 1968; Sullivan et al., 1949; Wood, 1941a, 1941b). However, *T. gerstaeckeri* is the most prevalent species and inhabits woodrat nests and rocky areas in the Lower Pecos with a smaller showing of *T. rubida* and *T. sanguisuga*.

In the southern Texas region, the species assumed as main host for *T. cruzi* are woodrats, especially *N. albigula*, *N. micropus*, and *N. mexicana* (Packchianian, 1942; Sullivan et al., 1949; Burkholder et al., 1980; Ryckman, 1986), however, several other mammals are also naturally infected in the area. These

include pocket mice (*Perognathus hispidus*, *Liomys irroratus*), grasshopper mice (*Onychomys leucogaster*), house mice (*Mus musculus*), opossums (*Didelphis virginiana*), nine-banded armadillos (*Dasypus novemcinctus texanus*), and Western Pipistrelle bats (*Pipistrellus hesperus*). All these animals may be excellent alternative reservoir hosts for *T. cruzi* (Wood, 1941a, 1941b; Packchianian, 1942; Burkholder et al., 1980).

7. GIS detection of larger ecosystem drivers

Archaeology shows a long pathoecological association of humans with reservoir hosts (Reinhard et al., 2007). The previous discovery of a mummy infected with *T. cruzi* was of significance in demonstrating that Chagas disease was a prehistoric zoonosis of the Lower Pecos region. At that time, coprolite and rockshelter analysis suggested that human predation on rodent reservoir hosts, combined with building rockshelter habitations in triatomine areas, put human populations at risk of infection. Adapting to the theory of Pavlovsky (Reinhard, 2008; Reinhard and Bryant, 2008), rockshelters were small scale nidi of infection. The larger ecosystem drivers of infection were previously unknown.

The emergence of GIS landscape archaeological investigation methods (Koenig, 2012) now allows us to evaluate the impact of humans on the environment of Chagas disease transmission and reveals larger ecosystem drivers. The value of this method is that researchers can look at the ecological connectivity of archaeological sites and natural habitats. The basic cooking features of Archaic humans overlapped with the habitat of the natural hosts and vectors of Chagas disease. The burned rock middens themselves amplified the number of environments adaptable to the triatomine vectors. Through the use of burned rock middens, human modification of the environment expanded the nidi in order for the distributions of vectors, hosts, and pathogens to overlap. Such local infection cycles, when intruded into rockshelter ‘home base’ habitations, amplified the ideal environment for transmission of Chagas disease to humans. It may well be that the burned rock middens enhanced the environments for both triatomines and *Neotoma* species, making both vector and host synanthropic, having benefited from association with humans.

We believe that this was the situation in the Archaic of the Lower Pecos. Indeed, even if Archaic populations were very mobile, the reestablishment of infection cycles when people returned to long-disused rockshelters may have been rapid. Establishment of middens 3–6 km from the rivers created an amplified environment for sylvatic transmission. In the river canyons where rockshelter home bases were located, the transmission cycle became established within human habitations. Prehistoric people in the Lower Pecos carried out activities in rockshelters that produced large quantities of vegetation mixed with rock. These activities created triatomine habitats. Food was prepared and roasted in earth oven facilities in the rockshelters. One of the most commonly prepared foods was agave, a desert succulent plant (Bryant, 1974; Bryant and Williams-Dean, 1975; Danielson and Reinhard, 1998; Reinhard and Danielson, 2005; Riley, 2008, 2010). The preparation and consumption of agave resulted in a considerable mass of fiber mixed with broken rock, which was an ideal habitat for triatomines. More vegetation was brought into the rockshelters as raw material for the manufacture of mats, baskets, and other artifacts. Beds were also made of woven mats, grass, and other plant material (Shafer, 1986). This additional fiber further enhanced the habitat for triatomines.

In the Archaic times, people used rockshelters in the region for a variety of purposes. Because some species of triatomines live in woodrat nests, and because woodrat nests were close to rockshelters, rockshelters brought together the reservoir hosts, vectors, and humans together in close proximity.

Sleeping in rockshelters was one activity that predisposed humans to Chagas disease transmission. The triatomines are active at night and are nocturnal feeders on their hosts. Thus, the hunter-gatherer subsistence and sleeping patterns of Archaic times contributed to Chagas disease transmission.

Predation is a factor that further exacerbated Chagas disease risk as shown by analysis of the two major coprolite excavations in the region. From Baker Cave, 34% of coprolites contained bones of *Peromyscus*, *Neotoma*, and *Sigmodon*, all of which are reservoir hosts for Chagas disease. From Hinds Cave, 28% contain bones of rodent genera known to host *T. cruzi* and 18% contain the main host, *Neotoma*. Woodrats would have been the main *T. cruzi* reservoir host without humans. In Archaic times, woodrats were a common food source for prehistoric people (Reinhard et al., 2007). This indicates that humans were reducing the numbers of reservoir hosts by predation while expanding the domestic triatomine habitat by accumulating vegetation and rocks close to or within human habitations. In other words, the human ecology of the area enhanced the possibility that triatomines would feed less on woodrats and more on humans. Thus, human predation on woodrats altered the pathoecology of triatomine behavior and humans supplanted woodrats as targets for triatomines.

Furthermore, the potential of oral transmission existed in the area. Analysis of the woodrat bones found in human coprolites indicates that people ate the woodrats in a raw or nearly raw state (Reinhard et al., 2007). The bones are not scorched nor do they show signs of boiling. Also, we sometimes find rodent hair in the coprolites. This raises the possibility that consumption of raw, infected rodents transmitted Chagas disease. The abrasive diet of Archaic people resulted in dental wear and abscesses (Marks et al., 1988). Of over 100 burials in the area examined, over 80% of skulls showed evidence of dental abscesses (Reinhard et al., 1989). Perhaps the ingestion of raw, infected wild mammals resulted in the transmission of infective forms called amastigotes or trypomastigotes to humans. Such human infection occurs today in several localities of Brazil, where outbreaks of the disease acquired by oral route have been described (Shikanai-Yasuda et al., 1991).

For archaeological cultures, Guhl et al. (2014) report that the ancient Chinchorro culture of Chile was likely infected by this oral route. They found it noteworthy that the prevalence of *T. cruzi* infection mummies was very high. This paleoepidemiological pattern is consistent with oral infection today. They conclude that ingestion of triatomines is the most likely explanation of infection.

For the Lower Pecos area, the potential for oral transmission existed in Archaic food processing areas. In the modern world, oral transmission of Chagas disease occurs when triatomines or triatomine feces are processed into food for human consumption (Covarrubias et al., 2007; Guhl et al., 2014). This potential is supported by experimental infections of mice (Hoft, 1996). Archaic Lower Pecos peoples processed food within rockshelters in near association to triatomine habitats. Often the deep mortars used to pound and grind food were found within recesses of rockshelters in good triatomine habitats. It is possible, even probable, that triatomines or their feces were trapped in the deep, vertical mortars and ground into foods for human consumption. Additionally, analyses of coprolites show that prehistoric people did not avoid eating insects. Rather, some types of insects were intentionally eaten.

8. Archaeology of Chagas disease

Was Chagas disease a major health threat in this region of Texas and Mexico? GIS analysis of archaeological sites helps define this question (Koenig, 2012). If we are correct in our

reconstruction of the role of burned rock middens in Chagas disease transmission, it is clear that the abundance of such middens related to the standard subsistence was part of the force that could have driven the expansion of transmission nidi in the area. Chagas disease could partly explain the enigmatic results of a review of Texas paleopathology (Reinhard et al., 1989). In that study, burial and pathological records for all skeletons recovered in four Texas ecological areas were evaluated. These included the Gulf Coast, the Coastal Plain, the Edwards Plateau, and the Lower Pecos region. All areas exhibited the same life expectancy at birth of about 19 years (Reinhard et al., 1989). However, relative to the other regions, evidence of infection, malnutrition, and trauma were rare in the Lower Pecos region. The absence of evidence of pathology in the desert area was, and is, enigmatic. We postulate that Chagas disease may have had an impact on hunter-gatherer health in the Lower Pecos desert, and contributed to the low life expectancy of Archaic desert people without leaving any skeletal evidence. Chagas disease might have occurred in acute and chronic forms.

There are several ways to test the hypothesis that earth oven cooking was associated with greater Chagas disease risk by focusing field work and lab work on analysis of the disease life cycle.

9. Planning excavation and analysis of triatomine insects

Triatomines are relatively large insects, about 2.5 cm long (Figure 1). In archaeological contexts, especially from rockshelter sites, we suggest that archaeologists take bulk samples from stratigraphic deposits to examine for insects. These samples could be dry screened or floated. In our labs, we have had success with dry sorting and wet screening archaeological remains for insect fragments. It is probable that rockshelter deposits will preserve intact or partially fragmented insects. If the deposits are not ideally preserved, then it is likely that the most durable anatomical structures will be found. Of the general body parts of triatomines, the thorax and head are most durable. The abdomen is adapted to swell when taking a blood meal, which leaves this body region particularly susceptible to decomposition. The thorax is about 7 mm and the head is about 5 mm long. Thus, the structures that should be recoverable are much smaller than the insect itself. Fine screened materials should be examined for the small, durable remains of these insects.

Samples from open-air burned rock middens will provide a greater challenge to sampling and identification. It may well be that paraffin flotation as developed by several archaeoentomologists (Kenward, 1974; Kenward et al., 1980; Bain, 2001) and evaluated by Rousseau (2011) would be necessary in open deposits. We recommend the readers to these authors.

If triatomines are discovered from securely dated contexts, they should be labeled and stored in paper containers for entomological identification and eventually for molecular biological analysis. These specimens should be vouchered permanently in museum collections that focus on parasitism, such as the Manter Laboratory of Parasitology at the University of Nebraska State Museum.

10. Analysis of woodrat remains

Woodrat bones are found mostly in rockshelter deposits (Jurgens, 2005; Lord, 1984; Reinhard et al., 2007). It is noteworthy that small animal bones are much less common in sediment samples (Jurgens, 2005; Lord, 1984) compared to coprolites (Reinhard et al., 2007). Woodrat bones could be tested for DNA evidence of Chagas disease. As summarized by Aufderheide et al. (2005), the trypanosome parasites are disseminated through the blood stream. Therefore, it is possible that

T. cruzi DNA could be recovered from the bones of intermediate hosts. *T. cruzi* DNA has been recovered from a variety of human tissues (Fernandes et al., 2008; Ferreira et al., 2000; Fornaciari et al., 1992; Guhl et al., 1997, 1999, 2000; Rohland and Hofreiter, 2007; Rothhammer et al., 1985). It stands to reason that molecular methods that are successful with human tissues would be successful with rodent remains and insect remains.

To test the efficiency of molecular methods in diagnosing Chagas disease from rodents, Bastos et al. (1996), tested PCR on desiccated tissue from mice that were infected with *T. cruzi*. Although they did not test bones, they were successful in recovering DNA from heart, liver, muscle, spleen, and pancreas tissues. They concluded that PCR would be successful when applied to archaeological remains.

11. Molecular approach to coprolites

Aufderheide and his colleagues made an interesting discovery in 2005 in the analysis of mummies and mummy intestinal contents from Chile. They found that coprolites contained *T. cruzi* DNA if they were recovered from mummies positive for Chagas disease. Therefore, there is a potential that molecular analysis applied to coprolites from rockshelter deposits will be a successful approach to identification of human infection. Aufderheide et al. (2005) suggested several reasons that coprolites were positive for *T. cruzi* DNA. First, they postulated oral ingestion of trypanosomes with uncooked meat. This is an aspect of potential infection for *T. cruzi* in Texas. Second, they hypothesized that there could be parasitemic invasion of intestinal contents through intestinal lesions. Third, ingesting of infected head lice could lead to *T. cruzi* DNA in coprolites. Finally, they suggested that this association of *T. cruzi* DNA in coprolites from infected mummies was simply a taphonomic effect of postmortem transfer of DNA to intestinal contents.

12. Conclusion

To explore our hypothesis that Chagas disease became established in human habitations associated with triatomines and woodrats, further work needs to be done to empirically assess whether or not this association existed. Specifically, archaeologists and parasitologists need to collaborate on methods to recover and analyze both the vectors and the hosts for Chagas disease. We propose a three-pronged approach of sampling archaeological middens for triatomines, sampling woodrats middens for triatomines, and testing human coprolites for *T. cruzi* DNA.

Our reconstruction of hunter-gatherer lifestyle addresses Zumaya-Estrada et al.'s (2012) question as to how hunter-gatherers maintained infections. Hunter-gatherers encroached into and modified their environments. As we can see in the hunter-gatherer archaeology of the borderland of Texas and Coahuila, this led to altered landscape that persisted for thousands of years. By altering the sylvatic life cycle, human promoted the switch of vectors from wild animals to themselves. It is quite possible that strains of *T. cruzi* followed suit such that bands of hunter-gatherers were able to sustain transmission for centuries.

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