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Late Quaternary tropical lowland environments on Halmahera, Indonesia

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Abstract

Results of a case study of landform development and sedimentation in humid tropical lowland environments on Halmahera island, eastern Indonesia, are presented with the aim to better characterise tropical lowland environments in the context of Late Quaternary environmental change studies. First, the geologic, morphologic and environmental settings of the two areas, the interior Kao River plain and the Kao coastal zone (N. Halmahera), are presented. Subsequently, data concerning Late Pleistocene and Holocene landform development, sedimentation and coastal processes are discussed. Pleistocene landform development involved volcaniclastic sedimentation, base levelling of coastal lowlands, prolonged weathering and crust formation, coastal uplift and eustatic sea level change. A conspicuous ferricrete crust in the subsoil of the coastal plain is tentatively dated with ^{14}C AMS analysis and isotopes of organic matter encapsulated in the soil ferricrete have been determined. Due to interacting sea level change, neotectonic uplift, climatic, hydrologic and vegetational change, unequivocal evidence for anomalous Late Pleistocene or Holocene environmental conditions is difficult to obtain. During the Mid-Late Holocene, a low-energy fluvial systems and swamps existed in the interior Kao River plain; a dense open swamp/swamp forest vegetation contributed to extremely high sedimentation rates in this depositional basin. Palynological analysis of the organic swamp deposits indicates little or no change in sedimentary environmental settings and swamp vegetations, and indications for early human presence in the area. In the coastal area accretion and delta progradation occurred after the Early-Mid Holocene formation of a marine erosion cliff. Tentative evidence for early human presence in the Kao area is derived from charcoal particle frequencies in sediments and the existence of natural grasslands in the coastal zone. As most of the geologic and environmental characteristics of the tropical lowlands in the Kao area are common in eastern Indonesia, the study provides useful information for ongoing research in the region.

Keywords: Late Quaternary; Indonesia; Tropical lowlands; Ferricrete; Freshwater swamp; Environmental change; Early human presence

1. Introduction

Tropical lowland environments on Halmahera, Indonesia have been studied in the context of research on Late Quaternary environmental change. Generally, information on geology, geomorphology and ecological settings, and the youngest environmental development of these milieus is rather poor. In south-east Asia, lowland sites have thus far received scant attention due to the scarcity of suitable proxies and the complicated nature of possible evidence of

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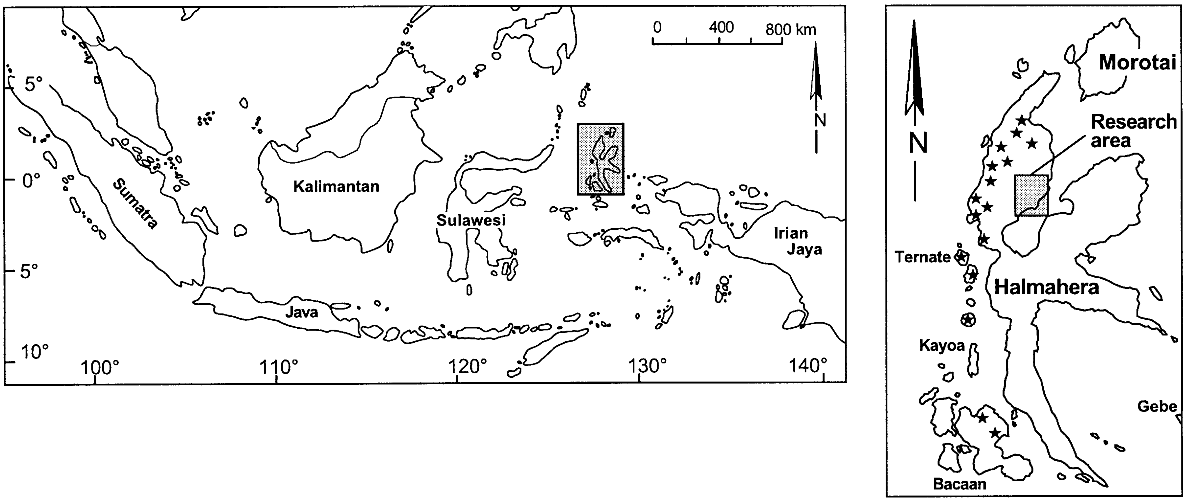


Fig. 1. Location of the study area in Indonesia and Halmahera. Black stars mark active volcanoes of the volcanic arc in western Halmahera.

palaeoenvironmental conditions. Nevertheless, palaeoenvironmental scenarios on the basis of palynomorph studies, combined sea level change and palaeogeographic reconstructions and geomorphologic evidence have been reported from the Indonesian region (i.e. Morley, 1976; Van der Kaars, 1991; Van der Kaars and Dam, 1995; Tjia, 1987; Thorp et al., 1990; Yakzan and Hassan, 1997; Verstappen, 1994; Thomas et al., 1999). In this study, data from various analyses (geo(morpho)logical, palynological, pedological, ecological) are combined in order to comprehensively characterise lowland environments and assess possible evidence for changing environmental settings. This results in a description and analysis of the changing Late Quaternary scene in the Kao area, northern Halmahera, but the inference of anomalous environmental conditions (substantially cooler, a more seasonal and reduced rainfall, an adapted vegetation) is hampered by problems with dating, the indirect character of possible evidence and the incomplete and scattered nature of the geohistorical record. The results of this study nevertheless provide useful data for studies in comparable lowland environments and reconstructions of Late Quaternary environmental change in the region.

Halmahera occupies an intermediate position between the major biogeogeographic and tectonic realms of Eurasian Sundaland and Sahul (New Guinea–Northern Australia). Evidence for Quaternary environmental change from this region is rather limited, and it is questionable whether data from the neighbouring (mostly continental) regions are representative for insular eastern Indonesia. Following exploratory investigations early this century (Campen, 1884; Baretta, 1917; Brouwer, 1923; Van Riel, 1943; Gogarten, 1918a,b; Verstappen, 1960, 1964), recent mapping surveys (Apandi and Sudana, 1980; Supriatna, 1980) and research (Sukamto et al., 1981; Hall et al., 1987, 1988; Barmawidjaya et al., 1989) have shed light on geologic, oceanographic and environmental settings of Halmahera. Results of marine geologic research in the Kao (sometimes spelled ‘Kau’) Bay area provided data on Late Quaternary environmental settings in general (Van der Linden et al., 1989; Middelburg, 1991) and palaeoclimatic, sea level and vegetational developments in particular (Van der Kaars, 1991; Barmawidjaya et al., 1989, 1993). In the following study, these older data are integrated with new data derived from terrestrial sites, namely the Kao coastal lowlands and the interior Kao River plain (Fig. 1).

2. Environmental settings

2.1. Geology and geomorphology

The study area is located in the middle of the northwestern arm of Halmahera and consists of the interior (intramontane) Kao River plain and the adjacent coastal zone including the Kao River delta (Fig. 2A). This part of Halmahera mostly consists of Tertiary and Pleistocene volcanic rocks with minor occurrences of Quaternary reef limestones and recent alluvium (Supriatna, 1980; Hall et al., 1988). The geotectonic configuration of western Halmahera and adjacent islands comprises a volcanic arc overlying the eastward subducting margin of the Molucca sea plate. The active volcanic centres form a curved line across northwestern Halmahera, from the western coast in the south to the eastern coast in the north. Hall et al. (1988), on the basis of stratigraphic evidence, estimate that the presently active volcanic arc is not older than 1 Ma. Major Late Pleistocene and Holocene activity occurred at the Gamkonora (west), Ibu (northwest) and Dukono volcano complexes (north of the study area), but these eruptions are poorly documented (Gogarten, 1918b; Van Padang, 1934; Supriatna, 1980).

The interior part of the study area is a river plain or basin situated amidst indistinct volcanic hills east of the main volcanic range. The basin is fault-controlled along its eastern margin and probably its initial formation is related to faulting of the Tertiary volcanic basement complex (cf. Verstappen, 1960). The main drainage divides trend south–north, both to the west and east of the plain. The gradual western margin is formed by low hills (200–400 m asl) composed of volcanic extrusives (probably Mid to Late Pleistocene) and deeply eroded remnants of Tertiary volcanic complexes. The presently active volcanoes closest to the area are Mt Dukono to the north and Mt Ibu to the northwest, but both volcanoes are not within the catchment of the Kao River system. Kao River is the trunk stream of a dendritic system that originates in the hills west and north of the interior plain. In the southeastern corner of the plain, three large streams converge and form the downstream part of Kao River. Through a narrow valley it crosses the fault-controlled ridge and continues its southern course towards Kao Bay. The downstream course of the river is fault controlled (Fig. 2A, on the basis of aerial photograph interpretation). The central and southeastern part of the plain is a seasonally flooded, poorly accessible swamp. This area, in particular, is further discussed below.

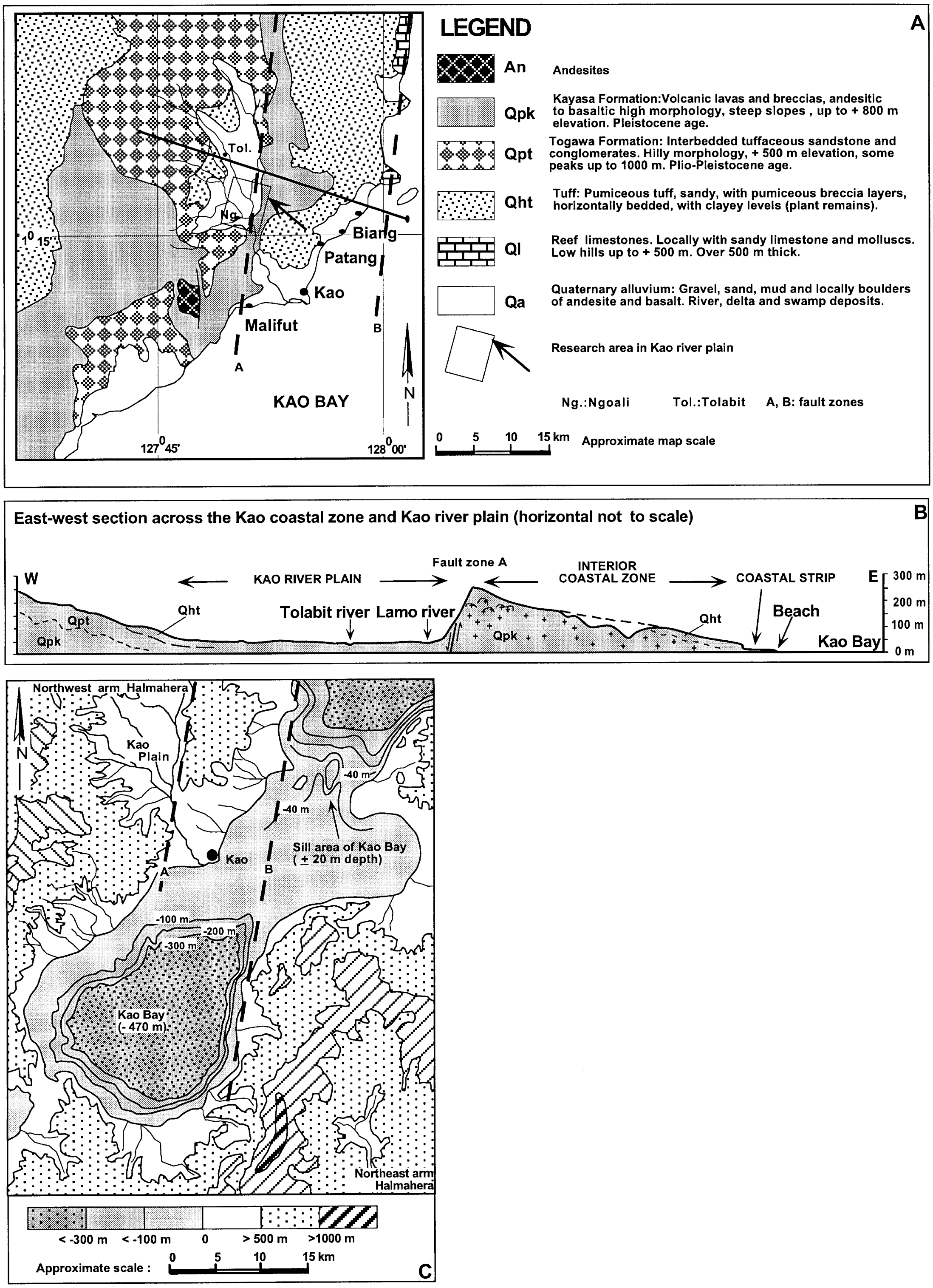
From the eastern margin of the interior basin, volcanic hills (±300 m asl) descend gradually to the coast near Kao (Figs. 2A,B and 3). The transition to the flat, low-lying coastal strip and Kao River delta is marked by a clearly visible, but locally discontinuous, erosional cliff-like feature. The young coastal zone near the Kao River delta is further described below. South of Kao River, volcanic hills descend rather steeply into Kao Bay; to the north low foothills composed of alluvial volcaniclastics are interrupted by small, elevated Pleistocene reef complexes along the coast. The study area is bordered to the east by Kao Bay, a pear-shaped marine basin (Fig. 2C). The palaeoenvironmental development of Kao Bay was studied during the Snellius I and II Marine Geology expeditions (Van Riel, 1943; Van der Linden et al., 1989). Pertinent aspects of its Late Quaternary evolution will be further introduced below.

2.2. Climate, vegetation and land use

The Kao area is situated in the perhumid equatorial zone. Regionally, annual average precipitation varies from ±2000 mm in southern Halmahera to some 4000 mm/yr in the northwest. Seasonal variation is small, but a drier period normally occurs in the months July–August–September (Table 1), coinciding with the SE monsoon. The lowlands adjacent to Kao Bay are significantly drier than the interior and west of northern Halmahera.

Table 1
Monthly rainfall figures for the study area. Both locations are along the eastern coast of N. Halmahera. Rainfall estimates for interior, somewhat more elevated locations give figures 1000–1500 mm/yr higher. Data after Berlage (1949) with measuring period for Kao 6 years (average annual total 1857 mm) and for Tobelo 34 years (average annual total 2121 mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kao	251	140	153	164	269	133	109	113	130	89	149	157
Tobelo	172	179	200	221	236	226	161	129	144	141	160	152


A
LEGEND
An Andesites
Qpk Kayasa Formation:Volcanic lavas and breccias, andesitic to basaltic high morphology, steep slopes , up to + 800 m elevation. Pleistocene age.
Qpt Togawa Formation: Interbedded tuffaceous sandstone and conglomerates. Hilly morphology, + 500 m elevation, some peaks up to 1000 m. Plio-Pleistocene age.
Qht Tuff: Pumiceous tuff, sandy, with pumiceous breccia layers, horizontally bedded, with clayey levels (plant remains).
Ql Reef limestones. Locally with sandy limestone and molluscs. Low hills up to + 500 m. Over 500 m thick.
Qa Quaternary alluvium: Gravel, sand, mud and locally boulders of andesite and basalt. River, delta and swamp deposits.
Research area in Kao river plain
Ng.:Ngoali Tol.:Tolabit A, B: fault zones
0 5 10 15 km Approximate map scale
Tol.
Ng.
Biang
Patang
Kao
Malifut
KAO BAY
1° 15'
127° 45'
128° 00'
A
B
N
B
East-west section across the Kao coastal zone and Kao river plain (horizontal not to scale)
W
KAO RIVER PLAIN
Fault zone A
INTERIOR COASTAL ZONE
COASTAL STRIP
E
300 m
200 m
100 m
0 m
Qpt
Qpk
Qht
Tolabit river
Lamo river
Qpk
Qht
Beach
Kao Bay
Northwest arm Halmahera
N
Kao Plain
-40 m
-40 m
Sill area of Kao Bay (± 20 m depth)
Kao
A
B
-100 m
-200 m
-300 m
Kao Bay (- 470 m)
Northeast arm Halmahera
< -300 m
< -100 m
0
> 500 m
>1000 m
Approximate scale :
0 5 10 15 km
C

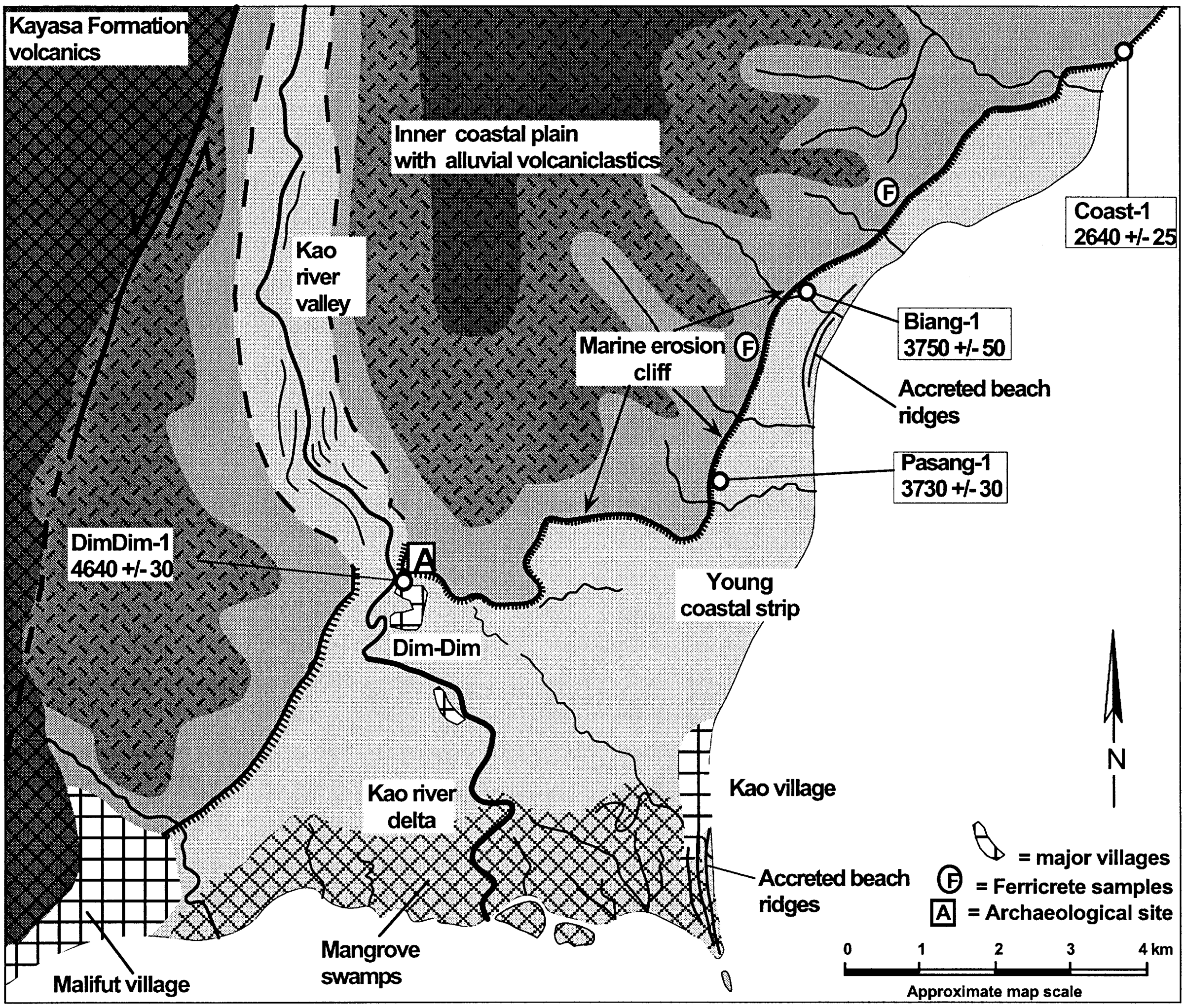


Fig. 3. The coastal region in the vicinity of Kao. Indicated is the inner coastal zone (built up of volcaniclastics), the extension of the marine erosion cliff, the young coastal strip and Kao River delta. Approximate positions of ^{14}C-dating samples of Holocene beach deposits and ferricrete samples (of residual ferricrete lumps on the surface, see also Fig. 4) are indicated.

Most of N. Halmahera used to be covered with dense stands of evergreen lowland rainforest, with minor patches of montane forests in the mountains (Whitmore, 1984). The species diversity of these forests was studied by Whitmore et al. (1987), and also Monk et al. (1997) provide useful descriptive information (see also Section 4.2). Whitmore (1984) further indicates a coastal belt along Kao Bay with secondary forest and scrub and natural grasslands. This non-forest vegetation was also mentioned by

Fig. 2. Geological and geomorphological setting of the study area. (A) Geological sketch map of the Kao area. After Supriatna (1980) with additional data from aerial photograph interpretation. (B) Topographic section across Kao River plain and the coastal zone. Data source: 1:100 000 scale topographic map series, sheet 25 (XIV-100), Topografische Dienst, Batavia, 1925. (C) Bathymetry of Kao Bay and topography of the adjacent land area (source: Van der Linden et al., 1989).

early explorers (Campen, 1884; Baretta, 1917) and World War II surveyors (Anon., 1944), prior to the population increase and logging activities of the later part of the last century. Grassland and open forest is visible on 1944–1945 aerial photographs in the coastal area, while in the interior Kao plain, large open grassland-herbaceous swamps (mainly with Poaceae and Cyperaceae), Sago palm swamps (mainly *Metroxylon sagu* or *Metroxylon rumphii*) and patches of swamp forest can be distinguished (Fig. 5). Mangroves occur in the Kao River delta.

Nowadays, stretches of coastal lowland forest have been converted into forest plantations (coconut, clove, nutmeg) and clearings for food crops (rainfed rice, cassave, maize, peanuts). Parts of the interior plain have been developed for transmigration settlers and, in large tracts of the basin, drainage has been improved and irrigated ricefields have been layed out. The area is known for its good rice crops. Also the margins of the central swamp area are presently being converted into agricultural land. Dense stands of Sago palm are exploited for the production of Sago pulp, a local staple food. During the last decades, forests throughout northern Halmahera have been logged at least once for tropical hardwoods, with the usual effects on forest structure, erosion and the opening up of the interior via logging tracks.

3. Pleistocene landform development

Geological and geomorphological developments that probably took place in the latest part of the Pleistocene have determined the physiographic characteristics of the Kao area. Of major signficance were: (1) volcaniclastic sedimentation; (2) weathering and denudation; (3) tectonics; and (4) coastal processes including reef building and relative sea level change.

3.1. Volcaniclastic sedimentation

The hills surrounding the interior Kao River plain are composed of Plio-Pleistocene volcanics (Fig. 2A). Geological map data, aerial photographs and new field data confirm the presence of young volcaniclastics in the northern and eastern margin of the plain (unit Qht). The deposit comprises thick sequences of massive, moderately sorted tuffaceous sand with a variable gravel content. Gravel-sized clasts are predominantly medium-rounded pumice. The sandy matrix shows vague horizontal bedding. The thickness of the unit could not be determined, but is estimated by Supriatna (1980) to amount to some 150 m. In the northern and eastern parts of the plain, fluvial erosion along major streams has resulted in locally steep-sided valleys in which thick sequences of the deposit are exposed. The tuffs appear to mantle the underlying relief. These sediments represent mass-flow deposits, possibly primary pyroclastic flows, with subsequent watery mass-flow deposits (debris flows, lahars) and fluvial sediments (initially braided and later meandering river systems). Towards the central plain, the coarser volcaniclastics are overlain by finer, better sorted, fluvial sediment; sand sheets, clayey overbank deposits (floodbasin) and coarse, gravelly sand deposits (channel fills). Results of our shallow drillings suggest these fluvial deposits interfinger laterally with even younger organic fluvial, swamp and lacustrine deposits in the central-southern part of the plain (see below).

Comparable volcaniclastics have not been observed in the eastern margin of the Kao River plain because of the younger sedimentary cover, and in the most elevated parts of the inner coastal plain because of deep weathering and poor exposure. Further towards Kao Bay coast, in good exposures in the marine erosion cliff and in small roadcuts further inland, again comparable volcaniclastics are encountered (Figs. 2A and 3). Facies here are characterised by the presence of abundant cross-stratified beds and multiple channel fills (sometimes poorly sorted, and with coarse gravels), indicative of braided fluvial systems. Intercalated massive gravelly sandstones suggest occasional pulses of high sediment concentration floods. In massive to horizontally bedded units overall texture is finer, with a substantial part of exposed deposits composed of fine sand to silt. These overbank sediments suggest a relatively low energy depositional environment, with low relief gradients close to base level (former sea level).

3.2. Denudation and ferricrete formation

It is inferred that landscape development and weathering (including the formation of a dense ferricrete crust) in the inner coastal zone are indicative of a

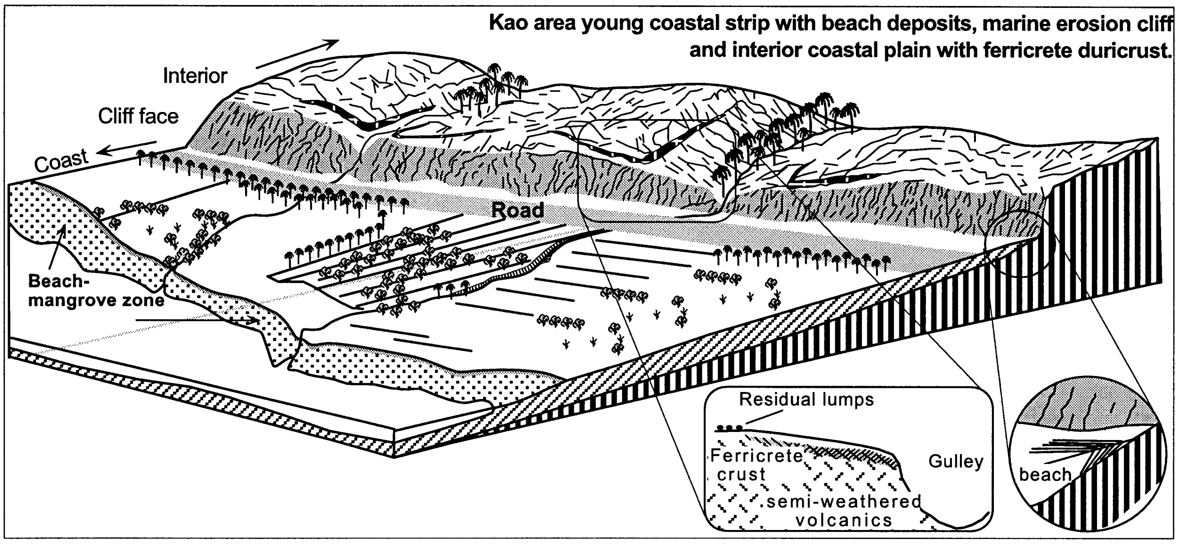


Fig. 4. The coastal zone in the Kao area with the young coastal strip (usually densely vegetated), the marine erosion cliff of some 10–15 m high and the interior allluvial plain with erosive relief. Ferricrete layers are exposed in the sides of the gulleys, close to the cliff face, while residual lumps and pisoliths occur on the interfluvia. The vegetation in the interior alluvial plain is mostly open grassland, with trees bordering incised creeks.

stable, base-levelled, tropical coastal lowland setting, possibly under a somewhat drier, more seasonal climatic regime. This stable setting is subsequently affected by tectonic uplift, relative base-level lowering and incision under a different morphologic regime.

A considerable part of the inner coastal zone is built up of older Pleistocene volcanics of the Kayasa Formation (Fig. 2A), with andesitic to basaltic lavas and breccias and finer volcaniclastics. Towards the coast, younger volcaniclastics (as introduced above) and younger shallow marine deposits form a surficial cover. Surficial deposits in the inner coastal zone are invariably deeply weathered, with thick oxisol/ferralsol type-soils. Nutrient poor, acid soils presently support widespread grassland vegetation (*alang–alang*) that possibly developed only after recent deforestation, but may have been present as a natural climax vegetation on mature, depleted soils. Along the higher interfluves and the S–N oriented fault escarpment ridge, exhumed intrusive basement or large andesitic lava flows (both brecciated) are exposed. The inner coastal zone morphology (Figs. 2A and 3) is characterised by well developed dendritic river systems with wide open valleys and low, rounded ridges. Small perennial streams have very low gradients and hardly any prevalent direction. The irregular, but roughly east–west oriented drainage pattern has developed conformably with the low primary slope of the inner coastal zone. The overall morphology of the inner coastal plain is indicative of the initial base-levelling of a former coastal lowland, followed by rejuvenation of incision and denudation.

In the eastern, lowest part of the inner coastal zone, oxisol/ferralsol type-soils exhibit a subsoil ferricrete crust (Thomas, 1994) in shallow valley-side exposures and iron pisoliths (small rounded nodules) on the surface of flat to gently sloping interfluves. The term *ferricrete* is used following Pain and Ollier (1992) (see also Thomas, 1994) and defined as “an iron-cemented mass of regolith, not necessarily part of an indurated layer, including the iron-cemented portions of large mottles”. In the Kao area, the ferricrete occurs as a distinct 20–40 cm thick crust of hard material (matrix cemented pisolithic nodules) at or near the ground surface in the sides of shallow incised valleys (Fig. 4). Residual material of the same ferricrete occurs as loose iron pisoliths (0.2–2.0 cm in size) on the soil surface. Massive, 5–15 cm sized, lumps of dense ferricrete are common as surface

Table 2
Results of XRF analysis of ferricrete lumps (excluding clayey matrix material), indicating the substantial content of volatile components, including organic matter.

Component sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	K_2O	Na_2O	P_2O_5	LOI	Total
Halma-1	16.94	0.49	9.42	59.62	0.08	2.04	0.03	0.05	0.00	0.06	9.68	98.42
Halma-2	17.16	0.50	9.40	59.59	0.09	2.04	0.04	0.05	0.00	0.06	9.68	98.60

detritus. Table 2 illustrates the predominant iron-oxide composition of the ferricrete. In XRD analysis, goethite, haematite and residual quartz were identified as major components.

The formation of the ferricrete crust (sometimes colloquially indicated as 'laterite', for terminology see the discussion in McFarlane, 1976, 1983; Pain and Ollier, 1992; Thomas, 1994) eventually results from the movement and precipitation of iron and aluminium substances in the subsoil and saprolith. As discussed in McFarlane (1983, 1987), Ollier and Galloway (1990) and Thomas (1994), ferricrete formation involves interrelated weathering, hydrologic and geomorphic processes. The initial formation of the ferricrete is determined by the groundwater level controlled formation of an iron illuviation horizon in the shallow subsoil (cf. Ollier and Galloway, 1990). This required high groundwater levels and absence of topographic relief as in a base-levelled alluvial coastal plain. In the Kao area, some lateral movement of iron-enriched groundwater towards slightly depressed river courses may have contributed to apparent discontinuous occurrence of the ferricrete (cf. Maignien, 1966 in Thomas, 1994; Pain and Ollier, 1992). Uplift of the coastal plain and progressive incision of the drainage system caused exposure to oxidising conditions of the iron accumulation horizon. This stimulated cementation and irreversible hardening of the incipient ferricrete and resulted in the development of the crust. Immobilization (fossilization) of the ferricrete material (mostly iron and aluminium compounds, with some organic matter) took place with induration. Although it is reported that the formation of ferricrete crusts is stimulated under more seasonal climate conditions, with a hot, dry season (Duchaufour, 1977/1982), lateritic crusts also occur in areas with (actual) perhumid climates (i.e. Mohr et al., 1972; Duchaufour, 1977/1982; Thomas, 1994). It appears that in the Kao area, under the present morphologic and climatic conditions and under influence of deep-rooting vegetation, the ferricrete is quickly broken up. It is postulated that the presence and formation of the ferricrete is indicative of a distinct, short phase in the morphologic and environmental development of the Kao coastal plain, namely the initial base level and groundwater level lowering, and stream incision, leading to subaerial exposure, oxidation, induration and immobilization of the iron accumulation horizon. The presence of a small fraction of organic compounds in the iron pisoliths (Table 2) enables the application of radiocarbon dating (see also Bird et al., 1994). Results of ^{14}C AMS analysis on two samples of Kao ferricrete are presented in Table 3.

A tentative interpretation of the dating results, considering also the ferricrete formation processes, suggests the pisoliths indurated and became inactive around the Pleistocene–Holocene transition, some 9500 yr B.P. (10 800 cal. yr B.P.). This would also place the phase of (renewed) incision in the latest Pleistocene or beginning of the Holocene. The possible implications of these palaeoenvironmental developments are further discussed in Section 5. The $\delta^{13}C$ values between −28 and −30‰ indicate ferricrete crust organic matter derives from C3 plant material and not from C4 plants with anomalously high $\delta^{13}C$ signatures or from other (soil) organic matter reservoirs. Middelburg (1991) reports on similar $\delta^{13}C$ figures for supposedly terrigenous organic matter of the same age in lacustrine deposits in Kao Bay. Predominantly C3 plants would normally constitute the prevailing lowland rainforest vegetation in the area under warm, perhumid conditions. Presently, however, the coastal zone is characterised by widespread open grassland and only narrow belts of riparian 'gallery' forests along the incised (lower and therefore wetter) drainage system (see also Fig. 6C). The possibility was mentioned that these grasslands constitute a natural climax vegetation due to a seasonally dry climate and impact of burning. It is

Table 3
Radiocarbon (AMS) dating results of Kao area ferricrete material (selected pisoliths). For sample locations see Fig. 4. The two samples give remarkably consistent results. The younger ages of the HCl solvable organic fraction illustrate that the ferricrete is indeed a relatively open system in which the organic compounds are partly mobile. Therefore, caution is needed to use the dates of the residue fractions, regardless of the good match. $\delta^{13}C$ values of organic fraction encapsulated in the ferricrete may be considered indicative of the isotopic signature of the source organic matter (most likely decomposing vegetation material in the surficial soil horizon) (UtC Nr.: laboratory number of analysis; $\delta^{13}C$ (‰): abundances ratio $^{13}C/^{12}C$ with respect to the PDB reference Age (B.P.): ^{14}C ages Before Present calculated from obtained abundance ratio $^{14}C/^{12}C$ after normalization to $\delta^{13}C = -25‰$

Sample	UtC Nr	Analysed fraction	Mass (mg)	$\delta^{13}C$ (‰)	Age (yr B.P.)	Calibrated age (cal. yr B.P.)[a]
Halma-1	7955	HCl residue	0.420	−28.0	9450 ± 70	10 790–10 763
	7956	HCl-sol. Fr.	1.400	−30.0	4827 ± 48	10 547–10 395
	8081	Total residue	0.130	−28.6	10 240 ± 170	
Halma-2	8082	HCl residue	0.270	−22.3	9690 ± 110	10 991–10 801
	7957	HCl-sol. fr.	1.570	−28.4	4133 ± 44	10 752–10 580
	8083	Total residue	0.110	−29.0	10 910 ± 190	

[a] Calibrated age (cal. B.P.): intervals (1 sigma) using version 3.03 of the program Calib (Stuiver and Reimer, 1993) for the atmospheric environment.

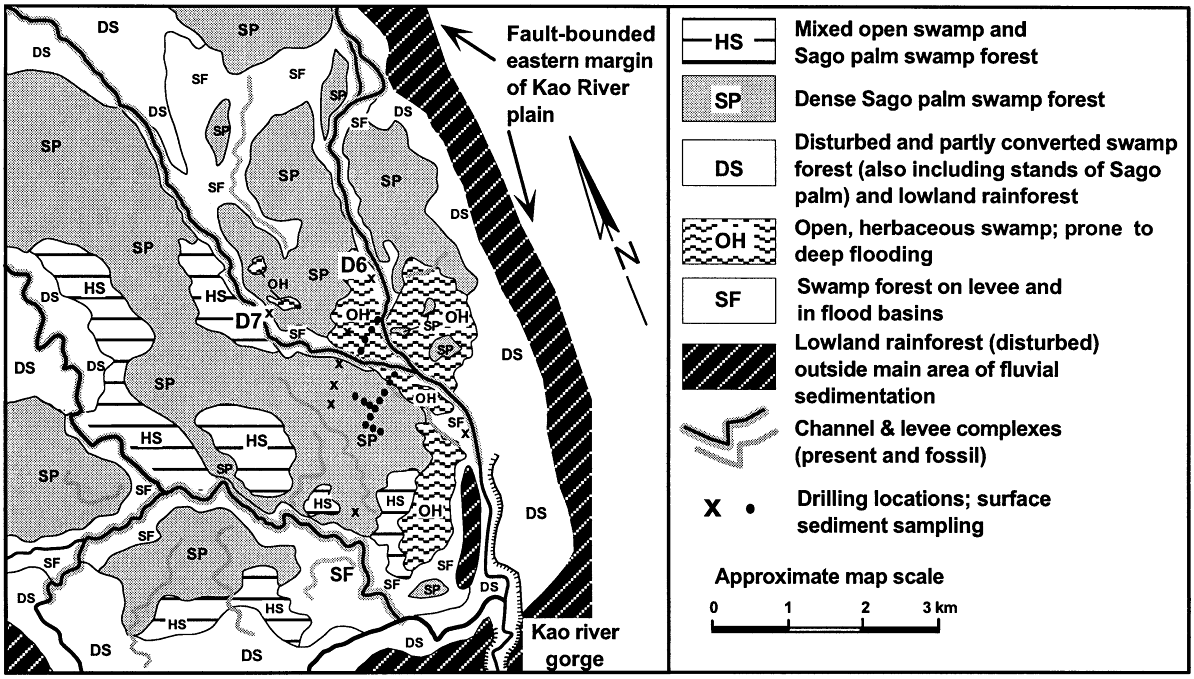


Fig. 5. Vegetation types/depositional environments in the study area in the central-southern Kao River plain, based on the interpretation of aerial photographs and field data. Dominant vegetation types appear to match depositional environments as both are largely determined by minor differences in elevation, proximity to main river channels, and degree of anthropogenic disturbance. Although present levees are very well developed (morphologically as well as texturally) there appear to occur very little fossil channel and associated levee systems. Sago swamp forest occupies extensive tracts in distal floodbasin settings. The location of the central swamp area is indicated in Fig. 2.

Fig. 6. (A) Swamp forest on levee. This extremely species rich vegetation only occupies a 20–50 m narrow strip along major river channels, on firm, slightly elevated ground. (B) Dense Sago palm swamps in perennially flooded, sediment starved floodbasins. (C) The marine erosion cliff in the coastal zone of the Kao area, Halmahera. (D) Impression of the sedimentology of raised beach deposits at the base of the cliff (stratified coarse sand with shell and shell debris layers). Radiocarbon sample Pasang-1 derives from this location.

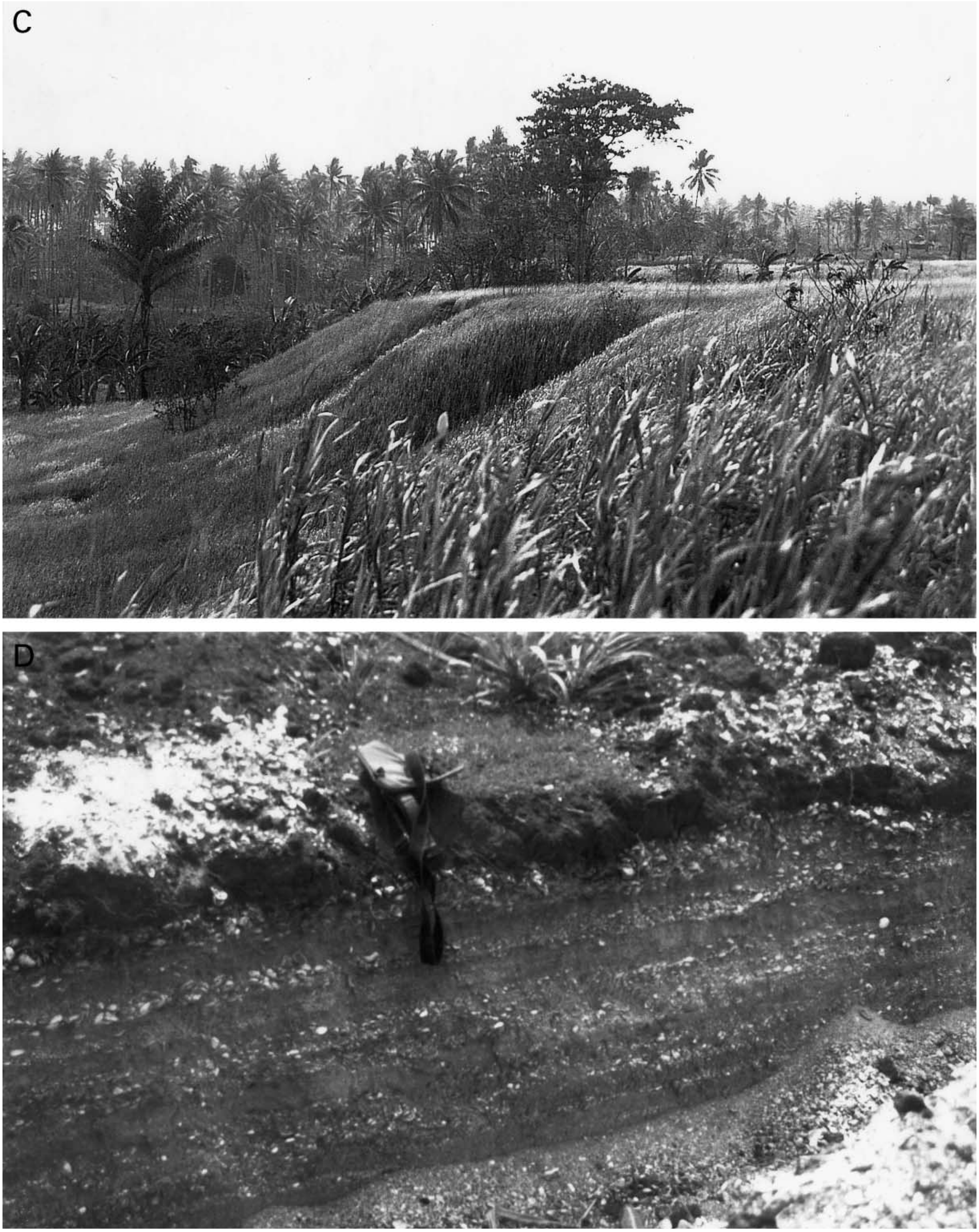


Fig. 6. (*continued*)

generally assumed that the *alang–alang* (tropical grasses) predominantly comprises C4 plants (i.e. Hofstra et al., 1972; Tieszen and Boutton, 1989). The isotope data of the ferricrete organic matter indicate the presence of lowland rainforests and probable absence of C4 plant grasslands during the late Pleistocene/earliest Holocene (or during ferricrete formation).

3.3. The Late Pleistocene coast

Pleistocene coral reef development only took place along the south–north oriented stretch of coast beginning some 17 km north of the present Kao River delta. Reef limestones occur in an isolated, slightly elevated (±30 m asl) patch north of Biang village, as a low, flattened ridge along the coast (Fig. 2A) and as low, reef terrace islands further north. The presence of the reef limestones along the present coastline suggests reef development took place in periods with a comparable coastal configuration, i.e. Middle to Late Pleistocene (or even Mid-Holocene) periods with high sea level. Tectonic uplift, a common feature in the eastern Indonesian region, has been responsible for the present elevated position (±30–50 m asl) of the former reef platform. It is speculated that the initial establishment of the reefs along this stretch of Kao Bay coast was aided by the presence of shoals resulting from the regional topographic and structural pattern, with fault-controlled north–south drainage divides and eastward tilted fault blocks (conform the eastern margin of Kao interior plain, as shown in Fig. 2). A south–north oriented fault zone along the coast north of Kao would, if extended further south, correspond with the steep eastern boundary of the deep Kao Bay basin (Fig. 2C). With the postulated Late Pleistocene–Holocene age for the reef limestones (Supriatna, 1980), this would imply Late Pleistocene and possibly younger activity for this N–S oriented fault system.

From the elevated positions of the former reef platforms, changes in the base level of the coastal plain and uplift of several tens of metres may be inferred. In addition, base level adjustments, following eustatic sea level change, have occurred. Maximum sea level lowering of 125–140 m occurred some 20 000 years ago (Aharon and Chappel, 1986). Studies on the palaeoenvironmental development of Kao Bay reveal that during the Late Pleistocene, a freshwater lake existed in the inner Kao Bay (Van der Linden et al., 1989; Barmawidjaya et al., 1989) and sea level was still around −40 m some 10 000 years ago. The maximum level of the former lake was presumably determined by a topographic sill of between −20 and −40 m to the northeast (Fig. 2C). This would imply a base level lowering of minimally ±40 m at the onset of the Holocene and possibly more during Late Pleistocene glacial times. The joint effects of tectonic uplift and eustatic sea level change on base level changes cannot be further quantified or precisely discerned. However, significant base level lowering (absolute: by tectonic uplift, and relative: by eustatic sea level lowering) during the younger part of the Late Pleistocene and even Early Holocene has enabled incision of earlier base-levelled coastal lowlands near Kao.

4. Holocene sedimentation and coastal evolution

During the Holocene, landform development in the interior Kao plain was, and is, characterised by sedimentation in low-energy fluvial systems and peat swamps, contrasting with earlier volcaniclastic sedimentation. Typical sedimentary facies, palynological data and sedimentary environmental and ecological aspects of these humid tropical, Mid-Late Holocene to (sub)recent depositional environments are discussed. In the coastal zone Mid-Late Holocene coastal accretion was stimulated by sediment supply and (relatively) falling sea levels, reversing earlier coastal erosion processes during the Early-Mid Holocene.

4.1. Sedimentary facies and environments in the Kao River plain

The interior Kao plain is a relatively well-confined, active depositional basin. Its central-southern part is characterised by the presence of extensive floodplain/channel, swamp and (probably) perennial lacustrine depositional environments (Fig. 5). In the following section, present-day environmental settings of this active depocentre are introduced, and the sedimentary facies of Late Holocene deposits are discussed. In Section 4.2, results of palynological analysis provide insight into the local and regional (palaeo/actuo) vegetation and ecology.

Coarser volcaniclastic and fluvial deposits along the western and northern fringes of Kao River plain (introduced in Section 3.1) merge into finer-grained and organic, fluvial and swamp/lacustrine sediments in the centre. On the basis of aerial photograph interpretation and ground checks, fluvial channel and levee complexes, backswamp/floodbasin, swamp forest and open herbaceous swamps can be distinguished (Fig. 5). Surficial deposits and sediments in shallow corings in these different settings indicate the presence of a variety of sedimentary facies and associated (active) depositional environments. The main types are:

- sand to gravelly sand: open, meandering channels (moderate to low currents, confined flow);
- clayey, silty sand to sandy clay, locally pronounced microrelief: fluvial levee and proximal overbank, with swamp forest to riparian swamp forest;
- fine-grained clastics (clay, silt, clayey sand, all with sand lenses) with low organic content, plant remains and abundant roots: proximal floodbasins, backswamps adjacent to larger channels, with swamp forest or open herbaceous swamp;
- peaty, organic clays, gyttja and peat: low energy backswamp (Sago palm — *Metroxylon Sago/ Metroxylon rumphii* swamp), open herbaceous swamp, partly open (perennial) shallow water.

Apart from small-scale, local differentiation (100–500 m^2) vegetation types correlate well with depositional settings and facies of recent (upper 0–30 cm) deposits, reflecting a consistent ecological response to evolving depositional (i.e. hydrological) conditions.

Analysis of sedimentary facies focused on corings D6–D7, located centrally in the active floodbasin/ swamp area (Fig. 5) and on selected surficial deposts (recent). Both cores comprise a sequence of mostly fine-grained, variably organic and occasionally peaty clastics, with intercalated compact peat layers. Data on sediment texture, organic content, C/N ratio and organic carbon $^{12}C/^{13}C$ ratios (Figs. 7 and 8) enable a more comprehensive description and interpretation of sedimentary environments. Four radiocarbon dates (Table 4) provide a chronology (Mid-Late Holocene) for continuous and active sedimentation. Sedimentation rates approximated on the basis of the four radiocarbon dates amount to 0.36–0.54 cm/yr (uncorrected for compaction, oxidation or erosion). This is very high for the type of deposit and illustrates the active infilling of the basin.

Texturally, the uppermost 1.5 m of core D6 consists of sandy, silty levee deposits. The next 5 m of the sequence is very fine-grained, with 40–50% clay and less than 5% sand, indicative of extremely low-energy environments such as herbaceous swamp or shallow water lake. From 6.5–10 m depth, sand layers occur, alternating with sandy clay. Frequent changes in texture are indicative of short-lived changes in depositional conditions: from channel/levee to floodplain/swamp. Below 10 m again fine-grained deposits (with >95% smaller than 64 μm and less than 5% sand) prevail, indicative of again low-energy environments (swamp to lake). In the lower section, several thin horizons with more sandy deposits could be the result of volcanic ash deposition (direct airfall or as fluvial fluxes).

Organic content of cored deposits is generally low to moderate, with marked peaks from 3–6 m and at 12 m depth; these peaty levels formed in swampy environments with little deposition of clastics. Organic content is rather low in channel and levee — proximal overbank sediments (6–9 m). Based on the close correlation of the N and organic C curves, nitrogen derives mostly from the organic matter in the sediment. Selected samples of recent (0–50 cm depth) deposits have a low (4%) to moderately high (30–45%) organic C content (see also Fig. 8). This reflects the relatively fresh, surficial accumulation of organic debris throughout the swamp area. The recent and ongoing disturbance of the swamp vegetation by human activity may have contributed to this thick, surficial organic layer.

C/N ratio and $\delta^{13}C$ isotope values ($^{12}C/^{13}C$ ratio) are indicative of organic matter type, enabling a broad distinction between dry terrestrial soil/swamp/lake, lake shore/deep lake organic matter (i.e. Talbot and Livingstone, 1989; Meyers, 1994; Aucour et al., 1999). For C/N ratios four levels can be distinguished:

0–1.5 m: the uppermost part of the sequence has C/ N values ≤10, coinciding with the change to levee deposits with minor amounts of residual (decomposed) organic matter;

1.5–6.5 m: C/N values rise to 10–15 with minor variations: these moderate values are probably indicative of a mix of decomposed and relatively fresh organic matter found in peat swamps;

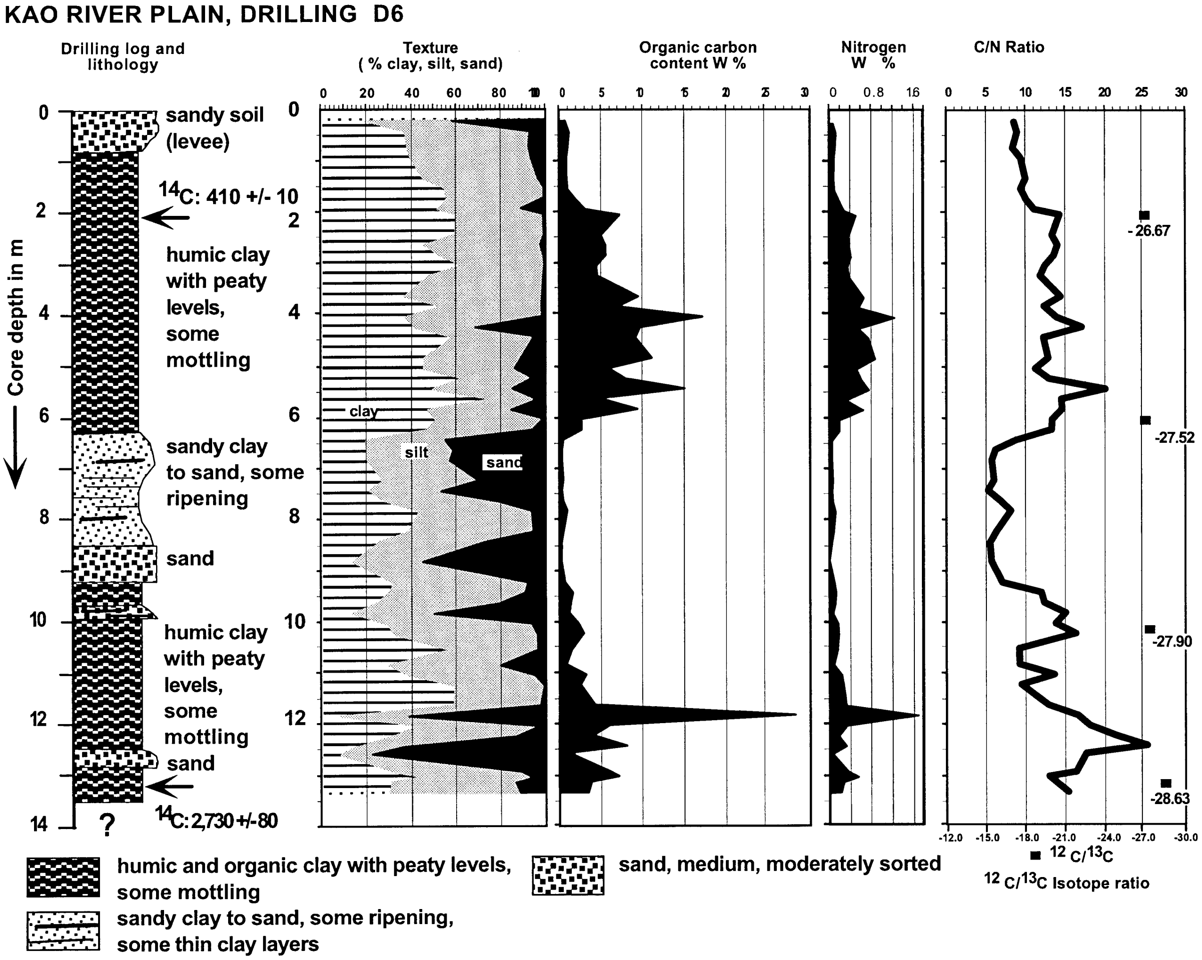


Fig. 7. Sedimentology and analytical data of Kao River plain sediments (core D6). Core samples were subsampled for texture, organic content and reconnaissance organic matter isotope analysis. Subsamples were freeze-dried and carefully homogenised. Texture was analysed in a Fritsch Laser particle sizer after pretreatment of bulk sample with 30% H_2O_2 (oxidation), boiling with 10% HCl (decalcification) and addition of dispersant ($Na_4P_2O_7 \cdot 10H_2O$) (Konert and Vandenberghe, 1997). Organic carbon and nitrogen content of 20 mg subsamples was determined after decalcification using a Carlo-Erba CNS analyser.

6.5–9 m: again low values occur of decomposed terrestrial organic matter that is deposited in small amounts with mostly clastic sediment in the fluvial system;
9–13.5 m: rather high values are indicative of advanced peat formation in a backswamp environment.

$\delta^{13}C$ values of core D6–D7 sediments vary around −27 to −28‰, and are indicative of terrestrial organic matter of C3 plants (forest plants, trees, dense vegetation in herbaceous swamp or swamp forest). Therefore, it is unlikely that C4 plants (tropical grasses, Cyperaceae species), or abundant lacustrine Algae have made a major contribution to the organic deposits in the sequence. Isotopic values of a variety of recent (0–50 cm depth) deposits with a low (1–3%) to moderately high (30–45%) organic C content and of selected herbaceous plants in the area are consistently in the range of −26 to −32‰ (Fig. 7). Consequently, it can be concluded that C4 plants are absent from (or only form very minor components) in both Mid-Late Holocene and recent swamp vegetation. $\delta^{13}C$ values of the 16 samples analysed do not

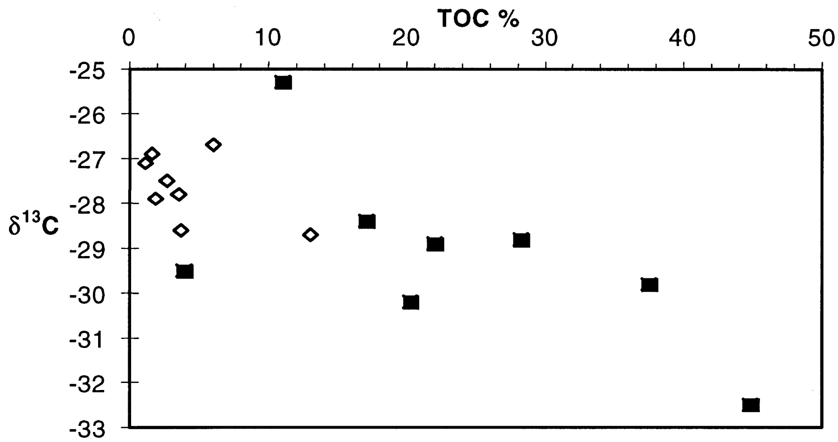


Fig. 8. $\delta^{13}C$ (of bulk organic matter) vs. organic carbon content of selected samples (◇) D6 and D7 core samples (2.0–13.5 m depth, see also Fig. 7; (■): recent deposits, 0–50 cm depth).

show any relation with organic C content (Fig. 8), radiocarbon age (or ^{14}C activity), sedimentary facies of the deposit or palynomorph content (relative amount of Cyperaceae + Poaceae, see below). The general similarity in organic carbon parameters of recent and older deposits suggest former vegetation types and ecological settings largely resembled that of today. Recent deposition of organic debris is probably stimulated by anthropogenic disturbance.

In general, sedimentary facies data do not provide indications that palaeomilieus in the Kao River plain were notably different from present-day environmental

Table 4
Results of radiocarbon dates of Holocene floodbasin deposits and beach shell in the Kao area, Halmahera (GrN: Groningen, The Netherlands). Groningen analysis (conventional ^{14}C and $\delta^{13}C$) follows procedures described in Mook and Streurman (1983) and Mook and Van der Plassche (1986). Radiocarbon ages were calibrated to the bidecadal tree-ring/marine coral calibration curve using CALIB v. 4.2 (Stuiver and Reimer, 1993, 2000). Ages are calibrated in years B.P., and expressed as the median age (bold) and two sigma (95.4% confidence) ranges. The sequence of core D6 is discussed in the text. The locations of cores D6 and D7 are indicated in Fig. 5. Core D7 consists of a comparable sequence (11 m in length) of fine-grained clastic–organic deposits, but with more, and compacted, woody peat levels. Sample locations of the Holocene coastal deposits are indicated in Fig. 3. Fig. 7D shows the typical beach deposit in location Pasang-1

Sample	Laboratory Ref.	Depth (cm)	$\delta^{13}C$	Radiocarbon age B.P. (uncal.)	Calibrated ages[a] B.P.
D6-1	GrN-22889	210–215	−26.67	410 ± 110	498 (572–274)
D6-2	GrN-22890	1320–1330	−28.63	2730 ± 80	2828 (3003–2735)
D7-1	GrN-22891	520–525	−27.81	950 ± 120	807 (1087–661)
D7-2	GrN-22892	1090–1050	−28.74	3030 ± 60	3226 (3364–3061)
Coast-1[b]	GrN-23585	100–110	+0.27	2640 ± 25[c]	2321 (2903–1721)
Biang-1[d]	GrN-23584	200–210	+0.23	3750 ± 50[c]	3673 (4982–2432)
Pasang-1[e]	GrN-23587	200–210	+0.94	3730 ± 30[c]	3637 (4420–2917)
DimDim-1[f]	GrN-23586	150–160	+0.93	4640 ± 30[c]	4837 (5575–4101)

[a] Calibrated age (cal. B.P.): intervals (1 sigma) using version 3.03 of the program Calib (Stuiver and Reimer, 1993) for the atmospheric environment.
[b] Shell debris sample from base of cliff exposure, upper beach; topographic level ±2.5 m + asl.
[c] Radiocarbon age including 400 year correction for marine shell samples.
[d] Shell debris sample from beach deposit, approximate topographic level 2.5–3.0 m + asl.
[e] Shell debris sample from beach deposit, approximate topographic level 1–1.5 m + asl.
[f] Shell debris sample from beach deposit, approximate topographic level 2.5–3.5 m + asl.

settings. In the vicinity of coring D6, extensive floodbasins (deep swamps) experienced perennial deep flooding, with deposition of fine-grained clastics and organics alternating with in situ organic deposition and peat formation. Spatially, these low-energy settings predominate. Very likely, no open water shallow lake environments have existed for prolonged periods. Coarser clastics are supplied by active fluvial systems and form levee, channel and occasional crevasse splay deposits. High sedimentation rates essentially result from high in situ organic production and the entrapment of fine-grained sediment by dense herbaceous vegetation (*Phragmites*) or dense stands of Sago palm. At least for the last 3000 years, these settings have prevailed in Kao River plain, with probably an intricate spatial and temporal alternation of the limited variety in depositional settings. Subtle environmental change was primarily controlled by autogenic fluvial system dynamics (i.e. meander migration, avulsion, floodbasin infilling, differential net vertical accretion). Allogenic effects on the fluvial system/catchment (i.e. neotectonics, variations in discharge, extreme changes in sediment influx due to volcanic activity) are not apparent in the depositional record, but this interpretation is hampered by the low number of deep cores. Present deforestation and drainage of parts of the swamp results in higher rates of mineralization.

4.2. Palynological data

A complete palynological analysis was performed on core D6 sediments. Samples for palynomorph and charcoal particle analysis were selected at mostly 20 cm depth intervals and prepared following standard methods (see Van der Kaars et al., 2000). Results of the palynological analysis are presented in Fig. 9.

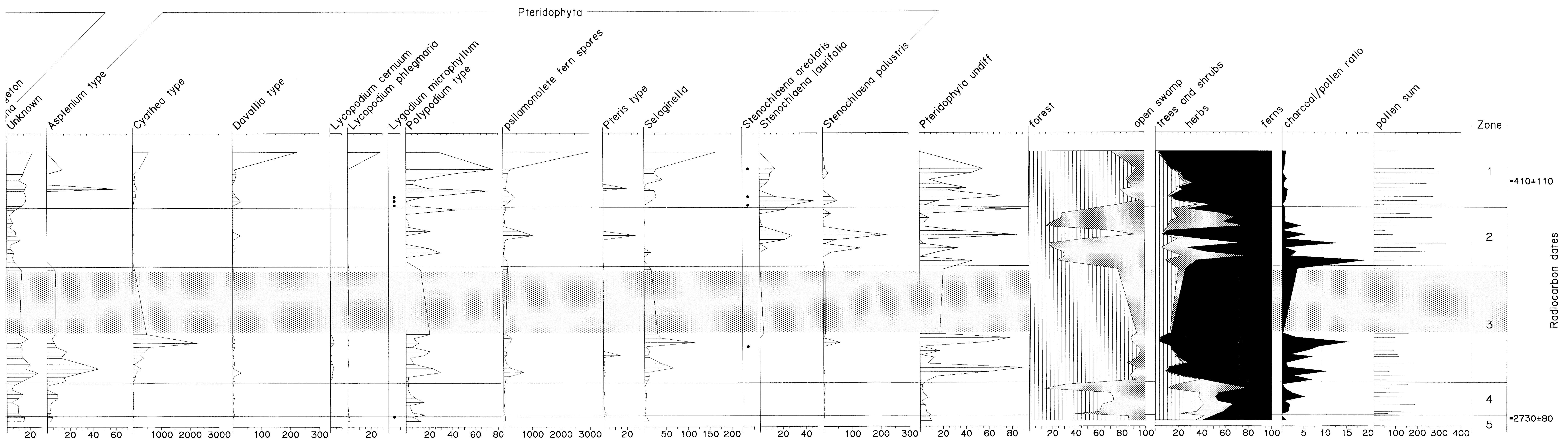
Results: In all, 64 samples were processed from core D6; the interval between 945 and 645 cm proved to be barren of palynomorphs, most of the other samples have been used for pollen analysis (46 in total). Non-siliceous Algae were not encountered during the analysis, with the exception of some *Spirogyra* at 345, 365, 385, 425, 545 and 565 cm. The pollen diagram (Fig. 9) has been divided into 5 zones based on major changes in the ratio between trees, shrubs and herbs. Pollen zone 5, 1335–1310 cm, is characterised by a diverse tree assemblage, with a high representation of Palmae and Pteridophyta. In pollen zone 4, 1310–1155 cm, Poaceae values are higher, with lower values for Palmae and Pteridophyta. However, the diverse tree assemblage is still present. Pollen zone 3, 1155–610 cm, shows the return of a Palmae and Pteridophyta-rich, diverse tree assemblage. In pollen zone 2, 610–335 cm, there is a strong increase in Poaceae numbers and a reduction in *Duabanga*, *Endospermum*, *Myristica* and Palmae. Pteridophyta numbers vary strongly, *Elaeocarpus*, *Stenochlaena laurifolia* and *Stenochlaena palustris* values are increased. Pollen zone 1, 335 cm to the core top, again shows the return of a Palmae and Pteridophyta-rich diverse tree assemblage. The charcoal record shows strong variation with many peaks from about the base of zone 4 to 425 cm core depth.

Discussion: Although little is known about the ecology of Halmahera, the very diverse nature of the palm and fern-rich tree pollen assemblages, containing many taxa described by Monk et al. (1997), is probably characteristic for lowland rain-forests on Halmahera and Seram (see Table 5). The assemblage is without any clearly dominant taxa and with relatively low representation of secondary taxa, suggesting the presence of a fully established lowland rain-forest vegetation for the last 3000 years. Pollen zones 2 and 4 probably represent two (short) periods of disturbance, characterised by the (local) expansion of a open, grass-rich, herbaceous swamp vegetation, possibly *Phragmites* swamp. However, it appears that lowland rain-forest vegetation remained present around the site and quickly recovered. There seems to be no direct link between the periods of disturbance and changes in the charcoal record, nor does there appear to be a strong link between the charcoal record and possible vegetation developments. The stronger presence of charcoal particles below 425 cm core depth suggests that burning was more frequent in the older part of the record. The absence of non-siliceous Algae suggests that a swampy to very shallow water environment prevailed for the last 3000 years.

4.3. Coastal development

Environmental stability in the coastal lowlands during the Pleistocene, with possibly river course incision reactivated during the youngest period with low sea level, was followed by coastal erosion induced by

Fig. 9. Results of palynological analysis of D6 core sediments. All taxa are shown as a percentage of the total pollen sum except for those taxa that occur infrequently and with low values. For these, only their presence is indicated with dots. The shaded zone indicates the interval from 945 to 645 cm that is devoid of pollen.



Pteridophyta
Unknown
Asplenium type
Cyathea type
Davallia type
Lycopodium cernuum
Lycopodium phlegmaria
Lygodium microphyllum
Polypodium type
psilamonolete fern spores
Pteris type
Selaginella
Stenochlaena areolaris
Stenochlaena laurifolia
Stenochlaena palustris
Pteridophyta undiff
forest
open swamp
trees and shrubs
herbs
ferns
charcoal/pollen ratio
pollen sum
Zone
1
2
3
4
5
410±110
2730±80
Radiocarbon dates

Table 5
Plant taxa identified in the palynological analysis of core D6 sediments ([hs]characteristic lowland rain-forest tree taxa on Halmahera[h] and/or Seram[s] (Monk et al., 1997))

Acalypha comp.	*Ficus* type[hs]	Rhizophoraceae[h]
Acanthaceae	*Freycinetia*	Rutaceae
Agathis[hs]	*Garcinia*[h]	Santalaceae comp
Aglaia	*Gironniera–Trema*[h]	*Sapium* type
Anacardiaceae[h]	*Glochidion* type	*Stemonurus* type
Anodendron type	*Grewia–Triumfetta*	*Terminalia* type[s]
Antidesma–Baccaurea type	*Helicia* type	*Alternanthera* type
Arenga type	*Ilex*	Amaranthaceae
Barringtonia[h]	*Ixora* type[s]	Asteraceae Liguliflorae
Blumeodendron type[h]	*Kleinhovia* type	Asteraceae Tubuliflorae
Calamus type	*Lagerstroemia*[h]	Campanulaceae
Calophyllum[hs]	Leguminosae[hs]	Convolvulaceae
Campnosperma	*Lithocarpus* type[hs]	*Crinum* comp
Casuarina type[s]	Loranthaceae	Cyperaceae
Celtis[s]	*Macaranga* type[h]	Malvaceae
Cocos nucifera type	Malpighiaceae	*Ludwigia* type
Combretocarpus rotundatus	Moraceae–Urticaceae	*Nymphoides*
Crudia	*Myristica* type[hs]	Poaceae
Cunoniaceae[h]	*Myrsine*	*Polygala* type
Cupressaceae	*Nauclea* type[h]	*Polygonum*
Dacrycarpus	*Neoscortechinia* type	*Potamogeton*
Dacrydium	*Nepenthes*	*Typha*
Dillenia[h]	*Nephelium* type	*Asplenium* type
Dipterocapaceae[hs]	Oleaceae	*Cyathea* type
Distyllium	*Palaquium* type	*Davallia* type
Dodonaea	Palmae undiff[h]	*Lycopodium cernuum*
Duabanga type[s]	*Pandanus*[h]	*Lycopodium phlegmaria*
Durio-Neesia type	*Pentace* type	*Lygodium microphyllum*
Elaeocarpus[h]	*Phyllocladus*	*Polypodium* type
Endospermum type	*Planchonella* type	psilamonolete fern spores
Engelhardia[h]	*Podocarpus*	*Pteris* type
Ericaceae	*Polyosma* comp	*Selaginella*
Eugenia type[hs]	*Pometia pinnata*[h]	*Stenochlaena areolaris*
Excoecaria type	*Quercus*	*Stenochlaena laurifolia*
Fagraea	*Randia* type	*Stenochlaena palustris*

rising sea levels and a Mid Holocene sea level highstand. This resulted in the formation of a conspicuous marine erosion cliff in the coastal area near Kao. During the Late Holocene (from ±4600 yr B.P. to Present) delta progradation and coastal accretion was facilitated by sediment fluxes from the interior and possibly a minor (absolute) drop in sea level. Aspects of early human presence are discussed.

4.3.1. The marine erosion cliff

One of the most conspicuous features in the coastal zone of Kao is a 10–15 m high marine erosion cliff that forms the interior boundary of the young coastal strip. The cliff face exposes older (Pleistocene) alluvial fan deposits (see Section 3) in a steep, seaward cliff face (Figs. 4 and 6C). This cliff face can be traced in the field and on aerial photographs from the northern bank of Kao River, northeastwards until it reaches the present coast. Further north, the present coast is a rocky (coral limestone) cliff, possibly the continuation of the same erosional coast. South of Kao River, intrusive igneous bedrock and volcanics are found up to the coast, with rocky headlands and steep topography. Exposures and shallow corings close to the base of the cliff reveal the presence of stratified, well sorted, rounded gravel and sand deposits in slightly inclined beds (Figs. 4 and 6D). Abundant whole shells and shell debris in lenses are intercalated. The deposits are clearly formed in a former beach environment. Whole marine shells form suitable sample material for radiocarbon dating. Results are included in Table 4.

The cliff marks a former coastline in the Kao area and forms a distinct boundary between the interior morphology (dissected relief, dendritic drainage pattern, deeply weathered red soils) and the young coastal strip (near-absence of relief, young swampy soils). The steep seaward slope of the cliff face, appears too steep to have been formed in loose sandy deposits, suggesting the alluvial fan sediment was already slightly cemented when erosion took place. The development of the ferricrete crust (well exposed in the cliff face) also preceded the formation of the cliff. A newly discovered archaeological site is situated on the cliff where it reaches the incised Kao River valley (see below).

Development of the erosional cliff feature most likely took place during a period with relatively high sea levels, i.e. the previous or present interglacial. The regional geological setting and the well-preserved cliff-face suggest that it most probably formed in the Early to Mid Holocene, following the rapid Late Pleistocene–Early Holocene sea level rise (Aharon and Chappel, 1986; Geyh et al., 1979). Active erosion and retreat of the cliff face ended with the deposition of beach sediment at the base of the cliff and coastal accretion (see below).

4.3.2. The Holocene coastal strip and Kao River delta

An active beach environment existed around ±4600 yr B.P. in front of the cliff face, but subsequently coastal accretion took place, resulting in the development of the young coastal strip and the initial formation of the Late Holocene Kao River delta (Figs. 3 and 4). Beach deposits, with abundant shell beds in a sandy to gravelly sand matrix, grade into finer, shallow marine deposits towards the present coast. In the Kao River delta and in front of smaller streams also stratified gravel beds occur. The young coastal strip has a level topography with a very faint coastward slope. In Kao and near Biang villages, microrelief visible in the field and vegetation patterns on aerial photographs are indicative of subrecently accreted beach sand bars. The sequence of surficial, shallow marine deposits in the young coastal strip, with thicknesses of 2–4 m, and recent beach deposits overly the older alluvial fan series (Fig. 4). An erosive contact is observed in drillings, and the levelled alluvial fan surface probably represents the former wave abrasion platform associated with the marine cliff. The young coastal strip decreases in width away from the Kao River delta and coastal accretion also starts later, as can be inferred from younger beach deposits near Pasang, Biang and further north. Around 2600 yr B.P., coastal accretion had progressed up to the northern end of the Kao coastal area. Kao River delta progradation and to a lesser extent coastal accretion was stimulated by sediment fluxes from Kao River, fed by sources in the interior Kao plain. Accretion is estimated to have been in the order of 5–6 km (Kao River delta, disregarding delta-front erosion), ±1.5 km (Pasang) and ±0.8 km near Biang in the north. Coastal accretion was enhanced by a small 2–3 m drop in sea level in the Mid-Late Holocene, but also minor uplift of the eastern coast of North Halmahera cannot be excluded (see also Section 3.3).

4.3.3. Human presence in the Kao area

Evidence of early human presence in the coastal area was discovered on the corner of the marine erosion cliff and the adjacent fluvial terrace edge (Fig. 3). On the basis of pottery sherds and small artefacts, this archaeological site was possibly a fairly large settlement. Furthermore, along Kao Bay coast (south of our study area) we encountered several kitchen middens with 1–3 m thick accumulations of salt water and estuarine shells, with stone and ceramic artefacts and pottery sherds. These sites are all situated next to the present coast, on elevated (+20–30 m) locations. Bellwood et al. (1998) recently presented a chronological framework for the prehistory of the Halmahera region with early (possibly ±33 000 yr B.P.) human presence on the neighbouring islands of Morotai, Gebe and Kayoa. The archaeological sites in the Kao Bay area provide new evidence for relatively early human presence on Halmahera itself, which, on the basis of the discovered artefacts and the chronology proposed by Bellwood et al. (1998), date to around 3000–1500 yr B.P. Evidently, humans were present in the Kao coastal area when the described Mid-Late Holocene environmental developments took place. Our data do not allow us to speculate on the presence of humans in the Kao area during the Late Pleistocene, (cf. Bellwood et al., 1998). Flannery et al., (1995) discuss the probable impact of early humans on non-volant Halmaheran faunal composition, leading to the selective extinction of marsupial mammal species. It is likely that human activity also affected lowland forest vegetation (burning, use of specific plant taxa, notably Sago). Thus, early human presence may be related to the widespread and pre-modern occurrence of open grasslands in the Kao coastal area and the occurrence of dense stands of Sago palm in the Kao River plain swamps.

5. Discussion and conclusions

Interior and coastal lowland environments in the Kao area, Halmahera have been described. Developments in the area since the Late Pleistocene include changes in sedimentation and geomorphic development, sea level fluctuations and varying patterns in coastal development, adaptation of vegetation to the prevailing environmental settings and possibly changing ecological/climatic conditions, and the appearance of humans in the region.

The differentiation in topography/morphology of the Kao area, with N–S oriented topographic highs adjacent to depositional basins (the Kao River plain and the coastal area) is controlled by the regional structural geology. Inferred Late Quaternary fault activity likely played a role in the geologic development of the Kao coastal area and Kao Bay. Voluminous volcaniclastic sedimentation (from sources in the interior of N. Halmahera) has occurred in the Kao River plain but deposition diminishes towards the coast, where, after initial volcaniclastic sedimentation, gradual denudation occurred, leading to the development of a low-relief coastal zone. Kao river transported surplus sediment from the interior Kao plain to the off-shore basin of Kao Bay where Van der Linden et al., 1989 describe the presence of (volcaniclastic) turbidite deposits. Marked changes in base level (tectonic uplift, eustatic sea level change) during the Late Pleistocene and Early Holocene ultimately controlled geomorphic development of the coastal plain and coastal accretion/erosion. Despite perceived high sedimentation rates in the interior areas, Late Pleistocene/Early Holocene rapid sea level rise caused coastal erosion and the formation of a conspicuous marine erosion cliff. Only with relatively stable, Mid-Late Holocene high sea levels, sediment is stored in the river delta and as relatively young, accreted coastal plain.

The development of a ferricrete crust in the shallow subsoil of the inner coastal zone marks the presence of a base-levelled coastal plain. Induration of the iron-oxide enriched illuvial horizon took place as a result of changing geomorphic and hydrologic conditions. Results of ^{14}C dating of organic inclusions in the ferricrete tentatively suggest that this took place at the onset of the Holocene, probably as a result of increased fluvial incision, following tectonic uplift. Although a ferricrete crust is sometimes considered an indicator of seasonally dry tropical climates, our Kao area data do not allow us to infer anomalous (i.e. different than present) palaeoclimate characteristics. If ferricrete organic carbon isotope ratios may be considered indicative, a forest-dominated vegetation occurred in the area, which suggests Late Pleistocene/Early Holocene climatic conditions in the area were not too different from those today. Natural grasslands in the area, on first sight possibly indicative of a drier, seasonal climate and thus occurring since Late Pleistocene glacial times, are more likely a result of human presence in the Kao area since Late Pleistocene times.

Kao River plain is a tropical lowland, non-coastal, fluvial plain where formation of substantial organic peat swamp deposits takes place, alternating with deposition of moderately organic and clastic, fine-grained floodbasin sediments. Sedimentary environments of Mid-Late Holocene deposits are characterised by facies, organic content and palynomorph content, and a tentative comparison with (sub)recent sediments and depositional settings suggests and palaeoenvironmental conditions are largely comparable. The main area of deposition is characterised by high to extremely high sedimentation rates, induced by (1) initial high sediment influx, (2) the topography of the intramontane basin, with a low gradient and a narrow, fault-controlled outlet, and (3) the hydrodynamic conditions in densely vegetated herbaceous and Sago swamps and swamp forests in the south-central plain, stimulating deposition of even the finest sediment. Mid-Late Holocene coastal accretion and the progradation of Kao River delta are linked to these high sediment fluxes in the interior.

Palynological analysis of Kao River plain deposits adds information about vegetation and ecology to the presented geological and geomorphological data, but these data do not enable further distinction of environmental settings in the swamp area. In the ± 3000 yr record no marked vegetational/environmental developments are apparent, apart from temporary disturbances. Charcoal particle data vary independently of the main palynomorph curves, and this suggests charcoal particles from allochtonous sources have been deposited in the interior basin. The occurrence of disturbed lowland rainforest and open, natural grasslands in the coastal zone during pre-modern times, in combination with human presence since at least the Mid-Holocene (and probably earlier), could indicate a correlation of Mid-Late Holocene burning of forest by early man in the coastal zone with charcoal deposition in the interior plain. Alternatively, natural burning during periods of prolonged, El Niño stimulated drought (as observed during the 1997 field survey) may have occurred. Marked charcoal peaks would therefore either correlate with short periods of increased, human-induced burning (may be higher population densities), or with natural, attenuated periods of decreased precipitation.

Environmental characteristics observed in the Kao area can be evaluated in a regional, eastern Indonesian context. As shown in this study, Late Quaternary to recent deposits provide useful information on possible (structural) geologic regimes and active neotectonics. This probably holds true for most of the geologically rapidly evolving parts of eastern Indonesia. Whereas Late Quaternary volcanism strongly influences sedimentation and landscape evolution in parts of N. Halmahera and other volcanic arcs, more gradual denudation, weathering and even ferricrete formation on low relief surfaces are probably characteristic for landforms in tectonically stable areas. Also this differentiation is regional, with active volcanism in western Halmahera, parts of Bacaan and northern Sulawesi, and relatively stable geomorphic environments in eastern Halmahera, the larger islands to the east (Gebe, Obi, Misool, Waigeo) and large parts of eastern Sulawesi. Sedimentary records provide information on past geologic and environmental developments, but their usefulness is strongly affected by the nature of local depositional conditions; proper appreciation of these is essential to improve the value of palaeoenvironmental records in the region. In a similar way, the implications of scarce evidence for early human presence in the eastern Indonesian region need to be treated. This study shows that complex interactions of geologic, geomorphologic, pedogenic, ecologic, coastal and anthropogenic processes can be studied and tentatively reconstructed in lowland environments of Halmahera, eastern Indonesia.

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