THE HOLOCENE EVOLUTION OF RHEBAN SPIT, TASMANIA
2. SOIL DEVELOPMENT TRENDS

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(with two tables and nine text-figures)

Calcareous sands and podzols of four different ages (0, 3 100, 4 200 and 5 500 calendar years) form a soil chronosequence at Rheban Spit, a prograded sand barrier, near Orford on the east coast of Tasmania. In terms of profile morphology the soils range from undifferentiated quartz sand with shell at the youngest site, to a well-developed podzol with prominent A_1, A_2 and B horizons at the oldest site. Age trends are derived for a number of soil features, the most significant of which are the leaching from the sediments of detrital marine shell carbonate, the increase in organic matter content in the A and B horizons, the decrease in profile pH, the progressive development of A_2 and B horizons in terms of acid-extractable iron and aluminium, the increase in thickness of the B horizon and the decrease in the average concentration of cations in the profiles. Most of these age trends are in accord with those derived from soil chronosequences in New South Wales and overseas, but some are markedly different.

Key Words: Rheban Spit, Tasmania, soil chronosequence, podzols, soil age trends, soil classification, Factual Key.

INTRODUCTION

Podzol soil profiles are extensively developed in quartzose sandy deposits along the eastern coast of Australia. Early studies at Woy Woy, New South Wales (Burges & Drover 1953), first identified the potential of these coastal podzols for soil chronosequence investigations (studies of the rate and mode of soil development). However, more systematic investigations of this type have been carried out only relatively recently: Bowman (1979, 1987) concentrated on Holocene sand barrier podzols in New South Wales, while Thompson (1981, 1983) and co-workers studied Holocene and Pleistocene podzols in the dune sands of south-eastern Queensland.

The progressive increase in age across a Holocene beach-ridge plain provides an ideal spatio-temporal framework for soil chronosequence studies (Bowman 1986a). In such situations, the "time factor" in pedogenesis (Jenny 1941) can be quantified by radiocarbon dating comminuted marine shell deposited with the sediments. The uniformity of the quartzose sands which form the coastal barriers of eastern Australia minimizes complications due to differences in the "parent material" pedogenic factor (Jenny 1946, Bowman 1979). Similarly, the simple ridge/swale morphology of most prograded sand barriers (Thom *et al.* 1978) allows the "relief factor" to be effectively negated by confining the study to one topographic position, i.e. either ridge crest or mid-swale (Thompson & Bowman 1984). Vegetation zonation and succession on these barriers have been documented (e.g. McDonald 1971, 1973, Osborn & Robertson 1939, Pidgeon 1940), allowing the "plant factor" to be assessed without many of the conceptual and practical problems envisaged by soil chronosequence theoreticians (Crocker 1952, Jenny 1958, Olson 1958). In addition, the mild coastal climate of eastern Australia is relatively uniform and unlikely to have changed significantly during the last 7 000 years.

This paper expands the literature on eastern Australian podzols by documenting the characteristics and pedogenic development of a soil chronosequence in eastern Tasmania, an area in which such an investigation had not been undertaken previously.

ENVIRONMENTAL SETTING

The study was carried out on Rheban Spit, a small prograded sand barrier on the eastern coast of Tasmania, in the lee of Maria Island. A complementary paper (Bowman 1986) describes the physical setting, Holocene age structure, geomorphic evolution and sediment characteristics of Rheban Spit, thereby providing the first dated soil chronosequence in Tasmania and pedogenic background data for the present study.
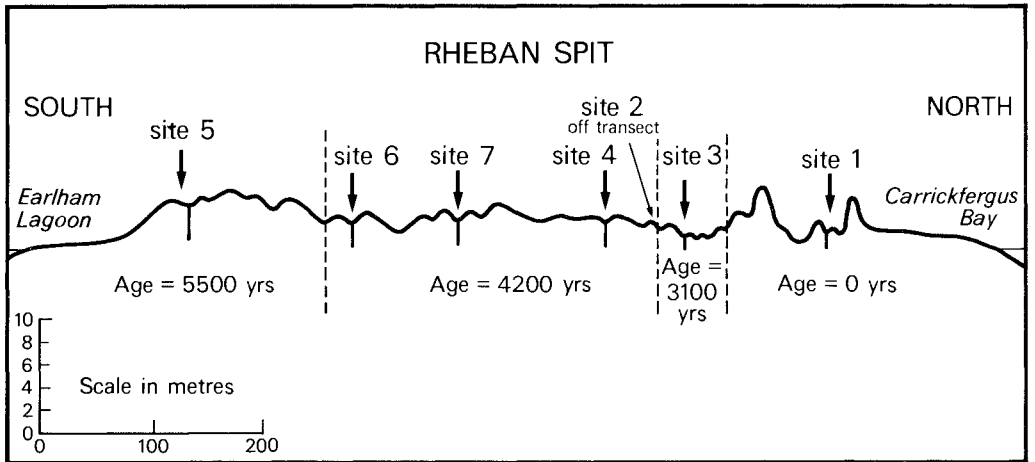
FIG.1 — Cross-section of Rheban Spit showing soil sampling sites 1 to 7 and rounded calendar ages assigned to each (after Bowman 1986).

Monthly rainfall and rainday figures (table 1) are based on observations at Rheban Farm but the temperature and humidity values relate to Orford, which is located about 10 km north of Rheban Spit. These data show that the area experiences mild summers and cool to cold winters, with a moderate rainfall that is very evenly distributed throughout the year.

The vegetation of Rheban Spit has been described in some detail (Bowden & Kirkpatrick 1974) as an open forest of *Eucalyptus globulus*, *E. viminalis* and *Acacia dealbata* on the uncleared beach-ridge plain, whereas the frontal dunes (where vegetated) carry associations dominated by *Banksia marginata*, *Ammophila arenaria*, *Pteridium esculentum* and various low herbs.

Rheban Spit is composed of well-sorted, fine-to medium-grained, quartzose sand of marine origin. Apart from the sand of the youngest foredunes, which has slightly different characteristics from that of the other depositional units at Rheban, the sediments provide a uniform parent material for soil development. There is only slight variation in mineralogy and granulometry both within and between depositional units (Bowman 1986, tables 3 and 4).

TABLE 1

Climatic data for Rheban Farm and Orford, Tasmania.
Source: Bureau of Meteorology (1975).

	J	F	M	A	M	J	J	A	S	O	N	D	Yr
Rheban Farm													
Av. rainfall, mm	48	58	47	47	62	64	52	53	41	55	56	67	650
Median rainfall, mm	42	42	41	37	47	46	46	40	37	49	39	59	590
Av. raindays	9	8	9	9	10	11	11	12	11	11	11	10	122
Orford													
Av. daily max. temp., °C	22.1	22.5	21.3	19.6	15.9	13.6	13.8	14.1	15.8	17.8	18.3	20.1	17.9
Av. daily min. temp., °C	11.2	12.3	10.0	8.3	5.6	3.0	2.5	3.5	4.4	6.1	8.4	9.4	7.1
Av. daily rel. humidity, %	61	64	56	64	74	79	78	74	61	59	63	59	66

METHODS

Field Sampling

The seven sites used previously for strati-graphic and sedimentologic analyses (Bowman 1986) were used in the present soil investigation. Six of these were located on the transect line established across the eastern end of the spit by Bowden & Kirkpatrick (1974) and an additional site was located so as to sample adequately one of the progradational units. The rounded calendar age (in years b.p.) assigned to each sampling site in Part 1 of this paper is here assumed to represent soil age, i.e. the elapsed time since the initiation of soil development at that site (Bowman 1987). Hence, the ages assigned to the soil profiles at Sites 1 to 7 are 0, 4 200, 3 100, 4 200, 5 500, 4 200 and 4 200 years, respectively (fig. 1). The identical age of 4 200 years for Sites 2, 4, 6 and 7 reduces the number of time-dependent soil profiles in the Rheban chronosequence but still allows the use of profiles of four different ages.

At each site pits were used for description and sampling (at 0.04, 0.15 and 0.3 m of the upper part of the soil profile) and auger samples were taken at 0.3 m intervals from the pit floor to the water table. Selected samples were also taken to represent adequately the A_1, A_2 and B horizons. The pedological features of each soil profile were recorded inluding the thickness, lower boundary configuration, structure and dominant colour (Munsell notation) of each horizon.

Laboratory Analyses

In the laboratory, pH was measured in a 1:5 water suspension and 10% hydrochloric acid was used to test for the presence of marine shell carbonate (deposited with the quartzose marine sediments). Total organic matter content of the <4 mm fraction was measured by weight loss following low temperature ignition of 2 g sub-samples, previously oven-dried at 105°C for 24 hours (*inter alios* Mitchell 1932). This technique is sufficiently accurate, given the absence of clay minerals in these arenaceous sediments and the furnace temperature being raised to 450°C, but no higher (Ball 1964). The ashed samples were then digested in hydrochloric acid for 18 hours at 90-95°C, using cold finger condensors to minimise evaporation. The resulting digests were filtered, made up to constant volume and the concentrations of six elements were determined by atomic absorp-tion spectroscopy.

RESULTS

Soil Profile Morphology

The morphology of the Rheban soils ranges from undifferentiated sand at Site 1, to moderately well-developed podzol profiles towards the land-ward side of the Spit (Bowman 1986, fig. 2). Selected morphological features of the Rheban profiles are given in table 2, together with infor-mation on shell carbonate occurrence and sample pH. The following general trends may be observed in the data.

A_0, A_1, A_2, B and C horizons are present in all the Rheban profiles, except at Site 1, where no horizon differentiation could be detected. With the exception of this site, the thickness of the A_0 and A_1 horizons is consistent across all the sites, but the A_2 and B horizons are of variable thickness, both in absolute terms and in the proportion of total profile depth. Except for the lower boundary of the A_1 horizon at Site 3 (classified as "sharp even": Northcote 1979), all other horizon boundaries are "gradational even".

Dominant horizon colours are mostly 10YR hue, but include some 2.5Y (Munsell Soil Color Charts 1975). Value/chroma ratings for the A_1 horizons all fall in the VC2 group (Northcote 1979), whereas the A_2 horizon ratings are in groups 2 and 3. Although B horizon dominant colours are well clustered, they overlap three value/chroma groups (VC2, 3 and 4).

The field-determined texture of all soil hori-zons was "sand" and all had "sandy" fabric (Northcote 1979). Parts of the B horizon at Sites 2, 4, 5, 6 and 7 had an "apedal massive" and weakly coherent structure but the remainder of these profiles and the entire soil profile at Sites 1 and 3 had "apedal single grain" structure (Northcote 1979).

Shell Carbonate

Reaction to the HCl test for the presence of marine shell carbonate ranged from moderate to strong down the Site 1 profile. However, no samples from above the watertable at the other sites gave a positive reaction.

Soil Reaction

Sample pH differentiates Sites 1 and 3 from the other soil sites at Rheban. All pH values for Site 1 were greater than 8.0 (mean = 8.4), with the exception of the surface sample (pH = 7.3). Site 3

TABLE 2

Soil profile morphology data for Rheban sampling sites.

	HORIZON	DEPTH OF LOWER HORIZON BOUNDARY mm	SAMPLE DEPTH mm	NATURE OF LOWER HORIZON BOUNDARY	DOMINANT HORIZON COLOUR	HORIZON STRUCTURE	SHELL CARBONATE TEST	HORIZON pH	OTHER FEATURES
SITE 1 AGE = 0 yrs PPF = Uc1.11	Nil	—	40 150 300 610 910 1220 1520	—	2.5Y 7/2	ASG	Moderate reaction Grading to strong reaction	8.46	No surface litter Few Spinnifex roots No visible organic matter Some shell visible, increasing with depth Watertable not reached
SITE 3 AGE = 3100 yrs PPF = Uc2.21	A_o	0	—	—	—	—	—	—	Decomposing litter
	A_1	60	40	S-E	10YR 6/1	ASG	Nil	6.60	Thin mat of fine roots and organic material
	A_2	150	150	G-E	10YR 7/2	ASG	Nil	6.25	Few fine roots Little o.m.
	B	450	300	G-E	2.5Y 6/4	ASG	Nil	6.40	Very few roots Little o.m.
	C	1210	610 910 1220	—	2.5Y 7/3 10YR 7/2	—	Nil	6.85	No organic matter
	W.T.						Strong		Brown groundwater
SITE 2 AGE = 4200 yrs PPF = Uc2.22	A_o	0	—	—	—	—	—	—	Decomposing litter
	A_1	100	40	G-E	10YR 4/1	ASG	Nil	6.20	Abundant organic matter Fine matted roots
	A_2	460	150 300	G-E	10YR 7/2	ASG	Nil	5.15	Few fine roots Less o.m. than above
	B	1370	610 910 1220	G-E	10YR 6/4 with mottles of 10YR 6/6	ASG AM (100 -130) ASG	Nil	6.25	Little visible o.m. Friable consistency Few small nodules
	C	1830	1520 1830	—	10YR 7/3	—	Nil	6.55	No o.m. or roots
	W.T.						Nil		Brown groundwater
SITE 4 AGE = 4200 yrs PPF = Uc2.22	A_o	0	—	—	—	—	—	—	Decomposing litter
	A_1	100	40	G-E	10YR 6/2	ASG	Nil	6.10	Rich in organic matter Matted fine roots
	A_2	350	150 300	G-E	10YR 7/2	ASG	Nil	5.25	Few roots Little organic matter evident
	B	1370	610 910 1220	G-E	10YR 6/4 with mottles 10YR 6/5	ASG AM (76- 121) ASG	Nil	5.62	Friable consistency No roots observed Little organic matter
	C	2130	1520 1830 2130	—	10YR 7/3	—	Nil	5.80	
	W.T.						Nil		Brown groundwater

TABLE 2 (cont.)

	HORIZON	DEPTH OF LOWER HORIZON BOUNDARY mm	SAMPLE DEPTH mm	NATURE OF LOWER HORIZON BOUNDARY	DOMINANT HORIZON COLOUR	HORIZON STRUCTURE	SHELL CARBONATE TEST	HORIZON pH	OTHER FEATURES
SITE 6 AGE = 4200 yrs PPF = Uc2.22	A_o	0	—	—	—	—	—	—	Decomposing litter Some charcoal
	A_1	60	40	G-E	2.5Y 5/1	ASG	Nil	6.90	Organic matter rich Fine matted roots
	A_2	280	150	G-E	7.5YR 7/1	ASG	Nil	5.02	Few roots Little o.m.
	B	1520	300 610 910 1220 1520	G-E	10YR 6/4 with mottles of 10YR 6/5	ASG AM (46-137) ASG	Nil	5.59	Friable consistency Single large root at 152 cm Very little o.m.
	C	2130	1830 2130	—	10YR 7/4	—	Nil	5.85	No o.m. No roots
	W.T.						Nil		Grey-brown Groundwater
SITE 7 AGE = 4200 yrs PPF = Uc2.22	A_o	0	—	—	—	—	—	—	Decomposing litter
	A_1	60	40	G-E	2.5Y 5/1	ASG	Nil	6.12	Matted roots O.M. rich
	A_2	280	110 150	G-E	10YR 7/1	ASG	Nil	5.04	Few roots Little o.m.
	B	1370	300 610 910 1220	G-E	10YR 6/4 with 10YR 6/6 mottles	ASG AM (61-120) ASG	Nil	5.50	No o.m. No roots Friable consistency
	C	2280	1520 1830 2130	—	10YR 7/3	—	Nil	5.88	No o.m. No roots
	W.T.		2440				Nil		Brown groundwater
SITE 5 AGE = 5500 yrs PPF = Uc2.23	A_o	0	—	—	—	—	—	—	Decomposing litter
	A_1	100	40	G-E	10YR 6/2	ASG	Nil	6.30	Rich in organic matter Matted roots
	A_2	250	150	G-E	10YR 7/2	ASG	Nil	5.70	Few roots Some organic matter
	B	1680	300 610 910 1220 1520	G	10YR 7/4 with 10YR 5/6 mottles	ASG AM (60-100) ASG	Nil	5.95	Friable consistency Few roots Little visible o.m.
	C	3350	1830 2130 2440 2740 3050 3350	—	10YR 8/4	—	Nil	6.14	No visible o.m. Few roots
	W.T.						Nil		Brown groundwater

PPF = Principal Profile Form; ASG = apedal single grain; AM = apedal massive G-E = gradational-even; S-E = sharp-even; W.T. = water table.
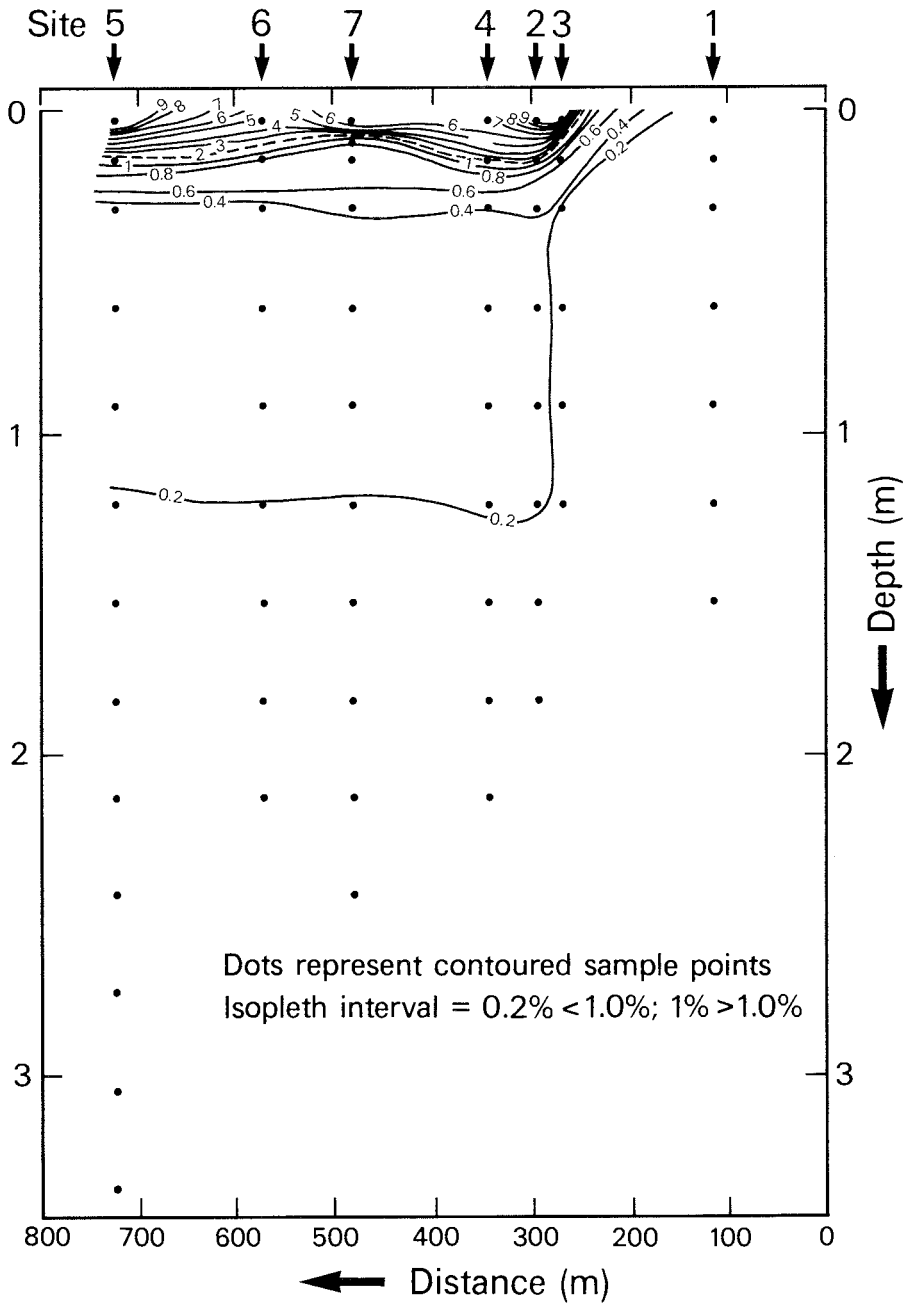
FIG.2 — Contoured cross-section (isogram) showing distribution of organic matter (as % O.M.) in Rheban Spit soils. Horizontal scale indicates distance from Carrickfergus Bay along section; vertical scale indicates sample depth. Note dual isopleth interval.

values all exceeded pH 6.0 (mean = 6.9), whereas subsurface samples from the remaining sites mostly had pH values below 6.0 (table 2). The mean pH for all samples from Sites 2, 4, 5, 6 and 7 were 6.1, 5.6, 6.0, 5.7 and 5.6, respectively.

Organic Matter

Distribution of organic matter in the Rheban soils is depicted in figure 2 by means of an isopleth cross-section (termed an isogram after Ryan & McGarity 1978). The horizontal axis of the isogram represents distance along the Rheban transect from the Carrickfergus Bay shoreline; the vertical axis shows the depth of sampling points. Dots indicate the organic matter determinations used to construct the isopleths (data from Bowman 1979). A dual isopleth interval was used, with 0.2% increments up to an organic matter content of 1.0%, and 1.0% increments above this figure. This arrangement allows both the sharp near-surface changes in organic matter content and the more subtle subsurface transitions to be adequately represented. The main feature of the distribution pattern shown in figure 2 is the very low organic matter content in the subsurface at all sites (<0.2% o.m.).

Distribution of Extractable Elements

Results of the analyses of hydrochloric acid-extractable cations are presented as isograms in figure 3 (after Bowman 1979). Note that some of these isograms use a geometric isopleth ratio while others use an arithmetic isopleth interval to best portray the element distribution patterns. However, all isograms have the same horizontal and vertical scales. In deriving element age trends for the Rheban chronosequence (see below), the element distribution patterns were used to select concentrations representative of the A_1, A_2, B and C horizons at each soil site. The main features of the element distribution patterns shown in figure 3 are:

Iron

All profiles landward of Site 3 exhibit moderate development of both A_2 and B horizons (in terms of iron distribution), although the A_2 horizon at Site 7 appears anomalously thin (fig. 3A). A pronounced discontinuity exists in the upper profile between Sites 1 and 3, with another between Sites 2 and 3. These probably reflect the age differences between the successive progradational units at Rheban. Below a depth of 1 m however, iron distribution forms a relatively systematic pattern across Rheban Spit. The exception is a

small irregularity near the base of Site 2, possibly caused by a minor concentration of heavy minerals (but not evident in sand grain counts: Bowman 1986, table 4).

Manganese

Relatively high concentrations of acid-extractable Mn are evident in the upper soil profiles except at Site 1 (fig. 3B). Vertical discontinuities occur on either side of Sites 3 and 7 but the distribution of manganese in the subsurface is relatively uniform.

Aluminium

As with the iron distribution pattern, pronounced vertical discontinuities are apparent between Sites 1 and 3 and between Sites 2 and 3, and at the surface between Sites 2 and 4 (fig. 3C). Otherwise, there is a systematic distribution of aluminium across the other sites with only slight irregularities around Site 7. Development of the A_2 horizon is prominent across Sites 4, 5, 6 and 7, and accumulation of aluminium in the B horizon is evident at Sites 5 and 6, and to a lesser extent at Sites 2, 4 and 7.

Calcium

Apart from Site 1, relatively high calcium values occur near the ground surface, reflecting the distribution of organic matter in the soil profiles (fig. 3D). Below the near-surface accumulation calcium values are much lower, probably indicating an eluviated horizon (except at Site 7). On the other hand, development of an illuvial B horizon is not evident in the calcium distribution pattern. Relatively high calcium values at depth at Site 1, and somewhat lower concentrations at Site 3, probably represent unleached detrital shell carbonate. In contrast, this has been completely removed from the older soil profiles, except near the water table.

Magnesium

Concentrations of magnesium are low in all the Rheban soil profiles and the distribution pattern is uniform, with little evidence of near-surface accumulation (fig. 3E). As with the distribution of calcium, the pattern indicates an eluviated horizon low in acid-extractable magnesium, except for an anomaly associated with Site 7. Magnesium distribution appears little affected by local concentrations of shell or weatherable minerals.

Sodium

The analyses indicate that this cation is very regularly distributed across Rheban Spit, with a thin eluviated horizon present at Sites 5, 6 and 7
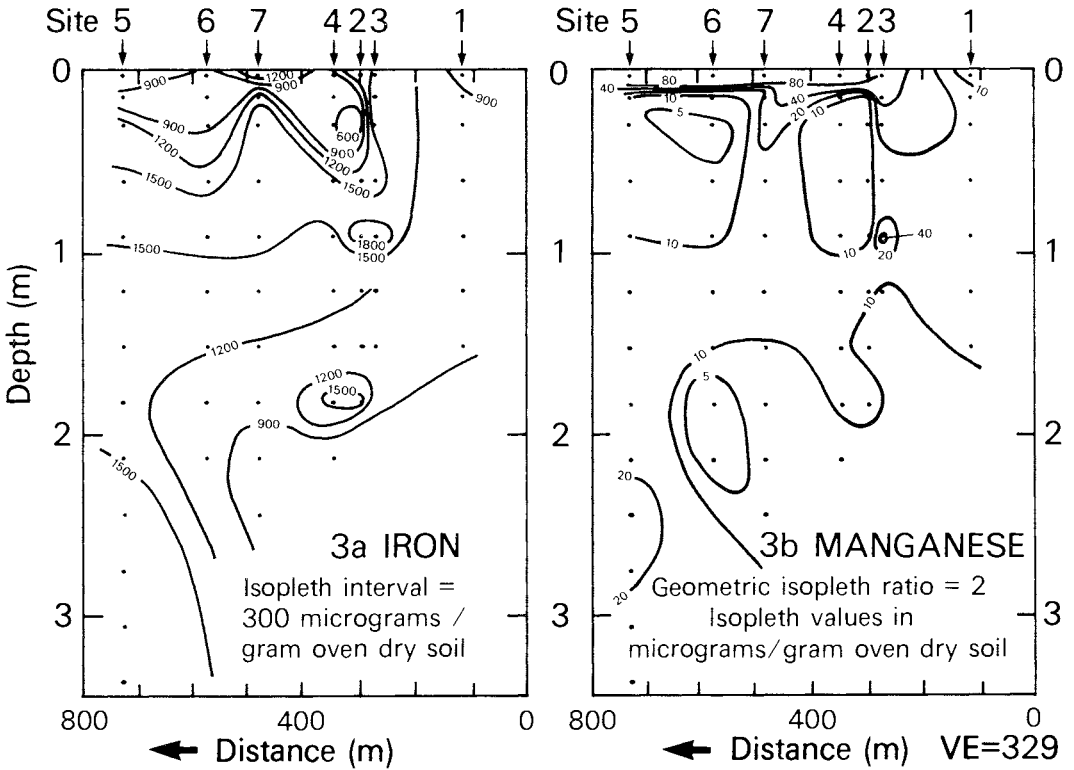
FIG.3 — *Isograms showing distribution of acid-extractable iron, manganese, aluminium, calcium, magnesium and sodium in the Rheban soil profiles. Note different isopleth intervals and ratios.*

(fig. 3F). Higher sodium concentrations occur in the lower parts of some profiles (reflecting saline groundwater) and irregularly down the Site 1 profile, probably as a result of high aerosol input of marine salt adjacent to Carrickfergus Bay (fig. 1).

DISCUSSION

Soil Classification

Using the Australian great soil group system to classify the Rheban soil profiles, the undifferentiated sediments at Site 1 constitute a "calcareous sand", but the profiles at all the other sites fall within the "podzol" great group (Stace *et al.* 1968). Insufficient data exist to satisfy the criteria for a spodic B horizon using the FAO-UNESCO (1974) classification. Therefore, none of the Rheban profiles may be classed as a "podzol" under this scheme; all are "arenosols". Thus, both great soil group classifications are relatively insensitive to the

degree of development of the podzols at Rheban and do not adequately distinguish the profiles in terms of the established age sequence.

In contrast, the *Factual Key* of Northcote (1979) classifies the profiles into a developmental sequence which relates to soil age, even though the profiles all key into the coarse-textured subdivision of the "uniform" primary profile form (i.e. Uc: Northcote 1979). The undifferentiated sands at Site 1 (age = 0 years) are classed as a "calcareous sand" (principal profile form = Uc1.11), whereas the Site 3 profile (age = 3100 years) displays an incipient "bleached A$_2$ with colour B horizon" (Uc2.21). Sites 2, 4, 6 and 7 (all = 4 200 years) are also classed as "bleached sands with colour B horizons", but are grouped on the basis of their B horizon value/ chroma ratings as Uc2.22. The Site 5 soil profile (age = 5 500 years) is also a "bleached sand", but is differentiated from the Uc2.22 profiles on the basis of the colour of the B horizon mottles (Uc2.23: Northcote 1979, Northcote *et al.* 1975).
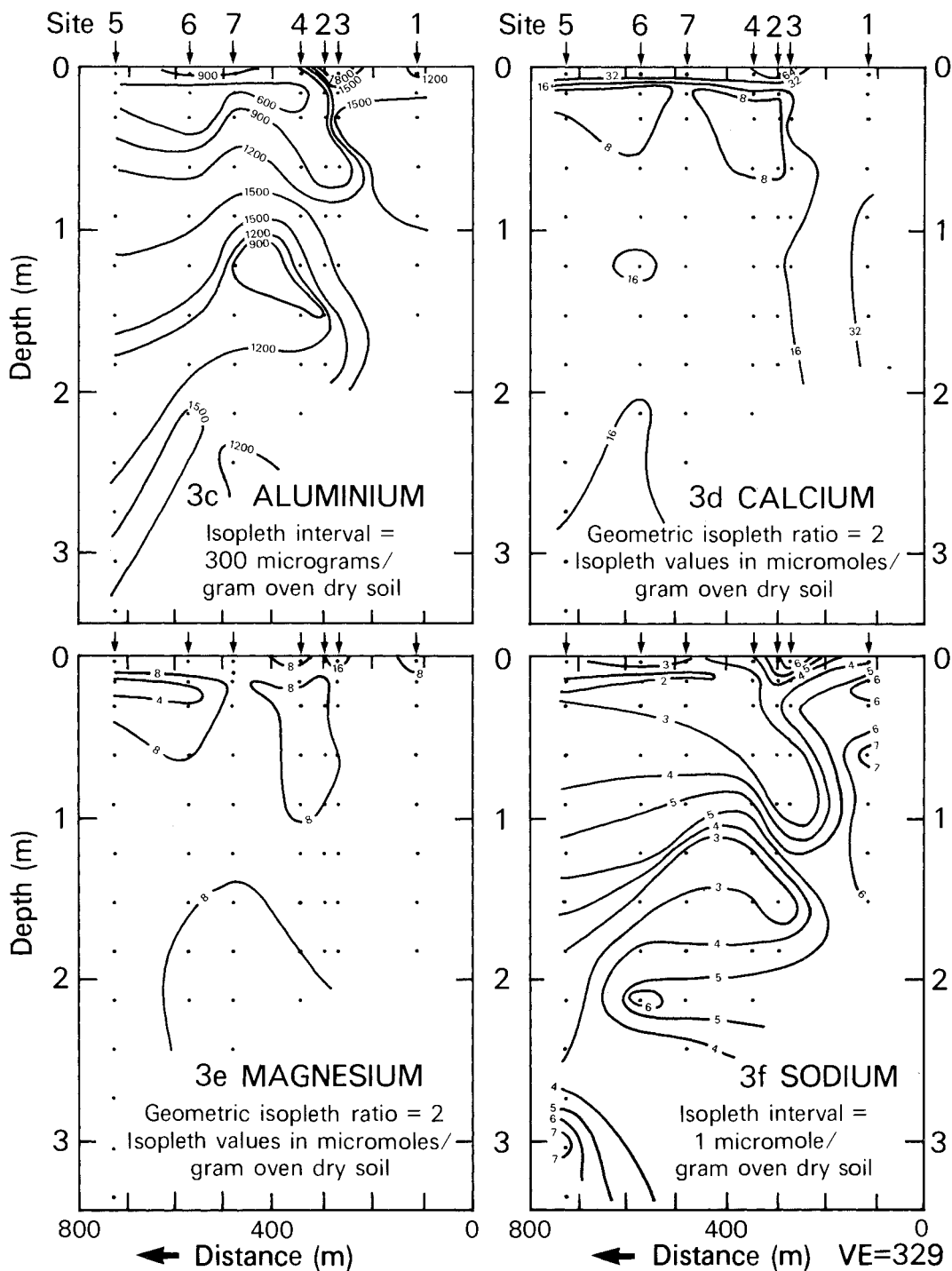
FIGURE 3 (cont.)

Insufficient chemical and micromorphological data are available to classify the Rheban soils adequately using the U.S. *Soil Taxonomy* (Soil Survey Staff 1975). However, from field observations and the analytical results presented above it seems unlikely that any of the Rheban soils would qualify as a "Spodosol", the *Soil Taxonomy* equivalent of a podzol (McKeague *et al.* 1983, Thompson & Hubble 1980).

Age Trends

The Rheban soil chronosequence and the age trends derived from it are based on four dated soil sites: a modern soil profile, two radiocarbon dated profiles and a composite soil profile consisting of averages obtained from the four soil profiles assigned identical ages in Part 1 of this study (Bowman 1986).
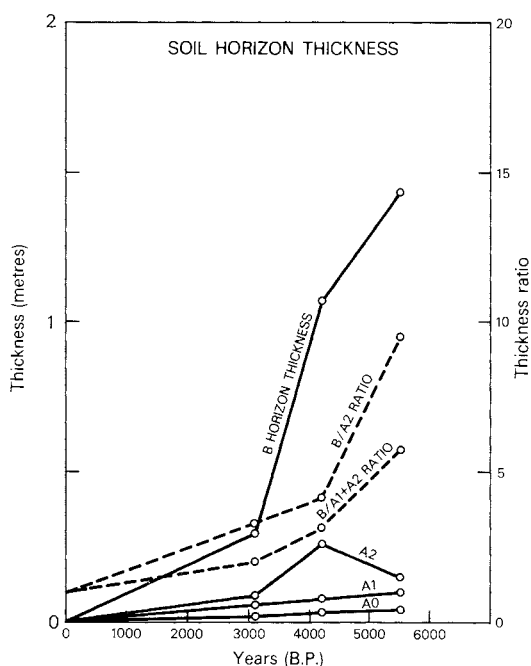
FIG.4 — Plot against soil age of horizon thickness and horizon thickness ratios for the Rheban profiles.

The profile morphology data in table 2 indicate that several progressive changes occur with increasing profile age. For example, some thickening is apparent in the A_1 and A_2 horizons, but this trend is slight in comparison with the pronounced development of the B horizon. Con-

sequently, plots of horizon thickness ratios against age show a systematic increase if the B horizon is included (fig. 4), but not otherwise. Similar increases with age in the thickness of podzol horizons have been reported from chronosequences overseas (e.g. Jenny 1941, Olson 1958, Franzmeier & Whiteside 1963, Birkeland 1984, Rockwell *et al.* 1985) and from eastern Australia (Burges & Drover 1953, Thompson & Hubble 1980, Thompson 1981, Thompson & Bowman 1984, Bowman 1987).

The dominant colours of the Rheban profiles do not appear to change systematically with soil age. This differs from trends recorded in other chronosequences in which colour (particularly of the B horizon) was found to darken, deepen or redden with increasing soil age (e.g. Dickson & Crocker 1954, Brewer & Thompson 1980, Birkeland 1984, Thompson & Bowman 1984). Further analysis of the Rheban data to quantify better the contrast between the dominant colours of the A_0, A: and B horizons in terms of *colour distance units* (Bowman 1979) also failed to yield systematic age trends similar to those obtained from a comparable podzol chronosequence in New South Wales (Bowman 1987). Also, the ubiquitous gradational-even A:-B horizon transition in the Rheban profiles contrasts with observations on the mainland (Bowman 1979, Thompson & Bowman 1984), where coastal podzols older than 4500 years invariably display sharp-irregular A:-B horizon boundary configurations.

However, the pH data from Rheban do yield systematic age trends, with horizon pH and average profile pH tending to decrease with age (fig. 5). The B horizon trend is in good agreement with that obtained for New South Wales podzols, but the pH values of the C horizon are somewhat lower than the corresponding figures for New South Wales (fig. 5). This decrease in soil pH with increasing age has been reported in many chronosequence studies of young, freely-drained soils (e.g. Salisbury 1925, Hissink 1938, Crocker & Major 1955, Olson 1958, Franzmeier *et al.* 1963, Stevens & Walker 1970). The age trend relates to the build-up of organic matter and the production of humic and fulvic acids, resulting in the progressive leaching of carbonate (where present) and mobile bases (Stevens & Walker 1970).

The lack of detrital shell in all the Rheban profiles except Site 1, probably indicates extensive leaching from the older sand deposits. Hence, the complete removal of visible shell from the sediment at Site 3 during the 3100 years since its deposition, provides a measure of the maximum time required for complete carbonate leaching at Rheban. As
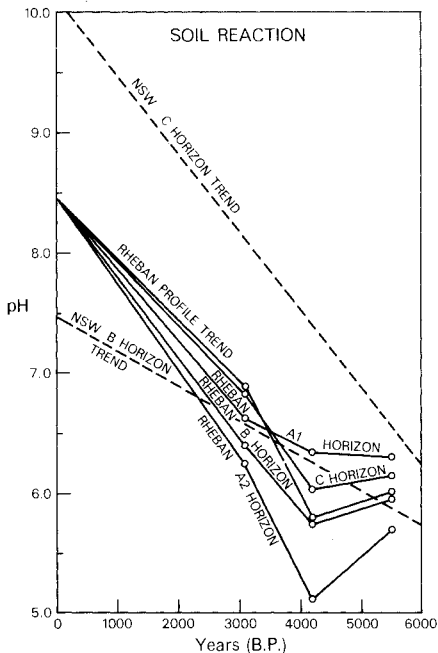
FIG.5 — Soil age:pH plots of average profile pH and horizon pH for Rheban and New South Wales podzols. Origin of Rheban graphs is mean of pH values for Site 1 (= 0 years). Rheban profile trend derived from mean pH of samples from each site. New South Wales regression trends in figures 5, 6, 7 and 8 from Bowman (1987).

Thompson & Bowman (1984) noted, the rate of removal of shell carbonate largely depends on the initial size of fragments and will vary locally. However, rates determined in comparable chronosequence studies using better short-term age control do accord with the Rheban estimate (e.g. Olson 1958).

There is good agreement between the age trend for B horizon organic matter content in the Rheban chronosequence and in New South Wales coastal podzols (fig. 6; Bowman 1987). Other measures of organic matter content in the Rheban profiles also increase with age (notably the A_1 horizon content: fig. 6), indicating accumulation of organic matter in the chronosequence. This agrees with northern hemisphere observations, and there is some evidence from Rheban for attainment of a "steady state" situation in organic matter gains and losses, as suggested by studies overseas (e.g. Crocker & Dickson 1957, Jacobson & Birks 1980, Jenny 1980, Ellis & Richards 1985).

Systematic age trends are evident in the concentrations in the Rheban samples of some acid-extractable elements. Extractable aluminium in the A_2 horizon progressively decreases with time, whereas in the B horizon it increases (fig. 7). Hence, the B/A_2 ratio for aluminium rises with increasing profile age, reflecting progressive soil development and chemical differentiation of podzol horizons. However, the *mean* aluminium concentration in the Rheban profiles decreases with age (fig. 7), indicating net loss of this cation from the soil. These trends are in agreement with New South Wales results, but the B horizon concentrations of aluminium at Rheban are substantially higher than the corresponding New South Wales averages, probably reflecting differences in parent material rather than organic matter accumulation.

Consistent age trends are not immediately evident in the distribution of acid-extractable iron in the Rheban chronosequence, mainly because the values for this cation are anomalously high in all horizons at Site 3 (fig. 8). This could be attributed to the pedogenic effects of the comparatively low topographic position of Site 3 (and hence relatively high water table) causing apparent compression of the soil profile (Thompson & Hubble 1980). However, if horizon concentration ratios for iron are examined, the B/A_2 ratio (for example) shows a consistent increase with age and is accordant with the B/A_2 age trend for New South Wales coastal podzols (fig. 8 and Bowman 1987).

The progressive leaching of both calcium and sodium from the Rheban chronosequence is evident in a plot against age of the average profile concentration of these cations (fig. 9). While this trend is the same as that observed in New South Wales podzols, the increase in calcium in the A_1 horizon at Rheban with increasing soil age (fig. 9) is the reverse of the New South Wales trend (Thompson & Bowman 1984, Bowman 1987). In addition, no manganese or magnesium age trends were identified in the Rheban chronosequence, although such trends have been recognized in New South Wales (Bowman 1979).

CONCLUSION

A soil chronosequence of four ages and four stages of development ranging from calcareous sands to podzols has evolved in the sediments of Rheban Spit. Classification of the profiles according to the Australian great soil groups (Stace *et al.* 1968) does not effectively separate the soils on the basis of age: this is better achieved by *A Factual Key* (Northcote 1979).
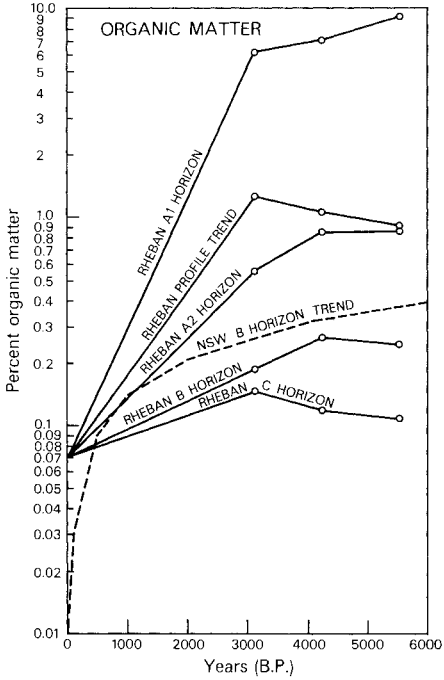
FIG.6 — Plot of organic matter content against soil age for Rheban and New South Wales profiles. Note: log scale used on the ordinate.
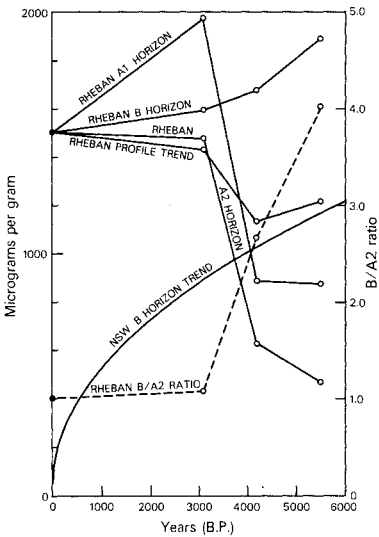
FIG.7 — Plot of acid-extractable aluminium against soil age for Rheban and New South Wales profiles. Origin of Rheban graphs is mean aluminium concentration in Site 1 samples. Rheban B/A₂ ratio refers to the ratio of acid-extractable aluminium in those horizons.
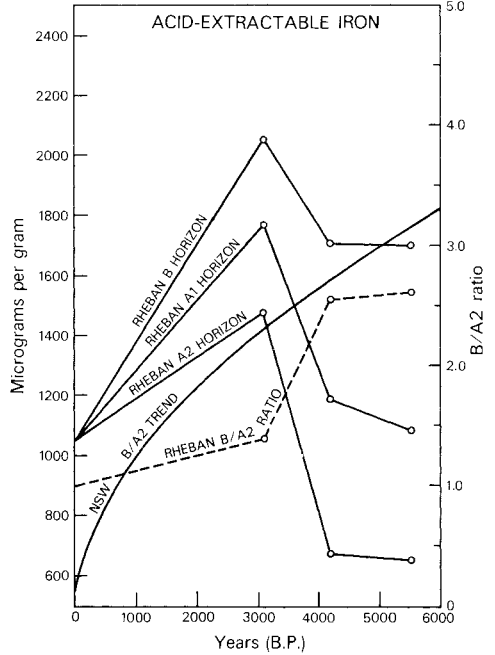
FIG.8 — Plot of acid-extractable iron against soil age for Rheban and New South Wales profiles. Origin of Rheban graphs is mean iron concentration in Site 1 samples. Rheban B/A₂ ratio refers to the ratio of acid-extractable aluminium in those horizons.
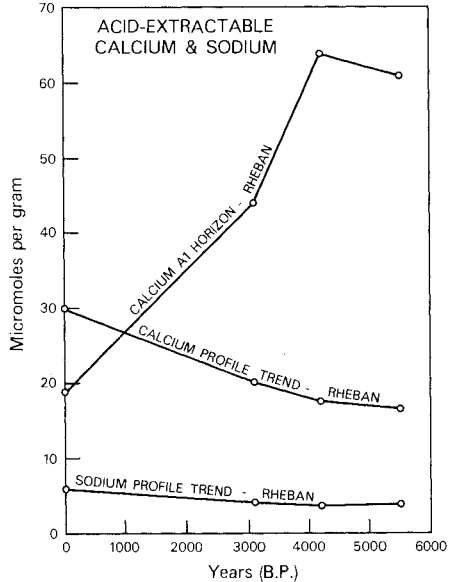
FIG.9 — Plot of acid-extractable calcium and sodium against soil age for Rheban soils.

Age trends are evident in a range of soil features recorded and measured in the Rheban soils. The most prominent of these are the leaching of marine shell carbonate, the accumulation of organic matter in the soils, the acidification of the profiles, the mobilisation of several acid-extractable elements and the thickening of the B horizon with increasing soil age. The soil horizons have become increasingly differentiated in terms of iron and aluminium distribution, while the average content of these elements in the profiles has decreased. In general, the age trends are in accord with those evident in a comparable podzol chronosequence in New South Wales and with similar overseas studies.

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