Bulletin of the Geological Society of Malaysia, Volume 72, November 2021, pp. 151 - 163
DOI: https://doi.org/10.7186/bgsm72202112

Explanation of marine lake formation at Misool Raja Ampat West Papua, Indonesia

Gandi Y.S. Purba[1,*], Lukas Rumenta[2], Purwanto[2], Leontine E. Becking[3,4], Eko Haryono[5]

[1] Department of Marine Science, Faculty of Fisheries & Marine Science, Universitas Papua, Gunung Salju St. Manowari-West Papua, Indonesia 98314
[2] The Nature Conservancy, Indonesia Marine Program, Pengembak St. No. 2, Sanur-Bali, Indonesia 80228
[3] Department of Marine Animal Ecology, Wageningen University and Research, De Elst 1-Wageningen, The Netherlands
[4] Wageningen Marine Research, Wageningen University and Research, Ankerpark 4-Wageningen, The Netherlands
[5] Faculty of Geography, Universitas Gadjah Mada, Bulak Sumur-Yogyakarta, Indonesia 55281
* Corresponding author email address: g.purba@unipa.ac.id

Abstract: Marine lake in a karst landscape is one of the macro karst forms known as doline and is only found in some locations in the world. Moreover, the theory of marine doline formation is always associated with global sea-level rise which differs from one place to another due to several factors. This research was conducted to understand the formation process of marine lakes in Misool and how the water fills the basins formed especially at Holocene time. This was achieved by obtaining information on the longest underwater terrace which is also the longest standing water position recorded on the sea wall. The marine terraces were measured by sounding profiles to the sea bordering the seven marine lakes including Lenmakana, Balbullol, Lenkafal, Keramat, Karawapop, Keramat-2, and Keramat-3 as well as Harapan Jaya Sea. A total of 24 profiles were measured and stable isotopes $\delta^{18}O$ and δD of water samples were used to determine the origin of water in the lakes. The results showed the longest terrace was at the depth of -33 and -3 m while the references from the area closest to Misool showed the same water level positions at 10,500 BP and 6,985 BP. Furthermore, the composition of $\delta^{18}O$ and δD from lake water indicated the water samples were a mixture of groundwater and seawater with the seawater having the more dominant concentration and this allows it to fill the lake first through a previously formed cavity system.

Keywords: Marine lake, Raja Ampat, karst, sea-level rise, stable isotope

INTRODUCTION

Marine lake is a body of water surrounded by land with variations in form, size, and distance to the sea, and some are found at karst areas such as Palau, Halong Bay Vietnam, Croatia, and Raja Ampat Indonesia. Most of the studies conducted are focused on Palau such as the first scientific article on the physical, chemical, and biological characteristics of Jellyfish Lake (Hamner *et al*., 1982) as well as the research on the thirteen stratified lakes (Hamner & Hamner, 1998). Other studies have also been conducted on stingless jellyfish, *Mastigias Papua*, living in marine lakes of Palau by Dawson (2004, 2005a & b), and Dawson & Hamner (2003). Moreover, the impact of global phenomena such as El Nino 1998 on the bio-physical dynamic in the lake was reported by Dawson *et al*. (2001) and Martin *et al*. (2006). The information produced from these articles and others on the marine environment including the marine lake in Palau has been documented by Colin (2009) while some others are on Vietnam and the whole of Indonesia. Some biota in the marine lake such as soft coral (Cerrano *et al*., 2006; Azzini *et al*., 2007; Santodomingo, 2009; Becking *et al*., 2011), Halimeda algae, and others (Tomascik & Mah, 1994) have also been selected for research. Tomascik & Mah (1994) also provided a comprehensive report on Kakaban Lake in East Kalimantan, Becking *et al*. (2011; 2009) on marine lakes in Raja Ampat, and the discovery of jellyfish lakes in Misool by Becking *et al*. (2014) and Purba *et al*. (2018b). These findings showed 40 out of the 55 marine lakes in Raja Ampat are in Misool Island (Becking *et al*., 2009; 2011).

The formation of a marine lake in Croatia has been briefly reported by Suric (2002, 2005) with late Pleistocene-Holocene transgression observed to have a role in the submergence of karst depression (Suric, 2005). Moreover, the collapse of the cavern roof was induced by the loss of buoyant support provided by the seawater during high stands while three out of four lakes are large at >23 ha having an ellipse or oval shape with a steep wall. The sea-level rise was also discovered to have contributed to marine lake formation in Palau and the glacial in Paleo-Palau from 20,000 years ago was reported to be an island having a width which is three times more than the recent ones (Colin, 2009). Meanwhile, lagoons were dry while the current position of reefs was above sea level and the edge of the island was a steep cliff, below, and up the surface thereby causing only a few lakes to have a shallow depth.

0126-6187; 2637-109X / Published by the Geological Society of Malaysia.

The last maximum glacial made the ravine and inner side of the atoll to be filled with water, therefore wetting the land and formed lagoons. This means the marine lake was formed slowly approximately 12,000 years ago at a depth of 60 m. Furthermore, the swallow lakes which are 5 m and less were formed when the sea level approached the present position at approximately 4,000 to 5,000 years ago and this shows the lakes in Palau were formed due to sea-level rise and tectonics. There are several pieces of evidence of uplift and subsidence due to tectonics which filled the concave part with water (Colin, 2009). It is also impossible to separate the marine lakes at the karst tower of Ha Long Bay (of Vietnam) from this theory of sea-level rise (Cerrano *et al*., 2006). The karstification formed towers and valleys as the high and submerged parts of the karst before the rise in the sea level. However, the phenomenon observed in Kakaban East Kalimantan-Indonesia is different from the marine lakes reported to have been formed due to the uplift in atolls as observed in its formation during slow subsidence of the shelf (Kuenen in Tomascik & Mah, 1994). The sinking plate-form was presumed to have curved upward at some point and this led to the increase in the atoll approximately 60 m above sea level thereby having no connection with the sea.

The geomorphological configuration shown in Misool-Onim-Kumawa is an extension of the northern part of the Banda basin while the Geosyncline Tertiary curve folds at the middle and south of Birds Head of Papua, and Misool-Onim-Kumawa zona (Sapin *et al*., 2009; Verstappen, 2014). Misool is a structural landform with morphogenetic property in the form of a folded ridge and its morpho structural aspect is shown at transcurrent north Irian Jaya belt zone with Raja Ampat, Bintuni, Misool, Fakfak, and Kaimana. Moreover, the north of Misool Island is an uplift reef while the southern part is a live reef such as a branching reef, barrier, or atoll (Verstappen, 2014). The rock formations on this island range from Paleozoic to Cenozoic (Rusmana *et al*., 1989) while the lithology is from the oldest at south to the north, with the western part having Ligu Metamorphic, and Keskain Formation towards the east. Moreover, the north part has calcareous shale, namely Facet Limestone, Fafanlap Formation, Deram Sandstone, and Zaag Limestone from the Cretaceous up to Oligocene. The small islands in the southeast with scattered lakes are dominated by Fafanlap Formation and Zaag Limestone while the north has younger Kasim Marlstone, Openta Limestone, Atkari Limestone, and alluvial deposits.

This research was conducted to explain the formation of lakes in Raja Ampat using several pieces of evidence of the global sea-level rise and tectonic activity. Papua region has high tectonic activity but reports on vertical movement have not yet been found on the Misool Island, which is on a shallow platform linked to the southern margin of Kraton Australia. This area is low but uneven, and covered by karstic limestone. The latest evidence of compression and uplift are the skeins of narrow, parallel, and tall karst hills stretching eastward at the eastern coast of Misool Island (Beehler, 2007).

MATERIALS AND METHODS

This study was conducted in the southeastern Misool Island which is a conservation area of Raja Ampat, covering an area of 343,200 ha (Mangubhai *et al*., 2012). The seven marine lakes that were measured using morphometry and physical characteristics include Lenmakana, Balbullol, Lenkafal, Keramat, Karawapop, Keramat-2, and Keramat-3, as shown in Figure 1. The three lakes at Keramat was observed to be close to each other.

Lake depth

The depth of the lakes was obtained by sounding using GARMIN GPSMAP 178C to record the pulse reflection which was used as the depth data. Meanwhile, the precision performance was high-contrast, h56-color LCD screen with backlighting, the 12-channel parallel receiver tracks with up to 12 satellites was used to achieve fast and accurate positioning.

Marine terrace

The depth profiles known as the marine terraces were obtained from measuring between two hills/land at the seaside for the 7 marine lakes including the Harapan Jaya Sea by sounding using GPSMAP 178C. The seven locations as well as the sea have three profiles each thereby producing a total of 24 profiles which were corrected with tidal height using data loggers. Further, the data used for correction were equated to the time of measurement. Meanwhile, the Mean Sea Level (MSL) was calculated from three consecutive days, which were the day before, during, and after the measurement.

The distance between two consecutive points was obtained by applying the Pythagoras formula after the geographical position to distance (m) measured has been copied. All the distances from different locations were further grouped based on the depth with 0 m used to cover from 0-0.99 m, 1 m for 1-199 m, etc. This was followed by plotting the number of distances in each of the squares (X) on the Cartesian graph of depth (Y).

Stable isotopes

The stable isotope parameters were ^{18}O and ^{2}H obtained from seven samples of lakes and seawater in Harapan Jaya. Results of their analysis on the composition ratio were plotted in the relationship graph of between $\partial^{18}O$ to ∂D using Global Meteoric Water Line (GMWL), with the equation $\partial D = 8\partial^{18}O + 10$ which is the relationship line of O isotope ratio -18 and Deuterium from rainwater samples obtained from 91 stations worldwide. Moreover, the reaction was conducted using ISOPREP-18 and the equilibrium result simultaneously was measured by Mass Spectrometer SIRA-9 in a series directly connected with the ISOPREP-18 and

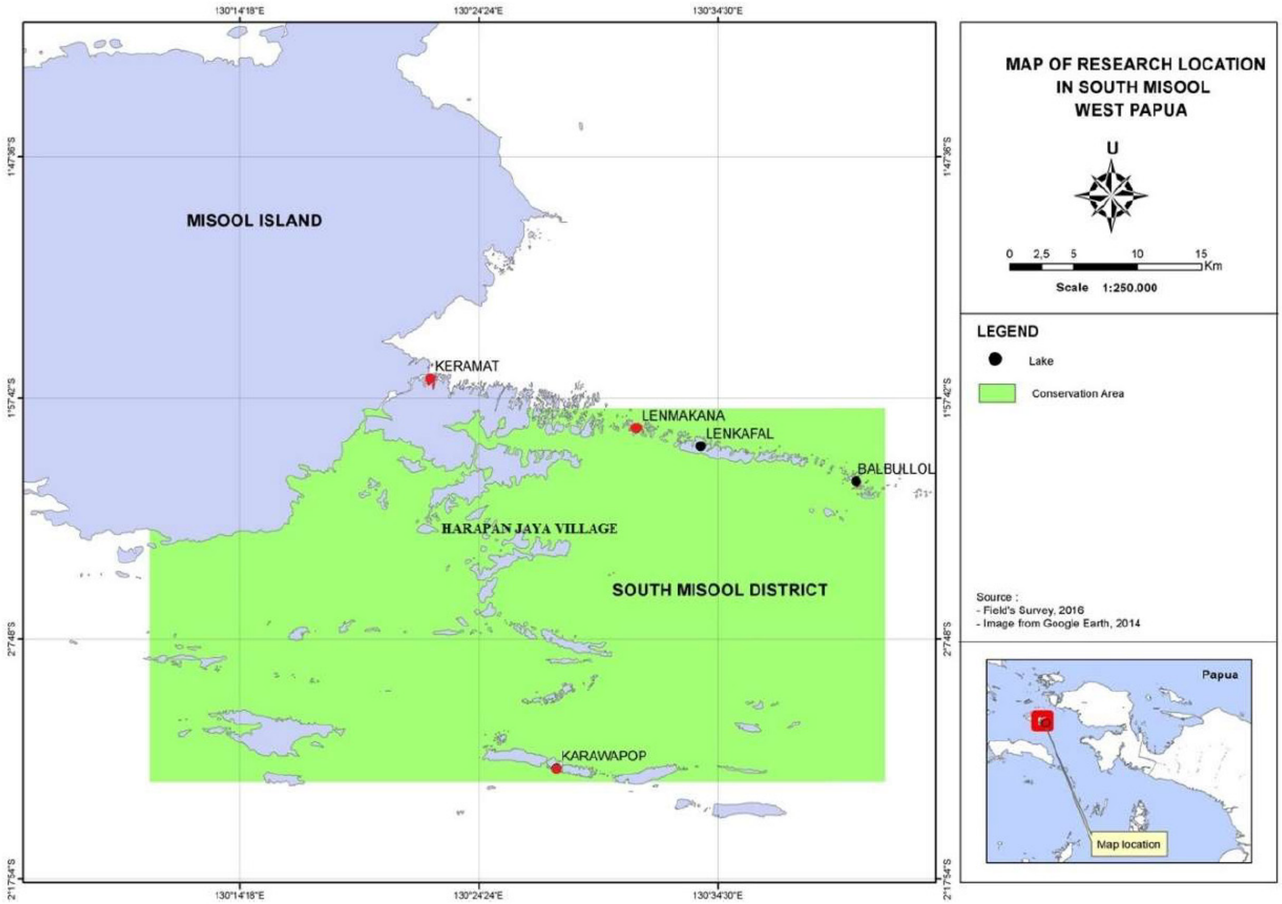

Figure 1: Location of the research sites (modified after Purba *et al.*, 2018b).

controlled by a computer. The results were measured as a ratio of O18/O16 to Mass Spectrometer and later corrected to V-SMOW (Standard Mean Ocean Water). The analysis of the stable isotope parameters was conducted at the Nuclear Energy Agency of Indonesia.

Water quality

Water quality parameters were measured using Atago hand-held refractometer to determine salinity percentage while the U20L HOBO water level logger was installed to obtain a time-series data of the water level with the recording time interval set at one hour. Meanwhile, long time-series measurements of 6 months duration were only performed in Lenmakana, Balbullol, and Harapan Jaya lakes due to the availability of only 4 water level loggers. The installation made in the sea was to obtain data to compare with the measurements from the lakes. The loggers were submerged at 2.5 m and 3.5 m depth in the lake and sea, respectively due to the condition of the place and safety of loggers. A correction logger was installed in the air at 4 m above sea level and as high as logistic camp on the sea. The data on tides in other lakes were collected during fieldwork with a time interval of 15 minutes for six hours and these are considered sufficient to determine the tide delay between lake and sea.

RESULTS

Physical characteristic of marine lake

The marine lakes at Misool are small compared to those in Palau, Croatia, and Kakaban West Kalimantan with the largest observed to be approximately only 3 ha while the deepest is 38 m (Purba *et al*., 2018b). The distance closest to the sea is also not too far away, with the dimension and distance observed to be similar to most lakes in Vietnam which range between 0.06-3.1 ha, except for one at Cat Bay Island which is 140 ha and has the farthest minimum distance to the sea i.e. 100 m (Cerrano *et al*., 2006). Meanwhile, the maximum depth of the lakes in Misool is more than those in Vietnam which were found to be only lesser than 10 m. The depth of lakes in Misool is gradually up to the middle part, and all the lakes are bowl and funnel in shape with each having a different connection with the sea through a pore, tunnel, cave, up to a wide channel as shown in Figure 2. The seawater and the tidal cycle enter and exit the lakes through a “gap” on this barrier wall which has its lowest from the flat to be up to 3.45 m as shown in Table 1. The

Figure 2: The communication between the lakes and the sea. From left to right: Lenmakana Lake, Balbullol Lake, Lenkafal Lake, Keramat Lake, Keramat-2 Lake, Keramat-3 Lake.

Table 1: Characteristics of the marine lakes at Misool.

Lakes	Distance to sea (m)	Area (ha)	Max depth (m)	Connection	Lowest cliff (m)	Tide delay (minute)	Salinity insitu (ppt)	Salinity time series
Lenmakana	55.78	1.25	18.30	medium cave	2	0-120	27.67	*27.78-28.62
Balbullol	44.63	1.94	38.00	pore, hole	3.45	60-240	32.50	**32.44-34.00
Lenkafal	117.24	0.73	24.00	pore	3.35	45	31.50	-
Keramat	108.95	3.23	7.30	big cave	2	45	32.00	-
Karawapop	23.29	0.57	4.5	pore	flat	30	32.00	-
Keramat-2	46.12	1.35	7.7	pore, hole	2	45	33.78	-
Keramat-3	70.41	3.26	8.9	canal	2	-	29	-
Sea Harapan Jaya	-	-	-	-	-	-	-	*24.90-29.14

* From 5 November 2015 to 13 January 2016
** From 4 November 2015 to 26 December 2015

connection level with the sea, however, delays the mass of seawater entering and leaving for 30 to 240 minutes (Purba *et al.*, 2018a, 2018b).

Some marine lakes in the world have been reported to have low salinity levels, with the lowest recorded at Hang Du Lake I, Halong Bay Vietnam; having only 7 ppt (Cerrano *et al.*, 2006). The lakes in Croatia have brackish salinity which is similar to groundwater and mixed by the wind-borne sea drop and seawater penetration (Suric, 2002). In contrast, the salinity in most of the marine lakes in Misool is higher than the values recorded for the sea as shown in Table 1. This was associated with the low connection between the sea and small basin as well as the high evaporation rate. The Arafura Sea has been reported to be the closest region to the source of southeast monsoon and is strongly influenced by the dry cold air mass (Wyrtki, 1961). This is due to the ability of high wind speed above sea level and low humidity offshore winds to cause very high evaporation up to 780 mm. The absence of surface caves or underwater caves in Balbullol was also found to have led to the higher salinity value of up to 4 ppt in the lake than the sea even though the distance between them is only 44.63 m.

Some lakes have also been discovered to have lower salinity compared to the sea such as the Lenmakana and this is associated with the cave at the northeast of the lake that is 110 cm high and 250 cm wide (Purba *et al.*, 2018b) which connects it to a small lake through tide cycles (Figure 3). The water from the small lake reduces the salinity of the Lenmakana Lake due to the groundwater penetration in the small lake which has the ability to dilute the seawater. The bathymetry for the lakes are shown in Figures 3a to 3g while their characteristics are summarized in Table 1.

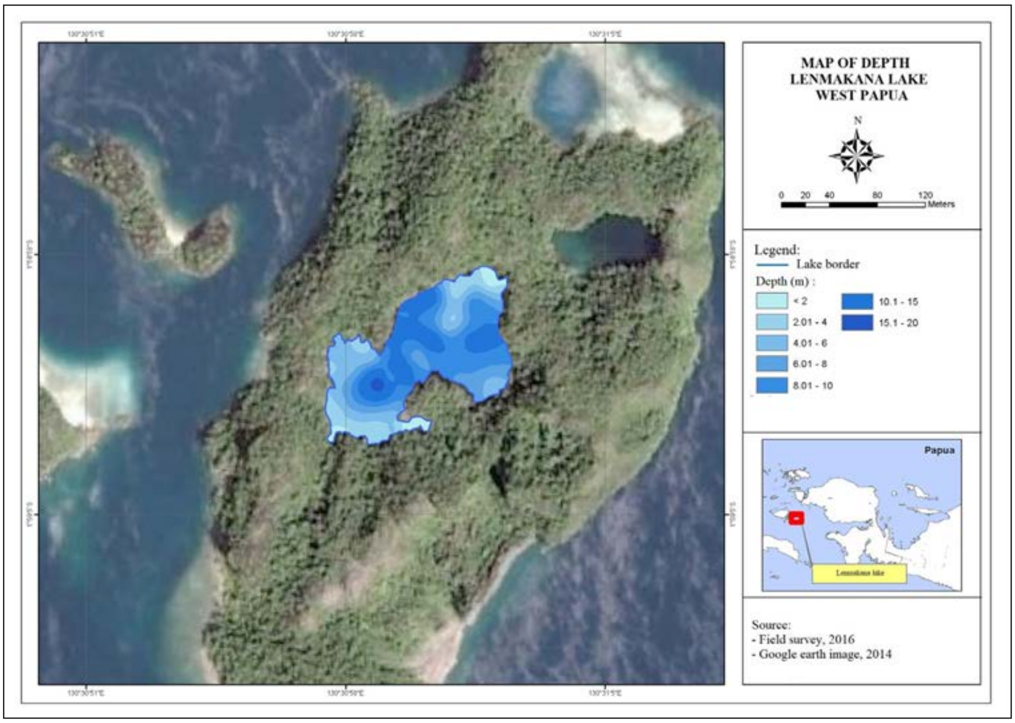

Figure 3(a): Map of depth of Lenmakana Lake (modified after Purba *et al.*, 2018b).

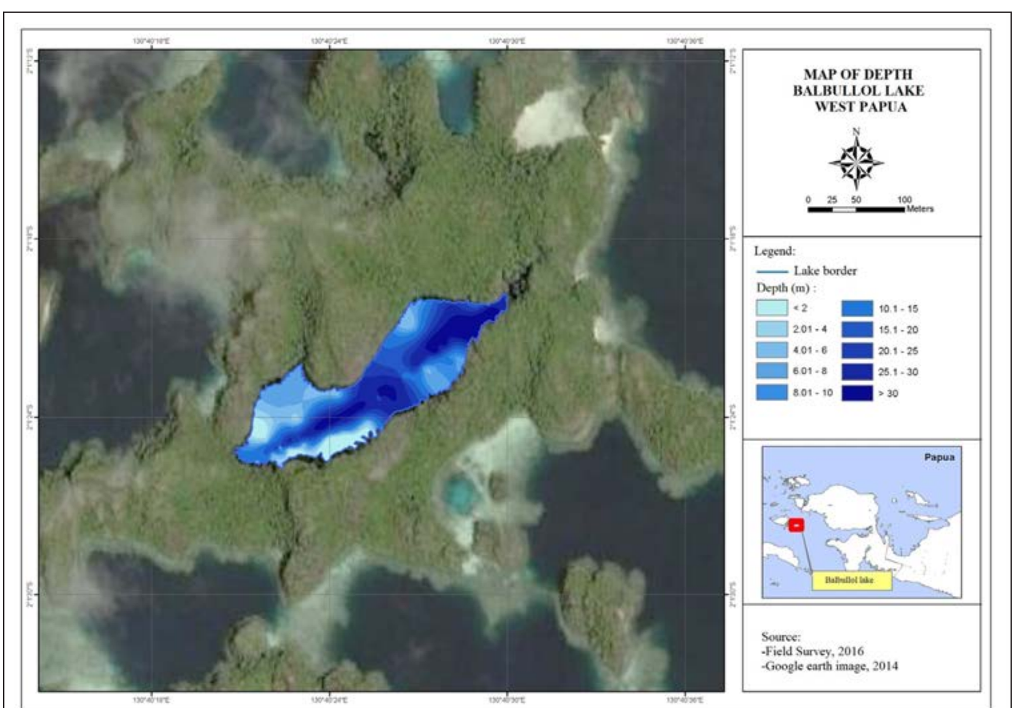

Figure 3(b): Map of depth of Balbullol Lake (modified after Purba *et al.*, 2018a).

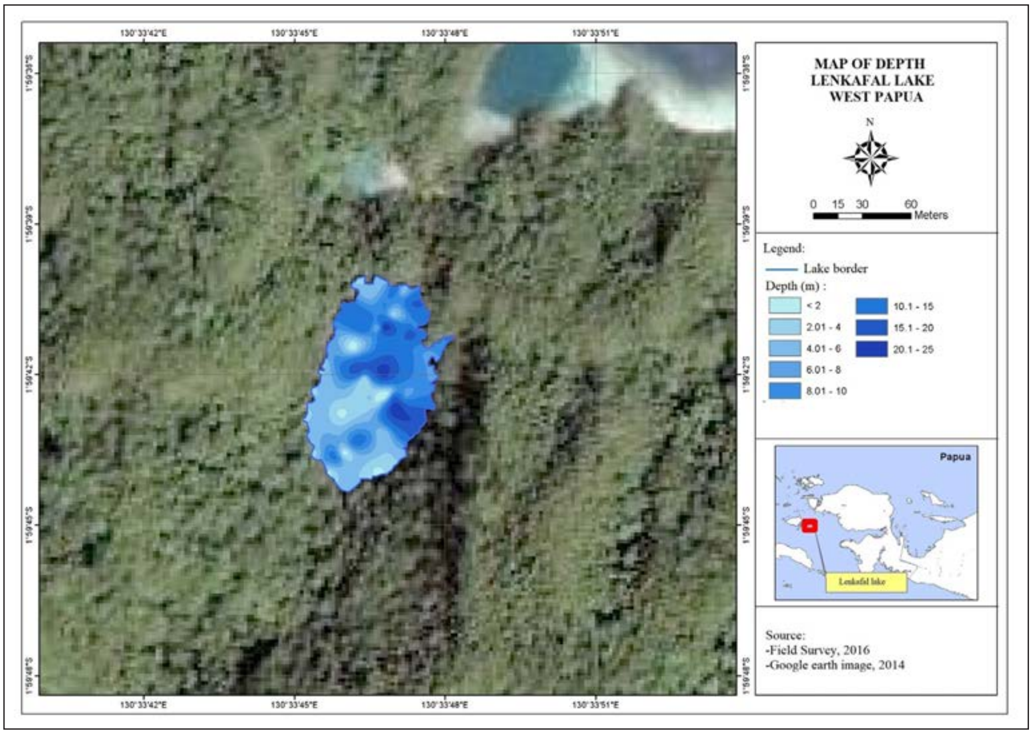

Figure 3(c): Map of depth of Lenkafal Lake.

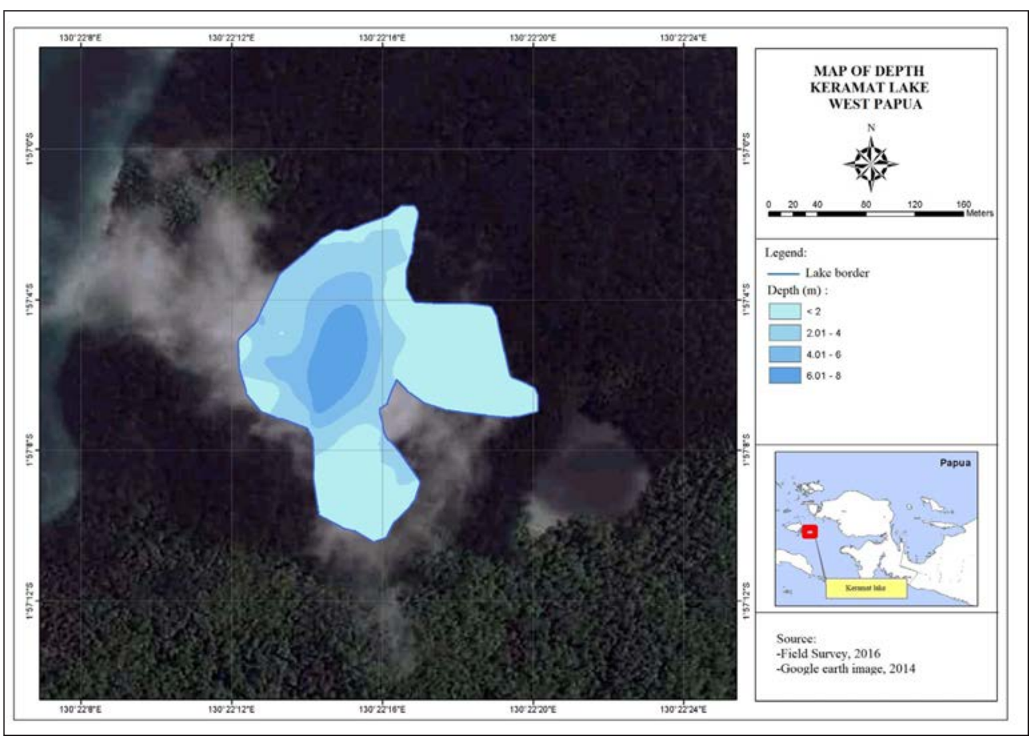

Figure 3(d): Map of depth of Keramat Lake (modified after Purba *et al*., 2018b).

Marine terrace

The marine lakes exist due to sea level and this means it is possible to determine the existence of sea level at the time using the marine terrace in Figure 4. This figure shows the longest terrace accumulation, found at -3 and -33 m depths.

Stable isotope

The composition of $\delta^{18}O$ and δD of lake water samples from Balbullol and Lenkafal lakes were related with the isotope ratios of seawater and they were found to be similar, while those from Lenmakana, Karawapop, Keramat, Keramat-2, and Keramat-3 lakes contained a mixture of

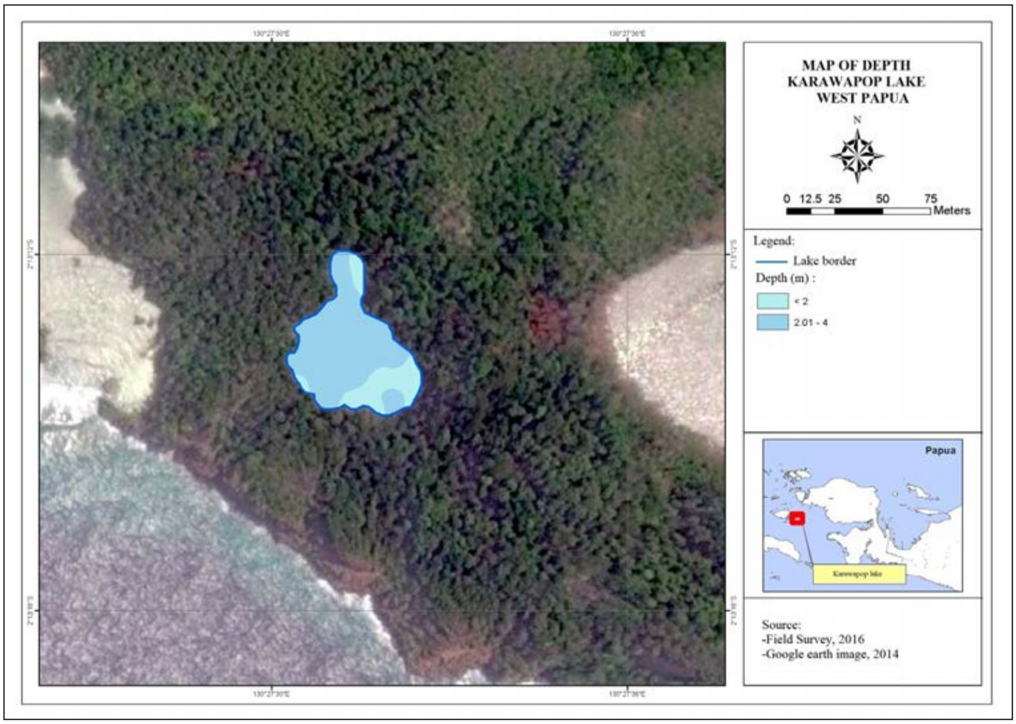

Figure 3(e): Map of depth of Karawapop Lake (modified after Purba *et al.*, 2018b).

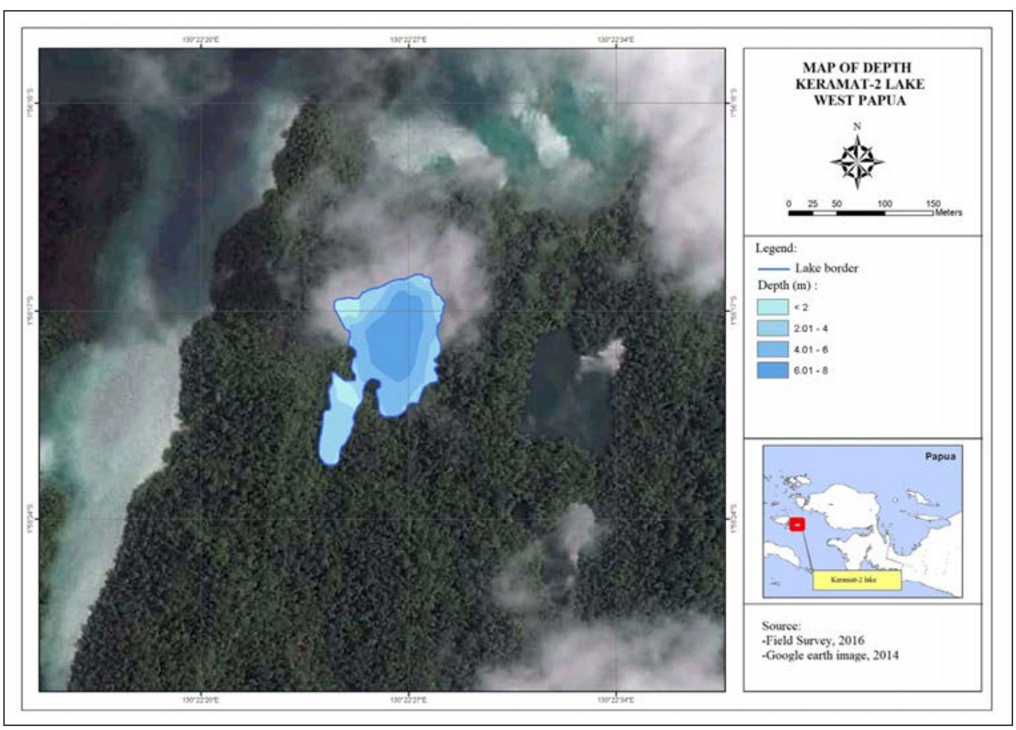

Figure 3(f): Map of depth of Keramat-2 Lake, at Misool.

groundwater and seawater with the seawater concentration more dominant. This was observed from the far distance between the location of the points for the three water samples to the point of intersection between the GMWL line with the Mixing Line but closer to the point of seawater sample, as shown in Figure 5.

DISCUSSION

Doline genesis

The marine lake is in the form of a submerged doline (Suric, 2005) and the genetics from those at Misool indicates a doline dissolution such that from the upside they appear asymmetrical, with the basin depth gradually becoming

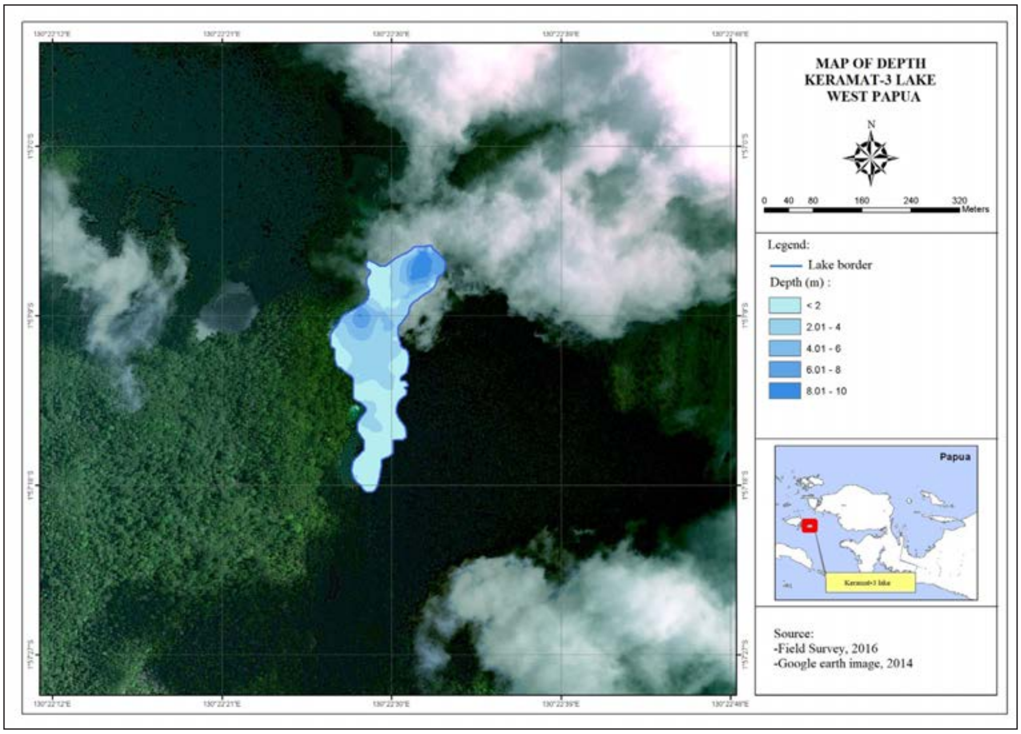

Figure 3(g): Map of depth of Keramat-3 Lake, at Misool.

deeper and having a bowl and funnel shape. In the same manner, there is a concentration of water flow in the epicarst towards the lateral direction and this means the movement of the greater slope of the water level to the doline center increases the hydraulic conductivity in the same direction. This hydrological process is concentrated to form doline and the formation is continuous with the repetition of the previous process with a change in the hydrological system in line with the variation in the flow path area.

The genesis of marine lakes in the Eastern Adriatic Coast of Croatia was due to semi-enclosed depression and collapsed dolines with the characteristics of steep basin wall and this is contrary to the submission by Suric (2002, 2005). Moreover, the roof of the cave or underground hole collapsed due to loss of balance at the beginning of lake formation when the sea level is on the surface as observed in the present times. It has also been reported that three out of four lakes in Croatia have large areas of more than 23 ha (Suric, 2002) while those in Misool are only less than 3.26 ha.

These dolines are estimated to start forming when the position of sea level was at -33 m depth and this is based on water surface position retrieved from Southeast Asia through certain references. For example, the radiometric dating of samples from the Straits of Malacca seabed at -33.41 m depth was reported to be 9,265 BP (Tjia & Mastura, 2013), while the minimum sea level position during the Holocene in Peninsular Malaysia and Thailand was 9,700 - 9,250 BP which is equivalent to -22.15 ± 0.55 m (Horton *et al*., 2005). This is 8 m above the water level at Misool and this means the -33 m position was recorded at an earlier time. Meanwhile, the bathymetric contour model shows the -33 m position of Southeast Asian water level occurred in the 17,000 years period at approximately 8,671 BP (Voris, 2000) while ETOPO2 NGDC extract indicated an earlier occurrence at 10,500 BP (Sathiamurthy & Voris, 2006). Moreover, U-series age showed the coral growth at a depth of 20-30 m at the south of Carpentaria Bay, northern Australia occurred at approximately 10,500-9,500 cal yr BP (Lewis *et al*., 2013) and this is similar to the situation in Peninsular Malaysia and Thailand (Horton *et al*., 2005) and Sunda Shelf (Sathiamurthy & Voris, 2006; Tjia & Mastura, 2013). The increscent of the water level becomes uniform due to the absence of influence from tectonic factors and Lewis *et al*. (2013) did not report the dynamic tectonics in Australia except for the local tectonic mid-time movement of Holocene on the east coast of Queensland. Furthermore, Malaysia and Thailand are parts of the Sunda Shelf considered to be tectonically stable as observed in Peninsular (Tjia, 1992).

The sea level increment continues after the -33 m position for approximately -3 m from the current average sea level and a report showed -3 m depth, precisely -3.435 m, was recorded at approximately 6,985 BP in Negeri Sembilan-Malacca (Steif, 1979 as cited by Tjia & Mastura, 2013) and 6,900 BP in Sundanese Shelf (Sathiamurthy & Voris, 2006). Meanwhile, the mangrove data of the Alligator River at the south of Australia's North Territory showed an earlier occurrence at 6,500 BP (Lewis *et al*., 2013).

The deeper lake is first watered (Colin, 2009) and this means the lakes at Misool are younger than those in Palau with the maximum depth of 60 m recorded in Tketau Lake. The formation of this lake started approximately 12,000

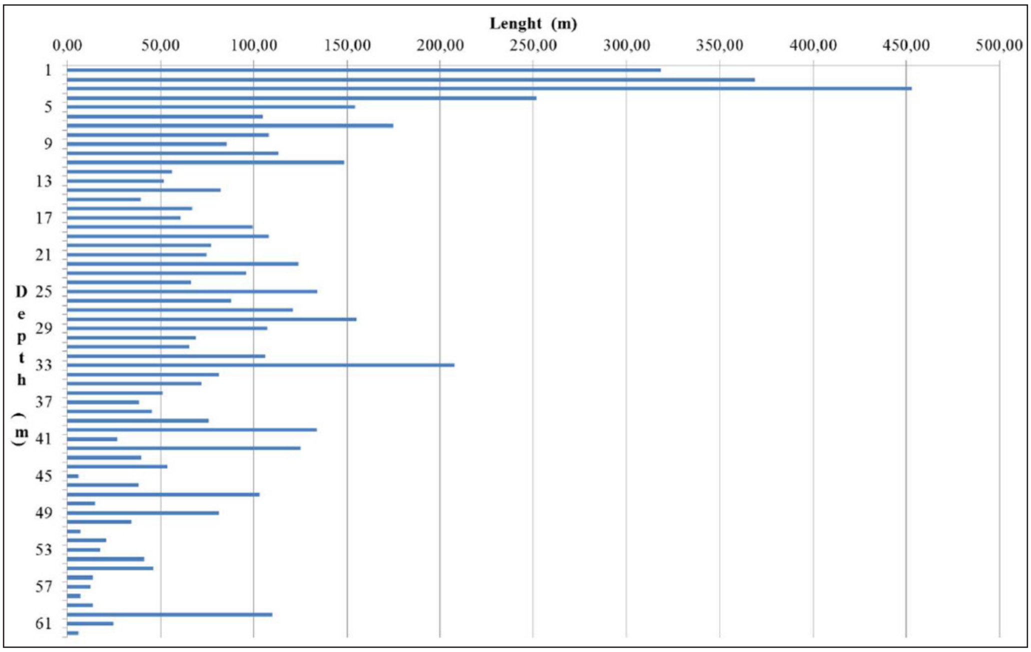

Figure 4: Hypsography of Marine Floor. The marine terrace between two land on the sea where closest to the 7 marine lakes.

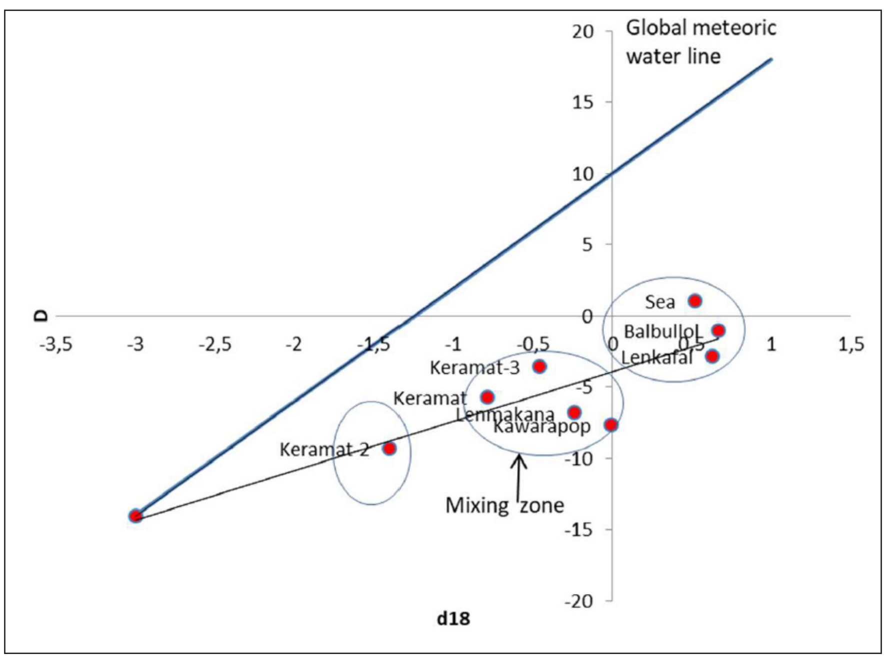

Figure 5: Correlation graph of $\delta^{18}O$ to δD lake water samples in Misool.

years ago while shallow lakes were estimated to have started at 4,000-5,000 years ago and the marine terraces results previously referenced showed that the deepest marine lakes at Misool and Balbullol started to be filled with seawater at least 10,500 BP and followed by other concave parts. The last to be formed is Karawapop Lake and this makes it the shallowest, therefore, this means the shallow lakes in Misool were formed earlier. Moreover, the sea level was already at -3 m position for almost 2,000 years before it happened in Palau due to the tectonic uplift in the Misool area (Tomascik *et al*., 1997). Some of the documentation collected from the sea wall of the Southeast Misool area also provide evidence to show the water level position exceeds the *high stand* with 9.05 m to 16.3 m above the mean sea level, as shown in Figures 6 and 7. Meanwhile, Haile (1975) in Tjia & Mastura (2013) reported that the highest sea level

Figure 6: Notches at the entrance of Balbullol Lake. The lower pictures are left, middle, and right portions of the upper picture.

in Quaternary was not more than 6 m and the evidence of higher value is associated with tectonic uplift.

Misool, as a part of the Bird's Head block, is actively deforming via anticlockwise rotation and subparallel sinistral strike-slip faulting with ~8 cm year^{-1} relative to the Australia plate (Pigram & Symonds, 1991; Stevens *et al*., 2002 and Bailly *et al*., 2009 in Baldwin *et al*., 2012). This plate continues to move horizontally and is also observed to be uninterrupted after the Miocene uplift. Meanwhile, the consideration of neighboring locations showed the occurrence of vertical uplift in the Banda arc at 0.16-1.2 mm/year from the beginning to the end of the Pleistocene (Tomascik *et al*., 1997) while approximately 1-1.5 m/1000 years average surface uplift was reported on the Rote Island. The rate of increase is associated with the coral samples being lifted at the lowest position of 1-2 m in the Holocene age. Moreover, the research conducted in Huon Papua New Guinea reported an uplift around the eastern New Britain coast, the Huon Peninsula to be as high as ~ 2-3 m/ka and 1.6-0.4 m/a for the south coast (Coleman *et al*., 2006). An earthquake experienced on May 15, 1992, from 45 km of Huon coastline showed ~ 8-14 cm subsidence at the northern end of the Sialum Lagoon, while the southeast lift was ~ 7-13 cm (Pandolfi *et al*., 1994).

Filled marine lake

The seawater enters the doline to form a marine lake by dissolving the cavities previously formed either below or

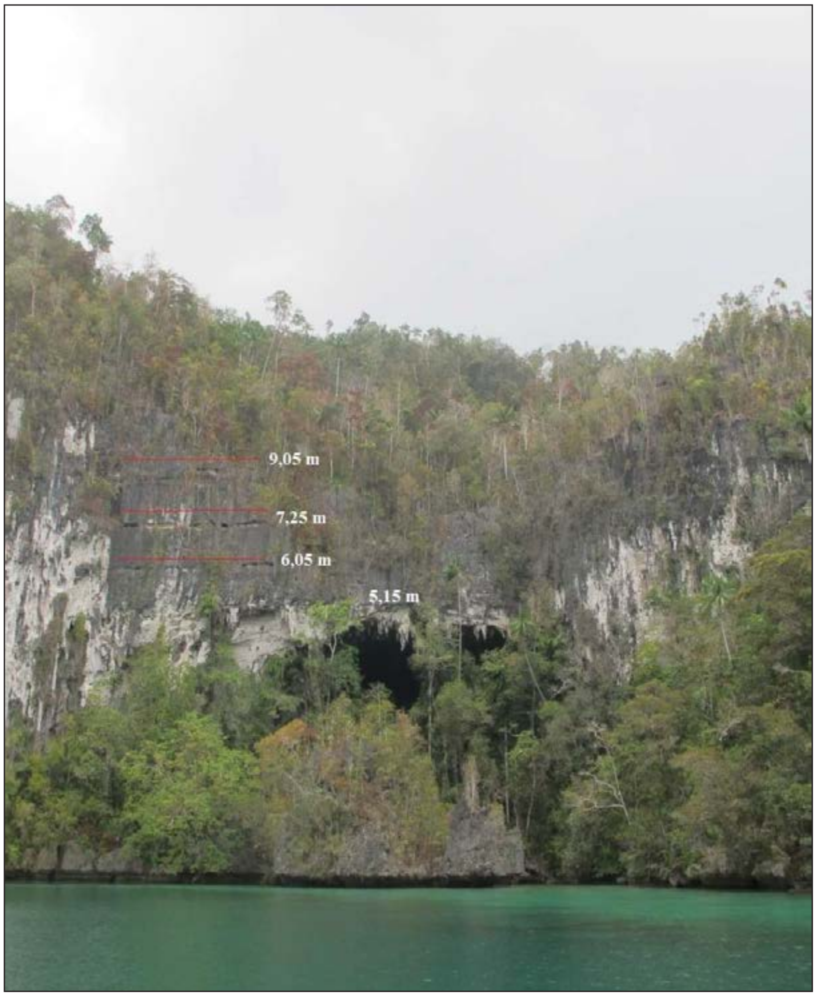

Figure 7: Cave and notch heights at the entrace of Keramat Lake.

above the sea level before the water level in the Holocene position. The entry of water into and out of the lake through caves or undersea tunnels has, however, not been explicitly proven at Misool with diving only conducted at one point each in Balbullol and Harapan Jaya lakes. This limits the opportunity to find caves which have been discovered in other places as observed in the underwater morphology studies in the Maldives at depths of -5 m to -42 m from 16 profiles (Rufin-Soler *et al*., 2014). The cave was formed during the interglacial periods when the sea was under the newest level. Meanwhile, most of the notches were discovered to be present at depth of -24/-26 m with 13 notches and -32/-35 m with 18 notches. The information on the NE European regional eustatic curve (Rufin-Soler *et al*., 2014) showed the cave and notch positions at -32/-35 m are estimated to be at 10,000 BP while -3 m with only 3 caves occurred at 5,500 BP (Rufin-Soler *et al*., 2014). However, this time is almost adjacent to the presence of the marine terrace at Misool.

The distance between the sea and the lake is relatively close due to the possibility of the seawater to easily flow, fill, and flood the doline to create a marine lake. All the seven lakes originated from seawater or through the mixture of seawater with a lesser percentage of groundwater. Balbullol and Lenkafal lakes are initially seawater, with deeper depths and lowest cliff edges compared to the others. Their basins are also not connected to the sea due to the possibility of being pre-filled by seawater during high stand through holes and pores on the wall. Furthermore, the connections between seawater and lakes become limited when the water level dropped, as observed in Balbullol Lake, while the absence of surface or underwater cave causes the salinity value in the lake to be higher than the sea even though they are just 44.63 m apart. Stagnant basins, minimal connection with the sea, and high evaporation rates also lead to 4° higher salinity in Balbullol Lake compared to the sea.

CONCLUSIONS

The marine lakes at Misool are doline sinks and these are a type of doline dissolution involving the filling of the doline with water due to an increase in sea levels during interglacial Holocene. The changes in sea level was observed to have filled the lakes at Misool for at least two times as observed in 10,500 BP and 6,985 BP. Moreover, tectonic activity caused the water level to reach a certain position first rather than elsewhere at the same time. The water in the lakes was observed to be purely seawater or a mixture of seawater with a lower percentage of groundwater. The entry of water from the sea to the lakes through a cavity system ensued as a result of karstification process both below the sea level and above the modern sea level.

ACKNOWLEDGEMENTS

The authors extend their gratitude to the Nature Conservancy (TNC), Public Service Agency of Raja Ampat (BLUD), and Wageningen University and Research (WUR) Netherland as well as Ali Oherenan, Wawan Mangile, and the students of Papua University for assisting in the process of conducting this research. Thank you to the anonymous reviewers for very constructive comments, suggestion, and detail English correction.

AUTHOR CONTIBUTIONS

GYSP wrote the original manuscript, revised, and collected data in the field. LR, P and LEB provided access to crucial research components. Also, LR and P helped in data collection and provided technical guidance in field. EH conceived the research design, result interpretation, supervised and provided revisions to the scientific content of this manuscript.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare that are relevant to the content of this article.

REFERENCES

Azzini, F., Calcinai, B., Cerrano, C., Bavestrello, G., Pansini, M., 2007. Sponges of the Marine Karst Lakes and of the Coast of the Islands of Ha Long Bay (North Vietnam). Porifera Res. Biodiversity, Innov. Sustain., 157–164.

Baldwin, S.L., Fitzgerald, P.G., Webb, L.E., 2012. Tectonics of the New Guinea Region. Annu. Rev. Earth Planet. Sci., 40, 495–520. https://doi.org/10.1146/annurev-earth-040809-152540.

Becking, L.E., de Leeuw, C., Vogler, C., 2014. Newly Discovered "Jellyfish Lakes" in Misool, Raja Ampat, Papua, Indonesia. Mar. Biodivers., 45, 597–598. https://doi.org/10.1007/s12526-014-0268-6.

Becking, L.E., Renema, W., Dondorp, 2009. Marine lakes of Raja Ampat, West Papua, Indonesia : General overview of first sightings. Survei Report 1–26.

Becking, L.E., Renema, W., Santodomingo, N., Hoeksema, B.W., Tuti, J., Voogd de, N.J., 2011. Recently Discovered Landlocked Basins in Indonesia Reveal High Habitat Diversity in Anchialine Systems. Hydrobiologia, 677, 89-105. https://doi.org/10.1007/s10750-011-0742-0.

Beehler, B.M., 2007. Papuan Terrestrial Biogeography with Special Reference to Bird. In: Marshall, A.J., Beehler, B.M. (Eds.), Ecology of Papua Part One. Periplus, Singapore, pp. 196–206.

Cerrano, C., Azzini, F., Bavestrello, G., Calcinai, B., Pansini, M., Sarti, M., Thung, D., 2006. Marine lakes of karst islands in Ha Long Bay (Vietnam). Chem. Ecol., 22, 489–500. https://doi.org/10.1080/02757540601024835.

Colin, P.L., 2009. Marine Enviroments of Palau. Indo-Pacific Press, Sand Diego. 414 p.

Dawson, M.N., 2005a. Five New Subspecies of *Mastigias* (Scyphozoa: Rhizostomeae: Mastigiidae) from Marine Lakes, Palau, Micronesia. J. Mar. Biol. Assoc. UK, 85, 679–694. https://doi.org/10.1017/S0025315405011604.

Dawson, M.N., 2005b. Morphological variation and systematics in the Scyphozoa: *Mastigias* (Rhizostomeae, Mastigiidae) - A golden Unstandard? Hydrobiologia, 537, 185–206. https://doi.org/10.1007/s10750-004-2840-8.

Dawson, M.N., 2004. Some implication of molecular phylogenetics for understanding biodiversity in jellyfish, with emphasis on Scyphozoa. Hydrobiologia, 530/531, 249–260.

Dawson, M.N. & Hamner, W.M., 2003. Geographic variation and behavioral evolution in marine plankton: The case of Mastigias (Scyphozoa, Rhizostomeae). Mar. Biol., 143, 1161–1174. https://doi.org/10.1007/s00227-003-1155-z.

Dawson, M.N., Martin, L.E. & Penland, L.K., 2001. Jellyfish Swarms, Tourists, and the Christ-child. Hydrobiologia, 451, 131–144.

Hamner, W.M., Gilmer, R.W. & Hamner, P.P., 1982. The Physical, Chemical, and Biological Characteristics of a Stratified, Saline, Sulfide Lake in Palau. Limnol. Ocean., 27, 896–909.

Hamner, W.M. & Hamner, P.P., 1998. Stratified Meromictic Lakes of Palau (Western Caroline Island). Phys. Geogr., 1, 175–220.

Horton, B.O., Gibbard, P.L., Milne, G.M., Morley, R.J., Purintavaragul, C. & Stargardt, J.M., 2005. Holocene Sea Levels and Palaeoenvironments, Malay-Thai Peninsula, Southeast Asia. The Holocene, 15, 1199–1213.

Lewis, S.E., Sloss, C.R., V, M.-W.C., Woodroffe, C.D. & Smithers, S.G., 2013. Post-glacial Sea-Level Changes Around the Australian Margin : a Review. Quat. Sci. Rev., 74, 115–138. https://doi.org/10.1016/j.quascirev.2012.09.006.

Mangubhai, S., Erdmann, M. V., Wilson, J.R., Huffard, C.L., Ballamu, F., Hidayat, N.I., Hitipeuw, C., Lazuardi, M., Muhajir, Pada, D., Purba, G., Rotinsulu, C., Rumetna, L., Sumolang, K. & Wen, W., 2012. Papuan Bird's Head Seascape: Emerging Threats and Challenges in the Global Center of Marine Biodiversity. Mar. Pollut. Bull., 64, 2279–2295. https://doi.org/10.1016/j.marpolbul.2012.07.024.

Martin, L.E., Dawson, M.N., Bell, L.J. & Colin, P.L., 2006. Marine lake ecosystem dynamics illustrate ENSO variation in the tropical western Pacific. Biol. Lett., 2, 144–147. https://doi.org/10.1098/rsbl.2005.0382.

Pandolfi, J.M., Best, M.M.R. & Murray, S.P., 1994. Coseismic Event of May 15, 1992, Huon Peninsula, Papua New Guinea: Comparison with Quaternary Tectonic History. Geology, 22, 239–242.

Purba, G.Y.S., 2010. Monitoring Suhu Permukaan Laut di Bentang Laut Kepala Burung, Papua. Laporan Akhir 2005-2010. Manokwari.

Purba, G.Y., Haryono, E. & Sunarto, S., 2018a. Danau Laut Balbullol di Misool Raja Ampat. J. Sumberd. Akuatik Indopasifik, 1, 53. https://doi.org/10.30862/jsai-fpik-unipa.2017.vol.1.no.2.35.

Purba, G.Y.S., Haryono, E., Sunarto, Manan, J., Rumenta, L., Purwanto & Becking, L.E., 2018b. Jellyfish Lakes at Misool

Islands, Raja Ampat, West Papua, Indonesia. Biodiversitas, 19, 172–182. https://doi.org/10.13057/biodiv/d190124.
Rufin-Soler, C., Mörner, N., Laborel, J. & Collina-G, J., 2014. Submarine Morphology in the Maldives and Holocene Sea-Level Rise. J. Coast. Res., 30, 30–41.
Rusmana, E., Hartono, U. & Pigram, C.J., 1989. Peta Geologi Lembar Misool Irian Jaya, Skala 1:250.000. Lembar Misool 2713-2714-2813-2814.
Santodomingo, N., 2009. Unravelling the Moon Sponges: On the Ecology and Phylogeni of Cinchyrella spp. and Paratetilla spp. (Spirophorida: Tetillidae) in Indonesian Anchialine Lakes. Master Pro., Laiden University-Naturalis, Leidein.
Sapin, F., Pubellier, M., Ringenbach, J.-C. & Bailly, V., 2009. Alternating Thin Versus Thick-Skinned Decollements, Example in a Fast Tectonic Setting : The Misool-Onin-Kumawa Ridge (West Papua). J. Struct. Geol., 31, 444–459. https://doi.org/10.1016/j.jsg.2009.01.010.
Sathiamurthy, E. & Voris, K.H., 2006. Maps of Holocene Sea Level Transgression and Submerged Lakes on the Sunda Shelf. Nat. Hist. J. Chulalongkorn Univ., 2, 1–44.
Suric, M., 2002. Submarine Karst of Croatia-Evidence of Former Lower Sea Levels. Acta Carsologica, 31(3), 89–98.
Suric, M., 2005. Submerged Karst-Dead or Alive? Examples From the Eastern Adriatic Coast (Croatia). Geoadria, 10, 5–19.
Tjia, H.D., 1992. Holocene Sea-level Changes in the Malay-Thai Peninsula, A Tectonically Stable Environment. Bulletin of the Geological Society of Malaysia, 31, 157–176.
Tjia, H.D. & Mastura, S., 2013. Sea Level Change in Peninsular Malaysia: Geological Record. University Kebangsaan Malaysia, Selangor.
Tomascik, T. & Mah, A.J., 1994. The Ecology of "Halimeda Lagoon" An Anchialine Lagoon of a Raised Atoll, Kakaban Island, East Kalimantan, Indonesia. Trop. Biodivers., 2, 385–399.
Tomascik, T., Mah, A.J., Notji, A. & Moosa, M.K., 1997. The Ecology of Indonesia Seas Part One. Oxford University Press, Singapore. 642 p.
Verstappen, H.T., 2014. Garis Besar Geomorfology Indonesia. Penerjemah: Sutikno. Gadjah Mada University Press, Yogyakarta. 219 p.
Voris, H.K., 2000. Maps of Pleistocene Sea Levels in Southeast Asia: Shorelines, River Systems and Time Durations. J. Biogeogr., 27, 1153–1167.
Wyrtki, K., 1961. NAGA REPORT. Scientific Result of Marine Investigations of the South China Sea and the Gulf of Thailand 1959-1961. The University of California & Scripps Institution of Oceanography, California.

Manuscript received 16 May 2020;
Received in revised form 18 September 2020;
Accepted 1 October 2020
Available online 16 November 2021