Estimates of Quaternary Philippine coastlines, land bridges, submerged river systems and migration routes: A GRASS GIS approach

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Abstract

This study uses Geographic Information Systems to reconstruct Philippine palaeocoastlines and palaeoriver channels for different sea levels during the Quaternary Period using topographic and bathymetric data. Island connections and land area calculations show drastic changes in land-sea configurations with respect to changes in the levels of the oceans. Least cost path analysis also shows the effects of sea levels in terms of the possible migration routes for different islands in the Philippines. Results are shown as maps that can serve as guides in the study of Philippine palaeohistory and biogeography.

Introduction

Global changes in sea levels during the Quaternary were primarily driven by the glacial-interglacial cycles and the exchange of water between the world's oceans and glaciers. These changes are well documented and have been estimated based on long isotopic records for global sea levels or sediments for relative sea levels (RSL) (Bintanja *et al.* 2005; Hanebuth *et al.* 2000; Hanebuth *et al.* 2011; Maeda *et al.* 2004, Ota and Chappell 1999, Waelbroeck *et al.* 2002) (Figure 1). The rising and lowering of sea levels had dramatic effects on the physiography of Southeast Asia including the

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Philippines (Figure 2). The distribution and the connectivity of the islands based on sea level history has been determined as one of the main factors in understanding the biogeography of the Islands (Heaney 1985; Van den Bergh *et al*. 2001; Voris 2000).

The same is true with respect to the discussion on Pleistocene human migrations in the region (Bellwood 1997; Sémah *et al.* 2000). During Periods of lower sea levels the large islands of Borneo, Sumatra, and Java were all connected to the Asian mainland forming the landmass known as Sunda. Papua New Guinea and Australia were also connected to form Sahul. The islands in between which includes the Philippines (called Wallacea) have been somewhat isolated from these two large landmasses although local changes in the distribution of islands also occurred.

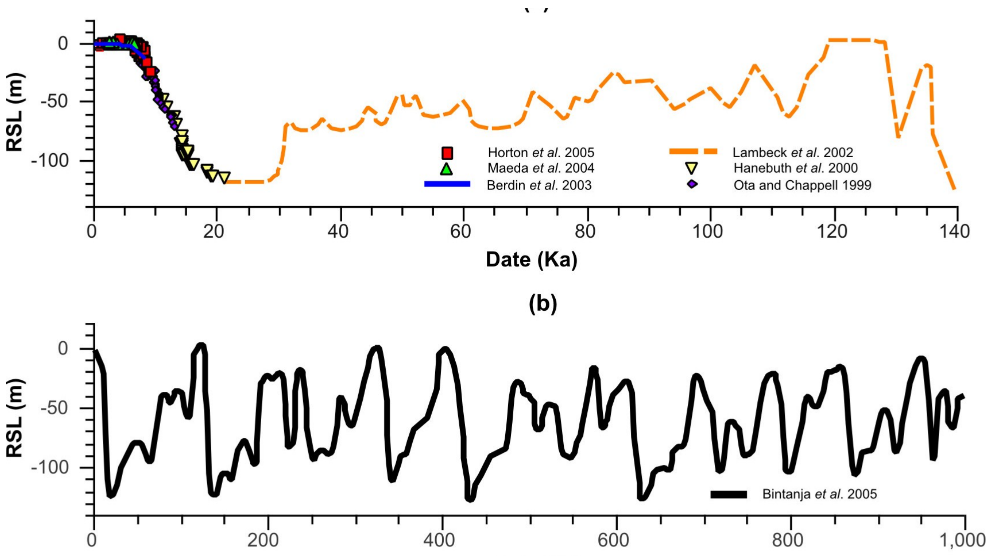

Figure 1: Sea level curve for the last (a) 140 Ka and (b) 1000 Ka

The Philippine archipelago (see Figures 2 and 3) situated between the Pacific Ocean and the West Philippine Sea is composed of more than 7000 islands and around 34500km of coastlines (calculated from coastline data provided by http://www.ngdc.noaa.gov). Throughout the Quaternary its land/sea distribution fluctuated due primarily to the changes in the levels of the seas and oceans. Understanding how these changes might have occurred is then important in the understanding of the cultural, biogeographic, palaeoenvironmental, and climatic history of the islands. In this study, bathymetric and topographic data are used to reconstruct the palaeogeography and shorelines of the Philippines at different sea levels by means of Geographic Information System (GIS),

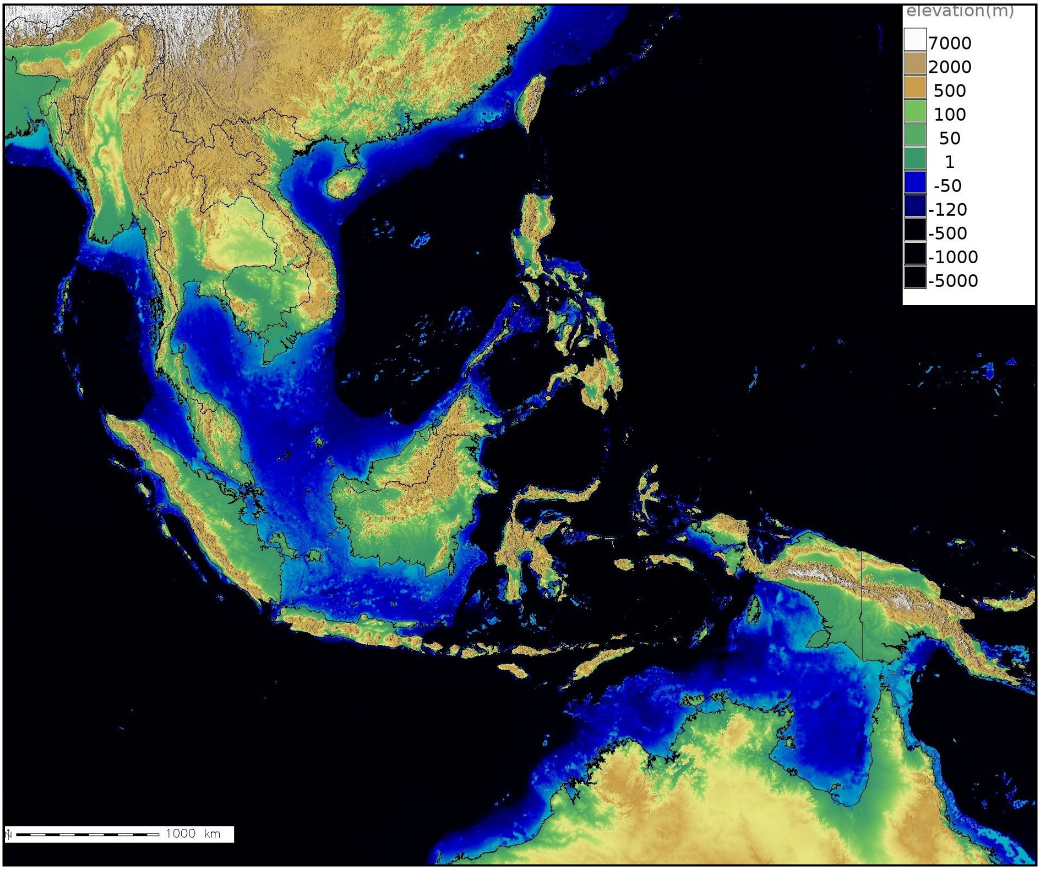

Figure 2. Map of Southeast Asia showing topography and bathymetry (GEBCO). Present day shorelines and country boundaries (black lines) are also shown.

particularly using Geographic Resources Analysis Support System (GRASS) software (GRASS Development Team 2011). Land exposed and land bridges are estimated and submerged river systems are modeled. In addition, least cost path analysis is done based on slope and elevation data to analyse possible migration routes for terrestrial mammals and humans during the Pleistocene period. The final aim is to provide researchers maps of the Philippines for different sea levels as well as provide scripts that can be used with GRASS to extract and analyse shorelines based on bathymetric data.

Materials and Methods

The palaeogeography analyses of the Philippine islands with respect to sea level changes have been conducted with GRASS GIS software (GRASS Development Team 2011; Neteler and Mitasova 2010).

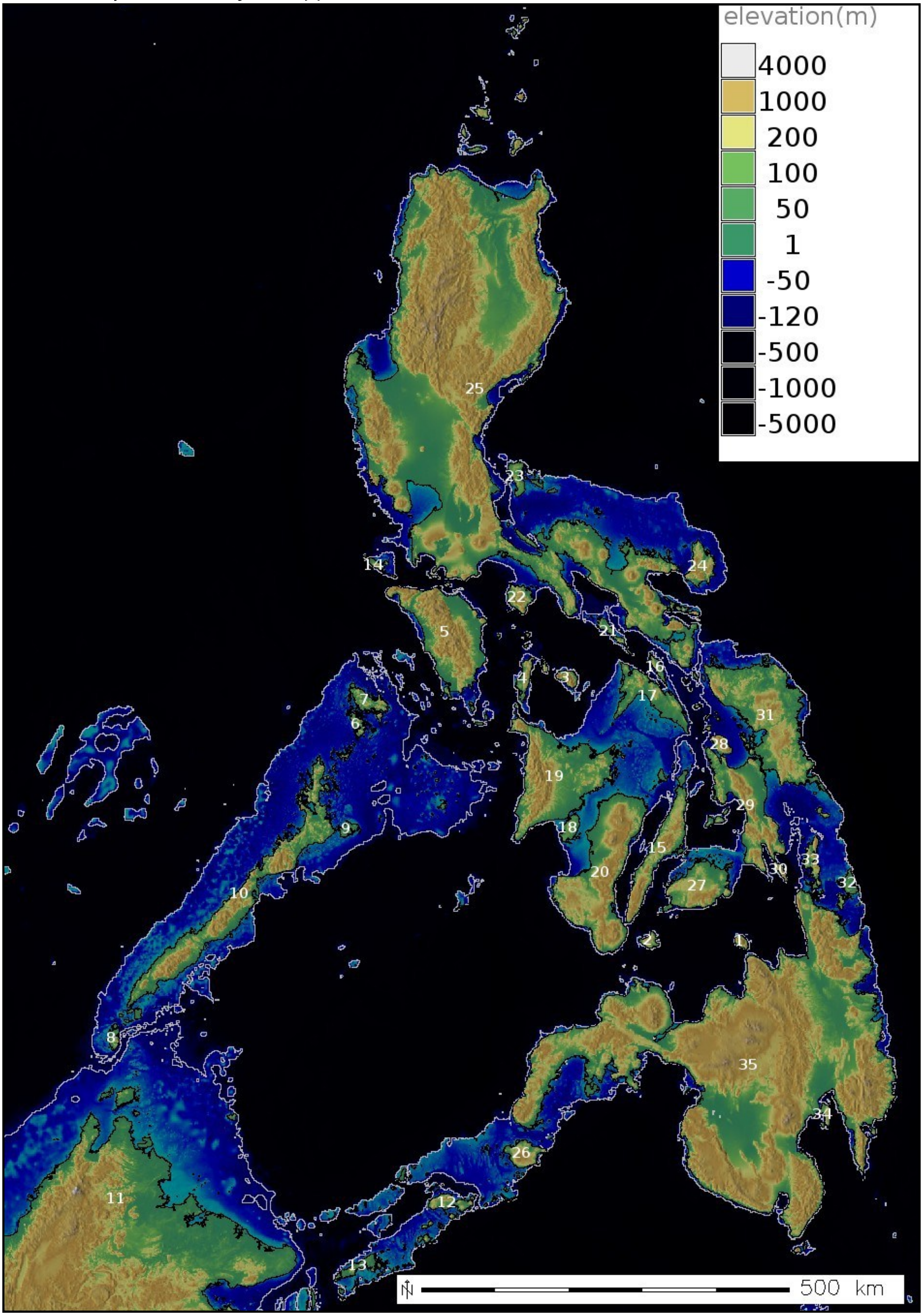

Figure 3: Topographic and Bathymetric Map of the Philippine islands (classified using GEBCO_08 dataset) showing present day shorelines (black lines) and -120m isobath (grey lines). Islands used in the calculations are labeled with numbers (corresponding island names are shown in Table 1).

GRASS is a powerful GIS tool for landscape analysis and is licensed under the GNU Public license (http://www.gnu.org/licenses/gpl.html), meaning it is free to download, install, use, and even further develop. In this study, GRASS was used for the analysis of topographic and bathymetric data to assimilate palaeocoastlines, calculate land areas, and analyse land connections for different sea level configurations.

Hydrologic analyses were also done to model major river systems for the country. The GRASS commands that were used are given in this paper and further descriptions and usage are given in the GRASS User's Manual (GRASS Development Team 2007). Global Bathymetric Chart of the Oceans (GEBCO_08 grid) dataset (Smith and Sandwell 1997) (downloaded from http://www.gebco.net/) is used as the basis for all reconstructions and models presented here. Command line scripts run in bash (Unix shell) were used to speed up the calculations. The GRASS commands used are shown italicised and described here by statements preceded by a "#" and bounded by "{" and "}". The resulting dataset, exported from GRASS in the form of shapefiles (.shp), can be downloaded via the author's Dropbox [1].

Bathymetry as Palaeocoastlines

The extent of land exposure and land bridges is a very crucial issue in the study of the distribution of animals and humans in the Philippine islands. This research uses the Global Bathymetric Chart of the Oceans (GEBCO_08 grid) dataset (Smith and Sandwell 1997) to model palaeoshorelines and land area exposed. The GEBCO dataset is a raster dataset with every pixel (approximately 900 x 900m resolution at Philippine's latitude) representing elevations and bathymetry. This method assumes that present day bathymetry of the Philippine archipelago has undergone minimal changes during the Quaternary. Tectonics, sedimentation, and erosion are unaccounted for because of the unavailability of these types of datasets for the country. This type of reconstruction has been done in a larger scale for Southeast Asia and have proven to be good approximations for land exposed (Sathiamurthy and Voris 2006; Voris 2000).

[1] https://www.dropbox.com/l/RGQgohbUJcoo1AHzNLAbWb

The whole process of modeling exposed land and calculation of land areas was done using a bash script run in GRASS shown below (seen as grey text):

```
#!/bin/bash
# {A) loop statement for extracting exposed land and calculate area for every 5m RSL from RSL=0m to -200m}
    x=0 #{set x to zero}
    while [ "$x" -lt "201" ] #{execute if the value of x is less than 201}
    do r.mapcalc "geb_"$x"b=if(gebco>=-$x,1,null())" #{extract exposed land for RSL=-x}
        r.to.vect input=geb_"$x"b output=land_"$x"b feature=area --overwrite #{convert raster area to vector}
        v.db.addcol map=land_"$x"b columns="area_km double precision" #{add column named "AREA" with "double precision" format for area calculation}
        v.to.db map=land_"$x"b option=area units=kilometers columns=area_km #{fills up database column with calculated areas}
        x=$(($x+5)) #{increment x by 5}
    done
exit 0
```

This script executes a loop command to extract, in 5m intervals, cells that have value equal to or greater than the negative of the incrementing variable (seen as "x" in the script) for values from 0 to 200. The resulting rasters (geb_xb in the script) are considered as estimates of land exposed if present day relative sea levels were set equal to -x (or x metres below present relative sea levels). They are then converted to vector (polygons) for separation of islands. During the process of converting from raster to vector, GRASS GIS automatically creates unique identifiers (id) in integer format as a separate column to the attribute table to every part of the vector dataset. The ids are used later on to analyse vector connections (see below). Land areas for each island are calculated (in km^2) and are written to the attribute table of these vectors using the *v.to.db* command.

Land areas and connections

The method highlighted above results in multiple vectors representing exposed land with attribute data containing unique ids and land areas calculated for each island. Another script is run to extract areas into a single vector data to contain all id and area data. The attribute table for this vector data can then be exported and analysed for land connections (see below). This script is shown here (in grey text):

```
#!/bin/bash

# B) loop statement for extracting area calculations to a single point vector dataset (island_data)

        x=0 #{set x to zero}

        while [ "$x" -lt "201" ] #{execute if the value of x is less than 201}

        do

        v.db.addcol map=island_areas column="AREA"$x"b double precision" #{add column named AREAxb in "double precision format}

        v.what.vect vector=island_areas column=AREA"$x"b qvector=land_"$x"b qcolumn=area_km #{extract area of vector map to newly created column AREAxb into the attribute table of point vector from above}

        x=$(($x+5)) #{increment x by 5}

        done

exit 0
```

A separate point dataset (“island_data” in the script) which represents island centroids is used here. The script extracts all id and area data to a single attribute table using spatial queries (*v.what.vect* in GRASS). The resulting vector attribute table would have all ids and calculated land areas for the islands at different sea level values. Island connections can then be determined by looking at the ids extracted. The principle behind this is that separate islands would be represented by two separate polygons each with its own unique id. Connected islands, on the other hand would be represented by a single polygon and thus only one id. If these are extracted to the point dataset representing present day islands, points with similar identifiers at a specific sea level value would mean they are connected at that level.

Hydrological analysis and river systems

The analyses of water flow and hydrology are one of the main functionalities that can be carried out in GRASS. In this study, they are much more significant as many of the areas to be analysed are submerged at present day. GRASS uses A^T algorithm to develop hydrological models (Ehlschlaeger 1989). The method simulates how water would flow given an elevation model. This was done using the commands:

r.walk elevation=gebco_120 friction=geb_120 output=cost_120 start_points = pts_start stop_points=pts.stop -k #{generate accumulated cost raster (cost_120) for traversing the model represented by elevation (gdem_120) and friction (geb_120) from starting points (pts.start) to stop points (pts.stop). NULL cells, representing water bodies, are set to have cost of 1000 to model routes that have the least water crossing}

r.drain input=cost_120 output=route_raster_120 #{calculates the least cost path (route_raster_120), in raster format, for the accumulated cost raster (cost_120)}

r.to.vect input=route_raster output=route_120 #{convert least cost path from raster (route_raster_120) to vector (route_120)}

These commands were also done for the -50m and present day elevation models for comparison. In addition, minimum sea crossing distance (MSCD) and the number of sea crossings (NSC) for different islands were also calculated. These were done using:

v.overlay ainput=route_120 atype=line binput=land_120 btype=area output=seacross_120 operator=not #{command to extract sea crossing (seacross_120) vector from route vector (route_120) using 'not overlay' function with land vector (land_120)}

v.to.db map=seacross_120 option=length units=kilometers columns=distance # {GRASS command to calculate line length and write into database column (distance)}

The *v.overlay* command extracts the route data (route_120) that does not overlay (because of the 'not' operator used) with the land data. This would represent the sea crossing data (seacross_120). The *v.to.db* command calculates the length (in kilometres) of the different sea crossing data.

Timing and duration of sea level changes

In order to better understand the timing of the reconstructions provided here, the total time in which sea levels were lower than certain values and the number of these events were calculated following Voris' (2000) methodology. The sea level curve published by Lambeck *et al.* (2002) based on raised coral reefs from the Huon Peninsula was used for the last 140 Ka while Bintanja *et al.*'s (2005) reconstruction from isotope records were also used for the last 1000 Ka. The resulting calculations are presented in Figure 4.

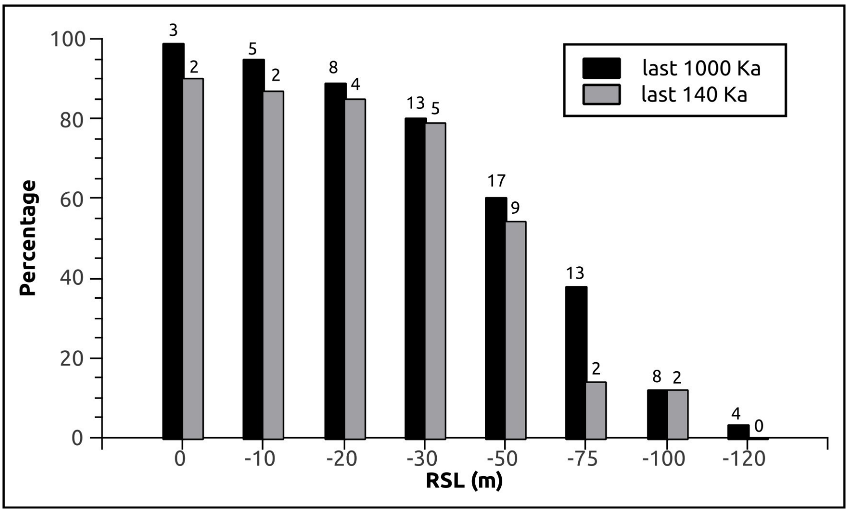

Figure 4: Graph showing percentage of time wherein sea levels were equal to and lower than sea level values (x-axis) for the last 140 Ka, and 1000 Ka (calculated using sea level curve published by Lambeck *et al.* (2000) and Bintanja *et al.* (2005)). The number of events that these occurred are seen as numbers over the bars.

Results and Discussions

Limitations and Caveats

Since the models and calculations presented here are based solely on the GEBCO dataset it is important to note that there are limitations in the data presented here. First and foremost, the dataset itself is lacking in precision in terms of high resolution analysis of the ocean floor. The 30 second pixel resolution is roughly equivalent to 900m in the Philippine latitudes and bathymetric changes that are smaller than this would not be represented by the dataset. Furthermore, the bathymetric measurements, either from soundings, gravitational data or interpolation of these datasets could also have possible errors (see Smith and Sandwell 1997).

The second limitation is that it is assumed that sea floor topography has changed minimally during the Quaternary period. Although the region is generally considered tectonically stable (see Voris 2000), some regions of the islands is known to be tectonically active attested by the presence of a number of major active faults and volcanoes (see for instance Acharya and Aggarwal 1980; Peña 2008; Yumul *et al.* 2003).

Furthermore, a number of other geomorphological processes have definitely occurred during the long period of the Quaternary which may have altered the topography of the shallow sea floor such as isostatic adjustments, erosion, and deposition of sediments. Hanebuth *et al.*'s (2011) research on the Sunda Shelf suggest that based on the acoustic profiling and ground truthing of sediment cores that the palaeo-topography of the Sundaland is only sparsely covered by younger sediment which could also be the case for the Philippines as shown in the sounding profile of the Balabac Strait (Krause 1966). But as one considers the older parts of the Quaternary period the accumulated geomorphologic processes might have altered the topography significantly which will not be represented in the analyses here.

In this regard, the reconstructions and calculations presented here must not be regarded as facts but rather as working calculated hypotheses. The models can be improved by incorporating higher resolution bathymetric data and sedimentary data available in a myriad of forms such as raw sounding data, nautical charts, seismic profiles, and sediment cores.

Palaeocoastlines and land connections

Reconstructions for Philippine coastlines for different sea levels (Figure 5) show considerable changes in land mass and island connections during periods of different sea level values. Area calculations (Table 1) show a significant increase in land area if sea levels were lowered to values associated with much of the Quaternary Period. The calculations suggest that the present day land area of the Philippines of 296,767km^2 would increase up to 488,685km^2 if sea levels were lowered to the Last Glacial Maximum value of -120m which probably also occurs during other Glacial maxima (e.g. 440 Ka 340 Ka, 270 Ka, and 135 Ka).

Table 1a. Area calculations (in km²) for the Philippines and islands (greater than 200 km² at present day) for sea level values between –100 m and 0 m in 5-metre intervals. Merged cells mean a connection between these islands. **NC** = Not calculated because of connection to Sundaland

LABEL	NAME	0 m	-5 m	-10 m	-15 m	-20 m	-25 m	-30 m	-35 m	-40 m	-45 m	-50 m	-55 m	-60 m	-65 m	-70 m	-75 m	-80 m	-85 m	-90 m	-95 m	-100 m
NA	**Philippines**	**296767**	**312741**	**320081**	**328369**	**337863**	**347683**	**357088**	**366727**	**375032**	**383849**	**392478**	**402728**	**415192**	**426082**	**435990**	**445244**	**453916**	**461664**	**467570**	**472601**	**476718**
1	Camiguin	250	271	271	271	271	272	276	276	276	279	280	282	284	287	287	288	290	294	296	298	299
2	Siquijor	325	366	369	369	371	371	374	380	385	390	394	399	399	402	405	409	416	424	429	436	439
3	Sibuyan	459	464	471	478	494	512	539	565	575	594	601	615	625	636	643	648	652	666	674	678	684
4	Tablas	688	781	796	808	837	862	883	909	948	985	1013	1039	1072	1091	1107	1278	1299	1322	1344	1360	1375
5	Mindoro	9858	10255	10336	10411	10490	10572	10633	10699	10767	10826	10890	10996	11064	11142	11215	11285	11610	11694	11765	11853	11926
6	Culion	403	572	592	607	646	680	2419	2623	2914	3752	4173	5120	6018	46103	49920	54169	58441	69072	71530	73645	75545
7	Busuanga	971	1278	1308	1350	1430	1528															
8	Balabac	329	471	523	629	719	802	881	947	999	1101	1148	33663	36608								
9	Dumaran	337	430	489	16236	17869	19869	21932	23645	25205	27012	28715										
10	Palawan	11579	13291	14142																		
11	Borneo	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
12	Jolo	860	992	1037	1088	1279	1465	2356	5859	6203	6819	7218	7514	7719	7916	8067	8204	8330	8426	8510	8584	8630
13	Tawi-Tawi	630	1061	1598	1958	2320	2827	3056														
14	Lubang	200	229	240	291	327	389	414	494	524	591	626	656	683	707	719	731	762	773	792	809	816
15	Cebu	4459	4772	4831	4887	4949	4991	5142	5210	5426	5501	5557	5599	5647	5698	5747	5785	5828	5880	5932	5973	54651
16	Ticao	332	404	411	425	5579	6158	6674	7181	7584	7996	44884	45456	45997	46436	46885	47264	47566	47915	48175	48410	
17	Masbate	3248	3752	4071	4616																	
18	Guimaras	589	705	13649	28607	29535	30429	31958	34488	35492	36134											
19	Panay	11476	12379																			
20	Negros	12715	13526	13891																		
21	Burias	430	516	542	568	580	613	635	652	727	753	788	817	846	876	895	919	942	966	992	1017	1040
22	Marinduque	915	981	992	1039	1061	1086	1098	1121	1132	1152	1175	1196	1224	1246	1268	141532	143573	145132	146394	147338	148189
23	Polillo	657	737	769	819	1385	1691	1854	1981	2078	2160	2372	2531	132837	136100	138467						
24	Catanduanes	1466	1608	1639	1681	1727	1763	1804	2023	2107	2191	2334	126249									
25	Luzon	105196	109287	110889	112368	113925	115221	116683	118300	119632	120938	122194										
26	Basilan	1249	1358	1386	1535	1662	1810	2768	3172	5128	7411	8158	9027	9791	10326	157751	159312	160823	162416	163794	164972	166069
27	Bohol	3769	4254	4788	28228	29014	29946	30611	31904	32686	33590	34688	35442	144124	145596							
28	Biliran	508	21920	22530																		
29	Leyte	7060																				
30	Panaon	208																				
31	Samar	12490																				
32	Siargao	431	809	884	946	1018	101166	101877	102872	103873	104849	105817	106921									
33	Dinagat	789	1002	98177	98820	99447																
34	Samal	258	96595																			
35	Mindanao	94201																				

Table 1b. Area calculations (in km²) for the Philippines and islands (greater than 200 km² at present day) for sea level values between –200 m and –105 m in 5-metre intervals. Merged cells mean a connection between these islands. **NC** = Not calculated because of connection to Sundaland

LABEL	NAME	-105 m	-110 m	-115 m	-120 m	-125 m	-130 m	-135 m	-140 m	-145 m	-150 m	-155 m	-160 m	-165 m	-170 m	-175 m	-180 m	-185 m	-190 m	-195 m	-200 m
NA	**Philippines**	**480335**	**483298**	**485994**	**488685**	**491195**	**493305**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**
1	Camiguin	301	305	307	310	310	312	316	318	321	326	330	342	345	350	355	362	368	380	383	388
2	Siquijor	442	452	461	469	480	485	492	500	508	520	533	545	554	565	576	583	595	601	613	623
3	Sibuyan	688	694	756	764	772	781	792	798	812	822	837	848	854	860	868	947	955	969	977	989
4	Tablas	1396	1414	1429	1446	1465	1481	1498	1514	1623	1646	1672	1691	1711	1727	1756	1784	1801	1821	1840	1857
5	Mindoro	11987	12038	12088	12149	12226	12275	12321	12373	12415	12455	12509	12570	12617	13198	13279	13359	13433	13498	13611	13685
6	Culion	76783	77710	78489	79464	80352	81004	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
7	Busuanga																				
8	Balabac																				
9	Dumaran																				
10	Palawan																				
11	Borneo	NC	NC	NC	NC	NC	NC														
12	Jolo	8688	8734	8787	8832	8873	8908	8966	9012	9082	9133	9807	9875	9938	9993	10070	10120	10178	10248	405960	407088
13	Tawi-Tawi																				
14	Lubang	831	838	851	860	893	899	906	916	932	943	965	978	1043	1066	1098	1120	1147	394333		
15	Cebu	54927	55229	55515	55806	56094	56328	56549	56756	57076	383993	385438	386565	387633	388688	389799	390908	391970			
16	Ticao																				
17	Masbate																				
18	Guimaras																				
19	Panay																				
20	Negros																				
21	Burias	1063	1088	1115	1142	322311	323316	324168	325086	325872											
22	Marinduque	149026	317540	318854	319903																
23	Polillo																				
24	Catanduanes																				
25	Luzon																				
26	Basilan	167130																			
27	Bohol																				
28	Biliran																				
29	Leyte																				
30	Panaon																				
31	Samar																				
32	Siargao																				
33	Dinagat																				
34	Samal																				
35	Mindanao																				

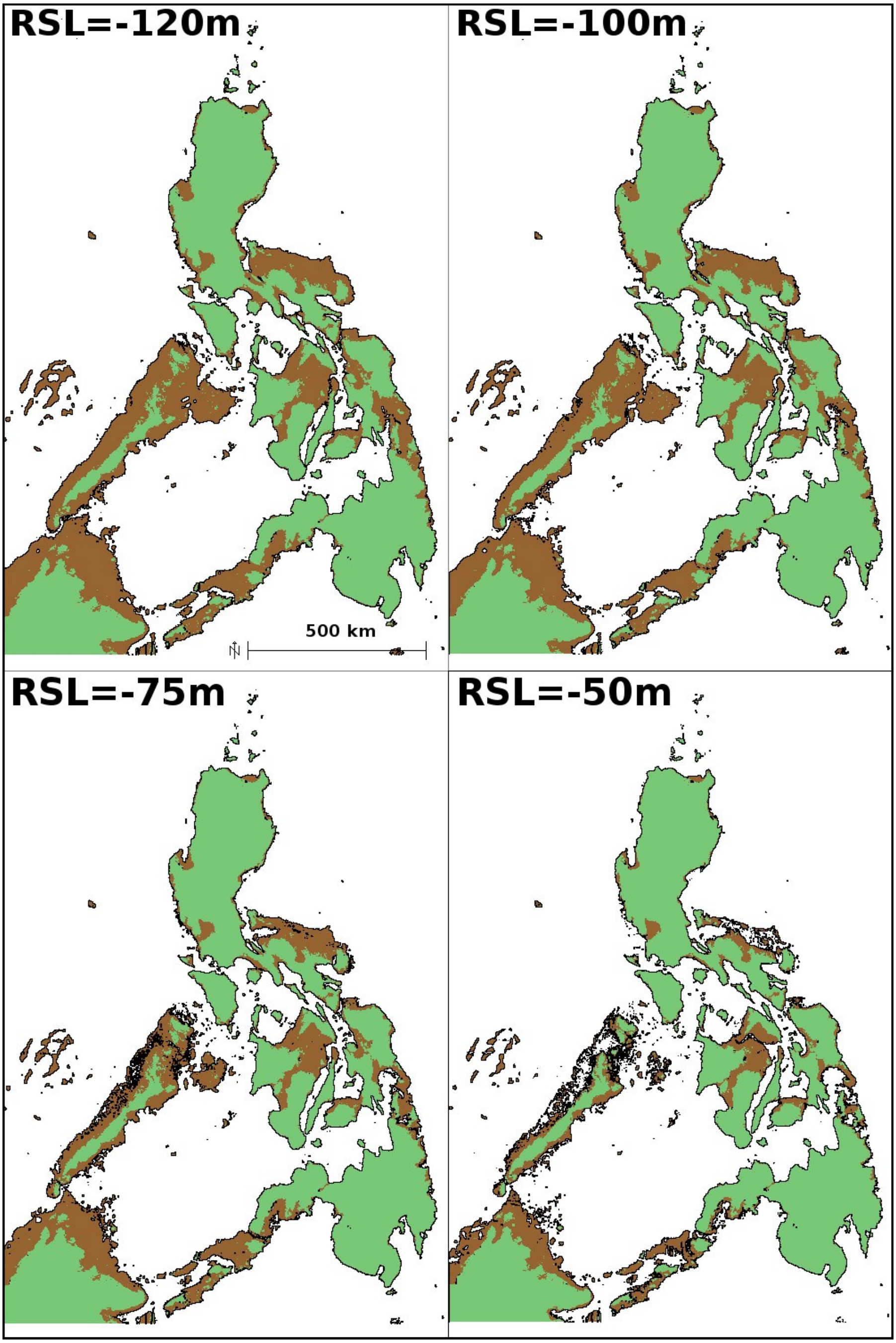

Figure 5a: Map of the Philippines showing exposed land (brown bordered by black lines) for different sea level values. Also shown are present day islands (green).

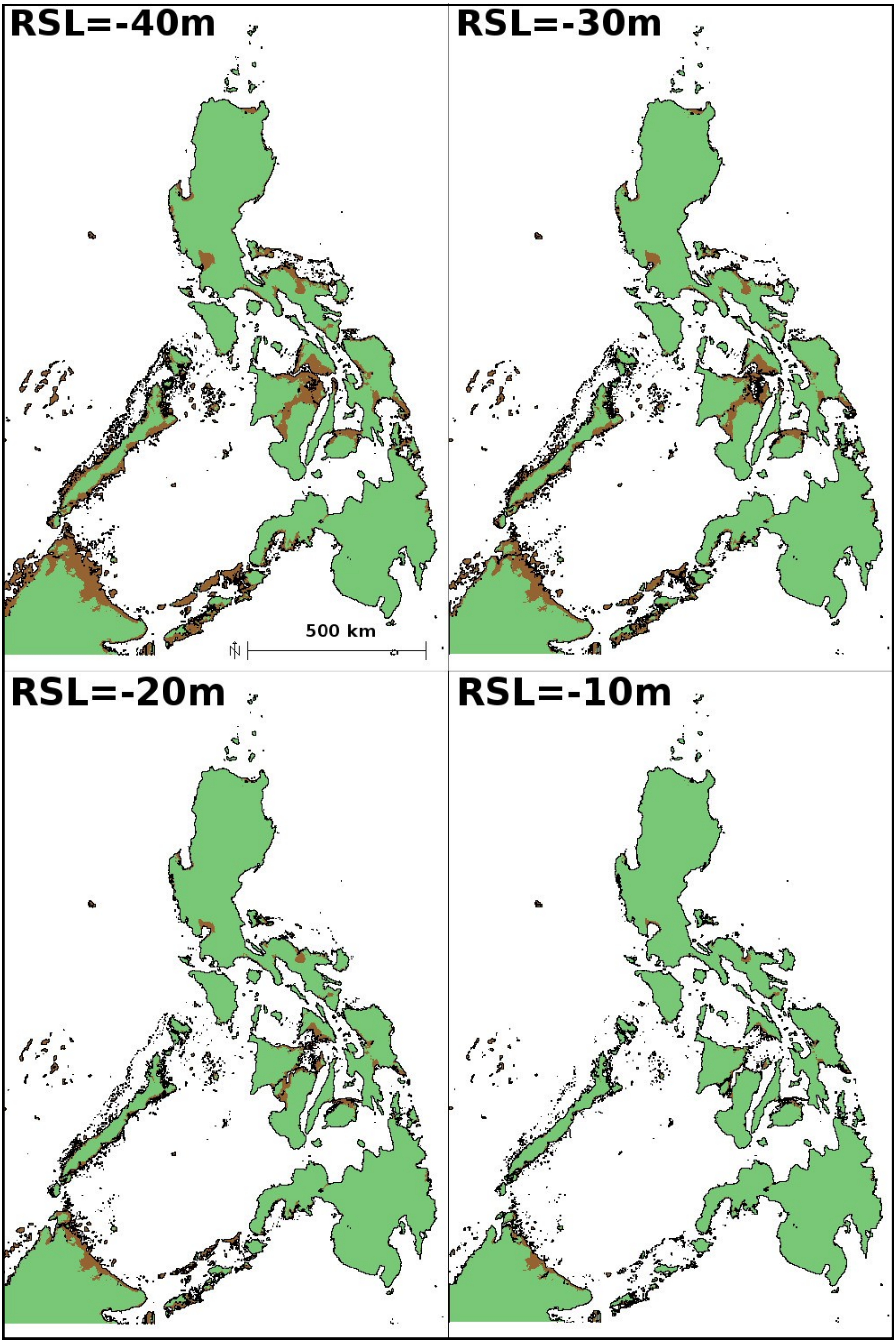

Figure 5b (cont.): Map of the Philippines showing exposed land (brown bordered by black lines) for different sea level values. Also shown are present day islands (green).

The model also shows the different groupings of islands in terms of connectivity based on RSL (Figures 5 and 6). The different biogeographic zones of the Philippine islands (Greater Palawan, Greater Sulu, Greater Negros-Panay, Greater Mindanao, and Greater Luzon) have been delineated based on faunal similarities and it has been suggested that Quaternary sea level changes is a major factor for island diversification and speciation (Heaney 1986; Heaney *et al.* 1998). This is supported in the reconstructions presented here.

Greater Palawan which includes the islands of Busuanga, Balabac, Dumaran among others would be formed if sea levels were lowered to -65m and thus leading to the similarities of their terrestrial fauna. Based on the model presented here, the connection between Palawan and Borneo (and thus Sunda shelf) would be exposed at -135m. This is based solely on the GEBCO dataset and can be further investigated with higher resolution bathymetric and sediment data.

For instance Krause (1966: Plate 10) published a bathymetric contour chart of the Balabac Strait based on numerous ship sounding expeditions that would suggest that a land exposure would occur between 80 and 100 fathoms (approximately -146m and -183m respectively) which is lower than the calculations here. Published sea level lowstand data suggest that the last time that sea levels went down to at least -135m and thus exposing a land connection was during OIS 12 (1ast 139 $\pm$ 9 m) (440 Ka) (Rohling *et al.* 1998) and probably also OIS 16 (640 Ka) (Bintanja *et al.* 2005) This supports the hypothesis suggested by Heaney (1986) based on the present faunal communities that there was no land bridge between Borneo and Palawan during the late Pleistocene (even during the LGM) and that the last time a land corridor was exposed was during the middle Pleistocene.

The islands of Jolo and Sulu which is unlikely to have been joined to Sunda or the rest of the Philippine islands would form the Greater Sulu Island at -35m RSL. Panay, Negros, and Masbate islands would have a land connection at -50m RSL forming the Greater Negros-Panay Island which would also include Cebu at -100m RSL. Greater Mindanao composed of Mindanao, Samar, Leyte, Bohol, and Basilan among other islands, would be formed at -70m while Greater Luzon at -75m RSL. A land bridge between these two land masses would be also be exposed at -110m based on this model.

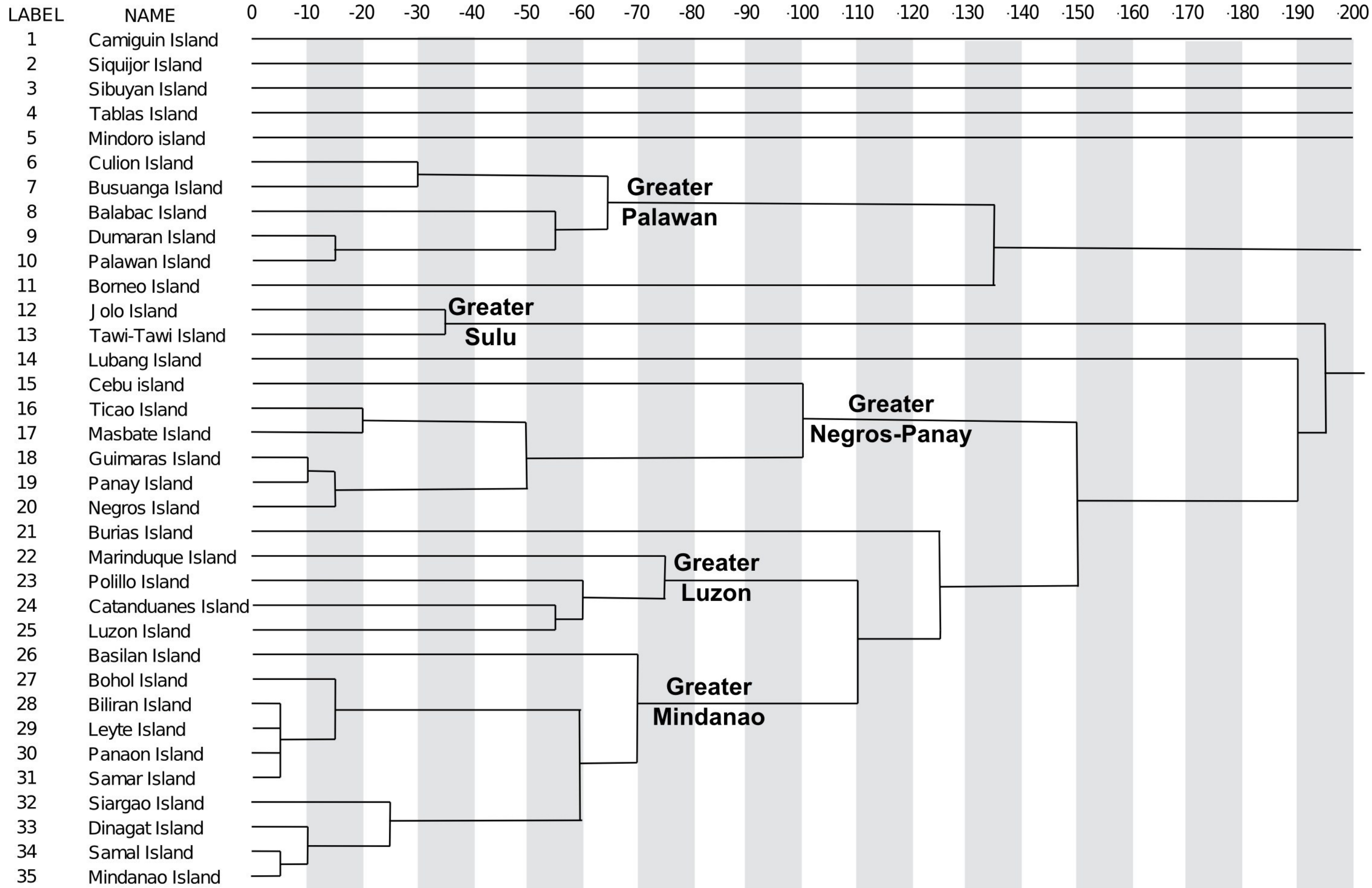

Figure 6: Island cluster diagram showing connectivity between islands with respect to RSL values. Connectivity for different sea level values were determined from Table 1. Also shown are biogeographic zones (bold characters) described by Heaney (1998).

River systems

The reconstructions of river systems using *r.watershed* as seen in Figure 7 shows the major river systems if one has to take into account submerged land areas during the Quaternary. Prominent rivers such as the Cagayan River in Luzon and Agusan River in Mindanao are also seen in the model. For Greater Luzon, the Pasig River which drains present day Metro Manila and the Laguna de Bay would join the Pampanga River at the exposed land area presently occupied by Manila Bay. Naga River would extend northward to also drain the exposed land area north of the western Bicol region. In Greater Negros-Panay, the model shows two distinct major river systems that join and drain at the northeastern part of the exposed island (Figure 7).

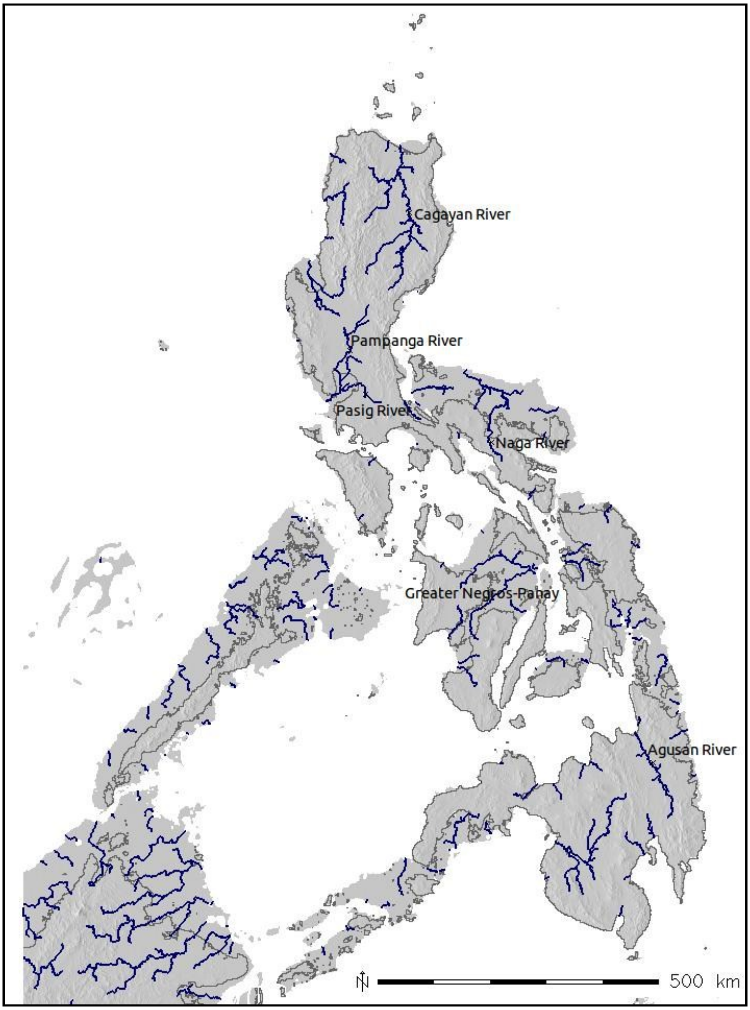

Figure 7: Main river systems (blue lines) modeled using *v.watershed* for land configuration at RSL -120m. Also shown are present day coastlines (black lines).

Migration routes and sea crossings

The *r.walk* analysis for the Philippine archipelago for RSL configurations of -120m, -50m, and present day conditions (0m) (Figure 8) show different calculated routes if minimum sea crossings are considered as primary factor. Calculations for minimum sea crossing distance (MSCD) and the number of sea crossings (NSC) (Table 2) to different islands from Borneo are drastically lower at -120m RSL levels compared to present day conditions supporting the hypothesis that colonisation of the islands probably occurred during glacial conditions.

The model shows that for the three different scenarios, the colonisation of Mindoro, Palawan, and Mindanao is the same although the distance and number of sea crossings changes. For RSL of -120m (Figure 8a), the colonisation of Greater Panay would occur via Palawan with a MSCD of 73km while the route with the least sea crossing to Luzon would be via Greater Mindanao. For RSL of -50m (Figure 8b), the route to Greater Panay and Greater Luzon passes via Mindanao. At present conditions (Figure 8c), the calculations show that the route with MSCD to both Greater Negros-Panay and Luzon passes via Palawan and the NSC's and MSCD's are much larger compared to the two previous conditions.

Biogeographical and archaeological implications

The reconstructions here estimate the geographical changes tied to sea level changes throughout the Quaternary and their implications on the migration routes if the minimum sea crossings are considered.

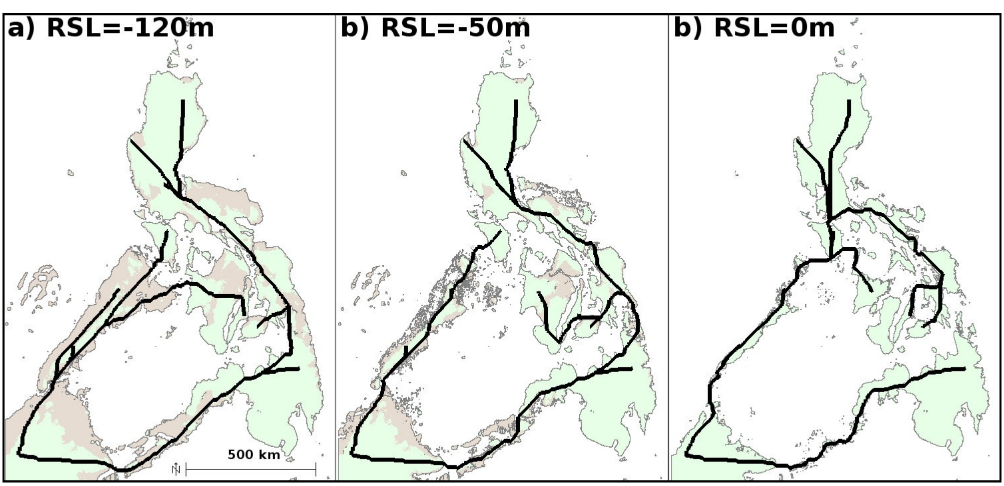

Figure 8. Migration routes analysis using *r.walk* in GRASS for (a) RSL -120m, (b) RSL -50m and (c) present day conditions.

Table 2. Calculations for minimum sea crossing distance (MSCD) and number of sea crossings (NSC) for calculated migration routes using *r.walk* for RSL -120m, -50m, and 0m.

Island	RSL -120m		RSL -50m		RSL 0m	
	minimum sea crossing distance (km)	Total number of sea crossings	minimum sea crossing distance (km)	total number of sea crossings	minimum sea crossing distance (km)	total number of sea crossings
Palawan	3	1	11	2	68	10
Mindanao	34	4	56	5	178	20
Panay	33	6	73	10	219	24
Bohol	34	4	64	7	193	43
Cebu	33	6	66	8	209	44
Mindoro	31	5	66	11	163	21
Luzon	34	4	68	9	168	39

It has been mentioned that the present day biogeography has been greatly influenced by these changes and the biogeographical zonation of the Philippine islands are actually delineated based on land exposures and connections during the glacial periods (Heaney *et al.* 1998). The fluctuation of sea levels has major biogeographical implications which depend on different interrelated physical factors such as the extent, rates and direction of sea level changes, and corresponding changes in the coastal morphology and land exposures (Hanebuth *et al.* 2011).

The presence of Pleistocene megafauna fossil throughout the Philippines suggest colonisation by terrestrial mammals during this epoch (Bautista and de Vos 2003; Beyer 1956; de Vos and Bautista 2001; Koenigswald 1956) and these probably occurred during sea level lowstands wherein the MSCD's are much lower compared to present and the stability of sea levels allowed the development of ecological gateways for these animals. The presence of humans during this time period has been implied based on stone tools found with the fossils (Beyer 1947; Fox 1971) although these have been questioned (Hutterer 1977).

The earliest concrete evidence of the presence of humans in the archipelago comes from Callao Cave in Luzon Island dated to 67 Ka (Mijares *et al.* 2010). Sea levels during this time period were around -70m and the analysis here would suggest a route via Mindanao with the least sea crossing (see Figures 8a and 8b). Reconstructions also show that coast lines were farther away from present day coastal sites during the Pleistocene especially islands such as Palawan.

This has been pointed out as the reason for the paucity or absence of evidence of coastal exploitation in Pleistocene archaeological layers despite their proximity to present day coasts (Fox 1970; Kress 2000). This is in contrast to shell midden sites throughout the archipelago which are dated to the mid to late Holocene (Aoyagi *et al.* 1993; Fox 1970; Kress 2000) wherein sea levels were equal to or even higher than present levels and shorelines were more or less the same or even closer to these sites.

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