

PALEOSOL RECORDS OF MIDDLE MIOCENE CLIMATE CHANGE

by

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DISSERTATION ABSTRACT

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Doctor of Philosophy

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Title: Paleosol Records of Middle Miocene Climate Change

The middle Miocene thermal maximum (~16 Ma) was a period of global climate unusually warm and wet for the Neogene and is of interest as a paleo-analog for future climate change from anthropogenic global warming. In Australia, paleosols of the Oligocene-Miocene Etadunna and Pliocene Tirari Formations formed in arid palaeoclimates and include pedogenic gypsum. The Middle Miocene paleosol has shallow calcareous nodules and stout root traces suggesting vegetation like dry woodland. Comparable mallee vegetation now grows no closer than 1200 km to the southwest, so middle Miocene warm-wet climate enabled range extension of mallee and woody thickening of plants in the Australia outback. There is no evidence in the outback of middle Miocene rain forest, which may have expanded its range to form kaolinitic Ultisols near Sydney, Mudgee, and Gulgong, in New South Wales. Nor is there evidence so far inland of swamp woodlands and heaths like those producing brown coals in the Latrobe Valley, Victoria.

In Argentina, the Santa Cruz Formation, in addition to its rich fossil vertebrate assemblages, contains a similar paleosol record of middle Miocene climate change. The early Miocene in the Santa Cruz Formation is characterized by a thick sequence of weakly to strongly developed grassland paleosols (Orthents and Ustolls) as well as paleosols with root traces and profile forms of open shrubland vegetation (Cambid). The middle Miocene thermal maximum is characterized by paleosols (Udepts, Udalfs) developed under open woodland-shrubland vegetation, during a period of climatic warmth and humidity. The late middle Miocene is characterized by a greater diversity of

pedotypes, all suggestive of an arid and cooler environment (Argids, Cambids, and Ustepts).

Middle Miocene soil maps compiled for this study show extension of tropical soils (Oxisols, Ultisols) into northern and southern mid-latitudes, accompanied by thermophilic flora and fauna. Peats, lignites, and Histosols of wetlands are also more abundant at higher latitudes, especially in the northern hemisphere, during the middle Miocene. The expansion of such soils is an expected result of greater precipitation associated with higher water vapor content of a warmer atmosphere during the Middle Miocene.

This dissertation includes previously published co-authored material in chapter II.

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For M.S.F. and M.M.F

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CHAPTER I

INTRODUCTION: THE MIDDLE MIOCENE THERMAL MAXIMUM

In a recently released report, the Intergovernmental Panel on Climate Change concluded that the global warming occurring at present is “very likely” due to human-induced increased greenhouse gas emissions (Alley et al., 2007). Models and data suggest a 1.4 to 5.8 °C increase from current global mean temperature by the year 2100 (Alley et al., 2007). The middle Miocene thermal maximum was a period of past climate change similar in magnitude, both in its global geographic scale and the extrapolated magnitude of temperature change, to the change predicted to occur by the year 2100. Thus, it provides an analogue for understanding modern climate change. This study uses paleosols (ancient soils) to reconstruct the global paleolandscape during and after the climatic warming and to investigate ecosystem shifts due to the climate shift. Middle Miocene sediments are globally well-preserved, abundant, and well-dated radiometrically and biostratigraphically. The middle Miocene is ideal for comparison to current climate change because by the Miocene, the continents were close to their modern configuration. In this study, I outline the shifts that soil-mantled landscapes and biotic ecosystems could expect to undergo as a result of the predicted increase in global mean temperatures by anthropogenic warming.

Multiple lines of evidence from locations around the globe document the middle Miocene warm period, which is marked by an expansion of tropical biomes and taxa to northern and southern latitudinal extremes. This evidence shows the drastic environmental changes that can be a result of a relatively small climate change. Deep ocean waters were 6 °C warmer than present during the Middle Miocene as recorded by the isotopic signature of benthic foraminifera (Flower and Kennett, 1994; Lear et al., 2000; Zachos et al., 2001). During the middle Miocene, reef-building corals were common near the North Island of New Zealand (today having a cool, temperate climate), growing under warm subtropical and warm temperate climate conditions (Hornibrook, 1992). Tropical plants such as *Cocos* (coconut palm) were also present in New Zealand (Fleming, 1975). Japan’s forests were mesic, warm-temperate mixed conifer and

broadleaf (Heusser, 1992); exotic foraminifera, reef-building corals, and mangroves also extended as far north as Japan (Itoigawa and Yamanoi, 1990).

The following chapters present two new Middle Miocene paleosol studies in Australia (Chapter II) and Argentina (Chapter III) and new Middle Miocene soil and climate maps derived from the new and extant literature (Chapter IV). These sites covered were chosen because they were both previously unstudied from the perspective of paleosols. Previous studies (Australia: Stirton et al., 1961; Callen and Plane, 1986; Argentina: Bown and Fleagle, 1993) at both locations characterized the vertebrate paleontology, sedimentology, and geochronology, which provided a framework for the new studies presented in this dissertation.

The chapters to follow are:

Chapter II, “Paleosol record of Neogene climate change in the Australian Outback,” has been submitted and published in the *Australian Journal of Earth Sciences* (Metzger and Retallack, 2010). This material was co-authored with G. Retallack. The field work was completely jointly with G. Retallack. G. Retallack examined core samples. Geochemical and thin section data were analysed by me and G. Retallack. Paleoenvironmental reconstruction figures were drafted by G. Retallack, based on my analyses and interpretations. The manuscript was jointly prepared for publication by me and G. Retallack. This chapter presents new data from an area previously unstudied from a paleosol perspective.

Chapter III, “The paleosol record of middle Miocene climate change, Santa Cruz formation, Argentina,” will be submitted to the *Geological Society of America Bulletin* for publication. This chapter presents original content and new data from an area previously unstudied from a paleosol perspective.

Chapter IV, “Middle Miocene climate change: a synthesis of the global paleosol record and an analysis of its potential ramifications for understanding future

global warming” will be submitted to *Geological Society of America Bulletin* for publication. This paper incorporates the new data of chapters II and III, with the existing body of literature, into a synthesis of global Miocene change.

Chapter V, “Conclusions” summarizes the results of these studies.

CHAPTER II

PALAEOSOL RECORD OF NEOGENE CLIMATE CHANGE IN THE AUSTRALIAN OUTBACK

This work was published in volume 57 of the *Australian Journal of Earth Sciences* in 2010. This study was co-authored with G. Retallack. The field work was completely jointly with G. Retallack. G. Retallack examined core samples. Geochemical and thin section data were analysed by me and G. Retallack. Paleoenvironmental reconstruction figures were drafted by G. Retallack, based on my analyses and interpretations. The manuscript was jointly prepared for publication by me and G. Retallack. This chapter presents new data from an area previously unstudied from a paleosol perspective.

INTRODUCTION

The middle Miocene thermal maximum was a period of past climate change similar in its global geographic scale and the extrapolated magnitude of temperature change to the change predicted to occur by the year 2100 (Alley et al. 2007; Retallack 2009). For example, benthic foraminiferal oxygen isotope records (Fig. 2.1) reveal that middle Miocene deep ocean waters were 6 °C warmer than present (Flower & Kennett 1994; Lear et al. 2000). Cooling from 15 Ma onwards coincided with the onset of glaciation in Antarctica (Zachos et al. 2001). As another example, palaeosol records in central Oregon, USA (Fig. 2.1), are evidence of palaeotemperatures peaking at 15 ± 4.4 °C and mean annual precipitation of as much as 1096 ± 181 mm (Retallack 2007a, 2008a), compared with 9.2 °C and 340 mm, respectively, now in John Day, Oregon (Taylor 2005). The middle Miocene thermal maximum is characterized globally by extension of thermophilic plant and animal taxa to high palaeolatitudes (Christensen 1975; Bestland et al. 2008; Blisniuk et al. 2005; Bown & Fleagle 1993; Wolfe 1994).

In the Australian outback, the magnitude of this global climatic change has proven controversial. Fossil mammal assemblages at Riversleigh, Queensland, have been used as evidence of middle Miocene rainforest expansion into the desert (Archer et al. 1991), although such dramatic transformation of the Australian outback has been

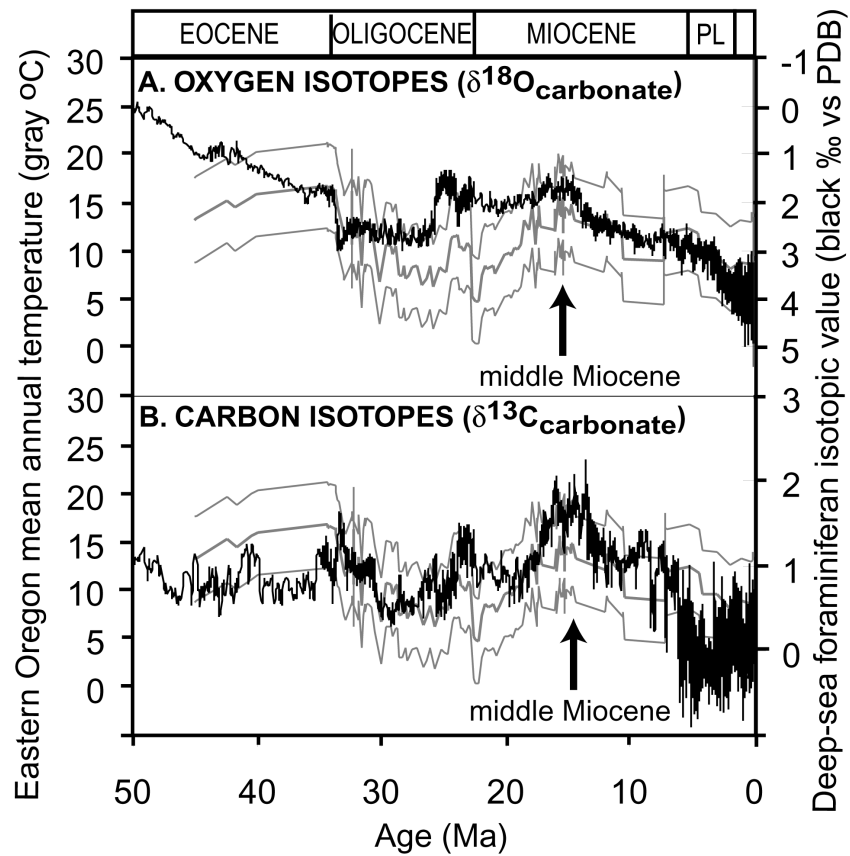


Figure 2.1. Middle Miocene (16 Ma) thermal maximum from palaeosols in Oregon (gray after Retallack 2007a, 2008a), and from oxygen (A) and carbon (B) isotopic composition of foraminifera in the Southern Ocean (after Zachos et al. 2001).

disputed (Megirian et al. 2004). The differences between soils of rainforest (Ultisols, Oxisols), woodland (Alfisols) and desert (Aridisols) are profound (Retallack 1997), and this study of palaeosols is thus a test of these conflicting reconstructions of Miocene vegetation and palaeoclimate in central Australia.

In northern South Australia, Cenozoic sediments around the Lake Eyre basin, an extensive network of ephemeral salt-pan lakes (Fig. 2.2), are famous for fossil vertebrates (Stirton et al. 1961, 1967; Woodburne & Tedford 1975; Williams 1976; Vickers-Rich 1979; Wells & Callen 1986; Woodburne et al. 1993). Oligocene-Pliocene sediments are best exposed and most easily accessed at Lake Palankarinna, located at the southern extent of the Tirari Desert, surrounded by northwest-striking sand dunes. Lake Palankarinna is one of the most productive Australian localities for mammal fossils, and its sequence of fluvatile-lacustrine sediments has been previously dated by palaeomagnetism, palynology, biostratigraphy, and radiometric dating (Woodburne et al. 1993), although its palaeosols have not been studied until now.

This study presents new work on the palaeosols from Lake Palankarinna that provides an understanding of landscape and ecosystem evolution during middle Miocene climate change in the Australian outback. Woody thickening has already been documented during 20th century warmer and wetter conditions in central Queensland (Krull et al. 2004), and our results provide a model for projected changes in ecosystems of inland Australia with continued climatic warming.

MATERIALS AND METHODS

Palaeosols were described and sampled during August 2006 within vertical stratigraphic sections in badlands at S28.76296°, E138.40215°, including the best-known fossil quarry at Mammalon Hill (Fig. 2.3). In addition, a palaeosol was sampled in the Mampuwordu Sand 100 m south of Mammalon Hill in Lawson's quarry (S28.763240°, E138.401784°). Field descriptions included Munsell colour (Munsell 1975), grain size, soil structure, horizonation, horizon boundaries, and the presence of other soil features such as root traces, nodules, animal or insect burrows, or fossils. Thickness of the calcic (Bk) or gypsic (By) horizon and depth to carbonate or gypsum nodules were measured. Detailed stratigraphic sections were also drafted in the field (Fig. 2.4). Palaeosols were

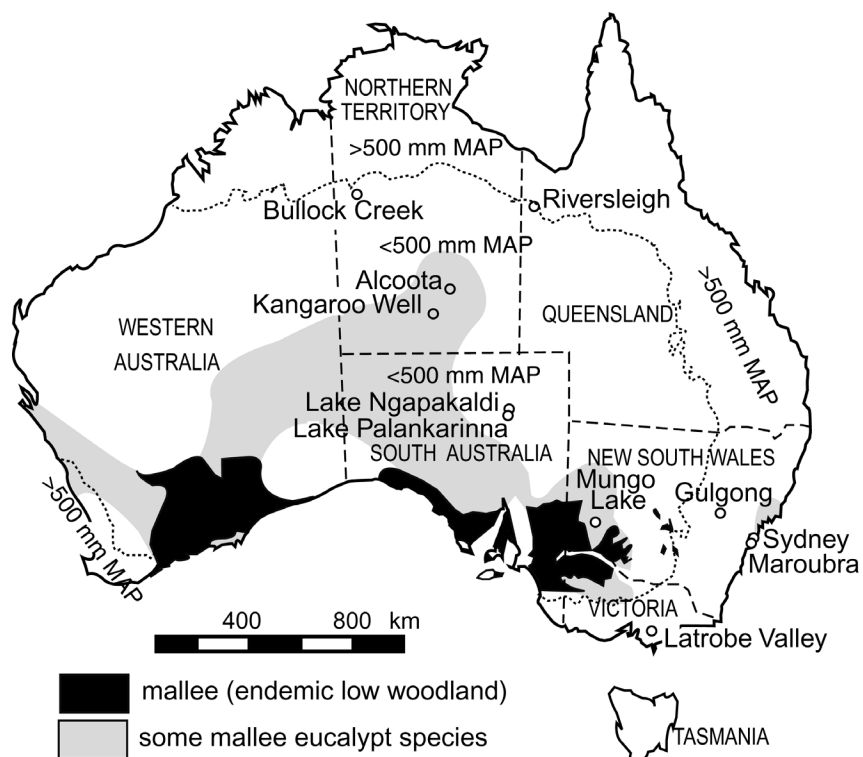


Figure 2.2. Location of Lakes Palankarinna and Ngapakaldi, and mentioned fossil mammal sites in central Australia, with the modern distribution of mallee vegetation and mallee species, distinctive Australian aridland trees (after Hill 1989). Also shown is the 500 mm isohyet (mean annual precipitation, dotted) separating the dry outback from humid coastal regions (www.bom.gov.au, accessed 4 Nov. 2009).

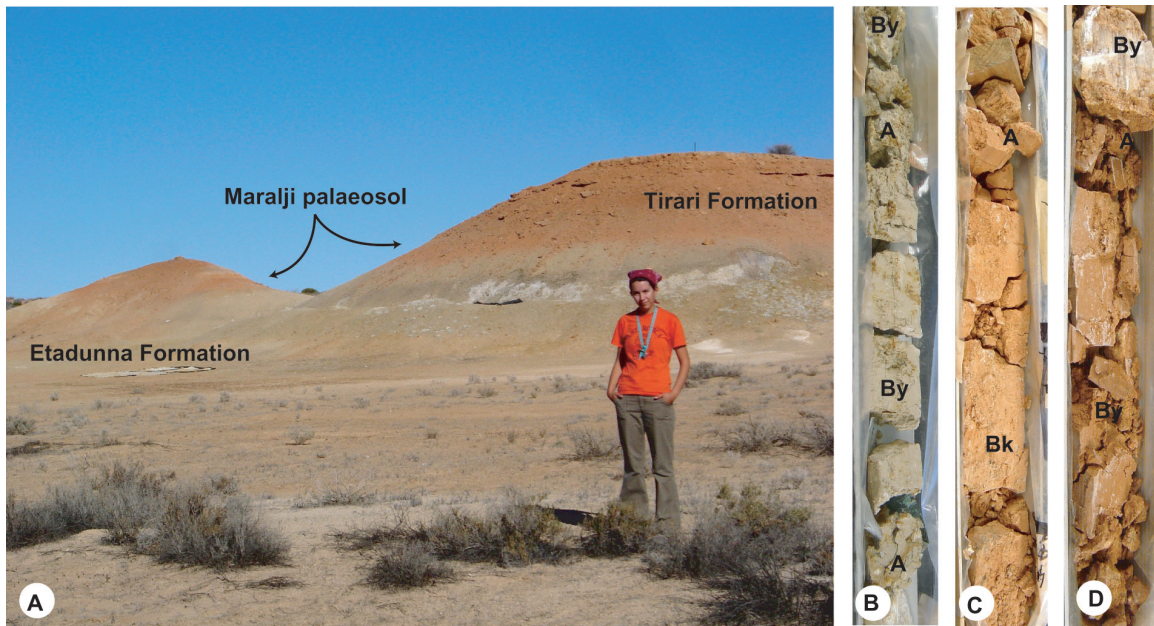


Figure 2.3. Field photograph of Mammalon Hill (left) from the east (A), with palaeosols observed in Palankarinna-2 core (B-D), including Kaldri pedotype at 8.1 m (B), Maralji pedotype at 4.3 m (C) and Chindina pedotype at 2.4 m (D).

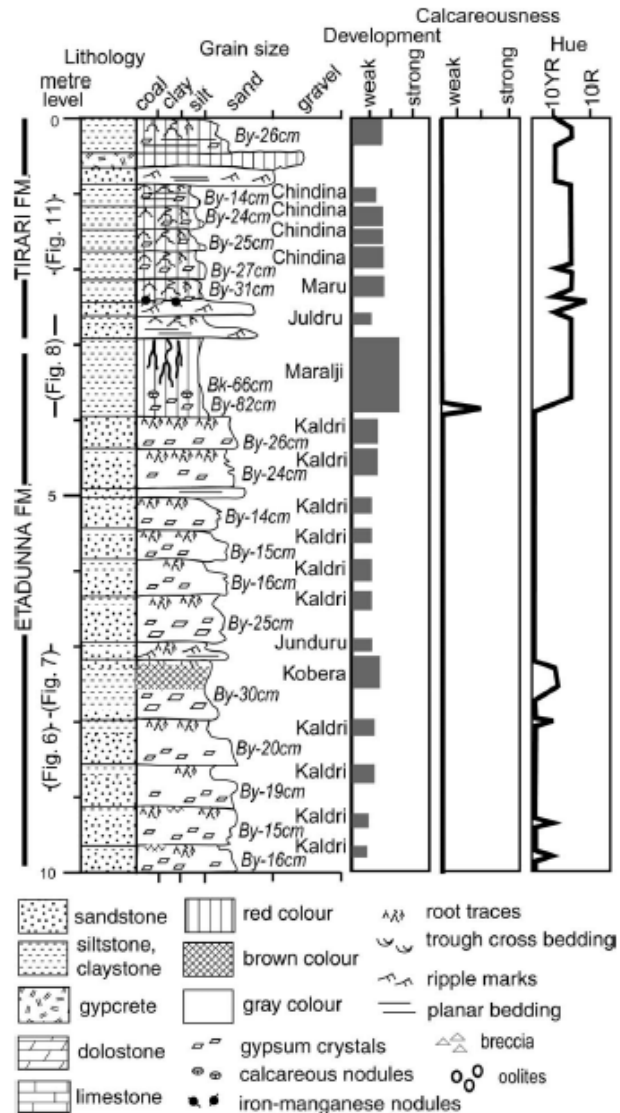


Figure 2.4. Measured section of palaeosols in outcrop at Mammalon Hill, northeast Lake Palankarinna, South Australia. Location of palaeosols is indicated by black boxes whose width corresponds to degree of development inferred by pedogenic destruction of bedding according to a scale devised by Retallack (1997). Calcreousness is from degree of reaction with dilute hydrochloric acid and hue from a Munsell Chart.

classified into groups using the pedotype approach (Retallack 2001) which characterizes different palaeosol types using field criteria. Descriptive names were given to each pedotype from the local Dieri language (Schoknecht & Schoknecht 1997). Naming conventions for the palaeosols in this study follow USDA Soil Survey (Soil Survey Staff 2000) nomenclature to soil-order level as well as the Australian soil nomenclature (Isbell 1998). A 35 m-section of drill-core (BMR Palankarinna-2) was examined, described, and sampled at Geoscience Australia, in Canberra in September 2006 (Fig. 2.5). The very close correspondence of these sections is unsurprising considering that the drill site on the nearby plateau at S28.76055°, E138.402070° is only 75 m northeast of the badlands outcrop sampled. The core was very helpful in revealing the nature of palaeosols at depth, unencrusted with gypsum common in outcrop.

Samples were collected from every horizon within a type section for each pedotype for geochemical analysis of major and trace elements and analyzed XRF at ALS Chemex in Vancouver, BC, Canada against BC Canada granodioritic stream gravel standard SDMS-2. Also analyzed were organic carbon using Walkely-Black titration (these values were all very low) and carbonate by gravimetry after acid digestion. Major element chemical composition is useful for investigating geochemical processes active during soil formation. Molecular weathering ratios, calculated from the weight percent of an element in its oxide form divided by its molecular weight, are commonly used as proxies of compositional changes in a rock or soil due to weathering (Marbut 1935). These ratios can illuminate the dominant chemical reactions at work in a soil, such as hydration, oxidation, and leaching (Retallack 1997, 2001), and are also useful as palaeoclimatic proxies (Table 2.1). Some widely used geochemical climofunctions based on North American soils (Sheldon et al. 2002; Sheldon & Tabor 2009) were not pursued here because of unreasonable calculated values: for example, near freezing temperatures in Oligocene palaeosols containing fossil crocodiles (Kobera pedotype). Australia-specific soil climofunctions are not available and may be needed, because high soda is a feature that sets these and many Australian soils apart from North American soils (McKenzie et al. 2004). There is also the possibility of inherited little-weathered clay from central Australian Neoproterozoic, Permian, and Cretaceous glacial deposits (Alley & Frakes 2003), and Paleogene bauxites and laterites (Firman 1994).

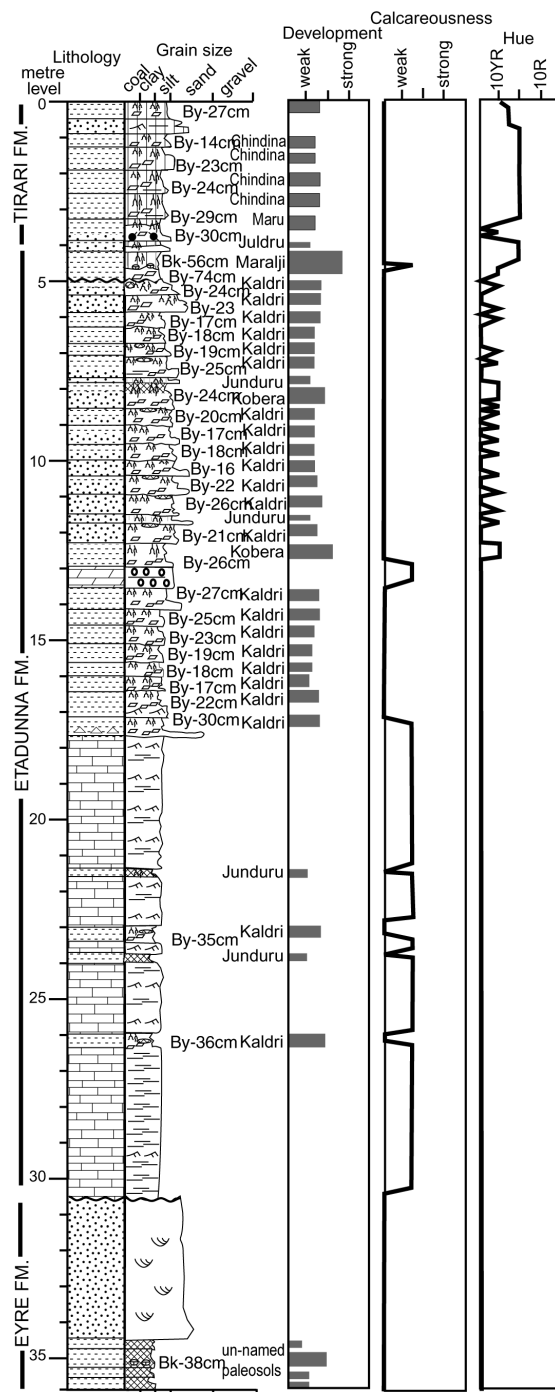


Figure 2.5. Measured section of palaeosols in BMR Palankarinna-2 core, South Australia. Location of palaeosols is indicated by black boxes whose width corresponds to degree of development inferred by pedogenic destruction of bedding according to a scale devised by Retallack (1997). Calcareousness is from degree of reaction with dilute hydrochloric acid and hue from a Munsell Chart.

No.	Independent variable	Dependent variable	Equation	R ²	Standard Error	Reference
1	Geological age (A in Ma)	Stratigraphic level in Palankarinna core (L in m)	$A=0.1168L+23.023$	0.98	± 0.35 Ma	Herein
2	Mean annual precipitation (P in mm)	Depth to salts (Dy in cm)	$P=58.53e^{0.0237Dy}$	0.99	± 14 mm	Dan & Yaalon 1982
3	Radiocarbon-age (K in ka)	Calcareous nodule diameter (M in cm)	$K=1.79M^{0.34}$	0.57	± 1.8 ka	Retallack 2005
4	Mean annual precipitation (P in mm)	Depth to Bk horizon (Dk in cm)	$P=137.24+6.45Dk+0.013Dk^2$	0.52	± 147 mm	Retallack 2005
5	Mean annual range of precipitation = difference between wettest and driest month precipitation (S in mm)	Thickness (H in cm) of calcareous nodular horizon (Bk)	$S=0.79H+13.7$	0.58	± 22 mm	Retallack 2005

Table 2.1. Transfer functions used for interpretation of Lake Palankarinna palaeosols

Oriented rock samples were collected from each diagnostic soil horizon for petrographic thin sections, prepared under kerosene and with resin encasement needed for fractured smectitic clays (Tate & Retallack 1995). The thin sections were then observed under a petrographic microscope to examine soil microfabrics (Brewer 1976; FitzPatrick 1993; Retallack 1997), genetic soil features, and mineralogy, as well as to obtain accurate grain size and mineral distributions by point counting using a Swift automated point counter and stage.

Sample numbers and raw geochemical and petrographic data are tabulated in Appendix A. Also tabulated there are measured Bk and By depths from these and other Australian Cenozoic palaeosol sequences examined in reconnaissance fashion (Fig. 2.2), including Kangaroo Well (Megirian et al. 2004: should be regarded as early Miocene confirming Rich et al., 1991; Long et al. 2002), Alcoota (Megirian et al. 1996), and Mungo Lake (Hope 1978).

GEOLOGICAL SETTING AND AGE

The oldest unit exposed around Lake Palankarinna and in Palankarinna-2 core is the Paleocene-Eocene Eyre Formation, which is disconformably overlain by the Oligocene-Miocene Etadunna Formation (Table 2.2). The late Miocene Mampuwordu Sands, filling a palaeochannel, are incised into the uppermost Etadunna Formation and overlain by the Pliocene Tirari Formation. The Tirari Formation is unconformably overlain by the Pleistocene Kutjitarra Formation and Katipiri Sands (Tedford et al. 1986; Woodburne et al. 1993).

Etadunna Formation pollen species, including samples from Mammalon Hill, are also known from the marine, early-middle Miocene Geera Clay of the Murray Basin (Johns & Ludbrook 1963; Truswell & Harris 1982), but magnetostratigraphic and biostratigraphic correlations suggests that the Etadunna Formation is late Oligocene (Woodburne et al. 1993). Pollen (Alley and Pledge 1990) and megafossil plants (Greenwood et al. 1990) from the upper Etadunna Formation, like those of the correlative and nearby upper Namba Formation (Martin 1994), lack humid forest elements such as *Nothofagus* and podocarps found in the lower Etadunna Formation and Eyre Formation. The foraminifer *Buliminoides chattonensis* at ~30 m in the Etadunna Formation in

Formation	Description	Mammal local faunas	Geological age
Katapiri Sands	Cross-bedded white quartz sand	Malkuni, Madigan Gulf, Price Peninsula, Kalamurina	Late Pleistocene
Kutjitarra Formation	Red gypsiferous claystones and sandstones	Keekalana, Lower Cooper	Early Pleistocene
Tirari Formation	Red sandstones and claystones with gypsum beds	Kanunka, Toolapinna	Late Pliocene
Mampuworudu Sands	Cross-bedded white to red quartz sand	Palankarinna	Early Pliocene
Wipajiri Formation	White quartz sand and gray shale	Kutjamarpu	Middle Miocene
Etadunna Formation	Gray dolomitic marls and shales	Ngama , Ngapakaldi, Dijimanka	Late Oligocene
Eyre Formation	Red claystones and silcretized sandstones		Palaeocene

Table 2.2. Stratigraphic formations and their geological ages near Lake Palankarinna (After Tedford et al., 1986; Woodburne et al., 1993).

Palankarina-2 core (Lindsay 1967) has a well calibrated age range within the marine Duntroonian Stage (25.2-27.3 Ma) of New Zealand (Cooper 2004). Illite of the lower Etadunna Formation at Moralina Station, equivalent to the ~26.5 m level in the Palankarina-2 core (Callen and Plane 1986), has a Rb-Sr age of 25 Ma (Norrish & Pickering 1983). These foraminiferal and radiometric constraints provide lower tie-points for the age-model used in this study, based on the best correlation (highest R^2) between stratigraphic levels of magnetic reversals in the Etadunna Formation and the known geological age of reversals (Fig. 2.6) from late Oligocene to middle Miocene (Ogg and Smith, 2004), not available at the time of the original palaeomagnetic work (Woodburne et al. 1993).

The best-fit age-model (Table 2.1) for the Etadunna Formation palaeomagnetic data gives geological age (A in Ma) for stratigraphic levels in BMR Palankarina-2 core (L in m). This age model yields an age range of late Oligocene, or 26.1-23.6 Ma for the Etadunna Formation, with the uppermost part almost Miocene, rather than 24.2-25.7 Ma of Woodburne et al. (1993). This extension of the age of the Etadunna Formation to the Oligocene-Miocene boundary also indicates that the Ulta Limestone and its Kangaroo Well local fauna of the Northern Territory, an evolutionary intermediate between the Ngama and Kutjamarpu faunas (Megirian et al. 2004), is more likely early Miocene than late Oligocene, as was previously proposed by Long et al. (2002).

The Kutjamarpu local fauna in the Wipajiri Formation east of Lake Ngapakaldi north of Lake Palankarina (Stirton et al. 1961, 1967) is middle Miocene (ca. 16 Ma), based on biostratigraphic correlation with the famous mammal faunas of the Riversleigh cave deposits (Archer et al. 1991; Travouillon et al., 2009). The Wipajiri Formation does not extend as far south as Lake Palankarina, but fills palaeochannels incised into the top of the Etadunna Formation at the same stratigraphic level as the Maralji palaeosol at Mammalon Hill. The Maralji palaeosol is palaeomagnetically normal (Woodburne et al. 1993), but which of the many short-lived middle Miocene normals (Ogg & Smith 2004) is unconstrained.

Incised into the Maralji palaeosol are palaeochannels of the Mampuwordu Sands containing the Palankarina local fauna (Stirton et al. 1961, 1967) and capped by the Dantu pedotype palaeosol. The Palankarina local fauna in Lawson's quarry 100 m south

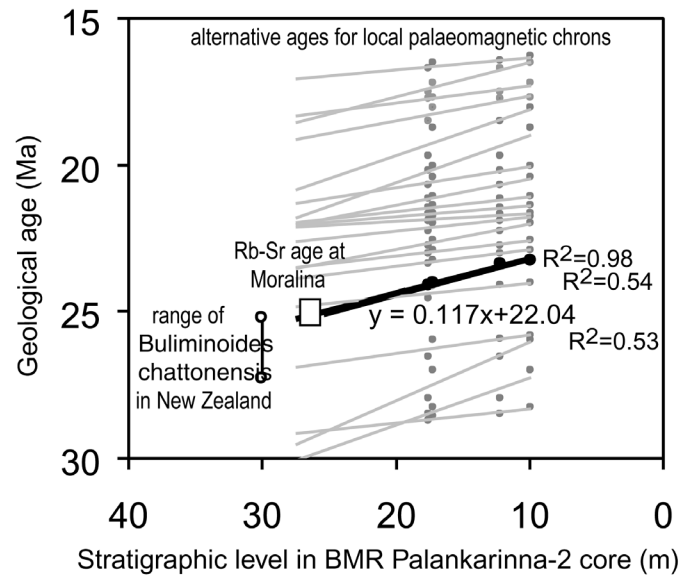


Figure 2.6. Selected age model (equation) for Etadunna Formation from best fit between local palaeomagnetic reversal levels of Woodburne et al. (1993) and the international geomagnetic time scale (Ogg & Smith 2004), and also extrapolating back to levels of a radiometric date and the known range of a foraminifer found in the BMR Palankarinna-2 core.

of Mammalon Hill has *Zygomaturus* more primitive than Pleistocene, but more derived than late Miocene (such as at Alcoota), and shares *Prionotemnus* with the Kanunka fauna, so the Mampuwordu Sands have been considered a member of the basal Tirari Formation (Stirton et al. 1961; Rich et al. 1991). Thus, the Tirari Formation is probably Pliocene (4-2.5 Ma). In the upper Tirari Formation, the Kanunka fauna is within the magnetically reversed Matuyama chron (Tedford et al. 1986), just above the Gauss chron and so late Pliocene (<2.59 Ma; Ogg & Smith 2004). The Kanunka fauna predates late Pleistocene (ca. 45 Ka) megafaunal extinctions (Hope 1978; Prideaux et al. 2007).

PALAEOSOLS

At Mammalon Hill, eight distinctly different kinds of palaeosols (pedotypes) within ten meters of exposed section were described, sampled, and logged (Fig. 2.4). Each pedotype is based on a type profile, sampled in more detail for chemical and petrographic analysis. The same eight pedotypes were found in the drill core, where a total of 35 m of section was described and logged, extending down to additional new pedotypes in the Eyre Formation, beyond the scope of this study (Fig. 2.5). Table 2.3 details diagnostic features and classification of the pedotypes, and Table 2.4 summarizes interpreted soil-forming factors of organisms, topography, parent material, and time.

Kaldri (Fig. 2.7), Junduru, and Kobera (Fig. 2.8) pedotypes are found within the uppermost Etadunna Formation at Mammalon Hill. The Ngama local mammal fauna (Tedford et al. 1986; Woodburne et al. 1993) is found throughout this portion of the Etadunna Formation, but the principal fossil quarry is in the Kobera pedotype at 7.3 m (Fig. 2.4). The Kaldri pedotype is the most common pedotype found in outcrop and core of the Etadunna Formation (Figs. 2.4-2.5). Kaldri soils are weakly developed, with small root traces and gypsic horizons, with little variation down profile in molecular weathering ratios within the pedotype section, but elevated Na₂O/K₂O ratios. The Kobera pedotype is distinguished by its brown A horizon and brown B horizon with significant gypsum accumulation at depth. The Junduru pedotype is a weakly developed, silty-sandy palaeosol with relict bedding and ripple marks.

The unconformable contact of the Etadunna with the overlying Tirari Formation is marked by a distinctive bright red palaeolandscape surface, the Maralji pedotype

Pedotype (meaning)	Diagnosis	Food & Agriculture Organization (1974, 1978)	US taxonomy (Soil Survey Staff 2000)	Old Australian (Stace et al. 1968; McKenzie et al., 2004)	New Australian (Isbell 1998; McKenzie et al. 2004)
Kaldri (salty)	Grey (5Y 6/1) thin clayey surface (A) over shallow gypsum (By <25 cm depth)	Gleyic Solonchak	Salid	Grey clay	Salic Hydrosol
Kobera (root)	Brown (7.5YR 5/6) surface (A) over shallow gypsum (By <34 cm)	Mollic Solonchak	Salid	Brown clay	Salic Hydrosol
Junduru (clay)	Dark olive grey (5Y 3/2) laminated clay (A) over sand (C)	Eutric Fluvisol	Fluvent	Alluvial soil	Stratic Rudosol
Maralji (red)	Reddish brown (5YR 5/4) clayey surface (A) over caliche (Bk at 66 cm depth) and gypsum (By at 82 cm)	Calcic Xerosol	Calcic	Calcareous red earth	Calcic Calcarosol
Dantu (soft)	Reddish brown (5YR 5/6) A over clayey Bw	Calcic Cambisol	Ochrept	Red earth	Orthic Tenosol
Chindina (soft)	Yellowish red (5Y 4/6) clayey surface (A) over gypsum (By at 12 to 29 cm depth)	Orthic Solonchak	Salid	Red clay	Red Dermosol
Maru (black)	Yellowish red (5Y 4/6) clayey surface over gypsum (By at 31 cm depth) with black Fe-Mn nodules and stains	Gleyic Solonchak	Salid	Grey clay	Red Dermosol
Juldru (narrow)	Laminated red (2.5YR 5/6) clay (A) over sand (C)	Eutric Fluvisol	Fluvent	Alluvial soil	Stratic Rudosol

Table 2.3. Lake Palankarinna pedotypes and classification

Pedotype (meaning)	Climate	Vegetation	Animals	Topography	Parent Material	Time (ka)
Kaldri (salty)	Arid ($85-137 \pm 14$ mm MAP), cool temperate	Halophytic shrubs	Uncertain	Saline lake margin	Dolomitic clay	~2
Kobera (root)	Arid ($103-108 \pm 14$ mm MAP), cool temperate	Halophytic shrubs	Ngama fauna (<i>Neohe- los, Nambaroo</i>)	Well-drained flood- plain by saline lake	Dolomitic clay	~2
Junduru (clay)	not diagnostic	Early successional wetland	Uncertain	Streamside wetland	Clay and quartz sand	~0.005- 0.1
Maralji (red)	Subhumid (506 ± 147 mm MAP), warm temperate, weak seasonality	Dry woodland (high mallee)	Kutjamarpu fauna (<i>Balbaroo, Neohelos</i>)	Well-drained flood- plain	Clay and quartz sand	2.3 ± 1.8
Dantu (soft)	Semiarid (401 ± 147 mm MAP), warm temperate, weak seasonality	Dry woodland (low mallee)	Palankarinna l.f. (<i>Pri- onotemnus, Meniscolo- phus</i>)	Well-drained fluvial levee	Clay and quartz sand	~1
Chindina (soft)	Arid ($86-116 \pm 14$ mm MAP), warm temperate	Similar to mulga and blue- brush scrub	Kanunka fauna (<i>Thy- lacoaleo, Macropus</i>)	Dry well-drained floodplain	Clay and quartz sand	~2
Maru (black)	Arid (122 ± 14 mm MAP), warm temperate	Similar to mulga and blue- brush scrub	Uncertain	Dry well-drained floodplain	Clay and quartz sand	~2
Juldru (narrow)	not diagnostic	Early successional riparian	Uncertain	Streamside levee	Clay and quartz sand	~0.005- 0.1

Table 2.4. Lake Palankarinna palaeosol interpretations

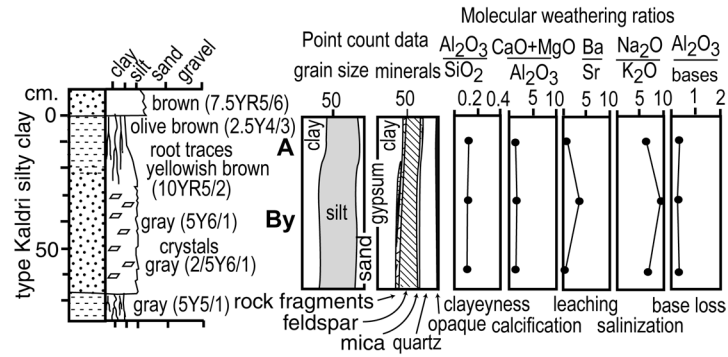


Figure 2.7. Field, petrographic, and geochemical data for the late Oligocene Kaldri pedotype of the upper Etadunna Formation in outcrop near Mammalon Hill, Lake Palankarinna (2.0 m in Fig. 2.3)

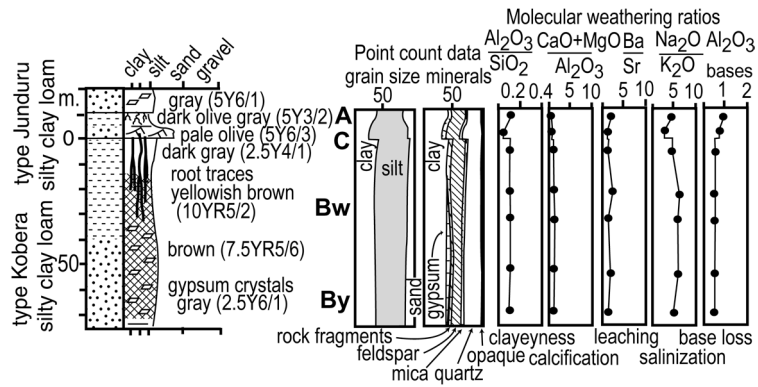


Figure 2.8. Field, petrographic, and geochemical data for the late Oligocene Kobera and Junduru pedotypes of the upper Etadunna Formation in outcrop near Mammalon Hill, Lake Palankarinna (2.8 and 3.2 m respectively in Fig. 2.3)

(Fig. 2.9) with a red surface (A) horizon, and a subsurface calcic (Bk) horizon above a gypsic (By) horizon. The Maralji pedotype has deep, thick root traces, and is at the same stratigraphic level as the Kutjamarpu fauna and a small assemblage of fossil leaves at Lake Ngapakaldi, 60 km to the north (Tedford et al. 1986; Rich et al. 1991).

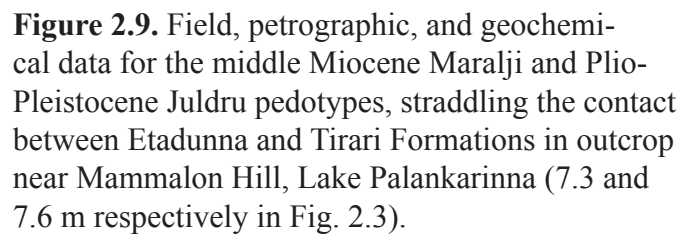
The Mampuwordu Sands of the basal Tirari Formation are incised into this Maralji landsurface and contains the Palankarinna local mammal fauna (Stirton et al. 1961; Tedford et al., 1986). The Dantu (Fig. 2.10) pedotype found within the upper Mampuwordu Sands is red in color and has stout root traces, but is less strongly developed, with fewer clay skins and more relict bedding (Bw horizon) than in the better developed Maralji pedotype.

Palaeosols within the overlying Tirari Formation, with its associated Kanunka fauna (Callen and Plane 1986), are weakly to moderately developed, mostly of the Chindina (Fig. 2.11) pedotype. Chindina palaeosols are red in color, with shallow gypsum (By) horizons and few root traces. The Maru pedotype also has a gypsic (By) horizon, in addition to prominent black nodules and mangans (manganese-coated cutans) deep in the profile. Interbedded with Chindina palaeosols, the Juldru pedotype is thin with abundant relict bedding, like the Junduru pedotype of the Etadunna Formation, but redder and of coarser grain size.

PALAEOENVIRONMENTAL RECONSTRUCTIONS

Late Oligocene

The lower Etadunna Formation (16.8–34.3 m in Palankarinna-2 core) contains foraminifera and is mainly lacustrine clayey dolostones. The entire Etadunna Formation was previously interpreted as lacustrine, with minor fluvial deposits, due to the presence of foraminifera, freshwater gastropods, ostracods, fish, crocodiles, turtles (Gaffney 1981), frogs (Tyler 1976), and birds such as pelicans, flamingos, ducks, cranes, gulls, rails, song birds, and pigeons (Miller 1963, 1966a, b; Rich & van Tets 1982). Different palaeosol pedotypes named here represent different parts of the landscape that can be inferred from sedimentary facies and evidence of former water tables. For example, Kaldri and Kobera pedotypes are interbedded within stratified lacustrine deposits of the upper Etadunna Formation, and would have formed along shores of



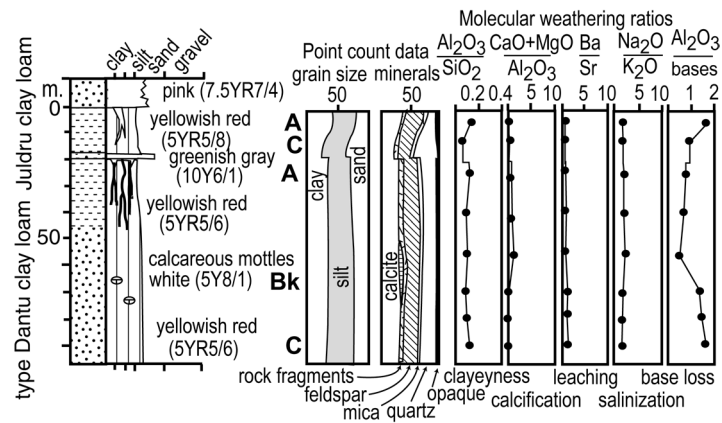
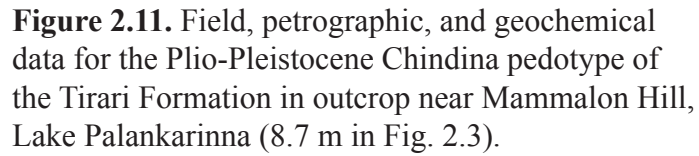


Figure 2.10. Field, petrographic, and geochemical data for the Pliocene Dantu pedotype of the upper Mampuwodu Sands in Lawson's quarry, Lake Palankarinna (offset from 7.6 m level of Fig. 2.3).



ephemeral lakes (Fig. 2.12). Both pedotypes are interpreted as Salids (of Soil Survey Staff 2000) or Solonchaks (of Food & Agriculture Organization 1974). Their well developed but shallow gypsic horizons indicate a mean annual precipitation declining from 137 ± 14 mm to 85 ± 14 mm up-section, as estimated from the known relationship between mean annual precipitation (P in mm) and the depth to salts (Dy in cm) in Holocene desert soils of sandy alluvial terraces in southern Israel (equation 2 of Table 2.1). These calculations can be compromised by burial compaction of palaeosols (Sheldon & Retallack 2001), but compaction is not significant in the very thin sequence at Lake Palankarinna, which has never been deeply buried (Callen & Plane 1986).

The most productive quarry for mammal fossils in the upper Etadunna Formation was the Ngama local fauna in a Kobera palaeosol, which included lungfish (*Neoceratodus* sp. indet.), catfish (Siluriformes), perch (Perciformes), turtles (cf. *Emydura*), horned tortoise (*Meiolania* sp. indet.), crocodile (Crocodylia), skink (cf. *Egernia*), boa (Boidae), cassowary (Casuariidae), duck (Anatidae), eagle (Accipitridae), rail (Rallidae), thick-knee (Burhinidae), flamingo (Phoenicopteridae), pigeon (Columbiformes), platypus (*Obdurodon* sp.), marsupial cat (*Dasyurina* sp. cf. *Dasyurina*), perameloid (Perameloidea), koala (*Litokoala kanunkensis*), diprotodon (*Neohelos* sp. indet.), palorchestid (*Ngapakaldia* sp. indet.), wynyardiid (cf. *Namilamadeta*), ilarid (*Kuterintja ngama*), wombat (Vombatidae), ektopodont (*Ektopodon stirtoni*), potoroo (*Purtia* sp. indet.), kangaroos (*Nambaroo* sp. indet. and *Macropodidae* sp. indet.), burramyid (*Buramys wakefieldii*), ringtail possum (*Pildra magnus*, *Marlu* sp. cf. *M. kutjamarpens*) and possum (Petauridae) (Rich et al. 1991; Woodburne et al. 1993). Standing water is needed for many of these species, such as platypuses, pelicans, ducks and cranes, but flamingos thrive around saline playa lakes, such as Lake Nakuru in Kenya (Owino et al. 2001). The marsupials are all extinct species smaller than modern related species, and are comparable in diversity with faunas of dry or riparian woodlands, similar to nearby Cooper Creek (Woodburne et al. 1993). Mammal assemblages of the comparable and coeval faunal zone A of the Riversleigh fossil localities of Queensland have the uneven size distribution of open habitats (Travouillon et al. 2009). Fossil pollen (Alley & Pledge 1990) and megafossil plants (Greenwood et al. 1990) of the upper Etadunna and nearby Namba Formations (Martin 1994) lack humid forest taxa known

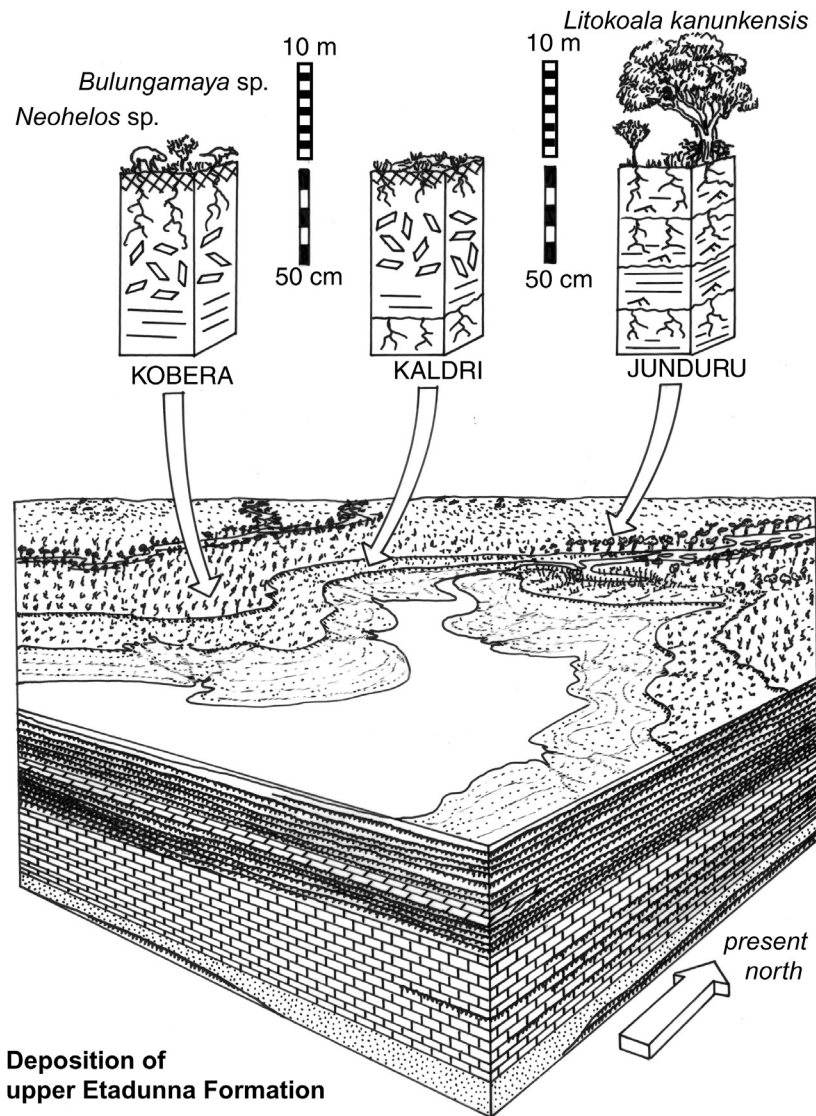


Figure 2.12. Reconstructed late Oligocene palaeoenvironment at Lake Palankarinna.

lower in these formations, and include evidence of *Acacia*, *Banksia*, *Casuarina*, cypress (Cupressaceae), grass (Gramineae) and desert shrubs (Chenopodiaceae). Evidence from palaeosols confirms these indications of dry conditions.

Fine root traces in Kaldri and Kobera palaeosols are comparable with those of glassworts such as *Sclerostegia arbuscula* common on the dry pan of Lake Palankarinna today (Costermans 1981), and such vegetation would be expected considering the gypsiferous and laminated clayey parent materials of these palaeosols, similar to margins of present Lake Palankarinna. The Junduru pedotype experienced more energetic influxes of sediments, as evidenced by thin ripple-marked sandy units. The drab color and thick root traces of the Junduru palaeosol are evidence of waterlogged conditions under riparian woodland, comparable with red gum (*Eucalyptus camaldulensis*) riparian vegetation of the Australian outback today (McKenzie et al. 2004).

In the Food & Agriculture Organization (1974) classification, the Kaldri-Kobera-Junduru assemblage of soils can be interpreted as Gleyic Solonchaks (Zg, Kaldri), Mollic Solonchaks (Zm, Kobera) and Eutric Fluvisols (Je, Junduru). As a group these are like the modern soilscape around Lake Amadeus, north of Uluru (Ayers Rock), Northern Territory (map unit Zo 36-2a of Food & Agriculture Organization 1978). The modern climate of Yulari airstrip (S25.19°, E130.97°), north of Uluru is 266 mm mean annual precipitation and 22 °C mean annual temperature (www.bom.gov.au, accessed 4 Nov. 2009). Lake Palankarinna was further south (S34.18°, E117.7° estimated using Point Tracker program of Scotese (1997)) during the Oligocene, close to the present latitude of Balladonia, on the western margin of the Nullarbor Plain, Western Australia, where comparable saline lakes and soils (Food & Agriculture Organization 1978) have a mean annual temperature of 16.8 °C and mean annual precipitation of 262 mm (www.bom.gov.au, accessed 4 Nov. 2009). This modern analog is a reasonable estimate for Oligocene palaeoclimate at Lake Palankarinna, especially considering the occurrence of frost intolerant ectothermic crocodiles and tortoises (Rich et al. 1991). The minimum mean annual temperature tolerated by crocodilians today is about 14.2 °C (Markwick 1998). Marine temperatures estimated from isotopic composition of late Oligocene marine rocks of Southern Australia were 10-15 °C (McGowran et al. 2004).

Middle Miocene

The top of the Etadunna Formation in outcrop at Mammalon Hill is an erosional land surface on which the Maralji palaeosol formed (Fig. 2.13). The Maralji palaeosol has calcareous nodules 2 cm in diameter, a size (M in cm) consistent with radiocarbon-age (K in ka) of nodules formed in soils of New Mexico desert alluvial fans formed over some 2.3 ± 1.8 ka (using equation 3 of Table 2.1). Also suggestive of moderate development for the Maralji palaeosol is blocky pedal structure obscuring original bedding and a differentiated subsurface horizon of gypsum (By). A shorter duration of pedogenesis is represented by the Juldru palaeosol, which is sandy with prominent relict bedding, a facies comparable with creek margins frequently disturbed by floods (Tooth & Nanson 2004). Juldru palaeosols are thus envisaged as streamside terraces, with Maralji palaeosols forming on drainage divides, as is common today in the Riverina district of New South Wales (McKenzie et al. 2004).

The deep (82 cm) gypsic horizon of the Maralji pedotype is evidence of mean annual precipitation of 409 ± 14 mm (using equation 2 of Table 2.1). A comparable estimate of 506 ± 147 mm comes from depth to the calcic horizon (Dk in cm) of the Maralji pedotype (66 cm), which is an indication of mean annual precipitation (P in mm, from equation 4 of Table 2.1). This is significantly more humid than for Oligocene palaeosols of the Etadunna Formation, but semiarid. In addition, the thickness (H in cm) of the calcareous nodular horizon (Bk) in soils is known to be related to mean annual range of precipitation, or difference between wettest and driest month precipitation (or seasonality S in mm), in modern soils (according to equation 5 of Table 2.1). By this metric, seasonality of precipitation during formation of the Maralji palaeosol was 26 ± 22 mm, a small difference considering mean annual precipitation inferred for this palaeosol. Such an equable non-monsoonal rainfall pattern would be expected this far south at ca.16 Ma ($S32.5^\circ$, $E123.12^\circ$, following Scotese 1997).

Stout woody root traces in the Maralji palaeosol are evidence of a vegetation of trees. These were probably *Eucalyptus* and *Acacia*, because fossils of these genera dominate a small collection of fossil leaves, including also aquatic dicots and reeds, at the same stratigraphic level in the Wipajiri Formation some 60 km to the north at Lake Ngapakaldi (Stirton et al. 1961; Rich et al. 1991). The leaf locality has also yielded the

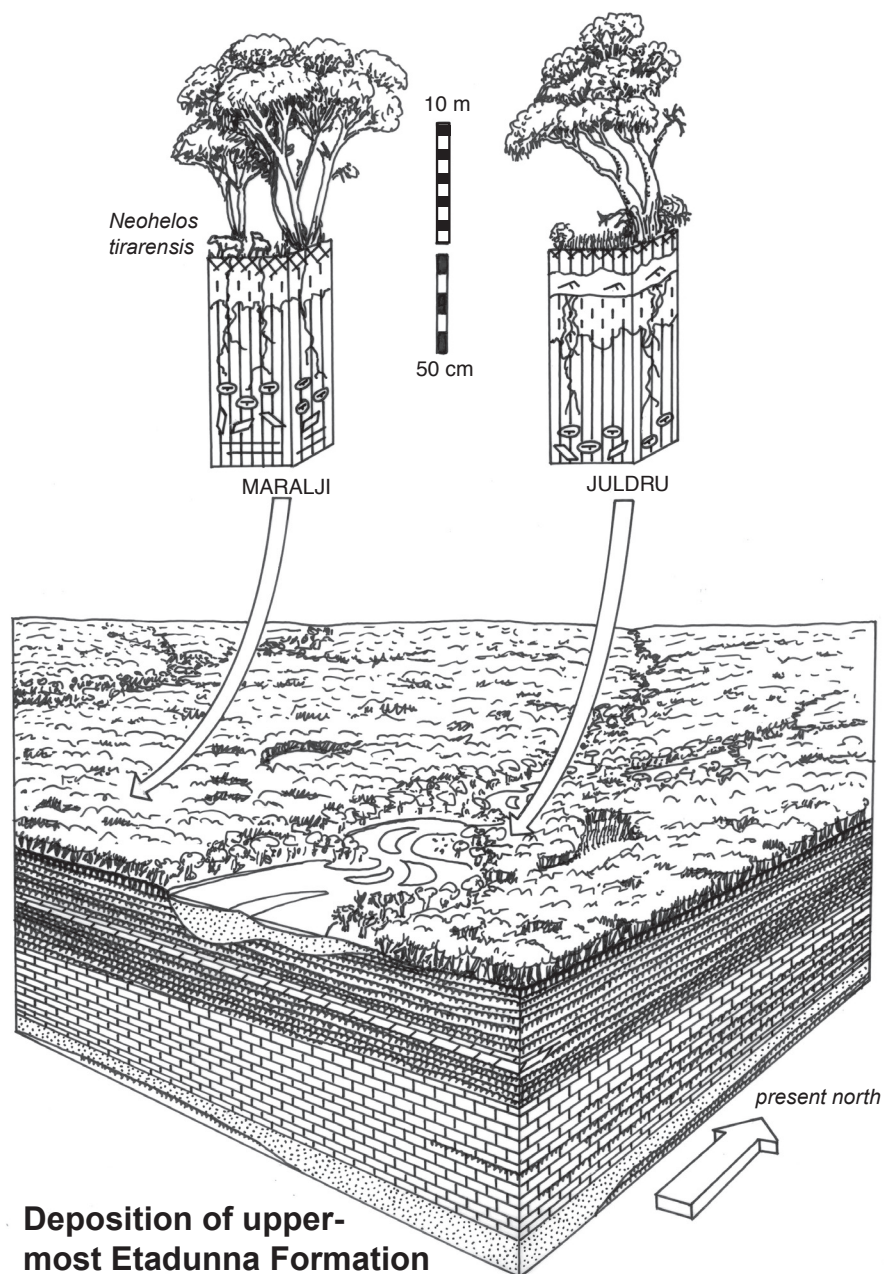


Figure 2.13. Reconstructed Middle Miocene palaeoenvironment at Lake Palankarinna.

Kutjamarpu local fauna, including lungfish (*Neoceratodus gregoryi*, *N. djelleh*, *N. eyrensis*, *N. spp.*), bony fish (Teleostei), turtle (*Emydura* sp. indet.), horned tortoise (*Meiolania* sp. indet.), skinks (*Egernia* sp. indet., *Tiliqua* sp. indet.), lizard (Agamidae), cassowary (*Dromaius gidju*), dromornithid (Dromornithidae), pelican (*Pelecanus tirarensis*), duck (Anatidae), plover (Charadriiformes), marsupial cat (*Wakamatha tasseli*, *Ankotarinja* spp., *Keeuna* sp. indet., Dasyuridae sp. indet.), perameloid (Perameloidae), koala (*Litokoala kutjamarpensis*), diprotodont (*Neohelos tirarensis*, *Diprotodontidae* sp. indet.), wombat (*Rhizophascolonus crowcrofti*), marsupial lion (*Wakaleo oldfieldii*), possum (Phalangeridae), ektopodont (*Ektopodon serratus*), potoroo (*Wakiewakie lawsoni*, *Bulungamaya* spp. indet.), kangaroo (*Balbaroo* spp., Macropodinae spp. indet.), burramyid (Burramyidae), and ringtail possum (*Pildra tertius*, *Paljara tirarensae*: Rich et al. 1991). This mammal assemblage is similar to that in modern Australian woodland and mallee, with both arboreal and open county mammals (Bennett et al. 1989, 2006).

The Maralji palaeosol is most like low woodland or high mallee soils (Blackburn & Wright 1989), which are solonized brown soils (of Stace et al. 1968), Calcarosols (of Isbell 1998), Calcids (of Soil Survey Staff 2000) and Calcic Xerosols (of Food & Agriculture Organization 1974). Comparable soils can be found today in the central Riverina region of New South Wales (map unit Xk 40-1/2b of Food and Agriculture Organization 1978). Within this region, Balranald currently has a mean annual rainfall of 320 mm, a mean annual range of precipitation of 9.8 mm, and mean annual temperature of 17.1°C (www.bom.gov.au, accessed 4 Nov. 2009). The current range of mallee soils, plants, and animals is restricted to Mediterranean climatic regions of South Australia, Victoria and New South Wales (Carnahan & Bullen 1990). Marine temperatures estimated from isotopic composition of middle Miocene marine rocks of southern Australia were 15-20 °C (McGowran et al. 2004).

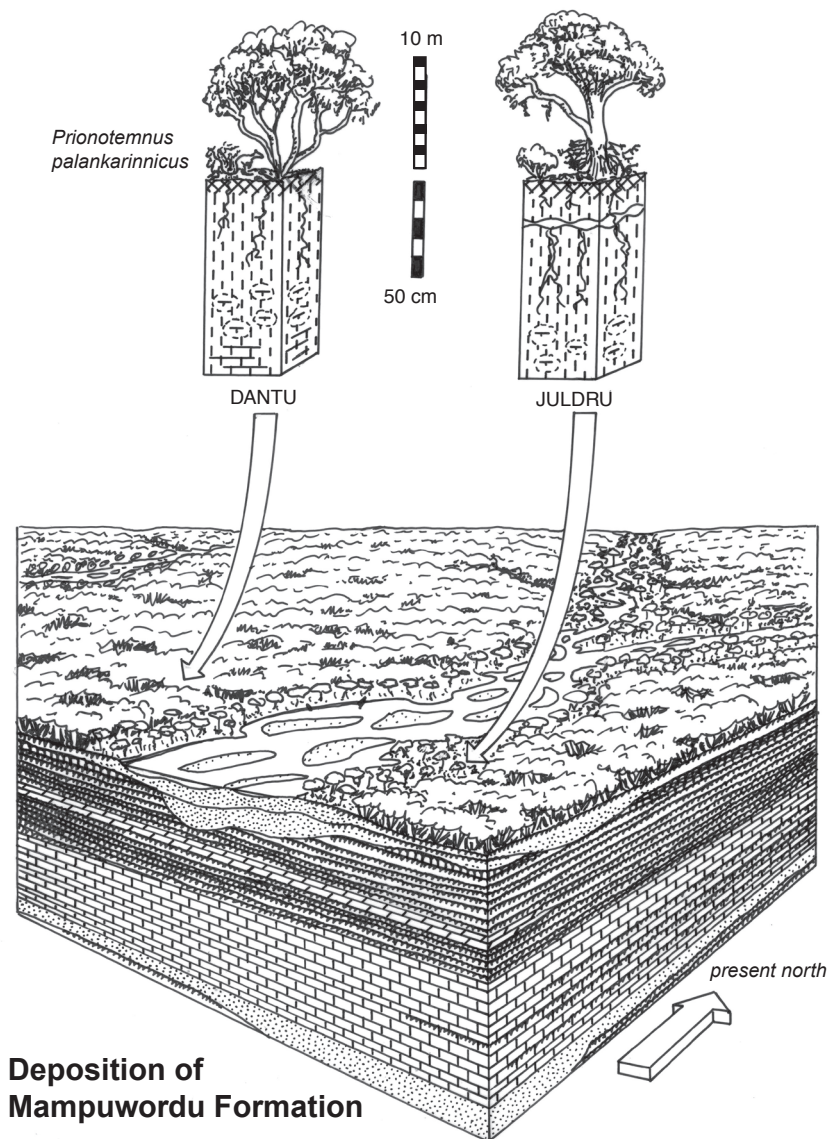
The Maralji palaeosol is evidence that during the middle Miocene, mallee vegetation and mallee soils were present much further north than currently in South Australia (Fig. 2.2). Scattered small trees of round-leaf mallee (*Eucalyptus orbifolia*) are widespread in central Australia (Hill 1989). Scattered trees alone would not give the profile depth and differentiation seen in the Maralji palaeosol, but it is difficult to determine whether range extension of mallee was due to northward expansion of biomes

as in postglacial North America (Williams et al. 2004), or due to climatically-induced woody thickening from existing seed stocks as currently documented in Queensland (Krull et al. 2004). Mammal faunas of the Kutjamarpu local fauna are evidence of continued diversification of lineages from the older Etadunna Formation (Rich et al. 1991), thus supporting the idea of woody thickening of vegetation rather than biome migration.

Early Pliocene

The Mampuwordu Sands (Fig. 2.14) form a large palaeochannel, and represent a large stream that drained southwest into the Lake Eyre Basin (Callen & Plane 1986). The Dantu pedotype, although not as well developed as the Maralji pedotype and lacking a nodular Bk horizon, does however contain a zone of calcareous mottles as a precursor of the Bk horizon, formed over a shorter duration of pedogenesis (ca.1 kyr) than estimated above for the Maralji palaeosol (using equation 3 of Table 2.1). These calcareous mottles are at a depth of 55 cm, as in modern soils receiving 453 ± 147 mm mean annual precipitation (using equation 4 of Table 2.1) and the 23-cm thickness of this horizon is evidence of precipitation seasonality of 32 ± 22 mm (using equation 5 of Table 2.1). This shallower depth and the smaller size of root traces than in the Maralji palaeosol, are evidence that the Dantu palaeosol supported low mallee vegetation (<5 m tall), as described by Carnahan & Bullen (1990). Such an ecosystem is also compatible with the Palankarinna local fauna collected from Lawson's quarry, where the Dantu palaeosol was sampled for this project. The fauna includes crab (Decapoda), lungfish (*Neoceratodus* sp. indet.), bony fish (Teleostei), crocodile (Crocodilia), cassowary (*Dromaius ocypus*), dromornithid (Dromornithidae), bandicoot (*Ischnodon australis*), large diprotodont (*Zygomaturus keanei*, *Meniscolophus maesoni*), and kangaroo (*Prionotemnus palankarinnicus*, *Sthenurinae* sp. indet.)(Rich et al. 1991).

The Dantu palaeosol is also similar to mallee soils, specifically solonized brown soils (of Stace et al. 1968), Orthic Tenosols (of Isbell 1998), Ochrepts (of Soil Survey Staff 2000) and Calcic Cambisols (of Food & Agriculture Organization 1974). With more time for soil formation, the Dantu palaeosol would have developed nodules comparable with the Maralji palaeosol, but its carbonate formed at a shallower level than for the



Deposition of Mampuwordu Formation

Figure 2.14. Reconstructed early Pliocene palaeoenvironment at Lake Palankarinna.

Maralji palaeosol. Comparable soils can be found today from the western Riverina region of New South Wales, around the head of South Australia's Spencer Gulf, west toward the Nullarbor Plain (map unit Xk 40-1/2b of Food & Agriculture Organization 1978).

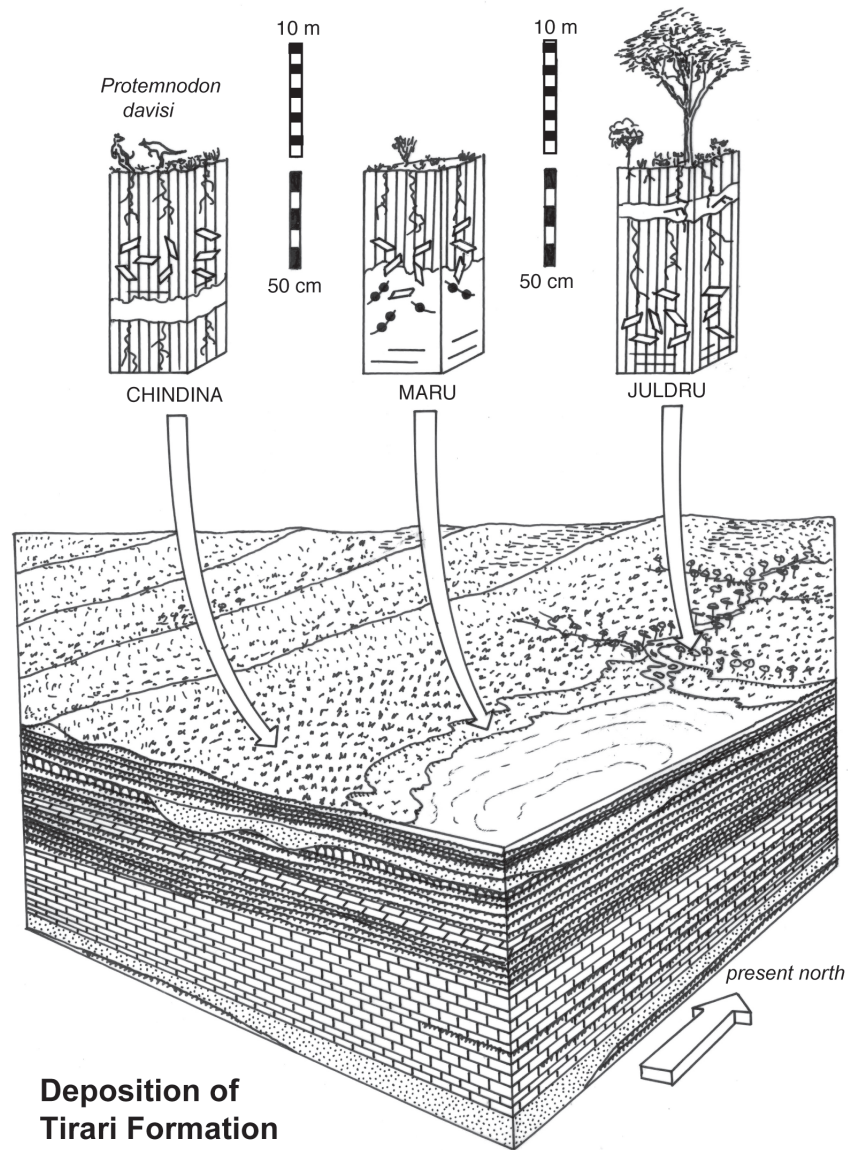
Mildura, for example, has a mean annual rainfall of 268 mm, a mean annual range of precipitation of 13.6 mm, and mean annual temperature of 17.4 °C (www.bom.gov.au, accessed 4 Nov. 2009).

Late Pliocene

Within the Tirari Formation, the Chindina, Maru, and Juldru pedotypes are red and oxidized, indicating landscapes with free drainage and a low water table (Fig. 2.15). However, iron-manganese nodules and coatings (mangans) like those of the Maru pedotype are common in soils with slow drainage, especially when groundwater is perched by hardpans or in rice paddies (Rahmatullah et al. 1990).

The very shallow gypsic (By) horizons in Chindina and Maru palaeosols are similar in depth to soils within Israel receiving 81 ± 14 to 119 ± 14 mm mean annual precipitation (estimated using equation 2 of Table 2.1). The surface soil at the top of the measured section near Mammalon Hill is similar in profile form to the Chindina pedotype, implying a dry climate like that today around Lake Palankarinna: nearby Marree has mean annual precipitation of 160 mm and mean annual temperature of 22 °C (www.bom.gov.au, accessed 4 Nov. 2009).

The Kanunka fauna of the upper Tirari Formation, largely from localities north of Lake Palankarinna, includes the following: crabs (Decapoda), lungfish (Ceratodontidae), bony fish (Teleostei), cassowary (*Dromaius novaehollandicus*), pelican (*Pelecanus cadimurka*, *P. conspicillatus*), anhinga (*Anhinga novaehollandiae*), shag (Phalacrocoracidae), stork (Ciconiidae), heron (Ardeidae), duck (Anatidae), eagle (Accipitridae), crane (*Grus* sp. indet.), rail (Rallidae), bustard (Otididae), plover (Charadriiformes), flamingo (*Ocyplanus proeses*, cf. *Phoenicopterus ruber*, *Xenorhynchus minor*), marsupial cat (Dasyuridae), diprotodont (*Zygomaturus* sp. indet., *Diprotodon* sp. indet.), wombat (*Phascolonus* sp. indet., *Vombatus/Lasiorhinus*), potoroo (*Bettongia* sp. indet.), kangaroo (*Lagorchestes* sp. indet., *Dendrolagus* sp. indet., *Kurrabi* sp. indet., cf. *Prionotemnus* sp. indet., *Troposodon kentii*, *T.* sp. cf. *T. minor*, *Protemnodon* sp. cf. *P.*



Deposition of Tirari Formation

Figure 2.15. Reconstructed late Pliocene palaeoenvironment at Lake Palankarinna.

devisi, *P.* sp. indet., *Osphranter* sp. cf. *O. woodsi*, *Macropus* (Fissuridon) *pearsoni*, *M.* (*Notomacropus*) sp. indet., Sthenurinae sp. indet.), and mouse (Muridae) (Rich et al. 1991). This diversity includes a variety of large mammals that were subsequently victims of late Pleistocene megafaunal extinctions (Hope 1978), as well as riparian communities from Cooper Creek and its antecedents to the north (Tedford et al. 1986).

Root traces within palaeosols of the Tirari formation are stout, and represent woody vegetation with sparse ground cover. There is no indication of the fine crumb peds associated with grassland cover (Retallack 2004). Such gypsic soils probably supported vegetation like that of well-drained clayey interfluvies in this region today, such as saltbush (*Atriplex nummularia*), with scattered bushes of mulga (*Acacia aneura*) and gum (*Eucalyptus intertexta*) (Carnahan & Bullen, 1990).

The Chindina-Maru-Juldru pedotype assemblage of the Tirari Formation can be classified as Orthic Solonchak (Zo, Chindina), with minor Gleyic Solonchak (Zg, Maru) and Eutric Fluvisol (Je, Juldru) (Food & Agriculture Organization 1974). As for the Upper Etadunna Formation, a comparable modern soilscape is Lake Amadeus, north of Uluru (Ayers Rock), Northern Territory (map unit Zo 36-2a of Food & Agriculture Organization 1978). The modern climate of Yulari airstrip (S25.19°, E130.97°), north of Uluru is 266 mm mean annual precipitation and 22 °C mean annual temperature (www.bom.gov.au, accessed 4 Nov. 2009). Although Orthic Solonchaks cover parts of the plateau west of Lake Palankarina, the principal soil map units of this area today are Dystric Regosols (Rd 1-1b, sand dunes) and Orthic Solonetz (So 14-1/2ab, duplex soils under gibber) (Food & Agriculture Organization 1978). These may reflect episodes of landscape instability during Pleistocene erosion of the Tirari Formation (Callen & Plane 1986).

DISCUSSION: ARID OR HUMID MIOCENE OUTBACK?

A long running controversy in interpreting Cenozoic mammal communities of outback Australia has concerned whether they lived in humid rainforest (Archer et al. 1991; Travouillon et al. 2009) or in semiarid to subhumid woodlands and shrublands (Megirian et al. 1996, 2004; Murray & Vickers-Rich 2004). Fossil plants and pollen of the lower Namba and Etadunna Formations include humid forest taxa such as southern

beech (*Nothofagus*) and podocarps, but the upper portions of these formations studied here have aridland taxa such as wattle (*Acacia*), belah (*Casuarina*), desert shrubs (Chenopodiaceae) and grasses (Graminaeae) (Martin 1994; Greenwood et al. 1990; Alley and Pledge 1999). The interpretation of such records is complex because many Australian plants that evolved in rainforests have adapted to deserts: notably the vine, Sturt's desert pea (*Swainsonia formosa*), which now spreads over bare sand (Murray & Vickers-Rich 2004). Thus "indicator taxa" of fossil plants and snails found with mammal assemblages at Riversleigh and Kangaroo Well have been disputed as evidence of woodland or rainforest (Megirian et al. 2004; Travouillon et al. 2009). Use of cenograms (plots of ranked body weights of mammal taxa) of Riversleigh mammals to address the question of habitat (Travouillon et al. 2009) may instead reflect sample size, as found in comparable cenograms of open habitat (not rainforest) mammals in the middle Miocene of Fort Ternan, Kenya (Retallack et al. 1992; Dugas & Retallack 1993) and Pasalar, Turkey (Andrews 1990).

Problems of individual "indicator taxa" and potential redeposition are avoided in this work by considering palaeosols, which are by definition in the place they formed and laterally extensive. Furthermore the fragmentary mammal fossils within the palaeosols, stained similar colors to the most altered parts of the palaeosols, are evidence that mammals were parts of these soil communities. Palaeosols of Mammalon Hill section are, for the most part, rich in pedogenic gypsum found in both outcrop and in drill core. Concentrations range from sparse fine-grained dispersal to individual nodules to laterally extensive gypcrete layers, representing different stages of pedogenic development seen in Quaternary desert soils (Dan & Yaalon 1982). Soil features (roots, peds) cross cut and overprint gypsum of palaeosols in both outcrop and core, suggesting that although there is also significant coarse secondary diagenetic gypsum precipitation in outcrop, much gypsum is pedogenic in origin. Depth to gypsum and to carbonate in a soil profiles is known to be related to mean annual precipitation (equations 2 and 3 in Table 2.1), and these relationships can be applied to palaeosols of Lake Palankarinna, Kangaroo Well, Alcoota, and Mungo Lake to create a preliminary time series of Neogene precipitation in outback Australia (Fig. 2.16). The middle Miocene Maralji palaeosol, with the deepest gypsic (By) and calcic (Bk) horizons, formed under the most humid conditions of the past

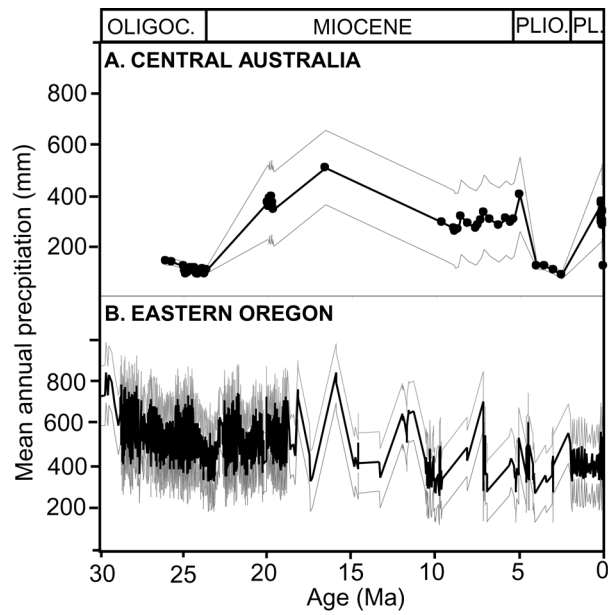


Figure 2.16. Neogene palaeoprecipitation history of outback Australia, including observations at Lake Palankarinna, Kangaroo Well, Alcoota, and Mungo Lake (Fig. 2), compared with a comparable more detailed record from Oregon, USA (Retallack 2007a).

25 Ma. Our paleoprecipitation estimates all fall well short of the 1186 mm mean annual precipitation required for Ultisols and 1270 mm for Oxisols and rainforest in Australia (Retallack 2008b). Oxisols and Ultisols are thick red kaolinitic and boehmitic soils with no free carbonate or gypsum (Retallack 1997, 2001), and so very different from the palaeosols documented here from Lake Palankarinna. Thus our study is compatible with interpreted woodland vegetation and a Miocene warm-wet spike of Megirian et al. (2004) for the Ulta Limestone, which includes red Aridisols palaeosols comparable with the Maralji pedotype described here (Retallack, personal observations).

Our study does not however imply that there was no Miocene rainforest in Australia. Miocene mammal faunas from Riversleigh come from cave deposits (Archer et al. 1991), which are isolated from surface climate, unlike palaeosol assemblages of fossil mammals (Retallack 2001). Palaeosols have yet to be reported in association with Riversleigh faunas, unlike Lake Palankarinna (herein), Kangaroo Well (Megirian et al. 2004), Alcoota (Megirian et al. 1996), and Mungo Lake (Hope 1978). Middle Miocene lateritic Ultisols and Oxisols typical of rainforest have been found at Maroubra (Pickett 2003) and other parts of the greater Sydney area (Faniran 1971). Middle Miocene kaolin deposits in the Gulgong-Dubbo region, New South Wales, also suggest similarly warm, wet climate during this time period (Dulhunty 1971; McMinn 1981). Microflora from the Home Rule clay pit (McMinn 1981) near Gulgong have two fossil pollen assemblages attributed to the *Triporopollenites bellus* zone of Stover and Partridge (1973) suggesting an age of late Early Miocene to Pliocene (17.5 Ma to 8.0 Ma). Also found in the Home Rule assemblage is *Elaeocarpus*, a tropical evergreen tree (Dettmann & Clifford 2000).

Extensive middle Miocene brown coals are found throughout Latrobe Valley and in the Gippsland Basin in Victoria, and represent widespread humid swamp and heath (Sluiter et al. 1995). Rainforests and wetlands in eastern and southeastern Australia were more extensive during the middle Miocene than before or since, but our study shows that such vegetation did not extend to inland Australia. Because Miocene mammal faunas of Riversleigh are so similar to those from Lake Palankarinna (Megirian et al. 2004), it is unlikely that they lived in a middle Miocene rainforest there. Further work on clay mineralogy, palaeosols and palaeobotany at Riversleigh is needed to settle the issue.

CONCLUSIONS

Palaeosols of Lake Palankarinna from before and after the middle Miocene thermal maximum reflect climatic and vegetative regimes similar to those found at the modern salina lake. A middle Miocene palaeosol (Maralji pedotype) reflects warmer and wetter climate than before or after, and is most like soils of mallee vegetation of southern South Australia and Victoria (Blackburn & Wright 1989). Because documented middle Miocene CO₂ and climate change (Retallack 2009) is comparable with changes predicted due to global warming by 2100 (Alley et al. 2007), mallee vegetation may expand into the Tirari Desert as it did during the middle Miocene. There are no rainforest palaeosols (Oxisols, Ultisols) yet recorded in Miocene sequences of central Australia, in support of paleoenvironmental interpretations of Megirian et al. (2004). Neither middle Miocene nor future global change is likely to have been, or to be, so extreme.

Palaeosols are a widespread and little exploited palaeoclimatic record of inland Australia (Firman 1994). Existing records still show significant temporal gaps (Fig. 2.16) compared with time series now available from palaeosols of North America (Retallack 2007a, 2008) and Kenya (Retallack 2007b). The approaches to their study outlined here could productively be applied more widely.

BRIDGE

Chapter II presented a new study of the middle Miocene paleosol record at Lake Palankarinna, northern South Australia. Chapter III presents a similar study of the middle Miocene paleosol record at Cerro Observatorio in Santa Cruz province, Patagonia, Argentina. These two studies were undertaken because both areas had been relatively unstudied from the perspective of paleosols.

CHAPTER III

PALEOSOLS AND PALEOENVIRONMENTS OF THE MIDDLE MIOCENE

SANTA CRUZ FORMATION, PATAGONIA, ARGENTINA

INTRODUCTION

The middle Miocene thermal maximum was an episode of paleoclimate change similar in magnitude, both in global geographic scale and extrapolated magnitude of temperature change, to global change predicted to occur by the year 2100 (Retallack, 2007, 2009). The middle Miocene is ideal for comparison to current climate change because Miocene sediments are globally well-preserved, abundant, and well-dated radiometrically and biostratigraphically (Gradstein et al., 2012), and at that time continents were close to their modern configuration. Benthic foraminiferal oxygen isotope records (Fig. 3.1) reveal a middle Miocene peak in deep ocean temperature, 6 °C warmer than present (Zachos et al., 2001). The middle Miocene thermal maximum is characterized globally by migration of thermophilic plant and animal taxa to high paleolatitudes (Axelrod and Raven, 1978; Bestland, 1990; Bestland et al., 2008; Bown and Fleagle, 1993; Bown and Larriestra, 1990; Christensen, 1975, 1976; Wolfe, 1992, 1994; Wolfe and Tanai, 1980). In the northwest United States, Oxisol paleosols of tropical forest extended as far north as latitude 46° N (Vancouver, Washington) (Retallack, 2010) and Alfisol paleosols of warm temperate forest as far north as latitude 48° N (Spokane, Washington) (Sheldon, 2003; Takeuchi and Larson, 2005). In North America, Australia, and Kenya, middle Miocene paleoclimatic warming was accompanied by increases in precipitation, as revealed by depth to calcic horizon and by degree of chemical alteration of paleosols (Fig. 3.2).

Paleosols can be used to provide a new perspective on Miocene global change. This study examines comparable changes in paleosols and ecosystems at mid-latitudes in South America during the middle Miocene. In Argentina, the middle Miocene thermal maximum occurs within the unusually diverse Santacrucian land mammal age (Marshall, 1976; Marshall et al., 1977, 1981, 1986). Paleosols of the middle Miocene Pinturas

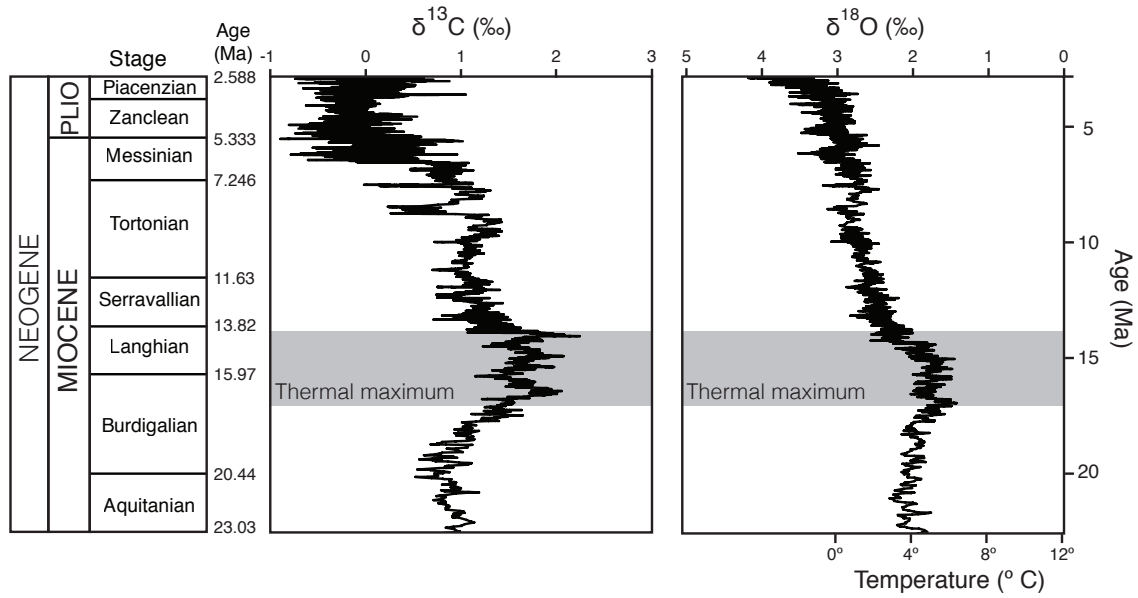


Figure 3.1. Oxygen and carbon isotopic data from Cenozoic benthic foraminifera from the Atlantic Ocean. The Middle Miocene thermal maximum is highlighted in grey. After Zachos et al., 2001.

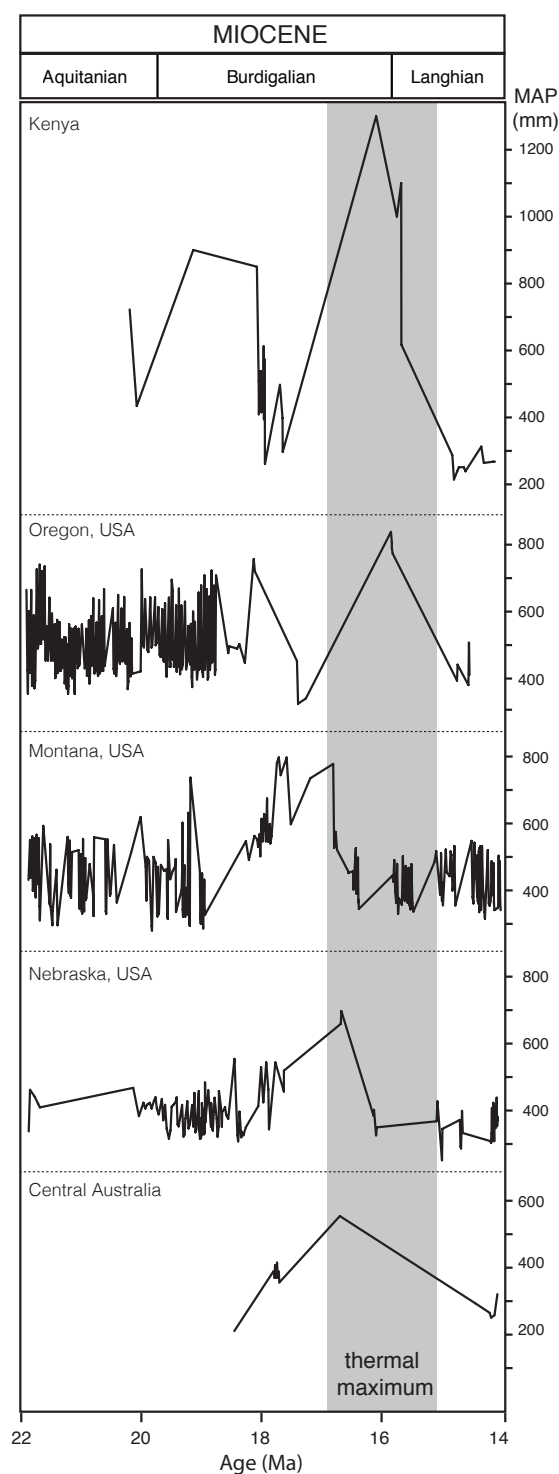


Figure 3.2. Mean annual precipitation (mm/yr) from paleosols in Kenya (Retallack et al., 2002); Oregon (Retallack, 2004; Bestland et al., 2008); Montana (Zheng, 1996; Nichols & Hanneman, 2000; Nichols et al., 2001; Retallack, 2001; Barnosky et al., 2007); Nebraska (Retallack 2007, 20013); and Central Australia (Metzger and Retallack, 2010). Grey box highlights the Middle Miocene thermal maximum.

Formation in northern Santa Cruz (latitude 46 °S) indicate that middle Miocene conditions were humid, as shown by translocation of clays, development of cutans, and lack of significant carbonate accumulation (Bown and Fleagle, 1993). Humid subtropical forests during deposition of the Pinturas Formation have been inferred from fossil termite mounds (Bown and Laza, 1990; Genise and Bown, 1994; Genise et al., 2004) and arboreal monkeys and marsupials (Bown and Laza, 1990; Bown and Larriestra, 1990; Bown et al., 1988; Fleagle, 1990; Fleagle et al., 1987). This study presents new work on paleoclimatic affinities of middle Miocene paleosols from the Santa Cruz Formation in southern coastal Patagonia (latitude 51° S) near Cerro Observatorio (Fig. 3.3), undertaken to determine the extent of unusually warm and wet ecosystems to the south during this time period.

MATERIALS AND METHODS

Paleosol investigations

Paleosols were located within well-exposed badlands (Fig. 3.4) and logged on a vertical stratigraphic section (Fig. 3.5), described, and sampled in January and November 2007. Field descriptions included Munsell color (Munsell, 1975), grain size, soil structure, horizonation, horizon boundaries, and the presence of other features such as root traces, nodules, animal or insect burrows, or fossils, note within detailed stratigraphic sections. Paleosols were classified into groups using the pedotype approach (Retallack, 2001b), with a distinctive name applied to each kind of paleosol as it was encountered in the field. Names for the pedotypes are from the nearly extinct Patagonian Tehuelche language (Beauvoir, 1998; Lista, 2006; Musters, 1997), and these local field units were classified according to the soil classifications schemes of the Food and Agriculture Organization (1971, 1974, 1988) and the U.S. Natural Resource Conservation Service (Soil Survey Staff, 2000). Table 3.1 contains complete field data and observations for each pedotype.

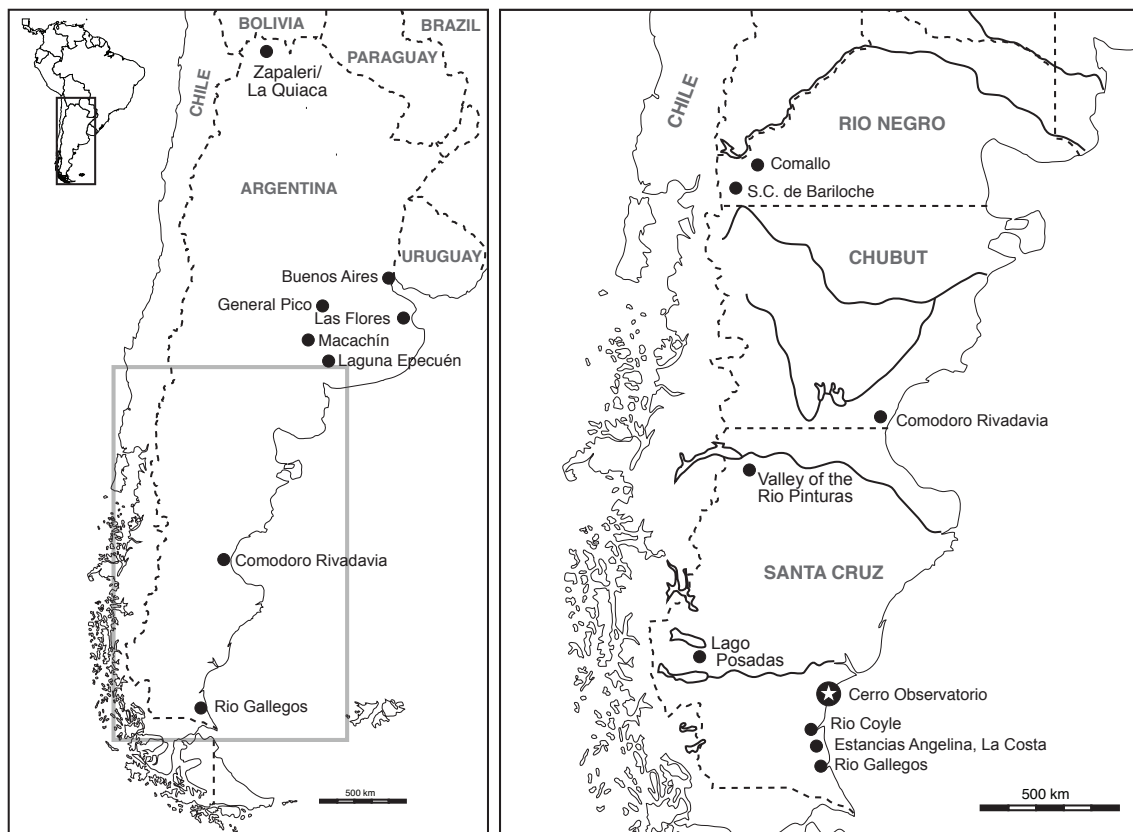


Figure 3.3. Location map. Circled star shows location of field area. Black circles show locations referred to in the text.

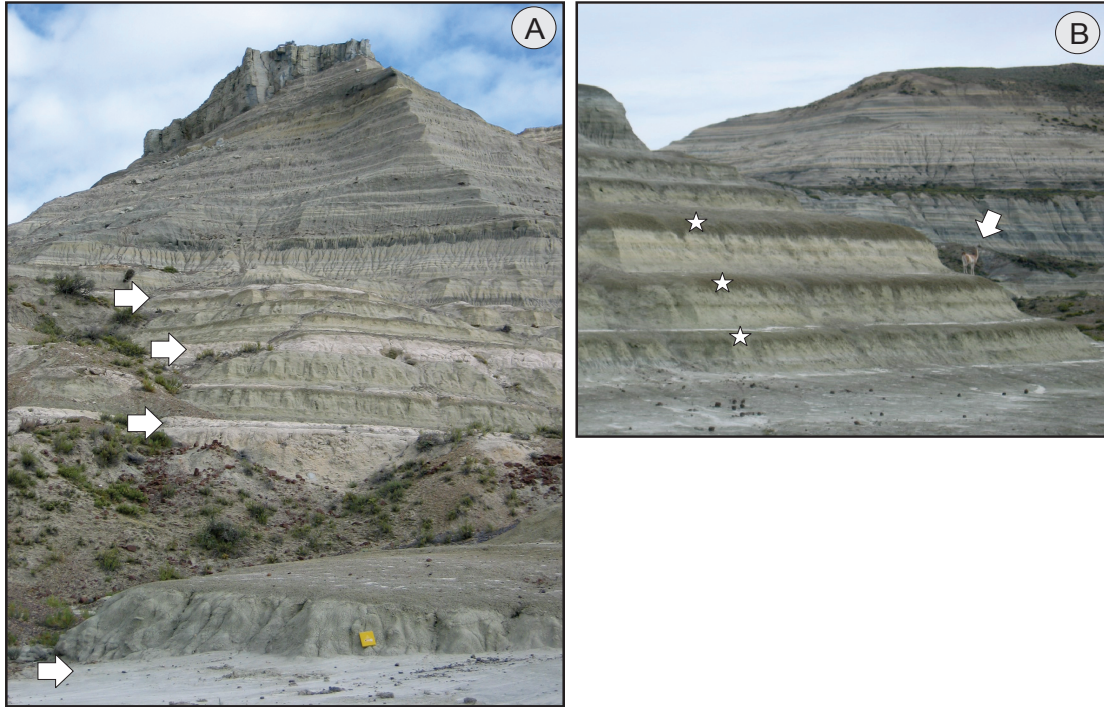


Figure 3.4. Santa Cruz Formation stratigraphy photographs. Photo A shows nearly complete stratigraphy; notebook in foreground is 20 cm tall. A total of ~100 m of section is exposed here. Arrows indicate locations of distinctive white volcanic ash layers used as marker beds and for radiometric dating. Photo B shows part of the lower section (slightly below the yellow notebook and out of the frame of photo A). A *guanaco* (Patagonian llama) on the second riser is approximately 1.5 m tall. Dark brown bandings (indicated by stars) are tops of Mollic Entisols (Uaye pedotype).

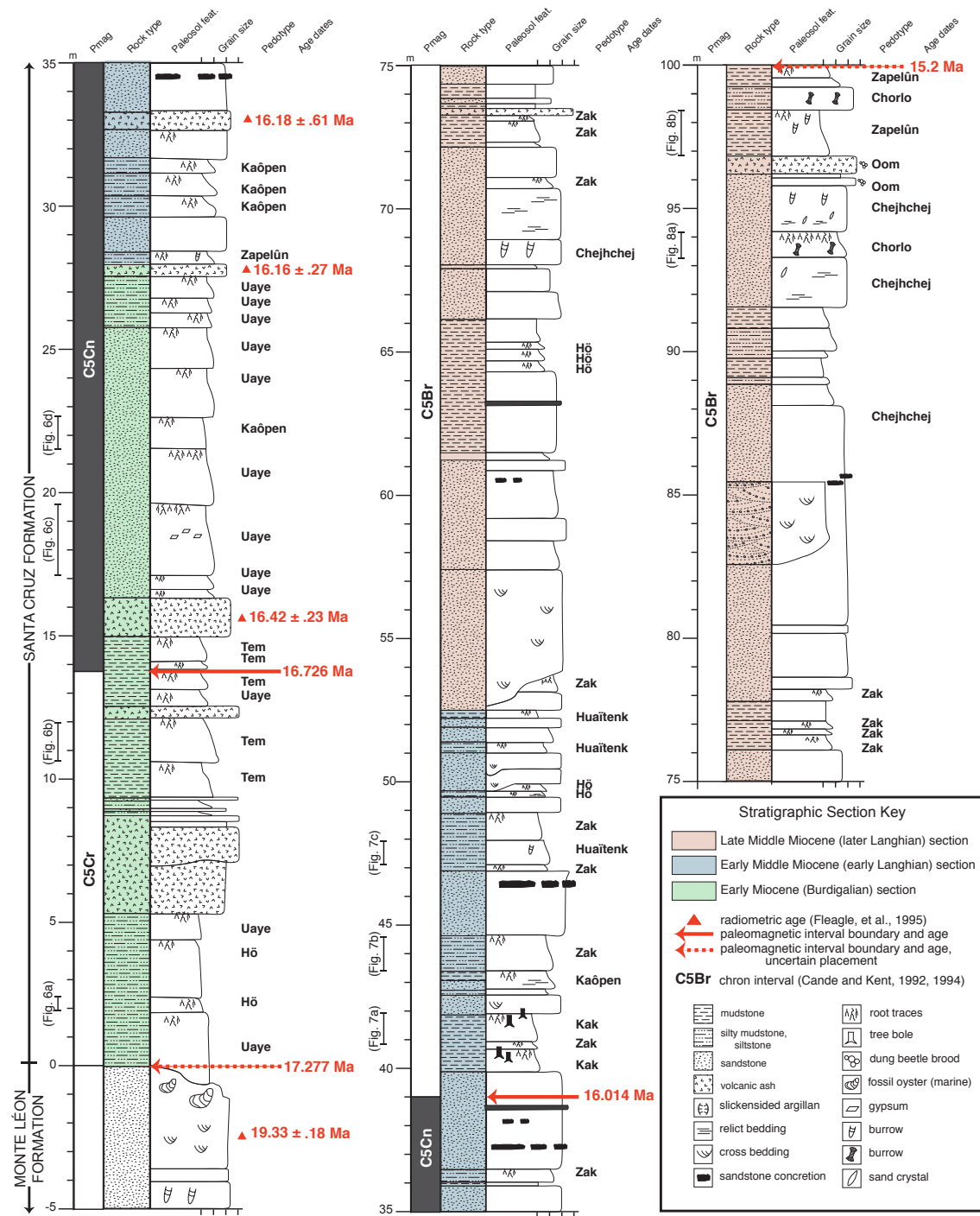


Figure 3.5. Measured section of Cerro Observatorio stratigraphy.

Pedotype	Tehuelche meaning	Diagnosis	Classification taxonomy	
			Soil Survey Staff, 2000	FAO, 1971, 1988
Chejhchej	<i>sand</i> ¹	Weakly developed sand with burrows and root traces	Gypsid	Gypsic Yermosol
Chorlo	<i>black</i> ³	Yellow-brown mottled (5Y7/3-10YR5/6) surface (A) with mangans and root traces over paleo yellow subsurface (Bg)	Aquept	Gleyic Solonchak
Hö	<i>thin pole</i> ³	Light gray (5Y6/2) with yellow brown (10YR4/6) roots (A) over gray bedded subsurface (C)	Fluvent	Eutric Fluvisol
Huaïtenk	<i>yellow</i> ²	Light gray (5Y7/3) surface with mangans, slickensides and brown (10YR5.8) mottles (A) over gray-brown mottled (5Y6/1-10YR5/6) subsurface (Bg)	Aquept	Humic Cambisol
Kak	<i>wood</i> ¹	Cumulic light brownish gray (2.5Y6/2) surface with yellowish brown (10YR5/6) stumps and mottles (A) over greenish gray (10Y7/1) clayey subsurface (Bg)	Ustalf	Mollic Solonetz
Kaôpen	<i>red</i> ³	Pale yellow (5Y8/2) surface with yellowish brown (10YR5/6) root traces (A) over pale yellow (5Y8/2) subsurface (Bw)	Ustept	Haplic Kastanozem
Oom	<i>egg</i> ³	Volcanic ash with root traces and dung beetle boli (<i>Coprinisphaera</i>)	Vitrand	Vitric Andisol
Tem	<i>soil</i> ¹	Pale olive (5Y8/2) surface with crumb peds (A) over clayey yellow-brown mottled (5Y7/3-2.5Y6/3) subsurface (Bt)	Ustoll	Haplic Phaeozem
Uaye	<i>field</i> ¹	Pale olive (5Y6/3) surface with crumb peds (A) over shallow white (5Y8/1) gypsum stringers (By)	Salid	Orthic Solonchak
Zak	<i>shrub</i> ¹	Light grey (5Y7/2) surface with yellowish brown (10YR5/6) roots and mottles (A) over grey-yellow (5Y7/3-2.5Y6/6) mottled subsurface (Bg)	Aquept	Humic Gleysol
Zapelûn	<i>insect</i> ¹	Cumulic pale yellow (5Y7/3) surface with bee nests (<i>Celliforma</i>) and thin roots (A) over pale yellow (5Y7/3) clayey subsurface (Bw)	Ustept	Haplic Kastanozem

¹ Beauvoir, 1998
² Lista, 2006
³ Musters, 1997

Table 3.1. Cerro Observatorio pedotypes and classifications.

Laboratory and microscopic analyses

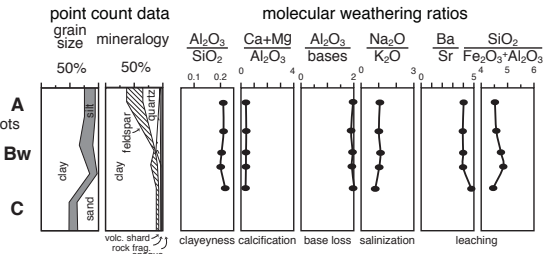
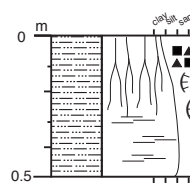
Bulk and oriented samples were collected for geochemical analyses and petrographic thin sections from every horizon within each pedotype. Samples for geochemical analysis of major and trace elements and analyzed by inductively-coupled plasma mass spectroscopy at Acme Analyticals Labs, Vancouver, British Columbia, Canada. Because soils develop in quantifiable ways, measured concentrations of certain elements or components of a soil can yield information about its degree of development and the conditions under which it formed. Bulk geochemistry is useful for investigating geochemical processes active during soil formation; molecular weathering ratios are commonly used as proxies of compositional changes in a rock or soil due to weathering (Marbut, 1935). Calculated from the weight percent of an element in its oxide form, these ratios can indicate the dominant chemical reactions (hydration, oxidation, etc.) at work in a soil (Retallack, 1997, 2001b).

Oriented rock samples were collected from each diagnostic soil horizon for petrographic thin sections. The thin sections were then observed under a petrographic microscope to examine soil microfabrics (Brewer, 1976; FitzPatrick, 1993; Retallack, 1997), genetic soil features, and mineralogy, as well as to obtain grain size and mineral distributions by point counting using a Swift automated stage and point counter. Summary petrographic data and molecular weathering ratios for each pedotype are shown in Figures 3.6-3.8, and raw data are tabulated in Appendix B.

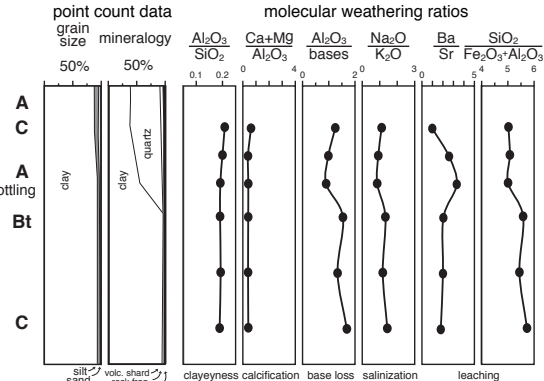
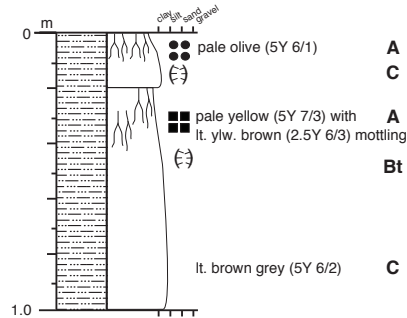
GEOLOGIC SETTING AND AGE MODEL

The Santa Cruz Formation crops out extensively throughout southern Argentine Patagonia, ranging from a thickness in the Andean foothills of more than 1500 m to about 225 m along the Atlantic coast (Tauber, 1997a). Santa Cruz Formation sediments (mainly reworked volcanoclastic sediments, weakly to moderately developed paleosols, and several primary ash fall deposits) were deposited in a Jurassic-Cretaceous basement basin during a sea-level regression (Barreda and Bellosi, 2003). The Santa Cruz Formation is one of South America's richest vertebrate fossil-containing formations (Marshall, 1976), collected since the late eighteenth century (Ameghino, 1887). In southern Santa Cruz,

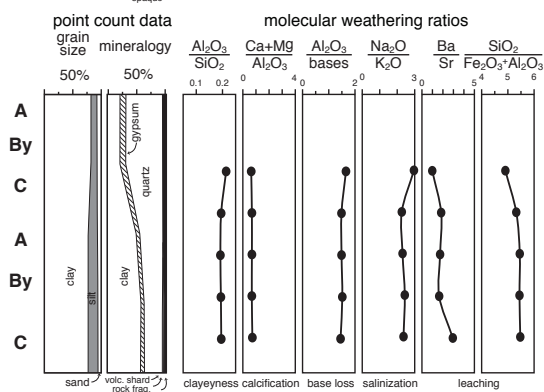
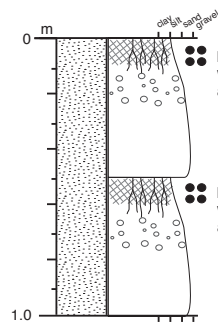
A. Ho pedotype



B. Tem pedotype



C. Uaye pedotype



D. Kaopen pedotype

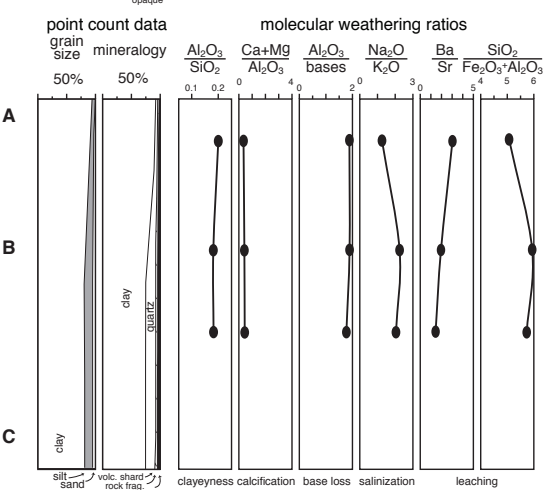
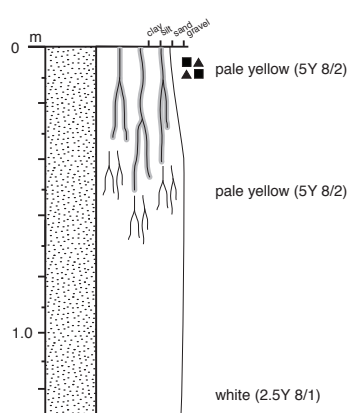
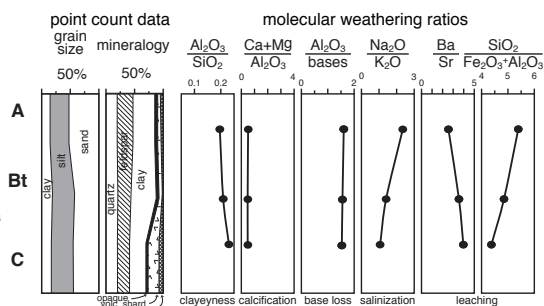
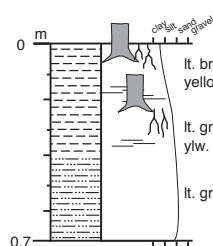
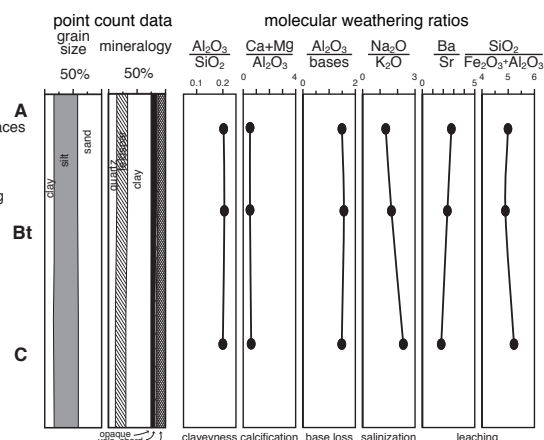
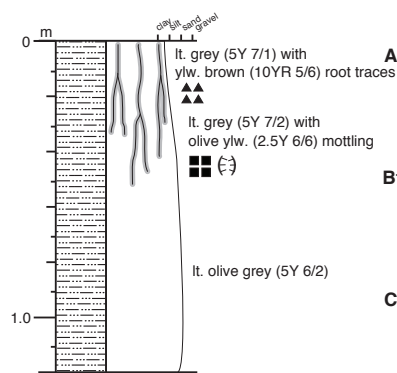


Figure 3.6. Field, petrographic, and geochemical data for the Early Miocene pedotypes, A) Ho; B) Tem; C) Uaye; and D) Kaopen. These pedotypes are located at 2 m, 11 m, 17 m, 21 m respectively in Figure 5. Complete key can be found in Fig. 3.5.

A. Kak pedotype



B. Zak pedotype



C. Huaitenk pedotype

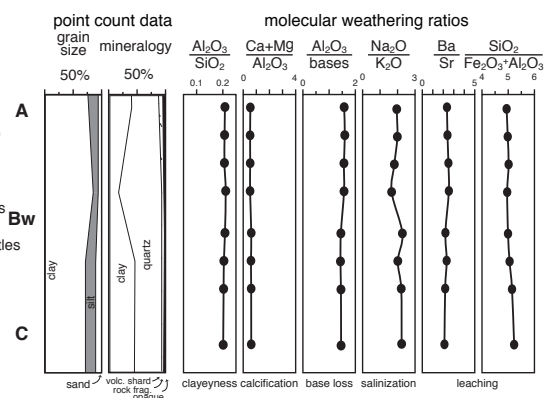
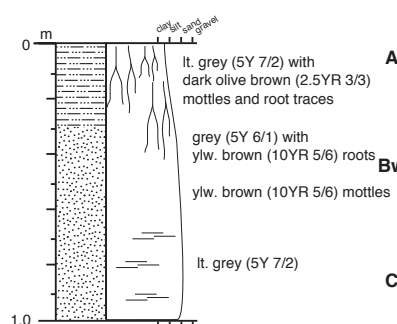
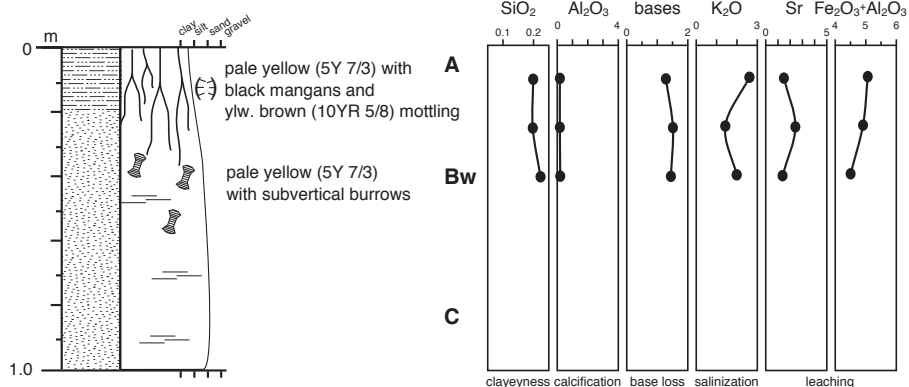


Figure 3.7. Field, petrographic, and geochemical data for the Early Middle Miocene pedotypes, A) Kak; B) Zak; and C) Huaitenk. These pedotypes are located at 41 m, 43 m, and 47 m respectively in Figure 5. Complete key can be found in Fig. 3.5.

A. Chorlo pedotype



B. Zapelun pedotype

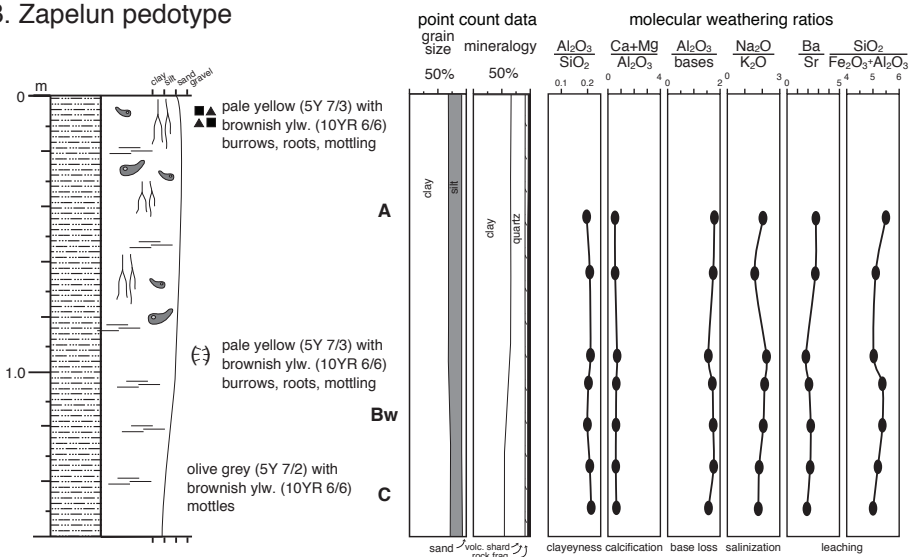


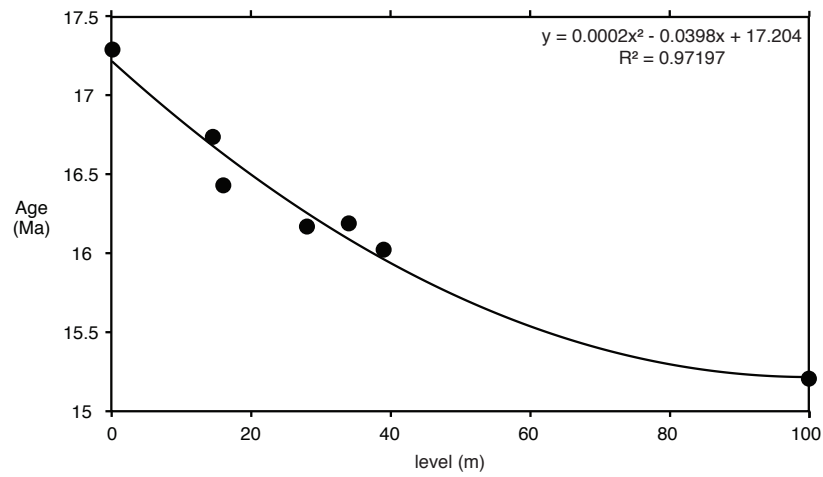
Figure 3.8. Field, petrographic, and geochemical data for the Late Middle Miocene pedotypes, A) Chorlo; and B) Zapelun. These pedotypes are located at 93 m and 97 m respectively in Figure 3.5. Complete key can be found in Fig. 3.5.

north of the Rio Gallegos, two members have been identified between the Rio Coyle and the Rio Gallegos, the lower Estancia de la Costa and the upper Estancia Angelina Members (Fig. 3.3) (Tauber, 1997a, b). The Estancia de la Costa Member is more fossiliferous than the Estancia Angelina Member. This study presents new paleosol data from the section at Cerro Observatorio north of the Rio Coyle, correlated with the Estancia La Costa member found to the south (Vizcaíno et al., 2006). At Cerro Observatorio, 100 m of Santa Cruz Formation is exposed in deeply weathered badlands bluffs, from the basal unconformable contact with the marine Monte León formation.

The geochronology (see Fig. 3.5) of the Santa Cruz Formation now includes information from both radiometric dating and magnetostratigraphy (Bown and Fleagle, 1993; Bown et al., 1988; Fleagle et al., 1995, 2004; Marshall et al., 1977, 1981, 1986). The top of the Monte León Formation at Monte León has been dated at 19.33 ± 0.18 Ma (single crystal plagioclase, $^{40}\text{Ar}/^{39}\text{Ar}$ date) (Fleagle et al., 1995) in agreement with the early Miocene age of its marine molluscs (del Rio, 2004). Three ashes from the lower Santa Cruz Formation exposed at Cerro Observatorio were dated at 16.42 ± 0.61 , 16.16 ± 0.27 , and 16.18 ± 0.23 Ma, using $^{40}\text{Ar}/^{39}\text{Ar}$ on single crystals of plagioclase (Fleagle et al., 1995). The Pinturas Formation, which crops out in northern Santa Cruz province in the Rio Pinturas valley, is of intermediate age between the Santa Cruz and Monte León Formations and Fleagle et al. (1995) interpreted it as deposition that occurred during the unconformity between the latter two formations. Other age constraints from Monte León and Cerro Observatorio come from the limits of a normal paleomagnetic interval identified by Fleagle et al. (1995) as Chron C5Cn (Fig. 3.5), which has been dated elsewhere at 16.721 to 15.974 Ma (Gradstein et al., 2012; slightly modified from older timescale of Cande and Kent, 1992, 1994). The reversed polarity section above the dated rocks is attributed to Chron C5Br with an age range of 15.974 to 15.16 (Gradstein et al., 2012; Fleagle et al., 1995).

From these geochronological constraints a non-linear age model can be constructed for the Cerro Observatorio section (Fig. 3.9a). Blisniuk et al. (2005) found a comparable increase in sedimentation rate of the Santa Cruz Formation near Lago Posadas (Fig. 3.9b), attributed to increased rain shadow and Andean uplift. To the south,

A. Age model for Cerro Observatorio section



B. Age model for Lago Posados section

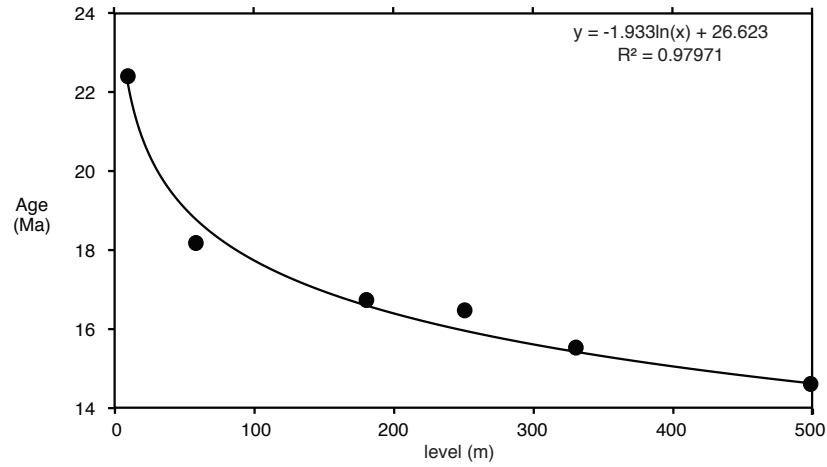


Figure 3.9. Age models for the Santa Cruz Formation based on correlation of sediment thickness with paleomagnetic and radiometric ages at Cerro Observatorio (A) and Lago Posados (B).

the Santa Cruz Formation is overlain by the Pliocene marine Fairweather Formation (Vizcaíno et al., 2006). Sedimentation rate was further enhanced by Pleistocene glaciation producing widespread and thick post-glacial *rodados patagónicos* (“Patagonian pebbles”: Blisniuk et al., 2005).

PALEOSOLS

Modern soils (and by comparison, paleosols) are produced by five major environmental factors: climate, organisms (mainly vegetation), topographic setting, parent material and time for formation (Jenny, 1941). These soil-forming factors, along with other paleosol features and processes, can then be used to infer ancient environments, as outlined in the results below. Table 3.2 contains the complete field observations for each pedotype, with their classification according to the Food and Agriculture Organization (1971, 1974, 1988) and the U.S. Natural Resource Conservation Service (Soil Survey Staff, 2000). Table 3.3 contains the complete interpretations for each pedotype based on the following discussion.

Paleoclimate

No carbonate occurs in the Cerro Observatorio section, which in itself suggests a humid climate, perhaps also cool with low evapotranspiration, as would be expected in high latitudes (Retallack, 2001a). Such general impressions can be quantified by using geochemical climofunctions for paleosols (Sheldon and Tabor, 2009). Table 3.2 details three useful paleothermometers: 1, the alkali index of Sheldon et al. (2002); 2, clayeyness index of Sheldon (2006) and 3, paleosol weathering index of Gallagher and Sheldon (2013). All three paleothermometers require paleosols with argillic (Bt) or well developed cambic (Bw) horizons, but point count and geochemical data on Miocene pedotypes (Figs. 3.6-3.8) reveal that only the Tem and Kak pedotypes are suitably clayey and developed for this kind of interpretation. The three climofunctions give similar mean annual temperatures 8.6 ± 4.4 °C, 10.7 ± 0.6 °C, and 11.1 ± 2.2 °C for the Tem pedotype dated at 16.6 Ma and 8.9 ± 4.4 °C, 11.2 ± 0.6 °C and 11.1 ± 2.2 °C for the Kak pedotype dated at 15.9 Ma (Fig. 3.5). Two useful paleohydometers also are detailed in Table 3.2:

A. Geologic age models (Ma)

Equation	Std. Er.	R2	Dependent variable	Reference
$y = 0.0002x^2 - 0.0398x + 17.204$	±0.24 m	0.97	Stratigraphic level in the Cerro Observatorio section	Herein
$y = -1.933\ln(x) + 26.623$	±1.48 m	0.98	Stratigraphic level in the Lago Posados section (Blisniuk et al, 2005)	Herein; Blisniuk, et al., 2005

B. Geochemical proxies for mean annual temperature (MAT) (°C) in paleosols

Equation	Std. Er.	R2	Geochemical soil variable	Applicability	Reference
$T(1) = -18.5S + 17.3$	±4.4 °C	0.37	Salinization (S)	Bw or Bt from lowland soils with moderate formation times (<100 ka)	Sheldon et al., 2002
$T(2) = 46.9C + 4$	±0.6 °C	0.96	Clayeyiness (C)	Bw or Bt from Inceptisols only	Sheldon, 2006
$T(3) = -2.74 \times \ln(PWI) + 21.39$	±2.1 °C	0.57	Paleosol weathering index (PWI)	Bw or Bt horizons from temperate (>6 °C) forest soils (Inceptisols, Alfisols, Ultisols) with argillans	Gallagher & Sheldon, 2013
$T(4) = -0.4359(\delta^{18}O) + 5.6097$	±0.42 °C	0.63	Oxygen isotopic value of carbonate		Stevenson et al., 2010

C. Geochemical proxies for mean annual precipitation (MAP) (mm/yr) in paleosols

Equation	Std. Er.	R2	Geochemical soil variable	Applicability	Reference
$P(1) = 221.1 e^{0.0197(CIA-K)}$	±181 mm	0.72	Chemical index of alteration without potassium (CIA-K)	CIA-K(Bw or Bt in paleosol) must be >5 units higher than CIA-K(parent material)	Sheldon et al., 2002
$P(2) = -259.3 \ln(\Sigma \text{ bases}/Al) + 759$	±235 mm	0.66	Bases (Ca, Mg, Na, K) over alumina	Bw and Bt horizons	Gallagher & Sheldon, 2013
$P(3) = -59.815(\delta^{13}C) - 52.668$	±55 mm	0.90	Carbon isotopic value of carbonate		Stevenson et al., 2005

Table 3.2. Equations and climofunctions used in this study.

Pedotype	Measured section	Paleoclimate	Vegetation	Animals	Paleotopography	Parent material	Time (ka)
Chejhchej	n/a	Not diagnostic	Grassy shrubland		Well drained sandy levee	Quartzofeldspathic sand	< 0.1
Chorlo	Fig. 8a	Not diagnostic	Grassy woodland		Streamside swale or lake margin	Reworked rhyodacitic ash	1-2
Hö	Fig. 6a	Not diagnostic	Early successional grassland		Streamside levee	Reworked rhyodacitic ash	<0.1
Huaïtenk	Fig. 7c	Not diagnostic	Wooded grassland		Streamside swale or lake margin	Reworked rhyodacitic ash	3-10
Kak	Fig. 7a	Cold temperate subhumid	Halophytic woodland	New World monkeys	Streamside swale or lake margin	Reworked rhyodacitic ash	5-10
Kaôpen	Fig. 7d	Not diagnostic	Wooded grassland		Alluvial floodplain	Reworked rhyodacitic ash	1-3
Oom	-	Not diagnostic	Grassy shrubland	Dung beetles (<i>Coprinisphaera</i>)	Well drained terrace	Vitric volcanic ash	<1
Tem	Fig. 6b	Cold temperate subhumid	Grassland		Moderately well drained floodplain	Reworked rhyodacitic ash	5-12
Uaye	Fig. 6c	Not diagnostic	Halophytic		Seasonally flooded salina	Reworked rhyodacitic ash	3-5
Zak	Fig. 7b	Not diagnostic	Wooded grassland		Streamside levee		<1
Zapelûn	Fig. 8b	Not diagnostic	Early successional grassland	Solitary bees (<i>Cel-liforma</i>)	Streamside levee	Reworked rhyodacitic ash	<1

Table 3.3. Cerro Observatorio paleosol interpretations.

1, the CIA-K index of Sheldon et al. (2002), and 2, the total bases index of Gallagher and Sheldon (2013). These also give similar mean annual precipitation 902 ± 181 mm, and 798 ± 235 mm for the Tem pedotype dated at 16.6 Ma and 916 ± 181 mm, and 930 ± 235 mm for the Kak pedotype dated at 15.9 Ma (Fig 3.5).

These paleoclimatic estimates from Cerro Observatorio are similar to estimates from the isotopic composition of carbonate nodules in the Santa Cruz Formation from Lago Posadas (Blisniuk et al. 2005) using isotopic climofunctions from Washington, USA (equation 4 in Table 3.2) by Stevenson et al. (2005, 2010) (Fig. 3.10). Soils on Palouse Loess of Washington are at a comparable latitude to Patagonia, and also support C3 vegetation in the rain shadow of a calcalkaline volcanic arc. These Washington soils are thus a better comparison set than isotopic climofunctions based on soils in the Texas coastal plain (Dworkin et al., 2005). Using the age model of Fig. 3.9b, the level in Lago Posadas dated at 16.6 Ma gives a mean annual temperature based on oxygen isotopic composition of 10.7 ± 0.4 °C and a mean annual precipitation based on carbon isotopic composition of 513 ± 64 mm, and the level dated at 15.9 Ma gives mean annual temperature of 10.4 ± 0.4 °C and a mean annual precipitation based on carbon isotopic composition of 608 ± 64 mm. These estimates from Lago Posadas are indistinguishable from those derived from Cerro Observatorio paleosols, but the Lago Posadas record is more continuous. The three-spikes of warm wet conditions at 17.4, 16.6 and 15.4 Ma match precisely the marine oxygen isotopic record of paleoclimate (Fig. 3.1), perhaps in part because these deep-sea records are primarily from the South Atlantic and nearby Antarctic Oceans (Zachos et al. 2001). Both the Lago Posadas and South Atlantic records differ from other continental records from equatorial Africa and North America with a distinct middle Miocene spike in precipitation and temperature (Fig. 3.2).

These warm temperate climates can be contrasted with the modern dry cold temperate climate of Cerro Observatorio. Nearby Santa Cruz, Argentina, has mean annual temperature 8.5 °C, mean annual precipitation 200 mm, mean annual range of temperature 12.5 °C and mean annual range of precipitation 18 mm (Müller, 1982)

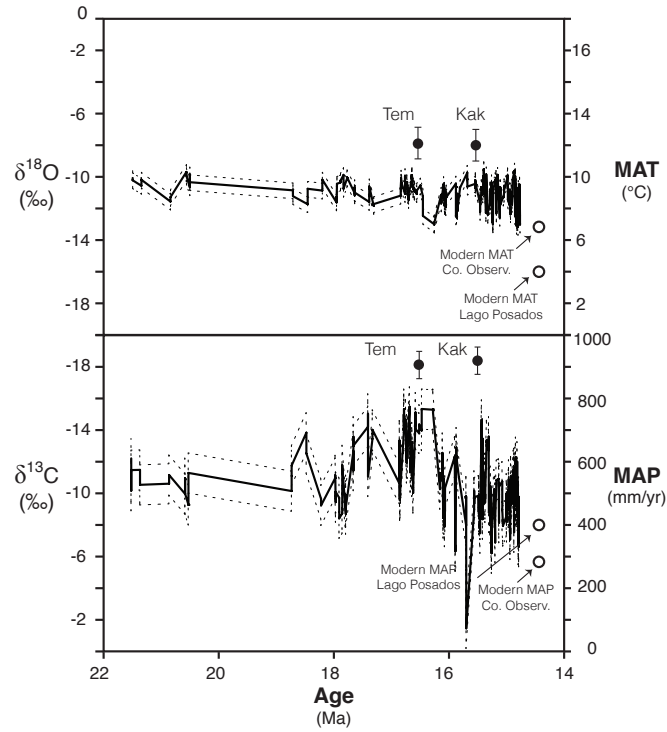


Figure 3.10. Mean annual precipitation and temperature records for Lago Posados, derived from the isotopic values of pedogenic carbonate (Blisniuk et al., 2005). Dashed lines reflect reflect error bars. Closed circles show the MAT and MAP for two pedotypes at Cerro Observatorio. Open circles show modern MAP and MAT values (Paruelo, 1998a). All equations used are listed in Table 2.

Former vegetation

Past vegetation supported by the various paleosols at Cerro Observatorio can be reconstructed from the form of root traces within them. The most striking of these were seen in Kak paleosols, which have casts of tree trunks arising from spreading woody roots (Fig. 3.11). The bole casts have a thin, uniform outer layer around a laminated (<1 to 1 cm) center, likely a result of a period of initial external infilling as the tree decayed, followed by complete replacement. These were not large trees; the maximum diameter observed is 38 cm. There is little observed taper from the root base to the trunk, and if this diameter can be assumed to be the same as that at breast height (1.2 m), then using the regression equation of Niklas (1994) for 670 species of modern vascular plants gives an estimated canopy height of 9.2 ± 0.9 m. This is an estimate of maximum height, as diameter at breast height is smaller than that measured. The Kak trunks thus represent a woodland, rather than a forest (White, 1983). Multiple boles from the same rooting base in some of the Cerro Observatorio trunks (Fig. 3.11) can also be taken as evidence of woodland, because multiple boles are widespread in modern African dry to open woodlands, but single trunks more common in forest trees (Retallack, 1991). Additional clues to the nature of this woodland come from the drab color, spreading roots, modest weathering and high soda of the Kak pedotype (Fig. 3.7a). Few roots penetrate deeper than 30 cm, and brown haloes to the roots in the grey matrix are like those of modern wetland soils (Vepraskas and Sprecher, 1997). Lack of root penetration beyond 30 cm indicates a water table at that depth in a climatic regime of seasonal drying that left the soil prone to seasonal salt efflorescences. Other pedotypes with high soda, drab colors and large root traces include Zak, Huañtenk and Chorlo pedotypes (Figs. 3.7b,c, 3.8a), and these may also represent woodlands and shrublands of seasonally dry salinas.

Fine root traces and crumb to granular ped structures in other pedotypes (Uaye, Tem, Kaôpen, Zapelûn, and Hö) are evidence of grass-dominated vegetation, found globally in paleosols of Miocene age (Retallack, 1991, 2001a, 2004). This group of pedotypes can be divided into two groups: those thoroughly rooted with good ped structure (Tem, Kaôpen) and those sparsely rooted with relict bedding (Uaye, Zapelûn, Hö). The thoroughly rooted pedotypes (Tem, Kaôpen) are comparable with modern

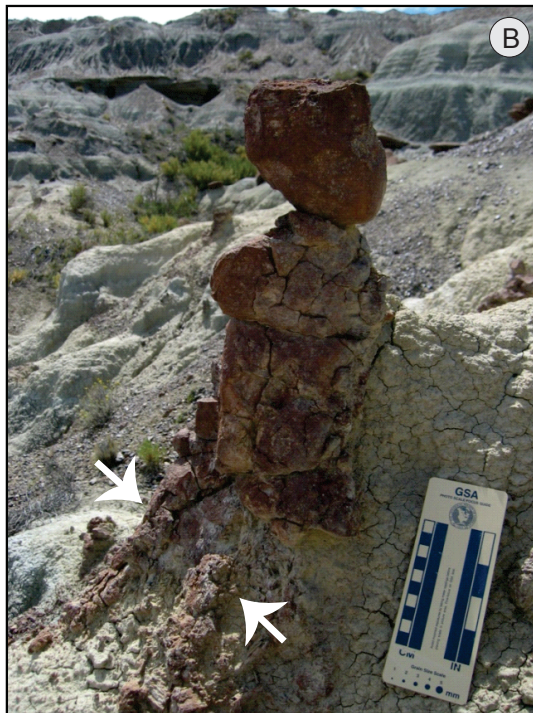


Figure 3.11. Tree boles from Kak paleosols. A shows the two A horizons from the lower Kak paleosol. B shows the preserved roots, indicating that the trees are *in situ*. Scale bar divisions are in centimeters and inches.

freely drained grassland soils with their warm colours and moderate surficial soda (Figs. 3.6b, d). The others (Uaye, Zapelûn, Hö) have high soda and also are thin with common relict bedding (Figs. 3.6c, 3.8b). Subsurface development of gypsum stringers in the Uaye pedotype is evidence of plant limitation by salt, and thus perennial halophytic plants (Retallack and Huang, 2010). In contrast, Hö and Zapelûn pedotypes have thin profiles with much relict bedding and surficially depleted soda, as evidence of a short time for development, and grassy communities early in the ecological succession of plant colonization of ground disturbed by flooding. Pedotypes of the uppermost part of the measured section (Chejhchej, Oom) also have weak structure and sparse roots indicative of early successional vegetation.

Several of these weakly developed paleosols (Zapelûn, Chejhchej and Oom) preserve trace fossils of invertebrates including ground nests of solitary bees (*Celliforma*) and boli of dung beetles (*Coprinisphaera*) (Fig. 3.12). Comparable trace fossils of bees in Argentine Miocene paleosols elsewhere have been interpreted as evidence of dry open vegetation and dung beetles as evidence of grasslands (Genise and Bown 1994; Genise et al., 2004).

Paleotopography

Cerro Observatorio paleosols are gray to brown in color (Fig. 3.4), unlike reddish brown paleosols in the Lago Posadas section of the Santa Cruz Formation (Blisniuk et al., 2005). Mild reddening of paleosol surfaces above drab subsurface horizons is evidence of groundwater gleization (Vepraskas and Sprecher, 1997). Water tables were persistently high during formation of the paleosols, but not permanently high because many pedotypes (Uaye, Kak, Huaïtenk, Chorlo, Zapelûn) have high soda/potash molar ratios, indicating salinization (Fig. 3.6c, 3.7a,c, 3.8a,b). These are characteristic of salt-affected soil types such as Solonetz and Solonchak of the Food and Agriculture Organization (1971). In sedimentological terms, these are soils formed in and around playas and salinas (Rosen, 1994). Other pedotypes (Tem, Kaôpen, Chejhchej, and Oom) show deeply reaching root traces, surface desalinization and brown to reddish colours indicative of free drainage, though still with subsurface horizons drab due to high water



Figure 3.12. Evidence of bioturbation. A. Solitary bee burrows (*Celliforma* sp.), indicated by white arrows, in the Zapelûn pedotype. Pencil for scale, about 15 cm. B. Silicified burrows from the Chejchej pedotype. C. and D. Dung beetle broods (*Coprinisphaera* sp.) from the Oom pedotype.

table (Vepraskas and Sprecher, 1997). Thus the Cerro Observatorio section of paleosols formed on a low relief coastal plain, in contrast with paleosols of the Santa Cruz Formation at Lago Posadas which formed on alluvial fans and high terraces close to the Andean mountain front (Blisniuk et al., 2005).

Former parent material

Paleosols of Cerro Observatorio are clayey and sandy, with modest amounts of silt, unlike silty paleosols of the Lago Posadas section of the Santa Cruz Formation (Blisniuk et al., 2005). The parent material of the paleosols at Cerro Observatorio was largely fluvial and lacustrine sediments, rather than windblown silt which characterizes soils of the fertile loess plains nearer Buenos Aires (Plaza and Moscatelli, 1989). Airfall vitric volcanic ash from Andean volcanoes was observed at several levels in the Cerro Observatorio section (Fig. 3.4), but exclusively formed parent material only to the Oom pedotype. Other paleosols also had a roughly rhyodacitic chemical composition, but consisted of recycled rhyodacitic ash and quartzofeldspathic rocks from the Argentine Precordillera.

Time for development

Point counting and geochemical analyses showing little variation within paleosols from Cerro Observatorio confirm field observations of relict bedding and sparse roots that many of the pedotypes (Zapelûn, Zak, Hö, Chejhchej) are very weakly developed (in scale of Retallack, 2001a). Pronounced surficial salinization of some profiles (Kak, Chorlo) would have taken many seasons of salt efflorescence and persistence through the wet season. Similarly gypsic stringers in the Uaye pedotype would have taken some time to accumulate. Unfortunately chronofunctions based on salt accumulation are useful only for freely drained desert soils (Retallack and Huang, 2009), not salina and playa soils in which salts are introduced from an evaporating high water table (Rosen, 1994). Other pedotypes show modest surficial (Kaôpen) or subsurface weathering (Tem, Huaïtenk), and can be regarded as weakly to moderately developed, respectively (in scale of Retallack, 2001a).

The Cerro Observatorio section is sufficiently well dated (Fig. 3.5) to allow upper limits to be placed on soil formation, with the proviso that many estimates of soil formation durations are an order of magnitude less than radiometric durations because of ubiquitous disconformities in paleosol sequences (Retallack, 1998). Nevertheless, four Tem and four Uaye paleosols between 13 and 20 m in the section represent 16.40-16.62 Ma for an average of 22.5 ka apiece, and a Chorlo, Chejhchej, 3 Oom and a Zapelûn paleosols between 94 and 99m represent 15.22-12.25 m for an average of 5 ka apiece.

The well-dated silty to sandy alluvial chronosequence of the San Joaquin Valley of California formed in a semiarid temperate climate (Harden, 1982, 1990), analogous with these Patagonian paleosols, and can be used to constrain their times of soil formation. The very weakly developed paleosols of Cerro Observatorio are comparable to Californian soils less than 200 years old on the post-Modesto surface, weakly developed paleosols are like those 3000-10,000 years old on the post Modesto II and upper Modesto surfaces, and moderately developed paleosols are no better developed than 40,000 year old Californian soils of the lower Modesto surface.

PALEOENVIRONMENTAL RECONSTRUCTIONS

Paleoenvironmental inferences from the various pedotypes of the Santa Cruz Formation are arranged as a summary narrative of early to late Miocene paleoenvironmental change in the following paragraphs. For this purpose the measured section at Cerro Observatorio (Fig. 3.5) has been divided into three parts: 1, a tuffaceous lower 33 m of Early Miocene (Burdigalian) age; 2, a middle sandy part (33-52 m) of early Middle Miocene (early Langhian) age; and an upper part 52-100 m with very thick paleochannels of later Middle Miocene (later Langhian) age. The assemblage of paleosols within each of these units can also be considered as a soilscape and compared with modern soil map units (Food and Agriculture Organization, 1971).

Early Miocene (16.9-16.0 Ma)

The early Miocene portion of the Santa Cruz Formation (Fig. 3.13) is dominated by crumb structured and finely rooted Tem paleosols, interpreted as cold temperate,

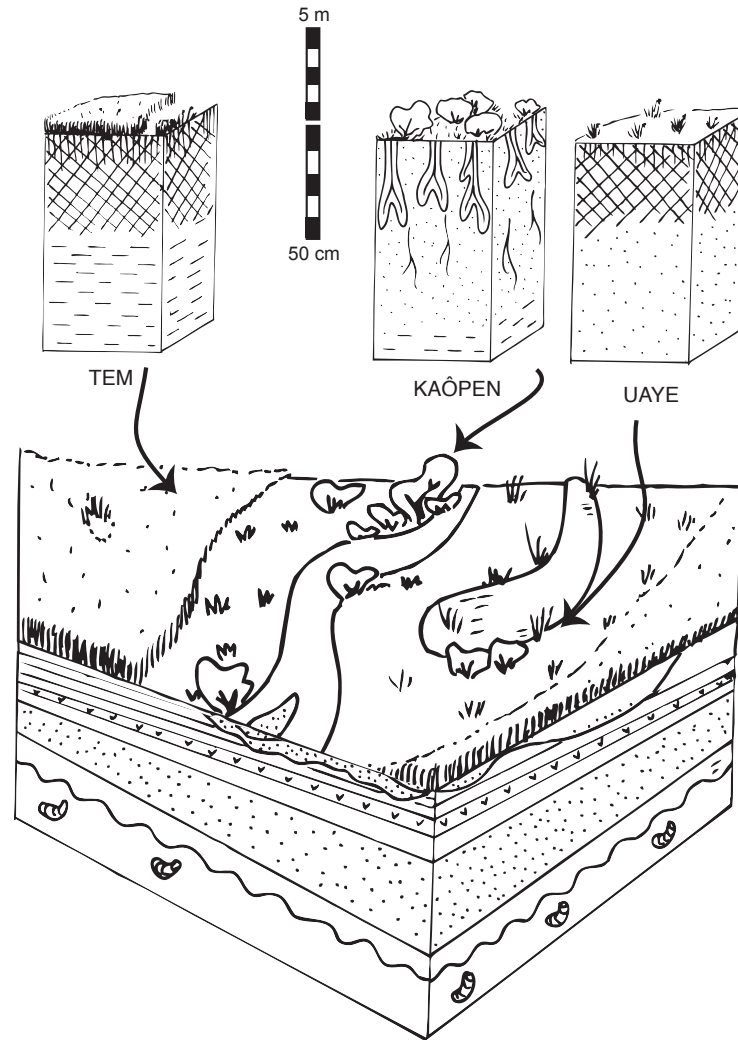


Figure 3.13. Reconstructed Early Miocene paleoenvironment at Cerro Observatorio.

subhumid grassland soils (Table 3.3). Also common are Uaye paleosols, shallow rooted, gray and sodic, formed in local salinas with sparse halophytic vegetation. A few Kaôpen paleosols represent areas of low wooded grassland, perhaps forming a riparian fringe. Closest to streams was a fringe of early successional grassland on Hô and Zapelûn paleosols. Only Tem paleosols are sufficiently well developed and well drained to reflect climate and these indicate a cold temperate (11.1 ± 2.2 °C mean annual temperature) subhumid climate (902 ± 181 mm mean annual precipitation)

In terms of the Food and Agriculture Organization (1971) soil map of South America, this lower unit is dominated by Haplic Phaeozems (Tem pedotype) with subsidiary Haplic Kastanozems (Kaôpen pedotype) and Gleyic Solonchaks (Uaye pedotype) like map unit Hh2-1b which covers a large are of the Pampas centered on General Pico, adjacent to map units Zg2-3a and Kh1-1a. The observed historic climate of Macachín nearby is mean annual temperature of 15.2 °C, mean annual precipitation 608 mm, with mean annual range of temperature 16.3 °C and difference between wettest and driest month precipitation 58 mm (Müller, 1981). Modern vegetation around Macachín is largely pampas grassland on rolling plains, with local salt scrub in saline depressions (Food and Agriculture Organization, 1971).

Early Middle Miocene (16.0-15.6 Ma)

The middle part of the Cerro Observatorio section (Fig. 3.14) also has a variety of pedotypes, of which Kak is most common. Tree bole steinkerns are found at two stratigraphic levels in Kak paleosols, and from their small (~30 cm) diameter represent woodland trees, many with multiple boles. High soda and gray color of Kak paleosols indicate salic soils with high water tables, perhaps around a lake margin. Almost as common are Zak paleosols, which like Huaïtenk paleosols also are grey and more or less sodic, representing different wooded wetland communities of a lake or river bottomland. Kaôpen paleosols of low wooded grassland and Zapelûn paleosols of early successional grassland may have formed a riparian fringe. Most paleosols at this stratigraphic level are too gleyed or weakly developed to be diagnostic of climate, but Kak paleosols are

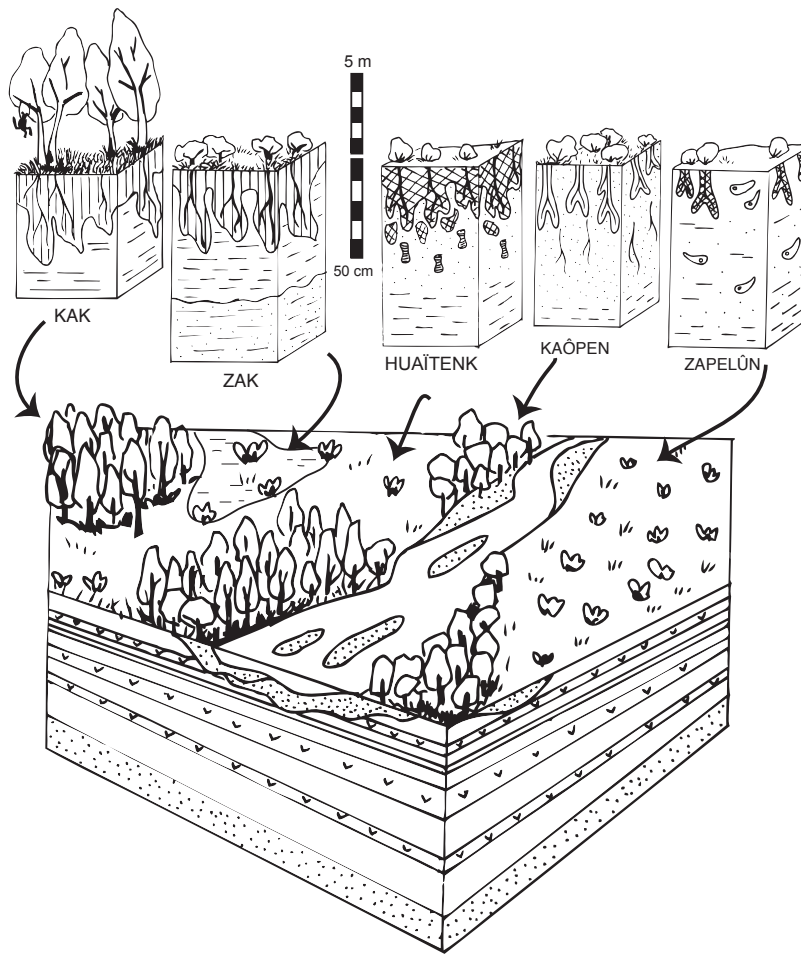


Figure 3.14. Reconstructed Early Middle Miocene paleoenvironment at Cerro Observatorio.

evidence of a cold temperate subhumid climate not much different than before (11.1 ± 2.2 °C mean annual temperature, 916 ± 181 mm mean annual precipitation).

In terms of the Food and Agriculture Organization (1971) soil map of South America, this central unit of the measured section is dominated by Mollic Solonetz (Zak pedotype) with subsidiary Humic Gleysol (Kak), Haplic Phaeozem (Kaôpen), Humic Cambisol (Huaïtenk) and Eutric Fluvisol (Hö) like map unit Sm3-3a, which extends from the coastal plain near Las Flores near Buenos Aires south in the Arroyo Vallimanca to Laguna Epecuén, Argentina. Las Flores enjoyed a 20th century climate with mean annual temperature of 15.4 °C, mean annual precipitation 919 mm, with mean annual range of temperature 13.7°C and difference between wettest and driest month precipitation 58 mm (Prohaska, 1976). Laguna Epecuén at the southeastern end of this map unit has the same climate as nearby Macachín, considered above for the Early Miocene part of the measured section. A fluvio-lacustrine setting is also more appropriate for the Gleysols, Cambisols and Fluvisols of the middle portion of the Cerro Observatorio section. Modern vegetation of Arroyo Vallimanca and Laguna Epecuén is xerophytic woodland (Food and Agriculture Organization, 1971).

Later Middle Miocene (15.6-15.2 Ma)

The upper part of the Cerro Observatorio section (Fig. 3.15) accumulated at a much faster rate than the lower part (Fig. 3.9a) and this is reflected in thick sandy paleochannels and abundant weakly developed paleosols such as common Chejhchej paleosols. These paleosols of sand and associated Oom paleosols of volcanic ash have stout and fine root traces of a grassy steppe. Oom paleosols also contain brood balls of dung beetles (ichnogenus *Coprinisphaera*) as evidence of grassland vegetation (Genise and Bown 1994; Genise et al., 2004). Both are well drained paleosols of elevated alluvial fan or terrace surfaces, but also found are gleyed paleosols of wooded wetlands (Chorlo) and wooded grasslands (Zak) presumably along streams. Such bog-meadows and ephemeral wetlands are known as *vegas* in Patagonia today (Bank et al., 2003). Hö paleosols also persist at this level as streamside early successional grasslands, judging from their close association with thick sandy paleochannels upland vegetation.

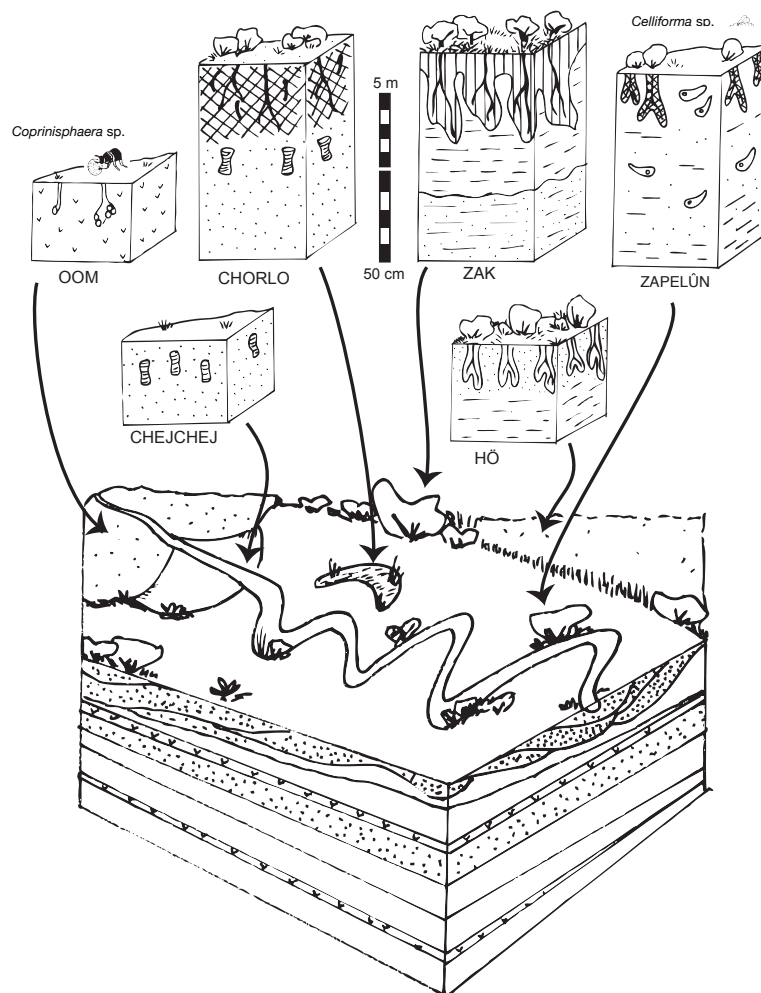


Figure 3.15. Reconstructed Late Middle Miocene paleoenvironment at Cerro Observatorio.

Slickensided argillans and mangans in the Chorlo paleosol (Fig. 3.8a; Ustepts) suggests at least a locally reducing and waterlogged environment, such as an abandoned meander or wetland, analogous to the pond-bog-meadow habitats and ephemeral wetlands known as *vegas* locally (Bank et al., 2003).

Sands with the Chejhchej pedotype with thick cross-bedded channel cuts and silicified burrows (Fig. 3.3.12b) also increase in volume in the upper part of the section. Two ash-rich paleosols (Oom pedotype) contain abundant *Coprinisphaera* sp. dung beetle brood balls (Fig. 3.12c,d) (Genise and Bown, 1994), as well as show signs of other bioturbation such as burrows. Oom paleosols show little pedogenesis, suggesting that soil development was limited or retarded in an arid paleoclimate during the late middle Miocene. The unweathered primary parent material, volcanic ash, may also have provided a geochemically favorable environment to preserve the abundant brood balls. The top of the section contains several Zapelûn paleosols (Fig. 3.8b; Argids), which are inundated with shallow penetrating solitary bee burrows (Fig. 3.12a), evidence of a well-drained and arid soil environment.

In terms of the Food and Agriculture Organization (1971) soil map of South America, this upper unit of the measured section is dominated by Gypsic Yermosol (Chejhchej pedotype) with subsidiary Gleyic Solonchak (Chorlo), Haplic Kastanozem (Zapelûn), Humic Cambisol (Huaïtenk) and Vitric Andisol (Oom) like map unit Yh5-1c, at moderately high elevation in northwestern Argentina near Zapaleri. La Quiaca nearby has climate with mean annual temperature of 9.5 °C, mean annual precipitation 322 mm, with mean annual range of temperature of 8.4 °C and difference between wettest and driest month precipitation 89 mm (Müller, 1982). This is a significant cooling and increase in seasonality compared with paleosols lower in the section. Vegetation of the region around Zapaleri and la Quiaca is puna steppe (Food and Agriculture Organization, 1971).

DISCUSSION: IS THE MIDDLE MIOCENE A VIEW OF THE FUTURE?

A section of Santa Cruz Formation at Lago Posadas, 150 km west from Cerro Observatorio and in the foothills of the Andes, contains pedogenic carbonate, unlike the

paleosols at Cerro Observatorio. Carbon isotope studies of pedogenic carbonate (Blisniuk et al., 2005) from there also support a significant ecosystem shift at 16.5 Ma. Isotopic carbon values in their lower (pre-16.5) section suggest a “pure C3 ecosystem” (balanced woodland and grasslands) with a decrease of -9.8 to -11.8 suggesting increased humidity. After 16.5 Ma, isotope values shift to greater than -10, and even greater than -8, which implies increased aridity and possibly higher proportion of C4 grasses. Blisniuk et al. (2005) also report increased sediment accumulation rates up section which is also suggested by this study’s findings. Surface uplift in the southern Andes likely instituted a strong rain-shadow induced aridification of this region. Middle Miocene (19-13 Ma) paleosols from the Atacama Desert in Chile also reflect a dramatic shift in moisture regimes, from >200 mm/yr to <20 mm/yr, due to a combined effect of global climate change and the onset of the Andean rain shadow effect (Rech et al., 2006). The Atacama Desert became hyperarid, so that sedimentation rate declined due to lack of transporting water, but the Patagonian sections changed from stabilizing woodland to open shrubland and bunch grassland in which soil erosion rates increased through time.

In the Estancia La Costa Member of the Santa Cruz Formation, 100 km to the south of Cerro Observatorio, from the middle Miocene to the Late Miocene there is a loss in brachydont-toothed animals (from 17.2% to 0%) and an increase in euhypsodonts (from 51% to 64%) (Tauber, 1997b). Tauber (1997b) also notes an overall decrease in taxonomic diversity, a decrease in the number of species with the largest and smallest body sizes, an increase in glyptodontid and toxodontid diversity, a decrease in megatheroideid body size, and a decrease in protheroteiid diversity, all suggesting a trend toward cooler, drier climate up section. Armadillo diversity also tracks a similar change during this time period, and reflects a paleoenvironment shifting to one like the modern Chaqueña biogeographic province, with open vegetation in a dry, seasonal climate (Vizcaíno et al., 2006). Thus, multiple lines of evidence also support the climatic shifts recorded in the paleosols of the Santa Cruz Formation at Cerro Observatorio.

Modern soils in the Santa Cruz province are mostly Aridisols (51.3%), Mollisols (20.0%), Entisols (19.0%), and Andisols (5.9%); at Cerro Observatorio, the modern soils are Argids, like those found in the early and late Miocene (del Valle, 1998) (Fig. 3.16).

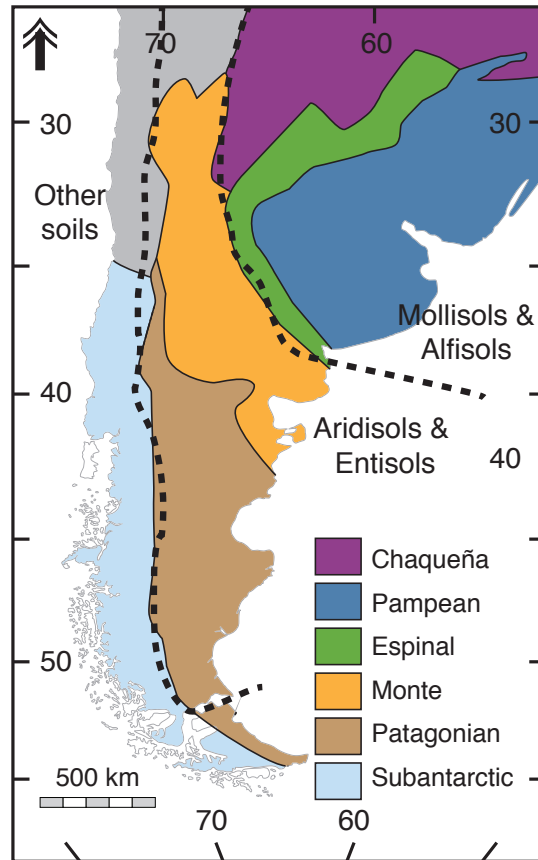


Figure 3.16. Modern phytogeographic provinces and dominant soil types. Colored polygons indicate phytogeographic provinces (after Cabrera, 1976; Iglesias et al., 2011). Dashed lines indicate the dominant soil types: Mollisols and Alfisols to the northeast and Aridisols and Entisols in the central region (after INTA, 1990; Garbulsky and Deregibus, 2006).

Alfisol like those that characterize the middle Miocene have limited extent in modern Patagonia, except in the Andean foothills and isolated locations in northern Patagonia. The modern landscape falls within the semi-desert and shrub-steppe Patagonian biozone (Fig. 3.16) (Paruelo et al., 1998b), also similar to the paleoenvironments reconstructed for the late Miocene in this study. The woodland vegetation and Alfisols that characterize the middle Miocene thermal maximum are more like the monte steppe or deciduous forest now found to the north and west, respectively, in Patagonia. A future climate change of the magnitude experienced in the middle Miocene could have similar effects on the regional soil and biozone distribution in Patagonia, increasing woodlands to the east and south in addition to increasing temperature and precipitation levels.

CONCLUSIONS

The Santa Cruz Formation, in addition to being one of the richest fossil vertebrate localities, contains a paleosol record of middle Miocene climate change. The middle Miocene thermal maximum is characterized by paleosols developed under open woodland-shrubland vegetation, during a period of climatic warmth and humidity. Paleosols before and after the middle Miocene are characteristic of arid environments in the Andean rain shadow.

Understanding how arid environments, like the open shrubland maintained in coastal Patagonia at present, respond to relatively small climate changes, like that of the middle Miocene, has important ramifications for understanding the possible effects of coming global climate change. The effect of coming warming and humidity, as in the middle Miocene, will probably result in increased weathering under higher biomass vegetation.

BRIDGE

Chapter III presented a new study of the middle Miocene paleosol record at Cerro Observatorio in Santa Cruz province, Patagonia, Argentina. Chapter IV combines the new studies presented in Chapters II and III with data from the existing Miocene paleosol record into a soil map of the middle Miocene thermal maximum.

CHAPTER IV

GLOBAL SOIL AND CLIMATE MAPS

OF THE MIDDLE MIOCENE THERMAL MAXIMUM

INTRODUCTION

Paleosols as paleo-analog for future change: Ancient soils, shifting landscapes

Paleosols represent ancient landscapes that record past climatic, biologic, and atmospheric conditions and hence have proven useful in the interpretation of past climates, environments, and geographies (Retallack, 1997a; Kraus, 1999). Soils systematically and distinctly change with alteration of any of the five soil-forming characteristics: climate, organisms, relief, parent material, and time (Jenny, 1941). The connection between soils and climate makes the study of paleosols a powerful tool to investigate the mechanisms of past global climate change (Retallack, 2001b, 2007a, b, 2013; Bestland et al., 2008), and to verify model predictions of paleoclimate and future climate change (Sheldon, 2006). Coupled with other paleoclimatic proxies such as palynofloras (Davis and Ellis, 2010), fossil plants (Dillhoff et al., 2009), fossil vertebrates (Fremd, 2010), and carbon and oxygen isotopes (Blisniuk et al., 2005; Takeuchi et al., 2010), paleosols can provide robust reconstructions of past climate changes and a whole ecosystem-type approach to understanding paleoenvironments (Retallack, 2004; Retallack et al., 2000). The global map of various types of paleosols compiled here enables a synoptic view of how climatic change during the middle Miocene thermal maximum shifted appearance of the land surface.

In this study, a new Micoene Soil Database (MSDB) combines new data from studies in Australia and Argentina (Metzger and Retallack, 2010; dissertation Ch III), with data from a thorough and recent literature survey and a targeted search of the Paleobiology Database. The data are used to derive a paleogeographic map that describes the middle Miocene climatic and soil type zones, in order to compare with predictions of modern global climate change.

Climate change: present and past

In a recently released report, the Intergovernmental Panel on Climate Change (IPCC) concluded that current rates of global warming are “very likely” the result of human-induced increased greenhouse gas emissions, particularly carbon dioxide (Alley et al., 2007). Climatic models and projected anthropogenic carbon emissions into the atmosphere suggest this warming trend could be 1 to 6 °C from current global mean temperature by the year 2100 (Alley et al., 2007). The consequences of such temperature increases include increased ocean heating, sea ice and glacier melting, and ecosystem shifts (Vitousek, 1994; Retallack, 2011). Christensen et al. (2007) predicted warming over all land areas, drying in the subtropics, and increasing precipitation in higher latitudes and parts of the tropics. While the extent of such environmental changes will be wide-reaching and the debate about how to address climate change impacts, vulnerabilities, and mitigation continues, global warming events are well known in Earth history (Retallack, 2010, 2011).

The middle Miocene thermal maximum (~16 Ma) was a period during the Cenozoic when climate change was similar both in its global geographic scale, magnitude of temperature change and inferred greenhouse gas content, to changes predicted to occur by the year 2100 (Flower and Kennett, 1994; Lear et al., 2000; Zachos et al., 2001; Sheldon, 2006; Alley et al., 2007). This point combined with the fact that by the Miocene, the continents were close to their modern configuration, meaning their effects on atmospheric and oceanic circulation were likely similar (Gradstein et al., 2012), suggests that this period can provide an analog for understanding modern climate change. Similar warm spikes occurred in the Eocene and Paleocene, but grasslands and large mammalian grazers had not yet evolved, rendering the world quite different from modern (Jacobs et al. 1999; Retallack 2001, 2013). Furthermore, the middle Miocene levels of ~900 ppmv atmospheric CO₂ estimated from pedogenic carbonate and from fossil *Ginkgo* stomatal index (Retallack, 2002, 2009, 2013) were of a similar magnitude to that projected to occur by the year 2100 by scenario A1, which posits continued population growth, high economic growth, and relatively high energy and materials consumption (Alley et al., 2007). Thus, past climate change and its associated ecosystem shifts can be

investigated to provide significant insight into the future shift in current ecosystems and environments due to global warming.

Globally, middle Miocene sediments, including paleosols, are abundant, well-preserved, and well-dated, both radiometrically and biostratigraphically (Alonso Zarza et al. 1992; Bestland, 1990; Bestland et al., 2008; Retallack 2004, Blisniuk et al., 2005). All major floral and faunal groups, including grasslands and herbivorous grazers are represented within this abundance of sediments (White et al., 1997; Retallack 2001a, 2007a, 2013; Utescher et al., 2011). Paleosol chemical composition in Oregon (Fig. 4.1) reveals a warming trend peaking during the middle Miocene 2 °C warmer than present (Gallagher and Sheldon, 2013) that correlates well with the deep ocean plankton record of Zachos et al. (2001). During this time period, thermophilic plant and animal taxa expand globally to high paleolatitudes (Axelrod and Raven, 1978; Bown and Fleagle, 1993; Bown and Larriestra, 1990; Christensen, 1975, 1976; Wolfe, 1971, 1994a, b; Wolfe and Tanai, 1980).

Throughout the Pacific Ocean, marine sediments record middle Miocene warm spikes lasting about two million years (Tsuchi, 1992). Lateritic paleosols, which now are restricted to tropical regions (Retallack, 2010), formed at high paleolatitudes such as Oregon, Japan, Germany, and New South Wales, Australia (Schwarz, 1997). Marine records show similar northern and southern habitat invasion of thermophilic molluscs and foraminifera (Itoigawa and Yamanoi, 1990; McGowran and Li, 1997). Paleotemperature reconstructions of middle Miocene Antarctica pollen flora indicates that its climate was similar to the South Island of modern-day New Zealand (Axelrod and Raven, 1978). Paleosols from Oregon, Montana, Nebraska, and Kenya record increases in mean annual precipitation during the middle Miocene thermal maximum, followed by decreases (Retallack, 2004, 2007a,b, 2009, Sheldon, 2006)

A cooling and drying pattern commences from 15 Ma onwards resulting from the onset of glaciation in Antarctica (Zachos et al., 2001), deep ocean water cooling (Flower and Kennett, 1994), and increased carbon and water vapor storage and albedo of newly evolved grassland soils (Retallack, 2001, 2007a, 2013). Ranges of lateritic and bauxitic soils contracted from their latitudinal extremes reached during the middle Miocene (Retallack, 2010). Cooling on land is also apparent from deuterium values for supergene

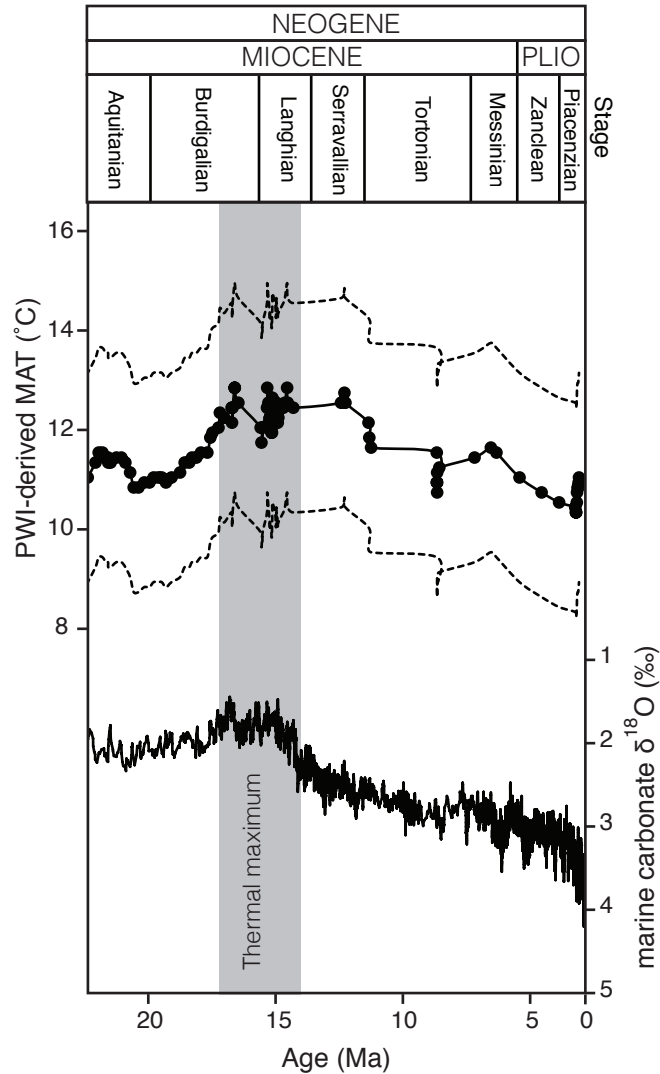


Figure 4.1. Paleotemperature records derived from the paleosol weathering index of Eastern Oregon paleosols (Retallack, 2007a; Gallagher and Sheldon, 2013) shows temperatures higher than modern or pre-Miocene. Dashed lines show $\pm 2.1^{\circ}\text{C}$ error range. Oxygen isotopic data from Cenozoic benthic foraminifera from the Atlantic Ocean similarly reflect middle Miocene warming (Zachos et al., 2001). The Middle Miocene thermal maximum is highlighted in grey.

alunite (Arehart and O'Neil, 1993). Global cooling and drying from 15 Ma is evidenced paleobiologically by decreasing plant diversity, fewer exotic plants, and greater numbers of cool-climate species (Axelrod and Raven, 1978; Mosbrugger et al., 1994; Wolfe, 1994a, b). Cooling at mid- and high-latitudes led to a salinity stratified ocean (Raymo, 1994; Schoell et al., 1994) and more distinctive climatic zones in marine microfossils and their oxygen isotopic composition (Savin et al., 1975; Wright et al., 1992; Flower and Kennett, 1994). This transition is recorded in both marine and terrestrial sediments and probably occurred synchronously in northern and southern hemispheres (Flower and Kennett, 1994; Gallagher et al., 2001).

Connection to carbon dioxide

Climate change throughout the Cenozoic era (the last 65 Ma) has been strongly linked to changes in atmospheric carbon dioxide (Berner and Kothavala, 2001; Kürschner, 2008; Pearson and Palmer, 2000; Retallack, 2001, 2002, 2009), although its role in the middle Miocene is controversial. During the early Miocene (20Ma) CO₂-levels are thought to have been three times preindustrial levels (900 ppmv) at 20 Ma dropping to preindustrial levels (280 ppmv) by 15 Ma, from evidence of both *Ginkgo* stomatal index (Retallack, 2002; Kürschner, 2008) and carbon isotopic composition of pedogenic carbonate (Retallack, 2009). High levels of atmospheric carbon dioxide in the middle Miocene are also supported by mass balance inventories of sedimentary rocks (Berner and Kothavala, 2001) and by the boron isotopic composition of marine foraminifera (Pearson and Palmer, 2000). However, some early studies of pedogenic carbonate isotopes (Ekart et al., 1999) and of *Ginkgo* stomatal index (Royer, 2003; Royer et al., 2001) failed to find evidence of high carbon dioxide because of coarse temporal spacing of their data. The marine alkenone paleobarometer of Pagani et al. (1999a,b) is alone in finding middle Miocene atmospheric carbon dioxide lower than modern, and appears to have been compromised by changing middle Miocene oceanic productivity (Retallack, 2002). Events that are thought to have contributed to the CO₂ increase that triggered the thermal maximum associated with the middle Miocene include those proposed by Hodell and Woodruff (1994) and Retallack (2004, 2009) who attribute increased carbon dioxide emissions to the eruption of the Columbia River Basalts

(Wignall, 2001). Retallack (2004) also suggests that a bolide impact at Ries, Germany (24 km wide, 15 ± 0.1 Ma), may have been contributor to climate warming during the middle Miocene. Researchers (Ekart et al., 1999; Pagani et al., 1999a, b; Royer, 2003; Royer et al., 2001) who found no evidence for elevated middle Miocene CO₂ concentrations argue that factors, other than or in addition to CO₂, such as atmospheric water vapor or cloud albedo, explain transient warm periods like that of the middle Miocene.

MIOCENE SOIL DATABASE AND MAPS

Database compilation

The Miocene Soil Data Base (MSDB) was compiled using paleosols from new data (Metzger and Retallack, 2010; dissertation Ch III), a new literature survey, and climatically sensitive lithologies from the Paleobiology Database¹ for the middle Miocene. Appendix C contains the MSDB, with location information, lithology and paleopedology, soil and vegetation information, mean annual temperature and precipitation estimates. Lithologic data were downloaded from the Paleobiology Database via the GEON PaleoIntegration Portal². Current longitude and latitude were taken from the primary references directly or, more commonly, estimated from the current geographical information and the Google Earth computer program (Butler, 2006). Paleolatitude and paleolongitude were then calculated using the AutoPointTracker program (Scotese, 2002). Data from previous studies of paleosols from 17-14 Ma were added to the database as the result of a literature survey of middle Miocene terrestrial formations, paleopedological studies, and paleobotanical collections. Data from the Paleobiology Database focus on the undifferentiated “middle Miocene,” including Langhian and Seravallian ICS stages, from 15.97-11.63 Ma (Gradstein et al., 2012).

The FAO-UNESCO Soil Map of the World defines soil map units on the basis of diagnostic horizons (soil layers) and properties, which are quantitative functions of soil development and processes (Food and Agriculture Organization, 1988). The USDA Global Soil Map (Soil Survey Staff, 2005) is similarly constructed, although differences

¹ <http://paleodb.org/> (accessed 4/2008) (Alroy et al., 2008)

² <https://portal.geongrid.org/gridsphere/gridsphere?cid=geonpaleo> (accessed 4/2008; currently offline)

between the two soil classifications means that direct correlation is sometimes not possible. The USDA soil taxonomy was used in this study, because it is the one most commonly used in paleosol studies to date (e.g., Retallack, 1991; Retallack and Dugas, 1995; Retallack et al., 2000, 2001; Bestland et al., 2008; Metzger and Retallack, 2010). The resolution of the MSDB is such that the 12 Order USDA taxonomy allows more meaningful mapping of the paleosol locations than the 26 World Classes of the FAO scheme. Each paleosol and lithology were assigned to soil order, selected on the basis of prescribed characteristics (Soil Survey Staff, 2000). For most other studies that have reliable stratigraphic or paleobotanical information, it was possible to draw inferences from rock type, floral communities, and faunal assemblages as to likely associated soil types. The Paleobiology Database units of interest were gypcretes, calcretes, evaporites, lignites or coals, and bauxites. Gypcretes were interpreted as Gypsic Aridisols (Gypsids), calcretes as Calcic Aridisols (Calcids), and halites and salt deposits as Salic Aridisols (Salids) of Soil Survey Staff (2000). Peat, brown coal, and lignite deposits were interpreted as Histosols. Kaolinite deposits were interpreted as Utisols, and bauxites, laterites, and goethite and hematite deposits were interpreted as Oxisols (Retallack, 2010). Mollisols, Alfisols, Oxisols, and Ultisols were also reported directly from the paleosol literature. Table 4.1 contains the dataset codes, map units, interpreted soil units and map symbols. Table 4.2 gives an overview of the six climatically significant soil orders used in the map construction.

Map construction

The location of each diagnostic paleosol type (Aridisol, Alfisol, Mollisol, Histosol, Oxisol, and Ultisol) was plotted as point data based on converted x, y coordinates of Robertson-projected modern latitude and longitude. Modern soil type by order is classified in Robertson-projected map units in the Global Soil Map dataset (Soil Survey Staff, 2005). Because the available base map and Global Soil Map dataset are modern maps, and the differences between the modern and Miocene map are slight, the modern latitude and longitudes of each location were used in plotting. Additionally, available Miocene base maps are low resolution and several millions years older than the time period covered in this study (Scotese, 2002).

Database codes	Dataset source	Lithologies	Mapped as	$n =$	Symbol
AA	MSDB	Arid soils, undifferentiated	Aridisols, undifferentiated	3	◆
CC	MSDB	Calcrete and calcic Aridisols	Aridisols, calcic (Calcids)	4	◆
G	PGAP	gypsum, anhydrite	Aridisols, gypsic (Gypsids)	163	◆
H	PGAP	halite and bittern salts	Aridisols, salic (Salids)	26	◆
P	PGAP/MSDB	peat, lignite, coal	Histosols	270	●
FF	MSDB	Forest soils	Alfisols	10	▲
GG	MSDB	grassland soils	Mollisols	4	■
X	PGAP/MSDB	limonite, goethite, or hematite; deeply weathered soils; laterites	Oxisols	21	●
KK,UU	MSDB	Kaolinitic soils, Ultisols	Ultisols	6	●

Table 4.1. Miocene Soil Database (MSDB) and map key.

Soil Order:	Alfisols	Mollisols	Aridisols	Histosols	Oxisols	Ultisols
Type of soil	Moderately leached forest soils	Grassland soils	Aridland soils	Organic-rich soils	Tropical rainforest soils	Highly leached forest soils
Diagnostic feature(s)	Ochric epipedon, with argillic horizon (Bt) with > 35% base saturation	Mollic epipedon with argillic, cambic horizons	Ochric epipedon with cambic, argillic, calcic, gypsic, and/or salic horizons	Histic epipedon (20-30% organic by weight, >30 cm thick)	Ochric epipedon with oxic horizon	Ochric epipedon with argillic horizon (Bt) with < 35% base saturation
Climate	Temperate humid and subhumid	Cryic to hypothermic	Cold polar, cool temperate and warm deserts	Cool and warm wetlands, swamps	Isomesic to isohyperthermic, isotropical	Humid temperate and tropical
Vegetation	Broadleaf deciduous forest	Prairie, grassland	Arid-adapted vegetation	Mangrove, wetland, swamp	Tropical rainforest	Mixed forest
Coverage of ice-free land globally today	10.1%	7.0%	12%	~1.2%	7.5%	8.1%

Table 4.2. Summary of soil orders used in the modern and Miocene soil maps. Diagnostic surface horizons (epipedons) include ochric (not distinguished from other epipedons), mollic (thick, organic-rich, with high base saturation) and histic (organic-rich, water-saturated). Diagnostic subsurface horizons include cambic (Bw, weakly developed), argillic (Bt, accumulation of clay), calcic (Bk, accumulation of carbonate), gypsic (By, accumulation of gypsum), natric or salic (Bn, accumulation of sodium salts), and oxic (Bo, accumulation of iron and aluminum oxides). After Soil Survey Staff, 2000, 2005.

Both the modern soil polygons and the paleosol data points were overlain on a world outline basemap. A Modern Soil Map (Fig. 4.2) for the diagnostic soil Orders and a Middle Miocene Soil Map (Fig. 4.3) were created as well as individual maps for each soil type that show modern extent at the Order level and locations of Miocene paleosols (Figs. 4.4-4.6). Using the soil-forming factors common to the mapped soil units (Table 3.2) and the location of diagnostic soil orders (Oxisols as a proxy for tropical rainforest, for example) and the Köppen-Geiger climate classification system (Peel et al., 2007), extent of paleoclimate zones were estimated with dashed lines.

REGIONAL SUMMARIES OF MIDDLE MIOCENE CLIMATE CHANGE

Paleopedological and other lines of paleoenvironmental evidence

The middle Miocene soil map (Fig. 4.3) shows the extension of tropical soils (Oxisols, Ultisols) into northern and southern mid-latitudes, accompanied by thermophilic flora and fauna, implying an expansion of such biomes away from the equatorial region. Indicative of wet (and warm or cool) climate, extensive peats, lignites, and Histosols are abundant during the middle Miocene, mostly at higher latitudes and especially in the northern hemisphere, which is where increased precipitation is expected to accompany current warming. The dominant paleosol trends and ecosystem shifts are summarized by region in Table 4.3.

North America

There is much paleobiological evidence from North America of middle Miocene warm paleoclimate (Graham 1999, Janis et al. 2004). In eastern North America, middle Miocene thermophilic taxa include exotic Asiatic plants such as *Glyptostrobus* (water pine), *Podocarpus* (podocarp) and *Pterocarya* (wingnut) (Chaney and Axelrod, 1959; Graham, 1999) and animals, such as elephants (*Zygodontophodon*) and gelocid deer (*Pseudoceras*; Janis et al., 2004). Alaskan middle Miocene floras were also diverse and deciduous, with broad-leaf vegetation, such as the thermophilic *Liquidambar* (sweet gum), which is now found no further north than Tennessee (Wolfe and Tanai, 1980). Mollisols of middle Miocene age are identified in Oregon, South Dakota and Montana implying the existence and expansion of grasslands (Retallack, 1997b, 2004, 2013;

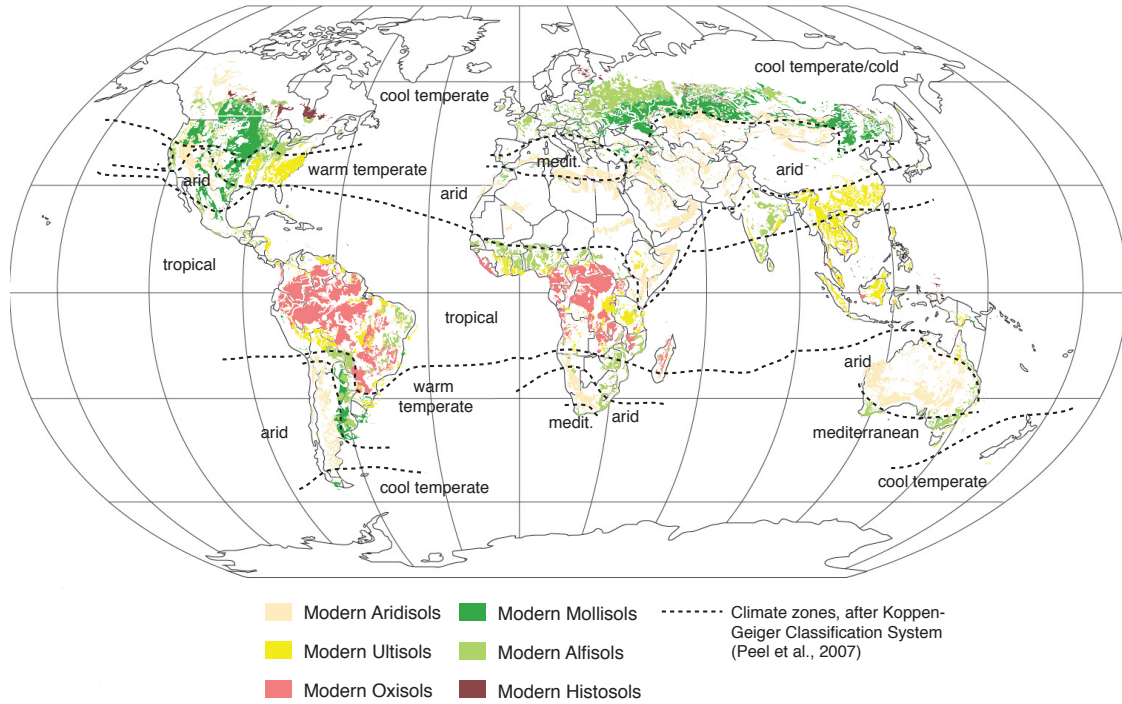


Figure 4.2. Modern soil and climate map. Colored polygons represent mapped units of climatically sensitive soils (Soil Survey Staff, 2005). Dashed lines show modern climate regimes according to the Koppen-Geiger Classification System (Peel et al., 2007).

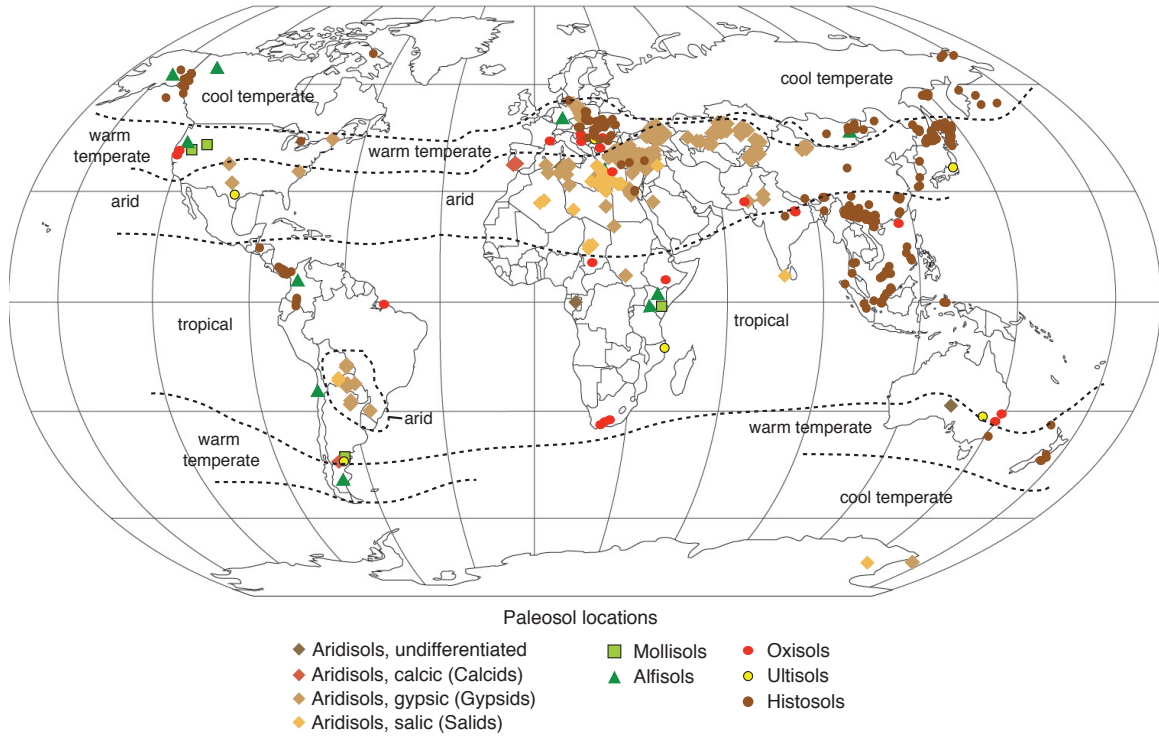
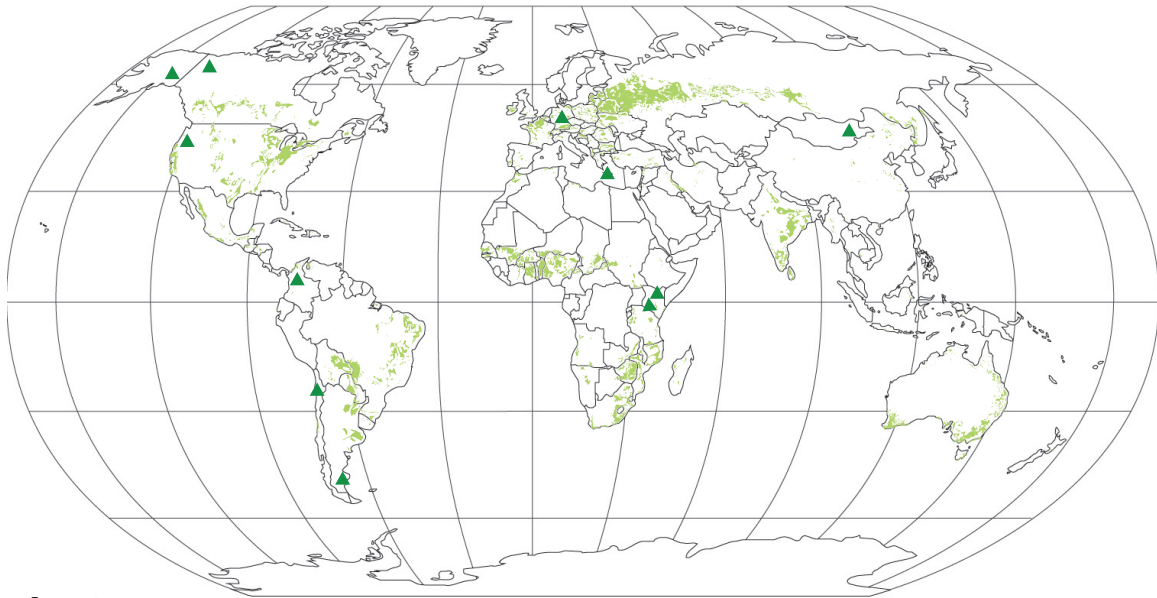
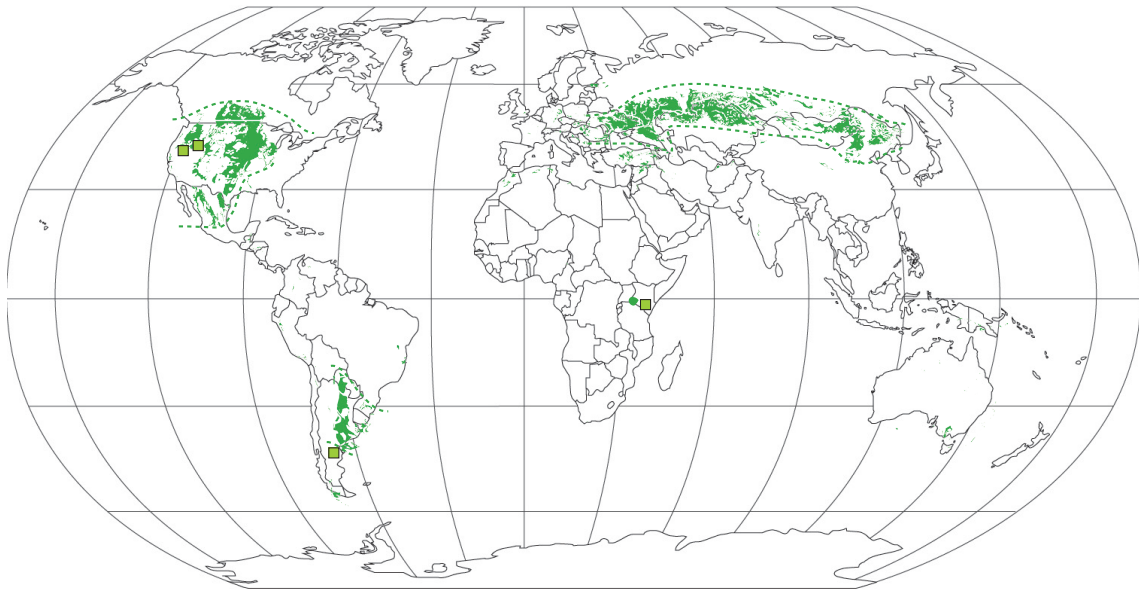


Figure 4.3. Middle Miocene paleosol and paleoclimate map. Colored symbols represent mapped paleosols (Appendix 1). Dashed lines show estimated climate regimes according to the Koppen-Geiger Classification System (Peel et al., 2007), based on interpretations of the paleoclimate under which the regional paleosols formed.



A

Modern Alfisols Modern extent Paleosol locations



B

Modern Mollisols Modern extent Paleosol locations

Figure 4.4. Modern range of Alfisols (A) and Mollisols (B) with Middle Miocene paleosols

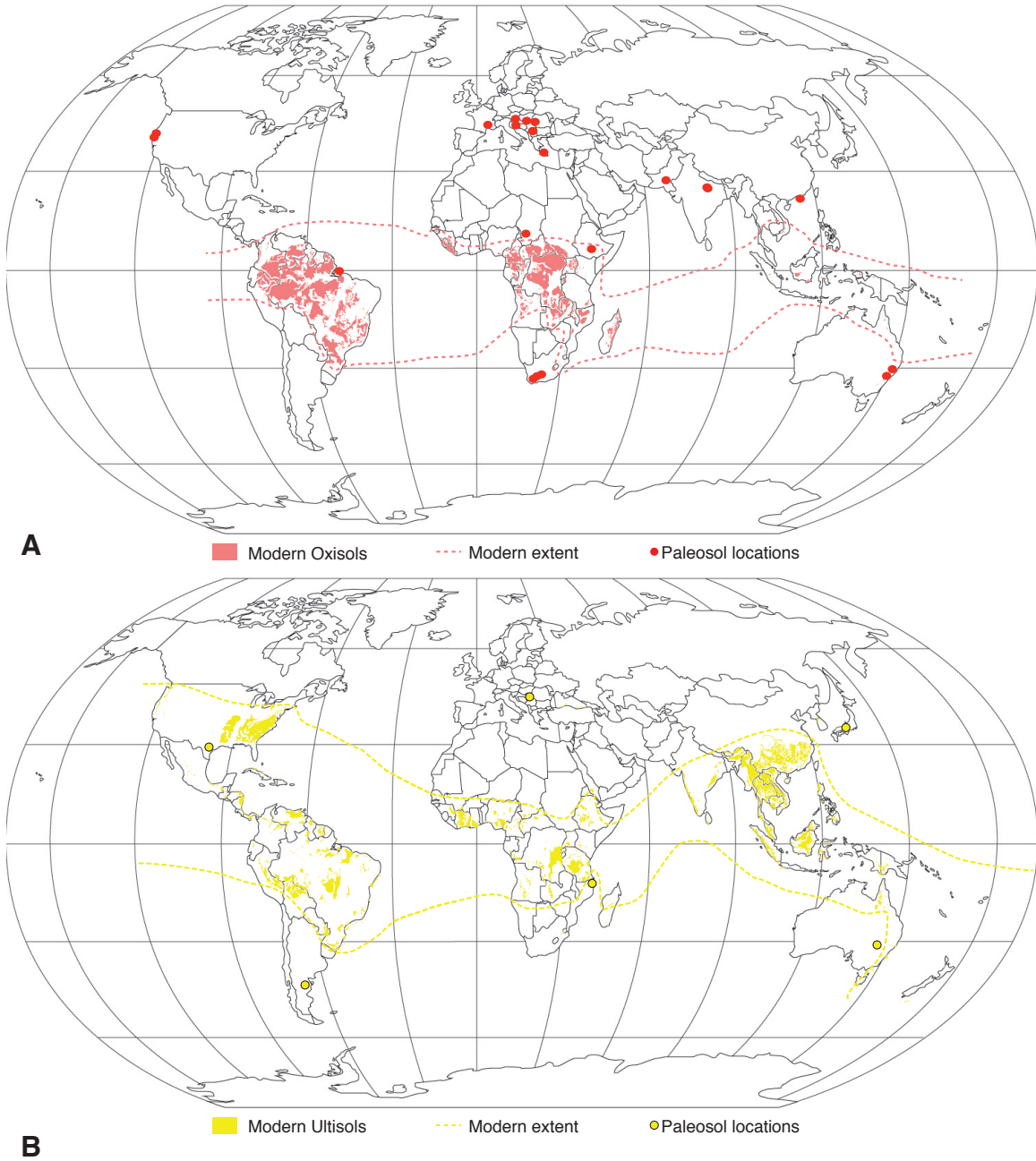


Figure 4.5. Modern range of Oxisols (A) and Ultisols (B) with Middle Miocene paleosols

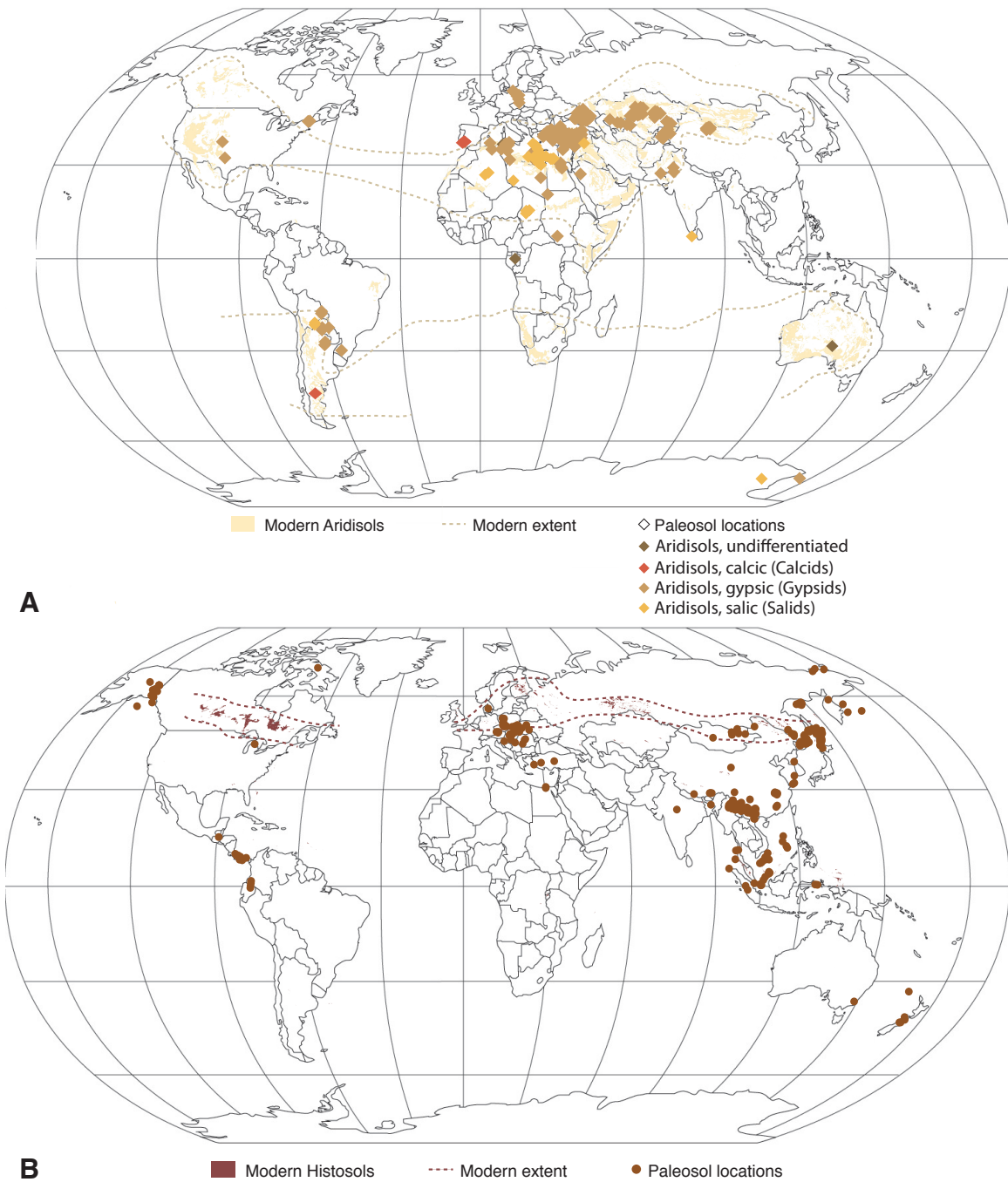


Figure 4.6. Modern range of Aridisols (A) and Histosols (B) with Middle Miocene paleosols

North America	Central & South America	Eurasia	Africa	Oceania
• Laterites as far north as Vancouver, WA, and south as Salem, OR • Expansion of grasslands in Montana and South Dakota • Expanded range of thermophilic taxa like <i>Liquidambar</i> • Brown coals (Histosols) common in Alaska and parts of Canada	• Tropical rainforest extending into northern Argentina • Expansion of forests to the south • Contracted arid region north of present • Histosols common in C. America • Increased MAP in southern Argentina • Increased MAP (>200mm) in Atacama Desert	• Brown coals (Histosols) common throughout northern Europe/Asia • Tropical rainforest (Oxisols) extend into southern Europe, India, China • Shifting forests in Germany, from rainforest to temperate • Forests (Alfisols) and grasslands (Mollisols) extend into Mongolia • Rainforest soils (Oxisols) in Nepal, shifting to Histosols	• Tropical rainforests (Oxisols) present in Kenya, extend to southern tip of Africa • Deeply weathered soils (Ultisols) in Tanzania • Similar extent of arid zone (Aridisols) to modern • Tropical forests shift to grasslands after 16 Ma in Kenya, South Africa	• Forests extend to southern extremes in South Australia • Subtropical/warm temperate forests in New Zealand, with <i>Cocos</i>, <i>Nothofagus brassii</i> • Deeply weathered soils (Ultisols) and rainforest soils (Oxisols) extend range south

Table 4.3. Summary of paleosol regimes and interpretations by region during the middle Miocene.

Bestland et al., 2008), as is also apparent from abundant grazing mammals (Janis et al. (2004). Mammal assemblages of the Great Plains reach a peak of diversity during the middle Miocene and suggest warmer, more humid and more productive conditions than before or after (Janis et al., 2004). In the Great Plains, the middle Miocene Sheep Creek Formation of Nebraska has over 60% grass in its phytolith assemblage (Strömberg, 2004).

In Oregon, the middle Miocene is characterized by soils that developed in warm and wet conditions, Alfisols in eastern Oregon (Sheldon, 2003), but lateritic bauxites in more humid western Salem and Portland Hills (Retallack, 2010). Chaney and Axelrod (1959) and Wolfe (1971) reconstructed the flora of the middle Miocene Mascall Formation of eastern Oregon as mixed mesophytic forest comparable with forests today living under mean annual precipitation of ca. 1270 mm, mean annual temperature of 8-13° C and a mean annual temperature range of 19-30° C.

Vertebrate fossils found in paleosols in Railroad Canyon on the border of Montana and Idaho reflect increased drying after the middle Miocene (Barnosky et al., 2007). The CIA-K paleohyrometer and alkali index paleothermometer applied to this sequence give a peak mean annual precipitation of 883 ± 182 mm and mean annual temperature of 11.5 ± 4.4 °C at 16.8 Ma, declining to 784 ± 182 mm and 8.0 ± 4.4 °C by 14.3 Ma (Retallack, 2007a, 2009).

In Alaska, Yukon, and far western Northwest Territories, mesothermal taxa like *Fagus* (beech) and *Quercus* (oak) were abundant in swaths of forest in the regionally widespread Usebelli Group (White et al., 1997).

In North America, post middle Miocene cooling resulted in a radiation of cool-climate taxa such as *Pinus* (pine) and *Picea* (spruce) and a decrease in taxa of exotic Asiatic affinities (Axelrod, 1964, 1992; Graham, 1999). Sod grasslands, and coevolved grassland-grazing animals, expanded in range with cooling and drying (Retallack, 2001, 2004, 2013). Calcareous paleosols have shallow calcic horizons and more depleted oxygen isotopic compositions in the late middle Miocene due to climatic cooling and drying (Retallack, 2007a; Takeuchi et al., 2010).

Central and South America

The Cucaracha Formation of Panama has middle Miocene (late Hemingfordian to early Barstovian, ca 16 Ma) fossil mammals identical to those of the same age in Nebraska, and is thus evidence that most of the central American isthmus, save a 300 km gap to Colombia, was already in place at that time (MacFadden, 2006). Paleosols in the Cucaracha Formation include a variety of Histosols of mangrove and coastal swamps, as well as Alfisols of subtropical humid forest (Retallack and Kirby, 2007)

In southern coastal Patagonia near Cerro Observatorio, the middle Miocene thermal maximum is represented by the Santa Cruz Formation that contains Mollisols and sodic Aridisols more like those around Buenos Aires than their current location near Rio Gallegos (Ch. III). A section of Santa Cruz Formation at Lago Posadas, 150 km west from Cerro Observatorio and in the foothills of the Andes, contains considerable pedogenic carbonate, unlike the paleosols at Cerro Observatorio. Stable carbon isotope analysis ($\delta^{13}\text{C}$) of the pedogenic carbonate (Blisniuk et al., 2005) also suggests a significant ecosystem shift at 16.5 Ma. Pre 16.5Ma a pure C3 ecosystem (woodland and C3 grasslands) is identified with a shift in $\delta^{13}\text{C}$ from -9.8 to -11.8 ‰ suggesting increased humidity during the middle Miocene. After 16.5 Ma, $\delta^{13}\text{C}$ become less depleted shifting to between -10 and -8 ‰, and are interpreted as a reflection of increased aridity and possibly a higher proportion of C4 grasses. Blisniuk et al. (2005) also reported increased sediment accumulation rates up-section, and attributes this to increased aridity.

Near the small town of Comallo in the Rio Negro province, the middle Miocene Comallo Formation produced the largest bird fossil ever found, an extinct phorusrachid, or terror bird (Chiappe and Bertelli, 2006). Preliminary field work (by Metzger, 2006, personal observation) suggests that the paleosols were mollic (organic-rich), indicating humid open grasslands.

Middle Miocene paleosols of the Pinturas Formation in Patagonia, Argentina, display translocation of clays, development of cutans, and lack of significant carbonate accumulation (Bown and Larriestra, 1990) indicating humid paleoclimate. Termite nests identified in these paleosols and arboreal monkeys, marsupials, and frogs identified in the fossil record are evidence of wet, subtropical forests were also present as far south as 47° S latitude in Argentina (Bown and Larriestra, 1990). Comparison by cenogram analysis

(Croft, 2001) of fossil and extant South American faunas suggests that the Santacrucian South American Land Mammal Age represents a paleoclimate more humid and less open than previously thought by Tauber (1997). The middle Miocene “Monkey Beds fauna” is interpreted similarly by Kay and Madden (1997) as a humid and partially open paleoenvironment. The diversity of primates found there suggests a woodland ecosystem (Croft, 2001). Rainfall estimates of 1500 to 2000 mm/yr for the “Monkey Beds fauna” are much higher than currently in this area, and comparable with lowland tropical South America (Kay and Madden, 1997). Humid forest is indicated by frugivorous fish, leaf-litter inhabiting snakes, land tortoises, forest birds, tree-dwelling marsupials and sloths, forest-dwelling tropical bats, and diverse arboreal monkeys (Kay and Madden, 1997).

The onset of aridity and cooling in the Atacama Desert of Chile is recorded in that region’s paleosol record (Rech et al., 2006). Between 19 and 13 Ma there was a transition from semiarid Argillisols and Vertisols (MAP > 200 mm/yr) to hyperarid, salic Gypsisols (MAP < 20 mm) reflecting both a response to global climate change and the increased rain shadow of the uplifting Andes (Rech et al., 2006).

Eurasia

In Denmark, permineralized wood is evident in middle Miocene alluvial sediments of the Odderup Formation (Weibel, 1996) supports the presence of a middle Miocene thermal maximum in the region. Silica permineralization may require, in the absence of volcanic source rocks, the weathering or pedogenesis of the alluvial sediments under a warm temperate to subtropical paleoclimate, in order to liberate the necessary silica (Weibel, 1996). *Liquidambar*, a thermophilic plant, was reported from a Danish Miocene flora (Christensen, 1976). Fossil assemblages from the Pannonian Sea in Hungary contain numerous mesothermal plants, suggesting a warm wet paleoclimate with mean annual temperature and precipitation ranges of 18 and 20 °C and 1200 and 1400 mm respectively (Jimenez-Moreno et al., 2005). This palynoflora represents a altitudinal belt of vegetation with swamps in the lowlands and elevation-controlled forests in the uplands.

In Germany, extensive middle Miocene bauxitic laterites developed on the Vogelsberg basaltic massif, which erupted during extension of the Rhine Graben Rift

system (Schwarz, 1997). These laterites often overlie kaolinitic saprolite, indicating deep (50 m) and intense chemical weathering, uncommon in high latitudes unless associated with warm and wet greenhouse conditions in Earth's history (Retallack, 2010). During the middle Miocene, kaolinite also peaks in concentration in oceanic sediment cores, reflecting increased global humidity during this time period (Robert and Chamley, 1987).

Silicified fossil woods also from Germany track the transition from paratropical evergreen forest (~17.5-17.3 Ma) to subtropical semi-deciduous forest (17.0~16.3 Ma) to subtropical oak-laurel forest (~16.3~15.3 Ma) to subtropical dry deciduous forest (14.3 to ~13.8 Ma) (Böhme et al., 2007). The paratropical evergreen forest likely corresponds to the pre-Middle Miocene "First Climatic Optimum" at 17.7-16.7 Ma (Böhme et al., 2007). The middle Miocene semi-deciduous forest experienced a quite humid climate, with strongly seasonal rainfall patterns and a distinct dry season (Böhme et al., 2007).

At least four species of palm, and other angiosperm and gymnosperm wood are identified in middle Miocene charcoallified wood in the Rhine Embayment, indicating the existence of tropical to subtropical swampy conditions (Figueiral et al., 2002). Fossil amphibian and reptile ecophysiological data suggest the initiation of a strong meridional precipitation gradient (threefold decrease to the south) across Europe during the middle Miocene that decreases in intensity by the early late Miocene (Böhme et al., 2006).

In central Anatolia, Turkey, the middle Miocene Kizilirmak and Bozkir Formations contain lacustrine sediments with pollen of Cupressaceae, *Taxodium*, Oleaceae, *Nyssa*, *Carya*, *Engelhardtia*, Cyrilliaceae, *Alnus*, *Ulmus*, and *Pterocarya*, which indicate that these sediments were deposited under a subtropical paleoclimate (Akgun et al., 2002). Palynological reconstructions of western and central Anatolia during the middle Miocene show an increase in tropical elements (Akgun et al., 2007). Turkish mid-Miocene paleosols are evidence of dry, subtropical, deciduous woodland (Bestland, 1990). Inner Mongolian paleosol formations also suggest a middle Miocene climate dramatically different from today's desert steppes, with a mixed conifer/broadleaf woodland and grassland mosaic (Wang et al., 2003). In China, lateritic paleosols preserved as xenoliths in tholeiites suggest the occurrence of intense tropical weathering during the middle Miocene (Zhou et al., 2004).

Further early to middle Miocene paleosol deposits in the Himalayan region prove excellent indicators of past climate. The Siwalik Group in Pakistan is characterized by Middle Miocene subhumid wooded Alfisols and Aridisols, giving way in the late Miocene to semiarid Mollisols and Aridisols (Retallack, 1991, 2001). In western Nepal the Siwalik Group has numerous Histosols interbedded with channel sands, as well as red and orange oxidized paleosols and calcareous red beds of better drained conditions (DeCelles et al., 1998). Palynological evidence records a subtropical to temperate broad-leaved taxa in the Himalayan foothills and a tropical forest taxa in the Gangetic floodplain in the middle Miocene, with grasslands increasing in the late Miocene (Hoorn et al., 2000; Ojha et al., 2000). In the late middle Miocene, paleovegetation reconstructed from fossil pollen indicates that subalpine forests were at elevations of between 3-4 km, subtropical/temperate/pine forests were between 1-3 km, and tropical forests below 1 km (Hoorn et al., 2000). Humid forest taxa in India migrated eastward and dry taxa radiated as drying occurred after the middle Miocene (Prakash, 1972).

During the middle Miocene exotic foraminifera, reef-building corals, and mangroves had extended as far north as Japan (Itoigawa and Yamanoi, 1990) and its forests were mesic, warm-temperate mixed conifer and broadleaf (Heusser, 1992). Post middle Miocene, Heusser (1992) recorded an increase in cool temperate and boreal taxa such as *Picea* (spruce), *Abies* (fir), and *Tsuga* (hemlock).

Africa

Kenyan paleosols from the Middle Miocene suggest the existence of humid, tropical forests with deeply weathered soils at 16 Ma (Retallack et al., 2002; Retallack, 2007b) followed by a shift to arid shrublands around 15 Ma (Retallack et al., 2002; Wynn and Retallack, 2001), then to wooded grassland by 14 Ma (Dugas and Retallack, 1993; Retallack, 1991; Retallack et al., 1990). Middle Miocene sandstones of the Pugu Formation, coastal Tanzania, exhibit an organic-rich A horizon containing hematite, corroded quartz, and pedogenic crystalline kaolinite (Mutakyawha, 1987). Deep kaolinitization of these paleosols suggests they were Oxisols and formed under a humid tropical paleoclimate.

Winteraceae pollen has been found at a middle Miocene locality in the Southwestern Cape, South Africa. Winteraceae are found today in tropical forests, subtropical to temperate rainforests, and subalpine shrubland (Coetzee & Praglowski, 1988). The overlying late Miocene to Pliocene deposits contain palynoflora indicative of a transition to sclerophyllous *fynbos*, the small-leaved shrublands characteristic of the area today, marking the transition to a Mediterranean climate (Coetzee & Muller, 1984).

Oceania

Australia contains a variety of middle Miocene paleosols including the thin, lacustrine paleosols of Lake Palankarinna in South Australia (Rich et al., 1991; Woodburne et al., 1993; Metzger and Retallack, 2010); brown coals in the Latrobe Valley, Victoria (Sluiter et al., 1995; Kershaw, 1997); laterites near Long Reef and Maroubra, New South Wales (Faniran, 1971; Hunt, 1985; Pickett, 2003); and kaolinitic paleosols around Mudgee and Gulgong, New South Wales (McMinn, 1981). Fossil vertebrates from caves of the Riversleigh district of Queensland reflect middle Miocene rainforest giving way to more open vegetation (Archer et al., 1991). The extensive and thick brown coals of Victoria and their paleofloras reflect a climate 5°C warmer and >700 mm wetter than present, with a mean annual temperature of 19°C and precipitation of >1500 mm in a closed-canopy humid rainforest (Sluiter et al., 1995; Kershaw, 1997). Kaolinite deposits around Gulgong and Mudgee, New South Wales, are found within valleys deeply incised into the basement rock, then in-filled by alluvium and overlain by basalt flows. The very fine-grained white kaolinite contains blackened vegetative fragments, root structures, and platy ped structure (Metzger, 2006, personal observation), as well as a palynoflora of tropical to subtropical plants (McMinn, 1981).

Lake Palankarinna located in the arid desert interior of the continent is one of the most productive Australian localities for Miocene mammals, and its thick sequence of paleosols has been dated by paleomagnetism, biostratigraphy, and radiometric dating (Woodburne et al., 1993). Pre- and post-middle Miocene thermal maximum paleosols of Lake Palankarinna reflect similar-to-modern climate and vegetation of desert shrubland (Metzger and Retallack, 2010). However, the middle Miocene paleosols likely formed under *mallee* woodland, a biome now located no closer than 1200 km to the southwest in

southeastern regions of Australia. Thus, the middle Miocene was warmer and wetter in central regions of Australia allowing for range extension of *mallee* northwards.

During the middle Miocene, reef-building corals indicative of warm subtropical and warm temperate climate conditions (Hornibrook, 1992), were common near the now cool, temperate North Island of New Zealand. Tropical plants such as *Cocos* (coconut palm) were also present in New Zealand (Fleming, 1975). Both the temperate *Nothofagus fusca* (red beech) and the thermophilic *Nothofagus brassii* (New Guinea beech), were common throughout New Zealand during the early and middle Miocene. Typical tropical genera are inconsistent in their occurrence, while the presence of *Nothofagus* spp. is suggestive of high humidity during the middle Miocene (Mildenhall, 1980, Mildenhall et al., 1989). While red and southern beech (*N. menziesii*) persists throughout New Zealand today, New Guinea beech is thought to have withdrawn north during the late Miocene, subsequently followed by other thermophilic taxa (Hornibrook, 1992).

Antarctica

In the Olympus Range of East Antarctica there is a dramatic change in tillite sedimentology from wet-based glaciers of the Circe till of Middle Miocene age to cold-based till of the late Miocene Dido drift (Lewis et al., 2007). Middle Miocene tundra vegetation dominated by mosses and bryophyte megafossils, with pollen evidence of beech (*Nothofagus*) and pinks (Caryophyllaceae), was destroyed by cold-based glacial advance (Lewis et al., 2008). *Nothofagus* persisted in the Dominion Range of Antarctic until the late Miocene (Ashworth and Cantrill, 2004), when it grew as stunted krummholz in gypsic Gelisols (Retallack et al., 2001). Pollen from the Cape Roberts deep drill hole reveal middle Miocene temperate forests of *Nothofagus* followed by forest decline and elimination of vascular land plants by the late Miocene (Warny et al., 2009).

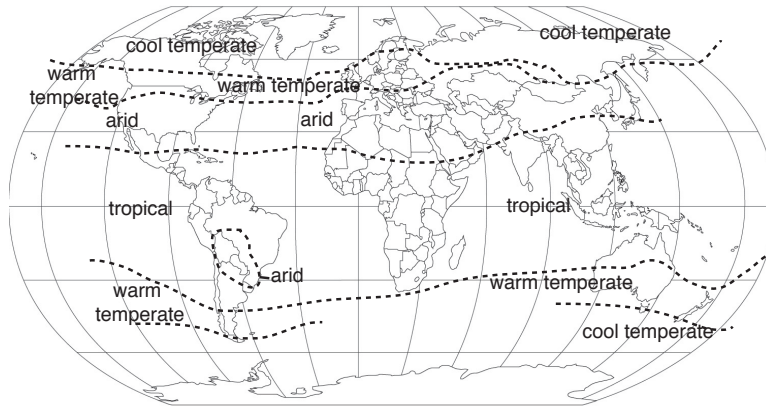
DISCUSSION

The middle Miocene thermal maximum as paleo-analog for future global warming

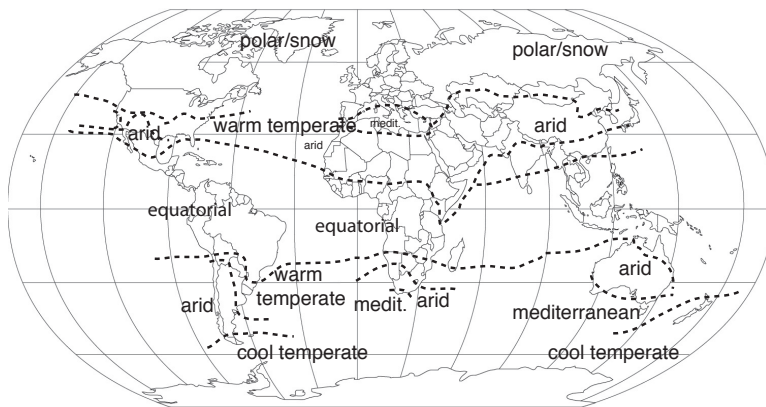
The middle Miocene thermal maximum provides an ancient analog for understanding the effects of climate change on soil and ecosystem regimes, as it contains records of similar ecosystem changes that could be expected from climate changes

associated with present and future warming. Thus, the Miocene Soil Map (Fig. 4.2) could provide a view into plausible soil ecosystem shifts expected with human-induced climate change. Figure 4.7 contains climate maps for the Miocene (this study), the present (Peel et al., 2007), and the future (2076-2100, Rubel and Kottek, 2010). The Miocene and the future maps allows comparisons between these two periods of similar-scale climatic change. Warm temperate climate may return to southern Argentina, southern Australia, and New Zealand as in the Miocene, and arid climate (with accompanying Aridisols) seems likely to expand north into Asia, with pockets of warm temperate climate. The soil changes that accompany these future changes are important for consideration of mitigation and adaptation to climate change induced vulnerabilities, while soil formation will lag in time.

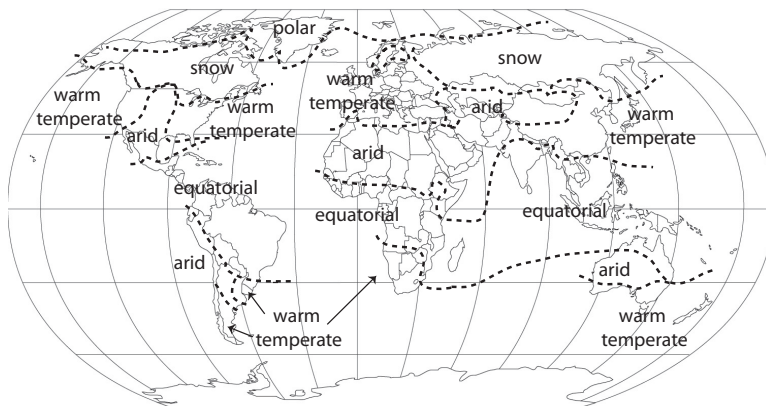
The global distribution of middle Miocene paleosols gives insight into ecosystem shifts resulting from climate change resulting from an increase of atmospheric carbon dioxide from 280 ppmv preindustrial value to an expected value of 900 ppmv with continued population growth of independent countries (scenario A1 of Alley et al., 2007). The most marked deviation from modern soil distribution is the expansion of tropical Oxisols during the thermal maximum at 16 Ma (Retallack, 2010). Tropical vegetation extended to high latitude regions, forests descended into the plains from hills of the American west and Europe, and swamp forest expanded at the expense of well-drained forests in higher latitudes (Graham, 1999). *Mallee* woodland expanded north and west throughout the arid Australian interior (Metzger and Retallack, 2010). Comparable woody thickening was seen in other summer-dry climate regions, such as Chile, South Africa, and the Mediterranean (Böhme et al., 2006, 2007). These increases in plant productivity are manifested in the transient replacement of Aridisols through much of North America by Alfisols and Mollisols (Bestland et al., 2008), and in Argentina, Chile, and Australia, replacement of Gypsic Aridisols with Calcic Aridisols (Blisniuk et al., 2005; Rech et al., 2006; Metzger and Retallack, 2010). Polar and subpolar ecosystems like taiga and tundra of Gelisols and dry ecosystems of desert Aridisols were restricted in distribution (Rech et al., 2006; Ashworth and Cantrill, 2006; Lewis et al., 2007, 2008). The general theme of all these changes is that the Middle Miocene was a peak of global soil productivity and carbon sequestration, with replacement of unproductive Aridisols



A. Miocene climate map (this study)



B. Modern climate map (Peel et al., 2007)



C. Predicted climate zones for IPCC A1F1 Tyndall SC 2.03 temperature and precipitation scenarios, period 2076-2100 (Rudel & Kotteck, 2010)

Figure 4.7. Climate maps for ~16 Ma, present day, and 2076-2100.

and Gelisols with more productive Oxisols, Alfisols, Mollisols and Histosols. These changes may explain the transient nature of the principal middle Miocene greenhouse peaks. Catastrophic injection of carbon into the atmosphere by igneous intrusion of the Columbia River Basalt or Ries asteroid impact (Retallack, 2004) created a warm wet global climate in which higher productivity soils and ecosystems actively sequestering carbon from the atmosphere (Retallack, 2010).

Climate modeling studies over the last decade, in conjunction with proxy data, have strongly suggested that climate-vegetation interactions have been important in many aspects of past climate change (Foley et al., 2000; Retallack 2001, 2007a, 2013). The use of global and regional climate models allows us to (i) isolate individual sensitivities of climate to atmospheric CO₂, vegetation distributions, and soil properties, (ii) spatially validate and explain geographical distributions by comparing to data in specific locations, (iii) compare model quantities such as soil moisture and vegetation type with corresponding proxy data. For example the GENESIS GCM includes a relatively detailed and well-tested treatment of the physical effects of vegetation on the surface climate, with a 2-layer vegetation canopy model and multi-layer models of soil, explicit soil moisture and ice fractions, and snow cover (Pollard and Thompson, 1995). GENESIS versions 1 and 2 (Thompson and Pollard, 1997) have been used extensively in paleoclimate applications and validations against proxy data, with many studies involving vegetation changes and feedbacks: for the Cretaceous (Otto-Bliesner and Upchurch, 1997; DeConto et al., 2000), Miocene (Dutton and Barron, 1997; Cosgrove et al., 2002), Quaternary (Crowley and Baum, 1997; Barron and Pollard, 2002); Holocene (Bonan et al., 1992; Pollard et al., 1998; Doherty et al., 2000), and recent and future (Pollard and Thompson, 1995; Levis et al., 2000; Bergengren et al., 2001; Wang et al., 2004). The Miocene studies listed above, although preliminary, found significant widespread cooling (modern relative to Miocene) due to the replacement of mid-latitude forest with grassland and desert, and warming in high latitudes due to the replacement of evergreen forest with tundra. These results are compatible with, though less detailed, than the spread of Mollisols in mid-latitudes and Histosols at high latitudes on soil maps provided here (Figs. 4.4-4.6).

In Europe, the NECLIME group used fossil floras to model cold month mean temperatures and found that the late Miocene, with pre-industrial atmospheric CO₂ levels, closely matches the prediction for the future scenario SRES A2 (Utescher et al., 2011). Other work based on fossil floras suggests that the Langhian and Tortonian were warmer and wetter than before or after (Bruch et al., 2011). Expanding the Miocene Soil Database to cover the entire Miocene would allow further comparison between the paleoenvironmental reconstructions based on vegetation or soil.

Complexities in the differences between modern and middle Miocene geographical and tectonic settings likely make the latter an imperfect, but useful, analog for the former. An expanded Miocene Soil Database could provide both input variables for climate modelers (soil depth, soil texture, soil albedo, and vegetation type) as well as comparison points to the output variables predicted by GCM experiments. Soil texture, for example, is used in the LSX model to parameterize physical and hydraulic properties of the soil column, and vegetation types are used to determine physical canopy attributes by modern analogs (Pollard and Thompson, 1995).

While the detailed output data do not exist for all sites at this time, a future expansion of the Miocene Soil Database could incorporate parameters useful to climate modelers. Future paleosol studies of this time period could be conducted with this collection of data in mind to improve the Database and to increase its utility to climate modelers. For example, soil moisture is one of the physical characteristics the IPCC is interested in modelling in present and future scenarios. Robock et al. (2000) found increasing soil moisture during the summer months in a survey of records of >600 stations in many climates in the former Soviet Union, China, Mongolia, India, and the United States. Because long-term records of soil moisture are extremely limited or non-existent, soil moisture values are based on formulae or LSMs (land surface models) which have limitations to their reliability (Trenberth et al., 2007). Paleosols could provide an important spatial alternative for providing soil moisture values. Soil moisture can be estimated from paleosols by using the ratio of ferric to ferrous iron oxides and the presence of gleying (Retallack, 1997a). Paleosol color, iron oxidation state, and clay content are guides to former soil moisture content, but all are altered after burial (Retallack, 1991). Table 4.4 details other possible comparison points to GCM output data

Parameter	How estimated from paleosols	Reference
1. Soil thickness (cm)	Measured in field, corrected for compaction by overburden	Sheldon and Retallack 2001
2. Soil texture (clay %)	Point-counting thin sections	Retallack 1997b
3. Soil moisture (%)	Ferric-ferrous ratios and gley mineral suites	Retallack 1997b
4. Water table (cm)	Measured depth to gley minerals from paleosol surface, corrected for compaction by overburden	Sheldon and Retallack 2001
5. Soil albedo (%)	Modern values for soil type	Retallack, 2013
6. Soil order (type)	Horizons, soil texture, petrography and chemistry	Retallack 1997b
7. Vegetation (type)	Root traces, burrows and nests, paleoclimatic indicators	Retallack 1997b
8. Plant albedo (%)	Modern values for vegetation type	Retallack and Krull, 1999
9. Mean annual temperature (oC)	Geochemical salinization index	Sheldon et al. 2002
10. Mean annual precipitation (mm)	Compaction-corrected depth to carbonate nodules, and chemical index of alteration without potash	Sheldon et al., 2002; Retallack, 2005
11. Mean annual range of precipitation (mm)	Compaction-corrected thickness of paleosol with carbonate nodules	Retallack, 2005
12. Soil C (gC.m2)	Modern values for vegetation type	Retallack 2001

Table 4.4. Possible parameters for GCM comparison

that can be estimated from paleosols, including vegetation type (for simulations with interactive vegetation), annual mean temperature, precipitation, and their annual ranges.

This study only focused on the climatically significant soil types of the middle Miocene. To increase its applicability, future expansion of the database could include the immature soils (Entisols, Inceptisols), climatically variable soils (e.g., Vertisols, for example), and non-climatically defined soils (e.g., the volcanic Andisols) excluded here, as well as paleosols from the entire middle Miocene. In summary, future work on the Miocene Soil Database will 1) include estimates of important GCM parameters as detailed in Table 4.4, and 2) map the entire terrestrial soil surface of the Earth.

CONCLUSIONS

Middle Miocene paleosols can provide an important dataset for computer models for future land use considerations of soils in times of global change. In intermontane western North America, for example, coming replacement of Aridisols by Alfisols and Mollisols will open the prospect of increased livestock and crop production (Retallack, 2013). In western Oregon, the replacement of Alfisols and Mollisols with Ultisols and Oxisols (as seen in the middle Miocene) will allow tropical tree crops, but also introduce tropical pests (Retallack, 2010). Site specific data is needed to improve ever more complex computer models, and can be provided by detailed studies of Miocene paleosols and expansion of the Miocene Soil Database.

BRIDGE

Chapter IV presented new climate and soil maps for the Middle Miocene Thermal Maximum. Chapter V summarizes the results of the preceding three chapters.

CHAPTER V

CONCLUSIONS

The studies presented in this dissertation highlight the utility of paleosols as indicators of past climatic and environmental conditions. Paleosols of the middle Miocene at Lake Palankarinna, Australia, and Cerro Observatorio, Argentina record the landscape shifts caused by global climate change during the Middle Miocene Thermal Maximum. Understanding how ancient ecosystems respond to climate change has important ramifications for understanding how modern ecosystems will respond to modern global climate change. The global paleosol map reveals a warmer, wetter world during the Middle Miocene with thermophilic ecosystems shifting to latitudinal extremes and with arid belts still present.

In Australia, paleosols of the Oligocene-Miocene Etadunna and Pliocene Tirari Formations formed in arid palaeoclimates and include pedogenic gypsum. The Middle Miocene paleosol has shallow calcareous nodules and stout root traces suggesting vegetation like dry woodland. Comparable mallee vegetation now grows no closer than 1200 km to the southwest, so middle Miocene warm-wet climate enabled range extension of mallee and woody thickening of plants in the Australia outback.

Paleosols of the Santa Cruz formation in Argentina reflect the transition from the warm, wet forests and grasslands of the middle Miocene at 16 Ma to more open rangelands by ~15 Ma. The early Miocene in the Santa Cruz Formation is characterized by a thick sequence of weakly to strongly developed grassland paleosols (Orthents and Ustolls) as well as paleosols with root traces and profile forms of open shrubland vegetation (Cambid). The middle Miocene thermal maximum is characterized by paleosols (Udepts, Udalfs) developed under open woodland-shrubland vegetation, during a period of climatic warmth and humidity. The late middle Miocene is characterized by a greater diversity of pedotypes, all suggestive of an arid and cooler environment (Argids, Cambids, and Ustepts).

Future work in Argentina will investigate lateral variations in the pedotypes found at Cerro Observatorio, Lago Posados, and other sites in an effort to improve

paleoenvironmental reconstructions. The Middle Miocene Soil Database and maps will be expanded and refined as additional data become available. Future expansion of the database could include the immature soils (Entisols, Inceptisols), climatically variable soils (e.g., Vertisols, for example), and non-climatically defined soils (e.g., the volcanic Andisols) excluded here. Additionally, parameters important to climate modelers, paleoclimatologists, and other database users could be estimated from paleosol type and added to the database, as detailed in Chapter IV.

APPENDIX A
SUPPLEMENTARY DATA, CHAPTER II

Table A.1. Chemical Analyses of Miocene Paleosols, Lake Palankarinna.

Pedotype	Soil Hz.	ID#	SiO2 (wt%)	Al2O3 (wt%)	Fe2O3 (wt%)	CaO (wt%)	MgO (wt%)	Na2O (wt%)	K2O (wt%)	Cr2O3 (wt%)	TiO2 (wt%)	MnO (wt%)	P2O5 (wt%)	SrO (wt%)	BaO (wt%)	LOI (wt%)	Total (wt%)	C _{org} (wt%)	C _{inorg} (wt%)	CO ₂ (wt%)	C tot (wt%)
Juldru	A	R3416	65.87	9.9	3.64	4.02	1.3	1.31	1.1	<0.01	0.57	0.02	0.12	0.04	0.03	10.4	98.32	0.08	0.25	0.9	0.33
Juldru	C	R3417	75.63	4.25	1.56	6.37	0.63	0.29	0.6	<0.01	0.27	0.05	0.05	0.07	0.04	8.42	98.23	<0.05	0.85	3.1	0.8
Maralji	A	R3418	70.01	11.28	4.28	0.37	1.23	1.9	1.25	<0.01	0.57	0.02	0.07	0.07	0.04	7.77	98.86	<0.05	<0.05	<0.2	0.03
Maralji	A	R3419	69.25	11	4.12	0.83	1.21	1.78	1.21	<0.01	0.53	0.03	0.07	0.02	0.03	8.22	98.3	<0.05	0.12	0.4	0.12
Maralji	Bt	R3420	66.3	12.58	4.62	0.26	1.37	2.13	1.36	<0.01	0.63	0.02	0.08	0.09	0.04	8.71	98.19	<0.05	<0.05	<0.2	0.02
Maralji	Bt	R3421	66.21	12.59	4.6	0.27	1.4	2.18	1.34	<0.01	0.6	0.03	0.08	0.07	0.03	8.7	98.1	<0.05	<0.05	<0.2	0.03
Maralji	Bk	R3422	63.41	13.59	5	0.21	1.55	2.62	1.46	<0.01	0.69	0.02	0.09	0.07	0.03	9.64	98.38	<0.05	<0.05	<0.2	0.02
Maralji	By	R3423	66.96	12.11	4.58	0.21	1.44	2.26	1.36	<0.01	0.61	0.02	0.07	0.16	0.05	8.75	98.58	<0.05	<0.05	<0.2	0.02
Chindinna	A	R3424	55.87	15.62	5.62	2.49	1.32	2.58	1.15	<0.01	0.71	0.01	0.09	0.04	0.03	12.85	98.38	<0.05	<0.05	<0.2	0.02
Chindinna	A	R3425	55.29	15.79	5.61	2.52	1.29	2.62	1.11	<0.01	0.66	0.02	0.1	0.04	0.03	13.2	98.28	<0.05	<0.05	<0.2	0.03
Chindinna	Bw	R3426	46.55	17.23	5.94	3.49	1.31	2.81	1.1	<0.01	0.76	0.03	0.09	0.02	0.03	14.8	94.16	<0.05	<0.05	<0.2	0.04
Chindinna	By	R3427	52.81	17.33	6.08	1.54	1.49	3.35	1.25	<0.01	0.75	0.07	0.07	0.02	0.04	13.35	98.14	<0.05	<0.05	<0.2	0.04
Chindinna	By	R3428	56.99	16.72	6	0.3	1.41	3.18	1.24	<0.01	0.71	0.05	0.08	0.02	0.03	11.75	98.48	0.06	<0.05	<0.2	0.06
Junduru	A	R3429	60.57	11.72	6.27	0.12	2.22	3.44	1.21	0.02	0.78	0.01	0.04	0.01	0.03	12.35	98.79	0.1	<0.05	<0.2	0.1
Junduru	C	R3430	80.4	5.26	2.43	0.09	1.13	1.97	1.01	0.01	0.66	0.01	0.02	0.01	0.02	5.84	98.86	<0.05	<0.05	<0.2	0.03
Kobera	A	R3431	56.5	9.89	6.36	0.57	3.41	4.2	1.46	0.01	0.58	0.03	0.35	0.01	0.02	15.35	98.75	0.09	<0.05	<0.2	0.09
Kobera	Bw	R3432	49.15	9.74	7.88	0.2	3.96	6.15	1.46	0.01	0.51	0.03	0.12	0.01	0.04	18.8	98.06	0.06	<0.05	<0.2	0.06
Kobera	By	R3433	51.99	9.08	6.8	0.41	3.81	5.36	1.42	0.01	0.51	0.04	0.26	0.01	0.02	18.75	98.48	0.08	<0.05	<0.2	0.08
Kobera	By	R3434	52.11	9.31	6.86	0.38	3.68	5.54	1.48	<0.01	0.64	0.02	0.23	0.01	0.03	18	98.29	0.07	<0.05	<0.2	0.07
Kobera	By	R3435	54.5	9.13	7.02	0.39	3.56	4.8	1.48	<0.01	0.59	0.04	0.24	0.01	0.02	16.45	98.24	0.1	<0.05	<0.2	0.1
Kaldri	A	R3436	46.47	9.89	6.87	0.25	4.68	6.27	1.48	<0.01	0.45	0.02	0.15	0.01	0.02	21.6	98.16	0.11	<0.05	<0.2	0.11
Kaldri	By	R3437	43.83	8.41	7.37	0.25	4.59	8.37	1.27	<0.01	0.41	0.35	0.14	0.01	0.06	23.1	98.15	0.08	<0.05	<0.2	0.08
Kaldri	By	R3438	46.64	9.87	7.24	0.34	4.42	6.93	1.5	<0.01	0.5	0.02	0.15	0.02	0.02	20.5	98.15	0.08	<0.05	<0.2	0.08
Juldru	A	R3439	62.81	15.11	4.63	0.14	1.44	2.42	1.57	<0.01	1.15	0.01	0.04	0.06	0.03	9.24	98.65	0.07	<0.05	<0.2	0.07
Juldru	C	R3440	74.83	7.79	2.88	1.48	1.05	1.56	1.07	<0.01	0.44	0.05	0.05	0.19	0.05	6.97	98.41	<0.05	0.31	1.1	0.31
Dantu	A	R3441	57.4	11.22	4.02	4.4	1.23	1.96	1.33	<0.01	0.58	0.04	0.07	0.04	0.02	12.05	94.35	<0.05	<0.05	<0.2	0.02
Dantu	A	R3442	59.46	9.75	3.54	5.2	1.06	1.81	1.14	<0.01	0.46	0.02	0.06	0.06	0.03	12.95	95.53	<0.05	0.05	0.2	0.06
Dantu	Bk	R3443	53.28	9.3	3.28	7.42	1.04	1.9	1.05	<0.01	0.52	0.01	0.06	0.03	0.02	13.8	91.71	0.1	<0.05	<0.2	0.1
Dantu	Bk	R3444	68.62	11.48	4.38	0.42	1.26	1.85	1.31	<0.01	0.58	0.02	0.07	0.03	0.03	8.16	98.21	<0.05	<0.05	<0.2	0.03
Dantu	C	R3445	68.25	11.88	4.41	0.47	1.3	1.82	1.35	<0.01	0.58	0.03	0.08	0.02	0.03	8.45	98.66	<0.05	<0.05	<0.2	0.02
Dantu	C	R3446	64.84	13.54	5.16	0.23	1.46	1.86	1.47	0.01	0.61	0.03	0.09	0.02	0.03	8.97	98.31	0.05	<0.05	<0.2	0.05
		error	2.75	0.825	0.395	0.22	0.175	0.105	0.125		0.06	0.025	0.035			3.53					

Note: From XRF analysis with Walkely-Black titration for organic carbon and acid dissolution for inorganic carbon by ALS-Chemex, North Vancouver, British Columbia, against BC Canada granodioritic stream gravel SDMS-2. Error is from 10 analyses by ALS-Chemex, Vancouver, BC, Canada.

Table A.2. Point count data on grain size and minerals of Miocene paleosols.

Pedotype	H _z	ID#	Clay (vol%)	Silt (vol%)	Sand (vol%)	Textural class	Quartz (vol%)	Feldspar (vol%)	Clay (vol%)	Opaque (vol%)	Mica (vol%)	Gypsum (vol%)	Calcite (vol%)	Rock frg.(vol%)	Birefringence fabric
Juldru	A	R3416	48.4	30.4	21.2	clay	17.6	17.2	46.6	4.6	3.8	3	0	7.2	mosepic porphyroscopic
Juldru	C	R3417	35.6	53	11.4	silty clay loam	37.6	24.2	33.2	2.4	1.4	0	0	1.2	silasepic granular
Maralji	A	R3418	60	27.8	12.2	clay	13.8	15	61.6	1.4	1.8	0	0	6.4	mosepic agglomeroplastic
Maralji	A	R3419	57.2	28.6	14.2	clay	17.4	16.2	55.6	3.6	1.8	0	0	5.4	mosepic agglomeroplastic
Maralji	Bt	R3420	49.4	32.4	18.2	clay	17.4	20	50.8	1.6	1	0	0	9.2	mosepic agglomeroplastic
Maralji	Bt	R3421	40.8	38.8	20.4	clay	21.2	23	41.2	4.6	1.8	0	0	8.2	mosepic agglomeroplastic
Maralji	Bk	R3422	47.8	31.6	20.6	clay	22	22.2	45.8	2.8	0.8	0	0.6	5.8	mosepic agglomeroplastic
Maralji	By	R3423	40.4	36.8	22.8	clay	23.6	26.2	40	3.2	4	0	0	3	mosepic agglomeroplastic
Chindinna	A	R3424	42.2	31.2	26.6	clay	20.8	25	43.4	1.6	2	5	0	2.2	mosepic agglomeroplastic
Chindinna	A	R3425	36.6	33.8	29.6	silty clay loam	23.6	28.4	35	2.2	4	4.4	0	2.4	bimasepic agglomeroplastic
Chindinna	Bw	R3426	43.6	36.4	20	clay	21.6	22.2	44.6	2	2.6	2.2	0	4.8	bimasepic agglomeroplastic
Chindinna	By	R3427	30	62	8	silty clay loam	17.6	22.2	31.2	2.6	0.6	25.2	0	0.6	crystic agglomeroplastic
Chindinna	By	R3428	42	36.8	21.2	clay	22.4	23.4	40.4	4.4	3.2	1.8	0	4.4	bimasepic agglomeroplastic
Junduru	A	R3429	37.8	42.8	19.4	silty clay loam	26.4	28.2	38	3.2	2.6	0.2	0	1.4	bimasepic agglomeroplastic
Junduru	C	R3430	27.8	61.4	10.8	silty clay loam	29.4	29.6	29	4.4	3.2	1	0	3.4	silasepic granular
Kobera	A	R3431	38.8	57.8	3.4	silty clay loam	25	27.2	39	3.2	1.6	0.8	0	3.2	mosepic intertextic
Kobera	By	R3433	36.8	56.4	6.8	silty clay loam	21.8	25.4	36	6	4	3.8	0	3	mosepic intertextic
Kobera	By	R3434	35.8	45	19.2	silty clay loam	22.8	26.8	35.2	0.2	3	8.2	0	3.8	mosepic intertextic
Kobera	By	R3435	36.8	50.2	13	silty clay loam	25.8	25.6	34	4.4	1.4	5	0	3.8	mosepic intertextic
Kaldri	A	R3436	42.2	47.4	10.4	silty clay	20.8	22.2	42.6	5.2	2.6	0.4	0	6.2	bimasepic porphyroscopic
Kaldri	By	R3437	33.4	55.4	11.2	silty clay loam	23.4	25.6	33.8	5	4	3.2	0	5	mosepic intertextic
Kaldri	By	R3438	32.6	56.4	11	silty clay loam	23.4	31	34	4.6	2.4	0	0	4.6	mosepic intertextic
Juldru	A	R3439	33.4	45.4	21.2	clay loam	23.2	24.6	37.8	4.4	2.4	2	0	5.6	bimasepic porphyroscopic
Juldru	C	R3440	20	39.4	40.6	loam	42.2	25.6	20	2.6	2	0	0	7.6	silasepic granular
Dantu	A	R3441	29.4	34.8	35.8	clay loam	31.4	25	29.8	5.2	1.8	1.2	0	5.6	mosepic agglomeroplastic
Dantu	A	R3442	28.8	35.6	35.6	clay loam	28	27.4	31.2	4.6	1.6	2.2	0	5	mosepic agglomeroplastic
Dantu	Bk	R3443	33.8	33.6	32.6	clay loam	25	24	36.6	4	0.6	4.2	2	3.6	insepic agglomeroplastic
Dantu	Bk	R3444	32.8	40.8	26.4	clay loam	26.4	26.2	33.4	4.4	3.6	0.2	1	4.8	insepic agglomeroplastic
Dantu	C	R3445	32.4	36.8	30.8	clay loam	28.4	26.8	31.6	3.6	1.8	0	0	7.8	insepic agglomeroplastic

Note: Two separate counts are tabulated here: one for grain size, and other for mineral content. Comparability of clay counts in each is a quality control. Error of these 500 point counts are $\pm 2\%$ for components at abundance > 5%. Textural classes are those of soil science, and birefringence fabrics follow the terminology of Brewer (1976).

Table A.3. Depth to Bk and By in Miocene paleosols of Australia.

Location	Coordinates	Level (m)	Age (Ma)	Depth to By (cm)	Depth to Bk (cm)	Thickness of Bk (cm)	Nodule size (cm)	MAP (mm)
Lake Palankarinna	S28.76296 E138.40215	0	0	27				117
Mungo Lake	S33.74156 E145.12711	10.23	0.05		23	25	1	279
Mungo Lake	S33.74156 E145.12711	9.075	0.05		25	27	1	290
Mungo Lake	S33.74156 E145.12711	8.25	0.06		24	25	3	285
Mungo Lake	S33.74156 E145.12711	6.6	0.07		25	27	4	290
Mungo Lake	S33.74156 E145.12711	6.435	0.07		33	30	5	336
Mungo Lake	S33.74156 E145.12711	5.28	0.08		32	37	4	330
Mungo Lake	S33.74156 E145.12711	4.785	0.09		26	29	3	296
Mungo Lake	S33.74156 E145.12711	3.795	0.09		25	30	2	290
Mungo Lake	S33.74156 E145.12711	2.805	0.10		29	25	1	313
Mungo Lake	S33.74156 E145.12711	2.475	0.10		27	22	5	302
Mungo Lake	S33.74156 E145.12711	1.815	0.11		40	38	1	374
Mungo Lake	S33.74156 E145.12711	0.99	0.11		38	37	3	364
Lake Palankarinna	S28.76296 E138.40215	0.8	2.5	14				82
Lake Palankarinna	S28.76296 E138.40215	1.2	3	23				101
Lake Palankarinna	S28.76296 E138.40215	2.6	3.5	29				116
Lake Palankarinna	S28.76296 E138.40215	3.4	4	30				119
Lake Palankarinna	S28.763240 E138.401784	5		45	22	0.3	401	
Alcoota	S22.86172 E134.42128	16.8	5.34		27	22	4	302
Alcoota	S22.86172 E134.42128	16.2	5.51		25	22	3	290
Alcoota	S22.86172 E134.42128	15.2	5.80		28	21	2	308
Alcoota	S22.86172 E134.42128	13.7	6.23		23	16	3	279
Alcoota	S22.86172 E134.42128	11.9	6.74		27	25	2	302
Alcoota	S22.86172 E134.42128	10.5	7.14		32	16	1.3	330
Alcoota	S22.86172 E134.42128	10	7.29		26	18	3.2	296
Alcoota	S22.86172 E134.42128	9.4	7.46		23	14	2.5	279
Alcoota	S22.86172 E134.42128	8.8	7.63		21	13	1.8	267
Alcoota	S22.86172 E134.42128	7.3	8.06		24	21	3	285
Alcoota	S22.86172 E134.42128	5.7	8.51		29	24	5	313
Alcoota	S22.86172 E134.42128	5.2	8.66		20	21	15	261
Alcoota	S22.86172 E134.42128	4.6	8.83		19	13	4	255
Alcoota	S22.86172 E134.42128	4.3	8.91		21	16	3	267
Alcoota	S22.86172 E134.42128	1.8	9.63		25	16	3	290
Lake Palankarinna	S28.76296 E138.40215	4.3	16.59	82	66	26	2	506
Kangaroo Well	S24.20874 E134.21617	6.9	19.69		34	20	2	342
Kangaroo Well	S24.20874 E134.21617	6.3	19.72		39	19	5	369
Kangaroo Well	S24.20874 E134.21617	5.7	19.75		36	23	1	353
Kangaroo Well	S24.20874 E134.21617	5	19.78		38	22	4	364
Kangaroo Well	S24.20874 E134.21617	4.4	19.81		43	21	7	391
Kangaroo Well	S24.20874 E134.21617	3.7	19.85		36	25	2.5	353
Kangaroo Well	S24.20874 E134.21617	3.1	19.88		37	24	3	358
Kangaroo Well	S24.20874 E134.21617	2.5	19.91		42	21	8	385
Kangaroo Well	S24.20874 E134.21617	1.8	19.94		36	24	1.5	353

Table A.3. (continued)

Location	Coordinates	Level (m)	Age (Ma)	Depth to By (cm)	Depth to Bk (cm)	Thickness of Bk (cm)	Nodule size (cm)	MAP (mm)
Kangaroo Well	S24.20874 E134.21617	1.2	19.97		38	22	1.8	364
Kangaroo Well	S24.20874 E134.21617	0.6	20.00		39	20	2	369
Lake Palankarinna	S28.76296 E138.40215	5.1	23.62	24				103
Lake Palankarinna	S28.76296 E138.40215	5.5	23.67	23				101
Lake Palankarinna	S28.76296 E138.40215	6.1	23.74	17				88
Lake Palankarinna	S28.76296 E138.40215	6.5	23.78	18				90
Lake Palankarinna	S28.76296 E138.40215	7	23.84	19				92
Lake Palankarinna	S28.76296 E138.40215	7.3	23.88	25				106
Lake Palankarinna	S28.76296 E138.40215	8.1	23.97	24				103
Lake Palankarinna	S28.76296 E138.40215	8.8	24.05	20				94
Lake Palankarinna	S28.76296 E138.40215	9.2	24.10	17				88
Lake Palankarinna	S28.76296 E138.40215	9.7	24.16	18				90
Lake Palankarinna	S28.76296 E138.40215	10.2	24.21	16				86
Lake Palankarinna	S28.76296 E138.40215	10.6	24.26	22				99
Lake Palankarinna	S28.76296 E138.40215	11.2	24.33	26				108
Lake Palankarinna	S28.76296 E138.40215	11.9	24.41	21				96
Lake Palankarinna	S28.76296 E138.40215	12.5	24.48	26				108
Lake Palankarinna	S28.76296 E138.40215	13.6	24.61	27				111
Lake Palankarinna	S28.76296 E138.40215	14.2	24.68	25				106
Lake Palankarinna	S28.76296 E138.40215	14.6	24.73	23				101
Lake Palankarinna	S28.76296 E138.40215	15.2	24.80	19				92
Lake Palankarinna	S28.76296 E138.40215	15.6	24.85	18				90
Lake Palankarinna	S28.76296 E138.40215	16	24.89	17				88
Lake Palankarinna	S28.76296 E138.40215	16.5	24.95	22				99
Lake Palankarinna	S28.76296 E138.40215	17.2	25.03	30				119
Lake Palankarinna	S28.76296 E138.40215	23.3	25.74	35				134
Lake Palankarinna	S28.76296 E138.40215	26.2	26.08	36				137

APPENDIX B
SUPPLEMENTARY DATA, CHAPTER III

Table B.1. Chemical Analyses of Miocene Paleosols, Cerro Observatorio.

Pedotype	Sample number	Soil Hz.	cm	SiO ₂ wt%	Al ₂ O ₃ wt%	Fe ₂ O ₃ wt%	MgO wt%	CaO wt%	Na ₂ O wt%	K ₂ O wt%	TiO ₂ wt%	P ₂ O ₅ wt%	MnO wt%	Cr ₂ O ₃ wt%	Ba ppm	Ni ppm	Sr ppm	Zr ppm	Y ppm	Nb ppm	Sc ppm	LOI wt%	SUM wt%
Uaye	AGR2.MO.I.1	A	27.5	59.39	16.82	5.68	2.15	2.51	2.33	1.15	0.67	0.09	0.12	0.004	185	22	179.1	189	26	9	16	8.6	99.63
Uaye	AGR2.MO.I.2	BC	42.5	61.82	15.48	6.49	1.59	2.9	2.89	1.88	0.74	0.105	0.12	0.007	562	28	296.2	141	26	<5	18	5.4	99.51
Uaye	AGR2.MO.I.3	C	57.5	62.57	15.36	6.29	1.57	2.89	2.9	1.85	0.73	0.118	0.12	0.007	544	33	303.4	153	26	<5	18	5.1	99.61
Uaye	AGR2.MO.I.4	C	72.5	62.48	15.54	6.02	1.56	2.9	3	1.81	0.75	0.115	0.12	0.007	577	<20	338.4	135	23	8	18	5.1	99.56
Uaye	AGR2.MO.I.5	C	87.5	62.45	15.68	5.62	1.48	3.26	3.02	1.88	0.75	0.123	0.11	0.007	1245	23	411.3	133	23	6	18	5	99.58
Kaôpen	CMARG-MO-II.1	A	15	60.51	15.42	7.41	1.79	1.01	2.14	2.5	0.66	0.03	0.11	0.007	503	22	163	104	21	5	19	8.2	99.89
Kaôpen	CMARG-MO-II.2	B	55	63.72	14.21	6.14	1.37	1.5	3.06	1.98	0.69	0.05	0.07	0.007	614	9	313	113	19	<5	16	7	99.93
Kaôpen	CMARG-MO-II.3	C	85	62.67	14.07	6.89	1.49	1.53	2.82	2.01	0.68	0.06	0.08	0.006	429	27	299	113	23	7	16	7.5	99.92
Zapelûn	CMARG-MO-III.2	A	45	61.6	14.89	6.49	1.59	1.67	2.83	2.07	0.71	0.1	0.1	0.007	806	21	297	120	25	<5	16	7.7	99.91
Zapelûn	CMARG-MO-III.1	C	35	59.73	15.64	6.62	1.76	1.74	2.31	2.19	0.69	0.1	0.1	0.006	811	20	305	112	27	<5	17	9	100.04
Zapelûn	AGR2.MO.III.1	A	95	59.93	15.98	6.68	1.47	3.01	2.78	1.85	0.71	0.094	0.09	0.005	411	<20	231.9	135	26	8	16	6.7	99.38
Zapelûn	AGR2.MO.III.2	B	105	61.47	15.58	6.11	1.24	2.66	2.82	1.97	0.71	0.099	0.09	0.005	469	<20	227.5	140	26	12	14	6.8	99.65
Zapelûn	AGR2.MO.III.3	B	120	61.08	15.07	6.71	1.21	2.43	2.73	1.98	0.7	0.124	0.1	0.005	483	<20	217	141	29	6	14	7.3	99.51
Zapelûn	AGR2.MO.III.4	B	135	60.21	15.77	6.17	1.48	2.29	2.35	1.92	0.71	0.074	0.1	0.005	435	24	200	139	28	11	16	8.2	99.38
Zapelûn	AGR2.MO.III.5	C	150	58.68	15.91	6.29	2.2	2.11	1.88	1.58	0.62	0.034	0.1	0.006	317	20	169.6	127	23	6	16	9.9	99.36
Zak	CMARG-MO-IVup.3	A	12.5	59.16	15.35	7.46	2.42	1.39	2.15	2.39	0.69	0.08	0.11	0.007	420	19	152	105	23	<5	18	8.6	99.89
Zak	CMARG-MO-IVup.2	B	42	58.87	15.57	7.59	2.35	1.47	2.41	2.15	0.73	0.05	0.13	0.008	427	32	179	110	24	6	19	8.5	99.92
Zak	CMARG-MO-IVup.1	C	90	59.85	15.23	6.61	2.21	2.05	2.74	1.73	0.7	0.09	0.1	0.008	400	17	223	120	22	5	17	8.5	99.92
Zak	CMARG-MO-IVlo.2	A	10	60.45	15.66	6.97	2.16	1.78	2.71	1.92	0.75	0.11	0.1	0.007	418	23	194	109	22	6	17	7.2	99.91
Zak	CMARG-MO-IVlo.1	C	25	58.2	15.55	8.5	2.37	1.32	2.11	2.21	0.72	0.1	0.13	0.007	390	31	136	110	27	<5	18	8.6	99.91
Kak	CMARG-MO-V.3	A1	12.5	61.17	14.81	6.91	2.31	1.3	3.03	1.89	0.78	0.15	0.15	0.008	446	29	174	121	23	8	17	7.3	99.9
Kak	CMARG-MO-V.2	A2	37	59.28	15.65	7.92	2.57	1.06	2.37	2.48	0.74	0.15	0.18	0.007	502	31	141	118	25	7	19	7.4	99.9
Kak	CMARG-MO-V.1	C	53	56.86	17.08	7.74	2.7	1.27	2.1	2.91	0.65	0.13	0.16	0.008	557	36	140	118	21	<5	20	8.2	99.91
Tem	AGR2.MO.VI.1	A	15	41.9	11.38	4.39	1.41	17.78	1.64	2.09	0.46	10.477	0.23	0.005	389	<20	410.4	100	78	6	13	7.4	99.25
Tem	AGR2.MO.VI.2	Bt	25	60.6	15.56	7.43	1.98	0.97	1.96	3	0.66	0.086	0.09	0.008	350	22	133.9	116	22	7	19	7	99.38
Tem	AGR2.MO.VI.3	Bt	35	60.06	14.57	9.12	2.01	0.92	1.79	2.93	0.61	0.061	0.1	0.007	355	40	105.2	105	25	7	18	7.2	99.42
Tem	AGR2.MO.VI.4	C	47	62.82	15.13	6.34	1.81	1.12	2.39	2.57	0.69	0.066	0.08	0.008	363	28	177.2	112	23	6	18	6.3	99.4
Tem	AGR2.MO.VI.5	C	67	62.24	15.23	6.66	1.76	1.1	2.26	2.73	0.67	0.071	0.08	0.008	343	24	170.7	115	25	9	19	6.6	99.51
Tem	AGR2.MO.VI.6	C	87	63.44	15.1	5.91	1.68	1.25	2.48	2.47	0.69	0.074	0.08	0.007	339	<20	189.4	120	27	10	18	6.3	99.56

Note: From ICP-MS analysis by Acme Analytical Labs, Vancouver, British Columbia. See Chapter III for details about methods.

Table B.1. (continued)

Pedotype	Sample number	Soil Hz.	cm	SiO ₂ wt%	Al ₂ O ₃ wt%	Fe ₂ O ₃ wt%	MgO wt%	CaO wt%	Na ₂ O wt%	K ₂ O wt%	TiO ₂ wt%	P ₂ O ₅ wt%	MnO wt%	Cr ₂ O ₃ wt%	Ba ppm	Ni ppm	Sr ppm	Zr ppm	Y ppm	Nb ppm	Sc ppm	LOI wt%	SUM wt%
Hö	AGR2.MO.VII.1	A	5	57.99	15.94	9.48	1.97	0.77	2	2.69	0.62	0.052	0.09	0.008	334	<20	81.8	109	33	12	20	8	99.71
Hö	AGR2.MO.VII.2	B	15	58.36	16.15	8.95	2.02	0.94	1.9	2.7	0.61	0.04	0.09	0.008	338	<20	84.6	105	32	15	19	7.7	99.49
Hö	AGR2.MO.VII.3	B	22.5	59.3	15.66	8.95	2.01	0.74	1.98	2.58	0.63	0.03	0.07	0.008	320	22	79.3	102	28	9	19	7.6	99.6
Hö	AGR2.MO.VII.4	B	27.5	59.63	15.39	8.92	2	0.68	1.9	2.65	0.61	0.035	0.07	0.007	332	47	82.5	103	29	8	20	7.8	99.71
Hö	AGR2.MO.VII.5	C	35	57.84	16.64	8.82	2	0.67	1.68	2.98	0.66	0.047	0.14	0.009	373	<20	77	123	36	6	23	7.8	99.38
Huaïtenk	AGR2.MO.VIII.1	A	5	59.06	15.67	7.34	2.01	2.02	2.76	2.02	0.75	0.118	0.11	0.006	456	<20	196.6	118	29	6	17	7.5	99.47
Huaïtenk	AGR2.MO.VIII.2	A	15	59.2	15.57	7.29	1.99	1.9	2.89	2.08	0.75	0.109	0.13	0.006	478	<20	201.6	119	26	9	18	7.4	99.36
Huaïtenk	AGR2.MO.VIII.3	A	25	59.25	15.53	7.16	2	1.93	2.74	2.15	0.75	0.112	0.13	0.007	469	29	190.2	117	25	7	17	7.5	99.38
Huaïtenk	AGR2.MO.VIII.4	B	35	59.28	16.01	6.78	2.17	1.85	2.55	2.18	0.76	0.113	0.11	0.006	452	<20	180.1	124	25	10	18	7.7	99.57
Huaïtenk	AGR2.MO.VIII.5	B	50	59.18	15.71	6.99	2.06	2.44	3.04	1.92	0.74	0.114	0.11	0.006	458	<20	211.6	121	22	10	18	7.1	99.54
Huaïtenk	AGR2.MO.VIII.6	C	60	59.13	15.3	7.22	2.14	2.14	2.87	2.04	0.74	0.117	0.11	0.007	447	25	195.4	118	24	12	17	7.5	99.43
Huaïtenk	AGR2.MO.VIII.7	C	70	59.84	15.37	6.9	2.14	2.25	2.77	1.8	0.7	0.099	0.1	0.007	442	<20	206.6	119	21	<5	17	7.5	99.55
Huaïtenk	AGR2.MO.VIII.8	C	90	60.37	15.35	6.71	2.13	2.28	2.69	1.73	0.7	0.093	0.09	0.006	429	<20	207.7	115	22	11	17	7.3	99.55
Chorlo	AGR2.MO.IX.1	A	10	60.03	15.53	7.1	1.91	3.36	2.72	1.52	0.81	0.15	0.11	0.006	386	<20	250.1	144	25	14	18	6.2	99.56
Chorlo	AGR2.MO.IX.2	B	25	59.17	15.17	8.18	1.91	2.02	2.07	2.09	0.73	0.112	0.11	0.007	415	<20	167.7	129	26	15	19	8.1	99.74
Chorlo	AGR2.MO.IX.3	C	40	57.14	17.15	6.74	1.92	3.3	2.23	1.63	0.77	0.108	0.09	0.006	333	<20	232.5	141	25	8	20	8.4	99.56

Note: From ICP-MS analysis by Acme Analytical Labs, Vancouver, British Columbia. See Chapter III for details about methods.

Table B.2. Point count data on grain size and minerals of Miocene paleosols.

Pedotype	ID#	Soil Hz.	cm	grain size (vol%)			mineralogy (vol%)					
				clay	silt	sand	clay	gypsum	qtz	volc	rock frag	opaque
Uaye	AGR2.MO.I.1	A	27.5	82	11.2	6.8	57	5.4	31	0.8	1.4	4.4
Uaye	AGR2.MO.I.2	BC	42.5	79	14.8	6.2	48.8	6.2	38.8	0.2	0	6
Uaye	AGR2.MO.I.4	C	72.5	76.8	18.2	5	21.4	9.8	62	0	0.2	6.6
Kaôpen	CMARG-MO-II.1	A	15	97.6	2.4	0	96	1.4	0.4	0	2.2	0
Kaôpen	CMARG-MO-II.3	C	85	90.8	9.2	0	75.8	18.6	1.2	0.2	3.8	0.4
Zapelûn	CMARG-MO-III.2	A	45	84.4	12.4	3.2	66.8	26.8	1.4	0.8	0.8	3.4
Zapelûn	CMARG-MO-III.1	C	65	86	11.6	2.4	54.6	39.6	4.6	0	0	1.2
Zak	CMARG-MO-IVupp.3	A	12.5	40.8	42.8	16.4	12.8	18.2	43.6	6.4	2.4	16.6
Zak	CMARG-MO-IVupp.1	C	90	42	41.2	16.8	15.2	18.8	40.8	9.4	2.4	13.4
Kak	CMARG-MO-V.3	A1	13	28.2	35	36.8	20	21.2	28.6	3.8	19	7.4
Kak	CMARG-MO-V.2	A2	37	44.8	46.4	8.8	20.8	23	44	7.2	3.4	1.6
Kak	CMARG-MO-V.1	C	53	37.6	47.2	15.2	19.6	27.6	38	5.2	5	4.6
Tem	AGR2.MO.VI.1	A	15	95.4	4	0.6	36.8	58.6	1.2	0	0	3.4
Tem	AGR2.MO.VI.3	Bt	35	97.6	2	0.4	53.4	44.6	1	0	0	1
Tem	AGR2.MO.VI.4	C	47	98.2	1.8	0	98.2	0.6	0	1.2	0	0
Hö	AGR2.MO.VII.1	A	5	48.6	15	36.4	38.2	0	30.6	28.4	0.6	2.2
Hö	AGR2.MO.VII.3	B	23	84.6	13	2.4	86.8	0	3.4	1	6.4	2.2
Hö	AGR2.MO.VII.4	B	28	66.4	23.6	10	81.4	0	12.8	4	0.4	1.4
Hö	AGR2.MO.VII.5	B	35	75.4	18.8	5.8	90.6	0	5.8	3.4	0.2	0
Huaïtenk	AGR2.MO.VIII.1	C	5	89.4	10.2	0.4	38.6	2.8	52.8	5.6	0.2	0
Huaïtenk	AGR2.MO.VIII.4	A	35	92.4	6.6	1	15.8	2.4	79.2	2.6	0	0
Huaïtenk	AGR2.MO.VIII.6	B	60	85.8	13.8	0.4	44.4	0	50.6	5	0	0

Note: Two separate counts are tabulated here: one for grain size, and other for mineral content. Comparability of clay counts in each is a quality control. Error of these 500 point counts are $\pm 2\%$ for components at abundance $> 5\%$.

APPENDIX C
MIDDLE MIOCENE SOIL DATABASE

Table C.1. Middle Miocene Soil Database.

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Africa	Chad	Oxisol	X	12.10	15.10	15.10	12.10	15.97	Bodeli	47041	PGAP	9668
Africa	Egypt	Aridisol, gypsic	G	29.00	33.20	33.20	29.00	15.97	Kareem Fm	48161	PGAP	6169
Africa	Egypt	Aridisol, gypsic	G	29.30	32.90	32.90	29.30	15.97	Gharandal-Ev	48686	PGAP	7018
Africa	Egypt	Aridisol, gypsic	G	28.40	33.10	33.10	28.40	15.97	Gharandal-Ev	48687	PGAP	7018
Africa	Egypt	Aridisol, gypsic	G	27.20	33.80	33.80	27.20	15.97	Gharandal-Ev	48688	PGAP	7018
Africa	Egypt	Aridisol, gypsic	G	27.70	33.40	33.40	27.70	15.97	Gharandal-Ev	48689	PGAP	7018
Africa	Egypt	Aridisol, salic	H	27.20	33.80	33.80	27.20	15.97	Gharandal-Ev	48688	PGAP	7018
Africa	Egypt	Histosol	P	30.30	29.90	29.90	30.30	15.97	Sidi Salem	49275	PGAP	24476
Africa	Egypt	Histosol	P	29.90	29.90	29.90	29.90	15.97	Sidi Salem	49276	PGAP	24476
Africa	Kenya	Alfisol	FF	-0.21	35.31	35.31	-0.21	18-16	Wayondo Alfisol, Gumba Beds, Hiwegi Formation	Rusinga Island, Kenya	MSDB	Forbes et al., 2004; Retallack, 1991; Retallack et al., 1995
Africa	Kenya	Alfisol	FF	0.64	35.95	35.95	0.64	16-13	Muruyur Beds	Kipsaramon site complex, Tugen Hills, Kenya	MSDB	Behresnmeyer et al., 2002
Africa	Kenya	Aridisol	AA	-0.21	34.72	34.72	-0.21	15	Maboko Formation	Maboko Island, Kenya	MSDB	Retallack et al., 2002; Wynn and Retallack, 2001
Africa	Kenya	Mollisol	GG	-0.10	35.21	35.21	-0.10	14	Fort Ternan Member, Kericho phonolites	Fort Ternan, Kenya	MSDB	Dugas and Retallack, 1993; Retallack, 1991; Retallack et al., 1990
Africa	Libya	Aridisol, gypsic	G	27.10	22.10	22.10	27.10	15.97	Marada A-C	46042	PGAP	1697
Africa	Libya	Aridisol, gypsic	G	30.00	21.00	21.00	30.00	15.97	Mid Mio	46248	PGAP	852
Africa	Libya	Aridisol, gypsic	G	32.20	20.40	20.40	32.20	15.97	Wadi Al Qat.	46359	PGAP	1698
Africa	Libya	Aridisol, gypsic	G	32.60	12.60	12.60	32.60	15.97	M. Miocene	46658	PGAP	12087
Africa	Libya	Aridisol, gypsic	G	32.00	21.50	21.50	32.00	15.97	Ar Rajmah Fm	46795	PGAP	12070
Africa	Libya	Aridisol, gypsic	G	30.50	18.00	18.00	30.50	15.97	Al Khums Fm.	46796	PGAP	12070
Africa	Libya	Aridisol, gypsic	G	30.50	13.50	13.50	30.50	15.97	Al Khums Fm.	46797	PGAP	12070
Africa	Libya	Aridisol, gypsic	G	32.80	21.80	21.80	32.80	15.97	Ar Rajmah Fm	46799	PGAP	12070
Africa	Libya	Aridisol, gypsic	G	32.10	20.10	20.10	32.10	15.97	Ar Rajmah Fm	46800	PGAP	12070
Africa	Libya	Aridisol, gypsic	G	31.60	20.50	20.50	31.60	15.97	Ar Rajmah Fm	46801	PGAP	12070
Africa	Libya	Aridisol, gypsic	G	32.30	20.10	20.10	32.30	15.97	Ar Rajmah	49052	PGAP	24498

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Africa	Libya	Aridisol, salic	H	30.00	21.00	21.00	30.00	15.97	Mid Mio	46248	PGAP	852
Africa	Libya	Aridisol, salic	H	29.20	19.20	19.20	29.20	15.97	Marada	49043	PGAP	6163
Africa	Somalia	Aridisol, gypsic	G	2.00	45.00	45.00	2.00	15.97	Miocene	46012	PGAP	47
Africa	South Africa	Oxisol	X	-34.50	24.90	24.90	-34.50	15.97	Phosphat. Ls	46910	PGAP	6127
Africa	South Africa	Oxisol	X	-36.00	21.80	21.80	-36.00	15.97	Phosphat. Ls	46913	PGAP	6127
Africa	South Africa	Oxisol	X	-35.10	23.20	23.20	-35.10	15.97	Phosphat. Ls	46914	PGAP	6127
Africa	Sudan	Aridisol, gypsic	G	21.20	37.00	37.00	21.20	15.97	Mag.-Abu Im.	47043	PGAP	10858
Africa	Tanzania	Histosol	P	-6.00	39.20	39.20	-6.00	15.97	Miocene	46609	PGAP	6197
Africa	Tanzania	Ultisol	KK	6.87	39.50	39.50	6.87	17-14	Pugu Sandstone Beds	Pugu, central Tanzania	MSDB	Mutakyahwa, 1987
Antarctica	Antarctica	Aridisol, gypsic	G	-77.50	161.50	161.50	-77.50	15.97	M-L Miocene	48025	PGAP	1117
Antarctica	Antarctica	Aridisol, salic	H	-77.50	161.50	161.50	-77.50	15.97	M-L Miocene	48025	PGAP	1117
Asia	Bangladesh	Histosol	P	25.00	89.20	89.20	25.00	15.97	Jamalganj Fm	46612	PGAP	861
Asia	Burma (Myanmar)	Aridisol, gypsic	G	22.60	94.70	94.70	22.60	15.97	Obogan Alt.	46364	PGAP	5453
Asia	China	Aridisol, gypsic	G	23.10	101.00	101.00	23.10	15.97	Unnamed	47913	PGAP	13874
Asia	China	Aridisol, gypsic	G	24.50	100.80	100.80	24.50	15.97	Unnamed	47914	PGAP	13874
Asia	China	Aridisol, gypsic	G	38.40	80.00	80.00	38.40	15.97	Unnamed	48036	PGAP	13242
Asia	China	Aridisol, gypsic	G	39.30	73.90	73.90	39.30	15.97	Unnamed	48037	PGAP	13242
Asia	China	Aridisol, gypsic	G	39.20	75.50	75.50	39.20	15.97	Unnamed	48038	PGAP	13242
Asia	China	Aridisol, gypsic	G	38.60	78.50	78.50	38.60	15.97	Unnamed	48039	PGAP	13242
Asia	China	Aridisol, gypsic	G	41.50	80.00	80.00	41.50	15.97	Unnamed	48040	PGAP	13242
Asia	China	Aridisol, gypsic	G	41.00	91.80	91.80	41.00	15.97	Unnamed	48043	PGAP	13242
Asia	China	Aridisol, gypsic	G	42.10	86.00	86.00	42.10	15.97	Unnamed	48044	PGAP	13242
Asia	China	Aridisol, gypsic	G	42.30	91.00	91.00	42.30	15.97	Unnamed	48046	PGAP	13242

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Asia	China	Aridisol, gypsic	G	44.10	86.20	86.20	44.10	15.97	Unnamed	48048	PGAP	13242
Asia	China	Aridisol, gypsic	G	44.40	82.40	82.40	44.40	15.97	Unnamed	48049	PGAP	13242
Asia	China	Aridisol, gypsic	G	44.30	85.00	85.00	44.30	15.97	Unnamed	48050	PGAP	13242
Asia	China	Aridisol, gypsic	G	42.80	93.00	93.00	42.80	15.97	Unnamed	48052	PGAP	13242
Asia	China	Aridisol, gypsic	G	41.40	81.80	81.80	41.40	15.97	Unnamed	48053	PGAP	13242
Asia	China	Aridisol, gypsic	G	41.70	83.70	83.70	41.70	15.97	Unnamed	48055	PGAP	13242
Asia	China	Aridisol, gypsic	G	43.00	92.00	92.00	43.00	15.97	Unnamed	48056	PGAP	13242
Asia	China	Aridisol, gypsic	G	42.30	94.50	94.50	42.30	15.97	Unnamed	48058	PGAP	13242
Asia	China	Aridisol, gypsic	G	42.70	81.80	81.80	42.70	15.97	Unnamed	48059	PGAP	13242
Asia	China	Aridisol, gypsic	G	42.00	84.60	84.60	42.00	15.97	Unnamed	48060	PGAP	13242
Asia	China	Aridisol, gypsic	G	41.90	92.80	92.80	41.90	15.97	Unnamed	48061	PGAP	13242
Asia	China	Aridisol, gypsic	G	37.40	116.60	116.60	37.40	15.97	Guan Tao	48395	PGAP	4545
Asia	China	Aridisol, gypsic	G	37.70	118.00	118.00	37.70	15.97	Guan Tao	48396	PGAP	4545
Asia	China	Aridisol, gypsic	G	36.90	116.70	116.70	36.90	15.97	Guan Tao	48397	PGAP	4545
Asia	China	Aridisol, gypsic	G	37.70	117.60	117.60	37.70	15.97	Guan Tao	48398	PGAP	4545
Asia	China	Aridisol, gypsic	G	37.10	118.40	118.40	37.10	15.97	Guan Tao	48399	PGAP	4545
Asia	China	Aridisol, gypsic	G	37.30	117.10	117.10	37.30	15.97	Guan Tao	48400	PGAP	4545
Asia	China	Aridisol, gypsic	G	37.60	118.60	118.60	37.60	15.97	Guan Tao	48401	PGAP	4545
Asia	China	Aridisol, gypsic	G	39.70	97.60	97.60	39.70	15.97	Bai Yang He	48477	PGAP	4447
Asia	China	Aridisol, gypsic	G	39.60	97.50	97.50	39.60	15.97	Bai Yang He	48478	PGAP	4447
Asia	China	Aridisol, gypsic	G	39.00	99.70	99.70	39.00	15.97	Bai Yang He	48479	PGAP	4447
Asia	China	Aridisol, gypsic	G	39.30	98.60	98.60	39.30	15.97	Bai Yang He	48480	PGAP	4447
Asia	China	Aridisol, gypsic	G	35.70	99.30	99.30	35.70	15.97	Unnamed	48624	PGAP	4453
Asia	China	Aridisol, gypsic	G	35.70	95.90	95.90	35.70	15.97	Cha Bao Ma	48633	PGAP	4453
Asia	China	Aridisol, gypsic	G	34.10	95.80	95.80	34.10	15.97	Cha Bao Ma	48636	PGAP	4453
Asia	China	Aridisol, gypsic	G	34.60	94.90	94.90	34.60	15.97	Cha Bao Ma	48637	PGAP	4453
Asia	China	Aridisol, gypsic	G	37.10	98.00	98.00	37.10	15.97	Bai Yang He	48655	PGAP	4453
Asia	China	Histosol	P	27.00	108.10	108.10	27.00	15.97	Weng Shao	46466	PGAP	10787

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Asia	China	Histosol	P	24.20	120.80	120.80	24.20	15.97	Nankang-Shih	46524	PGAP	4146
Asia	China	Histosol	P	24.70	121.30	121.30	24.70	15.97	Nankang-Shih	46525	PGAP	4146
Asia	China	Histosol	P	29.70	100.60	100.60	29.70	15.97	Unnamed	47047	PGAP	13873
Asia	China	Histosol	P	29.40	89.60	89.60	29.40	15.97	Mang.-Laiqin	47900	PGAP	13684
Asia	China	Histosol	P	29.40	89.00	89.00	29.40	15.97	Mang.-Laiqin	47901	PGAP	13684
Asia	China	Histosol	P	29.40	88.60	88.60	29.40	15.97	Mang.-Laiqin	47902	PGAP	13684
Asia	China	Histosol	P	25.20	102.30	102.30	25.20	15.97	Unnamed	47906	PGAP	13874
Asia	China	Histosol	P	23.40	103.40	103.40	23.40	15.97	Xiao Long T.	47907	PGAP	13874
Asia	China	Histosol	P	22.60	103.80	103.80	22.60	15.97	Unnamed	47908	PGAP	13874
Asia	China	Histosol	P	23.70	103.10	103.10	23.70	15.97	Xiao Long T.	47910	PGAP	13874
Asia	China	Histosol	P	23.30	102.90	102.90	23.30	15.97	Xiao Long T.	47911	PGAP	13874
Asia	China	Histosol	P	24.30	103.40	103.40	24.30	15.97	Xiao Long T.	47912	PGAP	13874
Asia	China	Histosol	P	23.10	101.00	101.00	23.10	15.97	Unnamed	47913	PGAP	13874
Asia	China	Histosol	P	24.50	100.80	100.80	24.50	15.97	Unnamed	47914	PGAP	13874
Asia	China	Histosol	P	23.80	99.70	99.70	23.80	15.97	Unnamed	47919	PGAP	13874
Asia	China	Histosol	P	24.10	99.40	99.40	24.10	15.97	Unnamed	47920	PGAP	13874
Asia	China	Histosol	P	24.50	99.70	99.70	24.50	15.97	Unnamed	47921	PGAP	13874
Asia	China	Histosol	P	24.90	99.50	99.50	24.90	15.97	Unnamed	47922	PGAP	13874
Asia	China	Histosol	P	23.50	99.40	99.40	23.50	15.97	Unnamed	47923	PGAP	13874
Asia	China	Histosol	P	23.90	97.80	97.80	23.90	15.97	Unnamed	47924	PGAP	13874
Asia	China	Histosol	P	25.10	99.20	99.20	25.10	15.97	Unnamed	47925	PGAP	13874
Asia	China	Histosol	P	24.30	98.30	98.30	24.30	15.97	Unnamed	47926	PGAP	13874
Asia	China	Histosol	P	25.30	103.90	103.90	25.30	15.97	Ci Ying	47927	PGAP	13874
Asia	China	Histosol	P	25.00	98.40	98.40	25.00	15.97	Unnamed	47928	PGAP	13874
Asia	China	Histosol	P	24.60	98.60	98.60	24.60	15.97	Unnamed	47929	PGAP	13874
Asia	China	Histosol	P	25.40	98.50	98.50	25.40	15.97	Unnamed	47930	PGAP	13874
Asia	China	Histosol	P	24.30	97.80	97.80	24.30	15.97	Unnamed	47931	PGAP	13874
Asia	China	Histosol	P	24.90	97.90	97.90	24.90	15.97	Unnamed	47932	PGAP	13874

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Asia	China	Histosol	P	26.70	99.90	99.90	26.70	15.97	Shung He	47933	PGAP	13874
Asia	China	Histosol	P	26.30	99.80	99.80	26.30	15.97	Shung He	47934	PGAP	13874
Asia	China	Histosol	P	24.40	103.30	103.30	24.40	15.97	Unnamed	47935	PGAP	13874
Asia	China	Histosol	P	24.70	103.30	103.30	24.70	15.97	Unnamed	47936	PGAP	13874
Asia	China	Histosol	P	25.00	103.30	103.30	25.00	15.97	Unnamed	47937	PGAP	13874
Asia	China	Histosol	P	23.40	102.20	102.20	23.40	15.97	Xiao Long T.	47938	PGAP	13874
Asia	China	Histosol	P	24.00	102.80	102.80	24.00	15.97	Xiao Long T.	47939	PGAP	13874
Asia	China	Histosol	P	23.30	102.60	102.60	23.30	15.97	Xiao Long T.	47940	PGAP	13874
Asia	China	Histosol	P	24.30	102.70	102.70	24.30	15.97	Unnamed	47941	PGAP	13874
Asia	China	Histosol	P	25.00	102.30	102.30	25.00	15.97	Xiao Long T.	47942	PGAP	13874
Asia	China	Histosol	P	25.80	103.90	103.90	25.80	15.97	Ci Ying	47943	PGAP	13874
Asia	China	Histosol	P	25.60	103.70	103.70	25.60	15.97	Ci Ying	47944	PGAP	13874
Asia	China	Histosol	P	24.90	103.20	103.20	24.90	15.97	Ci Ying	47945	PGAP	13874
Asia	China	Histosol	P	26.00	99.80	99.80	26.00	15.97	Shuang He Me	47985	PGAP	5006
Asia	China	Histosol	P	24.30	102.60	102.60	24.30	15.97	Unnamed	47986	PGAP	5006
Asia	China	Histosol	P	26.50	99.80	99.80	26.50	15.97	Shuang He Me	47987	PGAP	5006
Asia	China	Histosol	P	23.50	100.70	100.70	23.50	15.97	Unnamed	47988	PGAP	5006
Asia	China	Histosol	P	23.80	103.20	103.20	23.80	15.97	Xiao Long T.	47990	PGAP	5006
Asia	China	Histosol	P	24.80	99.50	99.50	24.80	15.97	Unnamed	48041	PGAP	13242
Asia	China	Histosol	P	24.20	99.50	99.50	24.20	15.97	Unnamed	48042	PGAP	13242
Asia	China	Histosol	P	47.40	132.60	132.60	47.40	15.97	Fu Jin	48307	PGAP	4448
Asia	China	Histosol	P	47.20	132.30	132.30	47.20	15.97	Fu Jin	48308	PGAP	4448
Asia	China	Histosol	P	47.70	132.80	132.80	47.70	15.97	Fu Jin	48309	PGAP	4448
Asia	China	Histosol	P	23.00	108.60	108.60	23.00	15.97	Na Du	48330	PGAP	4456
Asia	China	Histosol	P	22.20	108.00	108.00	22.20	15.97	Na Du	48331	PGAP	4456
Asia	China	Histosol	P	22.10	107.40	107.40	22.10	15.97	Na Du	48332	PGAP	4456
Asia	China	Histosol	P	22.10	106.90	106.90	22.10	15.97	Na Du	48333	PGAP	4456
Asia	China	Histosol	P	23.30	110.90	110.90	23.30	15.97	Yi Ning	48334	PGAP	4456

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Asia	China	Histosol	P	23.40	110.30	110.30	23.40	15.97	Yi Ning	48335	PGAP	4456
Asia	China	Histosol	P	23.20	110.10	110.10	23.20	15.97	Yi Ning	48336	PGAP	4456
Asia	China	Histosol	P	23.60	110.70	110.70	23.60	15.97	Yi Ning	48337	PGAP	4456
Asia	China	Histosol	P	21.70	108.90	108.90	21.70	15.97	Yi Ning	48338	PGAP	4456
Asia	China	Histosol	P	21.80	109.40	109.40	21.80	15.97	Yi Ning	48339	PGAP	4456
Asia	China	Histosol	P	22.20	108.80	108.80	22.20	15.97	Yi Ning	48340	PGAP	4456
Asia	China	Histosol	P	21.70	109.70	109.70	21.70	15.97	Yi Ning	48341	PGAP	4456
Asia	China	Histosol	P	21.60	111.00	111.00	21.60	15.97	Shang Cun	48342	PGAP	4456
Asia	China	Histosol	P	21.90	110.70	110.70	21.90	15.97	Shang Cun	48343	PGAP	4456
Asia	China	Histosol	P	29.40	120.00	120.00	29.40	15.97	Sheng Xian	48430	PGAP	4544
Asia	China	Histosol	P	29.30	120.20	120.20	29.30	15.97	Sheng Xian	48431	PGAP	4544
Asia	China	Histosol	P	29.70	120.20	120.20	29.70	15.97	Sheng Xian	48432	PGAP	4544
Asia	China	Histosol	P	29.30	121.40	121.40	29.30	15.97	Sheng Xian	48434	PGAP	4544
Asia	China	Histosol	P	29.10	121.00	121.00	29.10	15.97	Sheng Xian	48435	PGAP	4544
Asia	China	Histosol	P	29.40	121.00	121.00	29.40	15.97	Sheng Xian	48436	PGAP	4544
Asia	China	Histosol	P	28.80	121.20	121.20	28.80	15.97	Sheng Xian	48437	PGAP	4544
Asia	China	Histosol	P	23.70	106.80	106.80	23.70	15.97	Na Du	48552	PGAP	4456
Asia	China	Histosol	P	23.60	107.20	107.20	23.60	15.97	Na Du	48553	PGAP	4456
Asia	China	Histosol	P	24.00	106.60	106.60	24.00	15.97	Na Du	48554	PGAP	4456
Asia	China	Histosol	P	23.20	107.60	107.60	23.20	15.97	Na Du	48555	PGAP	4456
Asia	China	Histosol	P	23.00	108.00	108.00	23.00	15.97	Na Du	48563	PGAP	4456
Asia	China	Histosol	P	22.80	108.20	108.20	22.80	15.97	Na Du	48564	PGAP	4456
Asia	China	Histosol	P	19.70	110.40	110.40	19.70	15.97	Chang Cang	48565	PGAP	4456
Asia	China	Histosol	P	19.80	110.00	110.00	19.80	15.97	Chang Cang	48566	PGAP	4456
Asia	China	Histosol	P	39.00	98.90	98.90	39.00	15.97	Gui De	48656	PGAP	4453
Asia	China	Oxisol	X	24.00	117.00	117.00	24.00	17 to 15	Niuthousan tholeittes	Niuthoushan, China	MSDB	Zou et al., 2004
Asia	India	Histosol	P	23.20	72.70	72.70	23.20	15.97	Kalol Fm	48671	PGAP	12479

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Asia	India	Oxisol	X	27.50	82.70	82.70	27.50	middle Mio-cene	Laterite	Neyveli, Madras, India	MSDB	Valeton, 1967
Asia	Indonesia	Histosol	P	-5.00	139.70	139.70	-5.00	15.97	Iwoer Fm.	47820	PGAP	564
Asia	Indonesia	Histosol	P	-5.10	140.80	140.80	-5.10	15.97	Iwoer Fm.	47821	PGAP	564
Asia	Indonesia	Histosol	P	1.00	98.00	98.00	1.00	15.97	Unnamed	48721	PGAP	586
Asia	Indonesia	Histosol	P	-0.60	117.70	117.70	-0.60	15.97	Prangat Fm	48737	PGAP	18063
Asia	Indonesia	Histosol	P	-2.10	115.50	115.50	-2.10	15.97	Warukin	48797	PGAP	9749
Asia	Indonesia	Histosol	P	-3.30	114.60	114.60	-3.30	15.97	Warukin	48799	PGAP	9749
Asia	Indonesia	Histosol	P	-0.86	117.17	117.17	-0.86	23.03	Balikpapan Group	1108	OSR	
Asia	Indonesia	Histosol	P	-0.86	117.17	117.17	-0.86	23.03	Balikpapan Group	1109	OSR	
Asia	Indonesia	Histosol	P	-0.86	117.17	117.17	-0.86	23.03	Balikpapan Group	1110	OSR	
Asia	Indonesia	Histosol	P	-0.23	117.29	117.29	-0.23	23.03	Balikpapan Group	1111	OSR	
Asia	Indonesia	Histosol	P	-7.00	107.00	107.00	-7.00	23.03	Lower Cibulakan	1112	OSR	
Asia	Indonesia	Histosol	P	-5.50	106.00	106.00	-5.50	23.03	Talang Akar	1113	OSR	
Asia	Japan	Histosol	P	32.80	128.90	128.90	32.80	15.97	Najimo-Saseb	48869	PGAP	6801
Asia	Japan	Histosol	P	33.20	129.60	129.60	33.20	15.97	Najimo-Saseb	48870	PGAP	6801
Asia	Japan	Ultisol		35.36	137.25	137.25	35.36	16	Tokiguchi Porcelain Clay Formation	Mizunami, Japan	MSDB	Saneyoshi et al., 2000
Asia	Kazakhstan	Aridisol, gypsic	G	41.70	55.50	55.50	41.70	15.97	52 W	47524	PGAP	13120
Asia	Kazakhstan	Aridisol, gypsic	G	42.30	55.80	55.80	42.30	15.97	88 W	47547	PGAP	13120
Asia	Kazakhstan	Aridisol, gypsic	G	42.40	54.40	54.40	42.40	15.97	123 W	47554	PGAP	13120
Asia	Kazakhstan	Aridisol, gypsic	G	43.10	55.60	55.60	43.10	15.97	6 W	47564	PGAP	13120
Asia	Kazakhstan	Aridisol, gypsic	G	42.60	55.10	55.10	42.60	15.97	73 W	47596	PGAP	13120
Asia	Malaysia	Histosol	P	4.50	101.00	101.00	4.50	15.97	Unnamed	46428	PGAP	1691
Asia	Malaysia	Histosol	P	5.30	115.50	115.50	5.30	15.97	Belait-Meli.	46699	PGAP	859

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Asia	Malaysia	Histosol	P	6.80	116.70	116.70	6.80	15.97	Kudat-Bonga.	46701	PGAP	859
Asia	Malaysia	Histosol	P	4.40	117.30	117.30	4.40	15.97	Kapilit	46704	PGAP	859
Asia	Malaysia	Histosol	P	3.00	112.90	112.90	3.00	15.97	Kakus Member	46709	PGAP	20923
Asia	Malaysia	Histosol	P	3.30	113.70	113.70	3.30	15.97	Kakus Member	46710	PGAP	20923
Asia	Malaysia	Histosol	P	4.80	115.40	115.40	4.80	15.97	Meligan Fm	46712	PGAP	20923
Asia	Malaysia	Histosol	P	4.40	115.70	115.70	4.40	15.97	Meligan Fm	46713	PGAP	20923
Asia	Malaysia	Histosol	P	3.80	114.20	114.20	3.80	15.97	Setap Shale	46715	PGAP	20923
Asia	Mongolia	Histosol	P	51.30	99.40	99.40	51.30	15.97	Unnamed	48774	PGAP	24003
Asia	Mongolia	Alfisol	FF	43.50	113.00	113.00	43.50	middle Mio-cene	Tungurr Formation	Central Inner Mongolia	MSDB	Wang et al., 2003
Asia	Nepal	Histosol	P	29.00	81.00	81.00	29.00	11 to 7	Middle Siwalik Group	Western Nepal	MSDB	DeCelles et al., 1998
Asia	Nepal	Oxisol	X	27.85	82.37	82.37	27.85	14 to 11	Lower Siwalik Group	Western Nepal	MSDB	Barry et al., 2002; DeCelles et al., 1998
Asia	North Korea	Histosol	P	41.20	129.50	129.50	41.20	15.97	Meisen Gp.	48872	PGAP	4144
Asia	Pakistan	Oxisol		33.33	72.66	72.66	33.33	16-15	Chinji Formation	Kaulial, Pakistan	MSDB	Retallack, 1991
Asia	Philippines	Aridisol, salic	H	7.60	125.60	125.60	7.60	15.97	Kabagtican	46433	PGAP	801
Asia	Philippines	Histosol	P	11.20	123.90	123.90	11.20	15.97	Maingit Fm	46237	PGAP	7560
Asia	Philippines	Histosol	P	13.20	124.20	124.20	13.20	15.97	Bilbao-Carac	46605	PGAP	1472
Asia	Philippines	Histosol	P	9.50	125.70	125.70	9.50	15.97	Unknown	46986	PGAP	10320
Asia	Philippines	Histosol	P	8.80	126.20	126.20	8.80	15.97	Unknown	46992	PGAP	10320
Asia	Russian Federation	Histosol	P	52.30	99.20	99.20	52.30	15.97	(5) E	47198	PGAP	13120
Asia	Russian Federation	Histosol	P	50.20	90.20	90.20	50.20	15.97	(27) E	47303	PGAP	13120
Asia	Russian Federation	Histosol	P	49.20	142.90	142.90	49.20	15.97	1000 E	47377	PGAP	13120
Asia	Russian Federation	Histosol	P	47.60	142.10	142.10	47.60	15.97	1240 E	47384	PGAP	13120

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Asia	Russian Federation	Histosol	P	59.80	155.50	155.50	59.80	15.97	(215) E	47388	PGAP	13120
Asia	Russian Federation	Histosol	P	48.20	132.90	132.90	48.20	15.97	(57) W	47395	PGAP	13120
Asia	Russian Federation	Histosol	P	51.30	134.60	134.60	51.30	15.97	(20) E	47396	PGAP	13120
Asia	Russian Federation	Histosol	P	50.60	142.10	142.10	50.60	15.97	1000 E	47397	PGAP	13120
Asia	Russian Federation	Histosol	P	46.30	143.30	143.30	46.30	15.97	>0 E	47398	PGAP	13120
Asia	Russian Federation	Histosol	P	52.40	142.10	142.10	52.40	15.97	1650 E	47400	PGAP	13120
Asia	Russian Federation	Histosol	P	51.70	140.20	140.20	51.70	15.97	(50) E	47403	PGAP	13120
Asia	Russian Federation	Histosol	P	51.80	102.60	102.60	51.80	15.97	(250) W	47407	PGAP	13120
Asia	Russian Federation	Histosol	P	49.80	135.60	135.60	49.80	15.97	(25) W	47408	PGAP	13120
Asia	Russian Federation	Histosol	P	53.00	136.20	136.20	53.00	15.97	(100) W	47410	PGAP	13120
Asia	Russian Federation	Histosol	P	49.90	142.10	142.10	49.90	15.97	300 E	47412	PGAP	13120
Asia	Russian Federation	Histosol	P	48.80	142.10	142.10	48.80	15.97	1020 E	47413	PGAP	13120
Asia	Russian Federation	Histosol	P	51.10	142.60	142.60	51.10	15.97	300 E	47416	PGAP	13120
Asia	Russian Federation	Histosol	P	48.40	135.00	135.00	48.40	15.97	(70) W	47417	PGAP	13120
Asia	Russian Federation	Histosol	P	51.80	128.20	128.20	51.80	15.97	(42) W	47420	PGAP	13120
Asia	Russian Federation	Histosol	P	52.90	142.80	142.80	52.90	15.97	570 W	47425	PGAP	13120

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Asia	Russian Federation	Histosol	P	51.00	134.30	134.30	51.00	15.97	(25) E	47426	PGAP	13120
Asia	Russian Federation	Histosol	P	52.90	139.80	139.80	52.90	15.97	(25) E	47428	PGAP	13120
Asia	Russian Federation	Histosol	P	76.10	139.50	139.50	76.10	15.97	(25) E	47431	PGAP	13120
Asia	Russian Federation	Histosol	P	48.70	142.70	142.70	48.70	15.97	1075 E	47433	PGAP	13120
Asia	Russian Federation	Histosol	P	48.70	132.60	132.60	48.70	15.97	(100) W	47434	PGAP	13120
Asia	Russian Federation	Histosol	P	49.80	142.80	142.80	49.80	15.97	790 W	47437	PGAP	13120
Asia	Russian Federation	Histosol	P	54.40	110.30	110.30	54.40	15.97	200 W	47438	PGAP	13120
Asia	Russian Federation	Histosol	P	53.10	140.20	140.20	53.10	15.97	1380 W	47439	PGAP	13120
Asia	Russian Federation	Histosol	P	50.30	142.50	142.50	50.30	15.97	600 E	47442	PGAP	13120
Asia	Russian Federation	Histosol	P	53.50	138.20	138.20	53.50	15.97	(2) E	47443	PGAP	13120
Asia	Russian Federation	Histosol	P	48.50	136.70	136.70	48.50	15.97	(70) W	47448	PGAP	13120
Asia	Russian Federation	Histosol	P	47.30	142.10	142.10	47.30	15.97	>500 E	47455	PGAP	13120
Asia	Russian Federation	Histosol	P	47.90	134.90	134.90	47.90	15.97	(65) W	47457	PGAP	13120
Asia	Russian Federation	Histosol	P	50.90	129.50	129.50	50.90	15.97	(31) W	47458	PGAP	13120
Asia	Russian Federation	Histosol	P	52.30	140.30	140.30	52.30	15.97	(10) E	47461	PGAP	13120
Asia	Russian Federation	Histosol	P	49.10	142.10	142.10	49.10	15.97	1350 E	47462	PGAP	13120

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Asia	Russian Federation	Histosol	P	53.50	101.90	101.90	53.50	15.97	(8) E	47465	PGAP	13120
Asia	Russian Federation	Histosol	P	49.30	135.00	135.00	49.30	15.97	(40) W	47468	PGAP	13120
Asia	Russian Federation	Histosol	P	48.00	135.60	135.60	48.00	15.97	(90) W	47471	PGAP	13120
Asia	Russian Federation	Histosol	P	52.10	142.80	142.80	52.10	15.97	1420 E	47472	PGAP	13120
Asia	Russian Federation	Histosol	P	47.80	132.00	132.00	47.80	15.97	(60) W	47473	PGAP	13120
Asia	Russian Federation	Histosol	P	53.20	126.50	126.50	53.20	15.97	(30) W	47475	PGAP	13120
Asia	Russian Federation	Histosol	P	75.20	138.50	138.50	75.20	15.97	(1) E	47478	PGAP	13120
Asia	Russian Federation	Histosol	P	48.10	142.50	142.50	48.10	15.97	700 E	47481	PGAP	13120
Asia	Russian Federation	Histosol	P	52.50	137.10	137.10	52.50	15.97	(10) E	47486	PGAP	13120
Asia	Russian Federation	Histosol	P	51.60	105.80	105.80	51.60	15.97	(250) W	47488	PGAP	13120
Asia	Russian Federation	Histosol	P	51.50	129.40	129.40	51.50	15.97	(32) W	47494	PGAP	13120
Asia	Russian Federation	Histosol	P	53.90	140.20	140.20	53.90	15.97	(50) E	47496	PGAP	13120
Asia	Russian Federation	Histosol	P	51.80	143.10	143.10	51.80	15.97	1290 E	47497	PGAP	13120
Asia	Russian Federation	Histosol	P	60.30	162.20	162.20	60.30	15.97	300 E	47503	PGAP	13120
Asia	Russian Federation	Histosol	P	62.80	153.10	153.10	62.80	15.97	(200) W	47781	PGAP	13120
Asia	Russian Federation	Histosol	P	62.50	133.10	133.10	62.50	15.97	(20) W	47783	PGAP	13120

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Asia	Russian Federation	Histosol	P	63.50	132.70	132.70	63.50	15.97	(35) W	47784	PGAP	13120
Asia	Russian Federation	Histosol	P	63.10	133.20	133.20	63.10	15.97	(50) W	47785	PGAP	13120
Asia	Russian Federation	Histosol	P	64.50	146.00	146.00	64.50	15.97	(40) E	47788	PGAP	13120
Asia	Russian Federation	Histosol	P	62.80	131.90	131.90	62.80	15.97	(25) W	47789	PGAP	13120
Asia	Russian Federation	Histosol	P	75.90	143.90	143.90	75.90	15.97	(35) E	47793	PGAP	13120
Asia	Russian Federation	Histosol	P	62.80	130.60	130.60	62.80	15.97	(15) W	47795	PGAP	13120
Asia	Russian Federation	Histosol	P	63.20	131.90	131.90	63.20	15.97	(45) W	47797	PGAP	13120
Asia	South Korea	Histosol	P	35.90	129.60	129.60	35.90	15.97	Choki Gp	48871	PGAP	4144
Asia	Turkey	Histosol	P	40.00	34.00	34.00	40.00	middle Mio-cene	Kizilirmak/Bozkir Formation	Central Anatolia, Turkey	MSDB	Argun, et al., ????
Caribbean	Trinidad and Tobago	Aridisol, gypsic	G	10.20	-61.40	-61.40	10.20	15.97	Lengua Fm	46660	PGAP	1705
Central America	Panama	Histosol	P	8.98	-79.58	-79.58	8.98	16.1 +/- 1	Cucharacha Formation	Gaillard Cut, Panama Canal, Panama	MSDB	Tedford et al., 2004; Retalack and Kirby, 2007
Europe	Armenia	Aridisol, salic	H	40.20	43.90	43.90	40.20	15.97	1000 E	47650	PGAP	13120
Europe	Austria	Histosol	P	48.10	13.00	13.00	48.10	15.97	Coal-Bear.	46585	PGAP	13073
Europe	Austria	Histosol	P	47.50	9.80	9.80	47.50	15.97	Fore. Molasse	48715	PGAP	13073
Europe	Azerbaijan	Aridisol, salic	H	39.20	45.50	45.50	39.20	15.97	705 E	47655	PGAP	13120
Europe	Azerbaijan	Aridisol, salic	H	39.50	45.20	45.20	39.50	15.97	230 E	47658	PGAP	13120
Europe	Czech Republic	Oxisol	X	50.47	15.39	15.39	50.47	middle Mio-cene	Unnamed	Tecin, Czech Republic	MSDB	Ref

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Europe	Czech Republic	Histosol	P	50.10	12.90	12.90	50.10	15.97	Main Seam Fm	48844	PGAP	11505
Europe	Czech Republic	Histosol	P	50.80	14.90	14.90	50.80	15.97	Hradek+Volc.	48845	PGAP	11505
Europe	Czech Republic	Histosol	P	49.80	13.40	13.40	49.80	15.97	Unnamed	48846	PGAP	11505
Europe	Czech Republic	Histosol	P	50.20	12.60	12.60	50.20	15.97	Volc + Main S.	48847	PGAP	11505
Europe	Denmark	Histosol	P	56.01	9.70	9.70	56.01	middle Mio-cene	Odderup Formation	Voervadsbro, Denmark	MSDB	Weibel, 1996
Europe	Denmark	Histosol	P	56.10	8.90	8.90	56.10	15.97	Up. Lignite	47088	PGAP	13066
Europe	France	Oxisol	X	46.62	2.70	2.70	46.62	middle Mio-cene	Unnamed	Massif Central, France	MSDB	Dejou and Chesworth, 1979; Pierre and Dejou, 1990
Europe	Germany	Alfisol	FF	48.55	13.22	13.22	48.55	17 to 13.8	Ortenburg xyloflora	Southern Germany	MSDB	Bohme et al., 2007
Europe	Germany	Histosol	P	47.00	15.00	15.00	47.00	late Early to early Middle Mio-cene	Mydlovary Formation	Trebon and Budejovice Basins, South Bohemia	MSDB	Kovar-Eder et al., 2001
Europe	Germany	Histosol	P	49.60	12.30	12.30	49.60	late Early to early Middle Mio-cene	Unnamed	Wackesdorf mining area, Oberpfalz, Bavaria	MSDB	Kovar-Eder et al., 2001
Europe	Germany	Histosol	P	51.00	6.00	6.00	51.00	17 to 14	Unnamed	Lower Rhine Embayment, Germany	MSDB	Utescher et al., 2000

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Europe	Germany	Histosol	P	51.00	7.00	7.00	51.00	18 to 14	Unnamed	Lower Rhine Embayment, Germany	MSDB	Figueiral et al., 2002
Europe	Germany	Oxisol	X	51.13	11.24	11.24	51.13	17-15 Ma	Vogelsberg Basalt	Central Germany	MSDB	Schwarz, 1997
Europe	Germany	Oxisol	X	48.92	11.42	11.42	48.92	middle Miocene	Oxisol on Miocene basalt	Triebendorf/Oberpfalz, Bavaria	MSDB	Sobanski and Valetton, 1994
Europe	Germany	Histosol	P	52.90	13.60	13.60	52.90	15.97	Brieske-Rau.	8079	PGAP	22017
Europe	Germany	Histosol	P	53.50	9.10	9.10	53.50	15.97	Hemmoor	46521	PGAP	13041
Europe	Germany	Histosol	P	54.60	9.20	9.20	54.60	15.97	Hemmoor	46522	PGAP	13041
Europe	Germany	Histosol	P	54.10	9.70	9.70	54.10	15.97	Hemmoor	46523	PGAP	13041
Europe	Germany	Histosol	P	53.20	9.70	9.70	53.20	15.97	Reinbeck-St.	46879	PGAP	12795
Europe	Germany	Histosol	P	53.10	10.00	10.00	53.10	15.97	Reinbeck-St.	46880	PGAP	12795
Europe	Germany	Histosol	P	53.10	10.90	10.90	53.10	15.97	Reinbeck-St.	46881	PGAP	12795
Europe	Germany	Histosol	P	50.70	6.80	6.80	50.70	15.97	Reinbek	47158	PGAP	12898
Europe	Greece	Alfisol	FF	37.32	26.56	26.56	37.32	17-7	Pythagorean, Hora, Mytilini Formations	Hora, Samos Island, Greece	MSDB	Solounias, 1981; Solounias et al., 2010
Europe	Greece	Oxisol	X	39.07	21.77	21.77	39.07	middle Miocene	Unnamed	Vroderon, Greece	MSDB	Bardossy and Dercourt, 1990
Europe	Greece	Histosol	P	38.70	24.20	24.20	38.70	15.97	Burg.-Helv.	48013	PGAP	1720
Europe	Hungary	Histosol	P	46.53	18.72	18.72	46.53	middle Miocene	Tengelic 2	Pannonian Basin, Hungary	MSDB	Jimenez-Moreno et al., 2006
Europe	Hungary	Oxisol	X	46.98	17.70	17.70	46.98	middle Miocene	Unnamed	Nagyvazsony, Hungary	MSDB	Bardossy and Dercourt, 1990
Europe	Hungary	Oxisol	X	47.00	17.61	17.61	47.00	middle Miocene	Unnamed	Ocs, Hungary	MSDB	Bardossy and Dercourt, 1990

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Europe	Hungary	Ultisol	KK	46.53	18.72	18.72	46.53	middle Mio-cene	Tengelic 2	Pannonian Basin, Hungary	MSDB	Jiminez-Moreno et al., 2006
Europe	Hungary	Histosol	P	48.00	19.60	19.60	48.00	15.97	Helvetian	47174	PGAP	13063
Europe	Poland	Oxisol	X	50.10	18.54	18.54	50.10	middle Mio-cene	Unnamed	Rybnik, Poland	MSDB	Ref
Europe	Poland	Histosol	P	53.20	15.10	15.10	53.20	15.97	Adamow-L.Poz	8082	PGAP	22017
Europe	Poland	Histosol	P	52.40	18.30	18.30	52.40	15.97	Adamow-L.Poz	8084	PGAP	22017
Europe	Poland	Histosol	P	53.60	20.50	20.50	53.60	15.97	Adamow-L.Poz	8088	PGAP	22017
Europe	Poland	Histosol	P	51.80	21.80	21.80	51.80	15.97	Adamow-L.Poz	8106	PGAP	22017
Europe	Poland	Histosol	P	53.60	16.20	16.20	53.60	15.97	Adamow-L.Poz	8107	PGAP	22017
Europe	Poland	Histosol	P	51.60	16.80	16.80	51.60	15.97	Adamow-L.Poz	8108	PGAP	22017
Europe	Poland	Histosol	P	51.00	17.10	17.10	51.00	15.97	Helvetian	45940	PGAP	13115
Europe	Romania	Aridisol, gypsic	G	45.80	26.60	26.60	45.80	15.97	U Burd.-Helv	46173	PGAP	3030
Europe	Romania	Aridisol, gypsic	G	47.00	26.30	26.30	47.00	15.97	U Burd.-Helv	46174	PGAP	3030
Europe	Romania	Aridisol, gypsic	G	48.00	25.60	25.60	48.00	15.97	U Burd.-Helv	46175	PGAP	3030
Europe	Slovakia	Histosol	P	48.30	20.00	20.00	48.30	15.97	U. Buro.-Hel.	48762	PGAP	17097
Europe	Spain	Aridisol, calcic	CC	40.48	-3.53	-3.53	40.48	Langhian to early Tortonian	“Intermediate Unit”	Paracuellos, Madrid Basin, Spain	MSDB	Alonso Zarza et al., 1992
Europe	Spain	Aridisol, calcic	CC	40.83	-2.46	-2.46	40.83	Langhian to early Tortonian	“Intermediate Unit”	La Tajera, Spain	MSDB	Alonso Zarza et al., 1992
Europe	Spain	Aridisol, calcic	CC	41.01	-2.75	-2.75	41.01	Langhian to early Tortonian	“Intermediate Unit”	Baides, Spain	MSDB	Alonso Zarza et al., 1992

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Europe	Turkey	Aridisol	AA	39.98	28.31	28.31	39.98	16-15	Degirmendere Formation	Pasalar Hominoid site, Pasalar, Turkey	MSDB	Bestland, 1990; Ekart, 1992
Europe	Turkey	Histosol	P	39.42	27.63	27.63	39.42	middle Mio-cene	Middle Lignite, Soma Formation	Soma Coalfield, Turkey	MSDB	Inci, 1998
Europe	Ukraine	Aridisol, gypsic	G	49.20	24.30	24.30	49.20	15.97	100 W	47620	PGAP	13120
Europe	Ukraine	Aridisol, gypsic	G	49.70	23.60	23.60	49.70	15.97	75 W	47627	PGAP	13120
Europe	Ukraine	Aridisol, gypsic	G	48.70	25.30	25.30	48.70	15.97	1250 W	47661	PGAP	13120
Europe	Ukraine	Aridisol, gypsic	G	48.30	26.50	26.50	48.30	15.97	125 W	47756	PGAP	13120
Middle East	Iran	Aridisol, gypsic	G	32.70	48.00	48.00	32.70	15.97	Gachsaran Fm	46096	PGAP	2660
Middle East	Iran	Aridisol, gypsic	G	33.40	46.80	46.80	33.40	15.97	Gachsaran Fm	46098	PGAP	2660
Middle East	Iran	Aridisol, gypsic	G	31.90	49.30	49.30	31.90	15.97	Gachsaran	46099	PGAP	2660
Middle East	Iran	Aridisol, gypsic	G	34.20	45.70	45.70	34.20	15.97	Gachsaran Fm	46538	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	38.10	46.40	46.40	38.10	15.97	Upper Red Fm	46541	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	35.70	49.20	49.20	35.70	15.97	Upper Red Fm	46542	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	35.70	50.60	50.60	35.70	15.97	Upper Red Fm	46543	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	36.10	48.30	48.30	36.10	15.97	Upper Red Fm	46544	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	35.00	54.50	54.50	35.00	15.97	Upper Red Fm	46545	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	34.20	54.50	54.50	34.20	15.97	Upper Red Fm	46546	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	35.30	53.20	53.20	35.30	15.97	Upper Red Fm	46547	PGAP	12421

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Middle East	Iran	Aridisol, gypsic	G	34.30	56.60	56.60	34.30	15.97	Upper Red Fm	46548	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	35.40	56.70	56.70	35.40	15.97	Upper Red Fm	46549	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	35.80	54.30	54.30	35.80	15.97	Upper Red Fm	46550	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	33.70	51.70	51.70	33.70	15.97	Upper Red Fm	46551	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	34.70	52.00	52.00	34.70	15.97	Upper Red Fm	46552	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	35.50	52.00	52.00	35.50	15.97	Upper Red Fm	46553	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	34.80	53.00	53.00	34.80	15.97	Upper Red Fm	46554	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	33.70	52.90	52.90	33.70	15.97	Upper Red Fm	46555	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	34.80	53.80	53.80	34.80	15.97	Upper Red Fm	46556	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	33.60	55.40	55.40	33.60	15.97	Upper Red Fm	46557	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	33.80	53.50	53.50	33.80	15.97	Upper Red Fm	46558	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	36.80	56.80	56.80	36.80	15.97	Upper Red Fm	46559	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	34.50	55.50	55.50	34.50	15.97	Upper Red Fm	46560	PGAP	12421
Middle East	Iran	Aridisol, gypsic	G	31.40	53.30	53.30	31.40	15.97	L Upper Red	48714	PGAP	12421
Middle East	Iran	Aridisol, salic	H	32.70	48.00	48.00	32.70	15.97	Gachsaran Fm	46096	PGAP	2660
Middle East	Iran	Aridisol, salic	H	33.40	46.80	46.80	33.40	15.97	Gachsaran Fm	46098	PGAP	2660

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Middle East	Iran	Aridisol, salic	H	34.20	45.70	45.70	34.20	15.97	Gachsaran Fm	46538	PGAP	12421
Middle East	Iran	Aridisol, salic	H	38.10	46.40	46.40	38.10	15.97	Upper Red Fm	46541	PGAP	12421
Middle East	Iran	Aridisol, salic	H	35.70	49.20	49.20	35.70	15.97	Upper Red Fm	46542	PGAP	12421
Middle East	Iran	Aridisol, salic	H	35.70	50.60	50.60	35.70	15.97	Upper Red Fm	46543	PGAP	12421
Middle East	Iran	Aridisol, salic	H	36.10	48.30	48.30	36.10	15.97	Upper Red Fm	46544	PGAP	12421
Middle East	Iran	Aridisol, salic	H	35.00	54.50	54.50	35.00	15.97	Upper Red Fm	46545	PGAP	12421
Middle East	Iran	Aridisol, salic	H	34.80	53.00	53.00	34.80	15.97	Upper Red Fm	46554	PGAP	12421
Middle East	Iran	Aridisol, salic	H	34.80	53.80	53.80	34.80	15.97	Upper Red Fm	46556	PGAP	12421
Middle East	Iraq	Aridisol, gypsic	G	35.50	44.40	44.40	35.50	15.97	L. Fars	46336	PGAP	12224
Middle East	Iraq	Aridisol, gypsic	G	35.90	43.10	43.10	35.90	15.97	L. Fars	46337	PGAP	12224
Middle East	Iraq	Aridisol, gypsic	G	35.80	43.30	43.30	35.80	15.97	L. Fars	46338	PGAP	12224
Middle East	Iraq	Aridisol, gypsic	G	33.40	42.80	42.80	33.40	15.97	L. Fars	46339	PGAP	12224
Middle East	Iraq	Aridisol, gypsic	G	35.10	43.60	43.60	35.10	15.97	L. Fars	46340	PGAP	12224
Middle East	Iraq	Aridisol, gypsic	G	36.70	42.60	42.60	36.70	15.97	L. Fars	46341	PGAP	12224
Middle East	Iraq	Aridisol, gypsic	G	30.40	47.60	47.60	30.40	15.97	L. Fars	46882	PGAP	12223
Middle East	Iraq	Aridisol, salic	H	35.50	44.40	44.40	35.50	15.97	L. Fars	46336	PGAP	12224

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Middle East	Oman	Aridisol, gypsic	G	22.40	56.10	56.10	22.40	15.97	Miocene	46483	PGAP	12211
Middle East	Saudi Arabia	Aridisol, gypsic	G	24.30	47.20	47.20	24.30	15.97	Kharj Fm	46975	PGAP	12073
Middle East	Saudi Arabia	Aridisol, gypsic	G	26.10	46.50	46.50	26.10	15.97	Kharj Fm	46976	PGAP	12073
Middle East	Saudi Arabia	Aridisol, gypsic	G	25.70	46.20	46.20	25.70	15.97	Kharj Fm	46978	PGAP	12073
Middle East	Saudi Arabia	Aridisol, gypsic	G	24.80	46.80	46.80	24.80	15.97	Kharj Fm	46979	PGAP	12073
Middle East	Saudi Arabia	Aridisol, salic	H	16.80	42.00	42.00	16.80	15.97	Ras Hassis-3	46226	PGAP	1560
Middle East	Syria	Aridisol, gypsic	G	36.80	41.50	41.50	36.80	15.97	M. Miocene	45932	PGAP	1500
Middle East	Syria	Aridisol, gypsic	G	35.60	41.50	41.50	35.60	15.97	M. Miocene	45933	PGAP	1500
Middle East	Syria	Aridisol, gypsic	G	35.30	40.10	40.10	35.30	15.97	Vindobon	47887	PGAP	7709
Middle East	Syria	Aridisol, gypsic	G	34.70	38.20	38.20	34.70	15.97	Vindobon	47888	PGAP	7709
Middle East	Syria	Aridisol, gypsic	G	36.20	39.90	39.90	36.20	15.97	Helvet.-Tort	48805	PGAP	560
Middle East	Syria	Aridisol, gypsic	G	36.40	40.30	40.30	36.40	15.97	Helvet.-Tort	48806	PGAP	560
Middle East	Syria	Aridisol, gypsic	G	35.50	39.40	39.40	35.50	15.97	Helvet.-Tort	48808	PGAP	560
Middle East	Syria	Aridisol, gypsic	G	35.40	38.50	38.50	35.40	15.97	Helvet.-Tort	48809	PGAP	560
Middle East	Syria	Aridisol, gypsic	G	37.00	42.10	42.10	37.00	15.97	Tortonian	48811	PGAP	560
Middle East	Syria	Aridisol, gypsic	G	36.30	41.20	41.20	36.30	15.97	Helvet.-Tort	48812	PGAP	560

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Middle East	Syria	Aridisol, salic	H	35.60	41.50	41.50	35.60	15.97	M. Miocene	45933	PGAP	1500
Middle East	Tajikistan	Aridisol, gypsic	G	40.30	70.20	70.20	40.30	15.97	(1210) E	47671	PGAP	13120
Middle East	Tajikistan	Aridisol, salic	H	40.30	70.20	70.20	40.30	15.97	(1210) E	47671	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	41.50	54.50	54.50	41.50	15.97	85 W	47521	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	42.00	58.60	58.60	42.00	15.97	54 W	47530	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	40.70	60.40	60.40	40.70	15.97	151 W	47533	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	41.20	60.30	60.30	41.20	15.97	81 W	47534	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	41.20	57.10	57.10	41.20	15.97	91 W	47535	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	40.60	54.00	54.00	40.60	15.97	54 E	47537	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	40.00	59.20	59.20	40.00	15.97	2 E	47540	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	40.20	56.80	56.80	40.20	15.97	36 W	47545	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	40.30	57.30	57.30	40.30	15.97	47 W	47555	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	41.70	59.80	59.80	41.70	15.97	45 W	47557	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	40.70	56.90	56.90	40.70	15.97	64 E	47559	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	41.40	55.30	55.30	41.40	15.97	29 W	47561	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	41.30	59.20	59.20	41.30	15.97	27 W	47562	PGAP	13120

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Middle East	Turkmenistan	Aridisol, gypsic	G	41.50	60.40	60.40	41.50	15.97	60 W	47563	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	40.50	58.00	58.00	40.50	15.97	39 W	47568	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	40.90	59.20	59.20	40.90	15.97	24 W	47570	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	40.60	53.30	53.30	40.60	15.97	116 W	47575	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	40.00	58.50	58.50	40.00	15.97	40 W	47576	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	41.20	57.50	57.50	41.20	15.97	108 W	47582	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	40.90	56.40	56.40	40.90	15.97	52 W	47589	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	40.40	55.90	55.90	40.40	15.97	39 E	47594	PGAP	13120
Middle East	Turkmenistan	Aridisol, gypsic	G	41.80	54.90	54.90	41.80	15.97	124 W	47595	PGAP	13120
Middle East	Uzbekistan	Aridisol, gypsic	G	43.70	57.30	57.30	43.70	15.97	62 W	47522	PGAP	13120
Middle East	Uzbekistan	Aridisol, gypsic	G	43.40	57.50	57.50	43.40	15.97	107 W	47528	PGAP	13120
Middle East	Uzbekistan	Aridisol, gypsic	G	41.40	60.90	60.90	41.40	15.97	56 W	47529	PGAP	13120
Middle East	Uzbekistan	Aridisol, gypsic	G	42.70	58.30	58.30	42.70	15.97	32 W	47538	PGAP	13120
Middle East	Uzbekistan	Aridisol, gypsic	G	41.40	56.80	56.80	41.40	15.97	0.7 W	47542	PGAP	13120
Middle East	Uzbekistan	Aridisol, gypsic	G	42.50	57.10	57.10	42.50	15.97	74 W	47565	PGAP	13120
Middle East	Uzbekistan	Aridisol, gypsic	G	42.30	58.10	58.10	42.30	15.97	116 W	47567	PGAP	13120

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Middle East	Uzbekistan	Aridisol, gypsic	G	43.00	57.90	57.90	43.00	15.97	46 W	47569	PGAP	13120
Middle East	Uzbekistan	Aridisol, gypsic	G	42.10	57.20	57.20	42.10	15.97	137 W	47572	PGAP	13120
North America	Canada	Histosol	P	80.00	-89.50	-89.50	80.00	15.97	Beaufort Fm	46182	PGAP	18967
North America	Canada	Histosol	P	51.30	-120.1	-120.10	51.30	15.97	Chu Chua Fm	48031	PGAP	3368
North America	Costa Rica	Histosol	P	10.50	-84.90	-84.90	10.50	15.97	Lignite Beds	48017	PGAP	17405
North America	Costa Rica	Histosol	P	9.90	-83.50	-83.50	9.90	15.97	Lignite Beds	48018	PGAP	17405
North America	Costa Rica	Histosol	P	9.80	-84.20	-84.20	9.80	15.97	Lignite Beds	48020	PGAP	17405
North America	Mexico	Aridisol, gypsic	G	27.70	-114.90	-114.90	27.70	15.97	Tortugas Fm.	46812	PGAP	2301
North America	Mexico	Histosol	P	16.80	-92.90	-92.90	16.80	15.97	Zapoti.-Z. V.	48922	PGAP	20995
North America	Panama	Histosol	P	9.40	-82.40	-82.40	9.40	15.97	Gatun Fm.	47850	PGAP	2369
North America	Panama	Histosol	P	8.30	-82.80	-82.80	8.30	15.97	Gatun Fm.	47851	PGAP	2369
North America	Panama	Histosol	P	8.10	-81.50	-81.50	8.10	15.97	Gatun Fm.	48016	PGAP	17405
North America	Panama	Histosol	P	9.30	-83.00	-83.00	9.30	15.97	Gatun Fm.	48019	PGAP	17405
North America	United States	Alfisol	FF	44.52	-119.70	-119.70	44.52	16-15	Mascall Formation	Mascall Ranch, Antone, Oregon	MSDB	Downs, 1956; Bestland, 1998; Draus and Prothero, 2000; Bestland and Forbes, 2003
North America	United States	Alfisol		64.56	-149.09	-149.09	64.56	16-14	Usebelli Group	Nenana, Alaska	MSDB	White et al., 1997; Wynn, in prep.
North America	United States	Aridisol, gypsic	G	39.70	-74.90	-74.90	39.70	15.97	Mid. Miocene	46157	PGAP	2149

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
North America	United States	Aridisol, gypsic	G	39.80	-74.00	-74.00	39.80	15.97	Mid. Miocene	46160	PGAP	2149
North America	United States	Aridisol, gypsic	G	33.00	-116.10	-116.10	33.00	15.97	Alverson-F1	46251	PGAP	2702
North America	United States	Histosol	P	61.20	-151.60	-151.60	61.20	15.97	Kenai Fm	46011	PGAP	2912
North America	United States	Histosol	P	38.30	-76.10	-76.10	38.30	15.97	Mid. Miocene	46147	PGAP	2149
North America	United States	Histosol	P	38.70	-75.50	-75.50	38.70	15.97	Mid. Miocene	46153	PGAP	2149
North America	United States	Histosol	P	39.40	-75.50	-75.50	39.40	15.97	Mid. Miocene	46156	PGAP	2149
North America	United States	Histosol	P	39.80	-74.50	-74.50	39.80	15.97	Mid. Miocene	46159	PGAP	2149
North America	United States	Histosol	P	39.80	-74.00	-74.00	39.80	15.97	Mid. Miocene	46160	PGAP	2149
North America	United States	Histosol	P	60.00	-152.7	-152.70	60.00	15.97	Kenai Fm	46249	PGAP	2932
North America	United States	Histosol	P	56.00	-159.6	-159.60	56.00	15.97	Bear Lake Fm	46250	PGAP	3709
North America	United States	Histosol	P	61.60	-149.8	-149.80	61.60	15.97	U Tyonek	46735	PGAP	3429
North America	United States	Histosol	P	59.50	-151.6	-151.60	59.50	15.97	U Tyonek	46736	PGAP	3429
North America	United States	Histosol	P	57.40	-152.3	-152.30	57.40	15.97	Narrow Cape	46851	PGAP	2897
North America	United States	Histosol	P	65.10	-153.3	-153.30	65.10	15.97	Unit Ts	46930	PGAP	3430
North America	United States	Histosol	P	62.60	-150.5	-150.50	62.60	15.97	Tyonek Fm.	46993	PGAP	3433
North America	United States	Histosol	P	62.30	-150.8	-150.80	62.30	15.97	Tyonek Fm.	46994	PGAP	3433

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
North America	United States	Histosol	P	62.10	-152.0	-152.00	62.10	15.97	Tyonek Fm.	46995	PGAP	3433
North America	United States	Histosol	P	63.80	-148.8	-148.80	63.80	15.97	Suntrana-Lig	47828	PGAP	2937
North America	United States	Histosol	P	63.90	-148.9	-148.93	63.90	23.03	Suntrana	1309	OSR	
North America	United States	Histosol	P	63.90	-148.9	-148.91	63.90	23.03	Suntrana	1310	OSR	
North America	United States	Histosol	P	63.90	-148.9	-148.93	63.90	23.03	Suntrana	1311	OSR	
North America	United States	Mollisol	GG	43.52	-99.15	-99.15	43.52	16.1 +- 1	Fort Randall Formation	South Bijou Hill, South Dakota	MSD	Skinner and Taylor, 1967
North America	United States	Mollisol	GG					middle Mio-cene		Montana		Retallack, 1994
North America	United States	Oxisol	X	46.24	-122.2	-122.20	46.24	middle Mio-cene	Picture Gorge Subgroup, Columbia River Basalts	Oregon	MSDB	Bailey, 1989; Baksi, 1989; Bestland et al., 1994; Cummings and Fassio, 1990; Sheldon 2003, 2006
North America	United States	Oxisol	X	44.83	-123.0	-123.01	44.83	17-16	Columbia River Basalt	Salem, Oregon	MSDB	Parsons et al., 1970; Hook, 1976
North America	United States	Ultisol	UU	30.7	-95.5	-95.55	30.71	18 +- 3	Catahoula Fm.	Huntsville, Texas, USA	MSDB	McKee and Brown, 1977; Patton, 1969; Prothero and Manning, 1987; Wrenn et al., 2003
North America	United States	unclassified		43.17	-101.7	-101.73	43.17	16	Batesland Formation	Martin, Nebraska	MSDB	Harksen and MacDonald, 1967; Skinner and Taylor, 1967
North America	United States	unclassified	?	41.94	-103.81	-103.81	41.94	16-15	Sheep Creek Formation	Mitchell, Nebraska	MSDB	Galusha, 1975; Skinner et al., 1977
North America	United States	unclassified		44.68	-118.36	-118.36	44.68	16-15	Sixmile Creek Formation	Railroad Canyon, Idaho	MSDB	Barnosky et al., 2007; Zheng, 1996; Nichols and Hanneman, 2000; Nichols et al., 2001

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Oceania	Australia	Aridisol	AA	-28.78	138.40	138.40	-28.78	middle Mio-cene	Maralji pedotype, Etadunna Formation	Mammalon Hill, Lake Palankarina, South Australia	MSDB	Rich et al., 1991; Metzger and Retallack, 2010
Oceania	Australia	Histosol	P	-38.22	146.48	146.48	-38.22	middle Mio-cene	Brown coal deposit, Latrobe Valley Group	Latrobe Valley, Victoria	MSDB	Sluiter, et al., 1995
Oceania	Australia	Oxisol	X	-33.95	151.26	151.26	-33.95	middle Mio-cene	Tupia Formation	Little Bay/Maroubra, New South Wales	MSDB	Faniran, 1971; Hunt, 1985; Pickett, 2003
Oceania	Australia	Oxisol	X	-36.24	149.13	149.13	-36.24	middle Mio-cene	Rosebrook Member, Bunyan Formation	Cooma, New South Wales	MSDB	Walker et al., 1989
Oceania	Australia	Ultisol	KK	-32.42	149.63	149.63	-32.42	middle Mio-cene	Home Rule kaolin deposit	Home Rule, New South Wales	MSDB	McMinn, 1985
Oceania	New Zealand	Histosol	P	-34.50	173.00	173.00	-34.50	15.97	Mangonui Lig	47100	PGAP	12973
Oceania	New Zealand	Histosol	P	-45.10	171.00	171.00	-45.10	15.97	White R.-Can	47116	PGAP	12973
Oceania	New Zealand	Histosol	P	-44.10	170.90	170.90	-44.10	15.97	White R.-Can	47117	PGAP	12973
Oceania	New Zealand	Histosol	P	-46.10	169.00	169.00	-46.10	15.97	Unnamed	47119	PGAP	12973
Oceania	New Zealand	Histosol	P	-46.10	168.40	168.40	-46.10	15.97	Southland	47121	PGAP	12973
Oceans	Atlantic Ocean (N)	Histosol	P	59.80	2.00	2.00	59.80	15.97	Mio-Plio.	46497	PGAP	8300
Oceans	Indian Ocean (N)	Aridisol, gypsic	G	15.70	40.30	40.30	15.70	15.97	Adul-2	46228	PGAP	1560
Oceans	Indian Ocean (N)	Aridisol, salic	H	16.60	40.40	40.40	16.60	15.97	B-1	46227	PGAP	1560
Oceans	Indian Ocean (N)	Aridisol, salic	H	15.70	40.30	40.30	15.70	15.97	Adul-2	46228	PGAP	1560

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
Oceans	Indian Ocean (S)	Histosol	P	-4.50	110.20	110.20	-4.50	15.97	Unit 2	46202	PGAP	1215
Oceans	Indian Ocean (S)	Histosol	P	-5.30	113.30	113.30	-5.30	15.97	Unit 2	46204	PGAP	1215
Oceans	Indian Ocean (S)	Histosol	P	-5.20	113.70	113.70	-5.20	15.97	Unit 2	46207	PGAP	1215
Oceans	Indian Ocean (S)	Histosol	P	-4.80	113.20	113.20	-4.80	15.97	Unit 2	46208	PGAP	1215
Oceans	Pacific Ocean (N)	Histosol	P	7.80	101.30	101.30	7.80	15.97	Cycle 2	48914	PGAP	591
Oceans	Pacific Ocean (N)	Histosol	P	8.00	102.50	102.50	8.00	15.97	Cycle 2	48915	PGAP	591
South America	Argentina	Alfisol	FF	-50.56	-69.08	-69.08	-50.56	16	Santa Cruz Formation	Cerro Observatorio, Argentina	MSDB	Bown and Fleagle, 1993; Fleagle et al, 2004; Metzger, in prep.
South America	Argentina	Aridisol, calcic	CC	-47.53	-71.71	-71.71	-47.53	16	Santa Cruz Formation	Lago Posados, Santa Cruz	MSDB	Blisniuk et al., 2005
South America	Argentina	Aridisol, gypsic	G	-32.70	-66.70	-66.70	-32.70	15.97	Las Mulitas	46380	PGAP	8331
South America	Argentina	Aridisol, gypsic	G	-33.70	-66.90	-66.90	-33.70	15.97	Las Mulitas	46381	PGAP	8331
South America	Argentina	Aridisol, gypsic	G	-28.00	-68.10	-68.10	-28.00	15.97	Fm. Del Buey	47996	PGAP	12558
South America	Argentina	Aridisol, gypsic	G	-28.80	-68.20	-68.20	-28.80	15.97	Fm. Del Buey	47997	PGAP	12558
South America	Argentina	Aridisol, gypsic	G	-35.50	-58.80	-58.80	-35.50	15.97	Paranense	48024	PGAP	12878
South America	Argentina	Aridisol, gypsic	G	-28.00	-65.00	-65.00	-28.00	15.97	Fm. Guasayan	48794	PGAP	8337
South America	Argentina	Mollisol	GG	-43.30	-65.30	-65.30	-43.30	late Mio-cene	Aguada Escondida Formation	Chubut, Argentina	MSDB	Genise and Bown, 1994
South America	Argentina	Ultisol	KK	-47.03	-70.75	-70.75	-47.03	16.5	Pinturas Formation	Northern Santa Cruz, Argentina	MSDB	Bown and Larriestra, 1990; Bown and Fleagle, 1993

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
South America	Brazil	Oxisol	X	-2.51	-44.33	-44.33	-2.51	middle Miocene	Upper Barreiras Formation	São Luis/Grajaú Basin, northern Amazonia, Brazil	MSDB	Rossetti, 2007
South America	Chile	Alfisol	FF	-23.25	-69.00	-69.00	-23.25	~20	Unnamed	Atacama Desert, Chile	MSDB	Rech et al., 2006
South America	Chile	Aridisol, gypsic	G	-22.70	-68.40	-68.40	-22.70	15.97	San Pedro Fm	46481	PGAP	6695
South America	Chile	Aridisol, gypsic	G	-23.40	-68.50	-68.50	-23.40	15.97	San Pedro Fm	46482	PGAP	6695
South America	Chile	Aridisol, salic	H	-22.70	-68.40	-68.40	-22.70	15.97	San Pedro Fm	46481	PGAP	6695
South America	Chile	Aridisol, salic	H	-23.40	-68.50	-68.50	-23.40	15.97	San Pedro Fm	46482	PGAP	6695
South America	Chile	Histosol	P	-52.10	-70.20	-70.20	-52.10	15.97	Sebastianian	46837	PGAP	9757
South America	Chile	Histosol	P	-52.30	-69.80	-69.80	-52.30	15.97	Sebastianian	46838	PGAP	9757
South America	Chile	Histosol	P	-53.30	-68.80	-68.80	-53.30	15.97	Sebastianian	46839	PGAP	9757
South America	Chile	Histosol	P	-52.70	-69.30	-69.30	-52.70	15.97	Sebastianian	46840	PGAP	9757
South America	Chile	Histosol	P	-52.50	-71.80	-71.80	-52.50	15.97	Sebastianian	46841	PGAP	9757
South America	Chile	Histosol	P	-52.50	-70.40	-70.40	-52.50	15.97	Sebastianian	46842	PGAP	9757
South America	Chile	Histosol	P	-52.20	-72.10	-72.10	-52.20	15.97	Sebastianian	46843	PGAP	9757
South America	Chile	Histosol	P	-52.70	-69.00	-69.00	-52.70	15.97	Sebastianian	46844	PGAP	9757
South America	Chile	Histosol	P	-52.60	-71.20	-71.20	-52.60	15.97	Sebastianian	46845	PGAP	9757
South America	Chile	Histosol	P	-52.60	-70.80	-70.80	-52.60	15.97	Sebastianian	46846	PGAP	9757

Table C.1. (continued)

Region 1	Region 2	Soil Map Unit	Lith Code	Lat.	Long.	X _{rob}	Y _{rob}	Age (Ma)	Formation	Location (or PGAP Loc#)	Database	Reference (or PGAP Paper#)
South America	Chile	Histosol	P	-52.80	-69.90	-69.90	-52.80	15.97	Sebastianian	46847	PGAP	9757
South America	Chile	Histosol	P	-52.90	-68.70	-68.70	-52.90	15.97	Sebastianian	46848	PGAP	9757
South America	Colombia	Alfisol	FF	6.38	-72.70	-72.70	6.38	middle Mio-cene	Monkey Beds	Colombia	MSDB	Kay and Madden, 1996, 1997
South America	Ecuador	Histosol	P	-0.50	-77.30	-77.30	-0.50	15.97	Arajuno Fm	48875	PGAP	12566
South America	Ecuador	Histosol	P	0.30	-77.20	-77.20	0.30	15.97	Arajuno Fm	48876	PGAP	12566
South America	Ecuador	Histosol	P	-1.50	-77.50	-77.50	-1.50	15.97	U. Pastaz Fm	48877	PGAP	12566
South America	Ecuador	Histosol	P	-2.30	-77.60	-77.60	-2.30	15.97	U. Pastaz Fm	48878	PGAP	12566
South America	Suriname	Aridisol, gypsic	G	5.90	-54.90	-54.90	5.90	15.97	Olig-Mioc.	47190	PGAP	12121
South America	Suriname	Histosol	P	5.90	-54.90	-54.90	5.90	15.97	Olig-Mioc.	47190	PGAP	12121

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CHAPTER IV

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