MIDDLE TRIASSIC PALEOSOLS AND PALEOCLIMATE OF ANTARCTICA

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ABSTRACT: **The Lashly Formation in the Allan Hills of southern Victoria Land, Antarctica, is now at a latitude of 76°S and during the Middle Triassic was at least 70°S. The combined evidence of fossil roots and soils indicates a paleoclimate unusual for such a high latitude. Temperate paleotemperature is indicated by roots, logs, and leaves of woody plants and the degree of chemical weathering and clay formation within the paleosols. Paleosols of the Lashly Formation are more like soils of southern Sweden than those of either Finland or southern Europe. Silt infiltration structures around root traces and in cracks within the paleosols are evidence for a seasonally snowy climate, but there is no evidence of ice wedges or other permafrost features in the paleosols. Other evidence of climatic seasonality includes well-defined growth rings in fossil wood, and abscission scars at the base of fossil leaves. Diverse broadleaf plants, and noncalcareous paleosols, indicate a humid climate with mean annual precipitation of about 1200 mm. Such a wet climate is anomalous for the interior of the supercontinent of Pangea, and such a warm and mildly seasonal climate is anomalous for such high latitudes. This paleoclimatic anomaly may be a lingering effect of global greenhouse initiated at the Permian–Triassic boundary. Paleoclimatic variables calculated here may be useful for recalibrating global paleoclimatic models for the middle Triassic.**

INTRODUCTION

An intriguing puzzle emerging from exploration of polar regions in the late nineteenth and early twentieth centuries was the discovery there of fossil plants now characteristic of low rather than high latitudes (Heer 1868; Seward 1914). Some of these riddles were solved by the theory of plate tectonics, but others have remained as evidence of global climate very different in the past than now. During the Middle Triassic (240 Ma), for example, Antarctica was at high latitudes (73–69°: Barrett 1991; Scotese 1994; Veevers et al. 1994), yet fossil wood and leaves of forests are found in the continent now shrouded in ice (E.L. Taylor et al. 1990; E.L. Taylor et al. 1992; T.N. Taylor et al. 1990; Creber 1990). Fossil plants of such geological antiquity have only distant relatives in modern vegetation (T.N. Taylor et al. 1993) and preferentially preserve lowland peat-forming vegetation adapted to local waterlogging rather than regional climate (E.L. Taylor et al. 1989). Fossil vertebrates including large labyrinthodonts also can be argued as evidence for a nearly frost-free climate (Hammer 1990; Hammer et al. 1990) by analogy with living alligators (Markwick 1994), but the physiology of these extinct creatures remains controversial (Bakker 1986). In contrast, computer models give extreme paleoclimate in northern Victoria Land during the Middle Triassic: mean annual temperature of −5°C, and annual range of temperature of 55°C from −30°C in winter to 25°C in summer (Kutzbach 1994). Here we use paleosols, now known to be abundant in Triassic rocks of Antarctica (Pyne 1984; Gabites 1985; Barrett and Fitzgerald 1986; Woolfe et al. 1996; Retallack et al. 1997a, 1997b), as evidence for paleoclimate during deposition of the lower Lashly Formation of southern Victoria Land, Antarctica.

GEOLOGICAL SETTING

The Beacon Supergroup in southern Victoria Land is an undeformed backarc sequence (Collinson 1990; Collinson et al. 1994). In the Allan Hills (Fig. 1) the exposed sequence is entirely nonmarine and includes the Permian Weller Coal Measures, overlain by the Early Triassic Feather Conglomerate (here largely sandstone) and the Middle Triassic Lashly Formation (Fig. 2; Ballance 1977; Woolfe et al. 1996). Our observations are from the lower Lashly Formation (Members A and B), which is more volcaniclastic than the quartzose upper part of the formation (Members C and D; Collinson et al. 1983; Korsch 1984).

The age of Members A and B of the Lashly Formation in the Allan Hills has been determined as Middle Triassic (late Anisian to Ladinian) based on fossil plants of the *Dicroidium odontopteroides* zone of Retallack (1977c, 1978), an age confirmed by subsequent collections (Gabites 1985; E.L. Taylor et al. 1990; T.N. Taylor et al. 1990). Even the base of Member A of the Lashly Formation is Middle Triassic, as indicated by the following fossil plants collected from 200 m west of our measured section (at 258 m in Figure 2): *Dicroidium crassinervis* forma *stelznerianum, Dicroidium coriaceum, Umkomasia* sp., and *Neocalamites carrerei* (Condon Collection University of Oregon, nos. F35106-10). Recent high-precision dating of the *D. odontopteroides* zone indicates that it began at 243 Ma (Retallack et al. 1993) and ended at about 230 Ma (Veevers 1989; Veevers et al. 1994).

Pollen and spores have not yet been reported from the Allan Hills, but Members A and B of the Lashly Formation elsewhere in Victoria Land have yielded assemblages of subzones A and B of the Late Early to early Middle Triassic (late Scythian to Anisian) *Alisporites* zone (of Kyle 1977; Kyle and Schopf 1982). The upper part of the Lashly Formation (Members C and D) has yielded subzones C and D of the *Alisporites* zone of Late Triassic age (Kyle 1977; Kyle and Schopf 1982).

No Triassic fossil vertebrates have been found in the Allan Hills, despite several deliberate searches (Hammer and Zawiskie 1982; Chatterjee et al. 1983), but the Fremouw Formation in the central Transantarctic Mountains contains a fauna at levels with paleosols similar to those of the lower Lashly Formation in Victoria Land. The fauna has some genera of the *Cynognathus* zone of South Africa, but includes more advanced forms and so is late Early to early Middle Triassic (late Scythian to Anisian) in age (Hammer 1990; Hammer et al. 1990).

The Lashly Formation has pronounced upward-fining fluvial cycles: basal trough cross-bedded sandstones grading up through flaggy siltstones and sandstones into green–gray mudstones with abundant root traces. These claystones have been interpreted as flood-plain deposits and the sandstones as channel deposits of braided streams draining northwards (Collinson et al. 1994; Zwartz and Woolfe 1996; Woolfe et al. 1996).

MATERIALS AND METHODS

A stratigraphic section was measured in the central Allan Hills (Figs. 1, 2; 76° 42.2′S, 159° 44.4′E). Fossil plants were also collected (Condon Collection nos. F35100-10). Each paleosol type, or pedotype (in the sense of Retallack 1994) was characterized in detail (Tables 1–4), including observations on Munsell color and reaction with dilute acid (following Retallack 1988). Because of the local shortage of place names, each pedotype is named after Antarctic researchers (Retallack et al. 1997a). The type example and some other examples of the pedotypes were sampled for chemical and petrographic analysis, including point-counting 500 points in thin section for grain size (Table 5) and mineral composition (Table 6) using a Swift point-counter (by AAZ), with accuracy of about 2% (Murphy 1983). Full chemical analysis was by ICP and XRF, with FeO by titration and loss on ignition at 1000°C (Tables 7–8).

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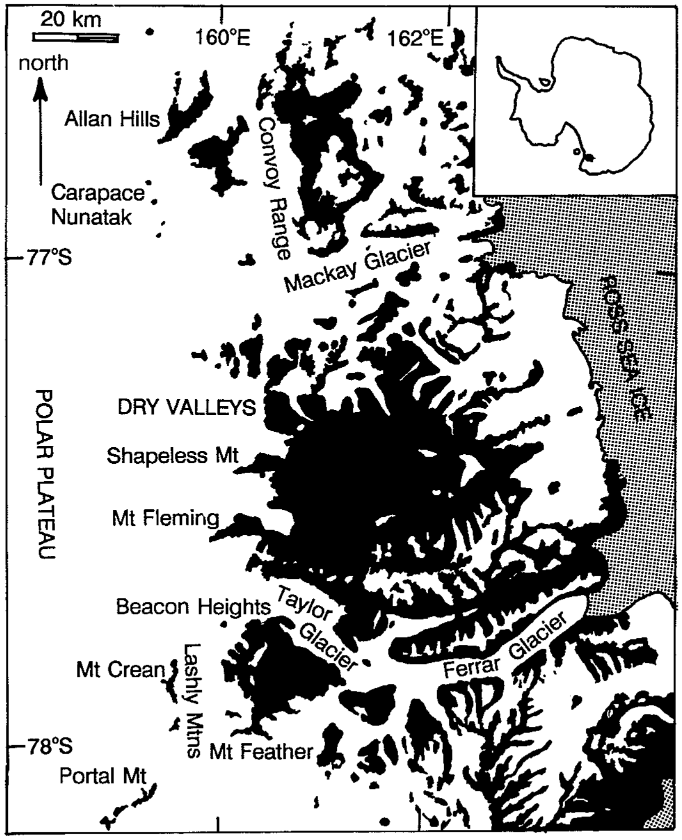

FIG. 1.—Rock and soil (black), and location of Allan Hills in southern Victoria Land, Antarctica.

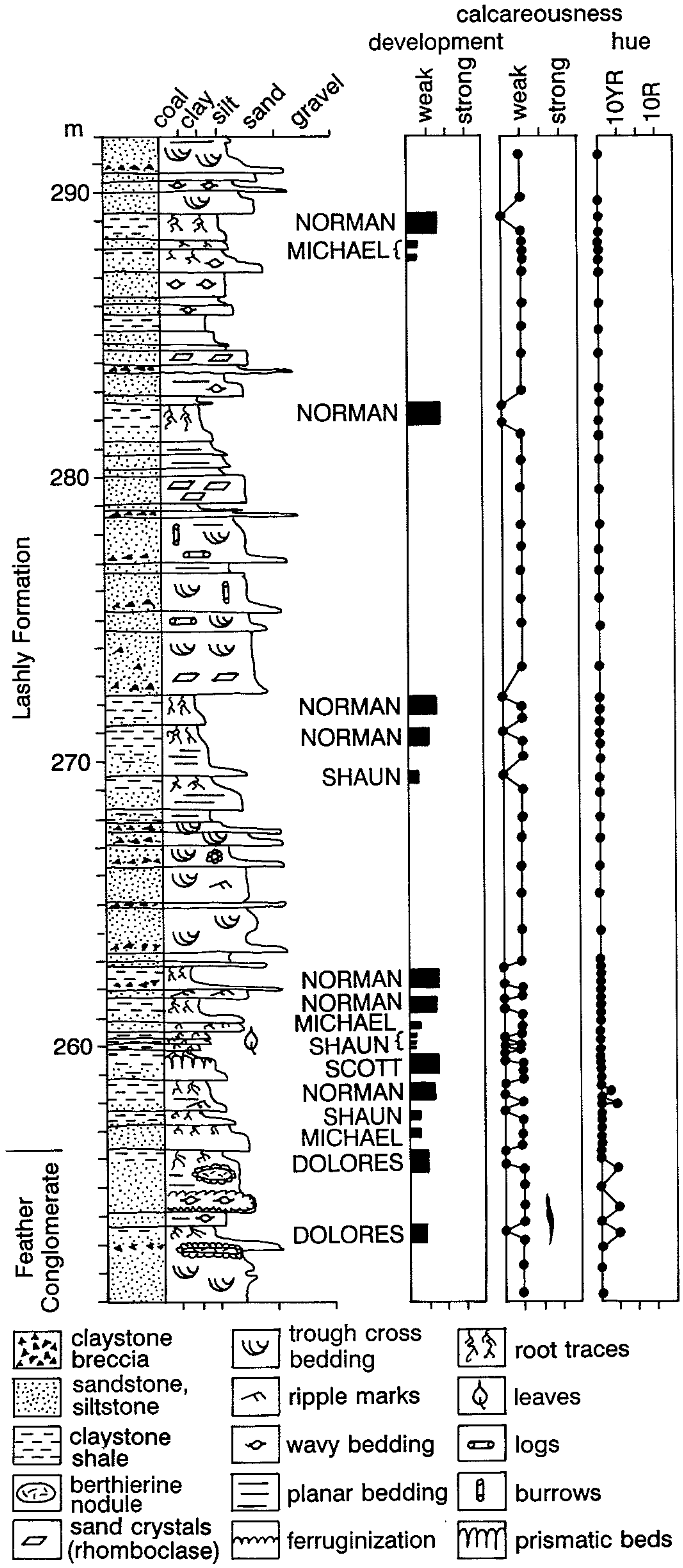

FIG. 2.—A measured section of paleosols in the upper Feather Conglomerate and lower Lashly Formation in the central Allan Hills, Antarctica (76° 42.2′S, 159° 44.4′E). Meter levels are from a longer measured section here (Retallack et al. 1997a). Hue is from a Munsell color chart, and reaction with acid for calcareousness and degree of development are from scales of Retallack (1988). Names of paleosols are pedotypes (of Retallack 1994).

FOSSIL ROOT TRACES

Field Observations

Carbonaceous root traces are found in some of the fossil plant localities, particularly those with fossil horsetails (258 m in Figure 2). The rhizomes and adventitious roots of the horsetails form planar mats, more or less concordant with strata. Such root mats are common in waterlogged soils, where root penetration is prevented by stagnant groundwater (Jenik 1978).

More abundant are deeply penetrating and copiously branching white root traces in greenish-gray claystones (Fig. 3). These are widespread in the Lashly Formation within southern Victoria Land (Gabites 1985), from Portal Peak north to the Allan Hills (Retallack et al. 1997a). Identical root traces and paleosols also are common in the Middle Triassic upper Fremouw Formation of the Beardmore Glacier region of the central Transantarctic Mountains (Horner and Krissek 1991; Retallack et al. 1997b).

These distinctive white root traces range in size from 1 to 12 mm in diameter, with the fine rootlets branching from stout, nearly vertical tap roots. Thick (up to 8 mm diameter) subhorizontal roots with lateral rootlets also were seen (Gabites 1985). Individual root systems emanate downward from bedding planes interpreted as the tops of paleosols, and could be traced for vertical distances of some 50 cm. No trace of the original carbonaceous material of the white root traces can be found. The clay-size mineral filling these root traces is banded concentrically in colors of white and light gray, and is unreactive to acid.

Petrographic and Mineral Composition of White Root Traces

Our XRD traces, EDAX microprobe analyses, and petrographic examination of the white root traces show that the main filling material is white

TABLE 1.—*Description of the type Michael paleosol.*

Depth (cm)	Hz	Rock	Color	Other Features	Micromorphology	Contact
+17 cm	C	Fine-grained sandstone	Light olive gray (5Y6/2)	Common relict bedding; medium mottles olive gray (5Y5/2); distinct medium nodules dark yellowish brown (10YR4/4); weakly calcareous	Intertextic mosepic to skelsepic common redeposited soil clasts, some quartz, feldspar, mica and opaques	Abrupt smooth to
0 cm	A	Fine-grained sandstone	Light gray (5Y7/2)	Common white (5Y8/1) root traces up to 13 mm in diameter; indistinct relict bedding; weakly calcareous	Intertextic mosepic to skelsepic; common quartz, few soil clasts and rock fragments; some feldspar, mica and opaques	Gradual smooth to
−13 cm	C	Fine-grained sandstone	Light gray (5Y7/1)	Prominent relict bedding; sparse copiously branching fine white (5Y8/1) root traces; few narrow (3–4 mm diameter) burrows filled with olive gray (5Y4/2) claystone	Intertextic skelsepic; common quartz and soil fragments, some rock fragments, feldspar and opaques	Abrupt smooth to

TABLE 2.—*Description of the type Norman paleosol.*

Depth (cm)	Hz	Rock	Color	Other Features	Micromorphology	Contact
+8 cm	—	Medium-grained sandstone	Light gray (5Y7/1)	Ripple marks, complex weathering rind (quasiferran) brown (10YR4/3) inside outer stain pale yellow (2.5Y7/3); grains gray (5Y5/1); weakly calcareous	Intertextic granular-skelsepic; common volcanic and metamorphic rock fragments	Abrupt, smooth to wavy to
0 cm	A	Clayey siltstone	Gray (5Y6/1)	Common large (8 mm diameter) white (5Y8/1) root traces; slickensided clay skins (argillans) light olive gray (5Y6/2), outlining coarse-medium subangular blocky peds; irregular medium mottles gray (5Y5/1); non-calcareous	Porphyroskelic mosepic; chalcedony infill of roots; mainly clay with rare quartz, mica and opaques.	Gradual smooth contact to
−14 cm	Bw	Silty claystone	Gray (5Y5/1)	Common white (5Y8/1) root traces; coarse angular blocky peds outlined by clay skins (argillans) of olive gray (5Y5/2); complex weathering rind (quasiferran) dark yellowish brown (10YR4/4) within outer rind of pale olive (5Y6/3); non-calcareous	Porphyroskelic mosepic; with striotubules and laminated clay skins; mainly clay with rare quartz, mica and opaques	Gradual smooth to
−49 cm	C	Fine-grained sandstone	Light olive gray (5Y6/2)	Common relict bedding; medium mottles olive gray (5Y5/2); distinct medium nodules dark yellowish brown (10YR4/4); weakly calcareous	Intertextic mosepic to skelsepic common redeposited soil clasts, some quartz, feldspar, mica and opaques	Abrupt smooth to

chalcedony and light gray illite, mixed-layer illite–smectite, and rare kaolinite (Figs. 4–8). Chemical composition of these clays is similar to that of the surrounding paleosol matrix. In some cases the concentric laminae within the root traces include silt and larger grains of the surrounding soil. Concentric interlamination of clay and chalcedony is common, as seen by microprobe mapping and traverses (Figs. 5–6). Degraded fibers of chalcedony were found in the root traces (Fig. 4A). The chalcedony is length slow and so could be called quartzine. Other crystalline structures proved to be sanidine (Fig. 4C) and orthoclase (Fig. 4D) in volcanic rock fragments. We looked hard for zeolites and carbonate in petrographic thin sections, EDAX analyses or XRD traces, but found none. These white root traces were not calcareous rhizoconcretions like those of soils in dry climates (for comparison see Retallack 1991a).

Origin of the White Root Traces

The lack of organic matter and deep penetration of the white root traces are evidence of well drained soils. In well aerated soils, root penetration and decomposition of organic matter are unhindered. The first phase in the formation of these white root traces would have been rotting out of the buried root traces, followed by filling with clay and silica. Some of the concentric fills could have been initiated before burial of the soil, when soil clasts and silt-size mineral grains fell down into a widening crack between the rotting root and its matrix. Most of the fill was probably formed during burial of the paleosol, because so many of them are free of sediment that fell into associated insect burrows (Gabites 1985). The time of filling was very early during burial because the white root traces fill fully inflated root holes, which have been little deformed by subsequent burial compaction. Carbonaceous root traces in the Lashly Formation are deformed by burial compaction into a concertina-like shape. In contrast, the white root traces are like permineralized logs in the Lashly Formation in resistance to burial compaction.

The source of silica filling the root traces is unlikely to be illitization or pressure solution because neither of these effects of deep burial are marked in the Lashly Formation. The 10 Å peak of illite in XRD traces of the paleosols is broad and low (Fig. 7; Weaver index 0.3–0.9, Kubler index 1.2–2.4; Weber index 422–800), more like that of soils than deeply buried clays (Retallack 1977a, 1991b). Even a sandstone (R1868 at 279 m in Figure 2) had illite peaks insufficiently sharp for deep burial diagenesis (Weaver index 1.4, Kubler index 0.8, Weber index 229). Metamorphic illites have sharp XRD peaks (Weaver index > 2.3, Kubler index < 0.42, Weber index < 181; Frey 1987). Quartz is not so abundant that dissolution between mutual grain contacts is observed in thin section.

Nor is it likely that the silica was mobilized in highly alkaline evaporitic environments that have been inferred from the presence of length-slow chalcedony (quartzine) in carbonates (Folk and Pittman 1971). Numerous exceptions to the association of length-slow chalcedony with evaporites have been found, especially in soils (Arby 1980; Bustillo 1976; Meyer 1983). The noncalcareous and base-poor nature of the paleosols together with the common broadleaf fossil plants (Townrow 1967; Gabites 1985; E.L. Taylor et al. 1990; T.N. Taylor et al. 1990) are evidence of a humid climate.

More likely the silica was derived from biogenic or weathering sources. Horsetails are well known as silica-accumulating plants, and opal from plants is known to be more soluble than quartz (Retallack 1977a). However, the chalcedony root traces do not have the distinctive fluted and jointed morphology of horsetail rhizomes. Some species of *Dicroidium* may have produced silica phytoliths on the leaves (Retallack 1977a), but no plant is

TABLE 3.—*Description of the type Scott clay paleosol.*

Depth (cm)	Hz	Rock	Color	Other Features	Micromorphology	Contact
+10 cm	—	Shale	Gray (5Y5/1)	Distinct bedding; common carbonaceous remains of *Neocalamites*; non-calcareous	Porphyroskelic argillasepic; with some quartz and opaques, and rare mica and feldspar	Abrupt smooth to
0	A	Claystone	Dark gray (5Y4/1)	Common white (5Y8/1) root traces; claystone clasts very dark gray (5Y3/1) and light gray (5Y5/2); blocky to platy peds defined by slickensided clay skins of dark yellowish brown (10YR4/4); non-calcareous	Porphyroskelic mosepic; with common quartz, few feldspar, opaques, mica and claystone clasts	Gradual irregular to
−16 cm	Bw	Clayey siltstone	Light gray (5Y7/2)	Prominent columnar peds 7–8 cm in diameter defined by silty planes (silans) of light gray (5Y7/2) with a core zone of gray (5Y6/1); common white (5Y8/1) root traces; some medium blocky subangular peds defined by dark gray (5Y4/1) clay skins; non-calcareous	Porphyroskelic mosepic; with common opaques and quartz, and few mica and feldspar	Gradual smooth contact to
−68 cm	C	Siltstone	Light gray (5Y6/3)	Massive to weakly bedded with sparse dark gray (5Y4/1) mottles and burrows; weakly calcareous	Porphyroskelic mosepic; with quartz, and few feldspar, mica and opaques	Abrupt smooth to

TABLE 4.—*Description of the type Shaun paleosol.*

Depth (cm)	Hz	Rock	Color	Other Features	Micromorphology	Contact
+17 cm	—	Sandy siltstone	Light gray (5Y7/2)	Distinct relict bedding; common white (5Y8/1) root traces; few slickensided clay skins (argillans) dark brown (10YR3/3); weakly calcareous	Porphyroskelic to intertextic skelsepic; common quartz and redeposited soil clasts, some opaques, mica and feldspar	Abrupt smooth to
0 cm	A	Claystone	Gray (5Y5/1)	Distinct relict bedding; common fine (2–3 mm) black (5Y2.5/1) root traces; mottles and clay skins of dark gray (5Y4/1) define fine subangular blocky structure; non-calcareous	Porphyroskelic insepic; common redeposited soil clasts some quartz and opaque, little feldspar and mica	Gradual smooth to
−13 cm	C	Siltstone	Gray (5Y5/1)	Distinct bedding with clayey laminae of gray (5Y5/1); non-calcareous	Porphyroskelic argillasepic; with opaques, quartz and mica and some feldspar	Abrupt smooth to

TABLE 5.—*Textures (volume) percent from point counting and calcareousness (scale of reaction) of Triassic paleosols.*

Paleosol	Horizon	Specimen	Reaction	Clay %	Silt %	Sand %	Gravel %	Texture
sandstone	above	R1816	1	27.0	1.2	71.8	0	sandy clay loam
Norman	A	R1817	1	82.2	16.0	1.8	0	clay
clay	Bw	R1818	1	71.6	18.4	10.0	0	clay
	Bw	R1819	1	52.6	15.6	31.8	0	clay
	Bw	R1820	1	74.6	14.0	11.4	0	clay
	C	R1821	1	18.4	2.2	39.0	40.4	sandy loam
	C	R1822	1	34.6	2.6	62.4	0	sandy clay loam
type	A	R1823	1	92.4	6.0	1.6	0	clay
Norman	Bw	R1824	1	92.6	6.8	0.6	0	clay
clay	Bw	R1825	1	96.2	2.8	1.0	0	clay
	C	R1826	1	93.0	4.6	2.4	0	clay
	C	R1827	1	65.4	8.0	26.6	0	clay
type	A	R1828	1	50.4	7.6	41.8	0	clay
Michael	C	R1829	1	51.4	4.4	44.2	0	clay
clay	C	R1830	1	49.4	2.4	48.2	0	clay
Shaun clay	A	R1831	1	73.8	14.6	11.6	0	clay
type Shaun	A	R1832	1	81.2	15.6	3.2	0	clay
clay	C	R1833	1	73.6	18.8	7.6	0	clay
Shaun clay	A	R1834	1	84.8	11.8	3.4	0	clay
type Scott	A	R1835	1	86.0	7.2	6.8	0	clay
clay	A	R1836	1	83.8	9.0	7.2	0	clay
	Bw	R1837	1	85.8	12.0	2.2	0	clay
	Bw	R1838	1	70.2	14.2	15.6	0	clay
	C	R1839	1	83.8	10.6	5.6	0	clay
	C	R1840	1	90.0	8.6	1.4	0	clay
Norman	A	R1841	1	87.7	8.4	3.0	0	clay

Note: Relative scale of calcareousness (1–5) by reaction with 1.2M HCl from Retallack (1988, 1990). Standard error of these 500 point counts is about 2 volume % (Murphy 1983).

known to produce them in roots. Sandstones of the Lashly Formation include mostly volcanic rock fragments, with little indication of tuffaceous glassy grains. Such volcanic glass is also more readily weathered than minerals or rock fragments. In a humid wet climate and volcanic terrain, groundwater could have carried moderately elevated concentrations of silicic acid, but there is no evidence from veining or mineralization of local geothermal activity needed for highly silica-charged waters.

Although the silica could be from plants or weathering, there is still a

TABLE 6.—*Mineral composition (volume percent) from point counting petrographic thin sections of Triassic paleosols.*

Paleosol	Horizon	Specimen	Clay	Feldspar	Mica	Volcanic Rock	Weathered Rock	Opaque	Quartz
sandstone	above	R1816	27.8	2.8	2.2	1.2	17.2	4.6	44.2
Norman clay	A	R1817	82.8	—	0.4	—	5.8	2.2	8.8
	Bw	R1818	71.2	0.6	3.4	2.6	0.8	1.2	20.2
	Bw	R1819	54.0	1.4	7.4	1.6	3.2	2.4	30.0
	Bw	R1820	73.6	1.4	3.2	3.4	0.8	3.4	14.2
	C	R1821	19.0	2.0	1.4	5.8	45.6	3.4	25.8
	C	R1822	35.6	4.0	3.0	14.6	7.6	3.6	31.6
type Norman	A	R1823	91.2	—	1.4	—	—	1.4	6.0
clay	Bw	R1824	91.6	—	1.6	—	—	2.6	4.2
	Bw	R1825	95.6	—	0.4	—	—	1.2	2.8
	C	R1826	92.8	0.2	0.8	—	—	—	6.2
	C	R1827	65.2	1.0	2.2	—	2.8	3.8	25.0
type Michael	A	R1828	51.4	1.8	5.0	1.8	5.2	3.6	31.2
clay	C	R1829	52.6	1.8	4.4	4.4	4.6	3.8	28.4
	C	R1830	49.8	4.4	2.0	4.8	11.2	2.6	25.2
Shaun clay	A	R1831	75.4	1.0	1.6	—	10.0	5.0	7.0
type Shaun	A	R1832	74.0	0.2	0.6	—	16.2	5.6	3.4
clay	C	R1833	74.4	2.4	7.0	—	—	9.6	6.6
Shaun clay	A	R1834	87.0	0.8	1.2	—	0.2	7.8	3.0
type Scott	A	R1835	81.0	0.4	1.2	—	0.4	5.6	11.0
clay	A	R1836	82.0	—	2.0	—	0.6	1.8	13.6
	Bw	R1837	87.6	0.6	0.2	0.4	0.6	5.2	5.4
	Bw	R1838	71.6	2.4	6.2	—	1.4	2.4	15.6
	C	R1839	84.2	1.0	1.4	—	—	10.6	2.2
	C	R1840	90.4	0.4	2.6	—	—	1.8	4.8
Norman clay	A	R1841	88.6	—	3.4	—	—	3.5	4.2

Note: Volcanic rock fragments are little weathered, but weathered rock fragments include resorted soil clasts, iron stained volcanic rock fragments and other indistinct grains. Clay includes some clay-size quartz cement. Errors are as for Table 4.

TABLE 7.—*Major-element chemical analyses and loss on ignition (weight percent) of Triassic paleosols.*

Paleosol	Horizon	Specimen	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
type	A	R1823	61.31	0.59	17.54	3.47	4.43	0.04	1.14	0.45	1.02	2.74	0.04	5.41	98.75
Norman	Bw	R1824	62.57	0.63	17.52	2.93	3.72	0.04	0.98	0.64	1.2	2.53	0.08	5.40	98.78
	Bw	R1825	58.11	0.67	19.12	3.28	4.73	0.05	0.95	0.80	0.79	1.82	<0.03	6.85	97.79
	C	R1826	59.73	0.69	19.34	3.21	3.65	0.09	0.91	0.85	0.86	1.91	0.04	7.26	99.03
	C	R1827	65.37	0.68	17.36	1.89	3.02	0.05	0.66	0.72	1.19	2.14	0.14	5.65	99.26
type	A	R1828	65.78	0.60	17.80	1.84	2.46	0.05	0.77	0.75	1.23	2.43	0.03	5.17	99.24
Michael	C	R1829	69.70	1.18	13.44	1.46	3.72	0.16	0.73	0.87	1.35	1.60	<0.03	3.74	98.42
	C	R1830	68.31	0.59	15.26	1.76	2.60	0.07	0.85	0.81	1.80	1.97	<0.03	4.26	98.62
Shaun	A	R1831	65.49	0.65	16.29	2.40	2.88	0.08	1.00	0.71	1.56	2.51	0.11	4.57	98.65
type	A	R1832	62.02	0.68	19.08	2.36	2.36	0.04	1.18	0.70	1.13	2.98	0.06	6.12	99.02
Shaun	C	R1833	65.05	0.68	17.17	1.12	2.46	0.05	1.18	0.87	1.01	2.19	0.14	5.65	97.89
Shaun	A	R1834	60.28	0.75	20.01	1.97	2.88	0.12	1.36	0.95	0.61	2.65	<0.03	7.40	99.35
type	A	R1835	60.39	0.86	22.73	1.23	0.28	0.05	0.36	1.36	1.09	1.47	0.10	8.71	98.48
Scott	A	R1836	58.66	0.85	22.39	1.21	1.05	0.05	0.43	1.34	0.95	1.97	0.05	8.85	97.94
	Bw	R1837	66.38	0.84	16.20	1.70	2.04	0.04	0.55	0.92	0.57	1.53	<0.03	6.33	97.36
	Bw	R1838	61.19	0.67	18.75	1.64	2.91	0.05	0.81	1.05	0.68	1.95	0.10	7.10	97.28
	C	R1839	60.75	0.68	18.31	2.39	4.15	0.05	0.96	0.68	0.73	2.50	0.09	5.77	97.63
	C	R1840	62.97	0.60	16.84	2.17	3.93	0.03	0.92	0.53	0.92	2.87	0.13	4.67	97.08
error	σ	all	0.25	0.02	0.17	0.15	0.08	0.005	0.05	0.10	0.05	0.01	0.004	—	—

Note: Analyses from inductively-coupled plasma-atomic fusion, ferrous ammonium sulfate titration and combustion at 1000°C for 4 hrs by Bondar-Clegg & Co., North Vancouver, B.C. Errors from 59 analyses of standard rock CANMET SY-3.

need for a concentration mechanism for selective silicification of root traces, peat fragments, and fossil wood in the Lashly Formation. Considering indications of low-temperature silicification early during burial and local pyrite cubes, a likely mechanism for silicification of root traces, peat, and wood is as a consequence of plant decay by sulfate-reducing bacteria (Birnbaum and Wireman 1984; Birnbaum et al. 1986). This process requires chemically reducing conditions and an organic substrate. During shallow burial the banded silicification may reflect seasonal warmth for decay and fluctuating silica concentrations in interstitial fluids. Such a microbially mediated origin also implies that the root traces that became filled with silica were the last crop of roots before burial, because earlier generations of roots would have decayed away without falling within the groundwater zone of anaerobic sulfate-reducing bacteria and silica accumulation. Furthermore, hydrated silica produced by bacteria in stagnant soil water would be flushed out during the dry season of plant growth, whereas in buried soils it would be dehydrated and recrystallized to chalcedony.

The overall pattern of roots includes a stout and deeply penetrating network most like that found today under woodland of well drained ground (Weaver 1919). It is neither a surface mat, patchy laterally, nor especially uneven in its size distribution, unlike root distribution in tundra, taiga,

TABLE 8.—*Trace element analyses (ppm) and bulk density ($g{\cdot}cm^{-3}$) of Triassic paleosols.*

Paleosol	Horizon	Specimen	Ba	Nb	Rb	Sr	Y	Zr	$g{\cdot}cm^{-3}$
type	A	R1823	793	12	184	106	57	208	2.21
Norman	Bw	R1824	645	14	167	145	56	221	2.21
	Bw	R1825	597	15	150	164	36	238	—
	C	R1826	557	15	148	176	45	248	2.28
	C	R1827	422	16	135	156	50	379	2.37
type	A	R1828	570	14	153	127	32	291	2.29
Michael	C	R1829	389	16	105	115	40	901	2.21
	C	R1830	525	13	121	147	58	270	2.23
Shaun	A	R1831	565	13	150	128	70	293	2.25
type	A	R1832	653	14	185	126	52	246	2.28
Shaun	C	R1833	496	15	134	108	49	342	2.37
Shaun	A	R1834	533	17	164	114	49	272	2.36
type	A	R1835	498	21	135	167	42	432	2.40
Scott	A	R1836	556	22	153	171	42	440	2.41
	Bw	R1837	324	20	122	116	35	429	2.31
	Bw	R1838	437	17	125	146	42	347	2.27
	C	R1839	587	15	165	123	33	239	2.30
	C	R1840	608	14	170	83	35	247	2.20
error	σ	all	16	0.6	1	3	0.6	7	0.02

Note: Trace elements are X-ray fluorescence and same analyst as Table 6, with errors from 59 samples of standard CANMET SO-2. Bulk densities are by Evelyn Krull using clod method with error from 10 replicates of R1839.

savanna, monsoon-forest, or rain-forest vegetation. It is likely that these distinctive white-root beds largely represent the fossil plant association dominated by *Dicroidium odontopteroides* (Townrow 1967; Gabites 1985; T.N. Taylor et al. 1990; E.L. Taylor et al. 1990), and that it was a humid, cold temperate woodland.

FOSSIL SOILS

Pedotypes and Paleosol Associations

Two distinct assemblages of paleosols were found in the Lashly Formation: a coal-measure association with fossil plants (Member C only) and a green claystone association with white root traces (Members A–D). Paleosols of the coal-measure association are described by Gabites (1985, paleosol type 7), but our study focused on the green-claystone association of the lower Lashly Formation (Members A and B), in which we found four distinctly different kinds of paleosols, or pedotypes (Fig. 2). Weakly developed pedotypes of the green-claystone association include sandy profiles of the Michael pedotype (paleosol type 4 of Gabites 1985) and shaly profiles of the Shaun pedotype (paleosol type 5 of Gabites 1985). Thicker paleosols of weak to moderate development that probably supported woodland vegetation include the Norman pedotype (paleosol type 6 of Gabites 1985) with locally prominent slickensides and surface undulation, and the Scott pedotype (2 of Gabites 1985), with prismatic structure some 7–10 cm wide and 40–50 cm high outlined by silty planes. These four pedotype names are meant only as field labels, and are nongenetic terms.

Burial Alteration

Alteration of paleosols during burial and metamorphism can seriously compromise paleoenvironmental interpretation (Retallack 1991a, 1991b). Although some of the paleosols include coal and carbonaceous fossil plant remains (Gabites 1985), others with abundant large white root traces have little carbonaceous material. This observation and their distinctly green hue are evidence of early burial decomposition of organic matter and burial gleization of the paleosols (Retallack 1991b). This may have changed noncarbonaceous yellow and brown soils into green paleosols.

Burial also has altered the paleosols by cementation, illitization, and compaction. Silica cement is especially obvious in the white root traces (Figs. 3–6), but is also more pervasive in the paleosols. At least some of this silica cement formed very early during burial, because permineralized fossil wood has remained uncompacted by subsequent deep burial (Gabites 1985; E.L. Taylor and Taylor 1993). One source of such cement is illiti-

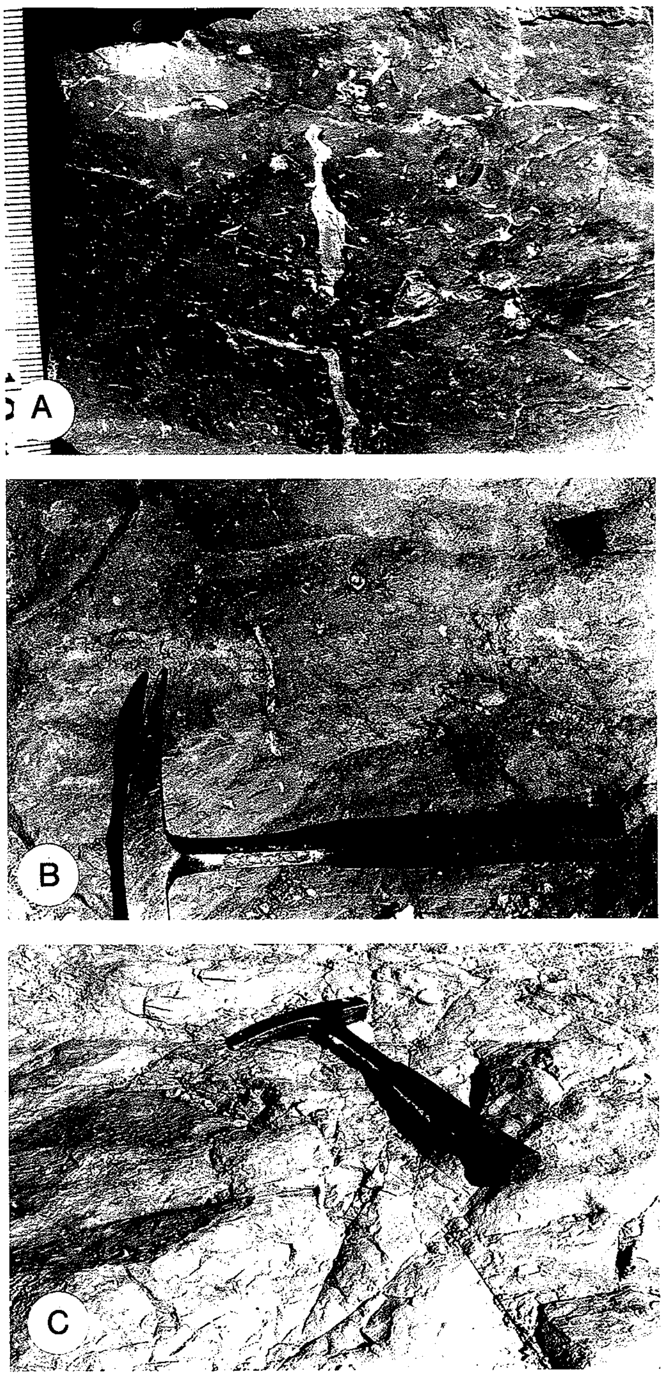

FIG. 3.—White fossil root traces of the Lashly Formation, Antarctica (all at level of Specimen R1841). Scale is in millimeters and geological hammers are 25 cm long.

zation of smectite clays (Eberl et al. 1990), but this could not have been pervasive because of the width of illite peaks (Fig. 7), as already discussed.

Burial compaction would have been significant and can be estimated using a formula of Sclater and Christie (1980):

$$C = \frac{0.5}{\frac{0.49}{e^{D/3.7}} - 1}$$

where C is compaction as a fraction and D is depth of burial in kilometers. Paleosols at the base of the Lashly Formation could have been overlain by as much as 520 m of the formation found elsewhere in southern Victoria Land, and 600 m of Jurassic volcanics, an estimate compatible with 2 km of overburden needed to explain the low-volatile bituminous coals of the Weller Coal Measures 170 m stratigraphically below the paleosols (Coates et al. 1990). Taking 2 km as an estimate for the equation given above gives 82% compaction of the paleosols due to burial. Observations of clastic dikes in paleosols versus shales indicate that this is a maximal likely compaction (Caudill and Driese 1996).

Chemical and Mineralogical Composition

Paleosols of the Lashly Formation show variations in chemical and petrographic composition both within and between profiles that indicate weathering. Mineral weathering in the form of etch pits and encrusting clays are prominent on feldspars within volcanic rock fragments (Fig. 4C, D). Primary bedding is disrupted by clay skins (Fig. 9B, C; argillans of Brewer 1976) and silt infiltration structures (Fig. 9A; siltans). These structures reflect cracking of the soil with drying or freezing, and modification of the crack surfaces. Nevertheless, the degree of variation in chemical and mineral composition within individual paleosol profiles is relatively muted (Fig. 8) compared with the range of alteration known from soils and paleosols (Retallack 1990). None of them show pronounced subsurface accumulations of clay, alumina, or carbonate.

The greenish gray color and dominance of ferrous over ferric iron in the paleosols indicate a surprising degree of chemical reduction for paleosols that must have been drained episodically to allow deep penetration of roots and soil cracks. Cool humid climate with low evapotranspiration, slow drainage, and a shallow water table in an extensive floodplain are likely, but also needed are chemically reducing agents such as vegetative cover and microbial gleization during early burial.

A humid paleoclimate can be inferred from the noncalcareous and base-poor chemical composition of the paleosols, like Early Triassic paleosols from Antarctica (Barrett and Fitzgerald 1986) and eastern Australia (Jensen 1975; Retallack 1977b). They have the chemical composition of soils of humid climates (pedalfers rather than pedocals of Marbut 1935), but are not intensely leached like soils of excessively rainy climates. Quantitative estimates of paleoprecipitation can be gained from the molecular ratio of bases/alumina (B) in the B horizons of North American soils, which can be shown to be related to mean annual rainfall (P, mm) according to the following formula (Ready and Retallack 1995):

$$P = -759B + 1300$$

with correlation coefficient of 0.7 and standard deviation (σ) of $\pm$ 174 mm. Estimates of rainfall for the B horizon of the type Norman clay and type Scott clay are 935–1016 and 986–1050 mm, respectively. In round figures and including regression error this is 800–1200 mm per annum.

This indication of wet climate is not contradicted by sand crystals found in paleochannels of Member A of the Lashly Formation (279 m in Figure 2), because these are not calcite, gypsum, or barite like sand crystals of arid regions (MacFayden 1950; Maglione 1981). XRD peaks at 9.69, 3.11, 3.33, and 4.73 Å (in order of intensity) indicate that this mineral is rhomboclase (Chen 1977). This is a sulfate [$HFe(SO_4)_2$] formed from the weathering of pyrite (Nickel and Nichols 1991). The rhomboclase sand crystals are comparable in size and shape to nodules of pyrite and jarosite found in sandstones of the Weller Coal Measures and Feather Conglomerate in the Allan Hills, and could have formed by redeposition and oxidation of those nodules. In the Lashly Formation, pyrite was not found in the paleochannels, but is locally found in paleosols.

Cracking Structures

Some Norman paleosols show sand-filled cracks, reaching down 50 cm into the profile. These cracks commonly emanate from a part of the profile

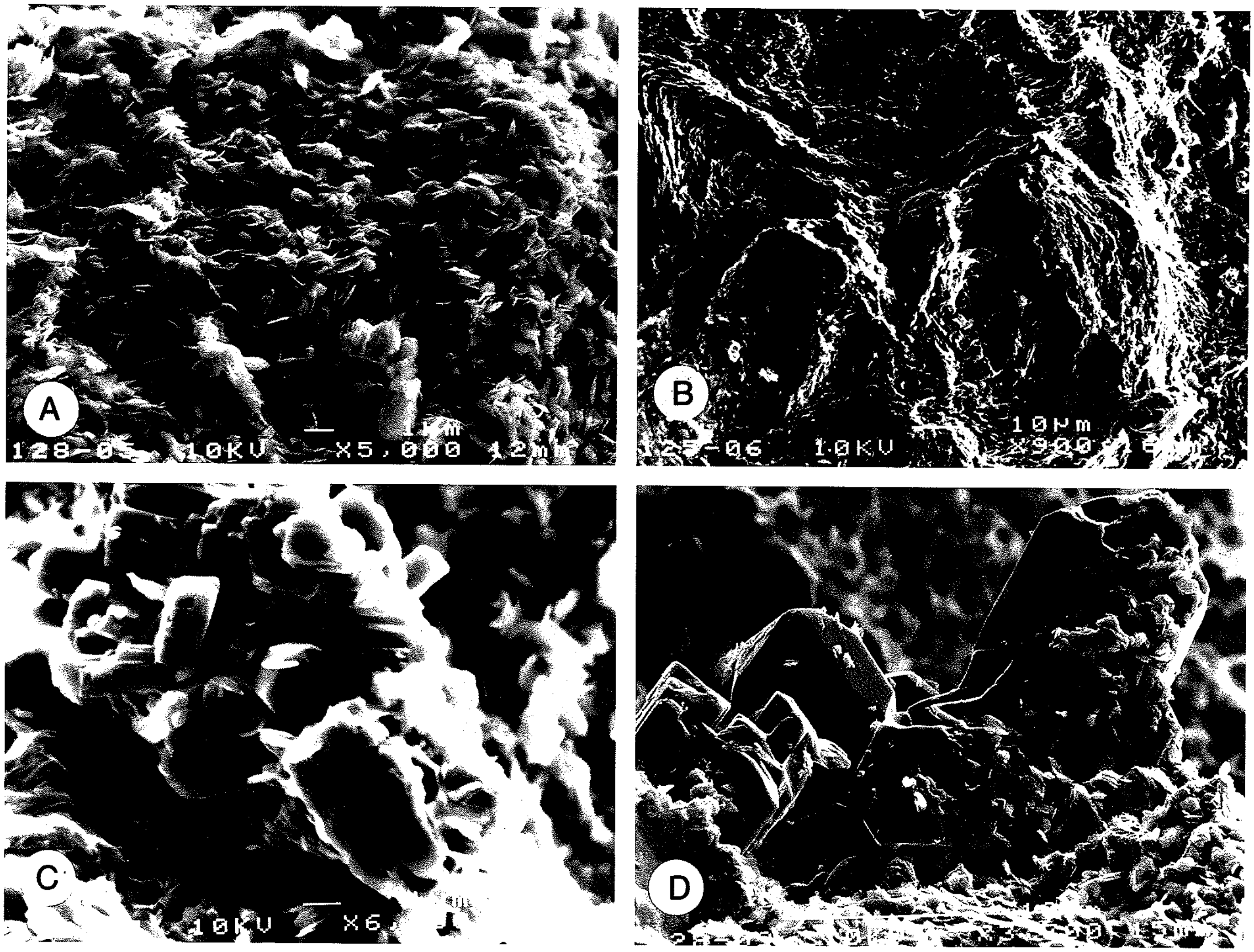

FIG. 4.—Scanning electron micrographs of minerals in white root traces of the Lashly Formation, Antarctica: **A)** clay-encrusted chalcedony fibers; **B)** chalcedony (massive) and clay (laminated); **C)** sanidine in volcanic rock fragment; **D)** orthoclase in volcanic rock fragment. Specimen numbers are R1838 (C) and R1841 (others).

that is elevated into a low ridge, separated at distances of 1–2 m by shallow surficial swales (Fig. 10). Some Norman paleosols also show extensive shallowly curved slickensided planes, in some cases distinctly basin-shaped. These structures are similar to the gilgai microrelief and its subsurface or mukkara structures of Vertisols.

These structures of Norman paleosols are much more subtle than in modern Vertisols, which have more marked microrelief and more abundant slickensides defining lentil peds (Krishna and Perumal 1948). Also lacking in petrographic thin sections are the pervasive randomly oriented planes of highly birefringent clays found in Vertisols (Holzhey et al. 1974). Nevertheless, these deep cracking structures indicate similar processes of shrinking and swelling, even if not so severe or in action for so long. Gilgai–mukkara are features of soils with smectites in climates with a pronounced dry season (Paton 1974). A short dry period or several dry spells within the growing season also may explain the deeply penetrating woody root traces in paleosols that have remained chemically reduced. Considering the wet climate indicated by base-poor chemical composition and associated coaly paleosols, the dry season is unlikely to have been a profound moisture deficit or to have lasted more than a few weeks during the summer.

Vertical Jointing

A prominent feature of the Scott pedotype is closely spaced (7–8 cm apart) vertical joints extending through some 60 cm or so of the subsurface of the paleosol (Fig. 11). These define prismatic peds of soil-science jargon (Brewer 1976). They are outlined by cracks filled with silt grains similar to those higher in the profile, or illuviation silans in soil jargon (Brewer 1976). Such features have been noted before in other Triassic paleosols of Victoria Land (as gammate and glossic structures of Gabites 1985; Fitzgerald and Barrett 1986).

Prismatic peds differ from columnar peds in lacking domed tops. Columnar peds are a characteristic feature of natric soil horizons (of Soil Survey Staff 1975, 1990; McCahon and Miller 1996), but this explanation does not work well for Scott paleosols because there is no evidence of sodium enrichment (Fig. 8) or abundant smectite clays (Fig. 7). Columnar and prismatic peds are also features of fragipans, which are loamy subsurface horizons that are low in organic matter, high in bulk density compared with covering soil, and cemented so that they are very hard when dry and brittle even when wet (Soil Survey Staff 1975). This explanation is supported by a variety of field, petrographic, and chemical observations of Scott paleosols. Redeposited claystone clasts are found at several levels within paleosols and in paleochannels of the Lashly Formation. Root traces in Scott paleosols tend to be molded around the peds, as if they were more difficult to penetrate than the cracks between them. Silica cement and fine clays are suspected as the primary causes of hardness in Quaternary fragipans (Nettleton et al. 1968), and both can be documented in fossil root

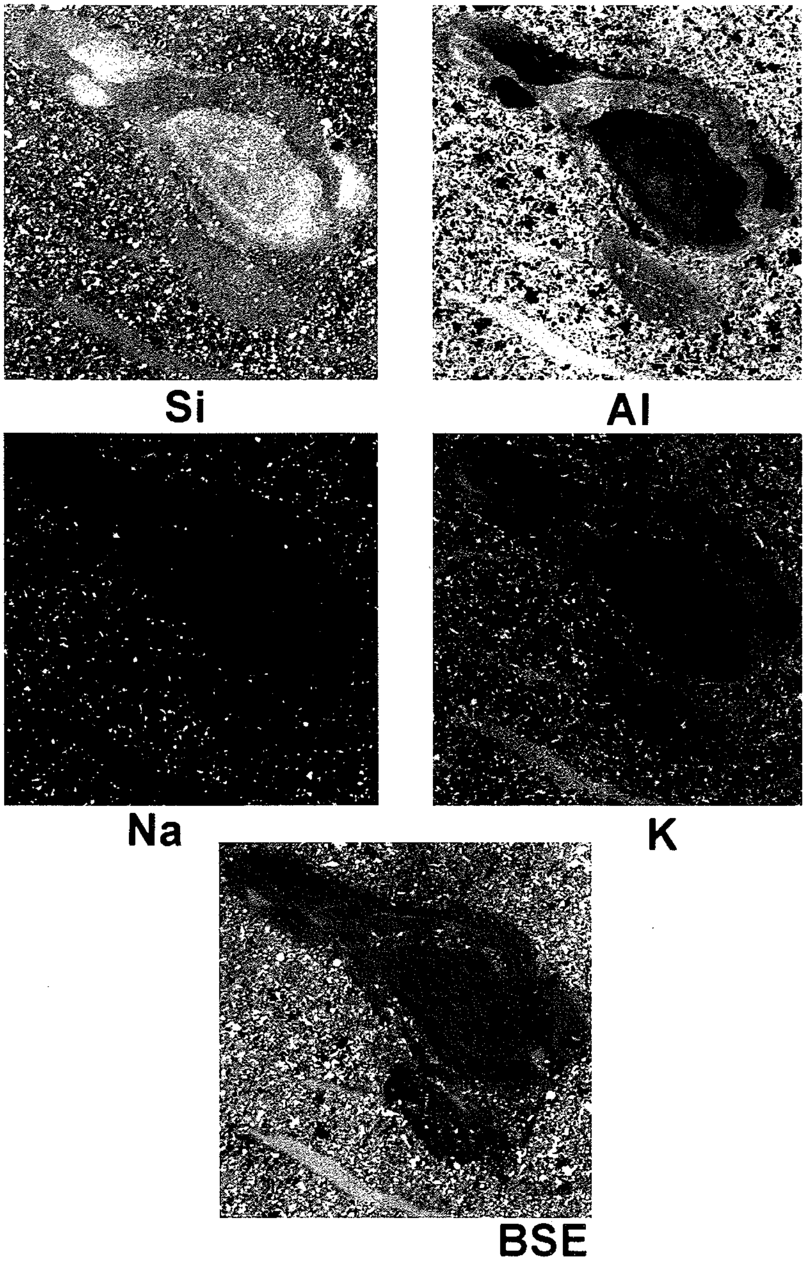

FIG. 5.—Microprobe chemical maps for silicon (Si), aluminum (Al), sodium (Na), potassium (K), and back-scattered image (BSE) of a white root trace from the Lashly Formation, Antarctica, showing concentrically interlaminated chalcedony and illite (Specimen R1841)

traces of early burial origin in the Lashly Formation (Fig. 5). Furthermore, colloidal cement bridges can also be seen as isolated pockets within the matrix of the columnar peds (Fig. 9B, lower right).

Fragipans are found mainly in moderately to strongly developed soils and take at least 2–5 kyr to form (Ciolkosz et al. 1979; Hall et al. 1982). Estimates on the low end of this range are compatible with the obliteration of bedding seen in the Scott pedotype. Fragipans also are common in soils with slow drainage (Buol et al. 1980), as seems likely for the green and chemically reduced Scott paleosols. Finally, fragipans, unlike other hardened horizons in soils such as duripans and petrocalcic or petrogypsic horizons, are found mainly in forested soils of humid climates (Ciolkosz et al. 1989; Lindbo and Veneman 1989), as seems likely considering the chemical composition and root traces of Scott paleosols.

The origin of fragipans in Quaternary soils remains poorly understood. Some fragipans appear to be cemented volcanic tuffs (Flores-Román et al. 1992), but there are no shards or other fresh tuffaceous material in Scott paleosols of the Lashly Formation. More than just a humid climate or forest vegetation is needed to encourage the formation of fragipans because they degrade with time under humid forested regimes of leaching, clay illuviation, or podzolization (Steele et al. 1965; Ciolkosz et al. 1989). Such observations have suggested that many fragipans may be relict from different conditions in the past, perhaps as old as the last glacial maximum of 15 ka. Repeated movement of a freezing front through this horizon may be the process that swept silt out to the margins of the pan, where it formed a system of conduits for colloidal cements (Buol et al. 1980). Frost cracking may explain the vesicular, prismatic, and platy structures of fragipans, defined by silty more porous planes through which ultrafine clay could be washed down into the profile. A frost barrier in or near the pan could also pond water at shallow levels within the soil during early spring melt. In a forested soil with thick leaf litter this water could become stagnant enough to encourage sulfate-reducing bacteria to generate patchy silica cement by mechanisms that have

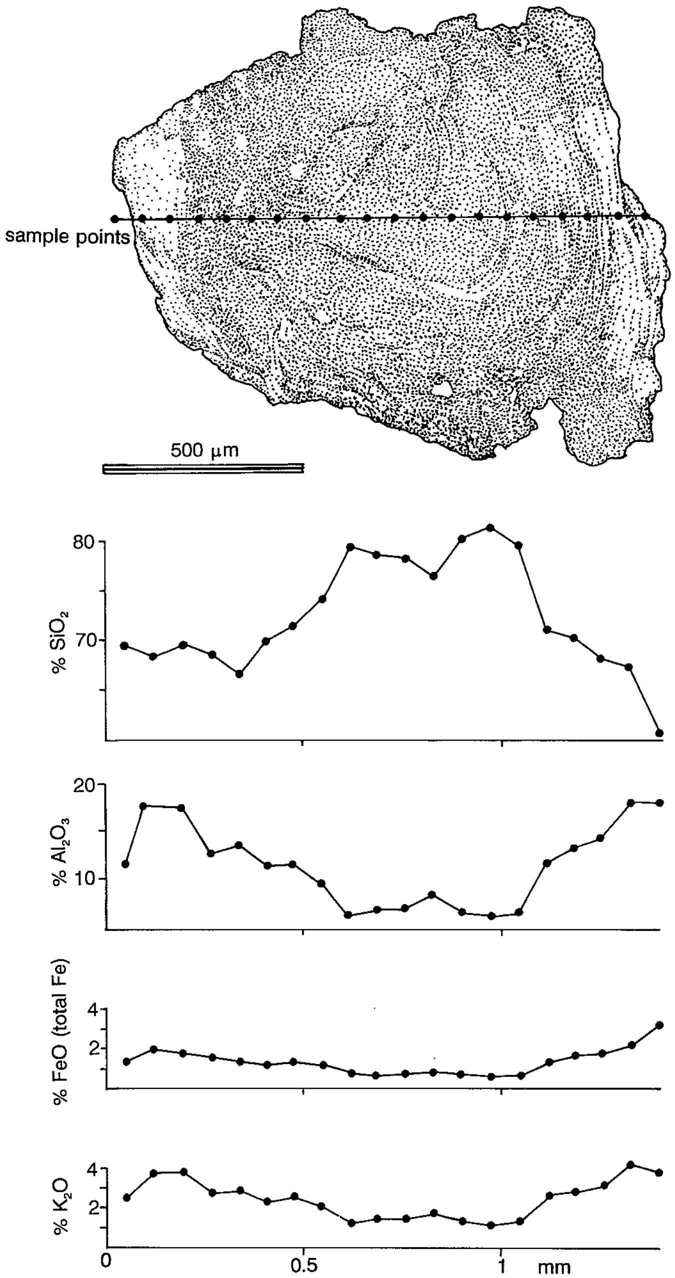

FIG. 6.—Microprobe traverse of white root trace from the Lashly Formation, Antarctica, showing concentrically interlaminated chalcedony and illite (Specimen R1841).

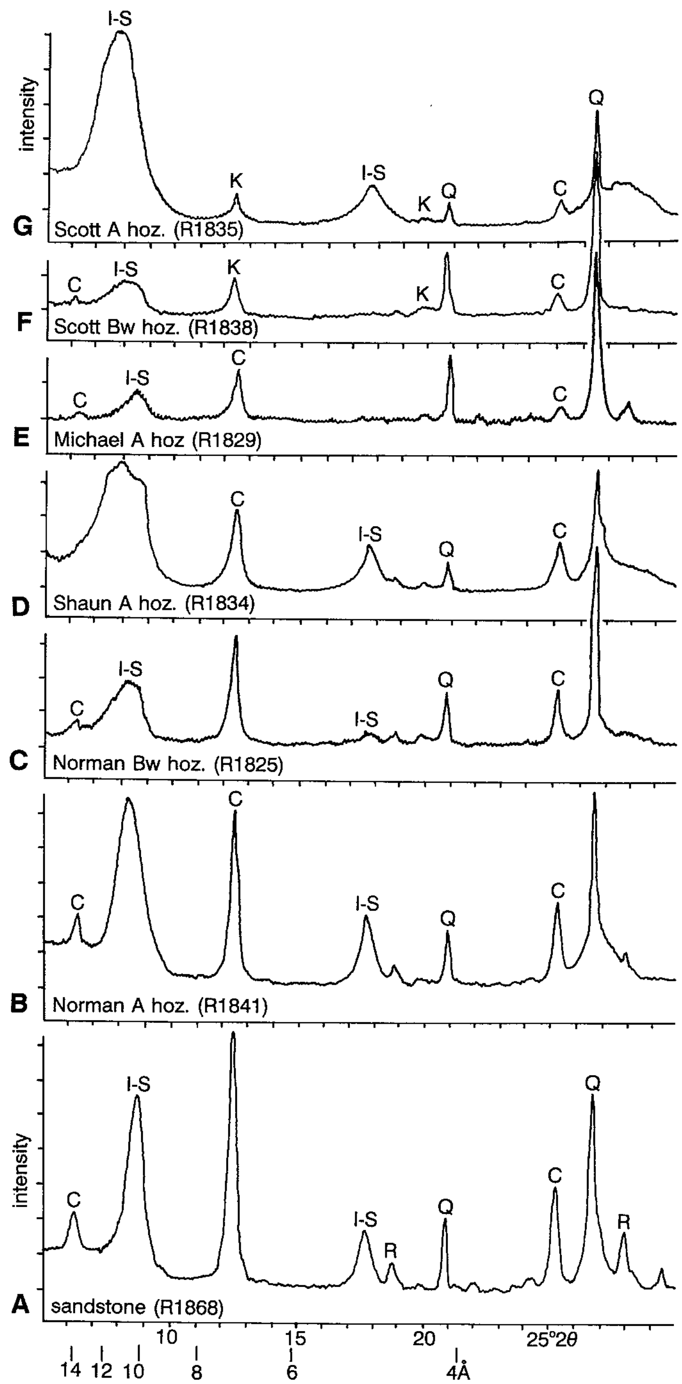

FIG. 7.—X-ray diffractometer traces of paleosols with poorly crystallized clays and sediments with well crystallized clay from the Lashly Formation, Antarctica. The following minerals can be identified: chlorite (C), mixed layer illite–smectite (I–S), kaolinite (K), rhomboclase (R), and quartz (Q).

been duplicated experimentally (Birnbaum and Wireman 1984; Birnbaum et al. 1986). By this model, prismatic peds of the Scott pedotype can be regarded as indications of a seasonally cold climate.

Landscape Paleoecology

Paleosols of the lower Lashly Formation show a consistent occurrence within sedimentary facies and with respect to fossil plant associations, so that a reconstruction of their sedimentary setting and vegetation can be attempted in a manner comparable to landscape ecology (Fig. 12). Within each fining-upward fluvial cycle, channel deposits are followed by levee deposits with Shaun and Michael pedotypes, and then floodplain deposits with Scott and Norman pedotypes. Shaun and Michael paleosols have abundant relict bedding, microtextures that are intertextic and insepic to skelsepic, and few clay skins (Tables 1–4). These are all indications of very weak development, due to a short time of soil formation and plant communities early in ecological succession after disturbance (Retallack 1990). In contrast, Scott and Norman paleosols are more massive and bioturbated, with porphyroskelic and mosepic microtextures, more clay films (Tables 1–4), and evidence of chemical and mineralogical weathering (Fig. 9). Development comparable to that of Norman and Scott pedotypes is found in

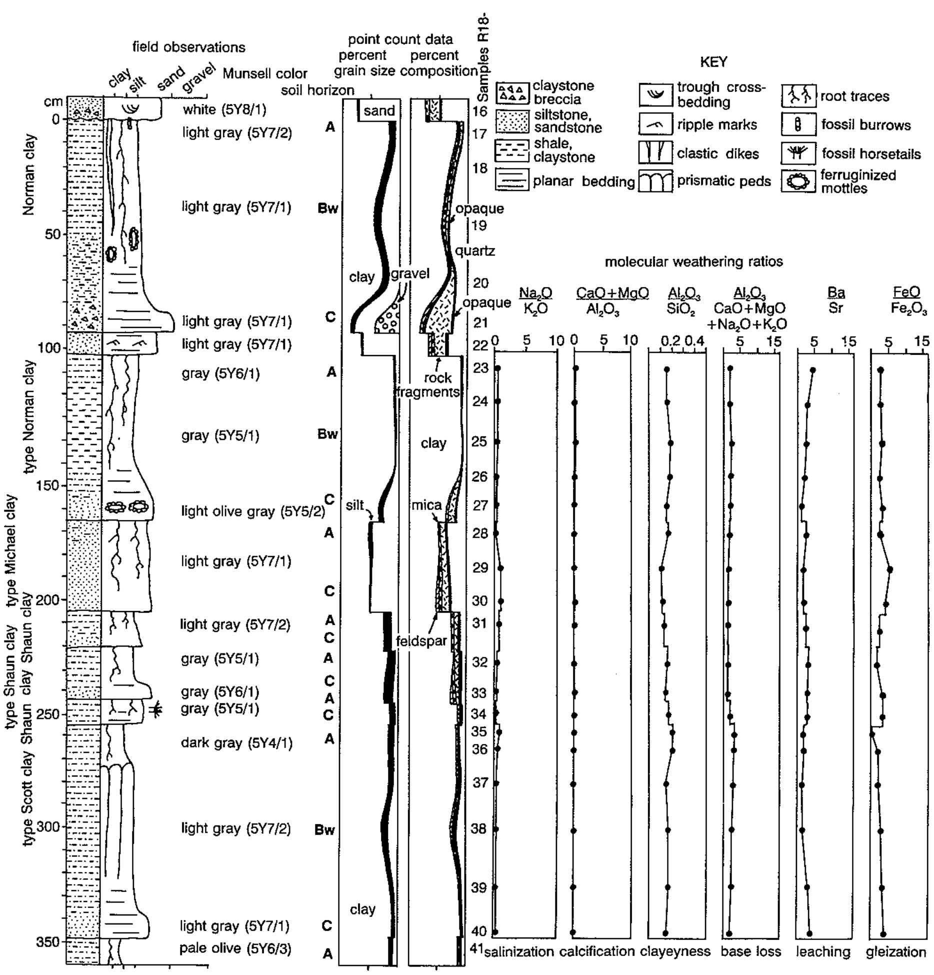

FIG. 8.—Measured section, Munsell colors, soil horizons, grain size, mineral composition, and selected molecular weathering ratios of the type Norman, Michael, Shaun, and Scott pedotypes and other paleosols from 258–263 m in the measured section (Fig. 2) in the Allan Hills, Antarctica.

modern gray soils of the Mississippi Delta, which are some 2000 years old under oak forest (Matthews 1983, 1984). Mississippi soils only 10–100 years old under grass and willow scrub show relict bedding comparable to that of Michael and Shaun pedotypes. Such estimates of duration are typical for comparable soils in a variety of environments (Retallack 1990). Within the braided-stream depositional environment of Zwartz and Woolfe (1996), the very weakly developed soils formed on near-channel sandy bars of crevasse splays and levees (Michael pedotype) and on clay-bottom swales of the levee system (Shaun). The better developed paleosols represent floodplains that were seasonally wet (Norman pedotype) and frozen (Scott).

This depositional landscape and soilscape can be related to three recurring associations of fossil leaves found in the lower Lashly Formation.

1. *Neocalamites carrerei* forms nearly monospecific assemblages in Shaun paleosols (258 m in Figure 2; Allan Hills locality 16, Mt Bastion 31, Portal Mt 2 of Gabites 1985). This herbaceous, marginally aquatic vegetation can be considered a part (synusia) of the *Dicroidietum odontopteroidium xylopterosum* of Retallack (1977c).

2. *Dicroidium odontopteroides* dominates a diverse assemblage of other species of *Dicroidium,* including the xeromorphic *D. elongatum,* with occasional ferns (*Cladophlebis*) and conifers (*Heidiphyllum, Rissikia*; 258 m in section 200 m southwest of line of section, Fig. 2; Allan Hills localities 13, 17, Mt Bastion 32, Portal Mt 1 of Gabites 1985; level 3 of E.L. Taylor et al. 1990). This plant assemblage was found in shale lenses and heterolithic low-angle cross-beds, representing floodplain ponds and levee deposits, respectively. Fossil logs of modest size (up to 8 cm in diameter) were seen within the lower Lashly Formation, and larger stumps and logs have been recorded from the upper Lashly Formation (Gabites 1985). The wood is pycnoxylic with pronounced growth rings, and the *Dicroidium* leaves have petiolar abscission scars, indicating they were deciduous trees (Retallack and Dilcher 1988; Meyer-Berthaud et al. 1992, 1993). This is the *Dicroidietum odontopteroidium xylopterosum* association interpreted as broadleaf woodland and forest (Retallack 1977c, 1978, 1987).

3. *Heidiphyllum elongatum* is found in very low-diversity assemblages, usually within Michael paleosols (Portal Mt 32 of Gabites 1985). The cones of this plant (*Telemachus*) have also been found near the Beardmore Glacier (E.L. Taylor and Taylor 1988), and were woody like those of conifer trees (Retallack 1981; Anderson and Anderson 1983). This *Heidiphylletum* association is interpreted as a colonizing woodland (Retallack 1977c, 1978, 1987).

These plant associations also have paleoclimatic implications, because they are more diverse than would be found in frigid, dry, or salty environments. On the other hand, diversity of communities (3 listed above) and within communities (22 species of Gabites 1995) is lower than would be expected in subtropical or warm temperate regions, even within Middle Triassic Gondwanan fossil floras of New Zealand, Australia, South Africa, and South America (Retallack 1977c, 1987; Anderson and Anderson 1983).

Analogous Modern Soilscapes

Another way of exploring the paleoenvironmental significance of paleosols is to find comparable soilscapes. The assembled petrographic and chemical data on paleosols of the Lashly Formation (Fig. 8) allow classification (Table 9), within the soil taxonomy of the U.S. Soil Conservation Service (Soil Survey Staff 1975, 1990), the soil map of the Food and

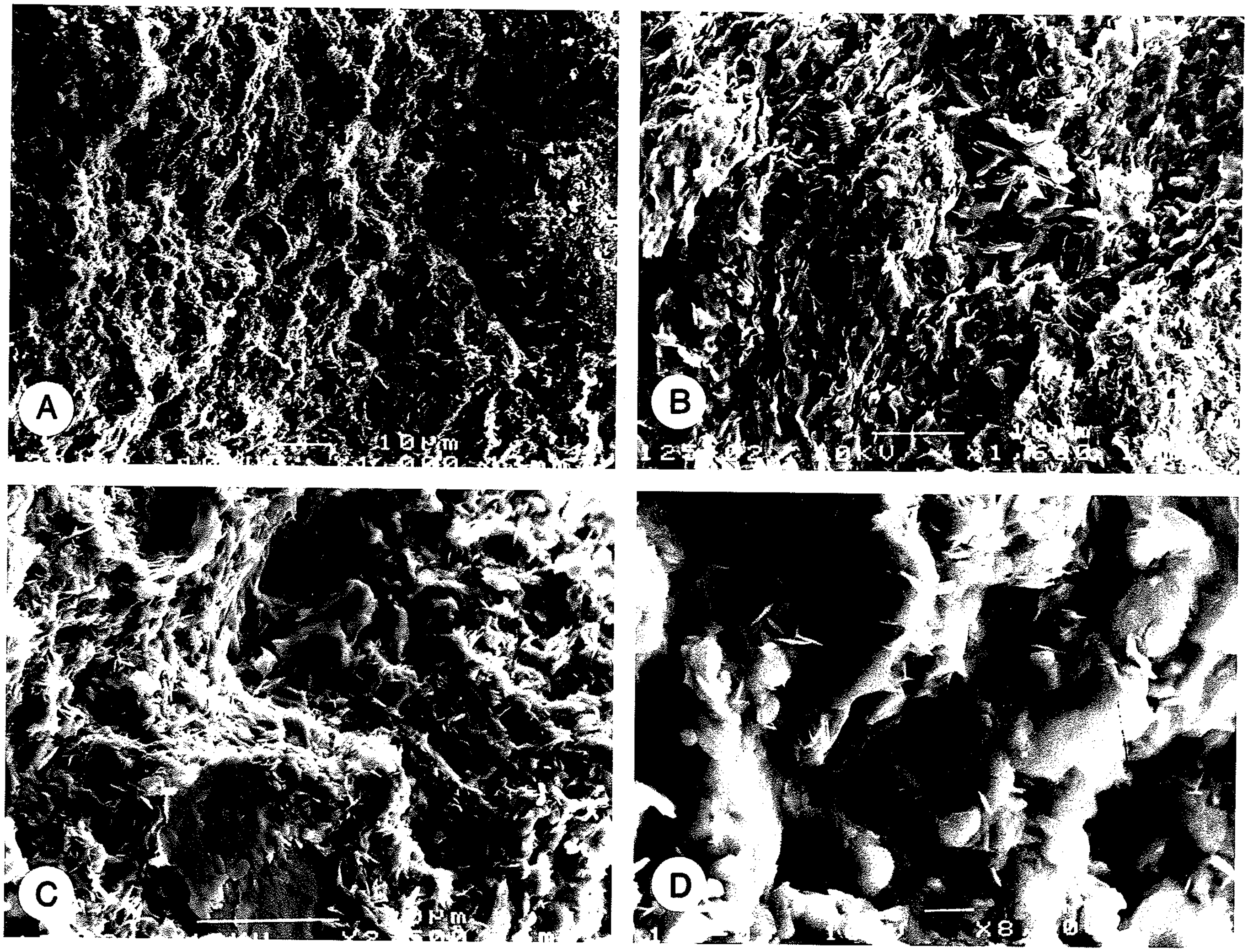

FIG. 9.—Scanning electron micrographs of silt infiltration structures (siltans) and clay skins (argillans) of paleosols in the Lashly Formation, Antarctica: **A)** siltan of coated grains; **B)** narrow skin of coarse clay; **C)** laminated clay skins; **D)** illitic clay of matrix. Specimen number for B is R1838. Others are from R1841.

FIG. 10.—Ridges of microrelief (at arrows) in a Norman paleosol of the Lashly Formation, Antarctica. Scott Robinson is for scale.

Agriculture Organization of UNESCO (FAO 1975, 1978a, 1978b, 1981) and other classifications (Stace et al. 1968; Northcote 1974; Isbell 1993). Shaun and Michael paleosols show minimal development like U.S. Entisols. They are clayey and sandy respectively, and so probably were U.S. Fluvents and Psamments. The greater homogenization but weak development of Norman and Scott pedotypes are most like U.S. Inceptisols. Both Norman and Scott pedotypes lack the prominent mottles and tabular root systems of Aquepts, the plow-features of Plaggepts, and the pervasive oxidation of iron found in Tropepts and Ochrepts. The suborder Umbrept offers a compromise of drab color with evidence of slow drainage. The lack of dispersed organic matter in the paleosols expected for Umbrepts can be attributed to burial gleization (a process described by Retallack 1991a, 1991b). Among Umbrepts the prismatic structures with siltans of the Scott pedotype are most like Fragiumbrepts and the cracking and silt infiltration structures of Norman paleosols are like Xerumbrepts. These are soils of high latitudes and altitudes in the United States, where they form on geomorphic surfaces of Holocene or latest Pleistocene age on glacial sediments. They form largely in humid, seasonally cold regions under coniferous forest. Such soils are common in high mountains of the western states and summer-dry parts of the Pacific Coast (Soil Survey Staff 1975).

The FAO classification is even more useful because its soil maps of the world can be used to identify particular analogous modern soilscapes. In

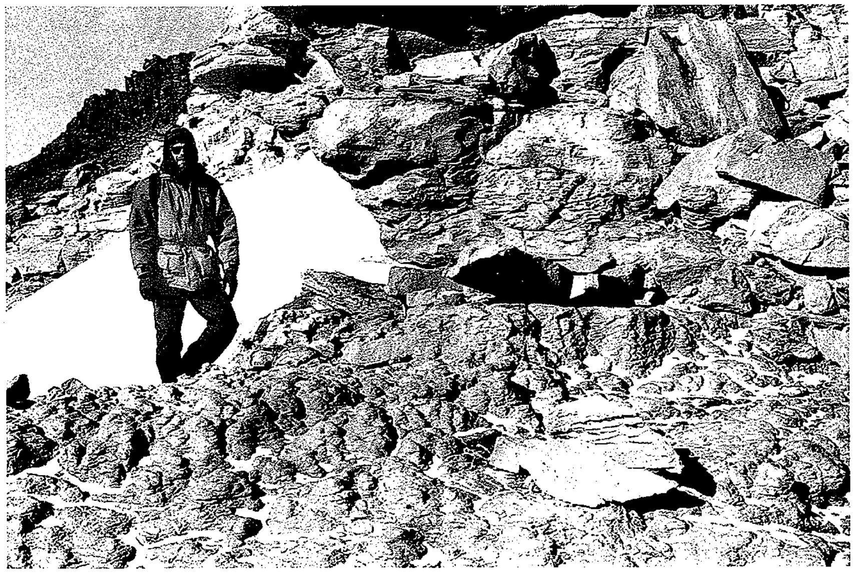

FIG. 11.—Prismatic structure (foreground, below and in front of figure) in Scott pedotype of the Lashly Formation, Antarctica. Scott Robinson is for scale.

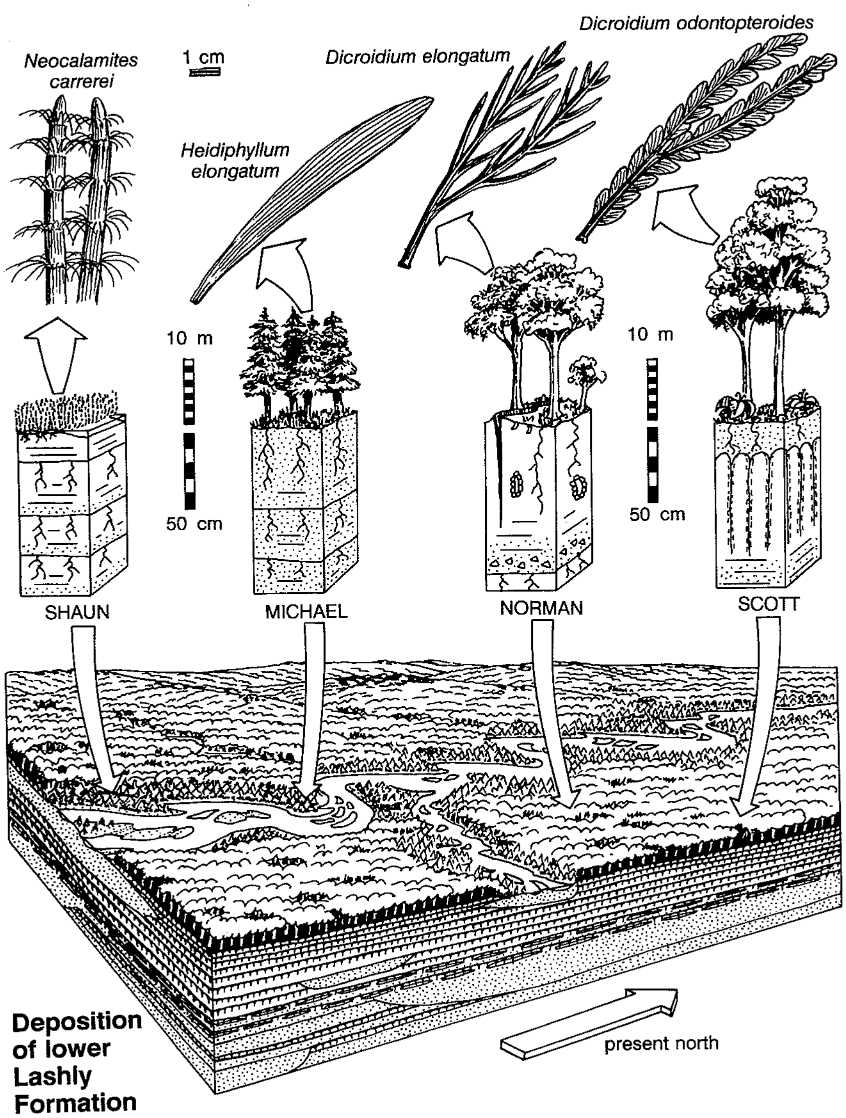

FIG. 12.—Reconstructed paleoenvironment of the lower Lashly Formation of Antarctica during the Middle Triassic. Soils are reconstructed from data presented here, but fossil plants are from Gabites (1985) and sedimentary setting is from Collinson et al. (1994), Zwartz and Woolfe (1996), and Woolfe et al. (1996).

TABLE 9.—*Identification of Triassic paleosols of the lower Lashly Formation.*

Pedotype	Diagnosis	Old Australian (Stace et al. 1968)	New Australian (Isbell 1993)	Northcote Key (Northcote, 1974)	FAO Map (FAO 1974)	U.S. Taxonomy (Soil Survey Staff 1990)
Michael	Green sandstone with root traces	Alluvial soil	Orthic Rudosol	Um1.21	Eutric Fluvisol	Psamment
Norman	Green silty claystone with white root traces and slightly more clayey subsurface (Bw) horizon	Grey clay	Chernic Tenosol	Gn3.91	Vertic Cambisol	Xerumbrept
Shaun	Gray bedded shale with root traces	Alluvial soil	Stratic Rudosol	Uf1.21	Dystric Fluvisol	Fluvent
Scott	Green silty claystone with prismatic peds in subsurface (Bw) horizon	Gray clay	Orthic Tenosol	Gn4.51	Humic Cambisol	Fragiumbrept

this classification Michael and Shaun paleosols are very weakly developed like Fluvisols. Their differing mineral and chemical compositions (Fig. 12) are compatible with interpretation as Eutric Fluvisols and Dystric Fluvisols, respectively. The better developed Norman and Scott paleosols lack diagnostic horizons of most soil orders other than Cambisols and Gleysols. Persistence of ferrous iron and green–gray color are compatible with a Gleysol interpretation, but against it is the general lack of high-chroma mottles, and presence of deeply penetrating root traces, vertic structures, and bleached prismatic peds. The Norman pedotype with its cracking patterns is best identified as a Vertic Cambisol, but could also be regarded as a vertic variant of a Humic Cambisol, an identification most appropriate for the Scott pedotype. Such Cambisols are not common today, but comparable soilscapes can be found around lakes Mälaren and Vänern, and on the coast near Västernik and north of Göteborg, all in southern Sweden (map units Bv 22-2a and Bv 23-2a of FAO 1981). Here they have formed on glacial sediments in a cold to cool temperate, humid climate, under mixed coniferous–deciduous boreal forests around the lakes and Baltic beech forests along the coast. Spruce (*Picea*) and pine (*Pinus*) are dominant on siliceous soils, but the more clayey and nutrient rich soils are covered by deciduous trees including elm (*Ulmus*), linden (*Tilia*), maple (*Acer*), aspen (*Populus*), birch (*Betula*), and hazel (*Corylus*). Also comparable to paleosols of the Lashly Formation are soils in the Wairau River Valley near Blenheim in the South Island of New Zealand (Bh 20-21a of FAO 1978b) and high in the Southern Alps of Australia from Mt Buller to Mt Feathertop in Victoria and Mt Kosciusko to Kiandra in New South Wales (Bh 19-2c of FAO 1978b). These areas also are cold to cool temperate, seasonally snowy and humid. Vegetation in the Australian Alps includes woodland of snow gum (*Eucalyptus pauciflora*), with local heath and alpine grassland, whereas in the northern part of the South Island of New Zealand it is beech forest.

Triassic paleosols of this former Gondwanan continental interior are not like Arctic soils of today, but similar to soils in southern Sweden (latitude 57–60°N), the South Island of New Zealand (latitude 41–42°S), and the southern Alps of Australia (latitude 35–38°S, but elevations of 2000–2500 m). This is puzzling when one considers the likely paleolatitude of the Lashly Formation in the central Transantarctic Mountains today. Recent estimates vary between 69–73°S for 240 Ma: 69°S with the pole offshore from the southern tip of South America (Scotese 1994); 71°S with the pole offshore from the central Transantarctic Mountains (Barrett 1991); and 73°S with the pole in central New South Wales, Australia (Veevers et al. 1994). The equator-to-pole decline in temperature must have been less marked in the Triassic than today.

A PALEOCLIMATIC ANOMALY

During the Middle Triassic the Lashly Formation of southern Victoria Land was at a latitude of 69–73°S (Barrett 1991; Scotese 1994; Veevers et al. 1994) and in the interior of the Gondwana supercontinent. It was some 600 km from the Andean-style Gondwanide fold belt that separated it from the Eopacific Ocean and thousands of kilometers south of subtropical northern Gondwana coasts (Collinson et al. 1994). Parts of Siberia are now similarly placed geographically. For example, the central Lena River between Zigansk and Dzardzan at 68–72°N is about 1200 km inland of the Pacific Ocean behind eastern Siberian fold mountain ranges, 500 km east of the central Siberian uplands, and 500 km south of the Arctic Ocean. The climate of this region is frigid, with a short growing season. At Ust Maistoje there are only five months above freezing, mean annual temperature is −10°C, with summer temperatures of 18°C, winters of −41°C, and mean annual rainfall of 152 mm (Walter et al. 1975). The vegetation of this region is a stunted open woodland (taiga) of larch (*Larix dahurica*), with Siberian pine (*Pinus sibirica*) and scrub alder (*Alnus fruticosa*). The soils include Gelic Cambisols (map unit Bx 4-2a of FAO 1978a) on rolling interfluves, with Eutric Fluvisols (Je 79-2a) in the floodplain of the Lena River. Lena floodplain soils also include Eutric Gleysols and Mollic Gleysols, as well as inclusions of Eutric Histosols. Many of these soils show permafrost features (FAO 1978a), which can be obvious in paleosols (Williams 1986) but were not seen in paleosols of the Lashly Formation. Thus the Middle Triassic paleoclimate of Antarctica was not as frigid as expected from paleogeographic considerations.

Paleoclimatic modeling of Pangea during the Middle Triassic also fails to duplicate conditions indicated by fossil plants and soils of the Lashly Formation of Victoria Land (Table 10). A computer model by Kutzbach

TABLE 10.—*Paleoenvironmental interpretation of Triassic paleosols of the lower Lashly Formation.*

Pedotype	Paleoclimate	Former Vegetation	Former Animals	Paleotopography	Parent Material	Time for Formation
Michael	Not sufficiently developed to be an indicator	Gymnosperms, early in the ecological succession after disturbance	Not known	Sandy bars, levee tops and crevasse splays of ancient rivers	Volcaniclastic sand	5–100 years
Norman	Humid (800–1200 mm mean annual precipitation) seasonally snowy, with summer dry spells, cold temperate	Gymnosperm woodland of open structure: probably deciduous woodlands dominated by *Dicroidium odontopteroides* found in associated pond deposits	Burrowing insects or spiders	Moderately well drained clayey floodplains	Volcaniclastic silt and clay	1000–5000 years
Shaun	Not sufficiently developed to be an indicator	Herbaceous vegetation early in ecological succession around pond and river margins, dominated by horsetails (*Neocalamites*)	Not known	Low lying swales and lakes in levee and floodplain	Volcaniclastic silt and clay	5–100 years
Scott	Humid (800–1200 mm mean annual precipitation) seasonally snowy, with locally frozen ground, cold temperate	Gymnosperm woodland of open structure: probably deciduous woodlands dominated by *Dicroidium odontopteroides* found in associated pond deposits	Not known	Moderately well drained clayey floodplains	Volcaniclastic silt and clay	1000–5000 years

and Gallimore (1989) gave Victoria Land a mean annual range of temperature of 50°C, with summers of 15°C and winters of −35°C, and mean annual precipitation of 300 mm. This frigid dry paleoclimate was at odds with paleontological and sedimentological evidence (Yemane 1993), so future runs explicitly included estimates of greenhouse warming due to atmospheric carbon dioxide. The computer model by Fawcett et al. (1994) used minimal snow cover, high relief (2 km), and elevated carbon dioxide (1000 ppm or three times present), to give winter temperatures in Victoria Land of −30°C and summer temperatures of 25°C. The model by Wilson et al. (1994) used minimal snow cover, moderate relief (1.5 km), and elevated carbon dioxide (1360 ppm, or four times present), to give southern Victoria Land during the early Late Triassic (Carnian) a summer temperature of 20°C, a winter temperature of −45°C, and a solid permafrost zone within the soil. A later model by Kutzbach (1994) used high atmospheric carbon dioxide (1650 ppm or five times modern value), very low topography (500 m), and minimal snow cover to compute that Victoria Land had a mean annual temperature of −5°C, with winter temperatures of −30°C and summer temperature of 25°C, mean annual rainfall of 1100 mm, and mean annual soil moisture of 8 cm. The extreme temperature fluctuation and permafrost conditions seen today in Siberia are unavoidable even when models are run under conditions of high atmospheric carbon dioxide, elevation, and lack of snow that should mitigate such extremes.

Fossil soils discussed here indicate a climate more like that of southern Sweden, the Australian Alps, or New Zealand. For example, Stockholm in southern Sweden has a mean annual temperature of 5.9°C and mean annual precipitation of 569 mm, with only four snow months. Hotham Heights in southeastern Australia has a mean annual temperature of 6.1°C and mean annual rainfall of 1260, with five snow months. Blenheim in New Zealand has a mean annual temperature of 12°C and mean annual rainfall of 645 mm, but only rare snow. These are cool temperate climates in the classification of Walter et al. (1975), not the frigid climate of the Siberian interior. It could be that modeling and paleosol comparisons disagree because of different regimes of cloudiness (Slingo and Slingo 1991), differing Milankovitch orbital forcings (Kutzbach 1994), or the presence of large lakes (Yemane 1993). The models may be profitably rerun with data on soil moisture and ecosystem albedo based on soils analogous to the paleosols reported here.

An overlooked factor that may account for this anomaly is lower primary productivity of vegetation, particularly in wetland habitats. Globally reduced productivity could affect world climate through a higher atmospheric ratio of CO_2/O_2, lower atmospheric water vapor, lower soil moisture, and higher overall albedo. There are several indications of low productivity in the Early and Middle Triassic. During the Middle Triassic only thin coal seams are known in a period of recovery from the Early Triassic, when there was no coal anywhere in the world (Retallack et al. 1996). The Middle Triassic is also a period of recovery of carbon isotopic composition of organic matter in nonmarine basins (Morante et al. 1994; Morante 1996) and in the diversity of plant life following abrupt decimation by extinctions at the Permian–Triassic boundary (Retallack 1995). The nadir of plant productivity and zenith of anomalous polar warmth was probably during the Early Triassic, as indicated by paleosols similar to Luvisols in Australia (Retallack 1977a, 1997a), southern Victoria Land (Retallack et al. 1997a), and the central Transantarctic Mountains (Retallack et al. 1997b). These paleosols indicating anomalous polar warmth can be contrasted with non-anomalous Gelic Histosols at high paleolatitudes in the mid-Permian of Antarctica (Krull and Retallack 1995), Late Permian of New South Wales (Retallack 1997b) and Late Triassic of Tasmania (Smyth 1980). Anomalously warm polar regions with Humic and Vertic Cambisols during the Middle Triassic may be a lingering effect of the early Mesozoic greenhouse (Zeigler et al. 1993). Whatever its cause, the warmer and milder than expected Middle Triassic paleoclimate of Antarctica remains an anomaly that can now be reassessed using paleosols.

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REFERENCES

Anderson, J.M., and Anderson, H.M., 1983, Palaeoflora of southern Africa, Molteno Formation (Triassic) Vol. 1. Introduction. Part 2. *Dicroidium*: Rotterdam, A.A. Balkema, 227 p.

Arbey, F., 1980, Les formes de la silice et l'identification des évaporites dans les formations silicifiés: Centres Recherche Exploration–Produccion Elf Aquitaine, Bulletin, v. 4, p. 309–365.

Bakker, R.T., 1986, The dinosaur heresies: New York, William Morrow, 481 p.

Ballance, P.F., 1977, The Beacon Supergroup in the Allan Hills, central Victoria Land, Antarctica: New Zealand Journal of Geology and Geophysics, v. 20, p. 1003–1016.

Barrett, P.J., 1991, Antarctica and global climatic change: a geological perspective, *in* Harris, C.M., and Stonehouse, B., eds., Antarctica and Global Change: Cambridge, U.K., Scott Polar Institute and Belhaven Press, p. 35–50.

Barrett, P.J., and Fitzgerald, P.G., 1986, Deposition of the lower Feather Conglomerate, a Permian braided river deposit in southern Victoria Land, Antarctica, with notes on paleogeography: Sedimentary Geology, v. 45, p. 199–208.

Birnbaum, S.J., and Wireman, J.W., 1984, Bacterial sulfate reduction and pH: implications for early diagenesis: Chemical Geology, v. 43, p. 143–149.

Birnbaum, S.J., Wireman, J.W., and Borowski, R., 1986, Silica precipitation induced by the anaerobic sulfate producing bacterium *Desulfovibrio desulfuricans*: effects upon cell morphology and implications for preservation, *in* Crick, R.E., ed., Origin, Evolution and Modern Aspects of Biomineralization in Plants and Animals: New York, Plenum Press, p. 507–526.

Brewer, R., 1976, Fabric and Mineral Analysis of Soils, 2nd Edition: New York, Krieger, 482 p.

Buol, S.W., Hole, F.D., and McCracken, R.J., 1980, Soil Genesis and Classification: Ames, Iowa, Iowa University Press, 406 p.

Bustillo, M.A., 1976, Texturas de las rocas silíceas inorgánicas en ambiente continental y significado genético: Estudios Geológicos, v. 22, p. 371–383.

Caudill, M.R., and Driese, S.G., 1996, Burial diagenesis in vertic paleosols: physical compaction and implications for paleo-precipitation estimates (abstract): Geological Society of America, Annual Meeting, Abstracts, v. 28(7), p. A472.

Chatterjee, S., Borns, H.W., and Hotton, N., 1983, Gondwana rocks of the Allan Hills: U.S. Antarctic Journal, v. 78 (5), p. 21–24.

Chen, P.-Y., 1977, Table of key lines in x-ray powder diffraction patterns of minerals in clays and associated rocks: Indiana Geological Survey, Occasional Paper 21, 67 p.

Ciolkosz, E.J., Peterson, G.W., Cunningham, R.L., and Matelski, R.P., 1979, Soils developed from colluvium in the Ridge and Valley area of Pennsylvania: Soil Science, v. 128, p. 153–162.

Ciolkosz, E.J., Waltman, W.J., Simpson, T.W., and Dobos, R.R., 1989, Distribution and genesis of soils of the northeastern United States: Geomorphology, v. 2, p. 285–302.

Coates, D.A., Stricker, G.D., and Landis, E.R., 1990, Coal geology, coal quality, and coal resources in Permian rocks of the Beacon Supergroup, Transantarctic Mountains, Antarctica, *in* Spletstoesser, J.F., and Dreschoff, G.A.M., eds., Mineral Resources Potential of Antarctica: American Geophysical Union, Antarctic Research Series, v. 51, p. 133–162.

Collinson, J.W., 1990, Depositional setting of Late Carboniferous to Triassic biota in the Transantarctic Basin, *in* Taylor, T.N., and Taylor, E.L., eds., Antarctic Paleobiology: New York, Springer-Verlag, p. 1–13.

Collinson, J.W., Isbell, J.L., Elliot, D.H., Miller, M.F., and Miller, J.M.G., 1994, Permian–Triassic Transantarctic Basin, *in* Veevers, J.J., and Powell, C. Mc.A., eds., Permian–Triassic Pangean Basins and Foldbelts along the Panthalassan Margin of Gondwanaland: Geological Society of America, Memoir 184, p. 173–222.

Collinson, J.W., Pennington, D.C., and Kemp, N.R., 1983, Sedimentary petrology of Permian–Triassic fluvial rocks in the Allan Hills, central Victoria Land: U.S. Antarctic Journal, v. 18, p. 20–22.

Creber, C.T., 1990, The South Polar forest ecosystem, *in* Taylor, T.N., and Taylor, E.L., eds., Antarctic Paleobiology: New York, Springer-Verlag, p. 37–41.

Eberl, D.D., Srodon, J., Kralik, M., Taylor, B.E., and Peterman, Z.E., 1990, Ostwald ripening of clays and metamorphic minerals: Science, v. 248, p. 474–477.

FAO (Food and Agriculture Organization), 1975, Soil Map of the World. vol. I, Legend: Paris, UNESCO, 59 p.

FAO (Food and Agriculture Organization), 1978a, Soil Map of the World. vol. VIII, North and Central Asia: Paris, UNESCO, 165 p.

FAO (Food and Agriculture Organization), 1978b, Soil Map of the World. vol. X, Australasia: Paris, UNESCO, 221 p.

FAO (Food and Agriculture Organization), 1981, Soil Map of the World. vol. V, Europe: Paris, UNESCO, 199 p.

Fawcett, P.J., Barron, E.J., Robison, V.D., and Katz, B.J., 1994, The climatic evolution of India and Australia from the Late Permian to mid-Jurassic: a comparison of climate model results with the geologic record, *in* Klein, G.D., ed., Pangea: Paleoclimate, Tectonics, and Sedimentation during Accretion, Zenith, and Breakup of a Supercontinent: Geological Society of America, Special Paper 288, p. 139–157.

Flores-Roman, D., Alcala-Martinez, J.R., Gonzalez-Velazquez, C., and Cama-Castro, J.E., 1992, Suelos con fragipán de origen volcánico en clima semicálido y subhumedo—el caso del noreste del Estado de Moreles, México: Universidad Nacional Autonoma de México, Instituto de Geología, Revista, v. 10(2), p. 151–163.

Folk, R., and Pittman, S., 1971, Length-slow chalcedony: a new testament for vanished evaporites: Journal of Sedimentary Petrology, v. 41, p. 1045–1058.
Frey, M., 1987, Very low grade metamorphism of clastic sedimentary rocks, *in* Frey, M., Low Temperature Metamorphism: Glasgow, Blackie, p. 9–58.
Gabites, H.I., 1985, Triassic paleoecology of the Lashly Formation, Transantarctic Mountains, Antarctica [unpublished MSc thesis]: Victoria University of Wellington, 141 p.
Hall, G.F., Daniels, R.B., and Foss, J.E., 1982, Rate of soil formation and renewal in the U.S.A, *in* Schmidt, B.L., ed., Determinants of Soil Loss Tolerance: American Society of Agronomy, Special Publication 45, p. 23–39.
Hammer, W.R., 1990, Triassic terrestrial vertebrate faunas of Antarctica, *in* Taylor, T.N., and Taylor, E.L., eds., Antarctic Paleobiology: New York, Springer-Verlag, p. 42–50.
Hammer, W.R., Collinson, J.W., and Ryan, W.J., 1990, A new Triassic vertebrate fauna from Antarctica and its depositional setting: Antarctic Science, v. 2, p. 163–167.
Hammer, W.R., and Zawiskie, J.M., 1982, Beacon fossils from northern Victoria Land: U.S. Antarctic Journal, v. 17, p. 13–15.
Heer, O., 1868, Die fossile Flora der Polarländer enthaltend die in Nordgrönland, auf der Melville-Insel, im Banksland, am Mackenzie, in Island und in Spetzbergen entdecken fossilen Pflanzen: Flora Fossilis Arcticis, Zurich, v. 1, 192 p.
Horner, T.C., and Krissek, L.A., 1991, Permian and Triassic paleosols from the Beardmore Glacier region, Antarctica: U.S. Antarctic Journal, v. 26, p. 7–8.
Holzhey, C.S., Yeck, R.D., and Nettleton, W.D., 1974, Microfabric of some argillic horizons in udic, xeric and torric soil environments of the United States, *in* Rutherford, G.K., ed., Soil Microscopy: Kingston, Ontario, Limestone Press, p. 747–760.
Isbell, R.F., 1993, A classification system for Australian soils: Commonwealth Scientific and Industrial Research Organization (CSIRO), Division of Soils, Technical Report 2/1993, 92 p.
Jenik, J., 1978, Roots and root systems in tropical trees: morphologic and ecological aspects, *in* Tomlinson, P.B., and Zimmerman, M.H., eds., Tropical Trees as Living Systems: Cambridge, U.K., Cambridge University Press, p. 323–349.
Jensen, A.R., 1975, Permo-Triassic stratigraphy and sedimentation in the Bowen Basin, Queensland: Australia, Bureau of Mineral Resources, Bulletin 154, 187 p.
Korsch, J.J., 1984, Petrographic comparison of the Taylor and Victoria Groups (Devonian and Triassic) in South Victoria Land, Antarctica: New Zealand Journal of Geology and Geophysics, v. 17, p. 523–541.
Krishna, P.C., and Perumal, S., 1948, Structure in black cotton soils of the Nizamsagar Project area, Hyderabad state, India: Soil Science, v. 66, p. 29–38.
Krull, E.S., and Retallack, G.J., 1995, Clastic dikes as evidence for discontinuous permafrost paleoclimate in Permian coal measures, Allan Hills, Antarctica (abstract): Geological Society of America, Abstracts, v. 27(8), p. A265.
Kutzbach, J., 1994, Idealized Pangean climates: sensitivity to orbital change, *in* Klein, G.deV., ed., Pangea: Paleoclimate, Tectonics, and Sedimentation during Accretion, Zenith, and Breakup of a Supercontinent: Geological Society of America, Special Paper 288, p. 41–55.
Kutzbach, J., and Gallimore, R.G., 1989, Pangean climates: megamonsoons of the megacontinent: Journal of Geophysical Research, v. 94, p. 3341–3357.
Kyle, R.A., 1977, Palynostratigraphy of the Victoria Group of South Victoria Land, Antarctica: New Zealand Journal of Geology and Geophysics, v. 20, p. 1081–1102.
Kyle, R.A., and Schopf, J.M., 1982, Permian and Triassic stratigraphy of the Victoria Group, Transantarctic Mountains, *in* Craddock, C., ed., Antarctic Geoscience: Madison, Wisconsin, University of Wisconsin Press, p. 649–659.
Lindbo, D.L., and Veneman, P.L.M., 1989, Fragipans in the northeastern United States, *in* Smeck, N.E., and Ciolkosc, E.J., eds., Fragipans: Their Occurrence, Classification, and Genesis: Soil Science Society of America, Special Publication 24, p. 11–31.
MacFayden, W.A., 1950, Sandy gypsum crystals from Berbera, British Somaliland: Geological Magazine, v. 87, p. 409–420.
Maglione, G., 1981, An example of recent continental sedimentation: the Chadian Basin (Africa), *in* Busson, G., ed., Evaporite Deposits: Houston, Texas, Gulf Oil Co., p. 5–9.
Marbut, C.F., 1935, Atlas of American agriculture. Part III. Soils of the United States: Washington D.C., U.S. Government Printing Office, 98 p.
Markwick, P., 1994, "Equability", continentality, and Tertiary "climate": the crocodilian perspective: Geology, v. 22, p. 613–616.
Matthews, S.D., 1983, Soil Survey of Jefferson Parish, Louisiana: U.S. Soil Conservation Service, Soil Survey, v. 24, 15 p.
Matthews, S.D., 1984, Soil Survey of Lafourche Parish, Louisiana: U.S. Soil Conservation Service, Soil Survey, v. 25, 106 p.
McCahon, T.J., and Miller, K.B., 1996, Climatic significance of natric horizons in Permian (Asselian) paleosols of north central Kansas, U.S.A.: Sedimentology, v. 43. p. 113–125.
Meyer, R., 1983, Fixacion de la silice dans les environnements continenteaux: Centres Recherche Exploration–Production Elf Aquitaine, Bulletin, v. 8, p. 195–207.
Meyer-Berthaud, B., Taylor, E.L., and Taylor, T.N., 1992, Reconstructing the Gondwana seed fern *Dicroidium*: evidence from the Triassic of Antarctica: Geobios, v. 25, p. 341–344.
Meyer-Berthaud, B., Taylor, T.N., and Taylor, E.L., 1993, Petrified stems bearing *Dicroidium* leaves from the Triassic of Antarctica: Palaeontology, v. 36, p. 337–356.
Morante, R., 1996, Permian and Triassic isotopic records of carbon and strontium in Australia and a scenario of events about the Permian–Triassic boundary: Historical Biology, v. 11, p. 289–310.
Morante, R., Veevers, J.J., Andrew, A.S., and Hamilton, P.J., 1994, Determination of the Permian–Triassic boundary in Australia from carbon isotope stratigraphy: Australian Petroleum Exploration Association, Journal, v. 34, p. 330–336.
Murphy, C.P., 1983, Point-counting pores and illuvial clay in thin section: Geoderma, v. 31, p. 133–150.
Nettleton, W.D., McCracken, R.J., and Daniels, R.B., 1968, Two North Carolina coastal plain catenas. II. Micromorphology, composition, and fragipan genesis: Soil Science Society of America, Proceedings, v. 32, p. 582–587.
Nickel, E.H., and Nichols, M.C., 1991, Mineral Reference Manual: New York, Van Nostrand, 250 p.
Northcote, K.H., 1974, A Factual Key for the Recognition of Australian Soils: Adelaide, Rellim, 123 p.
Paton, T.R., 1974, Origin and terminology for gilgai in Australia: Geoderma, v. 11, p. 221–242.
Pyne, A.R., 1984, Geology of the Mt Fleming area, south Victoria Land, Antarctica: New Zealand Journal of Geology and Geophysics, v. 27, p. 505–512.
Ready, C.D., and Retallack, G.J., 1995, Chemical composition as a guide to paleoclimate of paleosols (abstract): Geological Society of America, Abstracts, v. 27, p. A237.
Retallack, G.J., 1977a, Triassic palaeosols of the upper Narrabeen Group of New South Wales. Part 1. Features of the palaeosols: Geological Society of Australia, Journal, v. 23, p. 383–397.
Retallack, G.J., 1977b, Triassic palaeosols in the upper Narrabeen Group of New South Wales. Part II. Classification and reconstruction: Geological Society of Australia, Journal, v. 24, p. 19–35.
Retallack, G.J., 1977c, Reconstructing Triassic vegetation of eastern Australasia: a new approach for the biostratigraphy of Gondwanaland: Alcheringa, v. 1, p. 247–277.
Retallack, G.J., 1978, Floral ecostratigraphy in practice: Lethaia, v. 11, p. 81–83.
Retallack, G.J., 1981, Middle Triassic megafossil plants from Long Gully, near Otematata, North Otago, New Zealand: Royal Society of New Zealand, Journal, v. 11, p. 167–200.
Retallack, G.J., 1987, Triassic vegetation and geography of the New Zealand portion of the Gondwana supercontinent, *in* McKenzie, G.D., ed., Gondwana Six: Stratigraphy and Paleontology: American Geophysical Union, Geophysical Monograph 41, p. 29–39.
Retallack, G.J., 1988, Field recognition of paleosols, *in* Reinhardt, J., and Sigleo, W.R., eds., Paleosols and Weathering through Geologic Time: Principles and Applications: Geological Society of America, Special Paper 216, p. 1–20.
Retallack, G.J., 1990, Soils of the Past: London, Unwin–Hyman, 521 p.
Retallack, G.J., 1991a, Miocene Paleosols and Ape Habitats in Pakistan and Kenya: New York, Oxford University Press, 246 p.
Retallack, G.J., 1991b, Untangling the effects of burial alteration and ancient soil formation: Annual Review of Earth and Planetary Sciences, v. 19, p. 183–206.
Retallack, G.J., 1994, A pedotype approach to latest Cretaceous and earliest Tertiary paleosols in eastern Montana: Geological Society of America, Bulletin, v. 106, p. 1377–1397.
Retallack, G.J., 1995, Permian–Triassic extinction on land: Science, v. 267, p. 77–80.
Retallack, G.J., 1997a, Palaeosols in the upper Narrabeen Group of New South Wales as evidence of Early Triassic palaeoenvironments without modern analogue: Australian Journal of Earth Sciences, v. 44, p. 185–201.
Retallack, G.J., 1997b, Post-apocalyptic greenhouse paleoclimate revealed by earliest Triassic paleosols of the Sydney Basin, Australia: Geological Society of America, Bulletin, in press.
Retallack, G.J., and Dilcher, D.L., 1988, Reconstructions of selected seed ferns: Missouri Botanical Garden, Annals, v. 75, p. 1010–1057.
Retallack, G.J., Krull, E.S., and Robinson, S.E., 1997a, Permian and Triassic paleosols and paleoenvironments of southern Victoria Land, Antarctica: U.S. Antarctic Journal, in press.
Retallack, G.J., Krull, E.S., and Robinson, S.E., 1997b, Permian and Triassic paleosols and paleoenvironments of the central Transantarctic Mountains, Antarctica: U.S. Antarctic Journal, in press.
Retallack, G.J., Renne, P.R., and Kimbrough, D.L., 1993, New radiometric ages for Triassic floras of southeast Gondwana, *in* Lucas, S.G., and Morales, P., eds., The Non-Marine Triassic: New Mexico Museum of Natural History and Science, Bulletin, v. 3, p. 415–418.
Retallack, G.J., Veevers, J.J., and Morante, R., 1996, Global coal gap between Permian–Triassic extinction and Middle Triassic recovery of peat-forming plants: Geological Society of America, Bulletin, v. 108, p. 195–207.
Sclater, J.G., and Christie, J.A.F., 1980, Continental stretching: an explanation of the post-mid-Cretaceous subsidence of the North Sea Basin: Journal of Geophysical Research, v. 85, p. 3711–3739.
Scotese, C.R., 1994, Early and Late Triassic palaeogeographic maps, *in* Klein, G. deV., ed., Pangea: Paleoclimate, Tectonics, and Sedimentation during Accretion, Zenith, and Breakup of a Supercontinent: Geological Society of America, Special Paper 288, p. 7.
Seward, A.C., 1914, Antarctic fossil plants: Natural History Reports in Geology of the British Antarctic Expedition (Terra Nova), v. 1, p. 1–49.
Slingo, A., and Slingo, J., 1991, Response of the National Center for Atmospheric Research Community Climate Model to improvements in the representation of clouds: Journal of Geophysical Research, v. 96, p. 15,341–15,357.
Smyth, M., 1980, Coal encounters of the third kind: Triassic: Australian Coal Geology, v. 2, p. 161–177.
Soil Survey Staff, 1975, Soil Taxonomy: U.S. Department of Agriculture, Handbook 436, 754 p.
Soil Survey Staff, 1990, Keys to Soil Taxonomy: Soil Management Support Services, Blacksburg, Virginia, Technical Monograph 19, 422 p.
Stace, H.C.T., Hubble, G.D., Brewer, R., Northcote, K.H., Sleeman, J.R., Mulcahy, M.J., and Hallsworth, E.G., 1968, A Handbook of Australian Soils: Adelaide, Rellim, 435 p.
Steele, F., Daniels, R.B., Gamble, E.E., and Nelson, L.A., 1969, Fragipan horizons and Be masses in the middle Coastal Plain of north central North Carolina: Soil Science Society of America, Proceedings, v. 33, p. 752–755.
Taylor, E.L., and Taylor, T.N., 1988, Late Triassic flora from Mount Falla, Queen Alexandra Range: U.S. Antarctic Journal, v. 23(5), p. 2–3.
Taylor, E.L., and Taylor, T.N., 1993, Fossil tree rings and paleoclimate from the Triassic of Antarctica, *in* Lucas, S.G., and Morales, M., eds., The Non-Marine Triassic: New Mexico Museum of Natural History and Science, Bulletin 3, p. 453–455.
Taylor, E.L., Taylor, T.N., and Collinson, J.W., 1989, Depositional setting and paleobotany

of Permian and Triassic permineralized peat from the central Transantarctic Mountains, Antarctica: International Journal of Coal Geology, v. 12, p. 657–679.
Taylor, E.L., Taylor, T.N., and Cuneo, N.R., 1992, The present is not the key to the past: a polar forest from the Permian of Antarctica: Science, v. 257, p. 1675–1677.
Taylor, E.L., Taylor, T.N., Meyer-Berthaud, B., and Isbell, J.L., 1990, A late Triassic flora from the Allan Hills, southern Victoria Land: U.S. Antarctic Journal, v. 25, p. 20–21.
Taylor, T.N., Taylor, E.L., and Del Fueyo, G., 1993, Permineralized Triassic plants from Antarctica, *in* Lucas, S.G., and Morales, M., eds., The Non-Marine Triassic: New Mexico Museum of Natural History and Science, Bulletin 3, p. 457–460.
Taylor, T.N., Taylor, E.L., Meyer-Berthaud, B., Isbell, J.L., and Cuneo, N.R., 1990, Triassic osmundaceous ferns from the Allan Hills, southern Victoria Land: U.S. Antarctic Journal, v. 25, p. 18–19.
Townrow, J.A., 1967, Fossil plants from Allan and Carapace Nunataks and from the upper Mill and Shackleton Glaciers, Antarctica: New Zealand Journal of Geology and Geophysics, v. 10, p. 456–473.
Veevers, J.J., 1989, Middle/Late Triassic (230 ± 5 Ma) singularity in the stratigraphic and magnetic history of the Pangean heat anomaly: Geology, v. 17, p. 784–787.
Veevers, J.J., Powell, C.McA., Collinson, J.W., and Lopez-Gamundi, O.R., 1994, Synthesis, *in* Veevers, J.J., and Powell, C.McA., eds., Permian–Triassic Pangean Basins and Foldbelts along the Panthalassan Margin of Gondwanaland: Geological Society of America, Memoir 184, p. 331–353.
Walter, H., Harnickell, E., and Mueller-Dombois, D., 1975, Climate-Diagram Maps of the Individual Continents and the Ecological Climatic Regions of the Earth: Berlin, Springer-Verlag, 26 p.
Weaver, J.E., 1919, The ecological relations of roots: Carnegie Institute of Washington, Publication 286, 128 p.
Williams, G.E., 1986, Precambrian permafrost horizons as indicators of palaeoclimate: Precambrian Research, v. 32, p. 233–242.
Wilson, K.M., Pollard, D., Hay, W.W., Thompson, S.L., and Wold, C.N., 1994, General circulation model simulations of Triassic climates: preliminary results, *in* Klein, G.deV., ed., Pangea: Paleoclimate, Tectonics, and Sedimentation during Accretion, Zenith, and Breakup of a Supercontinent: Geological Society of America, Special Paper 288, p. 91–116.
Woolfe, K.J., Arnot, M.J., Barrett, P.J., and Francis, J.E., 1996, Geology of the Allan Hills, southern Victoria Land, Antarctica—with special reference to the Beacon Supergroup: New Zealand Journal of Geology and Geophysics, in press.
Yemane, K., 1993, Contribution of a Late Permian palaeogeography in maintaining a temperate climate in Gondwana: Nature, v. 361, p. 51–54.
Ziegler, A.M., Parrish, J.M., Yao, J.-P. Gyllenhaal, E.C., Rowley, D.B., Parrish, J.T., Nie, S.-Y., Bekker, A., and Hulver, M.L., 1993, Early Mesozoic phytogeography and climate: Royal Society [London], Philosophical Transactions, v. B341, p. 297–305.
Zwartz, D.P., and Woolfe, K.J., 1996, Superimposed litho- and pedo-facies in a fluvial–lacustrine sequence: Sedimentary Geology, in press.

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