


# Paleo-Critical Zones, windows into the changing life and landscapes during the Quaternary Period

Gail M. Ashley\* 

Department of Earth and Planetary Sciences, Rutgers University, Piscataway, 08854, NJ, USA

\*Corresponding author e-mail address: [gmaskley@eps.rutgers.edu](mailto:gmaskley@eps.rutgers.edu)

(RECEIVED February 1, 2020; ACCEPTED May 5, 2020)

## ABSTRACT

The Critical Zone (CZ) as visualized in 1998 was a way to integrate the research of the four scientific spheres (lithosphere, hydrosphere, biosphere and atmosphere) at the surface of Earth and to study the linkages, feedbacks and record of processes. Rather than closeting studies by a variety of disciplines into their respective pigeonholes the CZ perspective provides the symbiotic framework from which the tendrils of improved understanding can radiate outward to new disciplines and/or feedback into the component disciplines. During the last 2 decades, CZ research has been limited to the modern environment. Knowledge gained from the modern and the focus on interpreting ancient records allows for the development of paleo-CZs (PCZs). PCZs provide a powerful tool for improved understanding of the landscapes during the Quaternary Period and the response of this thin skin to glaciations, sea level fluctuations and evolving life. Case studies from hominins in East Africa and *Homo sapiens* in the Americas provide examples of the rich records stored in PCZs. As we move into the space age, the CZ can provide a platform from which to guide future exploration of the proto Critical Zones on the rocky planets and asteroids of our solar system.

## INTRODUCTION

Earth's Critical Zone (CZ) is the "heterogeneous, near-surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources" (NRC, 2001). The concept of the CZ as a means to integrate studies of the near surface terrestrial environment on planet Earth was introduced in 1998 (Ashley, 1998) and formalized in a National Research Council Report (NRC, 2001). It is now applied globally.

The CZ is the outer skin of Earth's surface recording the collective impacts of the atmosphere, cryosphere, hydrosphere, biosphere and pedospheres on the lithosphere by weathering (Amundson et al., 2007). Most CZs begin at the top of the plant canopy and extend down through the vadose zone into the groundwater, where biogeochemical mediation of biotic and abiotic reactions occur (Amundson et al., 2007; Chorover et al., 2007; Akob and Küsel, 2011). Various chemical gradients exchange matter and energy with the Earth

system through space and time (Brantley and Lebedeva, 2011). Processes acting in the CZ are affected by both: (1) the internal dynamics of that system, e.g., mantle convection, volcanism, and earthquakes; and (2) the external dynamics such as climate change and now anthropogenic forcing (TRANSITIONS, 2012).

To understand the full range of processes operating during the Quaternary Period, we need to understand how the CZ operates today (modern environmental studies). In the USA, National Critical Zone Observatories (CZO), 2007–2020, with 12 natural laboratories located in a variety of geological settings was an extremely successful NSF-funded program involving thousands of scientists, have produced a plethora of publications with continued output expected for years to come (Criticalzone.org,01/05/2020). There are also CZOs in China and Europe and they too mostly focus on modern processes. Ancient CZs may have responded in the past to different climatic and biotic states. To understand the full range of processes operating during the Quaternary Period, studies also need to focus on the buried CZs (Paleo Critical Zones, or PCZs) that archive the geological record. However, researchers need to be aware of those environmental settings such as terraces whose records can be overprinted or that might develop as palimpsests. The state of being "buried"

**Cite this article:** Ashley, G. M. 2020. Paleo-Critical Zones, windows into the changing life and landscapes during the Quaternary Period. *Quaternary Research* 96, 53–65. <https://doi.org/10.1017/qua.2020.49>

is key here as PCZs must be isolated from modern processes to maintain the integrity of the ancient environmental record.

PCZs are time slices that capture aspects of the: hydrosphere (e.g., precipitation amounts, seasonality records, groundwater discharge zones); atmosphere (pCO<sub>2</sub> and pO<sub>2</sub>); biosphere (e.g., organic molecular biomarkers, plant and animal remains); and lithosphere (e.g. bedrock, lava flows, clastics, soils). Tracking change from one PCZ to the next through geological time can, therefore, provide an integrative history that is robust and more comprehensive than the individual records would yield.

CZs are all-inclusive. They are more than just soils. Similarly, PCZs are more than just paleosols. The CZ research framework is a wide-ranging approach that has the ultimate goal of learning about the totality of conditions from the top of canopy to the bottom of the weathering zone. There exists a large community of scientists that has been active for decades conducting research using proxies and physical remains to interpret the environmental and climate records archived in sediments. Paleoenvironmental reconstruction is a form of PCZ research, but using different terminology. The contribution of PCZs is crucial to our understanding of Earth surface processes. However, many studies were narrowly focused on specific and often limited objectives. The PCZ framework ideally integrates every aspect of ancient records. The deposits can now be looked at with new and innovative ways.

Identifying and distinguishing competing influences in PCZs remains a major challenge. Preservation of the signatures of various contributing factors is subject to complexities of subsequent weathering and especially erosion, but significant records of hydrosphere, biosphere, atmosphere, lithosphere and pedosphere, can be preserved and provide the evidence needed to interpret the CZs of the Quaternary Period through time and space. The objectives of this paper are:

1. Demonstrate the relevance of CZ concepts to interpret the sedimentary record of the Quaternary preserved in PCZs.
2. Extract paleolandscape, paleoenvironment, paleoecology and paleoclimate records of “time slices” recorded in PCZs.
3. Demonstrate application of PCZs to human origin research using case studies: i) Early hominins (*Homo habilis*); and ii) Native Americans (*Homo sapiens*).
4. Open a discussion of Proto (i.e. abiotic) Critical Zones on rocky bodies of the Solar System, such as Mars that appear to lack an extant biosphere.

## THE CRITICAL ZONE CONCEPT

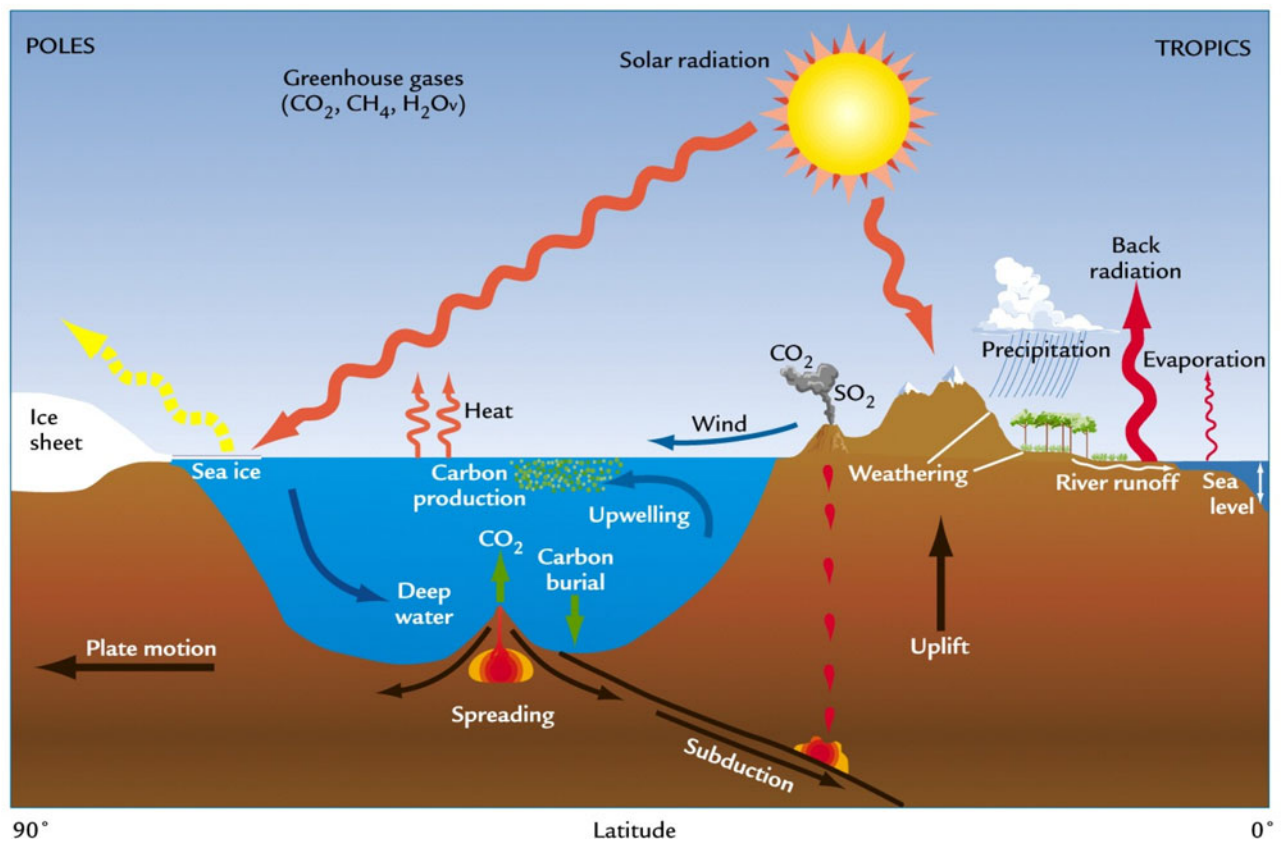
Earth's CZ as first defined in the NRC report (NRC, 2001) extends from the atmosphere at the top of the canopy through bedrock to the limit of weathering, although, the physical characteristics of this lower boundary are controversial (Anderson et al., 2007; Brantley et al., 2011). Tectonic processes at depths may create fractures well below the base of the CZ that locally focus groundwater and affect weathering, geomorphic processes and landform development (Molnar

et al., 2007; Riebe et al., 2017). The characteristics of individual PCZs are determined by chemical reactions triggered by gasses in the atmosphere, heat from the sun, or simply the presence of water or perhaps microbial forms of life? The CZ as originally visualized was a way to integrate the research of the four scientific spheres (lithosphere, hydrosphere [including cryosphere], biosphere and atmosphere) at the surface of Earth and to study the linkages, feedbacks and record of processes. Thus, the CZ concept represents the *spirit of system science*. Rather than closeting studies by a variety of disciplines into their respective pigeonholes the CZ perspective provides the holistic framework from which the tendrils of improved understanding can radiate outward to new disciplines and/or feedback into the component disciplines. The CZ includes the ocean bottom, lake bottoms, land beneath glaciers, forests, deserts, floodplains and volcanoes (Ruddiman, 2000). (Fig. 1). Aquatic environments have not been included in most CZ research, but they should be considered part of this research. Wetlands, lakes, coastal zones and the ocean are fundamental parts of Earth's CZ.

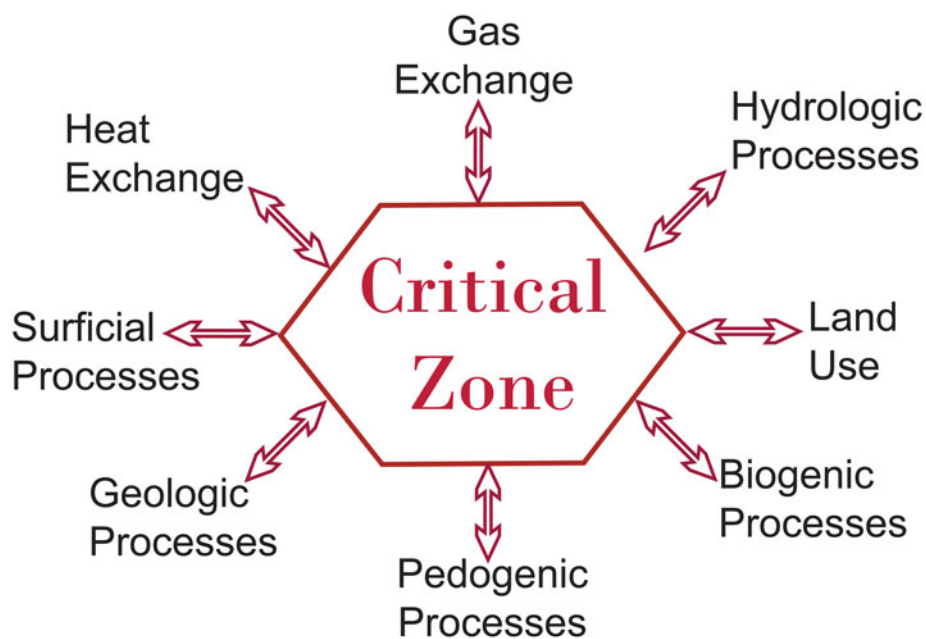
From the onset, the CZ was often equated by the scientific community to soil development and pedogenic processes (Wilding and Lin, 2003; Derry and Chadwick, 2007; Alekseeva et al., 2016). Paleopedologists and hydrologists have contributed hugely to our understanding of CZ processes, e.g., the work of Lin et al. (2006), Lin (2010) and Fan (2015). There is a definite overlap between the CZ as conceived and the pedosphere realm, but the CZ is much more. The CZ is the entire surface of Earth and it extends upward including the biomass on the surface and downward through the saturated and unsaturated portions of the pedosphere. But because of the possibility of erosion on the Earth's surface, paleosols are likely only a portion of the former CZ, i.e., a truncated part of the record.

## THE PALEO CRITICAL ZONE CONCEPT (PCZ)

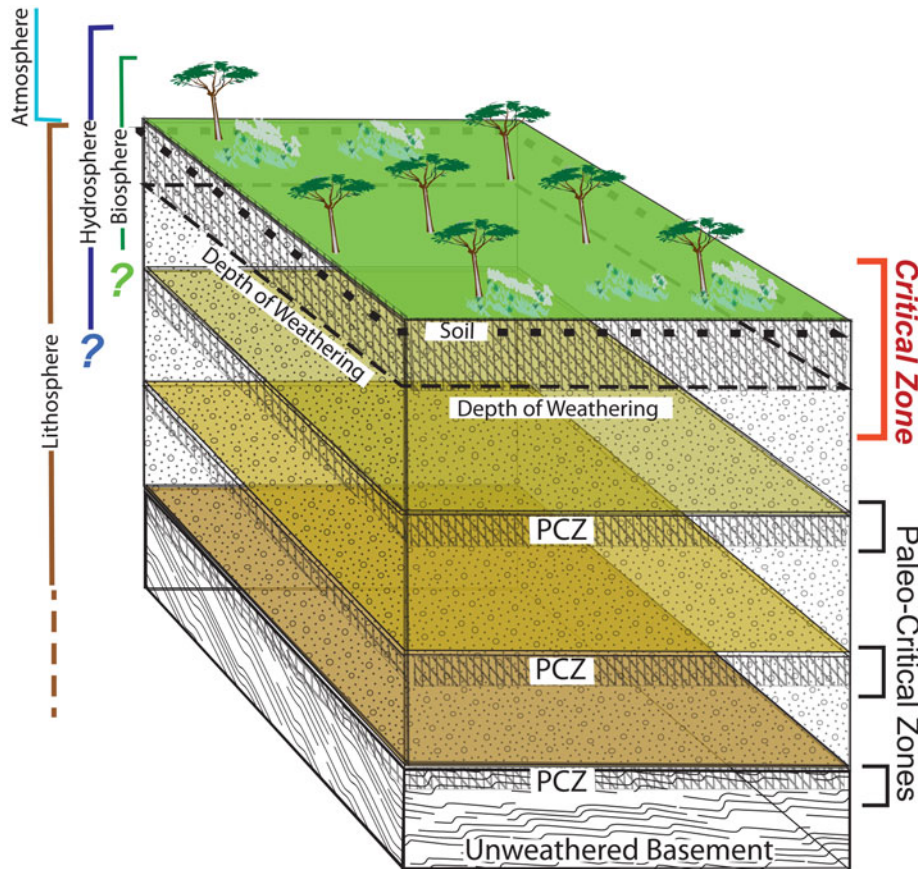
CZ is the thin skin of Earth upon which life thrives. The modern CZ is where the transfer of mass and energy takes place (Fig. 2). Internally, gas and heat exchange activate hydrological processes, increase biological productivity and generates pedogenic processes. Microbes are expected to be present everywhere (Akob and Küsel, 2011). Externally, large-scale geological processes, local surficial processes and anthropogenic input are causes that turn the crank and drive the weathering machine (Brantley et al., 2007). The integrative studies of the CZ as laid out in the National Resource Council Report (2001) made a strong case for applying the concept developed on modern Earth to geological time scales. The idea was to identify ancient (now termed PCZ) or deep time records that have been separated from the Earth's surface (Fig. 3). They are an untapped resource of paleoenvironmental information from time slices at key times in the four-billion-year history of CZ processes. They include environmental variations caused by major volcanic episodes, meteorite impacts and other extreme events. This archive of CZ history likely records a far richer range of states of the landscape and



**Figure 1.** Earth's CZ is the heterogeneous, near-surface environment in which complex interactions of the major components of the climate system, i.e., rock, soil, water, ice, air, and living organisms force and responded to climate variations (Ruddiman, 2000). The CZ is the interface between the lithosphere and hydrosphere, cryosphere and atmosphere.



**Figure 2.** Mass and energy flux for the CZ is a dynamic interval with mass and energy fluxes driven by solar energy. CZ is a unifying concept that accommodates a variety of near surface processes, feedbacks, linkages and most importantly is a physical record of them.



**Figure 3.** Schematic diagram depicting the elements of the CZ, a near surface environment that extends from the top of the vegetation canopy to the base of weathering. When buried CZs become PCZs but are usually truncated with the bedrock rarely preserved. In stacked PCZs the base is composed of sediment.

environment than we can observe directly in the tiny slice of time we occupy today living in the modern Earth's CZ.

Figure 4 illustrates what a complete PCZ textural record might look like and the geological factors, such as sedimentation rate or tectonism that would determine the potential for preservation. A high sedimentation rate, stable or subsiding surfaces lead to the thickest PCZs. Uplift, erosion and low sedimentation produces thin or no records. The position of the water table, vadose zone and phreatic zone are indicated. A complete idealized PCZ when forming would contain a basal layer of (1) dry unweathered bedrock, overlain by what would have been (2) wet unweathered bedrock, and in turn overlain with (3) fractured bedrock. Perhaps a more realistic depiction based on what we know of the natural environment might show a more complicated CZ architecture that has deep penetrating fractures generated by tectonic deformation (Molnar et al., 2007). The physical nature of the base of the CZ will vary with the geological context. The lithosphere will vary from bedrock to sedimentary deposits. Stacked PCZs will by their nature be sediment (Fig. 3) and vary in the time for their formation. Overlying the (3) the wet fractured bedrock is (4) a regolith mix of sediment and suspended bedrock clasts. Near the top (5) is irregularly layered sediment (clay, silt, sand and clasts) and (6) organic-rich sediment

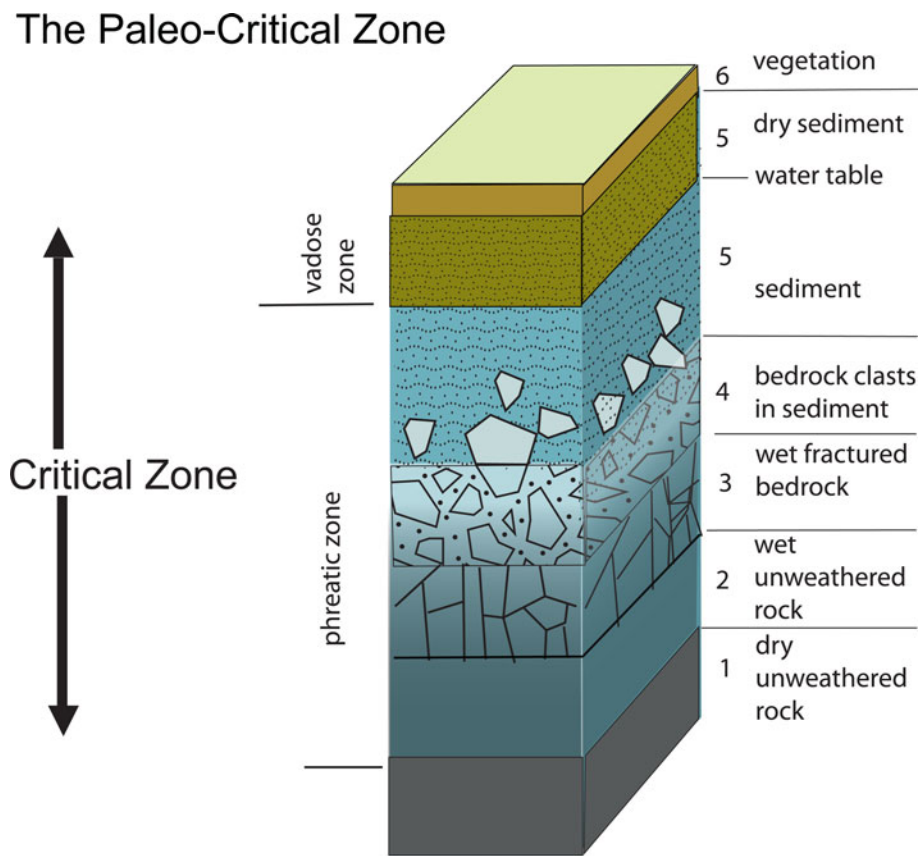
(humus) at the top in humid environments and mineral formation in arid environments.

Only few studies have been conducted on "PCZs", as such, however there have been many studies over the last decades on "buried soils" or "buried paleosols", e.g., although many have a narrow research scope such as of tracking climate change (Alexandrovskiy et al., 2004; Zech, 2006) or developing a new dating technique (Balco and Rovey, 2008). Lukens et al. (2017) studies an Early Miocene record successfully using the PCZ approach to reconstruct the flora and fauna. Nordt et al. (2012) applied the CZ concept to an early PCZ and Nordt and Driese (2013) to a Cretaceous alluvial record. Both of these studies were termed deep-time Critical Zones (DTCZ), which is defined in the 2001 NRC Report as pre-Quaternary (<2.6 Ma). But, to date there have been few Quaternary-age PCZ studies.

## THE QUATERNARY PERIOD

The Quaternary Period is divided into two epochs, the Pleistocene beginning at 2.588 Ma and ending ~ 12.7 ka and followed by Holocene that officially would merge with the Common Era (C.E.). We have entered the Anthropocene in which human activity is the dominant influence on climate





### Factors that affect development and preservation

#### Tectonics

Stable (thicker CZ)  
 Uplift (erosion)  
 Subsidence (stacked CZ)

#### Sedimentation

High (stacked CZ)  
 Low (thicker CZ)

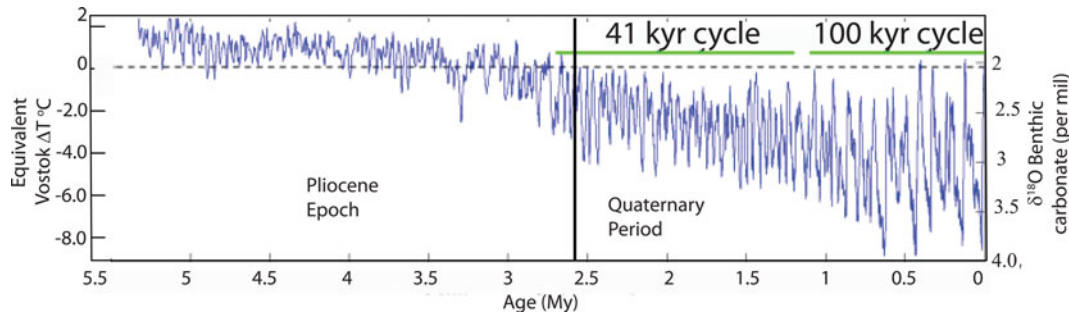
**Figure 4.** Factors that affect its development and preservation potential are listed together with a diagram of a complete PCZ from vegetation surface (top) to unweathered bedrock (base).

perhaps arguably beginning as early as 8,000 years ago (Ruddiman, 2005), The industrial revolution accelerated the rise of CO<sub>2</sub> in the atmosphere triggering major warming changes to Earth (Ruddiman, 2005; Cronin, 2010; Zalasiewicz et al., 2011).

The Quaternary Period is typically thought of as the “Ice Age”, a time driven by Milankovitch cycles characterized by growth and melting of glaciers at high elevations and high latitude (Fig. 5). The 41,000 year cycles dominated the first ~1.5 Ma and 100,000 cycles the latter portion (Lisiecki and Raymo, 2005). Sea level fluctuations up to 120 m tracked the growth and then decay of continental ice sheets and land bridges between land masses that opened and closed (Imbrie and Imbrie, 1986; Denton et al., 2010). Mid to lower latitude areas were also affected

by Milankovitch-driven climate cycles causing a shift in global temperatures (cooler) and changes to atmospheric circulation that affected the spatial and temporal distribution of rainfall (Ruddiman, 2000; Kieniewicz and Smith, 2009; Cronin, 2010). Major environmental changes occurred in vegetation and fauna (Lowe and Walker, 2015). There was a major extinction of large mammals, such as mammoths and mastodons, sloths and saber tooth cats during the late Quaternary (Stuart, 1991; Barnosky et al., 2004).

The early Quaternary Period was a time when the rate of evolution and the rate of speciation increased (Vrba et al., 1996; Barnosky, 2005; NRC, 2010). As this acceleration of change in hominins occurred climate variability (magnitude and frequency) increased (Fig. 5). The association between



**Figure 5.** Milankovitch-driven climate is present across 5.5 million years of climate change as shown by changes in  $\delta^{18}\text{O}\text{‰}$  in carbonate benthic forams. From Global Warming Art Project:Wikipedia Commons.

climate variability and human evolution is not necessarily a cause and effect connection, but the coincidence has been noted by several researchers e.g. (Potts, 1996; DeMenocal, 2011; Shultz and Maslin, 2013)

## PCZ RECORDS OF HOMININS: CASE STUDIES

### Case Study 1: *Homo habilis* (1.84 Ma), East Africa

Hominin evolution began in Africa and was well advanced by the beginning of the Quaternary Period (2.588 Ma; NRC, 2010). Most of the hominin archaeological sites are in the East African Rift System where extensional tectonics regularly produces accommodation space, localized high sedimentation and volcanic outpouring of datable lavas, pyroclastics and ash beds. Preservation potential is high in the rift. Rift tectonics (uplift and down faulting), changing base level, climate fluctuations and active volcanism produced a continually changing land surface and sedimentation rates. Most of the rest of the hominin record is found in fossil-rich cave deposits in South Africa (Kullmer, 2015). Oddly, the oldest hominin fossil  $\sim 7.2$  million years old was found in neither the rift valley or in the caves, but rather in the intracratonic basin of Lake Chad (Brunet et al., 2002). During the Late Pliocene, hominins evolved into two distinct lines, the Australopithecines who went extinct at  $\sim 1.0$  Ma (Grine, 1988; Wood and Richmond, 2000) and the hominins who thrived and culminated in *Homo sapiens*, the only species now left on Earth. Unfortunately, there is a dearth of hominin remains in Africa for study. However, the East African Rift System is comprised of copious rift basins that are infilled with huge thicknesses of sediment (Frostick, 1997; Gawthorpe and Leeder, 2000) and thus the region has great potential for future discovery of fossils and PCZ records.

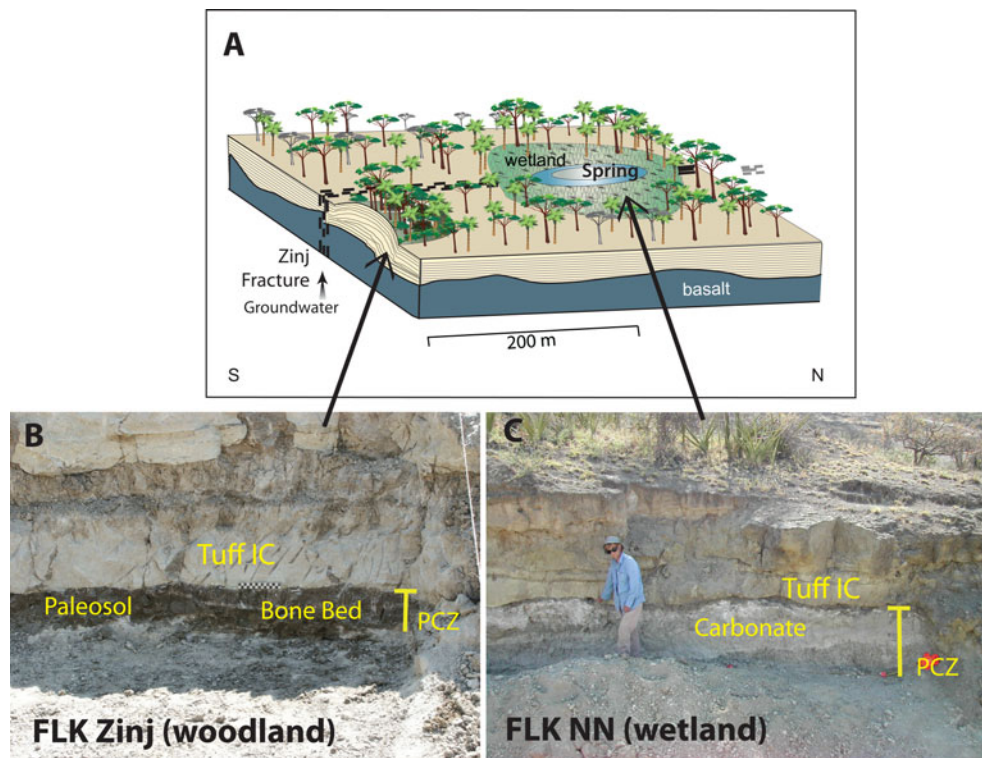
#### FLK Zinj Site, Olduvai Gorge

The study of human origins grabbed the world's attention with the discovery of *Zinjanthropus* in 1959 in Olduvai Gorge, Tanzania by Louis and Mary Leakey (Leakey, 1959). Although the fossil (OH5) was later reclassified as *Paranthropus boisei*, the name "Zinj" has stuck and the FLK Zinj archaeological site is now a World Heritage locality

visited by hundreds of thousands of tourists annually. The site is an excellent model of a high yielding PCZ and serves as an example of what valuable information on hominin habitats and behavior can be gleaned from the sedimentary record (Magill et al., 2016).

The site has two excavations (FLK Zinj and FLK NN) conducted by the Leakeys in the early 1960s (Leakey, 1971). Figure 6A depicts a paleoenvironmental reconstruction of a woodland covering a low topographic mound and a spring and wetland complex 200 m to the north. The Zinj fracture system, a north-south normal fault cuts directly through the wetland, but passes just to the west of woodland. The Zinj Fault can be traced southward for a least a mile (Driese and Ashley, 2016). The fault has been identified as a groundwater-conveying fracture system in this part of the Olduvai basin. A number of studies give details on this paleo water source and its importance to hominins living there (Ashley et al., 2010; Domínguez-Rodrigo et al., 2010; Arráiz et al., 2017). The sedimentary records, PCZs, the woodland (Fig. 6B) and wetland (Fig. 6C) are immediately overlain by an airfall tuff (Tuff IC), thus they are correlated and equivalent in age. Single crystal  $^{40}\text{Ar}/^{39}\text{Ar}$  dating yielded and age of 1.84 Ma for the tuff (Deino, 2012).

Figure 6B is a photo of a recent excavation at the FLK Zinj archaeological site that had yielded two hominins, *Paranthropus* (H5) and *Homo habilis* (H6) in 1959. The hominin remains were recovered from a buried soil, i.e. an organic-rich paleosol (325 m<sup>2</sup> area) along with 2500 stone tools (Leakey, 1971). Thousands ( $\sim 3500$ ) of vertebrate bones, many cut-marked presumably by hominins were also recovered from this bone bed. Recent biogeochemical studies of the biomarkers including lignin and leaf waxes revealed that the paleosol had formed beneath a woodland (Magill et al., 2016). Plant biomarkers relate to ecosystem structure including the canopy within the Critical Zone and can distinguish  $\text{C}_4$  arid-adapted grasses ( $\delta^{13}\text{C}_{\text{wax}}$  values =  $-20\text{‰}$ ) from  $\text{C}_3$  trees and forbs ( $\delta^{13}\text{C}_{\text{wax}}$  values =  $-36\text{‰}$ ). Figure 6C is a view of an excavation by the Leakeys in FLK NN that shows a 40 cm thick freshwater carbonate (tufa) containing admixed clay that is the same age as the bone bed. Stable isotope data, microfossils and biomarkers indicate diverse plants like sedge and ferns that formed in a freshwater spring-fed wetland (Fig. 6A). These aquatic plants may have served as food sources for hominins.



**Figure 6.** An example of a PCZ in Africa dated at 1.84 Ma. (A) Artists rendition of the paleoenvironment of hominins shows a small woodland and a spring-fed wetland 200 meters apart. (B) PCZ is outcrop of an organic-rich paleosol directly overlain by an airfall tuff (Tuff IC). Soil formed in the woodland and contains copious mammal bone fragments and stone tools. (C) PCZ is outcrop of freshwater carbonate (tufa) mixed with clay that was deposited in the spring-fed wetland located on a lake margin. Modified from Ashley et al. (2014).

Piecing together the information from the PCZ, the Zinj archaeological site was a small woodland to which hominins brought animal limbs and carcasses to eat in the safety of the trees. The assumption is that the vertebrates were drawn to the wetland-spring complex for the freshwater and were killed by carnivores and then scavenged or possibly hunted by hominins (Bunn and Kroll, 1986; Ashley et al., 2010; Domínguez-Rodrigo et al., 2010). Preliminary research on the taphonomy of the vertebrate remains from the Zinj site suggests that Early Pleistocene *Homo* was an ambush predator (Bunn and Gurtov, 2014).

Significance of the PCZ approach is that the multifaceted information that is accrued and allows interpretations beyond a simple presence or absence of a type of vegetation (Stinchcomb and Beverly, 2019). Paleoanthropologists have been struggling with interpretation of the archaeological sites, as to the hominin behavior involved with respect to food access and foraging. Were hominins hunting or scavenging? The details of the landscape, the presence of water and edible food and whether the canopy was opened or closed provides important information for developing models of sophisticated hominin behavior.

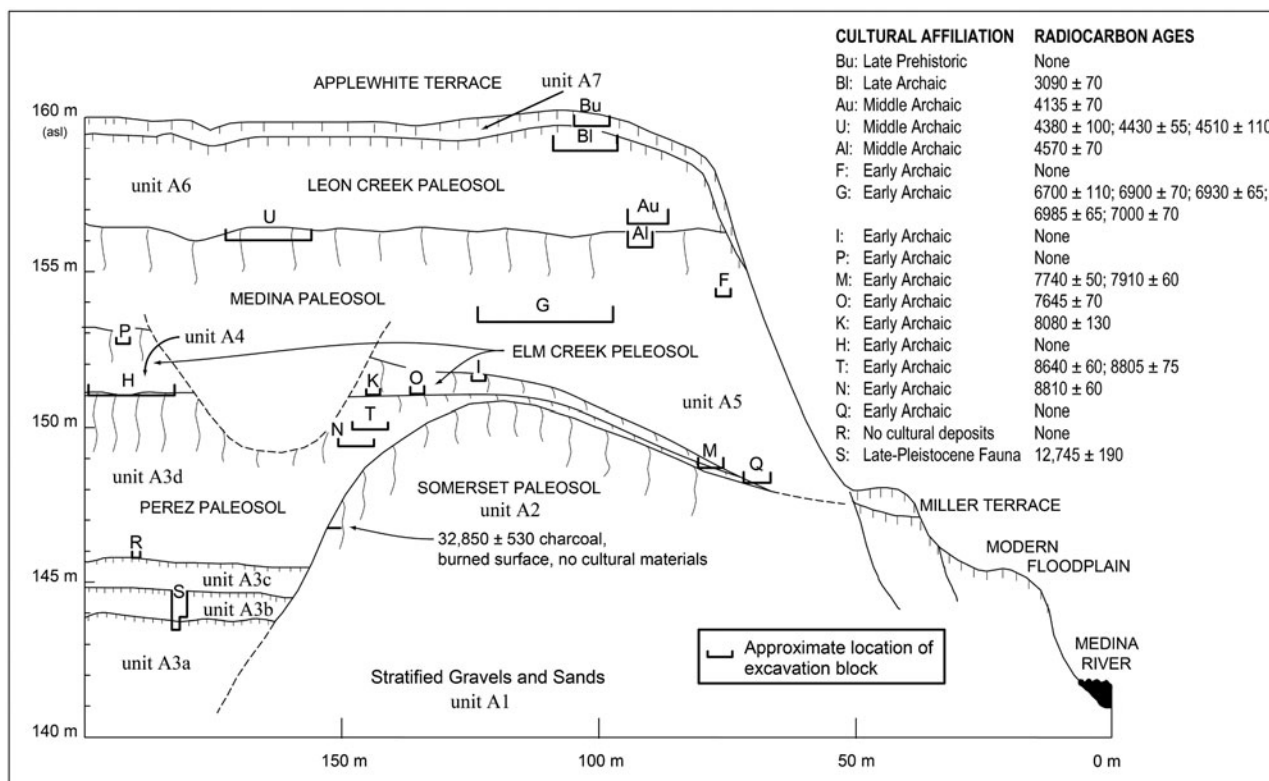
### Case 2: *Homo sapiens*, (10 Ka), The Americas

The chronology and route(s) taken by modern humans that migrated out of Africa and spread throughout the world is a

study in progress (Fleagle et al., 2010). DNA studies indicate migrations of small groups began by at least 80 ka and most likely followed coastal routes that ensured freshwater and food (Faure et al., 2002; Gugliotta, 2008). Humans eventually arrived in the Americas by crossing the Bering Land Bridge that connected the Asian continent to the North American continent (Waters, 2019). Evidence from nuclear gene markers, mitochondrial DNA and Y chromosomes indicates that all Native Americans came from Asia (Karafet et al., 2006; Merriwether, 2006).

This land mass, Beringia, was created by the lowering of sea level during the last glacial maximum (LGM at ~25-18 ka; Goebel et al., 2008). Glaciers covered the land between 33 ka to ~12 ka. Thus, migration routes, here too, likely followed the coast until an ice-free corridor on land opened up. The coastline and any archaeological records of humans arriving in the new world were unfortunately submerged under accelerated sea level rise that occurred due to massive continental ice loss at the end of the LGM-early Holocene. Sea level has been quasi-stable since ~6 ka. Eustatic sea level rise since the industrial revolution (~ CE 1850) is measured in decimeters, and less along much of the Pacific Coast of North America where tectonic uplift causes relative local sea level fall. Although, not abundant, pre-Clovis archaeological sites occur in both North and South America containing records of human bones and their cultural remains. Some notable archeological sites that have documented peopling of the





**Figure 7.** An example of a PCZ in North America dates to 10 ka. Generalized cross-section of the west wall from a quarry excavated into Medina River alluvium (Mandel et al., 2018). Exposure reveals stacked stratigraphic units, paleosols and sites of dated material (designated alphabetically). The radiocarbon ages were determined mainly on wood charcoal.

unglaciated land south of the ice sheets to as early as 17.5 ka are Monte Verde, Chile (~18 ka; Dillehay et al., 2015); Cooper's Ferry, Idaho (~16.0 ka; Davis et al., 2019); Debra L. Friedkin, Texas (15.5 ka; Waters et al., 2018); and Paisley Caves, Oregon (12.3 ka; Gilbert et al., 2008; Jenkins et al., 2012).

Studies in the central plains of the US indicate that buried paleosols of Paleoindian-age are found in alpine bogs, alluvial fans, and river valleys (Mandel, 2008). But, many are likely hidden from view deeply buried in river valleys that were infilled during postglacial adjustment of watersheds to change in vegetation, base level and climate (Mandel, 2008; Waters, 2019). Others may have been eroded or submerged on the continental shelf. However, many buried archaeological sites have been discovered and studied providing important information on where the first Americans came from, when they arrived and the cultural traditions they brought with them (Meltzer, 2009; Waters, 2019). These deposits have been termed "buried soils" or "buried paleosols" because of physical and chemical evidence of pedogenesis (Birkeland, 1999; Retallack, 2001). Buried soils display great variability in characteristics and are an important subset of the full spectrum deposits found in PCZs.

#### Richard Beene Site, Texas, USA

The Richard Beene archaeological site in southwestern, Texas, was chosen as a case study of *Homo sapiens* records

found in buried soils, that has the potential to continue to inform us about the Quaternary period. The site is well exposed, well dated and has been extensively studied (Mandel et al., 2007; Thoms and Clabaugh, 2011; Mandel et al., 2018). The site is an ideal candidate for applying the more inclusive PCZ methodologies. The use of the holistic approach of PCZ analysis provide new insights and hopefully maximize the understanding of the paleoclimate, paleoenvironment and subsistence strategies of early humans in the Americas (Ferraro et al., 2018).

A field sketch of an outcrop at Richard Beene archaeological site of Mandel et al. (2018) illustrated in Figure 7 shows the interpreted stratigraphy and radiocarbon ages. The 20-m-thick stratigraphic sequence is a spectacular exposure that reveals stacked sedimentary packages of floodplain alluviation alternating with periods of stability and pedogenesis overlying sand and gravel (33,000–20,000  $^{14}\text{C}$  yr BP). Records of vertebrates (14,000–11,000  $^{14}\text{C}$  yr BP) contained no human bones or cultural remains. However, overlying these layers, twenty stratigraphically distinct archaeological deposits were identified yielding > 80,000 artifacts excavated from areas totaling 730 m<sup>2</sup>. The archaeology represented Early Archaic (~ 8800  $^{14}\text{C}$  yr BP to Late Pre-Columbian (~ 1,200–400  $^{14}\text{C}$  yr BP) cultural periods (Fig. 7). Some paleoenvironmental data were collected: (1) the CaO<sub>3</sub> (%) that is used as a proxy to track changes in aridity through time; and (2) organic carbon (%). The relative proportion of C3 and C4

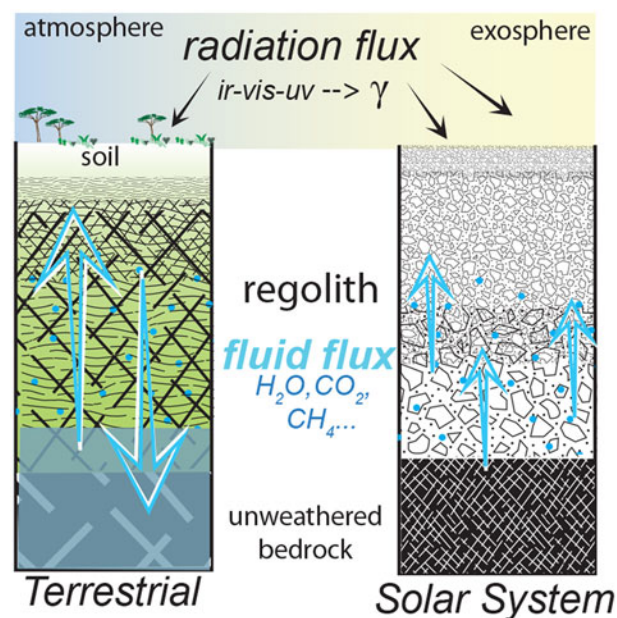


plants on landscape, that in turn reflect changes in temperature and moisture, was estimated from soil organic matter using a mass balance equation developed by Nordt et al. (2002). However, PCZs are time slices that capture much more, such as aspects of the hydrosphere (e.g., precipitation amounts, seasonality records, groundwater discharge zones), atmosphere ( $p\text{CO}_2$  and  $p\text{O}_2$ ), biosphere (organic molecular biomarkers, fossils including hominins), pedosphere (micromorphology and geochemical profiles), and lithosphere (clastic sediments and paleosols). Thus, tracking changes in PCZs through time can provide an integrative history of time humans were walking the landscape. Integrative, holistic records from PCZ inform us more than individual records on their own.

### CRITICAL ZONES IN THE SOLAR SYSTEM

PCZs are the “deep time” archives of Earth’s ancient surfaces that were buried, thus completely separated from mass and energy fluxes at the surface. As PCZs stack up they are a valuable record of the variability of CZ through time (Fig. 3). With the advent of the space age and exploration of other bodies of our solar system we will be looking into the unknown for other forms of life, useable sources of water, and valuable minerals. We will need to make observations to interpret and, hopefully, understand the geological processes operating on planet surfaces. Under this scenario, a logical next step is to apply the concept of the CZ and PCZ to the study of planetoidal surfaces within the Solar System, such as Mars, asteroids and comets. Abiotic CZs (proto-CZs), that support organic chemical reactions, may already be recognized on Ceres and comet 67P-Churyumov-Gerasimenko (European Space Agency, 2019). Terrestrial studies of the CZ have generally concentrated on the biological aspects of the concept so studies of proto-CZs on other Solar System bodies require a dramatic shift of emphasis. The exploratory focus will likely be on Mercury, Venus and Mars, the bigger planetoids in the asteroid belt and moons of the gas giants further out from the Sun (Ashley and Delaney, 2017). Exploration of Mars over the last decade with rovers and satellites have revealed sedimentary rocks (Grotzinger et al., 2013). These rocks could have PCZs and with the appropriate technology might be studied in future missions. Not enough is current known about PCZs on Mercury or Venus.

The CZ is a region of mass and energy flux, and is a multidimensional boundary zone(s) between the solid planetoid and its gaseous +/- liquid envelopes, at various locales on the surface (Fig. 8). Earth’s CZ’s have physical, chemical, biological and three-dimensional morphological aspects that evolve through time. All solid bodies of the Solar System must have proto-CZs though they should vary dramatically reflecting the boundary conditions on the specific planetary body. In particular, the effect of biological components, if any, remains to be assessed. Basic factors that influence the structure and evolution of planetary CZ’s are similar to those on Earth (Fig. 2), but terrestrial studies of the CZ have focused on the biological aspects of the concept and



**Figure 8.** Comparison of CZs on Earth and other bodies in the Solar System. Radiation flux from atmosphere/exosphere fuel reactions in regolith enhanced by fluid and gas fluxes. Proto-CZs (abiotic CZ’s) that support organic chemistry have been recognized (cf. Rosetta at comet 67P-Churyumov-Gerasimenko; European Space Agency, 2019).

are mostly limited to short time scales, in large part because of the turbulent nature of the atmosphere-hydrosphere system and its cascade of processes and effects on the physical and chemical weathering, transport, and deposition of sediment across space and time scales at Earth’s surface.

### Mars: A case study of a rocky planet

#### *PCZs as records of early processes on the Martian surface*

Mars has been explored since 1976, starting with data from orbiters and followed by Lander Missions that provided troves of high-resolution images as well as geochemical and geophysical data. From that we now know that Mars is geologically complex and may have had a history somewhat similar to Earth. Mars is a single plate planet with no extant plate tectonics. Similarly, the ambiguity about the presence or absence of biological activity contributes to these fundamental differences between Earth and Mars and will influence each planet’s CZs differently.

Mass and energy flux processes that are likely prior to the onset of biological activity are: (1) hydrologic cycles; (2) carbon cycles; (3) gas exchange (major and trace); (4) weathering (chemical and physical); (5) erosion and deposition (physical processes); (6) lithification (diagenesis); and (7) soil genesis (pedology) by impact “gardening”, the process by which impacts move material from depth and emplace it on or near to the surface. Gardening is also called “mixing” or “overturn”. In addition, extraterrestrial CZ’s include (9) solar and cosmic

radiation fluxes, and (10) impact caused resurfacing events that result in punctuated evolutionary histories not typically studied on Earth. Both contemporaneous proto-CZs and PCZs occur. PCZs provide a holistic integration of ancient landscapes including paleo-atmosphere, paleo-hydrosphere and paleo-biosphere (Retallack, 2014; EuropeanSpaceAgency, 2019). Evidence of CZ's can be over-printed, obliterated and even removed by surface processes, so proto-CZs may be poorly preserved or incomplete in the stratigraphic record.

Earth is a 'habitable zone' planet, but we here discuss the application of the CZ to other rocky planets and bodies in the Solar System (Morbidelli et al., 2012) where the physical evidence is more accessible than the biological evidence. Eight factors are essential for a habitable zone. (1) Water is an essential component of all CZs. The role of H<sub>2</sub>O phases must be considered in detail because the presence or absence of water influences not only the potential for extant life but also the physical evolution of planetary surfaces. (2) Carbon cycles for other bodies remain poorly understood. Both biogenic and abiogenic carbon cyclicity is fundamental and, indeed, is the 'Holy Grail' of biogenic CZ studies. (3) On Earth, interaction with the dense atmosphere, in addition to the hydro/cryosphere, is fundamental to CZ evolution, but atmospheres/exospheres on other bodies have analogous gas exchange processes (Figure 8). (4) Weathering and (5) erosion are the most readily accessible aspects of planetological CZs. Because the effects of these processes are observable from telescopes, satellites, and landers they have received most attention. (6) Lithification is critical to the preservation of the CZ evidence that can be studied either remotely or by detailed sampling. (7) Soil formation processes transform local regolith to the most widespread surface material on Solar System bodies (Vaniman et al., 1991). (8) The absence of unequivocal evidence of extraterrestrial life permits us to neglect biological aspects at present.

### Critical zones on Mars

Identification of CZ's on Mars, is already feasible at Gale Crater (Li et al., 2015) and using GPR but studies aimed at elucidating the internal structure of a CZ will require coring and sampling at a minimum. Investigating life on Mars requires that we identify and document the environments most conducive to life (CZ's) across the entire planet. The processes and thus the structure of the CZ's likely vary with latitude, longitude and elevation, aspect, bedrock, and energy flux just as they do on Earth.

If Mars was ever habitable (Boston et al., 1992), Martian PCZ's are more likely to reveal the transition from proto-CZ (abiotic) to biotic CZ than on Earth (Fig. 8) where biology dominates and has done since the first evidence of life appeared at ~3–4 Ga. Discussion of potential CZs on Mars in the form of "inverted" CZs (Boston, 2015) has begun, but remains to be explored in greater detail. Mars has abundant water (Kargel, 2004). The triple point of water is stable in the relatively shallow subsurface of Mars and may represent the locus of mass and energy fluxes in Martian regolith

and soil. The physical, chemical (and biological) consequences of coexisting H<sub>2</sub>O phases in the near surface will differ across the surface of Mars.

CZs on Mars are the optimum sites for identifying any extant life. PCZs will provide the record of any biological activity during the Noachian and Hesperian Periods from ~4.1 to 3.7 Ga and ~3.7 to 3.0 Ga, respectively.

Atmospheric pressure on Mars ranges from 610Pa in Hellas basin, to 72Pa on Olympus Mons. The triple point of water (611Pa) is easily achieved at depth in many regions of Mars and hence chemical reactions that are catalyzed by liquid water must occur in lowland regions (such as Hellas, Valles Marineris and Vastitus). The almost ubiquitous presence of briny solutions on Mars (Toner et al., 2014) is direct evidence of CZ processes on the planet.

Impact resetting of environments has occurred throughout geological time and provides a stratigraphic constraints on CZ studies. The effect of impacts ranges from microscale 'gardening' of the Martian landscape to basin scale erosion that disrupts and evacuates large volumes of crust and spreads debris planet wide. Such large impacts provide the chronometer for proto- and PCZ formation.

CZs are the most important archive of near surface planetary processes where deposition and erosion provide a mobile surface. On balance CZs are steady-state dynamic environments and their 3-D structure evolves (continuously) with time and should be the primary targets of surface exploration. The concept of the CZ, as a record of surficial mass and energy fluxes at surface of rocky bodies can be effectively applied throughout the Solar System.

## CONCLUSIONS

The CZ concept provides the framework for studying environments where biology, geology, and chemistry all interact to produce assemblages that provide holistic records of the wide variety of environments found on planet Earth. Over the last two decades scientists have restricted research to mainly chemical and physical weathering processes in the modern CZ. It is now time to take lessons learned from the modern environment and apply to ancient environments using the PCZ Concept. PCZs may also inform our understanding of the modern CZ.

The Quaternary Period is a time of continually changing landscapes, i.e., CZs, forced by astronomical climate cycles. This geologic period is also a time of biological change, of species evolution, extinctions and migrations. The buried sedimentary records are an untapped source of information. Case studies of the archaeological sites of two representative members of genus *Homo* successfully illustrate the rich records that can be gleaned from PCZs. Finally, as we enter the space age and begin to explore neighboring planets, the CZ concept has great potential as a research tool. Critical Zones, using an expanded definition to include proto-CZs, occur at the surface of all rocky bodies in the Solar System and provide the goal for the search for paleo-biology and life in the future. The holistic aspect of the CZ concept provides more complete targets for

missions to explore the near surface of planetoidal bodies such as Mars, asteroids and comets.

## ACKNOWLEDGMENTS

The views presented here have evolved over a couple decades in discussions with numerous colleagues. It is difficult to untangle where specific ideas have come from. I appreciate the insights and opinions of Steven Driese, Clayton Magill, Emily Beverly, Gary Stinchcomb, Henry Lin, Kate Freeman, Daniel Deocampo, Jeremy Delaney, Gregory Retallack, Susan Brantley, Lee Nordt, Doris Barboni, Michelle Goman, Andrea Shilling, Tim White, and Monica Norton. I am particularly grateful to Rolf Mandel for his support and assistance with the Richard Beene archaeological record. An earlier version was much improved by the constructive comments of Karl Wegmann, Lewis Owen and an anonymous reviewer.

## REFERENCES

- Akob, D.M., Küsel, K., 2011. Where microorganisms meet rocks in the Earth's Critical Zone. *Biogeosciences*, 3531–3543.
- Alekseeva, T., Kabanov, P., Alekseev, A., Kalinin, P., Alekseeva, V., 2016. Characteristics of Early Earth's Critical Zone based on Middle-Late Devonian paleosol properties (Voronezh High, Russia). *Clays and Clay Minerals* 64, 677–694.
- Alexandrovskiy, A.L., Glasko, M.P., Krenke, N.A., Chichagova, O.A., 2004. Buried soils of floodplains and paleoenvironmental changes in the Holocene. *Revista Mexicana de Ciencias Geológicas* 21, 9–17.
- Amundson, R., Richter, D.D., Humphreys, G.S., Jobbagy, E.G., Gaillardet, J., 2007. Coupling between biota and Earth materials in the Critical Zone. *Elements* 3, 327–332.
- Anderson, S.P., von Blanckenburg, F., White, A.F., 2007. Physical and chemical controls on the Critical Zone. *Elements* 3, 315–320.
- Arráiz, H., Barboni, D., Ashley, G.M., Mabulla, A.Z.P., Baquedano, E., Domínguez-Rodrigo, M., 2017. The FLK Zinj paleolandscape: Reconstruction of a 1.84 Ma wooded habitat in the FLK Zinj-AMK-PTK-DS archaeological complex, Middle Bed I (Olduvai Gorge, Tanzania). *Palaeogeography, Palaeoclimatology, Palaeoecology* 488, 9–20.
- Ashley, G.M., 1998. Where are we headed? 'Soft' rock research into the new millenium GSA, Program with Abstracts GSA, Toronto, Ont, p. Abstract# 50167.
- Ashley, G.M., Barboni, D., Domínguez-Rodrigo, M., Bunn, H.T., Mabulla, A.Z.P., Diez-Martín, F., Barba, R., Baquedano, E., 2010. A spring and wooded habitat at FLK Zinj and their relevance to origins of human behavior. *Quaternary Research* 74, 304–314.
- Ashley, G.M., Delaney, J.S., 2017. 'Critical Zones' on Mars and across the Solar System, Lunar and Planetary Science Conference. Lunar and Planetary Institute, Houston, TX, p. 1179.
- Ashley, G.M., De Wet, C.B., Karis, A.M., O'reilly, T.M., Baluyot, R.D., 2014. Freshwater limestone in an arid rift basin: a Goldilocks effect. *Journal of Sedimentary Research* 84, 988–1004.
- Balco, G., Rovey, C.W., 2008. An isochron method for cosmogenic-nuclide dating of buried soils and sediments. *American Journal of Science* 308, 1083–1114.
- Barnosky, A.D., 2005. Effects of Quaternary climatic change on speciation in mammals. *Journal of Mammalian Evolution* 12, 247–264.
- Barnosky, A.D., Koch, P.L., Feranec, R.S., Wing, S.L., Shabel, A.B., 2004. Assessing the causes of late Pleistocene extinctions on the continents. *Science* 306, 70–75.
- Birkeland, P.W., 1999. *Soils and Geomorphology*, 3rd ed. Oxford University Press, New York.
- Boston, P.J., 2015. Hypothetical inverted Critical Zones for subsurface biospheres on desert planets and icy ocean worlds., 2nd International Planetary Caves Conference. LPI Contributions, Flagstaff, AZ, p. 9039.
- Boston, P.J., Ivanov, M.V., McKay, C.P., 1992. On the possibility of chemosynthetic ecosystems in subsurface habitats on Mars. *Icarus* 95, 300–308.
- Brantley, S.L., Goldhaber, M.B., Ragnarsdóttir, K.V., 2007. Crossing disciplines and scales to understand the Critical Zone. *Elements* 3, 307–314.
- Brantley, S.L., Lebedeva, M., 2011. Learning to read the chemistry of regolith to understand the Critical Zone. *Annual Review of Earth and Planetary Sciences* 39, 387–416.
- Brantley, S.L., Megonigal, J.P., Scatena, F.N., Balogh-Brunstad, Z., Barnes, R.T., Bruns, M.A., Van Cappellen, P., 2011. Twelve testable hypotheses on the geobiology of weathering. *Geobiology* 9, 140–165.
- Brunet, M., Guy, F., Pilbeam, D., others, a., 2002. A new hominid from the Upper Miocene of Chad, Central Africa. *Nature* 418, 145–151.
- Bunn, H.T., Gurtov, A.N., 2014. Prey mortality profiles indicate that Early Pleistocene Homo at Olduvai was an ambush predator. *Quaternary International* 322–323, 44–53.
- Bunn, H.T., Kroll, E.M., 1986. Systematic butchery by Plio-Pleistocene hominids at Olduvai Gorge, Tanzania. *Current Anthropology* 27, 431–452.
- Chorover, J., Kretzschmar, R., Garcia-Pichel, F., Sparks, D.L., 2007. Soil biogeochemical processes within the Critical Zone. *Elements* 3, 321–326.
- Cronin, T.M., 2010. *Paleoclimates: understanding climate change past and present*. Columbia University Press, New York.
- Davis, L.G., Madsen, D.B., Becerra-Valdivia, L., Higham, T., Sisson, D.A., Skinner, S.A., Stueber, D., and 10 others, 2019. Late Upper Paleolithic occupation at Cooper's Ferry, Idaho, USA, ~16,000 years ago. *Science* 365, 891–897.
- Deino, A.L., 2012. <sup>40</sup>Ar/<sup>39</sup>Ar dating of Bed I, Olduvai Gorge, Tanzania, and the chronology of early Pleistocene climate change. *Journal of Human Evolution* 63, 251–273.
- DeMenocal, P., 2011. Climate and human evolution. *Science* 331, 540–542.
- Denton, G.H., Anderson, R.F., Toggweiler, J.R., Edwards, R.L., Schaefer, J.M., Putnam, A.E., 2010. The last glacial termination. *Science* 328, 1652–1656.
- Derry, L.A., Chadwick, O.A., 2007. Contributions from Earth's atmosphere to soil. *Elements* 5, 333–338.
- Dillehay, T.D., Ocampo, C., Saavedra, J., Sawakuchi, A.O., Vega, R.M., Pino, M., Collins, M.B., and 7 others, 2015. New archaeological evidence for an early human presence at Monte Verde, Chile. *PLoS ONE* 10.
- Domínguez-Rodrigo, M., Bunn, H.T., Mabulla, A.Z.P., Ashley, G.M., Diez-Martín, F., Barboni, D., Prendergast, M.E., Yravedra, J., Barba, R., Sanchez, A., Baquedano, E., Pickering, T.R., 2010. New excavations at FLK Zinjanthropus site and their relevance to origins of human behavior. *Quaternary Research* 74, 315–332.
- Driese, S.G., Ashley, G.M., 2016. Paleoenvironmental reconstruction of a paleosol catena, the Zinj archeological level, Olduvai Gorge, Tanzania. *Quaternary Research* 85, 133–146.



- European Space Agency, 2019. Rosetta's target: comet 67P/Churyumov-Gerasimenko.
- Fan, Y., 2015. Groundwater in the Earth's critical zone: Relevance to large-scale patterns and processes. *Water Resources Research* 51, 3051–3069.
- Faure, H., Walter, R.C., Grant, D.R., 2002. The coastal oasis: ice age springs on emerged continental shelves. *Global and Planetary Change* 33, 47–56.
- Ferraro, J.V., Hoggarth, J.A., Zori, D., Binetti, K.M., Stinchcomb, G.E., 2018. Integrating human activities, archaeology, and the Paleo-Critical Zone paradigm. *Frontiers in Earth Science* 6.
- Fleagle, J.G., Shea, J.J., Grine, F.E., Baden, A.L., Leakey, R.E., 2010. *Out of Africa I: The First Hominin Colonization of Eurasia, Vertebrate Paleobiology and Paleoanthropology*. Springer Netherlands, p. 294.
- Frostick, L.E., 1997. The East African rift basins, in: Selley, R.C. (Ed.), *African Basins: Sedimentary Basins of the World*. Elsevier Science, Amsterdam, pp. 187–209.
- Gawthorpe, R.L., Leeder, M.R., 2000. Tectono-sedimentary evolution of active extensional basins. *Basin Research* 12, 195–218.
- Gilbert, M.T.P., Jenkins, D.L., Gotherstrom, A., Naveran, N., Sanchez, J.J., Hofreiter, M., Thomsen, P.F., and 6 others. 2008. DNA from pre-Clovis human coprolites in Oregon, North America. *Science* 320, 786–789.
- Goebel, T., Waters, M.R., O'Rourke, D.H., 2008. The Late Pleistocene dispersal of modern humans in the Americas. *Science* 319, 1497–1502.
- Grine, F.E., 1988. Evolutionary history of the “robust” Australopithecines : a summary and historical perspective, in: Grine, F.E. (Ed.), *Evolutionary History of the “Robust” Australopithecines*. Aldine de Gruyter, New York, pp. 509–520.
- Grotzinger, J.P., Hayes, A.G., Lamb, M.P., McLennan, S.M., 2013. Sedimentary processes on Earth, Mars, Titan, and Venus, in: Mackwell, S.J., Simon-Miller, A.A., Harder, J.W., Bullock, M.A. (Eds.), *Comparative Climatology of Terrestrial Planets*. Univ. of Arizona Press, Tucson, pp. 439–472.
- Gugliotta, G., 2008. The Great Human Migration, *Smithsonian Magazine*, p. 6.
- Imbrie, J., Imbrie, K.P., 1986. *Ice Ages: Solving the Mystery*. Harvard University Press., Cambridge.
- Jenkins, D.L., Davis, L.G., Stafford, T.W.J., Campos, P.F., B., H., Jones, G.T., Cummings, L.S., and 13 others, 2012. Clovis age Western Stemmed projectile points and human coprolites at the Paisley Caves. *Science* 337, 223–228.
- Karafet, T.M., Zegura, S.L., Hammer, M.F., 2006. Y chromosomes, in: Ubelaker, D.H. (Ed.), *Environment, Origins, and Population*. Smithsonian Institution Press, Washington, DC, pp. 831–839.
- Kargel, J.S., 2004. *Mars: A warmer, wetter planet*. Springer Science & Business Media, Berlin.
- Kieniewicz, J.M., Smith, J.R., 2009. Paleoenvironmental reconstruction and water balance of a mid-Pleistocene pluvial lake, Dakhleh Oasis, Egypt. *Geological Society of America Bulletin* 121, 1154–1171.
- Kullmer, O., 2015. *Geological Background of Early Hominid Sites in Africa*. Springer, Berlin.
- Leakey, L.S.B., 1959. A new fossil skull from Olduvai. *Nature* 184, 491–493.
- Leakey, M.D., 1971. *Olduvai Gorge: excavations in Beds I and II; 1960–1963*. Cambridge University Press, Cambridge, UK.
- Li, H., Li, C., Ran, S., Feng, J., Zuo, W., 2015. *Applications of surface penetrating radar for Mars Exploration, American Geophysical Union*. AGU, San Francisco, pp. P51C-2077.
- Lin, H., 2010. Earth's critical zone and hydrogeology: concepts, characteristics and advances. *Hydrological Earth System Science* 14, 25–45.
- Lin, H., Bouma, J., Pachepsky, Y., Western, A., Thompson, J., van Genuchten, R., Vogel, H.J., 2006. Hydrogeology: Synergistic integration of pedology and hydrology. *Water Resources Research* 42, W05301.
- Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic  $\delta^{18}O$  records. *Paleoceanography* 20, 2–17.
- Lowe, J.J., Walker, M.J.C., 2015. *Reconstruction Quaternary Environments*, 3rd Edition. Routledge, London.
- Lukens, W.E., Lehmann, T., Peppe, D.J., Fox, D.L., Driese, S.G., McNulty, K.P., 2017. The Early Miocene Critical Zone at Karungu, Western Kenya: An equatorial, open habitat with few primate remains. *Frontiers in Earth Science* 5.
- Magill, C.R., Ashley, G.M., Domínguez-Rodrigo, M., Freeman, K.H., 2016. Dietary options and behavior suggested by plant biomarker evidence in an early human habitat. *Proceedings of the National Academy of Sciences* 113, 2874–2879.
- Mandel, R.D., 2008. Buried paleoindian-age landscapes in stream valleys of the central plains, USA. *Geomorphology* 101, 342–361.
- Mandel, R.D., Jacob, J.S., Nordt, L.C., 2007. Geoarchaeology of the Richard Beene Site, in: Thoms, A.V., Mandel, R.D. (Eds.), *Archaeological and Paleoecological Investigations at the Richard Beene Site (41BX831), South Central Texas*. Texas A&M University, College Station, Texas., pp. 27–60.
- Mandel, R.D., Thoms, A.V., Nordt, L.C., Jacob, J.S., 2018. Geoarchaeology and paleoecology of the deeply stratified Richard Beene site, Medina River valley, South-Central Texas, USA. *Quaternary International* 463, 176–197.
- Meltzer, D.J., 2009. *First Peoples in a New World*. University of California Press, Berkeley.
- Merriwether, D.A., 2006. Mitochondrial DNA, in: Ubelaker, D.H. (Ed.), *Environment, Origins, and Population*. Smithsonian Institution Press, Washington, DC, pp. 817–830.
- Molnar, P., Anderson, R.S., Anderson, S.P., 2007. Tectonics, fracturing of rock, and erosion. *Journal of Geophysical Research: Earth Surface* 112(F3014), 1–12.
- Morbiddelli, A., Lunine, J.I., O'Brien, D.P., Raymond, S.N., Walsh, K.J., 2012. Building terrestrial planets. *Annual Review of Earth and Planetary Sciences* 40, 251–275.
- Nordt, L.C., Boutton, T.W., Jacob, J.S., Mandel, R.D., 2002. C4 plant productivity and climate-CO2 variations in south-central Texas during the late Quaternary. *Quaternary Research* 58, 182–188.
- Nordt, L.C., Driese, S.G., 2013. Application of the Critical Zone concept to the deep-time sedimentary record. *The Sedimentary Record* 11, 4–9.
- Nordt, L.C., Hallmark, C.T., Driese, S.G., Dworkin, S.I., Atchley, S.C., 2012. Biogeochemical characterization of a lithified paleosol: Implications for the interpretation of ancient Critical Zones. *Geochimica et Cosmochimica Acta* 87, 267–282.
- NRC, 2001. *Basic research opportunities in Earth science*. National Research Council, Washington, DC, p. 154.
- NRC, 2010. *Understanding climate's influence on human evolution*. National Research Council, Washington, DC, p. 115.
- Potts, R., 1996. Evolution and climate variability. *Science* 273, 922–923.
- Retallack, G.J., 2001. *Soils of the Past: An introduction to paleopedology*, 2nd ed. Blackwell Science, Oxford.

- Retallack, G.J., 2014. Paleosols and paleoenvironments of early Mars. *Geology* 42, 755–758.
- Riebe, C.S., Jesse Hahm, W.J., Brantley, S.L., 2017. Controls on deep critical zone architecture: a historical review and four testable hypotheses. *Earth Surface Processes and Landforms* 42, 128–156.
- Ruddiman, W.F., 2000. *Earth's Climate, Past and Future*. W.H. Freeman and Co., New York.
- Ruddiman, W.F., 2005. *Plows, plagues, and petroleum: how humans took control of climate*. Princeton University Press, Princeton, NJ.
- Shultz, S., Maslin, M., 2013. Early human speciation, brain expansion and dispersal influenced by African climate pulses. *PLoS ONE* 8.
- Stinchcomb, G.E., Beverly, E.J., 2019. Editorial: The role of the Paleo-Critical Zone in shaping Quaternary hominin evolution. *Frontiers in Earth Science* 7.
- Stuart, A.J., 1991. Mammalian extinctions in the Late Pleistocene of northern Eurasia and North America. *Biological Review* 66, 453–562.
- Thoms, A.V., Clabaugh, P.A., 2011. The Archaic period at the Richard Beene site: six thousand years of hunter-gatherer family cookery in south-central North America. *Bulletin of the Texas Archaeological Society* 82, 77–115.
- Toner, J.D., Catling, D.C., Light, B., 2014. Soluble salts at the Phoenix Lander site, Mars: A reanalysis of the wet chemistry laboratory data. *Geochimica et Cosmochimica Acta* 136, 142–168.
- TRANSITIONS, 2012. The changing Earth-life system: critical Information for society from the deep past, NSF-SGP sponsored Workshop Report, Washington, DC, p. 63.
- Vaniman, D.T., Reedy, R., Heiken, G.H., Olhoeft, G., Mendel, W., Heiken, G.H., French, B.M., 1991. *The lunar environment, Lunar Sourcebook*. Cambridge University Press, New York, pp. 27–60.
- Vrba, E.S., Denton, G.H., Partridge, T.C., Burckle, L.H., 1996. *Paleoclimate and Evolution with Emphasis on Human Origins*. Yale University, New Haven, p. 547 + ix.
- Waters, M.R., 2019. Late Pleistocene exploration and settlement of the Americas by modern humans. *Science* 365, eaat5447.
- Waters, M.R., Keene, J.L., Forman, S.L., Prewitt, E.R., Carlson, D.L., Wiederhold, J.E., 2018. Pre-Clovis projectile points at the Debra L. Friedkin site, Texas -Implications for the Late Pleistocene peopling of the Americas. *Science Advances* 4.
- Wilding, L.P., Lin, H., 2003. Advancing the frontiers of soil science towards a geoscience, in: Lin, H., Bouma, J., Pachepsky, Y. (Eds.), *Hydropedology: Bridging disciplines, scales, and data*. Geoderma, Denver, CO, pp. 257–274.
- Wood, B., Richmond, B.G., 2000. Human evolution: taxonomy and paleobiology. *The Journal of Anatomy* 197, 19–60.
- Zalasiewicz, J., Williams, M., Haywood, A., Ellis, M., 2011. The Anthropocene: a new epoch of geological time? *Philosophical Transactions of the Royal Society A* 369, 835–841.
- Zech, M., 2006. Evidence for Late Pleistocene climate changes from buried soils on the southern slopes of Mt. Kilimanjaro, Tanzania. *Palaeogeography, Palaeoclimatology, Palaeoecology* 242, 303–312.