Palaeogeography, Palaeoclimatology, Palaeoecology 381–382 (2013) 98–109

Contents lists available at SciVerse ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Soil formation in the Transantarctic Mountains from the Middle Paleozoic to the Anthropocene

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ARTICLE INFO

Article history:
Received 14 February 2013
Received in revised form 16 April 2013
Accepted 19 April 2013
Available online 26 April 2013

Keywords:
Paleosols
Pedology
Soil chronosequences
Climate change
Gelisols

ABSTRACT

In the Transantarctic Mountains (TAMs), soils from the middle Paleozoic and from the Oligocene to the present have been examined. Soils representing other sections of the geologic column are missing, probably because of the low proportion of ice-free areas (0.35%) in Antarctica. The evolution of soils in Antarctica reflects changes in climate and geologic conditions as the continent became separated and increasingly isolated from Gondwana. A greenhouse climate existed during the middle Paleozoic; and an icehouse climate began in the early Oligocene. The climate of the TAMs has become increasingly hyper-arid since the middle Miocene. Humans have had a dramatic effect on the climate of the TAMs during the Anthropocene. The first forest soils (under *Callixylon–Archaeopteris* forest) on Earth, identified as Alfisols, were discovered in Antarctica and assigned to the middle Devonian. During the Permian, *Dicroidium* forests covered Entisols and Inceptisols. In the Oligocene, *Nothofagus*–Podocarpaceae forests contained Gelisols. Miocene-aged soils enriched in silt are common in the TAMs, but they tend to be poorly developed because they have been eroded. A soil evolutionary sequence exists in the TAMs from the Holocene through the Pliocene that includes Glacic Haploturbels on ice-cored Holocene drift, Typic Haploturbels on late Pleistocene surfaces, Typic Anhyorthels on middle Pleistocene surfaces, Salic Anhyorthels on early Pleistocene surfaces, and Petrosalic Anhyorthels on Pliocene surfaces. These changes reflect gradual sublimation of ice in ice-cored drift and ice-wedge polygons, a recovery of the surface from cryoturbation, accumulation of salts, and eventual development of a salt pan. Soils of the TAMs are undergoing rapid change as the climate warms, including loss of semi-permanent snowbanks, an expansion of the hyporheic zone, flushing of salts from soils along valley walls, and the development of thermokarst.

1. Introduction

From 500 to 160 Ma, Antarctica was part of a supercontinent known as Gondwana (Sandskrit, "forests of the Gonds"). The continent began separating from Australia, New Zealand, Africa, South America, and India and began its southward journey until about 55 Ma ago, when a deep ocean passage opened up at what is now the Drake Passage and finally isolated the continent (Cantrill and Poole, 2012) (Table 1).

Antarctica has experienced climate changes that include a brief hothouse climate, a greenhouse climate from 350 to 34 Ma, and an icehouse climate thereafter (Sugden and Denton, 2004; Cantrill and Poole, 2012). In the past 34 Ma, Antarctica has experienced incision of valleys by warm-based glaciers during the Oligocene (34–ca. 19); formation of the polar regolith and cold-based glaciers during the early Miocene (ca. 19–14.8 Ma); development of a cold-based ice sheet that overrode the high mountains in the middle Miocene (14.8–13.6 Ma); a shift to cold, hyper-arid conditions beginning 13.6 Ma (Sugden and Denton, 2004); and unprecedented warming during the Anthropocene.

Although currently occupying only a small proportion of Antarctica (0.35% of total area), soils in ice-free areas of Antarctica have yielded important clues to climate change beginning about 350 Ma (Retallack, 1997) and in particular over the past 14 Ma (Bockheim, 2007; Bockheim and Ackert, 2007). The Transantarctic Mountains contain soil chronosequences that extend from the middle Holocene to the Miocene that include some of the oldest non-lithified soils in the world (Bockheim, 1990, 2007; Bockheim et al., 1990; Prentice et al., 1993; Marchant et al., 1994; Bockheim and McLeod, 2006). A chronosequence was defined by Jenny (1941) as an array of soils in which time is the dominant soil-forming factor. Although the other soil-forming factors, climate, organisms, relief, and parent material, may change, particularly over long periods of time, the time factor is of greatest importance. Bockheim (1990) reported highly significant correlations between soil properties and time in several soil chronosequences in Antarctica.

These changes in climate are reflected in the properties and development rates of Antarctic soils. This paper highlights soil development during the middle Paleozoic and from the middle Miocene to

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http://dx.doi.org/10.1016/j.palaeo.2013.04.019

Table 1
Soil evolution in the Transantarctic Mountains from the Middle Paleozoic to the present.

Time period (Ma)	Soil record	Paleoclimate	Paleo-vegetation	Glacial form	Location of Antarctica	References
350	Alfisols	Warm humid	Earliest recorded forest Callixylon-Archaeopteris	None	Gondwana	Retallack (1997)
240	Psamments, Fluvents, Aquepts, Udepts,	Warm temperate	Temperate forest *Dicroidium* spp.	Warm-based	Gondwana	Retallack and Alonso-zarza (1998)
65–60		Warm temperate	*Nothofagus* forest on Antarctic Peninsula	None	Begin isolation Antarctica	Cantrill and Poole (2012)
55–40	[no data]	Seasonal wet/dry	[no data]	None	Increased isolation of Antarctica	
40–34	[no data]	Cool temperate		Continental ice sheet develops (warm-based)	Increased isolation of Antarctica	
34–ca. 19	Gelorthents, Haploturbels, Anhyturbels	Polar	*Nothofagus*–Podocarpaceae–ferns	Warm-based glacier	Complete isolation of Antarctica	Retallack et al. (2002)
ca. 19–14.8	??	Polar	Deciduous *Nothofagus*	Continental ice sheet (transition)	Complete isolation of Antarctica	
14.8–13.6	Lithic Haplorthels Typic Haplorthels	Polar	Isolated cryptogams	Overriding; cold-based glacier	Complete isolation of Antarctica	This paper
13.6–present	Petrosalic Anhyorthels	Polar, hyper-arid	Isolated cryptogams	Cold-based glacier	Complete isolation of Antarctica	This paper
Present	Typic Anhyorthels	Polar, hyper-arid (warming)	Isolated cryptogams	Cold-based glacier	Complete isolation of Antarctica	This paper

Sources: Sugden and Denton (2004) and Cantrill and Poole (2012).

the present. Its objectives are to show how soils in the TAMs have been used to show changes in the Earth's climate and landscape evolution.

2. Setting

The middle Miocene to the present portion of the study includes seven soil chronosequences in the central and southern Transantarctic Mountains (TAMs). The site locations are shown in Fig. 1, and the main features of these chronosequences are described in Table 2. The composition of the drifts can be grouped into two broad categories. Mixed, light-colored igneous (granites) and metamorphic (gneisses) materials dominate the three sequences in Wright and Taylor Valleys. The sequences in Arena and Beacon Valleys (Quartermain Range) and the Darwin and Beardmore Glacier regions are comprised of Beacon Supergroup sediments (primarily sandstones) intruded by sills of the Ferrar Group (primarily dolerite). Locally, some of the drifts may contain primarily dark-colored volcanic materials or diabase dike rocks. Both rock types are represented in all age categories, except for Miocene-aged soils derived from granite-gneiss.

The chronosequences represent the three major microclimatic zones identified in the Transantarctic Mountains, including coastal thaw, i.e., comparatively moist coastal regions; inland mixed, i.e., valley floor and sidewalls; and stable upland, i.e., high-elevation valleys (Marchant and Head, 2007). The approximate mean annual water-equivalent precipitation in these zones is 100–150 mm yr^{-1}, 50–100 mm yr^{-1}, and <50 mm yr^{-1}, respectively, and the approximate mean annual air temperatures are −20 °C, −25 °C, and −30 °C, respectively. Most of the soil chronosequences span one soil climatic zone. However, the sequences in lower Wright Valley and along the Darwin and Beardmore Glaciers span two soil climate zones, because their distance from the coast ranges from 35 to 220 km. The chronosequences range in elevation from 200 to 2200 m a.s.l. and span the time period from Holocene or late Quaternary to the Pliocene and/or the Miocene.

3. Approach

More than 600 soils were examined during the periods 1969, 1975–1987 and 2004–2013. At each site, the following properties were measured: (i) surface-boulder frequency and weathering features (Bockheim and Ackert, 2007), (ii) soil weathering features (Bockheim and Ackert, 2007), (iii) salt stage (Bockheim, 1990), (iv) a desert pavement development index (Bockheim, 2010b), and (v) form and developmental stage of patterned ground (Bockheim et al., 2009). These data are part of a multiple-parameter, relative-age chronology of landforms and soils that effectively has been used throughout the TAMs (Bockheim and McLeod, in press).

Soil pits were excavated to a depth of at least 100 cm, unless ice-cement or large boulders prevented digging to that depth. Detailed soil descriptions were taken using standard techniques (Schoeneberger et al., 2002). Samples were collected from each horizon and sent to the United States for characterization. Several soil morphological features, which have proved useful for distinguishing among drift sheets in the MDVs (Bockheim, 1982, 1990), were measured in the field. The depth of staining refers to the thickness of the layers showing the strongest hues and chromas from oxidation of iron-bearing minerals and corresponds to the bottom of the Bw horizon. The depth of coherence refers to the thickness of consolidated soil from accumulation of weathering products such as salts and iron oxide; below the depth of coherence, soil readily caves into the pit. The depth of "ghosts" (pseudomorphs) refers to the depth to which highly weathered clasts were observed in situ; this parameter varies with rock type as well as soil age.

The depth of visible salts refers to the maximum depth for which salt encrustations beneath clasts, salt flecks, and salt cementation are readily visible to the naked eye. Bockheim (1990) developed a six-stage sequence in which the form of soluble salts was related to total dissolved salts from electrical conductivity measurements and soil age. The stages included 0 = no visible salts, 1 = salt encrustations beneath clasts, 2 = salt flecks covering <20% of the horizon area, 3 = salt flecks covering >20% of the horizon area, 4 = weakly cemented salt pan, 5 = strongly cemented salt pan, and 6 = indurated salt pan. The depth to ice or ice-cemented permafrost was determined. The active layer (seasonal thaw layer) in the TAMs varies between 15 and 25 cm. Material not cemented by ice beneath the active layer may contain "dry-frozen" permafrost, i.e., perennially frozen materials lacking sufficient interstitial water to cause cementation.

The weathering stage is an overall representation of the landscape/material based on the degree of surface boulder weathering, soil morphology, and patterned ground and permafrost forms (Campbell and Claridge, 1975). The stages are 1 = unstained angular boulders, no horizonation (Cn), stage 0 or 1 salts, ice cement within 70 cm of surface, and patterned; 2 = lightly stained subangular boulders,