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Palaeoenvironmental developments in the Lake Tondano area (N. Sulawesi, Indonesia) since 33,000 yr B.P.

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Abstract

Geo(morpho)logical, sedimentological and ecological developments in the Lake Tondano area since ±33,000 yr B.P., and limnological changes in the moderately-sized lake situated at 680 m asl in the northern part of Sulawesi, Indonesia are discussed. First, the environmental setting of the lake is presented. Study of the regional distribution of lacustrine sediments, and a detailed analysis of their sedimentary facies (texture, organic matter content) suggest major changes in size and depth of the lake and in past sedimentation. Insight into the long-term development of the lake (sedimentation processes) is highly relevant for sustainable use of the present lake. Analysis of diatom assemblages provides further detail of the changing aquatic settings of the lake; lake levels rise quickly around 33,000 and 12,000 yr B.P., fall dramatically between ±30,000 and 13,000 yr B.P. and are lowered gradually since approximately 6000 yr B.P., following Early Holocene high lake levels. Drainage of the lake is affected by both volcanic depositional events and regional climatic events. Palynological analysis is indicative of local palaeoecological settings in the lake area and regional climatic change; a distinct, Late Pleistocene phase, with lower precipitation and lowered mean temperatures is inferred. Furthermore, progressive deforestation of the Tondano uplands is evident, as well as diffuse anthropogenic/volcanic vegetation disturbance from the early Mid Holocene onwards. Information from sedimentary facies, diatom assemblages and local palaeoecology (pollen) are integrated to reconstruct palaeoenvironmental settings and processes in the lake area. This record of environmental change as well as the pollen-based record of regional vegetation and climate change corroborates other palaeoenvironmental data derived from the few terrestrial sites in the region. The data attribute a greater magnitude of temperature and precipitation change in the region than is commonly deduced in studies based on marine faunal and sedimentary records. The Lake Tondano sedimentary record is highly suitable for further analysis aimed at determining the exact timing and amplitudes of environmental change in the SE Asian equatorial region.

Keywords: quaternary; environmental and climate change; south-east Asia; lake level fluctuations; sedimentology; pollen and diatom studies

1. Introduction

Sedimentary sequences from lakes and swamps in the Indonesian region can provide detailed and valuable records of local geomorphological and ecological developments and of regional climatic change (i.e. Newsome and Flenley, 1988; Stuijts, 1993; Dam

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1994; Hope and Tulip, 1994; Hope, 1996; Van der Kaars and Dam, 1995). In particular the nature of environmental change in the period including the Last Glacial Maximum (20–18 Ka B.P.), the Pleistocene–Holocene transition and the younger half of the Holocene (human presence) has received attention. Fine-grained, moderately organic lacustrine deposits and peat with intercalated palaeosol and fluvial beds form suitable material for this kind of research, utilizing sedimentary facies (texture, organic content), palynology, radiocarbon dating, sediment geochemistry and (stable) isotopes.

The diatom facies of the lake sediments are used as an additional indicator of palaeo-environmental settings, in particular of swamp/lake aquatic ecology and of lake water chemistry. To date, diatom analysis has been little used for this purpose in the south-east Asian region (for a rare example see for instance Vyverman and Sabbe, 1994 or Van der Kaars et al., 2001), although the taxonomy and ecology of many freshwater diatom species was originally established on Sumatra and Java by Hustedt (1938/1939). We believe the use of this additional technique can provide a valuable contribution to the proposed palaeoenvironmental reconstruction.

Lake Tondano is situated in an elevated basin on the northern arm of Sulawesi (Fig. 1), in a region from which few, and sometimes contradictory palaeoenvironmental records are available. Van der Kaars (1991), Hope (1996), and Van der Kaars et al. (2001) inferred changes in terrestrial vegetation and concomittant climatic change in the region; Barmawidjaya et al. (1993) and Thunell and Miao (1996) and others, on the basis of marine oxygen isotope data concluded that Late Glacial Maximum ambient temperatures were only 0–2°C lower than present. The significance of the region is due to its position next to the West Pacific Warm Pool, considered to be a major component of the Pacific (and global) coupled ocean-climate system. Long-term climate variation records from terrestrial sites in the region are essential to complement the information from the marine domain and improve understanding of SE Asian–Pacific palaeoclimates.

The Lake Tondano catchment is one of the more densely populated areas in the volcanic highlands of Indonesia. The intensive land use results in conflicting claims, particularly on the lake. The lake (water) is used for hydropower generation, aquaculture, irrigation, tourism and drinking water. In the meantime, it has become clear that the lake system is seriously threatened by increasing siltation, water quality deterioration and deforestation in the catchment. This study presents a long-term perspective on the dynamics of the lake system, as a result of natural environmental perturbations. It is against these natural dynamics that recent disturbances have to be viewed and strategies for sustainable use have to be designed.

In summary, this study aims (1) to integrate information about palaeoenvironmental developments in the Lake Tondano area since 33,000 yr B.P., on the basis of a range of proxies (lithofacies, pollen, diatoms, lake level change), (2) provide insight into the nature of Late Quaternary environmental change in the region (including lake level fluctuations, sedimentation, vegetation and climate changes), (3) further develop the analysis of diatom assemblages in freshwater sediments as a tool for palaeoenvironmental reconstructions in the SE Asian tropics, (4) to provide for data concerning the long-term development of the lake, in view of current management issues.

2. Environmental setting

2.1. Geology and lake basin morphology

Lake Tondano is situated in a structurally controlled basin within the Late Tertiary–Quaternary volcanic arc of northern Sulawesi and the Sangihe islands (Fig. 1). Formation of the depression, with characteristics of a collapse caldera and a pull-apart basin, probably took place in two phases. White rhyodacitic ignimbrite '*Domato tuffs*' date from the Pliocene and in the Pleistocene grey dacitic '*teras*' tuffs were deposited (Lécuyer et al., 1997). The latter tuffs form an important deposit in the surroundings of the lake (Effendi, 1976; see also below). Basin formation was further induced by the regional pattern of strike–slip faulting, as a result of which Lake Tondano formed within a larger, NNE–SSW oriented pull-apart basin (Fig. 1, inset A). Late Quaternary volcanism is mainly concentrated in the western part of the basin and presently the Soputan complex (Fig. 1) is probably the only active volcano partly situated

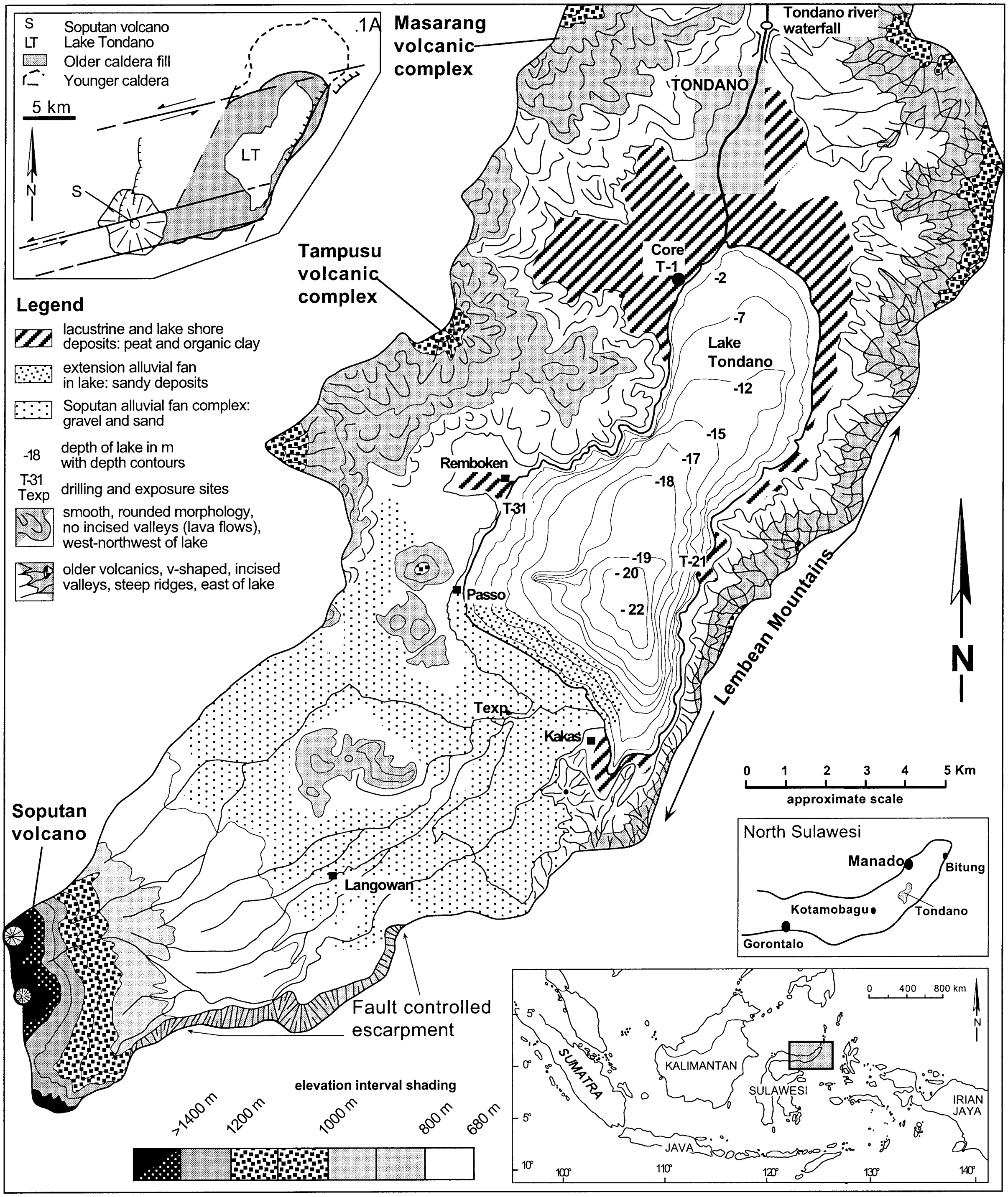


Fig. 1. Geomorphological and geological setting of the Lake Tondano basin. The geomorphological boundary is the drainage divide of the lake basin, on the basis of the 1:50 000 topographic map sheets (sheet 2417-23 Manado and sheet 2417-21 Langowan (Bakosurtanal, 1991). Geological information partly after Effendi (1976) and Lécuyer et al. (1997). Inset 1A: structural geological setting of the lake basin after Lécuyer et al. (1997).

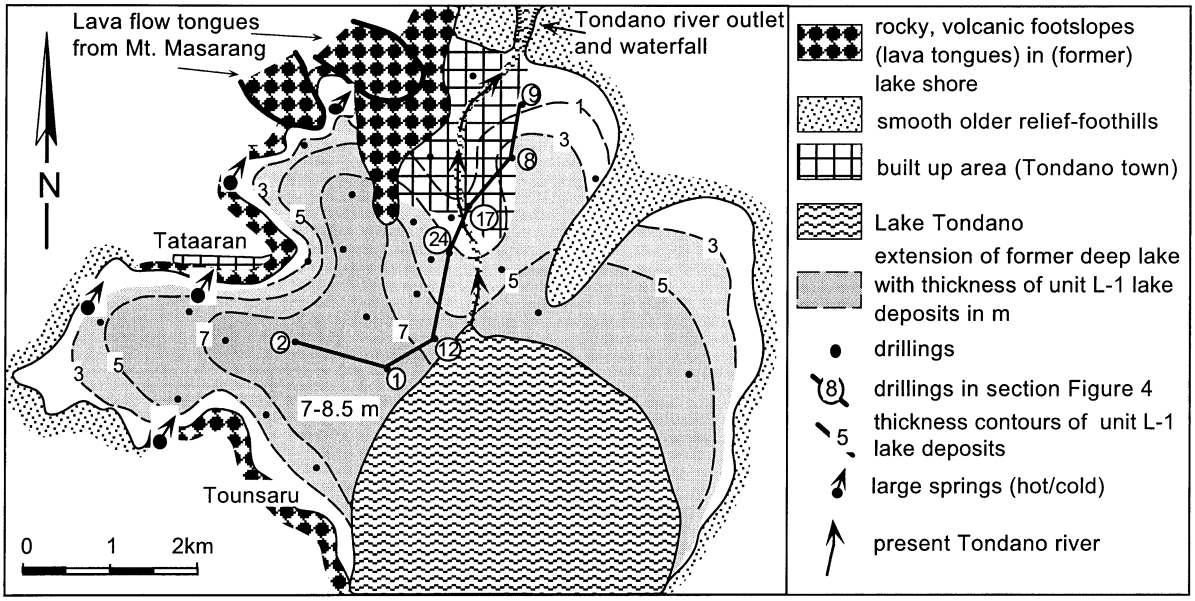


Fig. 2. Geomorphology and lacustrine sediment distribution in the northern Lake Tondano area.

within the lake basin. However, eruptions of the Masarang volcanic complex to the northwest of the lake have probably affected the development of Lake Tondano because relatively young lava flows occur adjacent to lacustrine deposits in the western part of the town of Tondano (Figs. 1 and 3).

Fig. 1 gives an overview of the regional geology and geomorphology of the lake shore and catchment area. The terrain along the eastern, fault-controlled, boundary of the lake consists of coarse dacitic ignimbrite tuffs. The intensively dissected slopes, with v-shaped valleys and ridges, become progressively steeper towards the south where the lake shore is formed by coarse igneous boulders and consolidated tuff matrix. In the far south, ongoing activity of the Soputan complex has resulted in the formation of a large volcaniclastic fan that extends into the lake. In contrast with other low-relief lake shore areas, the alluvial sediments here comprise volcaniclastic gravel, sand and clay, deposited by braided streams and mass-flows. Older volcanic cones in the southwestern catchment are partly obscured by younger volcaniclastic fan deposits, Locally, organic lake and lake shore deposits occur in embayments, as near the villages of Remboken and Kakas. A large part of the western lake shore consists of relatively young volcanic extrusives originating from Gn Tampusu complex (Gn = Gunung = Mountain). Lava flows form irregular relief with steep, rocky lake shores. Several hot springs occur (Fig. 2). This terrain is characterised by a near absence of a surficial drainage system, probably due to the high permeability of the fractured volcanic rock. In contrast to the hills in the eastern catchment no clear v-shaped valley and ridge morphology has developed. The difference in morphology is also suggested in Fig. 1. The northern part of the lake basin is bordered by presently inactive volcanic edifices to the northwest, with rocky or locally deeply weathered slopes. Sandy fluvial sediments, peaty lake shore and organic lake deposits cover a large area, and indicate the former expanse of the lake (see below and Fig. 2). Tondano River drains the lake in between the conspicuous lava flow ridge to the west and low, undulating relief (developed in ignimbritic deposits) to the east. The drainage level of the river and lake is controlled by the ignimbritic tuff deposits in the northern parts of Tondano town; further downstream a resistant lava flow forms a 30 m high cliff with a waterfall.

In the lake basin the absence of larger river systems entering the lake is partly due to the structurally controlled catchment configuration (Fig. 1, inset A)

Table 1
Rainfall data for the Lake Tondano region. Annual averages for Tondano town amount to 1958 mm (over a 37 yr observation period; Berlage, 1949). During this period an average number of 128 rain days/year (>0.6 mm/day) occurred

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tondano (680 m)	199	152	167	222	221	171	103	75	99	142	217	190
Masarang (800 m)	240	201	20–7	243	261	204	139	105	115	177	233	235

and the high permeability of the relatively young volcaniclastics and lava flows. Only the actively developing Soputan volcaniclastic fan is built up by somewhat larger streams that originate in the high terrain to the south and on the double cratered volcano. Small streams traverse the alluvial terrain north and northwest of the lake.

2.2. Climate and vegetation

Lake Tondano and its catchment, with mountains up to 1200–1600 m are situated in a NNE–SSW oriented mountain range which rises over a distance of 10–12 km from the Molucca Sea. The regional climate is determined by the seasonal passage of the Intertropical Convergence Zone (ITCZ), which brings heavy rainfall in the months of October/November until May. July–August–September are usually the driest months. The intensive El Niño of 1997 resulted in a severe and prolonged dry season (first author, personnel observation). Noon temperatures in Tondano town (680 m elevation) average 24–26° C year round and are accompanied by moderate to high humidity (60–90%). Orographic rains moving in with the eastern monsoon winds may bring heavy precipitation locally. Table 1 summarizes monthly rainfall averages.

The natural vegetation in the direct vicinity of the lake and surrounding highlands would have been evergreen lowland and lower montane rainforest, possibly with some natural grasslands and scrub (Whitmore, 1984). Bellwood (1976) and Clason (1980) present results of an archaeological investigation in the village of Paso, where, as early as about 8000 yr B.P. a human settlement occurred. The environmental impact of this early human presence was limited. Population densities in the Lake Tondano region increased strongly in the last two centuries (Henley, 1997). Widespread deforestation from the early 19th century onward has resulted in the virtual replacement of primary forest with forest plantations (clove, coffee) and impoverished secondary forests. The clove plantations are characterised by widely spaced trees and a herbaceous undergrowth. Impoverished forest vegetation with dense bamboo patches occupies rocky volcanic slopes. In the direct vicinity of the lake most of the flat to gently sloping alluvial terrain is now occupied by rice paddies. A narrow zone along the lake shore is locally used for vegetable gardens; some patches remain with Sago palms (*Metroxylon* spp.) and herbaceous swamps with abundant Cyperaceae and Gramineae. Nowadays, this herbaceous vegetation in the lake shore is often burned in the dry season.

2.3. Lake Tondano

Lake Tondano occupies some 4800–5000 ha (± 48 km^2) in the central-eastern part of the Tondano basin. In 1994 the water level of the lake was at an elevation of 683 (+0.50/−1.0 m) asl. (PLN, 1994). Lake Tondano was already considered a useful reservoir for hydropower generation early in this century. With the construction of the first hydropower station (probably in 1941) the lake level was lowered somewhat, following excavation of the volcaniclastic sill just downstream of Tondano. Nowadays the outlet level is strictly controlled to satisfy the various lake water users (irrigation, fish hatcheries, power generation and drinking water). The increasing demand for electricity has resulted in renewed attention on the capacity of Lake Tondano as a reservoir and on the perceived shallowing/siltation of the lake, supposedly due to deforestation and agriculture in the catchment (Whitten et al., 1988; Giesen, 1994). In 1994–1995, the outlet channel and Tondano river course were dredged to improve the outflow and flush some of the recently formed sediment. This was apparently successful as some parts of the lake became deeper. It is not clear whether these activities affected the lake level. Seasonal lake outflow, prior to these modifications,

Table 2
Tondano lake water quality data (after Pusat Penelitian Tanah dan Agroklimat, 1995, Rompas et al., 1996; in mg/l). Whitten et al. (1988) also present water quality data of the lake: pH range 7.5–8.8; conductivity 205–223 ohm/cm and Secchi disk transparency between 0.5–3.0 m. Lake water temperature is 24–26°C

Location	pH	K	Ca	Mg	Fe	NO3	SO_4	PO_4	sediment (mg/l)
Central Lake Tondano	7.5	3.51	11.8	7.32	0.19	0.62	–	0.00	27
Near outlet Lake Tondano	7.3	3.90	15.0	8.40	0.19	1.24	–	0.64	160
Shore Lake Tondano (fish cultures)	7.7	0.12	0.53	0.61	0.02	0.11	–	0.02	32
Tondano river upstream of Inlet hydropower station	7.7	5.07	21.8	9.48	0.38	3.72	–	0.32	93
Near outlet Lake Tondano[a]	6.5	1.70	14.4	7.46	–	–	18.5	–	–

[a] Data from Godschalk (1998) in ppm.

varied between ±10 and 1.5 m^3/s (Anon., 1923). The lake derives its water: directly from rainfall; from a large number of very small streams and a few bigger ones (Fig. 1); from a large number of (hot) springs in the lake shore around the water level and possibly from subaquous springs in the deeper southern part of the lake.

Data from a 1994 bathymetric survey (Fig. 1) show that a maximum depth of 21–22 m occurs in the central southern part of the lake. The steep morphology along parts of the western and most of the eastern lake shore continues below the water level. Depth contours furthermore reveal the subaquous extension of the volcaniclastic fan in the south and a steeper delta-front. Most of the northern part of the lake has only shallow depths of 6–10 m, and very gentle bottom gradients. Compared to the relatively large structural and topographic relief in the Tondano catchment the lake bottom appears rather flat and the lake shallow. This could imply a considerable accumulation of lake (?) sediment.

Water quality data for several locations in the lake and Tondano river are available from regional surveys (Pusat Penelitian Tanah dan Agroklimat, 1995 and Godschalk, 1998). Data are summarized in Table 2. Lake Tondano is considered eutrophic, in particular in comparison with other large lakes in Indonesia (Whitten et al., 1988; Giesen, 1994). It should be noted that local water quality in the lake shore and several small streams is strongly influenced by geothermal spring water and by recently introduced polluting fish (carp) breeding practices (pellet feeding) and semi-enclosed duck ponds. Human induced changes in Lake Tondano as reported by Giesen (1994) include significant siltation, changes in vegetation (introduction of exotic plants), introduction of fish species and overfishing.

The aquatic ecology of Lake Tondano is briefly discussed in several aquaculture and ecological studies (i.e. Rompas et al., 1996; Buchari, 1981)). Common species include (after Whitten et al. (1988) and Giesen (1991)) submerged weeds *Hydrilla verticillata*, *Ceratophyllum demersum*, *Najas indica*, *Ipomoea aquatica*, *Potamogeton malaianus* and *Polygonum* spp. Floating weeds include: *Pistia stratiotes*, *Spirodella polyrhiza*, *Lemna minor*, *Azolla pinnata* and *Salvinia* spp. Water hyacinth (*Eichhornia crassipes*) is present in small amounts. Predominant planktonic species are *Mycrocystis aeruginosa*, *Mycrocystis incerta* and *Westella botryoides* amidst some 40 other species; the presence of the dominant species varies little throughout the lake. Phytoplankton biomass amounts to 0.82 mg/l, dominated (in August 1993) by cyanophytes, diatoms (notably *Aulacoseira granulata*) and chlorophytes (Lehmusluoto et al., 2001). Lake Tondano also contains some 12 mollusc species (a.o. *Angulygra costata*, *Gyraulus tondanesis*, and the introduced species *Anodonta woodiana*). In conclusion it is posited that the Lake Tondano ecosystem is moderately disturbed but the most important natural functions of the lake remain relatively intact.

3. Lacustrine sediments

3.1. Distribution

Main focus of this study are the lacustrine deposits now exposed in the alluvial terrain adjacent to the present lake. A detailed description of these sediments is given in Section 3.2. The areas with identified lacustrine deposits (mainly organic clay, green–grey gyttja, peaty clay and peat, see below) are indicated in Fig. 1. These older lake deposits appear very similar to present lake sediments (gyttja, organic silty clay) that were observed and sampled as bottom sediment in the shallow parts of the lake. Along most of the lake shore, lacustrine gyttjas occur in the shallow water zone. Fine-grained, organic deposits also occur in the larger embayments in front of the larger valleys (as near Kakas, Remboken and Eris). These isolated occurrences consist of rather homogeneous successions 10–15 m thick, with sometimes minor peaty and sandy, organic clay intervals and thin tephra layers. In strong contrast, the exposed alluvial fan terrain along the southern lake shore consists of sorted sand and silt to the east and coarser sand and gravelly sand further west (Fig. 1). Towards the present lake shore, organic clay layers with large plant remains are intercalated in the clastic sequence, but these lake deposits probably wedge out towards the upper fan. Fine-grained and organic swamp deposits formed during periods when clastic sedimentation on the fan was inactive (around ±11–10,000 yr B.P., see also Section 4). Palynological analysis reveals no lacustrine, non-siliceous Algae, suggesting a terrestrial, swampy, fluvial depositional environment for these distal fan sediments. Sand deposits also occur subaqueously in the present lake, and this confirms the extension of the volcaniclastic fan as suggested by lake bottom bathymetry (see above).

The area with the most accessible and stratigraphically most complete deposits is found in the vicinity of the town of Tondano, mainly along the northwestern shore of the lake (Fig. 2). Drilling data indicate that the older volcanic relief dips steeply underneath younger lake deposits in the western 'embayment' between Tounsaru and Tataaran. A thick sequence of organic clays and peat (i.e. in drillings 1 and 2, Fig. 3) occurs in the centre, while organic clays with sandy and peaty levels (lake shore facies) are encountered in the vicinity of outcropping volcanics. In the northwestern and western part of Tondano town, coarse volcanics (lava flow boulders, mass flow deposits) directly border, and probably overly sequences of organic lake and lake shore deposits. Towards the northeast and east, relatively thin lacustrine deposits wedge out gradually over more subdued relief, developed in weathered older volcanics (Fig. 3). The stratigraphy and sedimentology of these lake shore and full lacustrine sediments is depicted in Fig. 3 and further discussed below.

3.2. Sediment lithofacies and chronology

Core T-1A/B contains a complete stratigraphic sequence and representative lacustrine sediments. Fig. 4 presents core log and analytical results, which are further discussed below. The sediment cores were taken with a hand-operated 6 cm D-section corer of 1 m length. Two separate corings were made next to each other, one (T-1A) shallow (0–10 m depth) the other (T-1B) deep (7–14 m). Core T-1A/B was described in detail in the field and the sequence was sampled in 10 cm parts for further analysis. For the interval 450–580 cm of the upper core T-1A poor quality sample was only suitable for visual description and no samples were taken. In the laboratory core samples were subsampled (every 10 cm) for texture, organic content and a reconnaissance geochemical analysis. Subsamples were freeze dried and carefully homogenized. 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.

In this core, sediments that consist of dark grey–green (Munsell colours 5GY 3/1-7.5 GY 3/1), silty–clayey gyttja, sometimes with large amounts of shell debris, are interpreted as full-lacustrine deposits (relatively deep, open water). Texture is predominantly clayey and silty with very minor amounts of sand. Organic content is in the order of 3–10%, while diatom content is generally high. Organic, silty, sometimes sandy, clay (black) and amorphous peaty clay to peat is considered shallow water, lake shore deposit. More sandy intervals may occur. Peaty levels contain more than 25% organic Carbon (organic matter content of >50%). Peat sometimes consists of recognizable plant remains with little wood, but is mostly amorphous. Thin volcanic ash

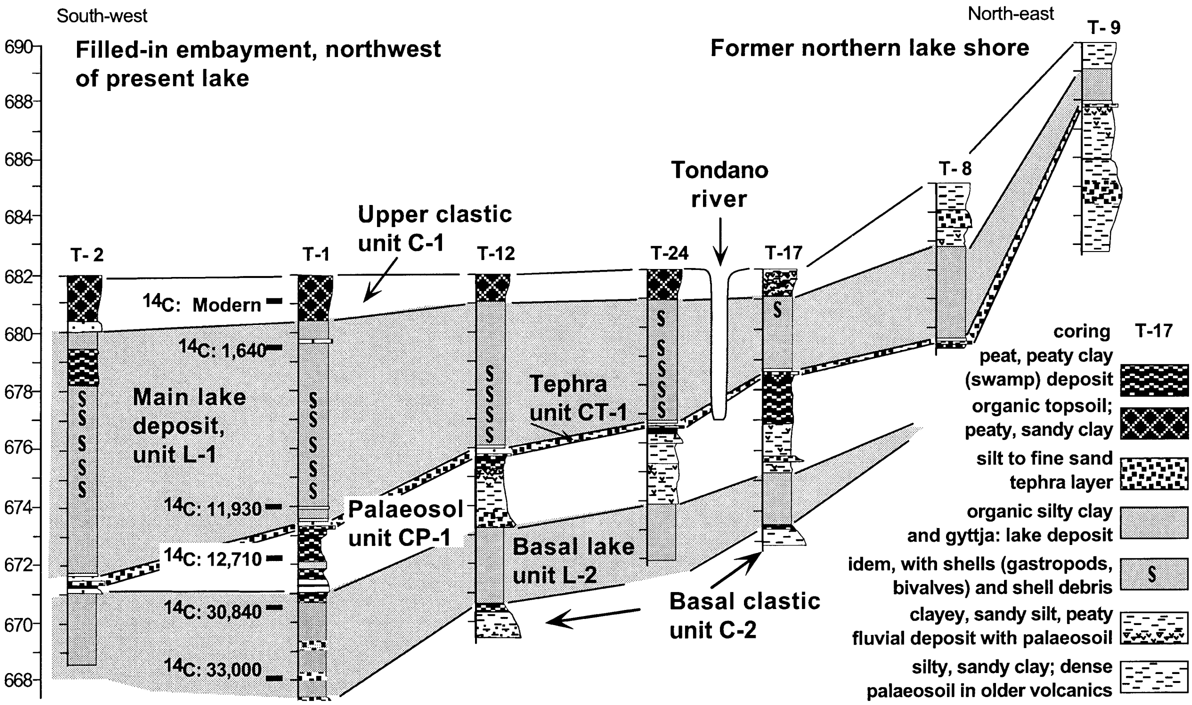


Fig. 3. Representative section with deep water lake, lake shore and clastic deposits in the northern Lake Tondano area, showing stratigraphy and distribution of Late Pleistocene and Holocene lacustrine deposits.

layers in lake and lake shore sequences show up due to distinct light grey colours, sharp bedding boundaries, lamination and sometimes coarser texture. Upper and basal clastic deposits exhibit greenish or brownish/red mottling, much stiffer consistencies, a crumbly structure, vertical root traces and clear organic content gradients, indicative of (palaeo)soil formation. Representative sequences are shown in Fig. 3, with correlation of the units based on clear similarities in lithofacies and stratigraphy. The complete sequence consists of (Fig. 4): a basal clastic unit C-2; a lower lake unit L-2; an intercalated clastic deposit with palaeosol, unit CP-1; the characteristic multiple tephra layer CT-1; the main, upper lake deposit, unit L-1 and at the surface a (sub)recent clastic deposit with the present soil, unit C-1. This sequence (or major parts of it) is encountered throughout the northern lake shore area (Fig. 3) but lacustrine sequences further to the south also fit this general succession. The upper lake unit L-1 is always encountered as an uninterrupted, homogeneous sequence of variable thickness.

Radiocarbon dating focuses on the sequence of master core T-1A/B with 6 radiocarbon dates (Table 3, Fig. 4). The latest Pleistocene onset of lacustrine sedimentation in core T-1A (sample T-1A/3 at a depth of 8.05–8.10 m) is confirmed in core T-31 (south-western shore of Lake Tondano, Fig. 1), where the base of the upper lacustrine sequence is dated 11,800 B.P. Organic deposits in the lower part of the core are considerably older and suggest the presence of a depositional hiatus between 10.0 and 10.9 m in the core. The bulk organic material (samples T-1B/2 and 3) does not show any signs of weathering or advanced decomposition, that could indicate the deposit contains older, reworked organic remains. The modern date for the uppermost sample at 90–100 cm is probably the result of admixture of recent soil organic matter. Results are further elaborated below.

3.3. Palynological analysis and results

A complete palynological analysis was performed

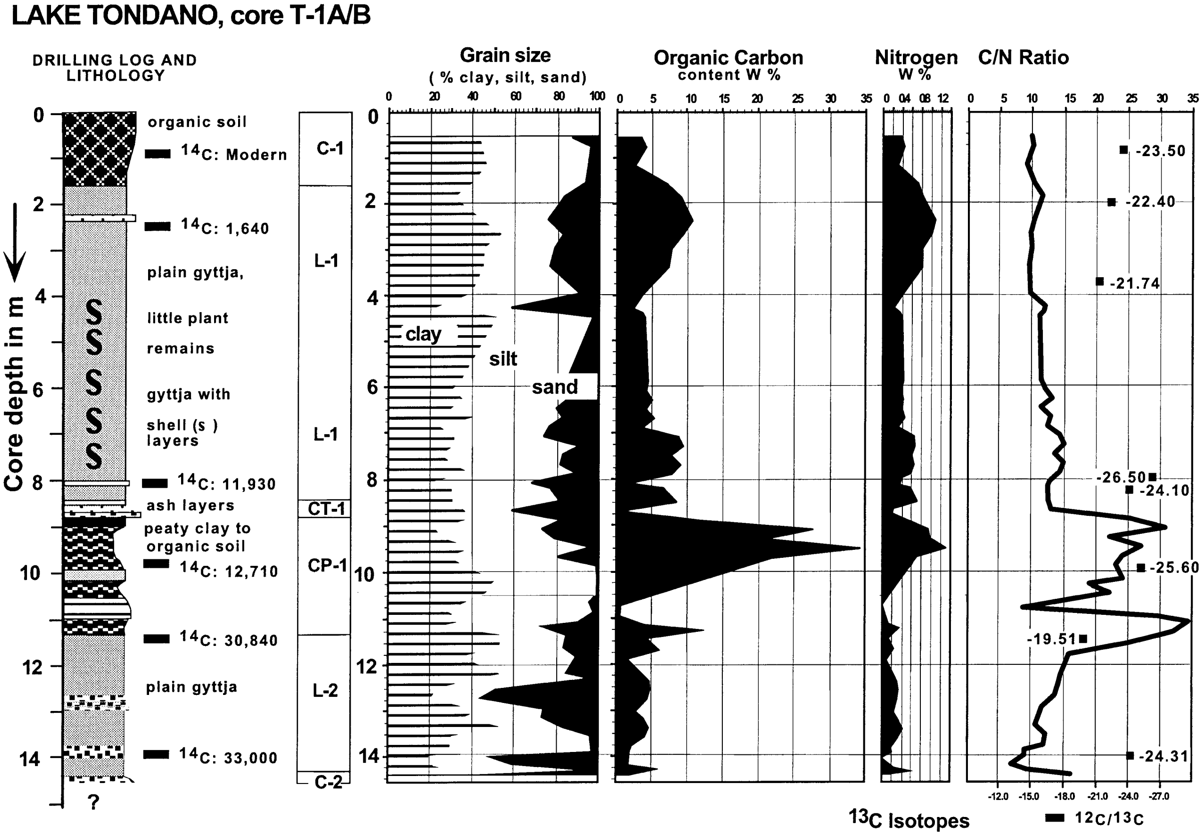


Fig. 4. Stratigraphy, sediment facies, texture, organic Carbon and Nitrogen content, C/N ratios and organic Carbon isotope ratios of core T-1A/B sediments. For meaning of sedimentary facies signatures, see Fig. 3. Radiocarbon ages in conventional yr B.P., see also Table 3. For the interval 450–580 cm of the core poor quality sample was only suitable for visual description and no samples were taken.

Table 3

Radiocarbon dates Lake Tondano sediment. T1- and T31 bulk samples of lacustrine gyttja and organic, peaty clay; Texp.-1: herbaceous and woody large plant remains: conventional radiocarbon dating. (GrN: Groningen, The Netherlands; Wk: Waikato, New Zealand). Groningen analysis follow 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 yr B.P., and expressed as the median age (bold) and two sigma (95.4% confidence) ranges

Sample	Laboratory Ref.	Depth (in cm)	$\delta^{13}C$	Radiocarbon Age B.P. (uncal.)	Calibrated ages B.P.
T-1A/1	Wk-6084	90–100	−23.50	Modern	–
T-1A/2	Wk-6082	250–260	−22.40	**1640 ± 80**	**1533** (1712–1350)
T-1B/1	Wk-6083	805–810	−26.50	**11 930 ± 200**	**13 937** (14 342–13 447)
T-1A/3	GrN-22895	990–995	−24.80	**12 710 ± 280**	**15 352** (15 961–14 129)
T-1B/2	GrN-23588	1090–1095	−19.51	**30 840 + 1900/−1500**	–
T-1B/3	GrN-23589	1350–1355	−24.31	**33 000 + 3700/−2500**	–
T-31	GrN-23827	1210–1220	−26.69	**11 830 ± 440**	**13 828** (14 498–12 309)
Texp.-1	GrN-24422	300–320	−28.25	**10 580 ± 80**	**12 738** (12 935–12 309)

on core T-1A/B sediments. Samples for palynomorph and charcoal particle (size fraction 8 to 180 μm) analysis were selected at mostly 20 cm depth intervals. 2 cm^3 of sediment was processed from every selected sub-sample. Samples were initially treated with hot 10% Na-pyrophosphate ($Na_4P_2O_7$) and sieved over a 180 and 8 μm mesh. The material retained in the 8 μm mesh was then treated with 10% HCl prior to acetolysis (9 parts $(CH_3CO)_2O$: 1 part H_2SO_4). Organic material was isolated from the remaining inorganic fraction using heavy liquid separation ($Na_6[H_2W_{12}O_{40}]H_2O$; s.g. 2.0, 20 min at 2000 rpm). The organic fraction was then treated with 40% HF to remove biogenic silica and any remaining fine silt. Samples were then dehydrated (with C_2H_5OH). Slides were mounted with glycerol and sealed with paraffin. All slides were counted along evenly spaced transects using an Olympus BH-2 microscope at ×600 magnification and a Zeiss Axioskop microscope at ×630 magnification. The minimum pollen sum was approximately 200 pollen grains for most of the samples. Charcoal particles were counted along three evenly spaced transects. Their values were calculated using the dilution of a known number of the *Lycopodium* spores added to each sample. Results of the analysis are presented in Fig. 5. The pollen diagram has been divided in seven pollen zones based on main changes in the relative frequencies of pollen taxa.

Pollen zones 7 and 6, from 1425 to 1300 cm and from 1300 to 1130 cm respectively are characterised by high values for tree taxa (*Acalypha*, *Casuarina*, *Celtis*, *Gironniera–Trema*, *Macaranga*, *Moraceae–Urticaceae*). The montane taxa *Agathis*, *Dacrycarpus*, *Dystillium*, *Lithocarpus* and *Podocarpus* have their highest and most continuous representation. Charcoal levels are relatively low, Pteridophyta values are generally high and non siliceous Algae are abundant. In zone 6, *Gironniera–Trema* values are strongly reduced, the other tree taxa values are somewhat reduced as well, while *Cyperaceae* show strongly increased values. A very low representation of tree taxa is recorded in pollen zones 5 and 4, from 1130 to 1000 cm and from 1000 to 855 cm respectively, with exception of *Moraceae–Urticaceae* in zone 4. *Gramineae* and *Cyperaceae* values are high (especially in zone 5), Pteridophyta values are generally low, and *Anthoceros* shows a very strong peak in zone 5. Charcoal levels are relatively high, especially in zone 4, while Algae are absent. Strongly increased tree taxa (*Acalypha*, *Baccaurea*, *Casuarina*, *Celtis*, *Duabanga*, *Elaeocarpus*, *Ficus*, *Gironniera–Trema*, *Macaranga*, *Moraceae–Urticaceae*) and Pteridophyta values characterise pollen zone 3, from 855 to 408 cm. Non siliceous Algae are abundant, charcoal levels are generally low. In pollen zone 2, from 408 to 210 cm, *Acalypha*, *Gironniera–Trema*, *Moraceae–Urticaceae* and *Gramineae* show high values. Algae are absent, leafspines of *Ceratophyllum* reach high values, charcoal levels are low and Pteridophyta are somewhat reduced. Pollen zone 1, from 210 cm to the core top, shows reduced tree taxa values, and increased values for *Gramineae*, *Cyperaceae* and *Compositae* (especially *Tubiliflorae*). Charcoal levels are relatively high while non-siliceous Algae are absent. An interpretation of the development of regional vegetation and local ecological settings is included in Section 4.

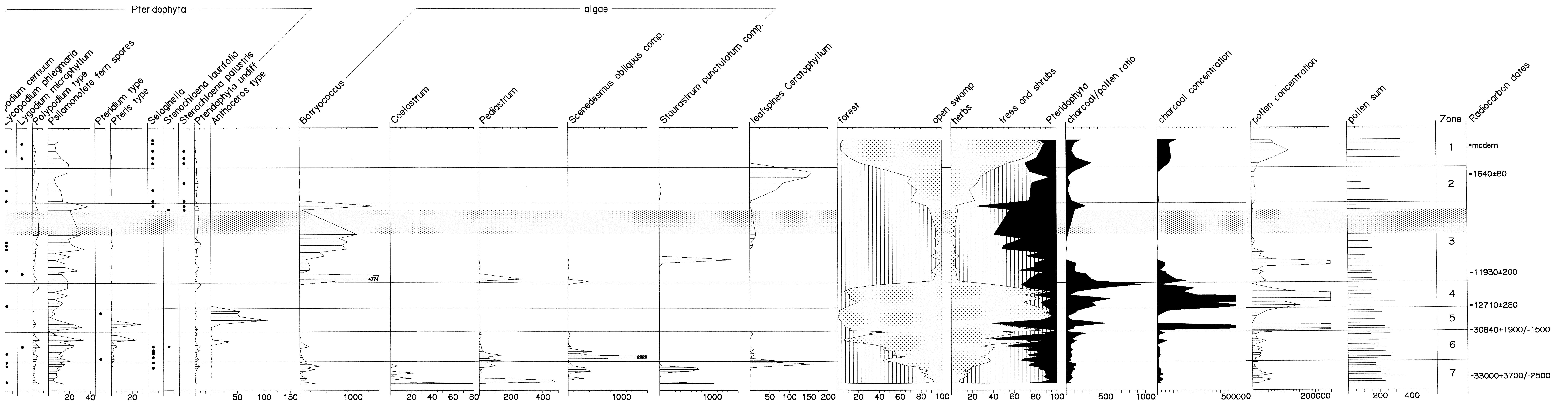
3.4. Diatom content analysis and results

3.4.1. Methods and materials

Sedimentary facies and the high biogenic silica content (63%) of a representative sample of lacustrine sediment are indicative of a high diatom content. Reconnaissance analysis of some recent lake shore deposits, deep lake sediment and core samples revealed a well preserved and diverse diatom facies. The scope of diatom facies analysis on a limited number of samples is to improve the reconstruction of palaeoenvironmental developments in the lake area, in particular changes in the aquatic ecology. The use of diatoms for this purpose is illustrated by Barker et al. (1994a,b), Gasse et al. (1987), Kilham et al. (1986, 1987) and Kilham (1987) in African lakes (Verschuren, 1996), but the approach is scarcely used in SE Asia (Van der Kaars et al., 2001). Work by Vyverman (1992) and Vyverman and Sabbe (1994) in New Guinea shows the potential applications of diatom analysis for specialised (palaeo)ecological studies.

In our study the diatom subsampling interval (about every 20 cm, with several interruptions) is rather coarse. Furthermore, most of the dominant diatom taxa have well known, but rather broad chemical tolerances (nutrients, pH, and to a lesser extent EC),

Fig. 5. Palynological results and distinguished pollen zonation (complete diagram, in support of local palaeoenvironmental development). For the interval 450–580 cm (grey shading) poor quality sample was suitable for visual description only and no samples were taken. 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.


Pteridophyta
algae
Lycopodium cernuum
Lycopodium phlegmaria
Lygodium microphyllum
Polypodium type
Psilamonolete fern spores
Pteridium type
Pteris type
Selaginella
Stenochlaena laurifolia
Stenochlaena palustris
Pteridophyta undiff.
Anthoceros type
Botryococcus
Coelastrum
Pediastrum
Scenedesmus obliquus comp.
Staurastrum punctulatum comp.
leafspines Ceratophyllum
forest
open swamp
herbs
trees and shrubs
Pteridophyta
charcoal/pollen ratio
charcoal concentration
pollen concentration
pollen sum
Zone
Radiocarbon dates
1
2
3
4
5
6
7
modern
1640±80
11930±200
12710±280
30840+1900/-1500
33000+3700/-2500
4774
2929
20 40
20
50 100 150
1000
20 40 60 80
200 400
1000
1000
50 100 150 200
20 40 60 80 100
20 40 60 80 100
500 1000
500000
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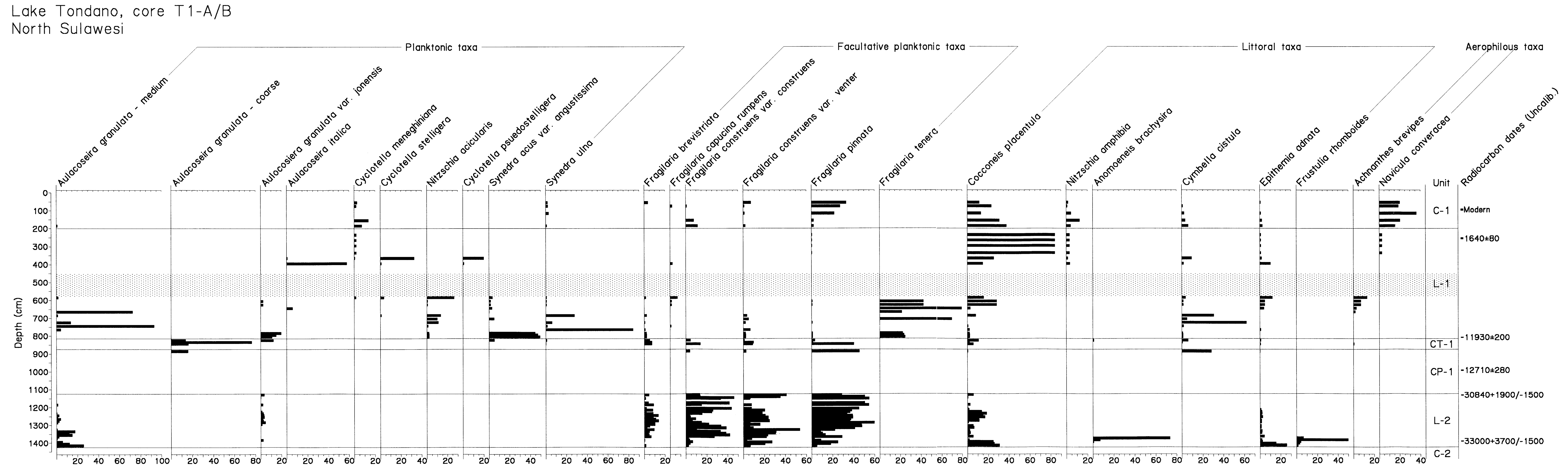

Fig. 6. Diatom content diagram of core T-1A/B. Represented are taxa which either occur in over 15% of the total count for at least one sample, and/or display significant frequency changes. The various forms and variants of *Aulacoseira granulata* have been arranged from least coarse (A. granulata-medium) to most coarse (A. granulata-coarse, from left to right). A minimum of 300 diatom valves were counted per sample. The indicated zonation follows the core lithostratigraphy given in Section 3.2.

which restricts detailed palaeolimnological (especially aquatic chemistry) reconstructions. Samples were digested in 10% hydrogen peroxide (H_2O_2) and 10% hydrochloric acid. The remaining material is diluted by a known amount and mounted with Naphrax mountant. Counts were undertaken on an Olympus BH-2 and a Zeiss Axioskop with Differential Interference Contrast. Diatom taxonomy followed standard references, in particular Krammer and Lange Bertalot (1986, 1988, 1991a,b). *Aulacoseira granulata* valves were identified to either recognised subspecies (i.e. *Aulacoseira granulata var. angustissima*), or to a variety of forms based on the density of aerolae on the valve girdle. This procedure was undertaken as a number of authors have shown that variations in valve ornamentation between species of *Aulacoseira* is related to environmental conditions (Kilham et al., 1986). Results (Fig. 6) are expressed as relative abundance of the total diatom community (including aerophilous taxa). The habitat classifications used (i.e. Figs. 6 and 7) are based on information contained in taxonomic references along with a number of other sources, in particular Denys (1991/1992).

3.4.2. Diatom facies

Pertinent results of diatom analysis are presented in Fig. 6. Diatoms valves are present in large numbers and a high diversity in the two sequences with lake deposits (units L-2 and L-1). Marked variations in the presence of aerophilous taxa (i.e. *Navicula converacea*), facultative planktonic taxa (i.e. *Fragilaria pinnata* and *Fragilaria construens var. venter*), littoral taxa (*Cymbella cistula* and *Cocconeis placentula*) and of planktonic taxa (*Aulacoseira* spp., *Fragilaria tenera*) are observed. The interval 450–580 cm (poor core quality, no samples) and the predominantly clastic levels between 850 and 1130 cm were not sampled in detail. Units CT-1 and most of unit CP-1 contain no diatom valves.

Most identified taxa have very wide ecological tolerances which hampers a detailed interpretation of palaeoecological settings on the basis of the diatom facies. The coring site is situated in the lake margin, which promotes deposition of diatom valves from contemporaneous but widely varying ecological settings (emergent lake shore vegetation with mostly epiphytic taxa, shallow water setting with littoral and facultative planktonic taxa and deeper water environments with planktonic taxa). However, for the main depositional units a broad interpretation in terms of water depth/lake level variations is possible. The observed diatom facies contains no taxa that suggest anomalous nutrient or pH conditions in the lake. Reference samples from warm (geothermal) springs in the lake margin and from specific lake edge settings contained useful indicator taxa (*Asterionella formosa* and *Navicula* sp.), but none of these were present in the analysed core samples.

The major variations in diatom facies are briefly summarized below, beginning from the base of the core upwards. The bottom sample at 1425 cm does not contain any preserved diatom valves. In the lower part of the core, unit L-2, the diatom assemblage is dominated by the species *Fragilaria contruens* var. *construens, Fragilaria construens* var. *venter* and *Fragilaria pinnata*, all of which are facultative planktonic and have a wide ecological tolerance. The basal lacustrine part does show marked peaks in the epiphytic taxa *Cocconeis placentula* and *Epithemia adnata*, while the predominantly littoral taxa *Anomoeoneis brachysira* and *Frustulia rhomboides* display peaks at 1385 and 1375 cm respectively. The planktonic forms of *A. granulata* and *A. granulata var. jonensis* are present throughout the lower core record, although never attaining abundances greater than 30%. This could indicate that relatively shallow water conditions prevailed at the coring site for most of this earlier period. From 1125 up to 885 cm (unit CP-1) diatoms are absent. From 885 up to 850 cm, the record is again dominated by the facultative planktonic taxon *Fragilaria pinnata*. Between 850 and 820 cm *Aulacoseira granulata* (coarse form) is strongly present. Between 820 and 750 cm the planktonic forms of *Synedra acus* var. *angustissima, Synedra ulna* and, initially, *Aulacoseira granulata* var. *Jonensis* occur, but also *Fragilaria tenera*. At 750 cm *Aulacoseira granulata* and *Synedra ulna* become dominant (reaching nearly 100% of the total count), but there is a significant presence of *Cimbella cistula* (littoral taxon). At 655 cm depth the record is abruptly dominated by *Aulacoseira granulata*, a deep water, eutrophic taxa. *Aulacoseira granulata* then disappears in the next sample and is again replaced by epiphytic forms. From 650 cm up the diatom facies is dominated by *Fragilaria tenera, Achnanthes* *brevipes,* an aerophilous taxon, *Cocconeis placentula* and *Epithemia adnata* (both epiphytic), and *Nitzschia acicularis* (planktonic). This mixed assemblage continues from 650 cm until about 580 cm. The interval 580–450 cm with poor core quality was not sampled for diatoms (indicated with shading). The 400 cm level is dominated by *Aulacoseira italica*, again a deep water taxon. The core level just below 350 cm is dominated by two planktonic species, *Cyclotella stelligera* and *Cyclotella pseudostelligera*. In the interval between 350 and 200 cm the dominant taxon is *Cocconeis placentula*, which generally grows exclusively attached to plants (Denys, 1991/1992). The interval from 200 cm upwards (mostly unit C-1) is dominated by *Navicula converacea* (an aerophilous taxon), *Fragilaria pinnata* (facultative planktonic) and *Cocconeis placentula* (mostly epiphytic). The substantial presence of aerophilous taxa indicates that the coring site has been close to the lake margin for this entire interval and subject to periodic wetting and drying. Both *F. pinnata* and *C. placentula* are very cosmopolitan.

Diatom facies in the basal lake unit L-2 and the upper lake unit L-1 differs markedly in terms of taxa composition and diversity. The differences are explicit when considering the different encountered taxa associated with the specific habitats, i.e. planktonic, facultative planktonic, littoral and aerophilous taxa (Fig. 7). Planktonic taxa, dominant in several levels of the upper lacustrine sequence, comprise three separate forms of *A. granulata,* and also single peaks of *A. italica* and *C. stelligera* forms. It could be argued that also *Fragilaria tenera* is a planktonic form but as the reconnaissance sampling in present day Lake Tondano habitats showed, this taxon also occurs in the littoral setting of the lake, and therefore it will be assumed that it is facultative planktonic. In contrast, planktonic taxa in the basal lacustrine sequence only contribute a relatively small amount to the total assemblage. These older lake deposits also have a much less diverse planktonic diatom flora. *Fragilaria tenera* and *F. pinnata* dominate the facultative planktonic taxa assemblage in the upper lacustrine unit L-1, while the basal unit L-2 contains mostly the taxa *F. construens* var. *construens* and *F. construens* var. *venter*. This may be explained by the fact that *F. tenera* is more suited to living in deeper water than the other facultative planktonic forms as it has a slender, less dense, valve. Therefore, it is possible that the presence of *Fragilaria tenera* represents an intermediate stage between the shallow lake small *Fragilaria taxa* and the deeper lake *Aulacoseira* taxa. Littoral taxa also dominate the basal lacustrine unit L-2, particularly at the very base of the sequence, but it is difficult to draw conclusions from the variations in taxa. The most common littoral taxon in both the basal and upper part of the core is *C. placentula*, an epiphytic taxon. In unit L-2 there are sudden appearances of *Anomoeoneis brachysira* and *Frustulia rhomboides,* whereas these littoral taxa are relatively absent from the younger part of the record. In the lower part of the younger lacustrine sequence (unit L-1) the abundance of littoral taxa is very irregular, and may be a result of (re)deposition, at the coring site, of an assemblage of diatom valves derived from a variety of lacustrine settings. Alternatively, fluctuating lake water depths would explain this variation in diatom taxa. Aerophilous taxa, represented almost solely by *Navicula converacea,* occur predominantly in the basal part of the upper lacustrine unit.

4. Palaeoenvironmental reconstruction

4.1. Sedimentation history, palaeoecology and geomorphologic development of Lake Tondano

4.1.1. Lake phase II (pre 33,000 until ±30,840 yr B.P.)

On the basis of sedimentologic evidence from cores in the northwestern Lake Tondano area the oldest lacustrine sedimentation was preceded by deposition of clastic unit C-2. The origin of this unit is not clear (fluvial or a tephra) but it is clearly affected by soil formation and therefore formed under dry conditions. The transition to the overlying lake deposits is sharp, suggesting a rapidly rising lake level (possibly the first formation of Lake Tondano, but more likely a rapid expansion of the already existing lake). Formation of unit L-2 with typical fine-grained moderately organic gyttjas took place in the northwestern Tondano area and sediment facies (texture, org. C, C/N ratio, δ^{13}C, diatom and non-siliceous Algae content) is indicative of full lacustrine conditions. Organic matter derived from a mix of lacustrine organic debris and washed in terrestrial and lake shore plant remains (resulting in

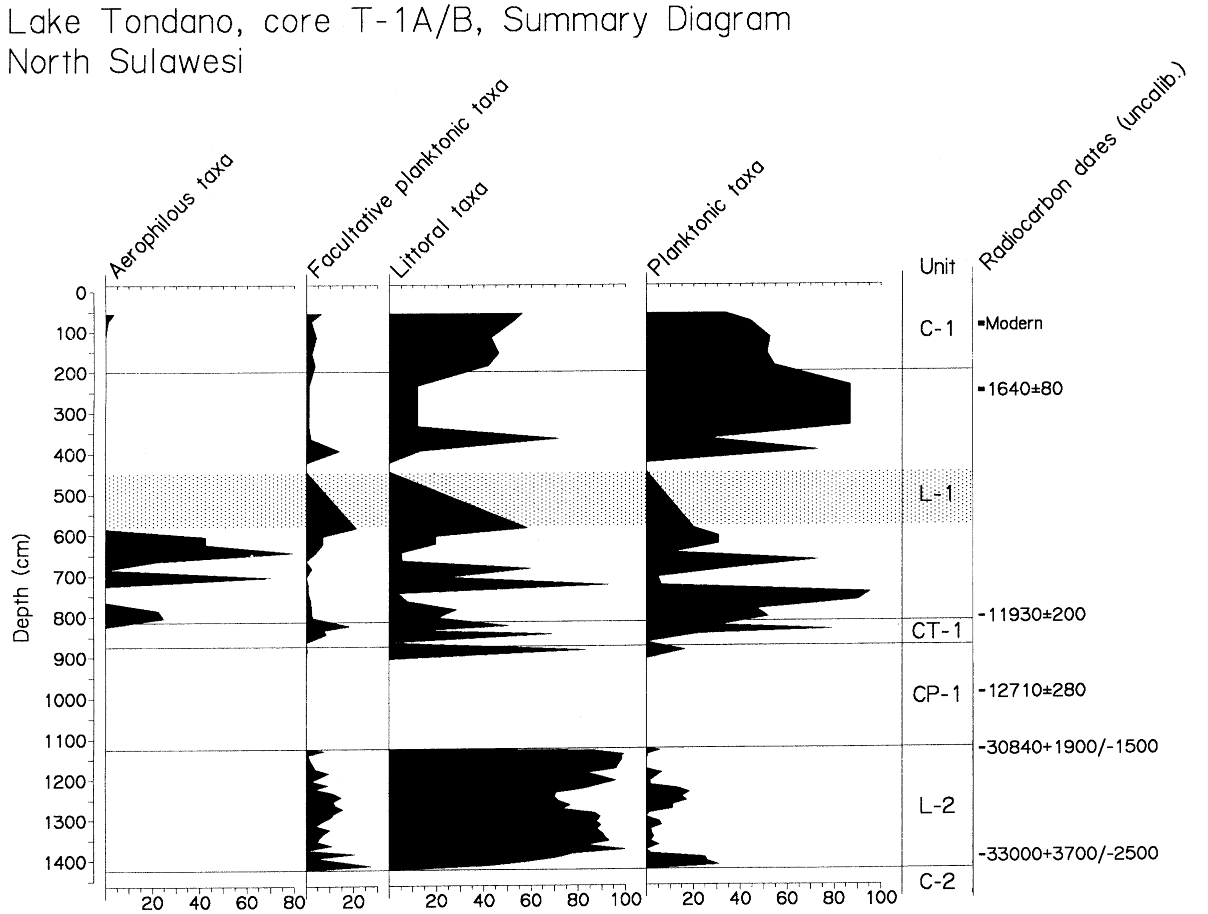

Fig. 7. Summary diatom assemblages diagram, with groupings according to preferential diatom habitats. The indicated zonation follows the core lithostratigraphy given in Section 3.2. Aerophilous taxa: *Navicula converacea* and *Achnanthes brevipes*; Facultative planktonic taxa: *Fragilaria brevistriata*, *Fragilaria capucina rumpens*, *Fragilaria construens* var. *construens*, *Fragilaria construens* var. *venter*, *Fragilaria pinnata* and *Fragilaria tenera*; Littoral taxa: *Cocconeis placentula*, *Nitzschia amphibia*, *Anomoeoneis brachysira*, *Cymbella cistula*, *Epithemia adnata*, *Frustulia rhomboides*; Planktonic taxa: *Aulacoseira granulata* forms, *Aulacoseira italica*, *Cyclotella meneghiniana*, *Cyclotella stelligera*, *Nitzschia acicularis*, *Cyclotella pseudostelli-gera*, *Synedra acus*. var. *angustissima*, *Synedra ulna*.

relatively high δ^{13}C values). Sediment textures suggest the site was within range of coarser clastic sediment deposition, probably distal deltaic deposits linked to small fluvial systems originating on the nearby hills. Roughly calculated sedimentation rates were relatively high ($\pm$1.20 m/kyr after consolidation). Approximate water depths (inferred from sedimentary facies) may have been >6 m (with a clear shallowing trend in the upper part of the unit) indicating the lake level was at least 677–680 m asl. The size of the lake must have been considerably larger then it is at present, with lake unit L-2 deposits observed in several drillings in the Lake Tondano area (Figs. 2 and 3).

In addition to the information from sedimentary facies, particular changes in aquatic and lake shore ecological settings are inferred from the analysed diatom and palynomorph content. In the basal part of the core (pollen zones 7 and 6, Fig. 5) a rich variety of pollen from lowland and submontane vegetation taxa indicates the presence of lowland-submontane forest in the direct vicinity of the lake. A diverse assemblage of non-siliceous Algae suggests full-lacustrine, relatively deep water conditions. The diatom facies of sediments at 1415 cm exhibits a dominance of the epiphytic taxa *Cocconeis placentula* and *Epithemia adnata*, and the planktonic *Aulacoseira granulata*, all present in relatively equal abundances. The combination of a eutrophic planktonic taxon and taxa that grow attached to plants suggests a deep, eutrophic lake that has abundant littoral or submerged vegetation (in extensive shallow water lake shore settings). Between 1415 and 1395 cm these taxa gradually decrease and are replaced by *Fragilaria pinnata* and *Fragilaria construens* var. *venter*, both facultative planktonic taxa which may indicate a shallowing trend. The samples at 1385 and 1375 cm are both dominated by single taxa, *Frustulia rhomboides* and *Anomoeoneis brachysira* respectively. Both taxa are often abundant in acidic waters. The SWAP pH data set (Stevenson et al., 1991) assigns pH optima of 5.1 to *F. rhomboides* and 5.9 to *Anomoeoneis brachysira*. This is much lower than established optima for the other taxa present in the record, with *A. granulata, C. placentula*, and *Fragilaria* spp. all being abundant in much more alkaline waters, generally with a pH >7 (Bennion, 1994; Gell 1995). The abrupt and anomalous presence of *F. rhomboides* and *A. brachysira* may represent a brief interval of lake acidification, with the former diatom taxon representing the most acidic phase, then being replaced by the latter as the process reversed and lake waters returned to their near-neutral pH level. In the upper part of lake unit L-2 the diatom assemblage consists of a mix of small *Fragilaria* spp. and *A. granulata,* reflecting a combination of full-lacustrine, open water conditions and shallow water, lake margin settings. *Aulacoseira granulata* decreases towards 1130 cm, and is absent between 1185 and 1130 cm, perhaps suggesting a gradual shallowing of the lake at the core site. The palynofacies of pollen zone 6 is indicative of an expansion of *Cyperaceae* and Pteridophyta-dominated swamps, probably as an open pioneer vegetation on the exposed lake shore in the vicinity of the coring site. Non-siliceous Algae gradually decrease. This corroborates the inferred gradual lowering of lake levels.

4.1.2. Low lake levels and formation of palaeosol unit CP-1 (± 30,000–12,000 yr B.P.)

Lacustrine conditions at the drilling site were interrupted due to lake level lowering and two phases of soil formation occurred (see also Section 3). Shallowing of the lake first took place around ±31,500 B.P. as indicated by the change to peaty sediment with higher organic content and weathering effects. C/N ratios rise sharply to 25–30, indicating a change to a swampy, possibly seasonally dry lake shore (or floodplain) setting with initially high production and decomposition of terrestrial organic matter. Clastic sedimentation took place throughout the northern lake area (Figs. 2 and 3). Net sedimentation in this setting was small and ongoing weathering/soil formation contributed to a virtual absence of sand in the sediment, in particular in the interval 11.00–9.30 m. Dating results suggest either very low sedimentation rates (or non-deposition) or the presence of an erosional hiatus somewhere between 30,800 and 12,700 yr B.P. No clear boundary is observed in the sedimentary facies and it is considered most likely that the hiatus is caused by subaerial weathering/oxidation during a period of relative environmental stability at the site. Environmental disturbance appears to have been limited to minor volcanic activity (as indicated by the presence of a thin clayey ash layer at 10.05 m). Regionally lower lake levels must have persisted until the latest Pleistocene. The former lake may have been comparable to its present size, but probably smaller, with in particular low-lying alluvial terrain in the north and northwest exposed.

No diatom valves are present in the core interval 1130–885 cm, including most of unit CP-1. Also the absence of non-siliceous Algae and high numbers of *Anthoceros* in pollen zones 5 and 4 (1130–855 cm) suggests the core location was (swampy) dryland in this period. Pollen zone 4 is characterised by high values for *Gramineae*, *Cyperaceae* and *Moraceae* (a gregarious, herbaceous lake shore vegetation), as well as high charcoal particle and palynomorph concentrations. The high pollen concentrations and high C/N ratio may be indicative of slowly accumulating organic soil material. Diatoms return to the record at 885 cm in the upper part of unit CP-1/pollen zone 4, with an assemblage dominated by *F. pinnata* and *Cymbella cistula,* indicating a swamp to shallow water lake with abundant aquatic vegetation.

Swamp soil formation and organic deposition resumed in the latest Pleistocene (around 12,710 yr B.P.), with the formation of the upper part of the peaty palaeosol, with associated high organic C. contents, high C/N ratios and low (regular) $\delta^{13}C$ values. A small increase in sand content (up to ±25%) suggests a more dynamic environment, such as a shallow lake shore or marginal, frequently flooded swamp. Therefore, in contrast to the preceding interval, higher, rising lake levels are inferred.

4.1.3. Deposition of tephra layer unit CT-1 (±12,000 yr B.P.)

Direct deposition (by airfall) of tephra unit CT-1 abruptly marks the end of swampy peat soil formation. The multiple (with sand, silt and clay laminae), fining-upward ash layer occurs throughout the Lake Tondano area directly at the base of the upper lacustrine sequence, and overlying the organic palaeosol. No distribution pattern could be inferred from spatial variation in thickness or coarseness of the tephra deposit. Therefore, it is not possible to infer a source, although several volcanic centres in the region (Soputan, Linau, Masarang, Lokon) are likely candidates. The homogeneous distribution may suggest a source volcano at considerable distance from the lake.

4.1.4. Lake phase I (±12,000–1500 yr B.P.)

Typical lacustrine sediments directly overly the tephra layer. The deposit contains little, but variable amounts (up to 25%) of fine sand. Organic carbon content is 6–9% at the basis of this unit, but decreases to some 4%, and the material has typical lacustrine C/N ratios (10–15). In most cores, this upper lake deposit contains variable amounts of small gastropod and molluscs shells and shell debris (in a gyttja matrix). The organic carbon isotopic signatures suggest sedimentary organic matter derived mostly from terrestrial sources (in particular in the basal part of the unit), and only a relatively small component derived from aquatic vegetation. On the basis of the undisturbed, continuous sequence that is encountered in all locations it may be concluded that lacustrine sedimentation persisted from around 12,000 yr B.P. all through the Holocene, until (sub) recent times. For the T-1A/B site approximate sedimentation rates were low, ±0.53 m/kyr. Sedimentary facies suggests a fairly stable lacustrine environment, with deeper water (>6 m deep) in the interval 8–5 m, and shallower conditions in the basal and upper parts (2–5 m water depth and decreasing). Site-specific ecological conditions are further elaborated below.

At the base of pollen zone 3 palynological data indicate the replacement of the herbs-dominated, open, local vegetation by a species-rich lowland-submontane forest, with notably *Celtis, Elaeocarpus, Ficus* type, *Macaranga* type and *Moraeae–Urticaceae*, and an assemblage of Pteridophyta. The disappearance of charcoal particles supports the establishment of a stable (humid–tropical) lowland forest. The reappearance of non-siliceous Algae, especially *Botryococcus* marks the onset of again lacustrine, open water conditions. It is unclear why the full assemblage of non-siliceous freshwater Algae, as in pollen zones 7 and 6, does not occur in pollen zone 3.

At the same level of 855 cm the sudden appearance of a diatom assemblage composed almost entirely of *Aulacoseira granulata*, suggests that water depth increased rapidly, following the deposition of the tephra layer CT-1. The effects of the tephra fall on the diatom assemblage are poorly understood. It may well be that the marked increase of *Aulacoseira granulata* is due to temporarily altered chemical conditions (changing Si:P ratios; pers. comm. S. Metcalfe) in the lake, but this has probably been a very short-lived event. Subsequently, planktonic taxa *Synedra acus*. var. *angustissima* and at 765 cm *Synedra ulna*, dominate the assemblage. The latter two taxa appear to have a wide tolerance to both pH and TP with conflicting published optima (Stevenson et al., 1991; Gasse et al., 1995; Bennion, 1994; Dixit and Smol, 1994) and therefore little ecological information can be gained from the marked shifts between the two. At 725 cm the deep water planktonic facies is replaced by a diatom assemblage dominated by *Cymbella cistula*, a littoral taxon (accounting for over 60% of the total count) which would suggest a dramatic fall in lake level. *C. cistula* is then replaced by the facultative planktonic *Fragilaria tenera. Cymbella cistula* briefly regains dominance in the assemblage of the next sample, before *A. granulata* makes a reappearance at 665 cm. This succession suggests fluctuating water levels and possibly an alternation of full-lacustrine with shallower water environments. *Aulacoseira granulata* decreases from this point and is replaced by Fragilaria tenera. This switch reflects a decrease in water depth, perhaps to 1–2 m. *F. tenera* is replaced by *Nitzschia acicularis* and various littoral forms at 585 cm. This is a confusing assemblage as *N. acicularis* is usually planktonic and indicative of deeper waters, while the large percentage of littoral taxa (Fig. 7) indicate either shallow waters or vast amounts of diatom inwash from the littoral zone. It is speculated that the lake shores were receding at this point, leading to a more extensive shallow water littoral zone around the coring site, with aquatic settings better suited to *N. acicularis* (i.e. shallow, turbid waters). No diatom data are available for the interval between 585 and 395, but the sedimentary facies suggests no major changes in depositional settings. The sediment at 395 cm is dominated by *Aulacoseira italica*, a deep water plankton that generally has a lower TP tolerance than *A. granulata* (Reavie et al., 1995). The assemblage at 365 cm is dominated by two planktonic species *Cycotella stelligera* and *Cyclotella pseudostelligera*, which both indicate a deep water environment. Interestingly, *C. stelligera* is generally indicative of oligotrophic waters while *C. pseudostelligera* is common in eutrophic waters (i.e. Bennion, 1994; Sayer, 1996). This probably highlights the caution needed in applying established palaeochemical reconstruction techniques to a region where there has been relatively no examination of diatom/water chemistry relationships.

Towards the upper part of lacustrine sequence L-1 the rapid decrease and subsequent near-absence of non siliceous Algae and the high numbers of *Ceratophyllum* leafspines (pollen zone 2) indicate shallowing of the lake. The surrounding forest vegetation becomes disturbed, as indicated by the increase in herbs (*Gramineae*) and decrease in forest taxa and Pteridophyta. The diatom assemblage between 395 and 235 cm becomes dominated by littoral taxa, predominantly *Cocconeis placentula* (reaching >80% of the total count). This would then indicate the definitive change to a more shallow water, swampy environment.

The widespread distribution of the unit L-1 lake sediment indicates the former expansion of the lake, inundating small embayments along the eastern and southwestern shores, and a large area in the north and northwest (Fig. 2). Near the village of Paso (in the southwest) a prehistoric settlement was situated in the lake shore- upper beach-like environment, some 5 m above the present lake level. Initial settlement of the site was estimated by Bellwood (1976) to have occurred around 8000 yr B.P. Coring around the site showed that younger lake sediments stratigraphically overlay the archaeological deposit. Mid and Late-Holocene lacustrine deposits also occur on topographically lower positions, indicating gradual lowering of the lake level in this period. On the basis of the distribution and stratigraphy of fluvial, lake shore and full lacustrine sediments in the Tondano, Remboken, Kakas and Eris areas (see Figs. 1 and 2), a similar conclusion can be reached.

Intercalations of organic lacustrine and peaty deposits within coarse fluvial sediments of the Soputan volcaniclastic fan in the south are also indicative of higher lake levels. Estimated topographic positions of these organic deposits are at least 6–8 m above present lake level. The age of ±10,500 yr B.P. for peaty lake shore sediment (Sample Texp.-1, Table 3) fits the latest Pleistocene–Early Holocene age for the inferred high lake levels. The internal build up of the alluvial fan, with organic lake deposits and incipient soil levels intercalated in between volcaniclastics shows that intermittent accumulation and progradation of the alluvial fan took place, possibly associated with periodic activity of the Soputan volcano.

4.1.5. Late Holocene to subrecent lake level lowering (±1500 yr B.P. — Present)

The upper clastic unit C-1 consists of very fine-grained deposits with a low organic content overlying shallow water lake deposits in the upper part of unit L-1. The unit C-1 deposits show evidence of soil formation/weathering (presence of structure, some compaction and reduction/oxidation mottling). Sediment colour varies from dark brown to greyish brown, but not the typical (for lacustrine sediment) grey–green gyttja colours. Recent vertical roots penetrate the upper 1.5 m of the sediment. Locally (not in core T-1A/B) thin peaty layers occur, with partly amorphous, partly recognizable plant remains. The upper clastic unit consistently increases in thickness away from the lake; in the present lake shore zone it does not occur. The unit marks the gradual lowering of the lake level and subsequent weathering and soil formation of minor fluvial (fine-grained overbank flood) deposits, and former lake shore deposits (transported and in situ formed organic debris) in a swampy and perennially dry setting. Sediment properties do not suggest a radical change in depositional activity. With very localised exceptions, fluvial or other sedimentation was and remains, very limited in the lake basin.

The absence of non-siliceous Algae indicates relatively dry swamp conditions for the core location since ±1500 yr B.P. (from 210 cm upward, pollen zone 1). Reappearing charcoal, decreasing tree and forest taxa mark increasing disturbance of the local vegetation and prominence of open herbaceous vegetation once again. The diatom assemblage shows that between 235 and 50 cm Cocconeis placentula decreases in abundance and is replaced by *Navicula converacea* and *F. pinnata. N. converacea* has been described (Denys, 1991) as an aerophilous diatom, that commonly occurs in semi-dry or moist environments such as swamp soil. Interestingly, Denys (1991/1992) also describes *F. pinnata* as being able to survive in moist subaerial environments. The assemblage in the upper part of unit L-1 and in unit C-1 is representative for the transition between gradually receding lake shore settings and the perennially flooded, swampy alluvial plain that is present today at the coring site.

4.2. Regional vegetation and climate change

Palynological data provide indications on changing regional vegetation, i.e. the wider lake shore area and the mountains in and beyond the catchment. The data are summarized in Figs. 8 and 9. Together with changes in the lake shore vegetation (Section 4.1) that reflect lake water level fluctuations (possibly affected by varying hydrological balances), the montane vegetation changes indicate adjustements to regional environmental and/or climate change.

During pollen zone 7, the main vegetation types in the wider Tondano area appear to have been species-rich humid lowland/lower montane forests, with characteristic tree species taxa *Agathis*, *Dacrycarpus*, *Dystillium*, *Lithocarpus* and *Podocarpus*. Relatively wet climatic conditions are inferred for this late Middle Pleniglacial phase (approximately 33,000 ± 1000 yr B.P.). In pollen zone 6, lower lake levels (Section 4.1.1) and a simultaneous decrease in forest pollen to low values are correlated with the transition to the colder/drier Late Pleniglacial. In comparison with the upper part of the record, the higher representation of montane taxa in pollen zones 7 and 6 is considered indicative for slightly cooler climatic conditions during the glacial period. The vegetation appearance had changed more radically in pollen zone 5, with *Gramineae* and *Cyperaceae* dominant, indicating a much more open vegetation type, with very low representation of trees. Although this change will be, in part, climatically driven, it probably also reflects the expansion of an open pioneer vegetation on the freshly exposed lake bed (Section 4.1.2). A comparable pattern was observed in the palaeoecological record of the Bandung basin, West Java (Van der Kaars and Dam, 1995). While showing a clear trend to more open vegetation during the last glacial period, generally associated with drier climatic conditions during especially the Last Glacial Maximum (±22,000–18,000 yr B.P.), maximum expansion of open, herbaceous vegetation is correlated first of all with periods of lake bed exposure and soil formation, rather than uniquely with the climax of the last glacial period. During pollen zone 4, dryland conditions persist at the core location. Peaks in charcoal particle content reflect a period of increased vegetation disturbance and burning (possibly the effect of volcanic activity, as also suggested by the presence of a tephra layer). The very low representation of trees in zones 5 and 4 make it difficult to give any indication of the temperature development in these periods. Increasing *Moraceae–Urticaceae* values possibly indicate a first increase in tree cover by a pioneer vegetation and slightly wetter conditions (regionally) during the Late Glacial–Holocene transition, although the initially high numbers of Lithocarpus in zone 3 may indicate cooler climatic conditions prevailed up to the Late Glacial–Holocene transition. In pollen zone 3 the regional vegetation was dominated by a diverse, Pteridophyta-rich lowland forest, indicating humid conditions. Montane taxa are poorly represented in comparison with zones 6 and 7, suggesting overall warmer conditions. In pollen zone 2 forest cover starts to decrease, and together with the high representation of *Gironniera–Trema* within the tree taxa, this suggests increasing vegetation disturbance. An intensification of disturbance can also be inferred from increased charcoal, a further reduction in tree cover and expansion of *Cyperaceae* and *Gramineae*-rich vegetation in pollen zone 1. Pollen zone 2 and 1 indicate a warm and humid climate comparable to present day conditions during the later part of the Holocene.

5. Conclusions and discussion

5.1. Lake level fluctuations and lake palaeogeography

Our study focused on alluvial, mostly lacustrine deposits in the vicinity of present Lake Tondano. Thick sequences of organic lacustrine deposits occur in alluvial terrain next to the lake, at elevations slightly above the present lake level. These deposits, and the results of our analysis of sediments of master core T-1A/B indicate substantial lake level lowering since the Mid-Holocene, following latest Pleistocene–Early Holocene lake level high stands (+4–6 m). The level of Lake Tondano was substantially lower (and below its present level) during the later part of the Pleistocene (30–12 kyr B.P.), but relatively high during the preceding period (a brief period before 30 kyr B.P.). Lake level fluctuations, in particular the inferred rapid lake level rise at ±33,000 and 12,000 yr B.P., may have been caused by volcanic (and/or associated tectonic) events in the catchment. Volcaniclastic deposits and lava flows may have caused a minor change in the position of the outlet near the town of Tondano. The high Early Holocene lake levels resulted in an increase in the size of the lake with some 20 km^2 as compared to the present 48 km^2 (with a major extension northwest of the present lake, Fig. 2). In contrast, the Late Pleistocene lake was substantially smaller.

5.2. Sedimentation history

The type of sedimentation in the lake basin has been fairly consistent since the Late Pleistocene with the formation of homogeneous successions of fine-grained, organic silt/clay sequences, with minor coarser clastics. Only in the southern Soputan volcaniclastic fan complex do fluvial/volcaniclastic deposits contribute markedly to the infilling of the lake. Sedimentation was interrupted at the T-1A/B coring site in the period from ±30,000 to 13,000 B.P. following substantial lake level lowering. Lacustrine sedimentation rates were apparently considerably higher in the Pleistocene part of the record than in the Holocene record (Fig. 8). This could be interpreted as resulting from inferred environmental disturbance (volcanic activity, deforestation, climate instability) in the Late Pleistocene. However, with low Pleistocene lake levels and a smaller lake, the coring site was situated in the shallow water margin of the lake, with consequently higher rates of sediment entrapment and accumulation. The ‘relative’ location effect obscures true sedimentation rates and it is problematic to compare Late Pleistocene with Holocene and recent sedimentation rates.

Human presence in the Tondano area (from the Early/Mid Holocene onwards) and inferred deforestation activities had a major effect on the catchment vegetation but this had no evident impact on sedimentation. In our view this could be due to the relatively minor fluvial runoff in the catchment and the presence, locally, of low-gradient alluvial terrain between footslopes and the subrecent lake shore, forming an effective sediment trap. Our study does not provide pertinent data that vindicate the assumed anomalously high, late 20th century siltation rates.

5.3. Lake palaeoecology

Throughout our record, Lake Tondano has supported a relatively stable diatom flora, with an evolving freshwater Algae community and emergent herbaceous lake shore vegetation. With the exception of possible minor pH fluctuations, there are no indications for significant water quality fluctuations. Strong fluctuations in the abundance of diatom taxa associated with littoral habitats tentatively indicate lake water depth fluctuations during the early Holocene. The production of organic detritus in full lacustrine settings has remained relatively stable as well. $\delta^{13}C$ signatures of detrital organic matter reflect differences in source material i.e. algal matter vs. emergent lake shore vegetation. A single higher $\delta^{13}C$ value in the late Pleistocene may reflect the anomalous isotopic composition (C4 plants) of dominant herbaceous lake shore vegetation (notably *Cyperaceae* and *Gramineae*). The observed diatom assemblage is indicative of a eutrophic lake all through the record; diatoms and non-forest palynomorphs (local vegetation) suggest the older lake phase was characterized by more widespread, shallow water lake margins. During most of the Holocene, deeper water conditions prevailed.

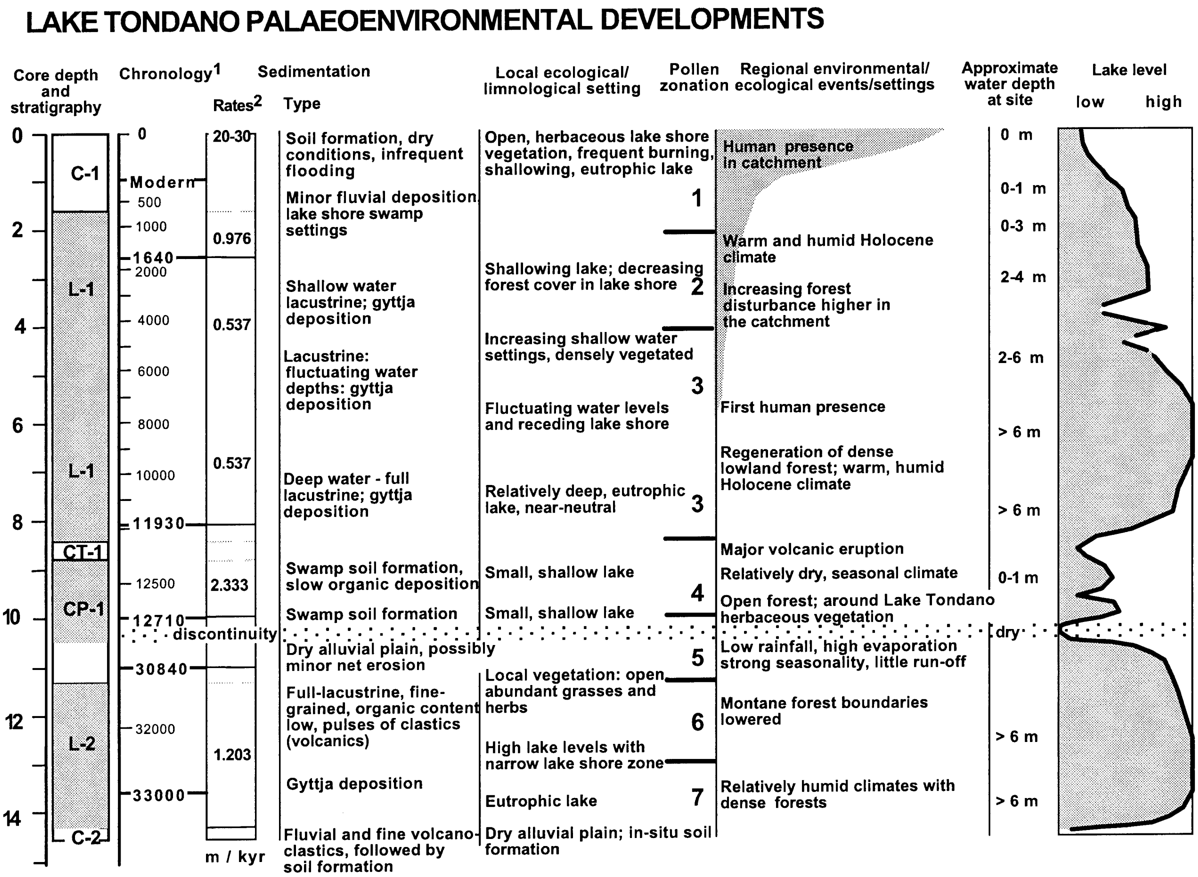

Fig. 8. Summary palaeoenvironmental developments in the Lake Tondano area. Core depth and stratigraphy; chronology (in large and bold font radiocarbon dated levels, in small font interpolated ages); sedimentation rates (calculated using fixed, radiocarbon-dated levels and assuming constant accumulation in each sedimentary environment; local ecological/limnological settings (on the basis of pollen, diatoms and sedimentary facies); pollen zonation; regional environmental/ecological events (based on the pollen and sedimentary records); approximate water depths (based on sedimentary, diatom and pollen facies) at the coring site.

5.4. Regional environmental and climatic change

Palynological data provide indications for changing forest and local vegetation types. A major drop in forest-derived palynomorphs is interpreted as a drastic decrease in lowland rainforest cover and change to an open, herbaceous vegetation during the last glacial period. With significantly lowered lake levels this is indicative of a drier and maybe somewhat cooler regional climate. Warm and wet atmospheric conditions are restored in the transition to the Holocene, as suggested by rapidly increasing forest cover and rising lake levels. During the Mid-Holocene, vegetation and environmental disturbance start, and probably mark the initial effects of human presence in the Lake Tondano area (deforestation, burning, soil disturbance). The presently available data from the Lake Tondano area do not allow for more detailed quantitative assessments of precipitation and temperature change. Nevertheless, the Tondano record adds significant palaeoenvironmental data to the small collection presently available for this sensitive region. The obtained results are in line with earlier palynological studies in the region (Van der Kaars, 1991; Hope and Tulip, 1994; Hope, 1996; Haberle, 1998). The inferred regional climate variations (reduced precipitation, somewhat lower average temperatures) may be stronger in amplitude as thus far considered to

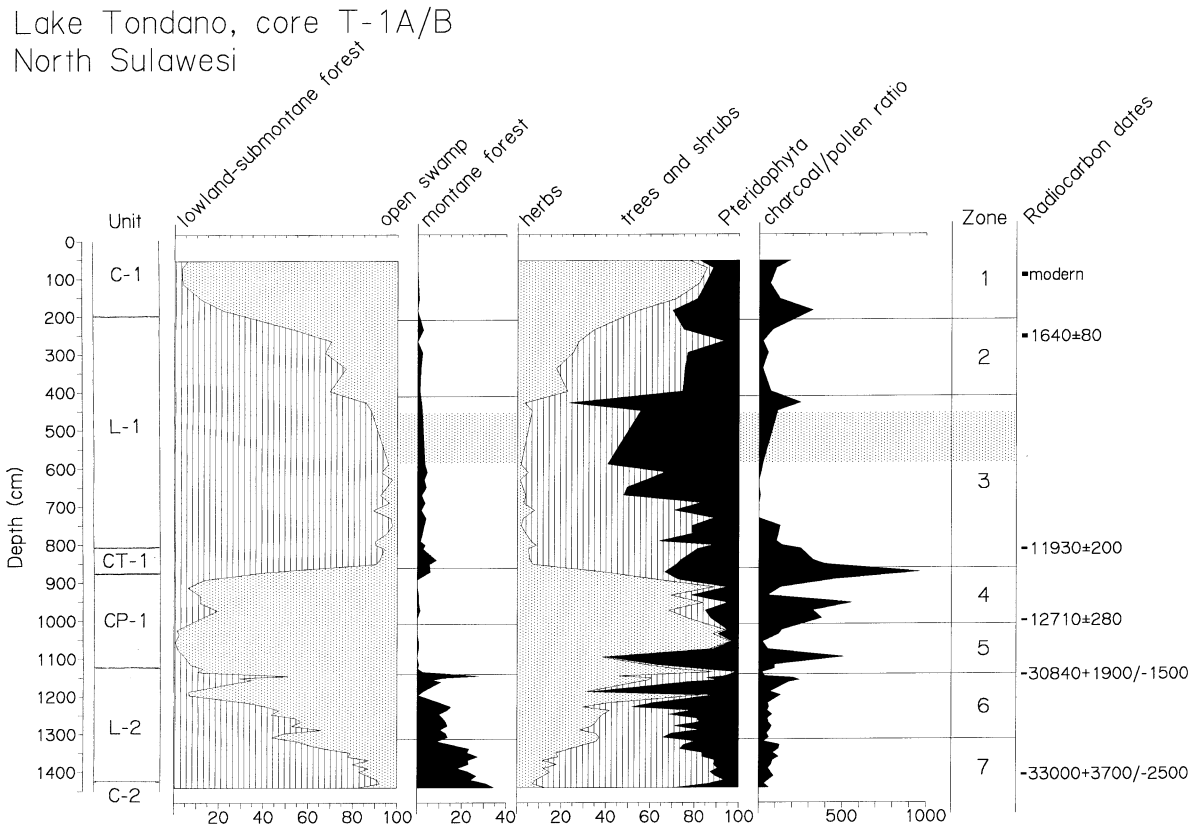

Fig. 9. Summary pollen diagram.

explain isotopic and faunal changes in Late Quaternary marine sediment records (Barmawidjaya et al., 1993; Linsley 1996). Further research on regional sedimentary records is needed to make a better qualitative assessment of the amplitude and exact timing of these climatic events.

On the basis of a range of proxies (lithofacies, pollen, diatoms) palaeoenvironmental developments in the Lake Tondano area have been reconstructed and the results, in particular referring to (1) lake level fluctuations and local palaeogeography, (2) sedimentation history in the wider lake area, and (3) lake palaeoecology have been summarized. The different proxy data are generally mutually confirmative and/or complementary and the comprehensive approach (looking at sediments, pollen diatoms, lake area stratigraphy and geo(morpho)logy, etc.) is strongly recommended. Although the analysis of the diatom assemblages has contributed to the reconstruction of palaeoecological conditions, a detailed interpretation of changes in the diatom record remains difficult, due to poor understanding of specific species ecology (especially for south-east Asia) and the abrupt changes in the assemblage, possibly indicating instant response by the lake diatom assemblage to changes in lake milieu. Higher resolution records are needed to better analyse these changes. Nevertheless, our approach should enable a better correlation between poorly understood diatom assemblage records, palynological data and sedimentary facies analysis.

Viewed in a regional context, the palaeoenvironmental change record of the Lake Tondano area (Fig. 8) clarifies Late Quaternary lake level fluctuations and vegetation and climate change. Although not clearly quantifying Glacial maximum temperature and precipitation change for the region, the impact of climate change on the lake system and regional vegetation is evident. The Lake Tondano data provide a valuable Late Quaternary environmental change record from a terrestrial site in the important Western Pacific Warm Pool region. The study illustrates the qualitative effects of climate change and anthropogenic disturbance of the lake catchment. This may be regarded as a subtle example of the effects of ongoing and increasing human activities in the lake area, and possibly, the consequences of future climate change on the lake system. In view of current management issues, understanding of these important environmental system dynamics is essential for maintaining the variable functions of the lake in a sustainable manner.

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