Redwood, S. D. 2020. Late Pleistocene to Holocene sea level rise in the Gulf of Panama, Panama, and its influence on early human migration through the Isthmus. *Caribbean Journal of Earth Science*, **51**, 15-31. © Geological Society of Jamaica. Available online 28th March 2020.

Late Pleistocene to Holocene sea level rise in the Gulf of Panama, Panama, and its influence on early human migration through the Isthmus

STEWART D. REDWOOD

Consulting Geologist, PO Box 0832-0757, Panama City, Panama. Corresponding author: Email: mail@sredwood.com

ABSTRACT. This paper describes the rise of eustatic sea level in the Gulf of Panama, Panama, and the formation of the Pearl Islands and Taboga archipelagos during the late Pleistocene and Holocene since the end of the last glacial maximum at about 21 ka. Sea level was then about 130 m below present and the Gulf was occupied by a wide grassy plain some 150 km long and 200 km wide, the Las Perlas drowned plain. A series of palaeogeographic maps, or time-slices, were made using bathymetric maps and published global sea-level curves. The first stage of sea-level rise was rapid, by 125 m to -5 m in about 14,000 years from 21 ka to 7 ka. Since then the rate of change has been slow. There is geomorphological evidence from raised beaches and stranded shorelines that relative sea level actually rose to about +2 m in the mid Holocene high stand and since then has regressed to the present-day shore line: further work is required to date this and determine whether the cause was eustatic or tectonic.

The Pearl Islands became a single big island by the time sea level reached about -40 m between about 10.2 and 10.0 ka. Pedro González Island and San José Island on the west side of the archipelago were separated from the other islands at about 8.8 to 8.3 ka. The remaining big island separated into smaller islands over the next 1,500 years by 7.5 to 7.2 ka. The Taboga archipelago became islands at about 9.4 to 9.0 ka. The main geomorphological and bathymetric effects of sea level rise include flooded valleys, submarine valleys and buried river valleys.

The wide grassy Las Perlas plain would have aided the first human migrations through the isthmus at 14.0 to 11.0 ka. The Gulf of Panama is inferred to have had a similar history of multiple regressions and transgressions related to fluctuating glacial and interglacial periods throughout the Pleistocene. The wide plains developed during sea level low-stands may also have been an important factor in the Great American Biotic Interchange at the start of the Quaternary.

Keywords: Pearl Islands, Taboga, Las Perlas drowned plain, Holocene high stand, Pacific muck, buried valleys, submarine valleys, early human migration, Great American Biotic Interchange.

1. INTRODUCTION

The Gulf of Panama is a large (28,000 km^2), shallow part of the Pacific continental shelf of Panama that was dry land during the last glacial maximum, about 21,000 years ago, when global sea level was about 120 to 130 m below present (**Figure 1**). As the ice melted, global sea levels rose. The rise in sea level in the Gulf of Panama, and the formation of the Pearl Islands (Las Perlas in Spanish) and Taboga archipelagos, was plotted using bathymetric maps and global sea-level curves, with supporting submarine and on-land geomorphological evidence.

There are four main themes to this work. The Gulf was occupied by a wide grassy plain, the Las Perlas drowned plain, some 21,000 years ago. Geomorphological evidence is presented for a relative sea-level high stand in the mid to late Holocene. This is well documented in the central and western Pacific (e.g., **Chappell, 1983**; **Dickinson, 2000, 2009**; **Peltier, 2002**; **Perry and Smithers, 2010**), but is previously undocumented in the eastern Pacific. The third theme is the effect of palaeogeographical variations on early human migration from North America to South America passing through the isthmus, human colonisation and activities in the isthmus, and the short-term regional variability of ecosystems (e.g., **Cooke et al., 2013**). Finally, the possible influence of sea level changes projected back to the early Pleistocene on the Great American Biotic Interchange is discussed (e.g., **Woodring, 1966**; **Marshall et al., 1982**; **Molnar, 2008**).

2. POST-GLACIAL EUSTATIC SEA LEVEL RISE

Global sea levels have risen rapidly by about 130 ± 10 m (**Rohde, 2005**) to 125 ± 5 m (**Fleming et al., 1998**) to 120 m (**Peltier, 2002**) since the low-stand of the Last Glacial Maximum (LGM) at 22 ± 3 ka (**Rohde, 2005**) to 21 ka (**Peltier, 2002**) due to the

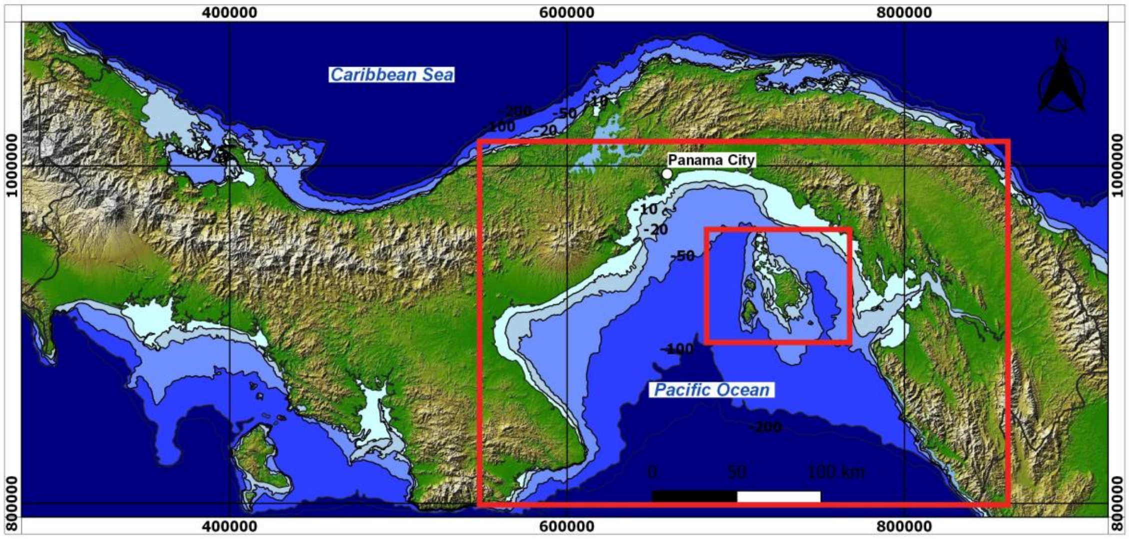

Figure 1. Location map of Panama showing the Las Perlas plain in the Gulf of Panama at a sea level of -100 m MLWS at about 16.2 to 14.5 ka, shortly after the low stand of the last glacial maximum. The large box shows the location of Figs 5 to 10, and small box shows the location of Figs 11 to 13. Based on the 1:500,000 scale topographic map of Panama. The grid on all maps is UTM WGS84.

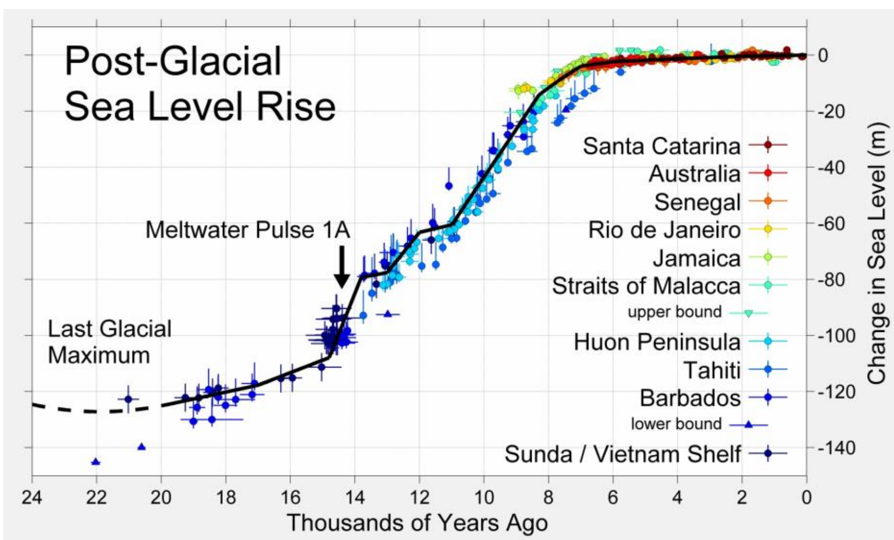

Figure 2. Post-glacial sea level rise curve. Compiled by Rohde (2005) in Wikipedia, based on Fleming et al. (1998) and updates. The data points are shown with ±2σ uncertainties. This figure is reproduced under the Creative Commons Attribution Non Commercial Share Alike Licence version 2.5.

release of glacial melt-water to the global ocean. The lowest point of sea level is not well constrained (**Rohde, 2005**). The LGM coincided with the time of lowest sea level. By about 6.8 ka sea levels had reached about -3 m, since when the rise has been slow and unpredictable, with no single sea-level curve available. There is no sea-level curve for the Gulf of Panama: the only one for the Isthmus is for Lake Gatun (**Bartlett and Barghoorn, 1973**). There are uncertainties in assigning a precise age to a particular depth due to the 2 sigma errors in the data used to construct sea level curves and differences between sea level data from different sites, especially in the last 6.8 ka. This paper uses the sea level curves of **Fleming et al.** (**1998**) as revised and plotted by **Rohde** (**2005, 2006**) (**Figures 2, 3; Table 1**).

There is a well-established mid Holocene sea level (hydro-isostatic) high stand of +2 m at about 6.0 ka in the western and central Pacific Ocean including Australia and the Polynesian islands (**Chappell, 1983**; **Dickinson, 2000**; **Peltier, 2002**; **Dickinson, 2009**; **Perry and Smithers, 2010**). Evidence is presented for a relative sea-level high

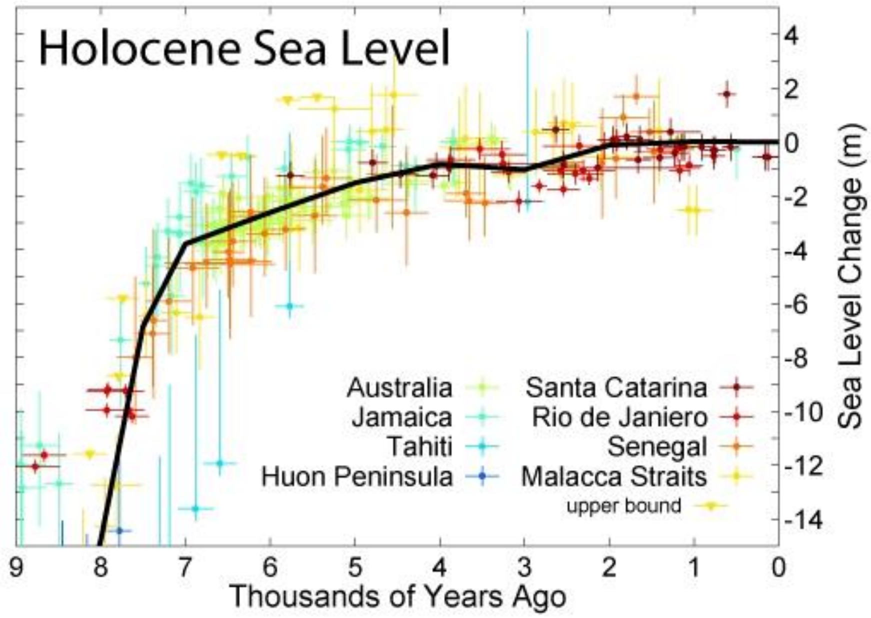

Figure 3. Holocene sea level curve. Compiled by Rohde (2006) in Wikipedia, based on Fleming et al (1998) and updates. The data points are shown with ±2σ uncertainties. This figure is reproduced under the Creative Commons Attribution Non Commercial Share Alike Licence version 2.5.

Table 1. Table of estimated dates for post-glacial, global eustatic sea level rise. Time 1: Fleming et al., 1998. Time 2: Rohde, 2005, 2006.

Depth (m)	Time 1 (years BP)	Time 2 (years BP)	Geological Series/Epoch (age years BP)
0	0	0	Holocene (11,500 - 0 BP)
-1.5		5,000	
-3	6,800		
-5	7,200	7,200	
-10	7,700	7,700	
-15	8,300	8,000	
-20	8,800	8,300	
-30	9,400	9,000	
-40	10,200	10,000	
-50	10,600	10,200	
-60	12,000	11,000	
-70	13,000	12,500	Upper Pleistocene (126,000 - 11,500 BP)
-80	14,000	14,000	
-90	14,500	14,200	
-100	16,200	14,500	
-110	18,000	15,000	
-120	21,500	17,800	
-130		21,000	

stand in the Gulf of Panama, which, if confirmed by further work to be eustatic rather than tectonic, would require modification of the sea-level curve for the Gulf. Milne et al. (2005) stated that the mid-Holocene sea-level maximum, or high stand, is evident in tectonically stable, far-field locations away from the major centres of glaciation, although it appears to be absent in the Atlantic. The Holocene high stand occurred only in the southern Hemisphere, whereas sea level is still rising in the northern hemisphere (Isla and Angulo, 2015).

3. Methods and Sources of Data

Two sets of data were used to make the bathymetric maps, one for the whole Gulf of Panama, and a second in more detail for the Pearl Islands. The bathymetric data for the Gulf of Panama was taken from British Admiralty chart number 1929 titled “Gulf of Panama”, published in 1998, at a scale of 1:300,000, which is the most recent survey available (Admiralty Charts and Publications, 1998). It was compiled from various U.S. Navy surveys made in the 1970s. Spot depths are marked and some seabed contours are drawn. The author interpreted additional contours at 10 m intervals. The chart datum is WGS84. The depths are in metres and are reduced to Chart Datum, which is approximately the level of Mean Low Water Springs (MLWS). The chart was geo-referenced in MapInfo GIS software and the seabed contours were digitized. From this a series of maps were made at 10 m intervals from -130 to 0 m.

For the Pearl Islands there are five detailed topographic maps with bathymetric contours at a scale of 1:50,000 published by the Tommy Guardia National Geographical Institution (IGN), Panama (sheets 4341-I, Saboga; 4341-II, Isla Pedro González; 4441-III, San Miguel; 4340-I, Isla de San José; and 4440-IV, Esmeralda). The map datum is

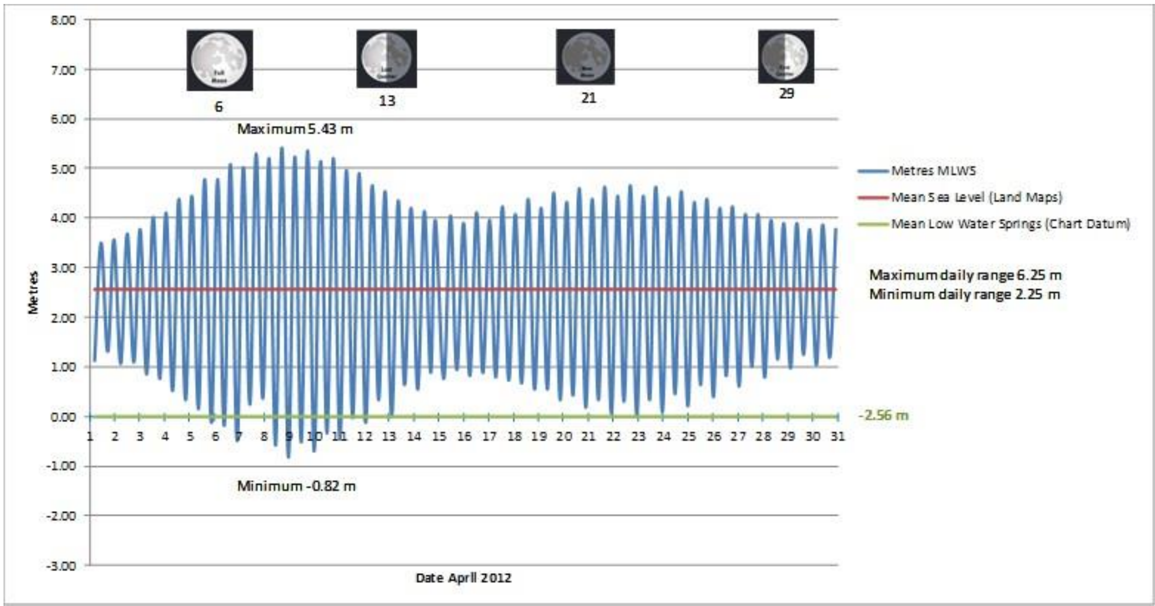

Figure 4. Tides at Balboa for one month (April 2012) showing the variation in the daily tide range, the phases of the Moon, and the difference between chart datum (MLWS) and land datum (MSL). Sea level curves refer to the land datum.

NAD27. The vertical datum for land is average sea level. The hydrographic data is based on soundings in fathoms (the exact conversion is 1 fathom = 1.8288 m) with datum of mean low-water springs. Bathymetric contours are drawn for 3, 6, 10, 20 and 30 fathoms (-5.5, -11.0, -18.3, -36.6 and -54.9 m rounded to 1 decimal place) and numerous soundings in fathoms are marked. The bathymetric data on these maps was compiled from U.S. Navy Survey sheets 145 and 4246, dated 1929, which are stated to have "good reliability", and U.S. Hydrographic Office chart numbers 5571, 5581, 5582 and 5585, dated 1934, which are stated to have "good precision". The topography was taken from air photos taken in January-February 1952. The maps were compiled in 1959, field checked in 1960, printed in 1962, and reprinted in 1994-1999. They were produced by Cartographic Directorate of Panama, the Inter-American Geodetic Survey and the U.S. Army Map Service. The maps were geo-referenced in MapInfo GIS software and the seabed contours were digitized. From this a series of maps were made at the original contour intervals of -5.5, -11.0, -18.3, -36.6 and -54.9 m.

Bathymetric charts use a different vertical datum from land maps (**Figure 2**). The vertical datum for land maps is Mean Sea Level (MSL), while the vertical datum for bathymetric charts is Chart Datum or Mean Low Water Springs (MLWS, or NMBSO in Spanish, "Nivel Media de Bajamares de Sicigias Ordinarias"). Mean Sea Level is higher than MLWS. According to the Panama Canal Authority, mean low water springs has been determined as being 8.4 feet (2.56 m) below Mean Sea Level at Balboa (Pacific) by the U.S. Coast and Geodetic Survey (*http://www.pancanal.com/eng/op/tide-tables.html*). This is assumed to be constant throughout the Gulf of Panama. This factor has to be added to MLWS to convert it to MSL. It should also be noted that there is a significant diurnal tidal range in the Gulf of Panama which can vary from 2.25 to 6.37 m, with high tides up to 5.73 m at spring tides in a monthly cycle (**Figure 4**).

Sea-level curves use the same vertical datum as land maps, namely Mean Sea Level. This is explicitly stated in some papers (e.g., **Fleming et al., 1998**; **Milne et al., 2005**; **Perry and Smithers, 2010**) and it is assumed for all others which omit to state the datum.

The time on sea-level curves is stated in years or thousands of years (ka) before present (BP), which is defined as AD 1950. The dates used to make sea level curves were determined by ^{14}C or U-Th dating (**Fleming et al., 1998**). Ages based on ^{14}C are calibrated years (cal BP) corrected for atmospheric ^{14}C, while for ^{14}C ages that lie beyond the range of calibration, a linear regression using coral samples dated by both ^{14}C and U-Th was used by **Fleming et al.** (**1998**).

The land topography on the Gulf of Panama palaeogeographical maps uses the 30 arc-second NASA Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM), with a 900 m pixel size. For the Pearl Islands maps the island outlines were digitized from the 1:50,000 topographic maps.

The assumption is made that the present seabed and depths represent the former land surface. The caveat is that post-transgression sediments of up to

20 m thickness have been deposited at depths up to 80 m, as determined by a sub-bottom reflecting layer detected by depth echo sounder in the north-western part of the Gulf by **Golik** (**1968**). Thus, the ages are minimum for a given contour or, to put it another way, the palaeo-shoreline was lower and further out than shown at a given time. In addition, Panama lies in a region of plate tectonic compression and shortening, which can result in variable up and down vertical effects, such as normal faulting with 10 m throw in Holocene sediments (**Golik, 1968**).

The biggest uncertainty, however, is the variation between different sea-level curves and the scatter of the data used, although the overall pattern is clear and consistent (**Figures 2-3**; **Table 1**). This can result in variations of up to 1,000 years or more for a given depth.

4. THE GULF OF PANAMA

At the last glacial maximum, sea level was about 120 to 130 m below present and the entire Gulf of Panama was dry land from Punta Mala, on the southeast point of the Azuero Peninsula, to the Colombian border (**Figure 1**). It formed a huge, flat plain about 200 km wide and 150 km long, named here as the Las Perlas drowned plain, which extended south from Panama City. The Pearl Islands formed a range of hills on the eastern side of the plain, and there were small, steep hills near to the present-day coast such as Taboga and Otoque. The plain was probably a dry and open habitat or grassland as the late Pleistocene climate was drier and cooler, based on pollen records from lake sediments at Lake Gatun (**Bartlett and Barghoorn, 1973**), El Valle (**Bush and Colvinaux, 1990**) and Monte Oscuro near Capira on the coast southwest of Panama City (**Piperno and Jones, 2003**). There was a central river canyon from near the mouth of the River Bayano and going along the west side of the Pearl Islands, which are bounded by a fault, and there was another canyon southwest of the River San Miguel.

Sea-level rise was rapid. It rose by 125 m (from -130 to -5 m) in about 14,000 years between 21 ka and 7 ka, at an average rate of about 9 mm per year, and it traversed 150 km horizontally almost to the present day shore in this time, a horizontal rate of 10.7 m per year (**Figures 5-9**). The changes would have been visible to early humans. In, say, a 30-year lifetime, sea level would have risen by 0.27 m and advanced 320 m inland. The sea level reached within 3 m of the present level at about 6.8 ka, and since then the rate of change has been very slow and the changes would not have been so readily noticeable (**Figure 9**). This is consistent with the age of oldest cored coral resting on rock of cal 6,900 BP from an unspecified location and depth in the Gulf of Panama or Gulf of Chiriqui (**Toth et al., 2012**).

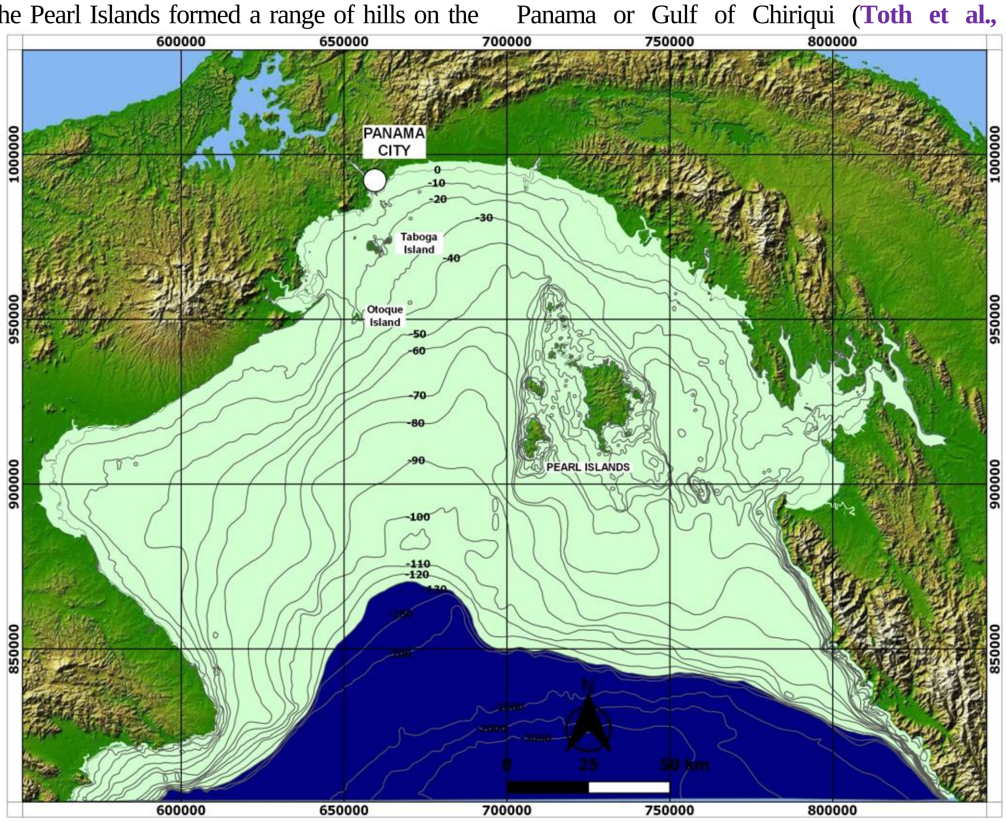

Figure 5. The Las Perlas plain in the Gulf of Panama was at its maximum size at the sea level low stand of -130 m MLWS at the last glacial maximum at about 21 ka.

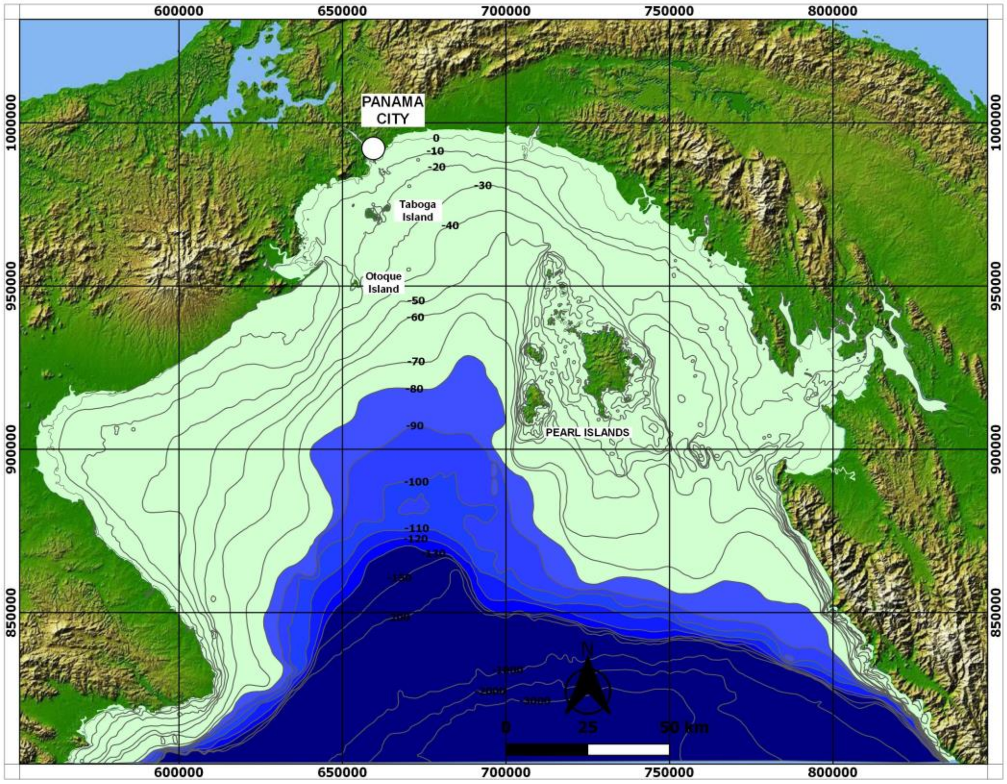

Figure 6. The Gulf of Panama with sea level at -80 m MLWS at about 14 ka. This is how the first humans to migrate through the isthmus to South America would have encountered the Las Perlas plain.

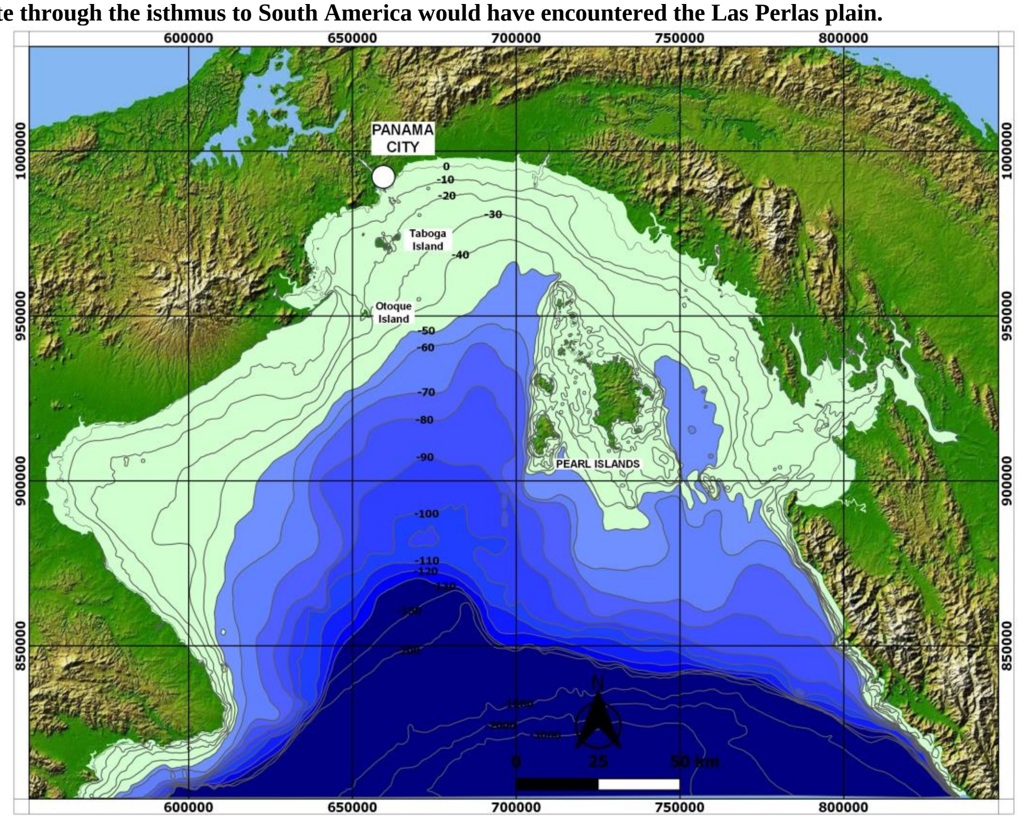

Figure 7. The Gulf of Panama with sea level at -50 m MLWS at 10.6 to 10.2 ka. The Pearl Island archipelago is now a peninsula.

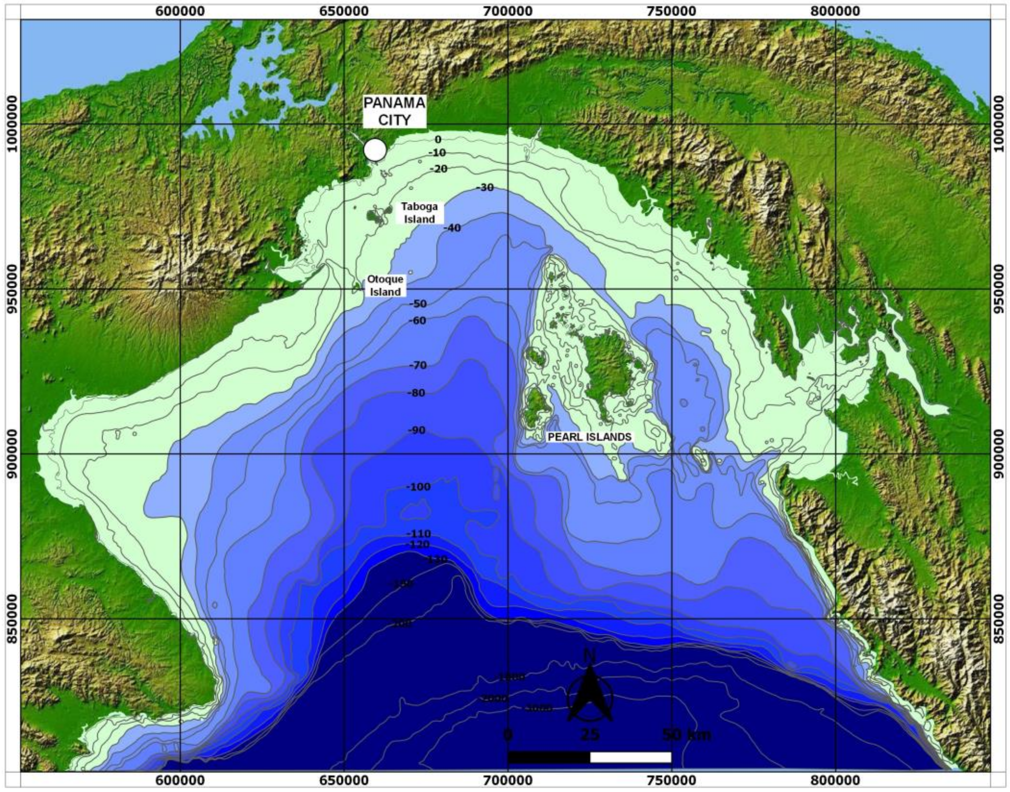

Figure 8. The Gulf of Panama with sea level at -30 m MLWS at 9.4 to 9.0 ka. The Pearl Island archipelago has now become a single big island.

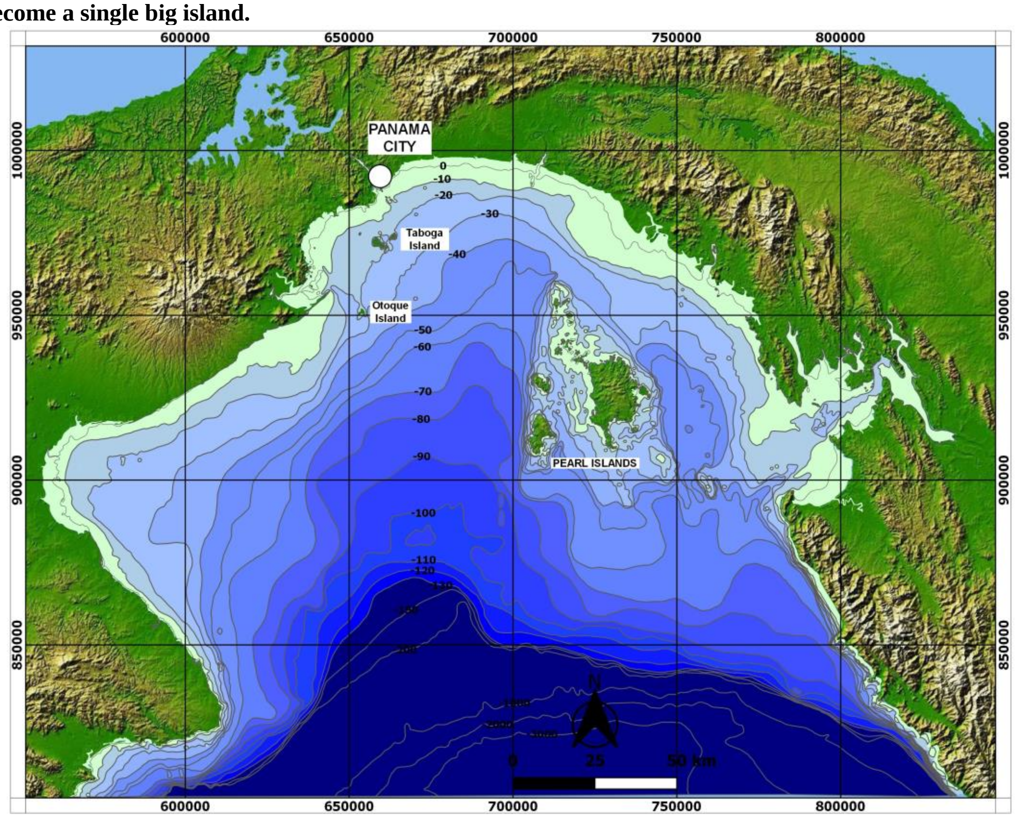

Figure 9. Sea level rose rapidly and reached -10 m MLWS by about 7.7 ka, and the Gulf of Panama was similar to today. Rapid sea level rise reached -3 m MLWS by about 6.8 ka, and the remaining 3 m rose more slowly over the last 6.8 ka.

Golik (**1968**) confirmed the history of the Holocene transgression in the Gulf of Panama based on seabed sediment sampling, shallow piston cores of the seabed, shallow seismic profiling using an echo sounder, foraminiferal studies to determine water depth and seven uncalibrated radiocarbon ages. He concluded that sea level was 50 m below present at 11,500 uncalibrated radiocarbon years BP (sea level curves give 10.6 to 10.2 ka for -50 m), and 30 m below present 8,500 uncalibrated radiocarbon years BP (sea level curves give 9.4 to 9.0 ka for -30 m).

Golik (**1968**) also showed up to 20 m of post-transgression sediments that his sea-level estimates take into account. The sediments on the inner continental shelf are clayey mud to a water depth of about 80 m, then sand and shells at greater depths on the outer shelf (**Figure 10**). The sand and shells are shallow-water beach and/or near-shore sediments characteristic of the transgressive sequence of the Holocene. The clayey mud is a modern sediment progressing outwards from the shoreline. It forms lens-shaped bodies up to 20 m thick overlying sand and shells, and forms a sub-bottom seismic reflecting layer. At the seaward side of the lens the sub-bottom layer forms the seabed. The rapid sea level rise means that the outer shelf is sediment starved. Sediment cores show a faunal change in foraminifers from near-shore to outer-shelf faunas. The sediment change from sand and shells to mud has been dated at about 11,500 uncalibrated radiocarbon years BP. The mud contains grass and wood debris, and interbedded sand-shell layers show local changes of marshes or tidal flats into beaches and vice versa. Dates above the faunal change vary from 11,000 to 5,150 uncalibrated radiocarbon years BP. In a study of sea-bottom sediments in the Gulf of Panama, **MacIlvaine and Ross** (**1973**) confirmed **Golik**'s (**1968**) findings and interpretations including the relict sand covering the central and outer portion of the shelf, with near-shore, recent fine-grained sediments.

5. The Pearl Islands Archipelago

The Pearl Islands archipelago was part of the mainland at 21 ka (**Figure 5**) and became, firstly, a peninsula (**Figure 7**) and then a single big island, separated by a channel from the Darien mainland to the east by the time sea level reached about -37 m between about 10.2 and 10.0 ka (**Figure 11**). Pedro González Island and San José Island on the west side of the archipelago were separated from the other islands by the North and South Channels by the time sea level reached -18 m at about 8.8 to 8.3 ka (**Figure 12**). The two islands were probably joined initially.

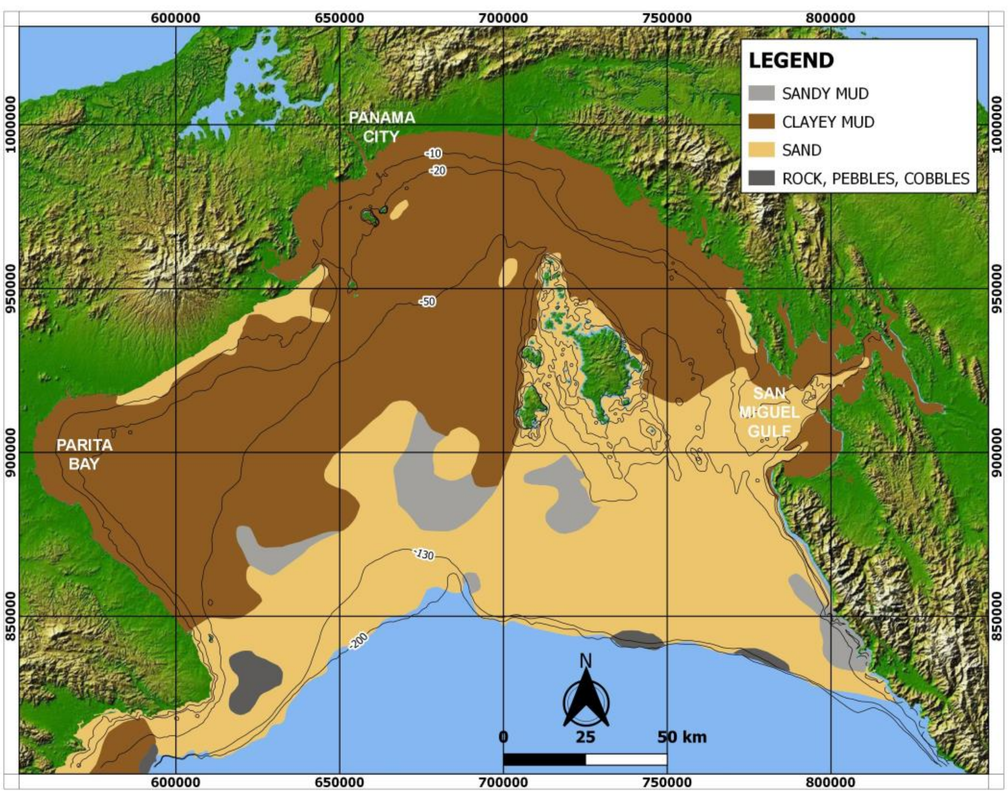

Figure 10. Sea bed sediment map of the Gulf of Panama. Redrawn from Golik (1968). Modified from. U.S. Navy Oceanographic Office Chart No. 1019 BS.

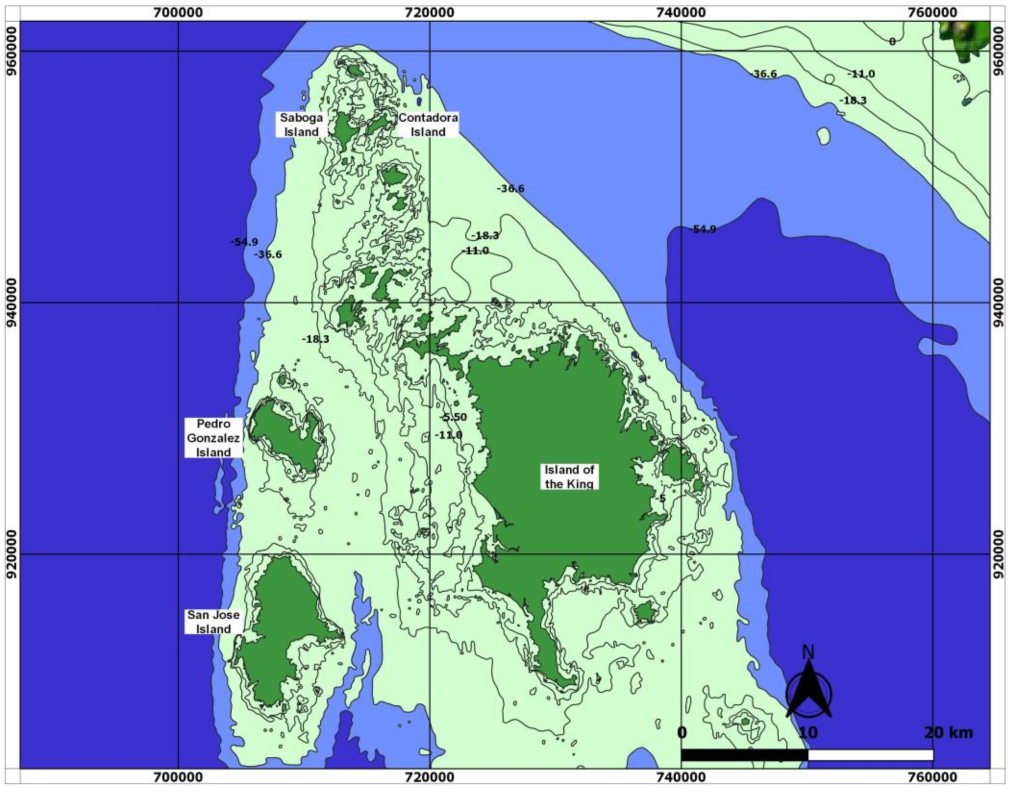

Figure 11. Separation of the single Pearl Islands shown by the -36.6 m MLWS contour at about 10.2 to 10.0 ka. Note that the more detailed bathymetry of the Pearl Islands maps shows a wider channel that opened up earlier to separate the Pearl Islands from the Darien (compare with Figure 8).

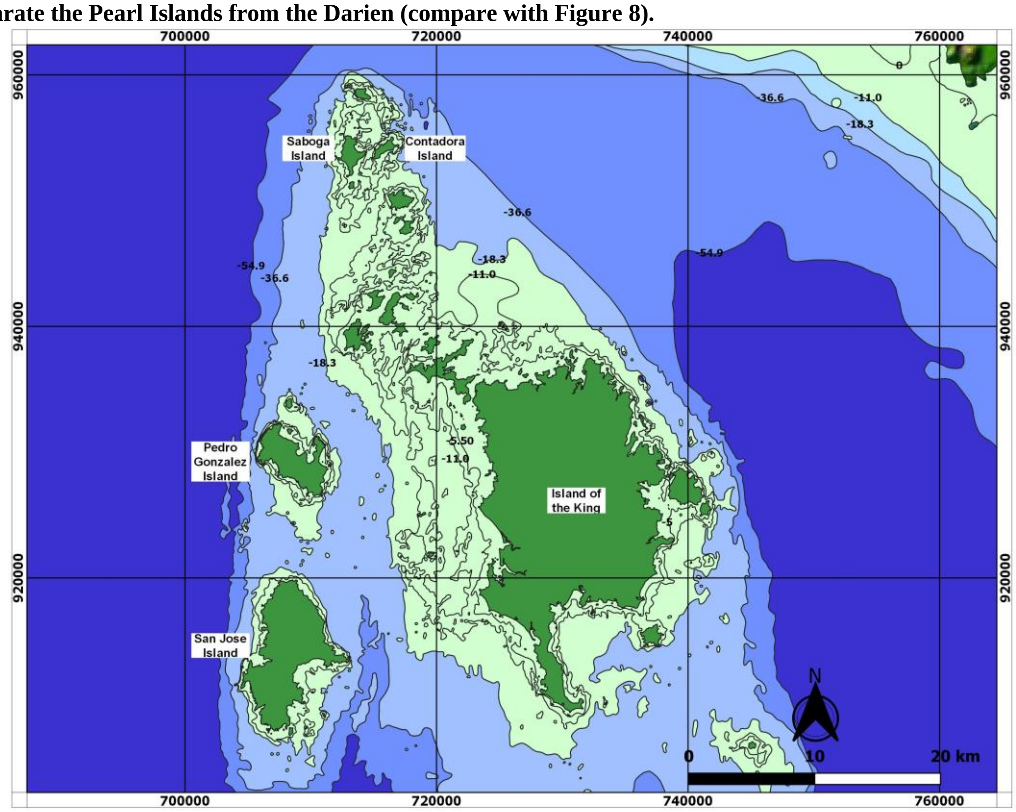

Figure 12. The Pearl Islands separated into three islands by 8.8 to 8.3 ka, shown by the -18.3 m MLWS contour.

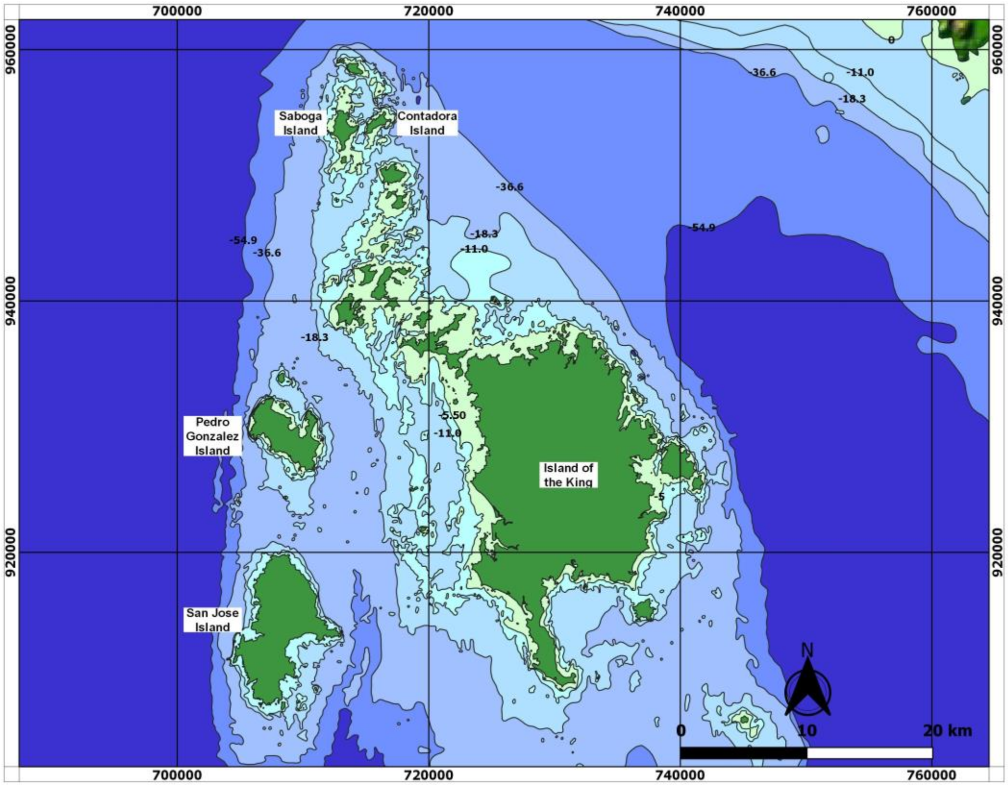

Figure 13. The present configuration of the Pearl Islands was reached by about -5.5 m MLWS at about 7.2 ka.

The other islands remained joined as one big island about 50 km long which extended from Isla del Rey north to Pacheca Island (**Figure 12**). They separated into smaller islands over the next 1,500 years by the time sea level reached -5.5 m, at about 7.2 ka (**Figure 13**). Since 6.8 ka the sea level rise curve is very gentle.

These depths and ages are minimums because they are based on current sea floor depths, and do not take into account post-transgression sedimentation. **Golik** (**1968**) showed up to 20 m of post-transgression sediments in the north-western part of the gulf. Thus, isolation happened earlier than these estimates and these are minimum ages. If there has been any significant accumulation of post-transgression sediments, then the depth of the original sea-floor is greater than the current sea-floor depth. The sea bed around the Pearl Islands is described as bedrock so this is not a problem, but on the eastern side there is young sediment and so the date of isolation could be a bit earlier than the estimate made above.

6. The Taboga Archipelago

The Taboga archipelago is formed by two clusters of islands: 1) Taboga, Taboguilla and Uraba; and 2) Otoque and Bona. The latter two would have become islands when sea level reached about -30 m at 9.4 to 9.0 ka (**Figure 8**). The age adjusted for about 4 m of post-transgression sediments would have been slightly earlier (**Golik, 1968**).

The Taboga islands became separated from the isthmus slightly later when the sea level reached about -20 m between about 8.8 and 8.3 ka based on the palaeogeographic maps. A NW-trending channel up to 35 m deep separates Taboga and Uraba from Taboguilla and this would have flooded earlier at between 9.9 and 9.6 ka. **Golik** (**1968**) showed 8 m of post-transgression sediments around Taboga, so the original land surface was approximately -28 m and isolation would have occurred earlier between about 9.4 and 9.0 ka, at about the same time as the Otoque archipelago (**Figure 8**). Taboga, at 305 m above MSL, would always have formed a prominent hill before becoming an island, as would Otoque (190 m MSL) and Bona (295 m MSL).

7. Geomorphology and Bathymetry

7.1 Flooded valleys

The Gulf of San Miguel forms the estuary of the River Tuira and is a major flooded valley or ria, 50 km long by up to 25 km wide, formed by the late Pleistocene to Holocene sea level rise. The submarine river channel can be clearly seen on the bathymetric maps (**Figure 14**).

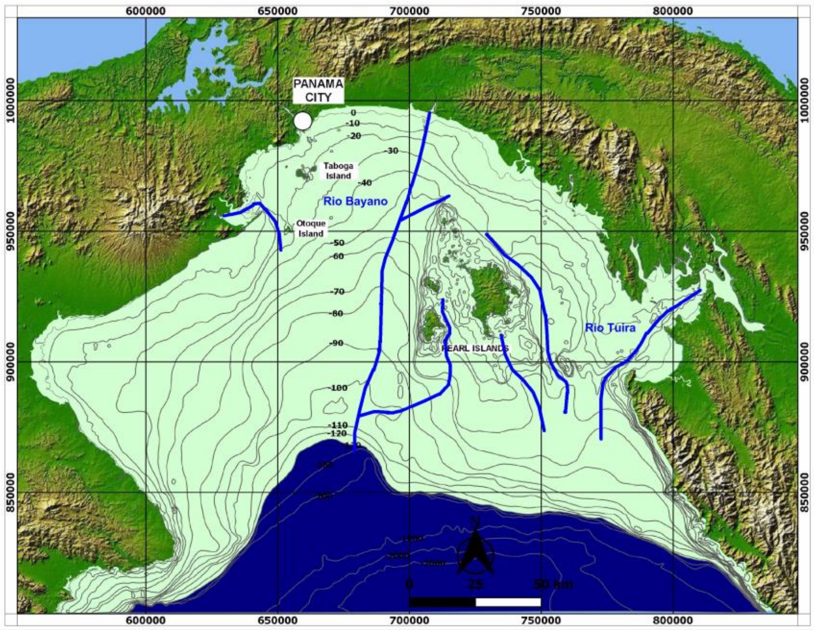

Figure 14. Map of interpreted submarine valleys of the Gulf of Panama.

7.2 Submarine valleys

Submarine valleys in the Gulf of Panama were first described from bathymetric data by **Terry** (**1940**) and are clear on the palaeogeographic maps (**Figure 14**). These formed by river erosion during times of low sea levels. There was a central palaeo-Bayano river valley beginning near the mouth of the River Bayano and running along the west side of the Pearl Islands, which are bounded by a fault. Three other valleys drain south from the Pearl Islands. The palaeo-Tuira river valley runs south from the River Tuira and the Gulf of San Miguel but is absent below 70 m depth which would indicate that it started to form after sea level reached -70 m at about 12.5 to 13.0 ka. It has been suggested that the palaeo-Tuira river originally drained northwest-wards from its present mouth and around the eastern and northern sides of the Pearl Islands before joining the central canyon of the palaeo-Bayano river (**Terry, 1940**). **MacIlvaine and Ross** (**1973**) claimed that this interpretation is supported by the distribution of heavy minerals, the modal sizes of sand samples and quartz to feldspar ratios.

7.3 Buried river valleys

Buried valleys of the Rivers Grande and Chagres encountered during test borings for dams for the Panama Canal in the early 1900s show additional evidence of valley cutting during periods of low sea level during the glacial maximum. **Howe** (**1907**, p. 652) described the borings made in the River Grande for the proposed La Boca dam and sea lock near the present Bridge of the Americas - the dam was not built and the site of the locks was moved inland to Miraflores: *"The borings have developed a Pleistocene channel below the present flood-plain of the Rio Grande like that of the Chagres at Gatun, but they have shown that at the point where the dam is to cross the maximum depth is only about 70 feet [21.3 m] below mean tide. The alluvium, like that in the upper part of the Pleistocene valley of the Chagres at Gatun, consists largely of clay with sand and fine gravel mixed with it at different elevations and will form an entirely impervious foundation for the dam."*

Borings in the River Grande further upriver for the proposed Sosa-Corozal dam (which was not built, either), west of the later port of Balboa in the entrance channel of the canal, and south of the Miraflores Locks, also showed a buried valley (**Howe, 1907**, p. 652): *"Material of essentially the same character as that at La Boca underlies the site of the Sosa-Corozal dam, but is of less thickness. The rocks beneath the alluvium at depths of from 30 to 60 feet [9.1 – 18.3 m] are sandy shales probably belonging to the Culebra beds. Rhyolite tuffs are exposed in the hills at the northern end of the dam."*

Howe (**1907**) interpreted the origin of the buried valleys as due to subsidence. However, the buried valleys formed due to lower sea levels during the glacial periods, when rivers had to cut to a deeper level to reach sea level. The valleys were subsequently filled in with fluvial sediments as sea levels rose.

MacDonald (**1913**, p. 573; **1915**, p. 26) described a buried channel of the River Chagres up to 325 feet (99 m) deep, and filled with *"swamp deposits, black soil and silt"*, which he attributed to uplift of the land and river down cutting in the Pleistocene. He described other *"Pleistocene"* deposits as *"river gravels up to 10 feet [3.0 m] above the present normal river levels"* and *"old sea beaches 6 to 10 feet [1.8-3.0 m] above the present beach level."* The buried valley deposits were also briefly described by **Woodring** (**1957**, p. 20) as *"swamp and stream deposits filling buried valleys"* which extend as far inland as Miraflores locks on the Pacific side of the canal, and as far inland as Gamboa on the Caribbean side.

Wood from a depth of 32.2 to 33.5 feet (9.8-10.2 m) in Pacific muck sediment (described below) from a drill hole in the River Grande at La Boca, at the canal entrance, for the foundations of the Bridge of the Americas, gave an uncorrected ^{14}C age of 7,680 ± 300 BP which gives a calibrated age of cal 9,291 – 7,934 BP, while another wood sample from 17 feet (5.2 m) depth gave an uncorrected age of 6,720 ± 300 BP which gives a calibrated age of cal 8,172 – 6,960 BP (**Mitchell et al., 1975**; the ages were kindly calibrated by Chris Patrick of Beta Analytic Inc. with the assumption that the ages are measured ages with no $\delta^{13}C$ corrections rather than conventional ages with $\delta^{13}C$ corrections, which introduces an unknown error for the calibrated ages). These depths are shallower than the corresponding depths on the sea-level curves of -15 m to -20 m at about 8.5 ka and -10 m at about 7.7 ka (**Table 1**). A point agate blade and a broken agate point, both blackened by the anoxic sediments, were found in 1963 nearby at Farfan, together with blackened agates (it was a popular black agate collectors' spot), near the Bridge of the Americas, in spoil of Pacific muck dredged from an unknown location in the River Grande in the Pacific entrance of the canal at depths of 32 to 50 feet (9.8-15.2 m), that is, similar to or deeper than the first dated sample (**Mitchell et al., 1975**). The point blade fragment is almost certainly from a waisted Clovis or Fishtail point dated between 11.2 and 10.0 ka in South America, but lacking tightly associated dates on the isthmus (**Bird and Cooke, 1977**; R. Cooke, pers. comm.). These are the only artefacts known to have been found in Pacific muck below the present day sea-bed in Panama and indicate early human presence in the buried valley of the River Grande.

7.4 Valley-fill and high stand sediments – the Pacific and Atlantic muck

Extensive unconsolidated deposits of black, organic-rich marine mud with horizontal bedding occur inland on the Pacific and Caribbean sides of the canal (**MacDonald, 1913, 1915**) and were informally designated as Pacific muck and Atlantic muck by the canal geologists (**Thompson, 1947**; **Jones, 1950**; **Woodring, 1957**). These sediments both fill buried valleys and were deposited during the sea level high-stand.

These sediments were described as occurring *"up to a few feet above sea level"* by **Thompson** (**1947**, p. 9). The Pacific muck extends inland to Miraflores Locks, a distance of about 6 km from the original river mouth before canal-related land reclamation, and about 11 km northeast along the coast to the ruins of Old Panama. **Thompson** (**1947**) described *"low marine terraces"* on the Pacific coast (p. 10) and *"a series of wave-cut benches and raised beach or shallow water bay deposits"* at various locations on the Pacific side of the canal *"above elevations attained by present tides"* (p. 22): neither of these features has been identified by the author. In the channel of the canal from Miraflores Locks south to the Pacific, muck deposits have been found to a depth of *"40 or more feet"* (12.2 m).

The muck deposits are soft silts with a high moisture content. **Thompson** (**1947**, p. 22) described four facies: 1) a grey to blue-grey silty clay border phase adjacent to the contact with older formations; 2) a black, organic-rich silt with abundant mollusc shells deposited in a brackish marine environment; 3) black silt with fine-grained organic material, wood, and other semi-decayed organic matter deposited in a swamp environment; and 4) a soft, light-grey or yellow-grey, weak, plastic clay which overlies the organic deposits and is probably fluvial. The four facies intergrade laterally and sandy lenses are present locally.

The Pacific and Atlantic muck were considered to be of late Pleistocene age by **Thompson** (**1947**) and **Woodring** (**1957**), although all identified fossils from the Atlantic muck are extant species which span the Pleistocene and Recent. Eighteen uncalibrated radiocarbon ages from cores from Lake Gatun gave ages from 11,300 ± 300 BP to 1,275 ± 80 BP at depths of 158 to 3 feet (-48.2 to -0.9 m) below sea level, from which a sea-level curve was constructed (**Bartlett and Barghoorn, 1973**). The swamp transitioned from salt water to freshwater by 4,200 BP at -28 feet (-8.5 m). A single sample of 35,500 ± 2,500 BP at a depth of 162 feet (-49.4 m) was interpreted to represent *"an interstadial high sea level"*.

Figure 15. Raised beaches extend up to 3.0 km inland and up to 8 to 9 m above mean sea level at Pacora, east of Tocumen airport, Panama. Image: Google Earth, GeoEye satellite image with 0.5 m resolution taken in 2011.

More recent radiocarbon ages for the Atlantic muck from geotechnical boreholes beneath the Gatun Dam are conformable and range from about cal 7,055 to 5,805 BP at elevations of -35.5 to -41.1 m, to cal 4,700 to 3,945 BP at elevations of 9.6 to 10.0 m (**Pratt et al., 2003**). The only radiocarbon dates of Pacific muck are those described in the preceding section which gave ages of cal 9,291 – 7,934 BP and cal 8,172 – 6,960 BP at depths of -9.8 to -10.2 m and -5 m, respectively (**Mitchell et al., 1975**). The elevations of up to +10 m of the Atlantic muck are higher than the Holocene high stand of about +2 m which may indicate that the high stand is due to regional tectonic uplift rather than a eustatic sea level high.

7.5 Geomorphological evidence for a sea level high stand

There is geomorphological evidence for a series of raised beach ridges above present day sea level which extend from the River Juan Diaz, east of Panama City, for about 28 km east to the mouth of the River Bayano. They are characterised by linear vegetation features, which look like ridges, sub-parallel to the present-day shoreline, which extend for 2.8 to 4.3 km inland. They are clearly visible on satellite images and from the air (**Figure 15**). They are cross-cut by active meandering rivers. A preliminary examination made at Pacora showed they are formed of deposits of sand with marine bivalves and gastropods in the upper section, as yet undated. There are no beach ridges east of the River Bayano due to the higher elevation of the terrain in the Maje mountain range.

Spot heights on topographic maps show elevations up to 8 to 9 m for the inner parts of the beach ridges. These elevations are higher than those of the active storm beach ridges of 4 to 7 m. Further work is being carried out to define the precise elevation and age of these features to determine whether they are related to the mid Holocene sea level high stand of the central and western Pacific, or a younger high stand, and whether the drop in relative sea level is eustatic or tectonic as a result of rise of the land due to faulting or compression and uplift, due to the active plate tectonic collision of the Panama arc with the South American plate (e.g., **Barat et al., 2014**; **Redwood, 2019**).

Additional evidence for a mid Holocene high stand comes from a detailed geomorphological study made of western Parita Bay and the River Santa Maria, on the western side of the Gulf of Panama, which showed that there has been nearly continuous progradation of the coastline for the past 7,000 uncalibrated radiocarbon years over a distance of several kilometres (**Clary et al., 1984**). This explains the location of shell middens along the old shoreline. A change in the Holocene sea level curve for the Gulf of Panama may be required if a eustatic origin is demonstrated for the Holocene high stand.

8. Discussion

8.1 Uncertainties in palaeogeographical maps

This paper is a study of sea-level rise using bathymetric data and global sea-level curves. The maps show how the Gulf of Panama flooded during the transgression after the last glacial maximum and how the islands formed. Panama is a long way from the glaciated regions so the sea-level changes are eustatic, that is, related to increase in sea-water volume from melting ice, with none of the isostatic effects of ice-loading and unloading that occur in glaciated regions such as northern Europe.

There are three main sources of uncertainty to be addressed in future work. The first two are related, namely the lack of sea-level data for the Gulf of Panama itself, and the two sigma errors and differences between published sea-level curves. Future work requires that sea-level curves be constructed for the Pacific coast of Panama using coral cores and sediment cores. The third uncertainty is to account for the thickness of post-transgression sediments, which means that for a given depth contour the age of transgression is too young, or to put it another way, for a given age the shoreline was deeper than the sea-bed. This means that the separation of the islands was slightly earlier than stated. Using bathymetric data is a good first approximation, but it requires shallow seismic data and sediment cores to define the depth either to bedrock or to the late Pleistocene-Holocene land surface, which is expected to be marked by a soil profile and plant remains.

8.2 Early human migration

The first humans are presumed to have migrated through the isthmus of Panama from North to South America during the Late Glacial Stage human migrations at 14.0 to 11.0 ka. A pre-Palaeoindian presence (14.0-11.2 ka) has only been inferred in Panama indirectly from genetic (mtDNA) evidence and from extra-Isthmian (South American) archaeological evidence (**Perego et al., 2012**; **Cooke et al., 2013**; **Grugni et al., 2015**). In contrast, a Palaeoindian (13.2-11.0 ka) presence is well documented in Panama and Costa Rica. It corresponds to the Palaeoindian fluted point tradition although only one site, Vampiros-1 in Parita Bay on the western side of the Gulf of Panama, has provided in situ materials (**Cooke et al., 2013**).

These first migrants would have encountered the sea level about 60 to 70 m below present and would have seen a landscape very different from today in the form of the extensive, dry, grassy Las Perlas plain (**Figures 6, 7**). Assuming that early humans migrated and settled along the coast, any archaeological record that they left behind likely lies underwater now.

The oldest human settlement yet identified in the Pearl Islands archipelago is an accumulation of cultural debris at Don Bernardo Beach on the north-eastern coast of Pedro González Island which was occupied between 6.2 and 5.6 ka on the basis of eight calibrated ^{14}C determinations (**Cooke et al., 2016**). Pedro González was an island by this time; a significant implication of this site is the use of sea-borne transport and navigation on open water sea crossings between the isthmus and islands out of sight of the mainland.

Comparisons of the Las Perlas drowned plain can be made with Doggerland in the southern North Sea, a landmass that connected the Britain Isles to Northern Europe and allowed human migrations into Britain as the ice retreated. Doggerland was flooded by rising sea levels by cal 8,500 to 8,200 BP (**Coles, 2000**; **Gaffney et al., 2007, 2009**).

8.3 Pleistocene sea level changes

Going further back in time, it can be inferred that the Pleistocene history of the Gulf of Panama and the Las Perlas plain was a series of multiple transgressions and regressions of up to a similar magnitude as the late Pleistocene-Holocene transgression as glacial periods fluctuated. Some transgressions had a higher sea level such as the last Interglacial, Marine Isotope Stage 5 (140-80 ka) which had a maximum sea level of 5 to 8 m higher than present (**Hearty and Neumann, 2001**; **Hearty et al., 2007**; **Isla and Angulo, 2015**). The islands of the Gulf of Panama thus have a history of multiple periods of isolation separated by sea-level low stands and dry-land connection with the isthmus, with implications for floral and faunal evolution. Marine isotope stages (MIS) determined from oxygen isotopes in deep-sea sediment cores have defined 103 glacial and interglacial periods in the Quaternary Period (2.58 million years to present), numbered backwards from the present Holocene interglacial period (MIS 1), with odd numbers for interglacial periods and even numbers for glacial periods (**Lisiecki and Raymo, 2005**).

8.4 The Great American Biotic Interchange

The Great American Biotic Interchange (GABI) of mammals between North and South America, which started at about 2.7 to 2.5 Ma (**Marshall et al., 1982**), coincides with the start of the Quaternary Period and the start of glaciations in the northern hemisphere, and with the associated drop in sea level and formation of the Las Perlas plain in the Gulf of Panama as described here. **Molnar** (**2008**) argued that while the formation of a land bridge by tectonic collision of Panama with the South American Plate was a prerequisite for the exchange, aided by a drop in sea level (as recognized by **Marshall, 1985**; **Savin and Douglas, 1985**), this alone was not enough. A drier climate was required to create savanna grasslands, since most of the mammals were savanna dwellers, rather than the tropical rainforest which now covers Panama and the northern Andes, and this has been argued to have been triggered by the onset of the glaciation in the northern hemisphere (**Molnar, 2008**; **Bacon et al., 2016**). The contribution of this present work is to show the development of the very wide Las Perlas plain in the Gulf of Panama during cyclical low sea levels caused by the northern hemisphere glaciations, which, combined with a drier climate, formed a wide savanna environment favourable for mammal migration.

9. Conclusion

Palaeogeographic maps show that the extensive Las Perlas plain existed in the area now covered by the Gulf of Panama during the last glacial maximum as a result of a global eustatic lowering of sea level. The maps document the rise of sea level and the formation of islands in the Gulf of Panama during the late Pleistocene and Holocene transgression. There is evidence that relative sea level actually rose to higher than present during the middle to late Holocene, which may correlate with the mid Holocene high stand of the central and western Pacific.

The palaeogeographic maps provide a base for other studies into human and faunal migration through the Isthmus of Panama. The Las Perlas plain would have aided the first human migration from North to South America during the Late Glacial Stage at 14 to 11 ka, and may have been an important factor in the Great American Biotic Interchange starting in the early Quaternary.

Acknowledgements. *Richard Cooke of the Smithsonian Tropical Research Institute, Panama, is thanked for his interest in and encouragement of this project. David Buchs of the University of Cardiff, Wales, is thanked for comments which improved the paper, as are an anonymous reviewer and the editor. Chris Patrick of Beta Analytic Inc. kindly calibrated some radiocarbon dates. José Cornejo Jr. expertly digitized and geo-referenced the charts, and prepared the palaeogeographic maps.*

REFERENCES

Admiralty Charts and Publications 1998. Gulf of Panama. The United Kingdom Hydrographic Office, Taunton, Somerset, United Kingdom, Chart No. 1929, 1:300,000 scale.

Bacon, C. D., Molnar, P., Antonelli, A., Crawford, A. J., Montes, C. and Vallejo-Pareja, M. C. 2016. Quaternary glaciation and the Great American Biotic Interchange. *Geology*, **44**, 375-378.

Barat, F., Mercier de Lépinay, B., Sosson, M, Müller, C., Baumgartner, P. O. and Baumgartner-Mora, C. 2014. Transition from the Farallon Plate subduction to the collision between South and Central America: Geological evolution of the Panama Isthmus. *Tectonophysics*, **622**, 145-167.

Bartlett, A. and Barghoorn, E. S. 1973. Phytogeographic history of the Isthmus of Panama, during the past 12,000 years. (A history of vegetation, climate and sea-level change). In: **A. Graham (Ed.)**, *Vegetation and Vegetational History of Northern South America*, Elsevier, New York, 233-247.

Bird, J. and Cooke, R. 1977. Los artefactos más antiguos de Panamá. *Revista Nacional de Cultura*, **6**, 7-31.

Bush, M. B. and Colvinaux, P. A. 1990. A pollen record of a complete glacial cycle from lowland Panama. *Journal of Vegetation Science*, **1**, 105-118.

Chappell, J. 1983. Evidence for smoothly falling sea level relative to north Queensland, Australia, during the past 6000 yr. *Nature*, **302**, 406-408.

Clary, J. H., Hansell, P., Ranere, A. J. and Buggey, T. 1984. The Holocene geology of the western Parita Bay coastline of central Panama. In: **F. W. Lange (Ed.)**, *Recent Developments in Isthmian Archaeology. British Archaeological Reports*, Oxford (International Series 212), 55-83.

Coles, B. C. 2000. Doggerland: the cultural dynamics of a shifting coastline. In: **K. Pye and S. R. L. Allen (Eds.)**, *Coastal and Estuarine Environments: Sedimentology, Geomorphology and Geoarchaeology. Geological Society Special Publication* **175**, The Geological Society, London, 393-401.

Cooke, R., Ranere, A., Pearson, G. and Dickau, R. 2013. Radiocarbon chronology of early human settlement on the Isthmus of Panama (13,000-7,000 BP) with comments on cultural affinities, environments, subsistence, and technological change. *Quaternary International*, **301**, 3-22. doi:10.1016/j.quaint.2013.02.032.

Cooke, R. G., Wake, T. A., Martínez-Polanco, M. F., Jiménez-Acosta, M., Bustamante, F., Holst, I., Lara-Kraudy, A., Martín, J. G., and Redwood, S. 2016. Exploitation of dolphins (Cetacea: Delphinidae) at a 6000 Yr old Preceramic site in the Pearl Island archipelago, Panama. *Journal of Archaeological Science: Reports*, **6**, 733-756. doi: 10.1016/j.jasrep.2015.12.001

Dickinson, W. R. 2000. Hydro-Isostatic and Tectonic Influences on Emergent Holocene Paleoshorelines in the Mariana Islands, Western Pacific Ocean. *Journal of Coastal Research*, **16**, 735-746.

Dickinson, W. R. 2009. Pacific Atoll Living: How Long Already and Until When? *GSA Today*, **19**, 4-10.

Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K. and Chappell, J. 1998. Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth and Planetary Science Letters*, **163**, 327-342.

Gaffney, V. L., Thomson, K. and Fitch, S, 2007. *Mapping Doggerland: The Mesolithic Landscapes of the Southern North Sea.* Archaeopress, Oxford, 131 pp.

Gaffney, V. L., Fitch, S. and Smith, D. 2009. *Europe's Lost World: The Rediscovery of Doggerland*. Council for British Archaeology, York, 232 pp.

Golik, A. 1968. History of Holocene Transgression in the Gulf of Panama. *The Journal of Geology,* **76**, 497-507.

Grugni, V., Battaglia, V., Perego, U. A., Raveane, A., Lancioni, H., Olivieri, A., Ferretti, L., Woodward, S. R., Pascale, J. M., Cooke, R., Myres, N., Motta, J., Torroni, A., Achilli, A. and Semino, O. 2015. Exploring the Y Chromosomal Ancestry of Modern Panamanians. *PLoS ONE*, **10**, 24 pp. doi:10.1371/journal.pone.0144223

Hearty, P. J., Hollin, J. T., Neumann, A. C., O'Leary, M. J. and McCulloch, M. 2007. Global sea-level fluctuations during the Last Interglaciation (MIS 5e). *Quaternary Science Reviews*, **26**, 2090-2112.

Hearty, P. J. and Neumann, A. C. 2001. Rapid sea level and climate change at the close of the Last Interglaciation (MIS 5e): Evidence from the Bahamas Islands. *Quaternary Science Reviews*, **20**, 1881-1895.

Howe, E. 1907. Isthmian Geology and the Panama Canal. *Economic Geology*, **2**, 639-658.

Isla, F. I. and Angulo, R. J. 2015. Tectonic processes along the South America coastline derived from Quaternary marine terraces. *Journal of Coastal Research*, **32**, 840-852. Doi: 10.2122/COASTRES-D-14-00178.1.

Jones, S. M. 1950. Geology of Gatun Lake and Vicinity, Panama. *Bulletin of the Geological Society of America*, **61**, 893-922.

Lisiecki, L. E. and Raymo, M. E. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. *Paleoceanography*, **20**, PA1003, 17 pp. doi:10.1029/2004PA001071.

MacDonald, D. F. 1913. Report of D. F. Macdonald, Geologist. *Annual Report of the Isthmian Canal Commission*, Appendix. S, Washington D. C., p. 565-582.

MacDonald, D. F. 1915. Some Engineering Problems of the Panama Canal in their Relation to Geology and Topography. *U. S. Bureau of Mines Bulletin* No. **86**, 88 pp.

MacIlvaine, J. C. and Ross, D. A. 1973. Surface Sediments of the Gulf of Panama. *Journal of Sedimentary Research*, **43**, 215-223.

Marshall, L. G. 1985. Geochronology and land mammal biochronology of the transamerican faunal interchange. In: **Stehli, F. G. and S. D. Webb, S. D. (Eds.)**, *The Great American Biotic Interchange*. Springer, New York, 49– 85.

Marshall, L. G., Webb, S. D., Sepkoski, J. J., Jr. and Raup, D.M. 1982. Mammalian Evolution and the Great American Interchange. *Science*, **215**, 1351-1357.

Milne, G. A., Long, A. J., and Bassett, S. E. 2005. Modelling Holocene relative sea-level observations from the Caribbean and South America. *Quaternary Science Reviews*, **24**, 1183-1202.

Mitchell, R. H., Stewart, R. H. and Mitchell, J. L. 1975. Otra punta paleoindia de Panama. *La Antigua (Universidad Santa María La Antigua, Panama)*, **4**, 99-103.

Molnar, P. 2008. Closing of the Central American Seaway and the Ice Age: a critical review. *Paleoceanography*, **23**, PA2201, doi: 10.1029/2007/PA001574.

Peltier, W. R. 2002. On eustatic sea level history: Last Glacial Maximum to Holocene. *Quaternary Science Reviews*, **21**, 377-396.

Perego, U. A., Lancioni, H., Tribaldos, M., Angerhofer, N., Ekins, J. E., Olivieri, A., Woodward, S. R., Pascale, J. M., Cooke, R., Motta, J. and Achilli, A. 2012. Decrypting the Mitochondrial Gene Pool of Modern Panamanians. *PLoS ONE*, **7**: e38337. doi:10.1371/journal.pone.0038337.

Perry, C. T. and Smithers, S. G. 2010. Evidence for the episodic "turn on" and "turn off" of turbid-zone coral reefs during the late Holocene sea-level highstand. *Geology*, **38**, 119-122.

Piperno, D. R. and Jones, J. G. 2003. Paleoecological and archaeological implications of a Late Pleistocene / Early Holocene record of vegetation and climate from the Pacific coastal plain of Panama. *Quaternary Research*, **59**, 79-87.

Pratt, T. P., Holmes, M., Schweig, E. S., Gomberg, J. and Cowan, H. A. 2003. High resolution seismic imaging of faults beneath Limón Bay, northern Panama Canal, Republic of Panama. *Tectonophysics*, **368**, 211-217.

Redwood, S. D. 2019. The Geology of the Panama-Chocó Arc. In: **F. Cediel and R. P. Shaw (Eds.)**, *Geology and Tectonics of Northwestern South America: The Pacific-Caribbean-Andean Junction.* Frontiers in Earth Sciences series. Springer International Publishing AG, Cham, Switzerland, 901-932.

Rohde, R. A. 2005. *Post-Glacial Sea Level chart.* Wikipedia Commons, Global Warming Art Project, http://en.wikipedia.org/wiki/File:Post-Glacial_Sea_Level.png, accessed 05-12-19.

Rohde, R. A. 2006. *Holocene Sea Level chart.* Wikipedia Commons, Global Warming Art Project, http://commons.wikimedia.org/wiki/File:Holocene_Sea_Level.png, accessed 28-09-09.

Savin, S. M. and Douglas, R. G. 1985. Sea level, climate, and the Central American land bridge. In: **F. G. Stehli and S. D. Webb (Eds.)**, *The Great American Biotic Interchange*. Springer, New York, 303-324.

Terry, R. A. 1940. Notes on submarine valleys off the Panamanian coast. *Geographical Review*, **31**, 377-384.

[**Thompson, T. F.**] **1947.** *Geology* [Geological investigation for the Panama Sea-Level Canal]. Report of the Governor of the Panama Canal under Public Law 280 to the 79th Congress, United States of America, 1st Session, Appendix 8, 84 pp.

Toth, L. T., Aronson, R. B., Vollmer, S. V., Hobbs, J. W., Urrego, D. H., Cheng, H., Enochs, I. C., Combosch, D. J., van Woesik, R. and Macintyre, I. G. 2012. ENSO drove 2500-Year Collapse of Eastern Pacific Coral Reefs. *Science*, **337**, 81-84.

Woodring, W. P. 1957. *Geology and Paleontology of Canal Zone and Adjoining Parts of Panama: Geology and Description of Tertiary Mollusks (Gastropods: Trochidae to Turritellidae).* United States Geological Survey Professional Paper **306-A**, 145 pp. + 23 plates.

Woodring, W. P. 1966. The Panama Land Bridge as a Sea Barrier. *Proceedings of the American Philosophical Society*, **110**, 425-433.

Larger sized versions of the maps in this paper are available as a supplementary file on the Journal's webpage (Link).

Editorial Responsiblity: S. James-Williamson. Type setting: S. F. Mitchell

Accepted 27th December 2019