



The Towuti Drilling Project: paleoenvironments, biological evolution, and geomicrobiology of a tropical Pacific lake

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Received: 17 June 2016 – Revised: 29 June 2016 – Accepted: 30 June 2016 – Published: 27 July 2016

Abstract. The Towuti Drilling Project (TDP) is an international research program, whose goal is to understand long-term environmental and climatic change in the tropical western Pacific, the impacts of geological and

environmental changes on the biological evolution of aquatic taxa, and the geomicrobiology and biogeochemistry of metal-rich, ultramafic-hosted lake sediments through the scientific drilling of Lake Towuti, southern Sulawesi, Indonesia. Lake Towuti is a large tectonic lake at the downstream end of the Malili lake system, a chain of five highly biodiverse lakes that are among the oldest lakes in Southeast Asia. In 2015 we carried out a scientific drilling program on Lake Towuti using the International Continental Scientific Drilling Program (ICDP) Deep Lakes Drilling System (DLDS). We recovered a total of ~ 1018 m of core from 11 drilling sites with water depths ranging from 156 to 200 m. Recovery averaged 91.7%, and the maximum drilling depth was 175 m below the lake floor, penetrating the entire sedimentary infill of the basin. Initial data from core and borehole logging indicate that these cores record the evolution of a highly dynamic tectonic and limnological system, with clear indications of orbital-scale climate variability during the mid- to late Pleistocene.

1 Introduction

The Towuti Drilling Project (TDP) is an international research program, whose objective is to understand long-term environmental and climatic change in the tropical western Pacific, the impacts of geological and environmental changes on the biological evolution of aquatic taxa, and the geomicrobiology and biogeochemistry of metal-rich, ultramafic-hosted lake sediment. To accomplish this goal, the TDP recovered over 1000 m of sediment core from the floor of Lake Towuti, the largest tectonic lake in Southeast Asia. Analysis of these cores is just beginning, but will provide a new long, high-resolution record of tropical western Pacific paleohydrology during the Pleistocene, information on the age and history of the lake and the limnological conditions that gave rise to Towuti's endemic fauna and flora, and new insight into the microbial processes operating at depth in Towuti's sediments and their effects on sediment mineralogy and biogeochemistry.

Lake Towuti is a large tectonic lake at the downstream end of the Malili lake system (Fig. 1), a set of five ancient, tectonic lakes that have formed over the past ~ 1.5 million years on the island of Sulawesi, Indonesia (Haffner et al., 2001; Lehmusluoto et al., 1995; Russell and Bijaksana, 2014). These are the oldest lakes in Indonesia and are thought to contain the longest continuous terrestrial records of climate in the Indo-Pacific Warm Pool (IPWP), a vast pool of warm surface waters in the western tropical Pacific. The IPWP exerts enormous influence on global climate through its interactions with the El Niño–Southern Oscillation (ENSO), the Australasian monsoons, and the Intertropical Convergence Zone (ITCZ) (Chiang, 2009; Clement et al., 2001; Seager and Battisti, 2007) and through its influence on the concentration of atmospheric water vapor – the Earth's most important greenhouse gas (Pierrehumbert, 1999, 2000). Our ability to make accurate predictions about future climate, and in particular future precipitation, thus rests on our understanding of the tropical Pacific climate under different climate boundary conditions than today. Global climate models exhibit significant inter-model differences in their simulations of recent and future precipitation change over the IPWP (Kumar et

al., 2013; Meehl et al., 2007), as do simulations of IPWP precipitation under glacial boundary conditions (DiNezio et al., 2011; DiNezio and Tierney, 2013), motivating scientific drilling at Lake Towuti.

In recent years the global lakes drilling program under the auspices of the International Continental Scientific Drilling Program (ICDP) has made substantial contributions to understanding Pliocene–Pleistocene climate variability, including multiple paleoclimate records from the northern and southern tropics. These records, together with many long speleothem data sets, have highlighted the importance of 21 000-year cycles in subtropical rainfall, indicating strong forcing of the strength of the monsoons by orbital precession (e.g., Fritz et al., 2007; Hodell et al., 2007; Scholz et al., 2007; Wang et al., 2008). Despite these advances, we lack long records of terrestrial paleoclimate from equatorial regions and particularly the Indo-Pacific. Previous sedimentary records from Lake Towuti span the last ~ 60 kyr BP, and contain an intriguing record of past climate that differs markedly from that of the subtropics (Russell et al., 2014). In particular, we observed grassland expansion, lowered lake levels, and strong drying during the last glacial maximum (LGM) relative to both marine isotope stage 3 (~ 30 – 60 kyr BP) and the Holocene (Costa et al., 2015; Konecky et al., 2016; Russell et al., 2014; Vogel et al., 2015). The strong glacial–interglacial signal at Lake Towuti challenges the hypothesis that tropical hydroclimate is predominantly controlled by precessional orbital forcing, with little influence of glacial–interglacial changes in climate boundary conditions (Carolin et al., 2013; Meckler et al., 2012). A critical goal of TDP is, therefore, to obtain a continuous sedimentary record to document orbital-scale patterns of climate change spanning as many glacial–interglacial cycles as possible to test and differentiate the forcings that govern Indo-Pacific rainfall variations.

Lake Towuti is not simply a repository of information on past climate. The lake is situated within the East Sulawesi Ophiolite (Fig. 1; Kadarusman et al., 2004; Monnier et al., 1995), the third largest ophiolite in the world, which releases iron, chromium, and other metals that catalyze biogeochemical activity by a unique and diverse microbial community in the lake and its sediments (Crowe et al., 2008). Lake Towuti's

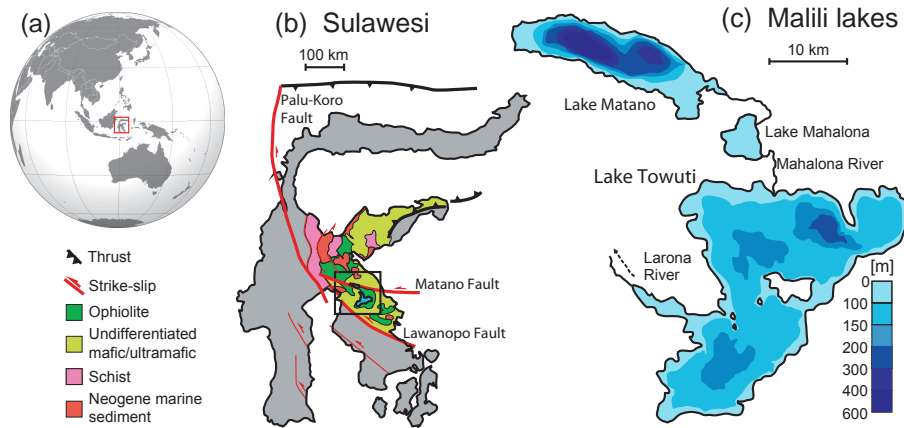


Figure 1. Overview map of the study area showing (a) the location of Sulawesi in the Indo-Pacific region, (b) the regional geology of Sulawesi (modified after Kadarusman et al., 2004), and (c) the configuration of the Malili lake system.

sediments are extremely Fe rich and thus stand out as an end-member microbial habitat. The prevalence of Fe-rich sedimentary rock units in the Precambrian suggests that ferruginous conditions were a prominent feature of the deep ocean throughout the Earth's history (Poulton and Canfield, 2011), and with mounting evidence for Fe-rich Martian soils and lake sediments dominated by ultramafic weathering products (e.g., Ehlmann et al., 2008), the study of an active biosphere in environments such as Towuti is timely and critical. Moreover, Towuti's pelagic microbial ecology, biogeochemistry, and sediment mineralogy are tightly linked to climate variations through varying lake mixing regimes, soil erosion, and weathering (Costa et al., 2015; Tamuntuan et al., 2015). These processes are directly or indirectly responsible for the production and deposition of many paleoclimate proxies, and postdepositional alteration of those proxies is often linked to the activity of sedimentary microorganisms. In light of these issues, a critical component of the TDP is to investigate the microbial community at depth and its effects on iron mineralogy, carbon, and metal cycling using a variety of state-of-the-art geochemical, molecular genetic, and isotopic tools.

Towuti is surrounded by one of the most diverse tropical rainforests on Earth, and harbors endemic species flocks of fish, snails, shrimp, crabs, and other organisms. Identifying the role of past environmental change in governing the evolution and biogeographical range of these organisms will be crucial for identifying conservation priorities and strategies to cope with anthropogenic climate change and land use. In terms of its flora, Sulawesi lies within one of the world's most biologically complex and diverse regions and is home to fundamentally important faunal and floristic boundaries such as the famed Wallace Line (which separates fauna of Australian and Asian origin). The regional phyto geography is controlled by these diverse geological origins and by subsequent modification by climate variations, particularly the glacial–interglacial cycles, which have influenced the con-

nectivity between adjacent islands as well as drought tolerance and resilience of the regional flora (Cannon et al., 2009; van Welzen et al., 2011). Understanding the past dynamics of these forest communities therefore is critical for our understanding of their response to future change. Faunally, the Malili lakes offer by far the most outstanding example of lacustrine biological evolution in Southeast Asia, with parallel adaptive radiations of gastropods (Rintelen et al., 2004), crabs (Schubart et al., 2008), shrimps (Rintelen et al., 2010), and fishes (Herder et al., 2006). Genetic and morphological data indicate multiple colonizations of the lakes in several of these groups; a high level of endemism within each lake, suggesting allopatric speciation despite the presence of riverine connections among the lakes; and intralacustrine diversification through shifting trophic structure suggesting ecological speciation (Rintelen et al., 2012). These faunal data thus have strong links to the climatic, limnological, and geological evolution of Lake Towuti. Drilling in Lake Towuti will document the environmental and climatic context that shaped the evolution of these unique lacustrine and terrestrial ecosystems, and their resilience to long-term environmental change.

These outstanding characteristics motivated the TDP, under the auspices of the ICDP. Through continuous coring of the entire sedimentary sequence of Lake Towuti, the project aims to

1. reconstruct long-term hydrologic change in central Indonesia in order to understand the processes controlling long-term climate change in the tropical western Pacific;
2. discover the micro-organisms living in Towuti's metal-rich sediments, and determine their impacts on the lake's sediments and biogeochemistry;
3. evaluate the history and stability of Sulawesi's lush rainforests, and the impacts of past climate change on these ecosystems;

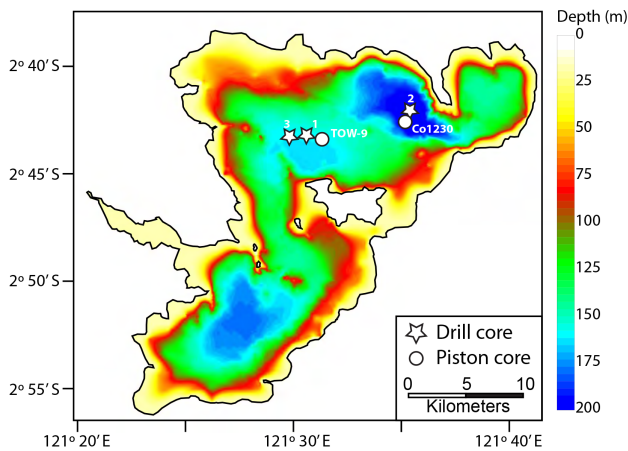


Figure 2. A bathymetric map of Lake Towuti showing the location of core sites discussed in the text.

- document the age of Lake Towuti, its long-term limnological history, and the environmental background shaping the diversification of Towuti's endemic flora and fauna.

2 Study site

Lake Towuti is located near the Equator (2.75° S, 121.5° E; Figs. 1 and 2) at 318 m above sea level in central Sulawesi, Indonesia. The island of Sulawesi has a complex tectonic history. At the large scale, a complex zone of deformation extends across central Sulawesi and absorbs the collision of Australia with Asia (Sundaland). Three major sinistral strike-slip fault systems accommodate this motion: the Palu-Koro, Matano, and Lawanopo faults. Lake Towuti and neighboring lakes occupy small transtensional basins along the Matano Fault. Northeast of Sulawesi, the Molucca Sea subduction zone accommodates convergence between the Philippine Sea Plate and Sundaland, giving rise to extensive volcanic fields in northern Sulawesi (Hamilton, 1988).

Sulawesi is composed of four elongate “arms”, which broadly correspond to lithotectonic units (Hamilton, 1979). The southeast arm, which houses Lake Towuti, is dominated by the highly tectonized East Sulawesi Ophiolite, which is inter-thrust with Mesozoic and Cenozoic sediments. These rocks are comprised of ultramafic mantle peridotites (lherzolites and harzburgites), cumulate gabbros, and basalts of normal mid-ocean ridge composition (Kadariusman et al., 2004; Monnier et al., 1995). The ophiolites have sourced large lateritic nickel deposits that have attracted the mining industry since the beginning of the 1970s, with active operations and extensive infrastructure in the region currently operated by PT Vale Indonesia (a subsidiary of Vale SA).

The three largest of the Malili lakes, Matano, Mahalona, and Towuti, are connected with surface outflow from Matano to Mahalona to Towuti via the Mahalona River, the largest

river inflow to the lake (Fig. 2). Lake Towuti is the largest of the Malili lakes, with a surface area of 560 km^2 and a maximum water depth of 200 m (Haffner et al., 2001; Lehmusluoto et al., 1995). A chain of islands divides the lake into two basins: a larger northern basin that contains the deepest part of the lake, and a smaller southern basin. Lake Towuti is presently hydrologically open with outflow to the southwest through the Laron River, which flows to the Bay of Bone.

Lake Towuti experiences a tropical humid climate. The region receives $\sim 2700 \text{ mm yr}^{-1}$ of precipitation, with a wet season from December–May, during which strong northeasterly flow, warm sea surface temperatures (SSTs), and local convective activity (Hendon, 2003) maintain precipitation at $>250 \text{ mm month}^{-1}$. Precipitation falls below $150 \text{ mm month}^{-1}$ from August–October, when southeasterly flow and cool SSTs suppress regional convection. This circulation and precipitation seasonality is characteristic of much of southern Sumatra, southern Borneo (Kalimantan), Java, and the Moluccas (Hendon, 2003), suggesting our record should represent climate change across a broad swath of central and southern Indonesia (Aldrian and Susanto, 2003; Konecky et al., 2016).

Towuti's surface water temperatures vary between ~ 29 and 31° C. The lake water column is thermally stratified, with seasonal mixing to a depth of $\sim 100 \text{ m}$ (Costa et al., 2015). Lake Towuti is relatively dilute ($210 \mu\text{S cm}^{-1}$) and circum-neutral ($\text{pH} \sim 7.8$) with a chemistry dominated by Mg and HCO_3^- (Haffner et al., 2001; Lehmusluoto et al., 1995). The lake is among the least productive tropical lakes on Earth (ultraoligotrophic), likely due to low nutrient delivery from intensely weathered soils and sedimentary PO_4^{3-} trapping by very high Fe concentrations. The surface waters are well-oxygenated, but hypoxic to anoxic conditions exist below $\sim 120 \text{ m}$ depth allowing for the development of ferruginous conditions with very low concentrations of dissolved sulfur.

3 Core site selection

Site selection for the TDP was guided by three surveys carried out between 2007 and 2013 that collected over 1000 km of seismic reflection data and piston cores that document the nature of the upper 10–20 m of Towuti's sediment column. Seismic data include “CHIRP” data acquired with an Edgetech™ 216s Towfish with a topside 3200XS collection system, and both single channel and multichannel data collected using a Bolt™ 5 in³ airgun and a 150 m long Geometrics™ GeoEel solid digital streamer with 24 channels.

The seismic data revealed two major sedimentary units in Lake Towuti (Fig. 3; Russell and Bijaksana, 2012). Unit 1 consists of a well-stratified sequence that extends from the lake floor down to $\sim 100 \text{ m}$ sub-bottom, and is characterized by parallel acoustic reflectors that can be traced across most of the basin. These reflectors do not exhibit obvious geomet-

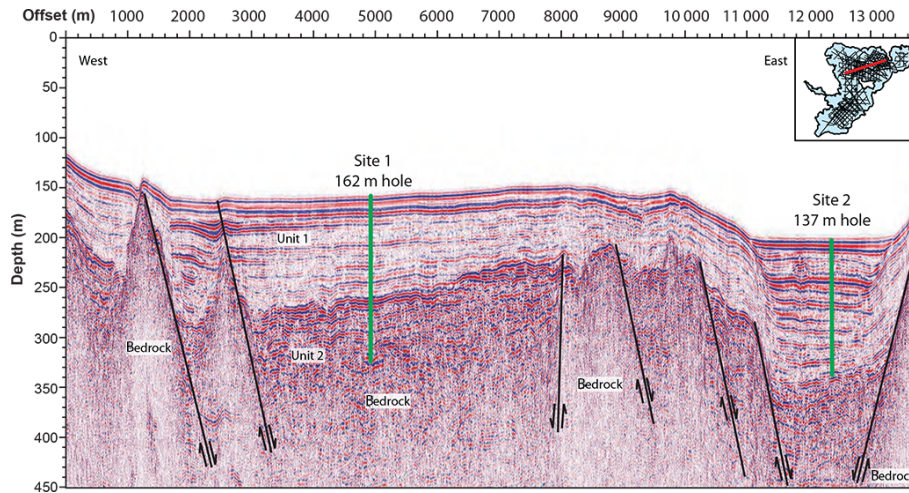


Figure 3. Seismic reflection profile oriented WSW–ENE over Lake Towuti’s northern basin (see inset for line position) crossing TDP Sites 1 and 2. Thick green lines show the borehole depths for TDP-TOW15-1B and TDP-TOW15-2A. Seismic Units 1, 2, and bedrock are labeled, and major faults are indicated by thin black lines.

ric relationships such as angular contacts that would indicate large lake-level changes, suggesting stable, continuous, fine-grained sediment deposition in Towuti’s deep basins. Some of the thickest Unit 1 accumulations are found in the deepest basin of Lake Towuti, located near the northern shore of the lake. This basin receives distal deltaic sediments derived from the Mahalona River, which drains the upstream lakes Matano and Mahalona.

Our piston coring survey sampled only the uppermost sediments of Unit 1, but confirmed the observations from our seismic reflection data. A core collected at site TOW-9 (Fig. 2) documented continuous, fine-grained sedimentation in the central part of Towuti’s northern basin, with sedimentation rates of $\sim 5.5 \text{ kyr m}^{-1}$ during the past $\sim 60 \text{ kyr BP}$ (Russell et al., 2014). We found very frequent distal deltaic turbidites in the deepest part of the lake (Site Co1230, Fig. 2), particularly during lake-level low stands that remobilize delta topset beds and force deltaic progradation (Vogel et al., 2015). Elsewhere, the piston cores generally consisted of fine-grained clays interbedded with more or less frequent turbidites. Turbidites increased in frequency and thickness with proximity to the Mahalona River delta, but were also common near shorelines or in the deepest parts of sub-basins within the lake, perhaps originating from seismically induced failure of poorly consolidated sediments in this tectonically active basin.

Unit 1 is underlain by Unit 2, a more poorly stratified unit that varies between a few tens to $\sim 150 \text{ m}$ in thickness. Unit 2 is characterized by a range of sediment types, from continuous, sub-parallel reflectors to short, discontinuous reflectors. Prior to drilling, Unit 2 was interpreted to reflect alternating fluvial and lacustrine sedimentation that occurred during the initial stages of formation of Lake Towuti. Drilling Unit 2 could provide insight into Lake Towuti’s age, processes of

basin formation, and the early lake stages, which is information critical to understanding the biological evolution of Towuti’s endemic fauna.

Based upon these data, we selected three primary drilling sites, between 156 and 200 m water depth, and with drilling targets between ~ 130 and $\sim 175 \text{ m}$ sub-bottom. Our primary goals in selecting drilling sites were to recover

1. high-quality continuous sections with as few turbidites as possible through Unit 1 for paleoclimate, paleolimnological, and geomicrobiological studies;
2. a distal record of the Mahalona River system to monitor changes in deltaic sedimentation forced by lake-level changes and possible changes in the river system itself signaling changes in the hydrological connectivity of lakes Towuti, Mahalona, and Matano;
3. as long a section as possible through Unit 2, preferably at sites containing more lacustrine than fluvial sedimentation (fine-grained deposits).

Site 1 is TDP’s primary drilling target, located in the central part of Towuti’s northern basin in $\sim 156 \text{ m}$ water depth (Fig. 4a). This “master site” is located close to our piston coring site TOW-9, which has yielded high-quality paleoclimatic and paleolimnologic reconstructions. The site is located upslope of slightly deeper areas of the lake on the northern edge of Loeha Island, and south of a large WNW–ESE trending intrabasin fault that limits sediment inputs from the Mahalona River, and thus contains few turbidites. Site 1 is well-suited to address most of our key studies in paleoclimate, paleolimnology, paleoecology, and geomicrobiology. Seismic data over Site 1 show that Unit 1 is approximately 100 m thick, and piston cores suggest the site is undisturbed

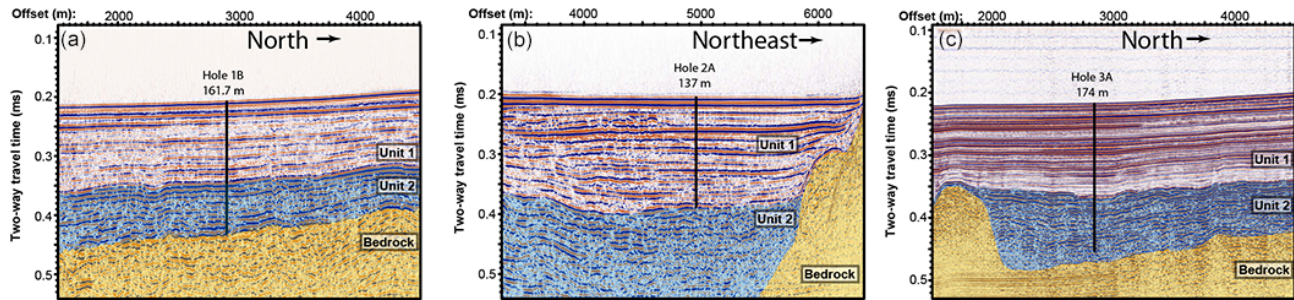


Figure 4. Expanded seismic reflection sections over the TDP core Sites 1 (a), 2 (b), and 3 (c), with seismic Units 1 and 2, and bedrock labeled. Black lines show the positions and depths of TDP-TOW15-1B, TDP-TOW15-2A, and TDP-TOW15-3A.

by turbidites or other event deposits. Seismic data also imaged approximately at least 75 m of sediment in Unit 2, including two intervals marked by roughly parallel acoustic reflectors centered at ~ 115 and ~ 160 m depth, indicating relatively well-stratified sediments. Our primary goals at Site 1 were to obtain overlapping triplicated cores through the upper ~ 100 m, to obtain 100 % recovery of Unit 1, and to recover as complete a section as possible of Unit 2 including cores to bedrock if possible.

Site 2 is located in the deepest part of Lake Towuti at 200 m water depth (Fig. 4b). Piston core Co1230 indicates that this site receives distal deltaic sediments derived from the Mahalona River, and seismic reflection data indicated a major change in the acoustic character of the sediments at ~ 65 m depth that could reflect the beginning of distal deltaic sedimentation from the Mahalona River. The principle objectives of drilling this location were therefore to provide a record of lake-level changes and/or major changes in the hydrological connection between lakes Towuti, Mahalona, and Matano through study of these distal deltaic deposits. Changes in the amount and style of clastic sedimentation, together with sediment provenance studies, at Site 2 may provide relatively direct insight into the history of hydrological connectivity between the Malili lakes, with important implications for the biological, hydrological, and geological evolution of Lake Towuti. Seismic reflection data suggested ~ 130 m of well-stratified lacustrine sediment at this site, so our goal was to recover duplicate overlapping cores to the Unit 1–Unit 2 boundary.

Site 3 was originally proposed for Towuti’s southern basin to provide a sedimentary sequence unaffected by sedimentological changes associated with the evolution of the Mahalona River, in order to test the reproducibility of our reconstructions of terrestrial weathering and sediment supply obtained from Site 1. The long transit times to Towuti’s southern basin, combined with equipment failures, forced us to relocate Site 3. An alternate site was selected to the west of Site 1 in 159 m water depth (Fig. 4c). Seismic data suggested that this site could have the most continuous lacustrine sedimentation through the time period represented by Unit 2, as the site is located in a small structural sag that may have al-

lowed for continuous lacustrine conditions while other sites in the basin were dry. Our goal at this site was to obtain overlapping duplicated cores as deeply as possible.

4 Drilling, logging, and on-site geomicrobiological operations

Drilling in a remote part of central Indonesia was a difficult logistical undertaking. Major logistical activities began in September 2014, when we shipped 14 containers of drilling equipment and supplies from the United States of America to the town of Sorowako, Sulawesi Selatan, Indonesia; initiated research permit applications and paperwork; began on-site construction of a dock and crane pad from which we could launch the drilling barge; and developed agreements with PT Vale Indonesia for local logistical support including the use of cranes, housing, and assistance with environmental, health, and safety planning. We shipped the GFZ “Buglab” to Sorowako to support on-site sample processing for geomicrobiological investigations, as well as borehole logging equipment from the Leibniz Institute for Applied Geophysics (LIAG), Hanover, Germany. Logistical preparations were completed in May 2015, when the drilling team arrived and set up on-site analytical facilities and the drilling barge on Lake Towuti’s shore.

Drilling commenced at Site 1 on 23 May 2015 using the ICDP Deep Lakes Drilling System (DLDS) operated by DOSECC Exploration Services. Boreholes were drilled using PQ (122.6 mm hole, 66 mm core) diameter drill string, which uses the hydraulic piston corer (HPC) for soft sediment and the “Alien” rotating corer to recover more resistant lithologies; attempts to recover more resistant lithologies with the Extended Nose Corer (EXN) resulted in poor core recovery and quality. All cores were recovered into standard butyrate liners. Geophysical downhole logging data, including natural gamma radiation, magnetic susceptibility (MS), electrical resistivity, temperature, acoustic velocity, vertical seismic profiles, and borehole diameter and dip, were measured at varying depth resolutions in a subset of holes.

A multisensor core logger (MSCL; Geotek Ltd.) was used to collect magnetic susceptibility (MS) and p wave veloc-

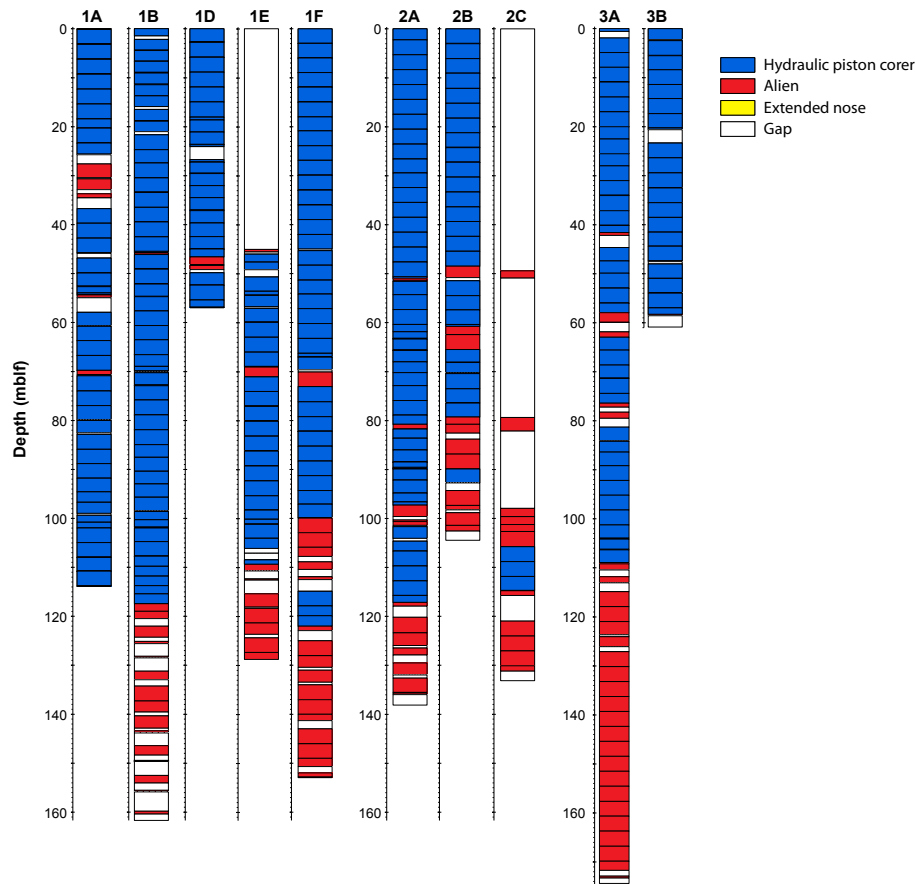


Figure 5. Core recovery from the TDP drill sites in Lake Towuti. Colors indicate the various tools used to recover cores from all TDP sites except 1C. White boxes indicate intervals that were not recovered.

ity data on whole cores in an on-site laboratory immediately after drilling, though the p wave velocity data were of low-quality due to gas expansion in most cores. At Hole 1A, also known as the “bughole”, a fluid contamination tracer was used to aid geomicrobiological sampling. Samples were collected from cores from Hole 1A immediately upon recovery on the drilling barge to measure trace and redox-sensitive gas concentrations (such as methane), and over 450 samples were subsequently processed in the BugLab for analyses of pore-water chemistry, cell counting and microbial fingerprinting, experiments on microbial turnover and processes, and organic geochemistry.

Upon conclusion of drilling operations, cores were shipped via air freight to LacCore, the National Lacustrine Core Facility at the University of Minnesota, USA, for full processing, description, scanning, and subsampling. There, physical properties for whole cores were analyzed via MSCL-S to obtain p wave velocity, gamma density, loop MS, electrical resistivity, and natural gamma radiation data at intervals of 2–4 cm. After splitting, cores were logged using an MSCL-XYZ to obtain high-resolution MS and color reflectance spectrophotometry at 0.5 cm resolution. Split cores

were cleaned and scanned with a Geotek™ Geotek Single Track Core Imaging System (MSCL-CIS) digital linescan imager. Visual core description and smear slide analyses were carried out to classify the sediment into major compositional units, and subsamples were extracted at intervals coordinated to obtain stratigraphically equivalent samples for sedimentological, geochemical, and paleoecological parameters. All cores received identical treatment except cores from Hole 1C, which were left in Indonesia to aid in educational and outreach activities, and cores from Hole 1A, many of which were completely sampled in the field leaving no material for logging nor core description.

5 Initial coring and core description results

TDP drilled 11 boreholes in total (Table 1), although several of these were relatively short due to twist offs that broke drilling rods, or other equipment malfunctions. In total we drilled ~1228 m of sediment and recovered ~1018 m of core within the intervals where coring was attempted, resulting in a recovery of 91.7% (Fig. 5). Recovery was generally very high through the upper ~100 m of sediment (Unit

1), but much lower in Unit 2 due to the presence of coarse-grained unconsolidated lithologies. We acquired borehole logging data from three holes, though not all parameters were logged at all depths due to borehole collapse in shallow unconsolidated sediment. Attempts to collect vertical seismic profiles at Site 1 were unsuccessful due to equipment malfunction, and were not repeated at other sites.

Six boreholes were drilled at Site 1 yielding approximately 524 m of core. Drilling commenced at Site 1A on 23 May 2015, and penetrated ~ 115 m reaching ~ 10 m below the Unit 1–Unit 2 boundary. Our geomicrobiology team did extensive sampling of this core in the field. The majority of the core consists of relatively soft clays that were cored with the HPC; however, we encountered four relatively hard beds between ~ 25 and 70 m sub-bottom that required drilling with the Alien tool. These hard beds were later determined to be tephtras, which, despite their deposition as airfall, were frequently semi-lithified. Drilling the soft sediments surrounding these tephtras with the Alien tool resulted in significant homogenization and contamination of these cores, as revealed by our contamination tracer, will be published elsewhere. We subsequently adjusted our drilling strategy to maximize recovery of the tephtras while minimizing disturbance of the soft clays. Drilling was terminated in this hole upon encountering the first resistant sand bed, in order to start a new hole to ensure duplication of the upper 100 m of the sediment column.

Our second hole, 1B, was our deepest hole at Site 1, extending to 162 m below lake floor (m b.l.f.). The upper ~ 115 m b.l.f. was very similar to Hole 1A, but the lower ~ 46 m b.l.f. consisted of a variety of coarser-grained lithologies that resulted in relatively low recovery. Coring was terminated at ~ 162 m b.l.f. after coring ~ 0.40 m of bedrock, which consisted of a lithified mafic conglomerate that appears similar to Eocene-aged deposits that occasionally outcrop in the region.

While drilling Hole 1B, we began to experience problems with the hydraulic power system of the drilling rig, and after completing Hole 1B, we completely lost rig function. Drilling operations had to be shut down for 18 days in order to replace the main hydraulic pumps of the rig. We then repositioned the drill rig and cored a short hole, 1C, which extended only ~ 5.5 m b.l.f. After correcting additional hydraulic problems identified while drilling this hole, we drilled three additional holes at Site 1 (1D, 1E, and 1F). Hole 1D extends ~ 54 m b.l.f. with excellent recovery, and was terminated due to a stuck tool. We repositioned and reamed to ~ 45 m b.l.f. with a non-coring assembly (NCA) at Hole 1E, and then cored the interval from 45 to ~ 129 m b.l.f. with 91 % recovery. In light of the various equipment issues and difficulties recovering sediments around tephtras in Unit 1 and coarse sediments in Unit 2, we drilled a sixth and final hole, 1F. This hole extends to ~ 154 m b.l.f., with nearly 95 % recovery, and was terminated when we encountered gravel that, based on 1B, cap a bedrock–soil–fluvial sequence. Holes 1B

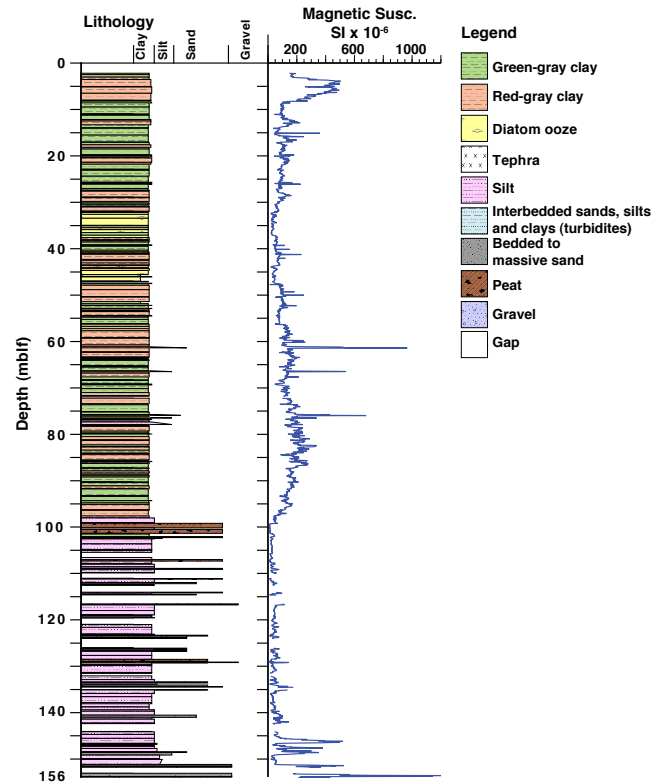


Figure 6. Summary stratigraphy of core TDP-TOW15-1F, based on initial core descriptions. Lithology data are based upon visual and smear slide descriptions, and are rendered in PSICAT. Magnetic susceptibility data measured on the whole (unsplit) core from the Geotek MSCL are shown in the central panel, and at far right is the key to the lithologic symbols. Blank (white) areas indicate zones with no recovery.

and 1F were successfully logged for various geophysical parameters, though barge movement and borehole collapse prevented logging of the upper ~ 20 m of sediment.

Core 1F is the most complete section from Site 1 and its lithology is representative of the section recovered from this site (Fig. 6). The basal sediments consist of a variety of lithologies including alternating gravels, poorly to well-sorted sands, silts, clayey silts, and peats. This unit is capped by a ~ 2.5 m thick woody peat at ~ 100 m b.l.f., which correlates to the transition from Unit 2 to Unit 1 in seismic reflection data. The upper 100 m of sediments consist largely of alternating thinly bedded to massive dark reddish-gray to dark-green gray clays. Normally graded silts (turbidites) are relatively rare but more common in the lower ~ 50 m of this interval, and we discovered ~ 14 light gray tephtras that range from ~ 1 to ~ 40 cm thickness and are scattered through the upper ~ 95 m. The source of these tephtras is currently under investigation, but they likely derive from the Tondano caldera system in northern Sulawesi, which is the closest tephra source to Lake Towuti. We also observed two

Table 1. Summary information about TDP drill sites. Drilled depth indicates the bottom depth of each hole; % recovery indicates the meters of core recovered within the depth intervals where coring was attempted, and thus excludes intervals drilled with a non-coring assembly.

Labels	Water depth (m)	Core length (m)	Drilled depth (m b.l.f.)	Recovery (%)	Borehole logging	Remarks
Site 1						
TDP-TOW15-1A	156	105.837	113.58	93.2	N	Geomicrobio Site
TDP-TOW15-1B	156	137.871	161.7	85.3	Y	
TDP-TOW15-1C	156	4.455	5.64	79.0	N	Rig failure
TDP-TOW15-1D	156	53.21	53.91	98.7	N	Ended in twist off
TDP-TOW15-1E	156	76.19	128.72	91.0	N	Continuation of 1D
TDP-TOW15-1F	156	145.965	154.06	94.7	Y	
Site 2						
TDP-TOW15-2A	201	134.515	137.58	97.8	Y	
TDP-TOW15-2B	201	103.918	104.55	99.4	N	Ended in twist off
TDP-TOW15-2C	201	34.175	133.21	82.9	N	Continuation of 2B
Site 3						
TDP-TOW15-3A	159	166.08	174.09	95.4	N	
TDP-TOW15-3B	159	55.3	60.88	90.8	N	Ended in twist off
TOTAL		1017.5	1227.9			

3–5 m thick intervals of laminated to medium-bedded diatomaceous ooze. Diatoms are not a significant part of the pelagic phytoplankton in the present-day lake (Haffner et al., 2001; Lehmusluoto et al., 1995), suggesting that these intervals mark major changes in the biogeochemical functioning of Lake Towuti.

Three holes were drilled at Site 2 to obtain a record of the evolution of the Mahalona River delta. Hole 2A reached ~134 m b.l.f. with ~98 % recovery, though there was significantly more gas expansion at Site 2 than at Site 1, which contributed significantly to the high apparent recovery. Coring was terminated when we reached sandy gravel, interpreted to correspond to the Unit 1–Unit 2 boundary observed in seismic reflection data (Fig. 4b). Hole 2B extended to ~105 m b.l.f., and ended in a twist off of the drilling rod. We repositioned and in Hole 1C reamed down to 100 m using a NCA, with spot coring to close coring gaps in 2A and 2B. We then cored from ~100 to ~133 m with 83 % recovery.

Hole 2A provides the most complete and representative stratigraphy from Site 2. The upper ~71 m of this core consist of 1–80 cm thick normally graded silts (Fig. 7), reflecting deposition by turbidity currents, interbedded with dark reddish to greenish-gray silty clay, whereas the lower 64 m consists largely of alternating thinly bedded to massive dark reddish-gray to dark-green gray clays similar to Site 1. We observe multiple tephra beds as well as two intervals of diatomaceous ooze, similar to Site 1. The tephra are much thicker than observed at Site 1, likely reflecting enhanced reworking of tephra from the Mahalona Delta and steep slopes bordering the basin.

We drilled our deepest hole of the project at Site 3, where Hole 3A reached ~174 m b.l.f. with over 95 % core recovery. Drilling at 3A was terminated when we encountered gravel near the contact with bedrock (Fig. 8). We began a second hole, 3B, which ended in a twist-off while trying to drill through a tephra at ~61 m depth. Due to time and budgetary constraints, we were not able to drill a third hole at Site 3 and concluded the project. Hole 3A, however, contains an excellent record of sedimentation at this site. Unit 1 at Site 3 is similar to that of Site 1, but is slightly expanded (~10 % thicker) and contains much more frequent turbidites, particularly in the lower ~50 m. Peats are less common in Unit 2 of Site 3 than at Site 1, and the sediments are generally finer grained, resulting in better recovery. These observations are consistent with our interpretation of the seismic reflection data that places Site 3 in a small structural basin that supported more continuous lacustrine sedimentation during the early stages of formation of Lake Towuti basin.

6 Conclusions

The TDP cores record the evolution of a highly dynamic tectonic and limnological system. Sediments in Unit 2 represent a mixture of lacustrine, fluvial, and terrestrial sediments deposited during the initial stages of extension and subsidence of the Lake Towuti basin. Comparison of Unit 2 sediments between Sites 1 and 3, or even between different holes drilled at Site 1, suggest Unit 2 is highly spatially variable over short distances, perhaps reflecting a variety of lake, swamp, and riverine environments that existed simultaneously in a large,

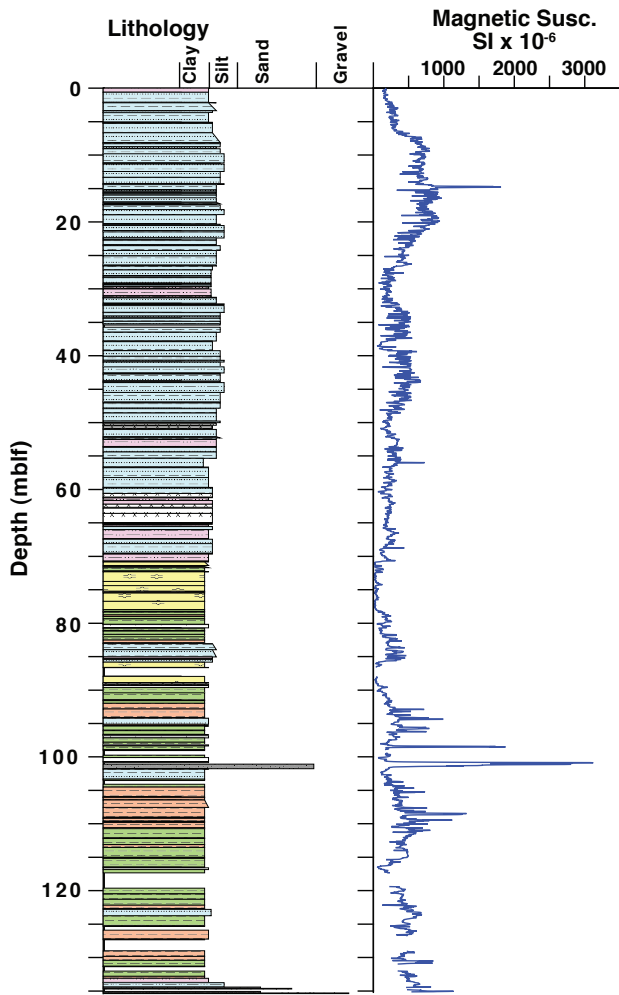


Figure 7. Summary stratigraphy of core TDP-TOW15-2A, based on initial core descriptions, and magnetic susceptibility data measured on the whole (unsplit) core from the Geotek MSCL. The key to the lithologic symbols is given in Fig. 6.

slowly subsiding swampy plain. The rapid transition from Unit 2, which represents sedimentation near base level, to Unit 1, which represents sedimentation permanently below base level, suggests rapid fault movement and creation of accommodation space.

We interpret Unit 1 to represent sedimentation in a generally deep lake, with red/green alternations reflecting climate-driven transitions in lake level and mixing (Costa et al., 2015). Unit 1 sediments are quite similar at Sites 1 and 3, but differ substantially at Site 2, where the upper ~70 m of sediment predominantly consists of distal deltaic sedimentation. This supports our interpretation of the seismic reflection data and could indicate relatively recent establishment of the Mahalona River.

Magnetic susceptibility profiles from Lake Towuti show very similar patterns at all three sites, and show generally excellent correlation to borehole profiles (Fig. 9). These data,

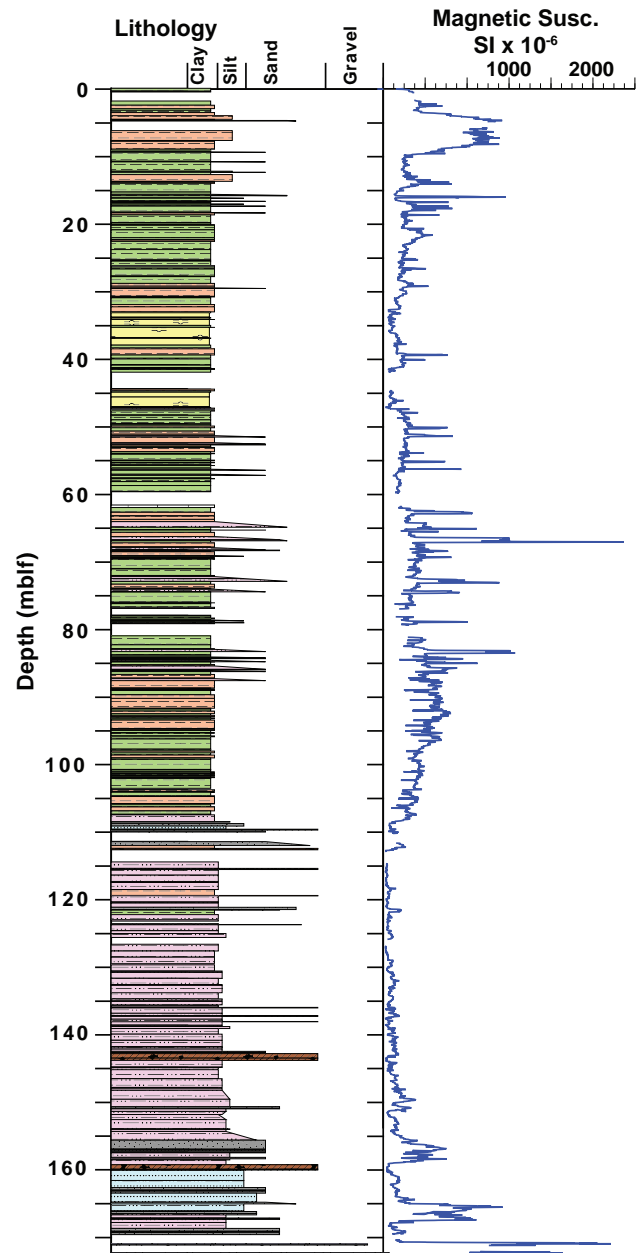


Figure 8. Summary stratigraphy of core TDP-TOW15-3A based on initial core descriptions, and magnetic susceptibility data measured on the whole (unsplit) core from the Geotek MSCL. The key to the lithologic symbols is given in Fig. 6.

together with tephtras, biogenic opal beds, and other distinct beds, allow for a preliminary correlation of cores from the three holes. This correlation highlights the relatively rapid influx of sediment to the upper 70 m of Site 2 relative to Sites 1 and 3, likely reflecting the rapid influx of sediment from the Mahalona River to the core site during this time. Interestingly, the basal sediments of Site 2 appear to be younger than those at Sites 1 and 3, despite the fact that Site 2 currently lies

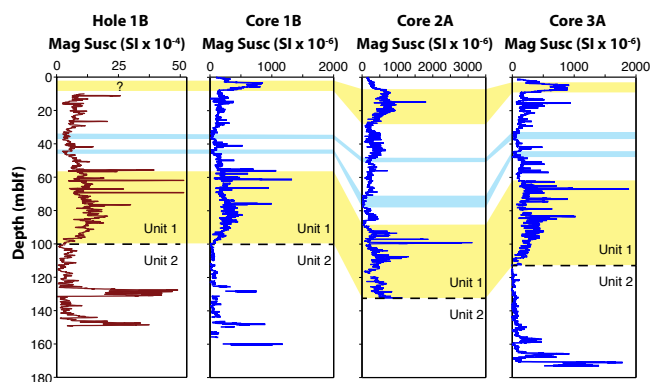


Figure 9. Magnetic susceptibility data from borehole logging of Hole 1B as well as MS data of cores 1B, 2A, and 3A. Yellow shading indicates correlative high magnetic susceptibility features in each site, whereas blue shading indicates correlative low susceptibility features. The dashed line marks the interpreted boundary between Seismic Unit 1 and 2; note that this boundary appears younger in core 2A than at sites 1 and 3.

in deeper water than the other sites. This could suggest relatively fast subsidence of the northernmost part of the lake relative to the central part of the basin, perhaps reflecting recent changes in fault motion.

Our analysis of these cores is just beginning and includes an array of geochronological, sedimentological, geochemical, geophysical, and biological methods. The geochronology is being assembled through a combination of $^{40}\text{Ar}/^{39}\text{Ar}$ ages on tephtras, paleomagnetic, luminescence, and ^{14}C dating. State of the art isotopic, organic geochemical, and elemental methods are being applied to understand the climate history of the tropical western Pacific and the evolving biogeochemistry of the basin. Analyses of the pore fluid chemistry, Fe-mineralogy, and microbial communities in the sediments will reveal the nature of the deep biosphere that inhabits these iron-rich sediments, and fossil pollen and fossil diatoms will reveal the dynamics of the evolving terrestrial and aquatic biota in central Sulawesi. Ultimately, through interactions between these groups we will try to unravel the coupled tectonic, biologic, and climatic evolution of this unique system.

7 Data availability

Cores and project data are archived at the National Lacustrine Core Repository, USA and are under a 2-year moratorium during which time only project scientists have access. The data will become publicly available in 2018, but could, through request to LacCore, be made available earlier to other individuals on a case-by-case basis.

Acknowledgements. This research was carried out with partial support from the International Continental Scientific Drilling

Program (ICDP), the U.S. National Science Foundation (NSF), the German Research Foundation (DFG) the Swiss National Science Foundation (SNSF), PT Vale Indonesia, the Ministry of Research, Education, and Higher Technology of Indonesia (RISTEK), Brown University, the GFZ German Research Centre for Geosciences, the Natural Sciences and Engineering Research Council of Canada (NSERC), and Genome British Columbia. We thank PT Vale Indonesia, the US Continental Scientific Drilling and Coordination Office, and US National Lacustrine Core Repository, and DOSECC Exploration Services for logistical support. The research was carried out with permissions from RISTEK, the Ministry of Trade of the Republic of Indonesia, the Natural Resources Conservation Center (BKSDA), and the Government of Luwu Timur of Sulawesi. We thank Andy Cohen and Christine Lane for helpful comments on a previous version of this paper.

Edited by: U. Harms

Reviewed by: A. S. Cohen and C. S. Lane

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