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THE EARLY PLEISTOCENE AQUATIC PALAEOECOLOGY AND PALAEOCLIMATE IN CENTRAL JAVA, INDONESIA AS RECORDED IN MOLLUSC ASSEMBLAGES FROM THE KALIBENG AND PUCANGAN LAYERS OF SANGIRAN DOME

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The early Pleistocene aquatic palaeoecology and palaeoclimate in Central Java, Indonesia as recorded in mollusc assemblages from the Kalibeng and Pucangan layers of Sangiran Dome

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SUMMARY

This study explores quantitative patterns recorded in mollusc assemblages with the goal of elucidating the palaeoenvironment and palaeoclimate reconstructions, and the relationship between the established palaeodatasets of analysis and levels of variability in palaeontological data. Mollusc fossil assemblages obtained from the Upper Kalibeng to the Lower Pucangan of the early Man Site, Sangiran Dome in Central Java, Indonesia were analyzed by using bulk samples that were collected from the different facies of the dome which were deposited during the early Pleistocene.

A total of 58,216 specimens from 19 samples were collected from the Blue Clay Kalibeng, *Corbicula* bed, Lower Lahar, and Black Clay Pucangan. All specimens were identified up to the species level with a total of 61 species, which were further classified in terms of their ecology. These samples were then subsequently analyzed using ecological statistics methods and shell geochemistry. Specimens were compared based on the overall composition and taxa abundances, as well as autoecological investigation of its life habit, substrate preference, depth range, and the ecological implication of the identified species.

The Kalibeng mollusc assemblage exhibits generally similar overall composition and ecological marine structure with those that inhabited the soft bottom sublittoral zone. This assemblage contained predominant species from family Arcidae (*Anadara* sp., *Arca* sp. and *Arcopsis* sp.) and genus *Turritella* sp. (Turritellidae) suggesting the development of a shallow body of water in Central Java of the Sunda arc around 2 million years ago (Ma). Species from the *Corbicula* Bed assemblages, characterized by the presence of numerous *Corbicula*, contained shell species that originated from both freshwater and marine environment. Mollusc assemblages from the Lower Lahar and Black Clay Pucangan were pure freshwater shells. The examined mollusc assemblages in the Lower Pucangan were associated with marine and

swampy coasts, and lotic ecosystems with flowing waters landward indicating landmass deposits. Their presence characterizes the start of marine episodes linked to shift in marine regression and continental lacustrine environments, and counterparts of Pleistocene glacials/interglacials and volcanic activities within the last 2 Ma. These lines of evidence suggest that the molluscan diversity in Sangiran is associated with sub-environmental diversity of the localities with patterns likely resulting from a combination of ecological, environmental, and taphonomic processes.

Stable isotope composition, $\delta^{18}O$, $\delta^{13}C$, $^{87}Sr/^{86}Sr$, and riverine strontium flux data were obtained from the shells *Glycymeris* sp. (marine) and *Corbicula pullata* (freshwater) to ascertain the climatic conditions during the early Pleistocene in Sangiran Dome. Results of the chemical analysis is indicative of the evolving aquatic ecology and carbon cycles in the Solo basin during the early Pleistocene. The $\delta^{18}O$ and $\delta^{13}C$, and carbon isotopes in marine and freshwater shells relate to local climatic parameters and environmental conditions during the shell’s lifetime. Differences in $\delta^{18}O$ and $\delta^{13}C$ values between mollusc shells reflect the specific climate and subhabitat of each carbonate secretion. Shell $\delta^{18}O$ record indicates that early Pleistocene climate was dry, interspersed with occasional periods of precipitation. Whole shell isotope analysis reveals that between 2.2 to 1.8 Ma, climatic conditions became increasingly dry, and between 1.8 to 1.6 Ma conditions became wet with very high amount of precipitation. The $\delta^{13}C$ record reflects the productivity level in the basin, with ^{13}C-enriched carbonates. Variations in the isotopic compositions of carbonate values were controlled by a changing environment—marine to wetland—during the early Pleistocene. The abrupt downward shift in $\delta^{13}C$ from the Blue Clay Kalibeng to the *Corbicula* Bed was influenced by substantial changes in the hydrological process of the basin and were related to evaporation effects, which indicate that dry climatic conditions have prevailed at the beginning of early Pleistocene. The increase in $\delta^{13}C$ values in the Pucangan Black Clay suggests a high level of productivity in the basin. Depletion in strontium is attributed to alteration by meteoric waters indicating that there was a change in marine water and freshwater system in Sangiran.

Overall, this study illustrates the usefulness of fossil shells obtained from Sangiran. Species richness and stable isotope compositions of mollusc assemblages is useful in tracing the environment and climate sequence of early Pleistocene succession of the Sangiran Dome in Central Java. The changing environment has resulted in significant shifts in the density and distribution of Sangiran molluscs as revealed by the mollusc assemblages that were deposited on the different facies of Kalibeng and Pucangan layers. Similarly, results obtained by the study of the 2 Ma record of Sangiran in Solo basin clearly document that isotopic proxy data from mollusc assemblages are useful in describing climatic changes of early Pleistocene in Central Java. The approach provides a narrative of the relevant transformation of the aquatic ecology and climate regimes in Sangiran as well as in elucidating the sources of variability on paleontological patterns. Likewise, the study has direct implications on the important discussions about the past, present, and future changes of the environment and climate.

INTRODUCTION

Research in Sangiran engages in the movement of hominid species and cultural exchanges explained through migratory waves. Most of the previous studies describe the impact of Quaternary environmental changes as to how these exchange movements and migration occurred. Sangiran Dome (referred hereafter as Sangiran), the early man site, is among the most important places in tracing human’s origin and evolution, culture, and environment during the Pleistocene. It is the primary stratigraphic window for the Solo Basin, a coastal feature on the Plio-Pleistocene Sunda subcontinent south margin. The dome exhibits a continuous stratigraphy of the Quaternary with various conditions of sedimentation namely, marine, volcanic, swampy, and fluviatile environments. The deposits include many fossil-bearing beds linked to the migrations of animals and hominid species. Java is part of Sundaland, a landmass extension of Southeast Asia and is linked with the Asian mainland, during the Pleistocene glacial periods and is considered as an important faunal and hominid collection in Southeast Asia.

Throughout the Quaternary period in the islands of Southeast Asia, prehistoric groups met in diverse and changing environments. Among which are aquatic ecosystems that played a critical part in the evolution and adaptation of early humans. For instance, the oldest *Homo erectus* who reached the southernmost margins of the Sunda shelf had to adapt to the vast but still developing mangrove and swamp forests around the nascent islands of the Sunda volcanic arc (Sémah AM, 1984). Early human settlements in the late lower Pleistocene were located at the intersection of riverine, marshy, and littoral environments. During the Pleistocene to Holocene boundary, these environments experienced a severe eustatic rise which favored groups that closely occupied the shoreline. Eventually, a stronger relationship between prehistoric people favoring settlement in aquatic environments became apparent according to the multiple evidence from most of the archaeological sites studied in the zone, e.g.

presence of shell assemblages and middens (Bowdler, 1976; Godfrey, 1989; Erlandson et al., 1999; Cannon, 2000; Mannino and Thomas, 2001).

Shell deposits in Quaternary fossil-bearing formations produce paleontological records that describe the ecology and evolution of environments. These fossils are widely distributed in varied environments and are abundant from the tropics to the poles. Subsequently, they provide potential taphonomic windows and high-resolution time series analyses from almost every geographic region. They also offer molluscan patterns or models on diversity, ecology, and taxonomic structure. For these reasons, these fossils are good proxies for reconstructing the palaeoenvironmental condition.

Shell assemblages in Sangiran embody this information. Shell assemblages are evident from the basal layers of the Sangiran dome in Java. Volcanic activities and numerous climatic cycles during the Pleistocene period created the Sangiran dome. The stratigraphy is well studied in the early 1900s (i.e., see van Es, 1931; von Koenigswald, 1934; van Bemmelen, 1949) and is of great palaeontological interest in relation with the Plio-Pleistocene boundary in Southeast Asia. These geological and climatic activities generated four strata: Kalibeng, Pucangan, Kabuh, and Notopuro. The Sangiran dome started with the Kalibeng stratum, a shallow marine layer containing blue clay (Upper Kalibeng) that were deposited during the Late Pliocene. It is then followed by the Pucangan layer, which contains lahar and black clay deposited at the beginning of the Pleistocene. The next layer, the Kabuh layer, contains volcanic materials with fluviatile facies that were deposited during the Middle Pleistocene. The Sangiran dome ends with the Notoporo layer, which contains lahar that was deposited from the Late Middle Pleistocene.

This thesis re-examines the mollusc assemblages deposited in the Pucangan and Kalibeng stratigraphic series sequence of Sangiran (Central Java, Indonesia) more than two million years ago (Ma). Our intent is to elucidate the influence of climate and environmental changes in the aquatic landscape evolution of Sangiran and emergence of land in Central Java by examining the information that was recorded in fossil molluscs in these beds from the early Pleistocene. Our research is an effort to address this knowledge gap and used (1) a molluscan taxonomic approach and (2) shell stable isotope analysis.

The thesis is divided into five chapters; each chapter is divided into sections. Chapter 1 provides a preview and description of Java island which includes its geographic and geological setting, and climatic histories. We used a similar approach to describe the Sangiran dome in the Solo basin: its location and stratigraphy. Also, we described the multi-disciplinary research that was conducted in Central Java. We postulated the purpose of this research using this information as our background.

Chapter 2 describes the presence of fossil shells in the Sangiran Dome. The first section discussed the relevance of malacology in the archaeology and paleontology milieu. We then reviewed the extant literature about Java fossil shells and their importance as a state-of-the-art tool for paleoecological reconstruction at the turn of the 20th century. The chapter ends with the account on the Sangiran mollusc assemblages.

Chapter 3 examines shells retrieved from sampling sites in Kalibeng and Pucangan, earmarked by taxonomical and taphonomical studies with details on the abundance of shell species and their habitat, and the implication of such information in describing the palaeoecology composition and reconstruction. Chapter 4 proceeds with a study on geochemistry from shell samples gathered in Sangiran dome. We analysed stable isotopic signals from *Glycymeris sp.* and *Corbicula pullata* shells from Kalibeng and Pucangan series to describe marine and freshwater palaeohabitats, respectively, in Sangiran and Central Java.

Chapter 5 synthesizes our data analysis and discusses their implication within the framework of the studies carried out in Sangiran. Synthesis focuses on the comprehension of mollusc assemblages from the Kalibeng and Pucangan deposits illustrated by species abundance, richness and diversity, aquatic ecology, and taphonomy. The occurrence from indicators represented by the taphonomy and geochemical signatures of mollusc assemblages from Sangiran dome inferred the aquatic ecological environment, biostratigraphy, and climate adapted by hominins and fauna in Central Java in the Plio-Pleistocene period. Finally, it recalls the key points gleaned from this study to support our conclusion in reconstructing the environmental history of the Sangiran dome deposits using molluscs as a repository of this information during the Plio-Pleistocene. Overall, this study demonstrates the potential of utilising shells as recorders of their environment. It illustrates that there is environmental information that can be extracted from shells. Furthermore, the physiological influence on many of the studied proxies may be useful surrogates of shell physiology, which in turn could provide information about palaeoecology and palaeoclimate. Likewise, we integrate the data presented in the different chapters and viewed the implication of our conclusions from a broader perspective.

CHAPTER 1:

THE SANGIRAN DOME IN THE GENERAL SETTING OF JAVA ISLAND

1. Geography, climate, and vegetation of Java Island in the Indonesian archipelago

Indonesia is an archipelagic country extending about 5,120 km from east to west and 1,760 km from north to south **(Figure 1).** The country consists of 13,466 islands according to a geospatial survey conducted between 2007 and 2010 by the National Coordinating Agency for Survey and Mapping.

Java is one of the largest islands of Indonesia. It lies between Sumatra to the west and Bali to the east, surrounded by the Java Sea to the north, Sunda Strait to the west, the Indian Ocean to the south and Bali Strait and Madura Strait in the east. The island is almost entirely of volcanic origin. It contains 38 mountains forming an east-west spine that has at one time or another been active volcanoes. The area of Java is approximately 150,000 km^2. It is about 1,000 km long and up to 210 km wide. The island's longest river is the Solo River. The river rises from its source in central Java at the Lawu volcano, then flows north and eastward to its mouth in the Java Sea near the city of Surabaya. In the center of the island, the Sangiran site is located 15 km north of the city of Surakarta (Solo).

Figure 1. Using this information as our background, Geographical map of Indonesia; Java Island shaded in red. © CC BY-SA 3.0/ Java Island geographical map

Java Island has an equatorial maritime climate characterized by an alternation between dry season and wet season (wet monsoon). Different climatic zones can nevertheless be distinguished on the island. The tropical rainforest in the west is giving way from the center of the island eastward to deciduous forest, reflecting a decline in average annual rainfall and a more contrasted seasonal pattern. The climate in the eastern part of Java Island is semi-arid in some places. The displacement of the Inter-Tropical Convergence Zone (ITCZ), an aero logical structure **(Figure 2)** defined as the meeting zone between monsoon winds (coming from the NW) and the trade winds (coming from the SE), causes seasonal alterations (Estienne and Godard, 1970; Tapper, 2002). During the northern winter, ITCZ is placed at the level of Java which leads to abundant rainfall. During the boreal summer, this zone moves towards North-West and East Java and is subjected to dry trade winds coming from Australia.

El Niño events also influence the Java climate by making the dry season longer and more intense, as in the years 1972, 1976, 1982-83, 1986-87, 1991 (Wasser and Harger, 1992), 1997 and 2015 (King et al., 2016).

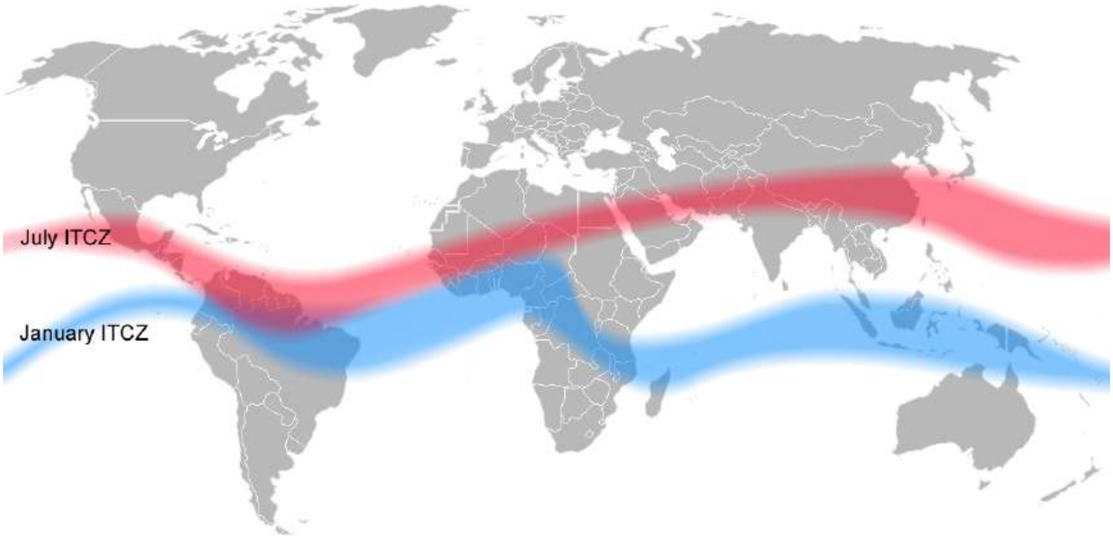


Figure 2. The northern shift in July and southern shift in January of Inter Tropical Convergence Zone (ITCZ) ©Matts Haldin, 13 Dec 2006

The natural (climax) environment of Java is tropical rainforest, with ecosystems ranging from coastal mangrove forests on the north coast, rocky coastal cliffs on the southern coast, and low-lying tropical forests to high altitude rainforests on the slopes of mountainous volcanic regions in the interior.

Indonesian coastal zone is rich in tropical marine ecosystems such as estuarial beaches, mangroves, coral reefs, seagrass, and algal beds, which are homes to diverse living communities with various association as well as richness in species diversity including molluscs (Hutomo & Moosa, 2005). Soegiarto & Polunin (1981) mentioned about 1,000 species of bivalves and about 1,500 species of gastropods. Budiman (1991) reported the presence of 303 species of molluscs from mangrove in Asia and Oceania of which 183 species possible occur in Indonesian mangroves. The water molluscs have 247 species from Java Sea and Madura Strait (Moosa et al., 1980).

Snail assemblages in different habitat types in Java differ clearly in composition (Ayu Savitri Nurinshiyah et al., 2016). There are 209 land snail species known in Java (Dharma 1992). 69 species and 17 subspecies are endemic, and 12 are introduced species. Among them, 55 species were identified in Kendeng Mountains in Malang regency, East Java (Dharma, 1992). Species richness was highest in primary forest. Plantations and agroforest are dominated by pulmonate species while primary forest is dominated by native prosobranchs.

2. General geology and history of Java Island within the Indonesian archipelago

2. a. The Indonesian tectonic plates

The Indonesian archipelago lies within one of the most active seismic regions in the world and the Pacific Ring of Fire, an area where a large number of earthquakes and volcanic eruptions occur. It is located in between two continental plates, the Eurasian (Sunda Plate) and Australian Plate (Sahul Shelf), and between two oceanic plates, Philippine sea and Pacific Ocean plates. West Indonesia consists of the outer non-volcanic arc and the inner volcanic arc, and the Sunda shelf. The Sunda shelf is an old and stable part of the continental crust that became the foundation of west Indonesia. The evolution of the Sunda shelf and inner volcanic arc determined the palaeogeographic changes in the central depression of Java island from the beginning of the Tertiary to Quaternary era.

2. a. 1. The Sunda arc

The Sunda Arc is a volcanic arc in Indonesia that formed the islands of Java and Sumatra, the Lesser Sunda Islands, and the Sunda Strait. The arc is characterized by a series of volcanic mountains. Java Island, an example of an island arc, is built through multi-events of Cenozoic (up to the present) arc magmatism produced by the subduction of Indian-Australian oceanic crust along the southern margin of Eurasian plate. This explains a series of active volcanoes and numerous eruptions that occur on the island. There is also a non-volcanic arc, formed of an accretionary wedge, and a forearc basin.

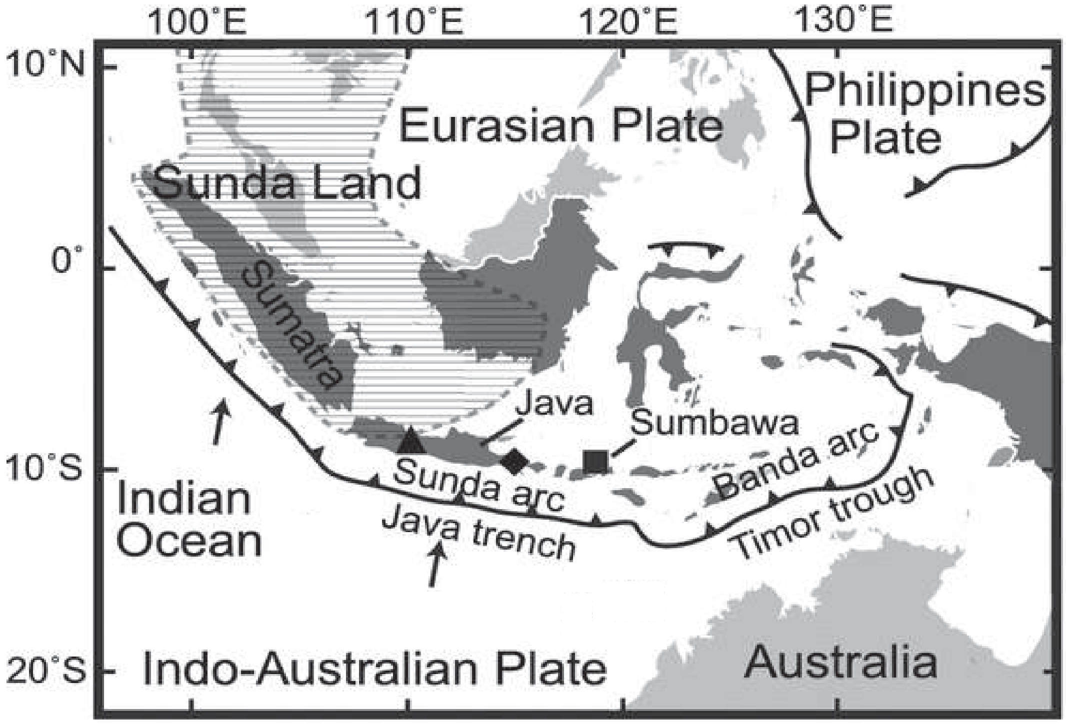


Figure 3. The Sunda arc. Overview map of the Sunda arc, Indonesia, showing the locations of Galunggung, Kawah Ijen, and Tambora volcanoes. The thatched region labeled Sunda Land delineates the inferred extent of the continental hemisphere beneath the arc (Hamilton, 1979). Arrows indicate relative plate motions (Tregoning et al., 1994) and convergence rate (Syracuse and Abers, 2006). © Vigoroux et al., 2012

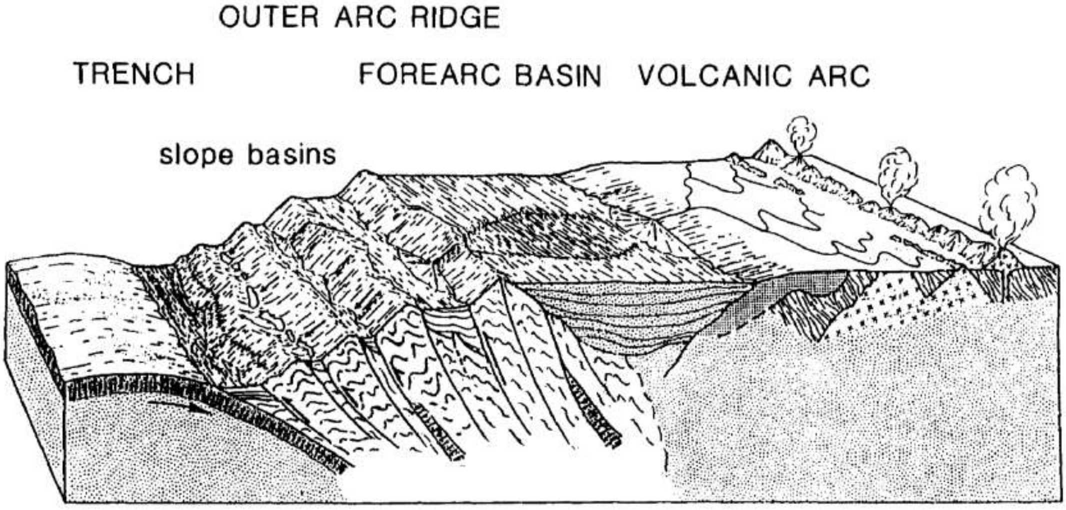


Figure 4. Diagrammatic section across Sunda arc ©Curray, 1989

2. a. 2. The Sunda shelf

The Sunda shelf is a southeast extension of the Eurasian continent. It is bordered by the islands of Java and Sumatra in the South West and the island of Borneo in the East. Formation of the shelf would date from the final Triassic (Hartono & Tjokprosapoetro, 1986) during the collision of the Indosinia terrane (allochthonous tectonic block including a proto-Kalimantan, eastern Malaysia, and Indochina) with the Mergui terrane (south Burma). Orogenic movements in the Paleocene gave the shelf its current form. The shelf has resulted from millennia of volcanic activity and erosion of the Asian continental mass, and the buildup and consolidation of debris along the margins as sea levels rose and fell. The area, where the sea is shallow (less than 100 meters most of the time) has been subject many times during the eustatic variations of the Quaternary, as evidenced by several ancient drainage systems, particularly in the Java Sea (Mollengraaf, 1921; Kuenen, 1950; Ollier, 1985; Voris, 2000). These periods of low sea levels, corresponding to the glacial episodes, allowed the migration of the continental faunas.

2. b. History of Java Island

2. b. 1. Brief geological background of Java

The base of Java were rock deposits originated from the closure of Tethyan oceans from the Mesozoic era. The island of Java was formed by large volumes of sediments which covered the rock foundation of the island due to intense volcanic activities occurred during the Cenozoic. They are distributed in the Bayah areas in the west and in the Central to the western mountains of Progo. Diversity gradient and metamorphism indicated orogenic activity and increased towards the West evident in pre-tertiary rocks.

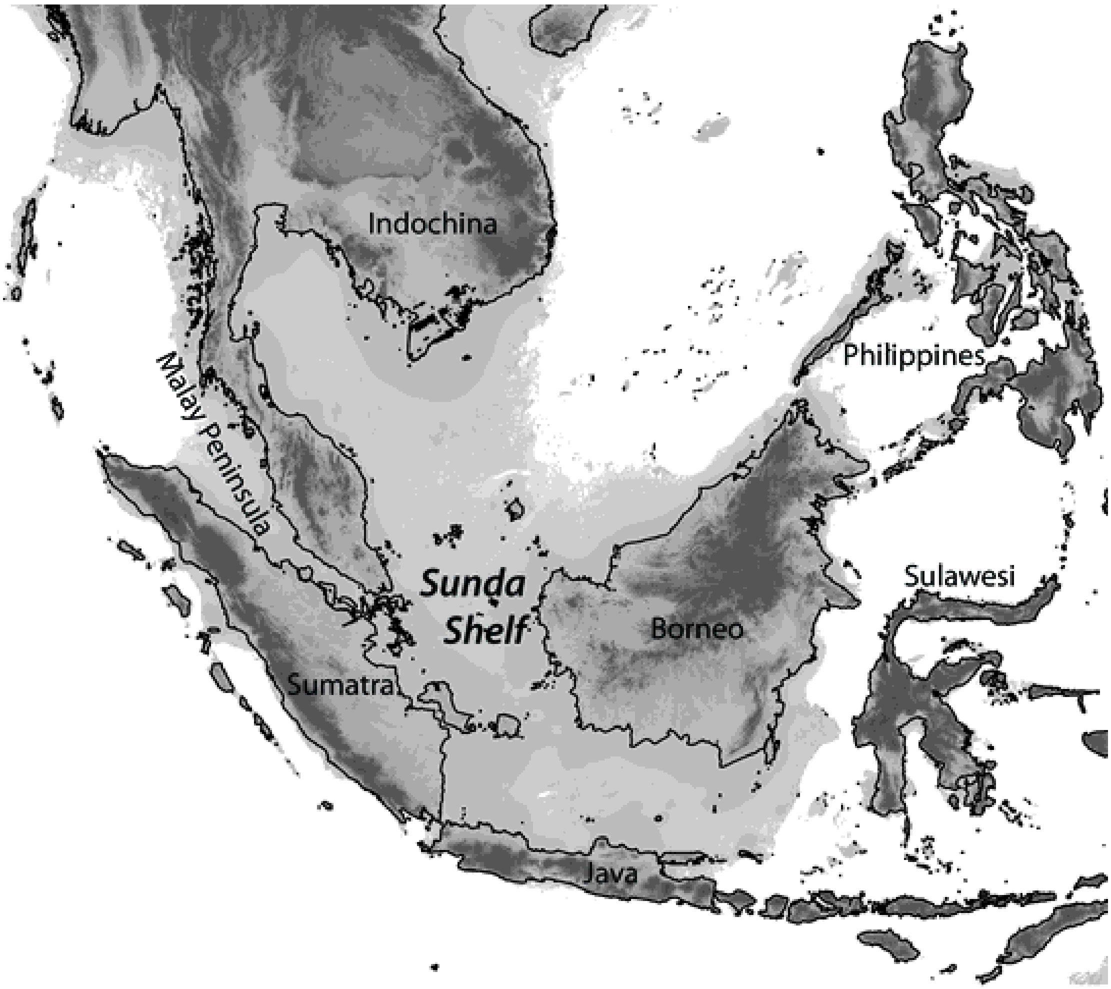


Figure 5. The Sunda shelf. Map of Southeast Asia with land extent (depicted in gray) during glacial low stands estimated using 120m bathymetry (data from ETOPO1) ©Phyletica

Continuous strong episodes of tectonic events paved the way to the emergence of Sundaland and metamorphism of Mesozoic deposits. These episodes were marked by the erosion of secondary formations of a continental land further to the south (van Bemmelen, 1949). Only 2/3 of the north of Java island was exposed and the south was covered by the sea as evidenced by littoral sediments namely, clays, tuffs, quartz sandstones, conglomerates, and open sea with clays, marls and foraminiferal limestone during the Eocene epoch. During the Lower Miocene, the sea continues to retreat to the north and the whole island currently forming the island of Java is submerged. In the Middle Eocene, the volcanic arc was formed that ran the length of Java (Hall & Smyth, 2008; Smyth et al., 2007). During the Plio-Pleistocene, a third tectonic phase associated with an important orogenic phase finishes drawing the current structure of the island (Saint-Marc et al., 1977).

2. b. 2. Quaternary vegetation and climatic history of Java

The palaeoenvironmental record was provided by sedimentological, limnological, and palynological analyses conducted from different regions in Java. Rain forest shaped the vegetation of Central Java during the Lower Pleistocene as seen from fossil-bearing sites namely, Bumiayu, Gemolong, and Sangiran between 2.6 and c. 1 Ma (Sémah, 1982, 1984; Sémah et al., 2001) (See Figure 1). Pollen records in the Bumiayu region in the North Seraju chain show a marine environment with an upland rainforest covered emerged lands behind immense coastal mangroves and back mangrove formations, often along with extensive swamp forests (Sémah AM & Sémah 2012). Rainforest was replaced by drier and more open formations during glacial stages. Since the end of the Lower Pleistocene, it underwent austere fragmentation, especially during glacials, restricting to locally humid patches among open landscape with extensive grasslands. The vegetation pattern was present in several-studied stratigraphy at the southern foot of the Kendeng hills and in the Solo depression in central Java (Sémah 1982, 1986; Brasseur, 2009) (see Figure 1). Open landscape was represented by a semi-arid and sub-humid climate with an open savanna-like environment and forest galleries along the rivers between 1.5 – 0.9 Ma (Saleki, 1997; Larick & Ciochon, 2015). Evidence of open landscape and dry season were verified from vegetable leaf prints (Schuster, 1911), and fossil fish and molluscs (Joordens et al., 2009) retrieved in Trinil Site dated around 1 Ma.

Glacial and interglacials have contrasting conditions in Java in the last 200,000 years ago (kyr) of Middle Pleistocene. Sediment cores from the Bandung Basin of West Java provided a palaeoclimatic record of 135 kyr (van der Kaars & Dam, 1995 and 1997). Palaeosol development indicated dry conditions in the last part of the penultimate glacial period around 135 kyr. Very warm and humid interglacial conditions prevailed due to the infrequency of altitudinal taxa from 126 to 107 kyr.

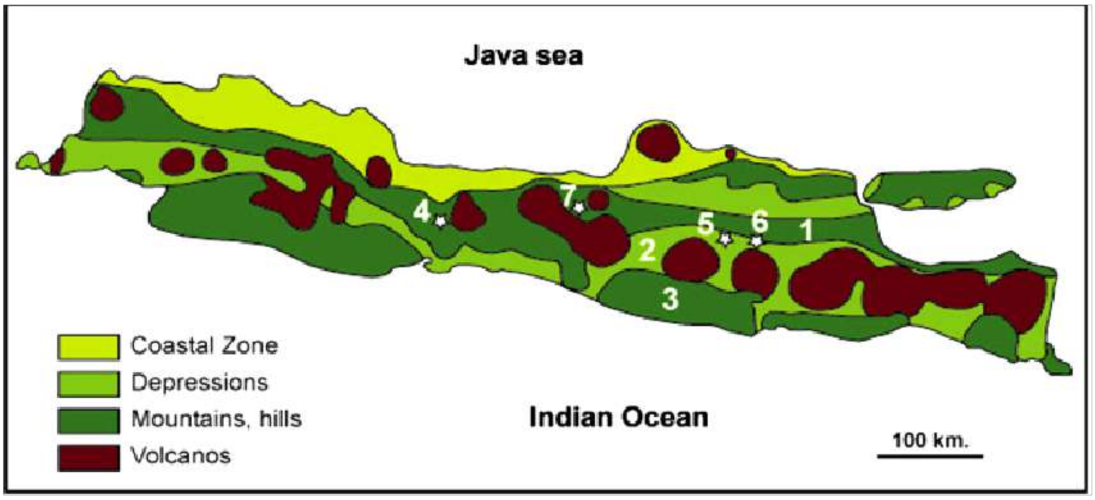


Figure 6. Schematic geomorphological map of Java (after van Bemmelen, 1949): 1. Kendeng hills; 2. Solo depression (Sangiran); 3. Southern Mountains (Punung, Song Terus); 4. Bumiayu; 5. Trinil; 6. Kedungbrubus; 7. Ambarawa, see Sémah AM et al., 2016.

The Bandung basin is hosting a freshwater swamp forest. Afterward, it was replaced by open swamp vegetation dominated by grasses and sedges, indicating a change to considerably drier conditions, possibly related to reduced moisture uptake by the NW monsoon as a consequence of lower sea levels at the onset of glacial periods around 81 kyr. Downward shifts of montane forest taxa and temperature by maximum of 7°C suggested cooler and drier climatic conditions in the area which represented the Last Glacial Maximum (LGM) between 47 and 20 kyr.

Severe climatic changes affected the island during the LGM, 20 kyr based from palynological data gathered at Rawa Danau in West Java (van der Kaars et al., 2001) and Ambarawa basin in Central Java (Sémah AM et al., 2004). Pollens from Rawa Danau indicated the presence of open herbaceous swamp vegetation dominated by grasses, while the character of the sediment deposited at this time suggests a deep lake (van der Kaars et al., 2001). The climate was characterized by a long dry southeast monsoon, a much less humid northwest monsoon and a significant drop which influenced landscapes throughout the region.

The swamp series analysed in the Ambarawa basin shows that areas below the lower altitude range of downward shifted lower montane rain forest was covered by open vegetation, mostly consisting of grasslands (Sémah et al., 2004). Followed by climatic amelioration with an increase of precipitation, initially marked by the expansion of rain forest taxa on the surrounding hills, and the development of a swamp forest in the basin itself at 15 kyr (Sémah AM & Sémah, 2012).

Climatic optimum and condition were observed in the Ambarawa basin by the beginning of the Holocene around 8500 BP. During the Holocene, more humid climatic condition and development of a closed rainforest vegetation type abounded. It has a seasonal climate, similar to the present conditions, associated with some fragmented rain forest between 7000 and 4000 BP. This drying is also evident in Western Java from 8000 – 6000 BP (Stuijts, 1993). In Central Java, two phases of forest recession occurred at 4000 BP associated with the development of grasslands and clear recession of the rainforest attributed to climate change at 2800 BP. Human influence on the vegetation happened on the island at the beginning of 1500 CE.

3. The Sangiran dome in Solo basin

Climatic oscillations, environmental changes, and volcanic deposits shaped the morphology of the Java island during the Quaternary. This vegetation and environmental changes are manifested in the quaternary deposits of Sangiran in Solo basin in central Java.

Sangiran dome is located in the Solo depression of Java Island, bordered to the north by the Kendeng Hills, less than 300 m high, an anticlinorium of folded Miocene and Pliocene limestones and marls. It is the Early Man Site and located 12 km north of Surakarta (Solo) City, Central Java, at about 7.5°S latitude and 110.8°E longitude. It lies in an intersection of three different regions: Kalijambe and Plupuh (Kabupaten Sragen) and Gondangrejo (Kabupaten Karanganyar). The area is characterized by a dome structure, which was truncated by erosion (van Es, 1931; Duyfjes, 1936; von Koenigswald, 1940). The dome offers a stratigraphic window into the Solo Basin, part of a Plio-Pleistocene inner-arc basin along the southern margin of Sundaland. The dome features important information on cultural and environmental histories of 2 million years. To wit, the history of climates, the emergence of the island, tectonic and volcanic activities, the transformation of landscapes, and the presence of *H. erectus* unraveled in the site during the Quaternary period.

Various phenomena of human life and the environment from that long-time span have been recorded in the layers exposed by geological processes in Sangiran (von Koenigswald, 1940; van Bemmelen, 1949; Watanabe & Kadar, 1985; Sémah, 1986). The dome consists of marine, swamp, alluvial, and volcanic ash layers from base to top order. Tectonic uplift produced the Kendeng Hills to the north of Sangiran towards the end of the Middle Pleistocene.

During the end of the Pliocene and Early Pleistocene times, shallow marine sedimentation persisted and some regions around Sangiran was partly under the sea where a long marine strait occupied much of the present Solo Valley (Djubiantono, 1992). Followed by-products from massive volcanic activities from large volcanoes related to the Sunda inner arc, which yielded important deposits, and lahars filled the lagoon near Sangiran. These emitted volcanic products built the land in the center of the Solo depression (Sémah et al., 2000). Moreover, they induced more pronounced regressive conditions in sedimentation, which reflect a palustrine environment (Sémah, 1984). The last uplift of the Kendeng hills northwards and of the Southern Mountain Java led to a continental development and marine influence disappeared at the lower to middle Pleistocene boundary (Djubiantono, 1992).

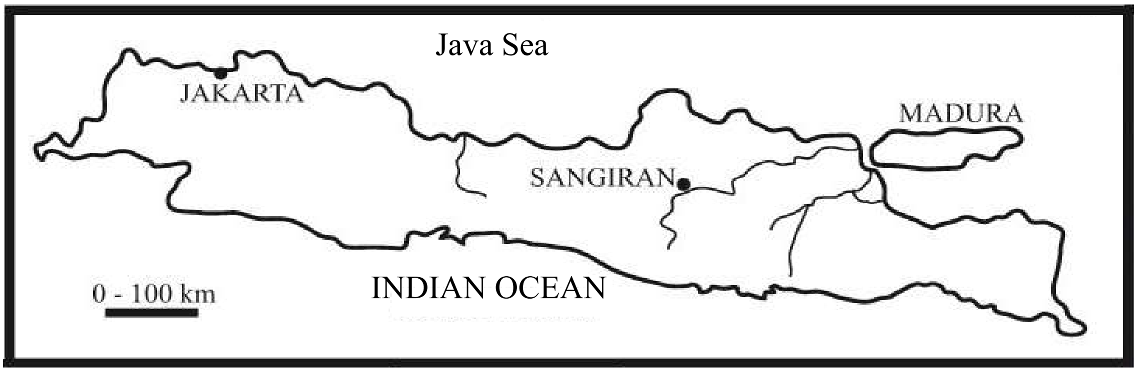


Figure 7. Location of Sangiran in Java Island

3. a. The Sangiran stratigraphy

The palaeogeography of Sangiran in Solo basin in the Quaternary period is based on the stratigraphic sequence of the dome found within the depression and discovered in Soko and Barong on the southern flank of the Kendeng Hills (Sémah et al., 2001).

Volcano-tectonic processes in central Java have a major impact on the landscape of Sangiran during the Quaternary. The interplay between tectonism and volcanic activity influenced stratigraphic evolution in the Sangiran dome (van Bemmelen, 1949). The terminal Pliocene presented shallow marine sedimentation despite the proximate areas of Sangiran had already emerged (Djubiantono, 1992). Larger volcanoes present in the Sunda inner arc yielded important volcanic products, and their lahars mostly filled the lagoon near Sangiran at the beginning of early Pleistocene (Sémah et al., 2000). The lahar deposits were mixed with marine and freshwater molluscs. Afterward, a palustrine environment has been characterized based on the regressive conditions induced in sedimentation (Sémah, 1984). The last uplift of Kendeng hills northwards and of the Southern Mountains of Java exhibited a marine to terrestrial succession at the time of the lower-middle Pleistocene (Djubiantono, 1992). Afterward, volcano-sedimentary layers were deposited.

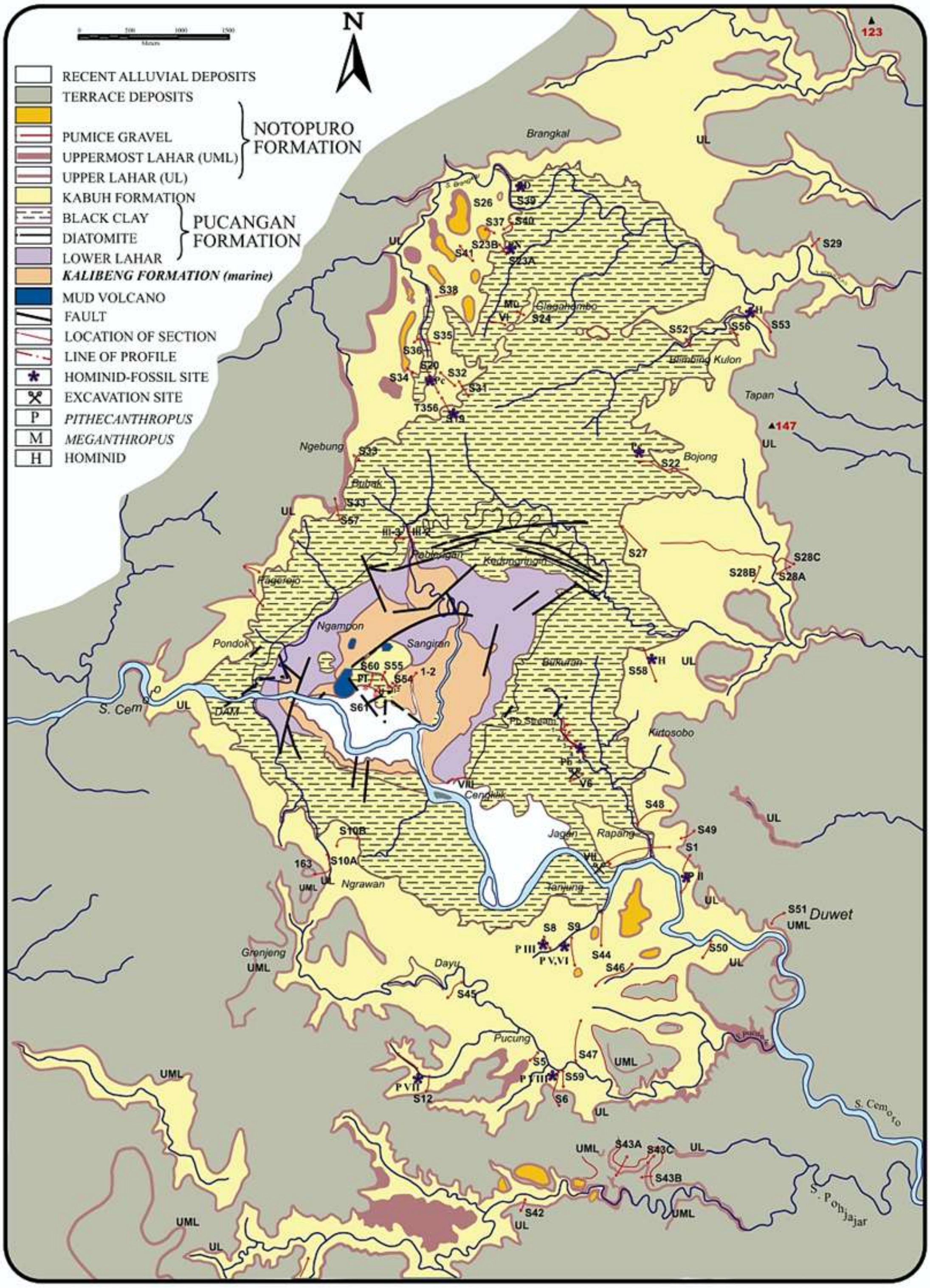


Figure 8. Geological map of the Sangiran dome. The dome shape arose as mud volcanoes pushed up older sediments from below. After subsequent erosion, a sequence of Pliocene and Early Pleistocene sediments outcrop in concentric rings, the oldest at the middle of the dome. The exposed sequence consists of four principal sediment deposits (from oldest to youngest): Kalibeng, Pucangan, Kabuh and Notopuro ©Watanabe & Kadar, 1985

3. a. 1. The Sangiran dome: a general overview

The first geological map and lithostratigraphy of Sangiran Dome were published by van Es (1931). In 1936, Duyfjes presented a new stratigraphical classification based on faunal assemblages. He proposed names Kalibeng, Pucangan, Kabuh, and Notoporo. These names were borrowed from the geological descriptions of East Java (see Duyfjes, 1936). This classification was used by von Koenigswald (1940) to note the geological units of the Sangiran Dome from the faunal fossils they contained. Later, new names have been proposed later, Puren, Sangiran, Bapang, and Pohjajar, accordingly (Watanabe & Kadar, 1985). Many authors have accepted this nomenclature, even though some of them are still using the old names. The various sediments distribution is shown in a geological map of the Sangiran area **(Figure 8).**

Sangiran dome oldest deposit is called the Kalibeng (Puren). They revealed a marine recession of the Plio-Pleistocene series and exposed only in the central part of the anticlinal dome of Sangiran. Duyfjes (1936) divided the Kalibeng layer into Lower and Upper Kalibeng. The lower layer is characterized by marine marls with abundant *Globigerina* and pelagic foraminifera (Marks, 1957) and not visible in the stratigraphy of Sangiran. While the upper Kalibeng is also of marine origin composed of bluish-gray clay and silty clay that have marine molluscs, foraminifera, and diatoms deposited in the transition of late Pleistocene and early Pleistocene (Sémah, 1986). Volcanic activities in the area resulted in clay formation from alteration of ashes, and sea level climatic variations leading to an environment of shallow marine with silt sand in *Turritella* beds and *Balanus* limestone. These materials were deposited in shallow seas and possibly originated in a tidal zone, respectively. The formation ends with clay and silt sediments in *Corbicula* beds. The marine mollusc deposit from the Kalibeng layer is concentrated in the upper part of the stratum.

The profile of Kalibeng indicates a change in the environment from full marine to wetland represented by a facies of gray silty clay with numerous *Corbicula*, a freshwater mollusc, known as the *Corbicula* bed in the topmost part of Kalibeng (von Koenigswald, 1940; Watanabe & Kadar, 1985; Sémah AM, 1986; Bettis III et al., 2004). The Corbicula bed also bears marine molluscs and foraminifera, which may be explained the coastal transgression and regression in the Pablengan Kulon area. This environmental change presents the beginning of brackish or freshwater continental sedimentation (von Koenigswald, 1940; Watanabe & Kadar, 1985). Palynological contents indicate a nearby shoreline covered by a mangrove forest (Semah, 1986). Work in diatom biostratigraphy and paleomagnetic measurements yielded an age range of 2.14 to 1.67 Ma (Ninkovich & Burckle, 1978, Semah, 1984).

Progression of the continental environment continued in more clayey deposition of Pucangan (Sangiran). It has the Lower Lahar and the Black Clays (Watanabe & Kadar, 1985). The Lower Lahar overlies the Kalibeng layer that traverses the central part of the dome. These facies contain fine volcanic material, fossil molluscs, and coral fragments. Von Koenigswald (1940) also mentioned the first mammal fossils in this deposit. The volcanic activities resulted in a thick deposit in the Solo depression and filled what was then a Sangiran lagoon (Sémah et al., 2000). At present, these deposits were exposed along the streams and irrigation channel in the center of Sangiran dome. Recent datings by the Argon/Argon method (Ar/Ar) yielded ages of 1.90 Ma (Bettis III et al., 2004) and 1.66 Ma (Semah et al., 2000) and may have crossed Olduvaï episode.

Afterward, Black Clay deposits developed wetland vegetation. It initially started as an estuarine environment then followed by a lacustrine environment. These clays have several marine transgressions. Changes of littoral environments were indicated by diatom fossil contents (Yokoyama & Koizumi, 1989), foraminifera (Kadar, 1985) and marine and freshwater molluscs (Watanabe & Kadar, 1985). The Pucangan unit contains the oldest fossil remains of vertebrates at Sangiran. They are attributed to the Satir fauna. Pollen analysis revealed that faunas lived in coastal wetlands dominated by tropical rainforest (Tokunaga et al., 1985; Sémah AM, 1986).

Absolute ages from volcanic tuff levels were obtained by Fission Tracks (FT) and have ranges of 1.56 Ma (Saleki, 1997) and 1.16 Ma (Suzuki & Wikarno, 1982). The palaeomagnetic study of Pucangan clays revealed a dominant inverse polarity attributed to the Matuyama period (Sémah, 1982; Shimizu et al., 1985). An inversion at the top has been initially attributed to the base of the Brunhes period but it could also be at the Jaramillo episode (Yokoyama & Koizumi, 1989; Langbroek & Roebroeks, 2000).

A dense calcareous pebbly sand bed called Grenzbank happened in 1 to 0.9 Ma which covered the Pucangan Black Clays (von Koenigswald, 1954; Sudijono, 1985). This zone is rich in vertebrate (Leinders et al., 1985) and hominid fossils (von Koenigswald, 1940; Grimaud-Hervé et al., 1985) where vegetation indicated an open landscape with wide coastal marshes and mangroves and a rain forest cover on the hinterland (Brasseur et al., 2015). These sediments are locally cemented; possibly with clay or silt intercalations attributed to the uplift and subsequent erosion of the hill ranges and last to reflect marine influences in the Solo depression (Djubiantono et al., 1992; Sémah et al., 2000; Sémah AM et al., 2010).

The Kabuh (Bapang) deposits have a complex formation and mostly fluviatile volcanic sediments. The volcanic sediment accumulations presented a long dry season and an open vegetational landscape indicated by pollen grains of Poaceae, Asteraceae, Fabaceae, Mimosaceae related with the circulation corridors on the Sunda shelf (Sémah & Sémah, 1998).

Most of the hominids were found in this layer (Widianto, 2001; Widianto et al., 2001; Indriati, 2004; Grimaud-Hervé et al., 2012). The lower and middle parts of the Kabuh hold the majority of *H. erectus* fossils and occurrence of *Elephas* sp. fauna, related to Kedung Brubus faunal association, was unearthed (de Vos et al., 1982; Aziz, 2001). Small sized lithic artifacts called Sangiran flakes made from jasper, silicified limestone, quartzite, and chalcedony were also retrieved from the deposits (von Koenigswald, 1936; Simanjuntak & Sémah, 1996). Larger andesitic lithic artifacts (e.g., polyhedral, bolas, hamlet) together with broken mammal fossils on an excavated occupational floor in northwestern part of the dome in Ngebung were also found in this layer (Sémah et al., 1992).

Numerous dates have been made on the pumice, tuff, and volcanic sand of Kabuh. Most ages obtained from Potassium / Argon (K / Ar), Ar / Ar and FT were around 0.8-0.7 Ma (Jacob & Curtis, 1971; Nishimura et al., 1981; Suzuki & Wikarno, 1982; Saleki, 1997) but an isolated series of latest dating in this deposit delivered much older ages from 1.51 to 1.02 Ma (Larick et al., 2001). Other elements have been studied and dated in Sangiran, these are tektites discovered in the middle and upper part of Kabuh (Itihara et al., 1985). Their rearrangement indicates that the sedimentary layer including the tektites is inconsonance with the date of the meteorite impact, 0.8 Ma (Ninkovich & Burckle, 1978, Schneider et al., 1992, Langbroek & Roebroeks, 2000).

The last and younger deposit is the Notopuro (Pohjajar) layer. The base is called the Upper Lahar and followed by coarse fluvio-volcanic sands alternating with tuffs with interference by a more lahar. It has a higher proportion of fine-grained volcanic sediments (Bettis et al., 2004). No hominid fossils were found in any part of the Notopuro deposits in the dome. The dates on volcanic effluents gave 0.15 Ma by Ar/Ar (Saleki, 1997) and 0.25 Ma by FT (Suzuki & Wikarno, 1982).

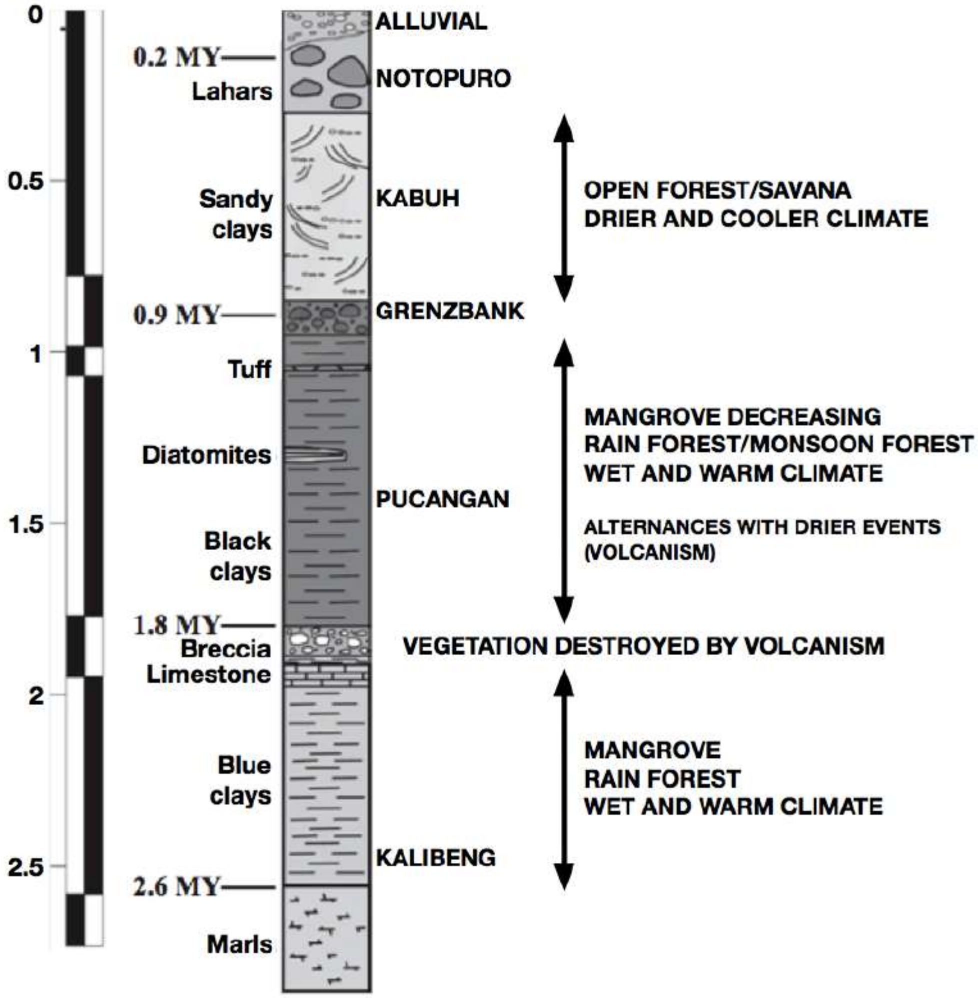


Figure 9. Sangiran lithostratigraphy in correlation to vegetation and climate reconstruction (Sémah AM & Djubiantono, 2007) © HOPSEA: First Islanders, 2007

3. b. Sangiran Palaeontology and Prehistory

3. b. 1. Human paleontology and fauna

Many fossils of hominids have been found in the central and eastern parts of Java namely in Sambungmacan, Trinil, Kedungbrubus, Ngandong, Ngawi, and Mojokerto. All of these mentioned sites are located in the Solo River, Brantas River or Kendeng Hills depression.

The term *Pithecanthropus erectus* was created when Eugène Dubois discovered a skullcap and a human fossil on the locality of Trinil (hills of Kendeng, East Java), 60 km northeast of Sangiran in 1891. Although the term Pithecanthropus is still used, these fossils are now grouped in the species *Homo erectus.*

3. b. 1. a. Hominids discovered in Sangiran

Notable discoveries in Sangiran were the presence of hominid fossils (von Koenigswald, 1954, Widianto, 1993, Grimaud-Hervé, 1994; Grimaud-Hervé & Widianto, 2001; Kaifu et al., 2008; Zanolli et al., 2011). Around 60 fossils of *Homo erectus* were discovered chiefly from the Late Lower to Middle Pleistocene. These discoveries represent 50% of Homo erectus remains found in the world (Simanjuntak, 2001).

Hominid fossils started to appear at the Upper layers of Pucangan black clay deposits. These are mandibles labeled as Sangiran 1b and Sangiran 5 and skullcaps referred to as Sangiran 4 (see figure 10) and Sangiran 31. Other mandibles found are the *Meganthropus palaeojavanicus* or known as Sangiran 6a, *Pithecanthropus* C and Hanoman 13. More cranial fragment remains were recovered namely Arjuna 13 and Hanoman 1 in the same deposits. Mandibles yielded in Grenzbank are Meganthropus B, Sangiran 15b, Arjuna 9 as well as femur fragments, Kresna 10 and 11, and teeth, Arjuna 18 and Brahmana 13. Majority of Sangiran hominids came from Kabuh deposits. Most of them are cranial fragments or skullcaps, i.e., Sangiran 2, 3, 10, 12 17, 25, 26, 38 and fossils from Grogol Wetan (Widianto & Grimaud-Hervé, 2000) and Bukuran (Grimaud-Hervé et al., 1999).

Paleoanthropologists were able to characterize the morphology and biometrics from the hominid fossils discovered not only in Sangiran as well as in Java and came up with evolutionary stages of *Homo erectus* in Java (Widianto, 2001). They are the Robust group, Trinil-Sangiran group, and Ngandong group. Sangiran hominid fossils only exemplify Robust and Trinil-Sangiran groups. The Robust group is represented by the hominid fossils from the Pucangan series. They are archaic and present primitive morphological characters. On the other hand, the Trinil-Sangiran group refers to the fossils from the lower and middle parts of the Kabuh series of Middle Pleistocene. They show the classical morphology of the *Homo erectus* (Widianto, 1993; Grimaud-Hervé & Widianto, 2001; Widianto & Zeitoun, 2003).

Figure 10. The Sangiran 4 in anterior and lateral view without scale, in Semenanjung ©Donan Satria Yudha, 2008

Figure 11. Sangiran 17, the most complete Homo erectus skull ever found in Java © Paleoanthropology Collection of the Natural History Museum, London

3. b. 1. b. The vertebrate faunas and the established Lower and Middle Pleistocene biostratigraphy in Sangiran

Remarkable fossil mammals and considered as premier faunal reference collection were retrieved from various eustatic conditions, which refers to the isolation or connection of Java Island to the Asian continent, during the Quaternary period. Different biostratigraphic hypotheses have been proposed from studied fossils found in Java (von Koenigswald, 1934; de Vos & Sondaar, 1982; Sondaar, 1982; Leinders et al., 1985). All hypotheses were applied in studying fossil faunas collected in Sangiran. The first established vertebrate faunal succession for Java was conducted by von Koenigswald (1934, 1935). He correlated Javanese faunal fossils with Siwalik in India and Sino-Malay in China. A new concept of faunal biostratigraphy of Java was proposed in the 1980s (de Vos et al., 1982; de Vos, 1983; Sondaar, 1984). The faunal units, in ascending order, are: the Satir, Ci Saat, Trinil H.K., Kedung Brubus, Ngandong, Punung, and the Wajak faunas.

Sondaar (1984) summarized the correlation of the Sangiran fauna with his new concept of Javanese mammalian biostratigraphy. The lower part of Black Clays in Pucangan deposits correlates with the Satir fauna. It was explained that the fauna from this unit presents an island condition (Sondaar, 1981). While the upper part from the same facies is associated with Ci Saat. The terrestrial faunal assemblage showed isolated conditions but not far from those in the mainland. Diverse fauna (e.g. *Axis, Duboisia* and large cattle) were retrieved from the Grenzbank unit and referred to Trinil H.K. Lastly, the Kedung brubus unit was characterized by the fauna from Kabuh. The assemblage was described that there was a faunal interchange with the mainland. *Elephas* sp. first appeared in this deposit. Leinders (1985) complete the proposed biostratigraphy of fauna in Java by associating the outcomes of stratigraphy and dating from studied sites.

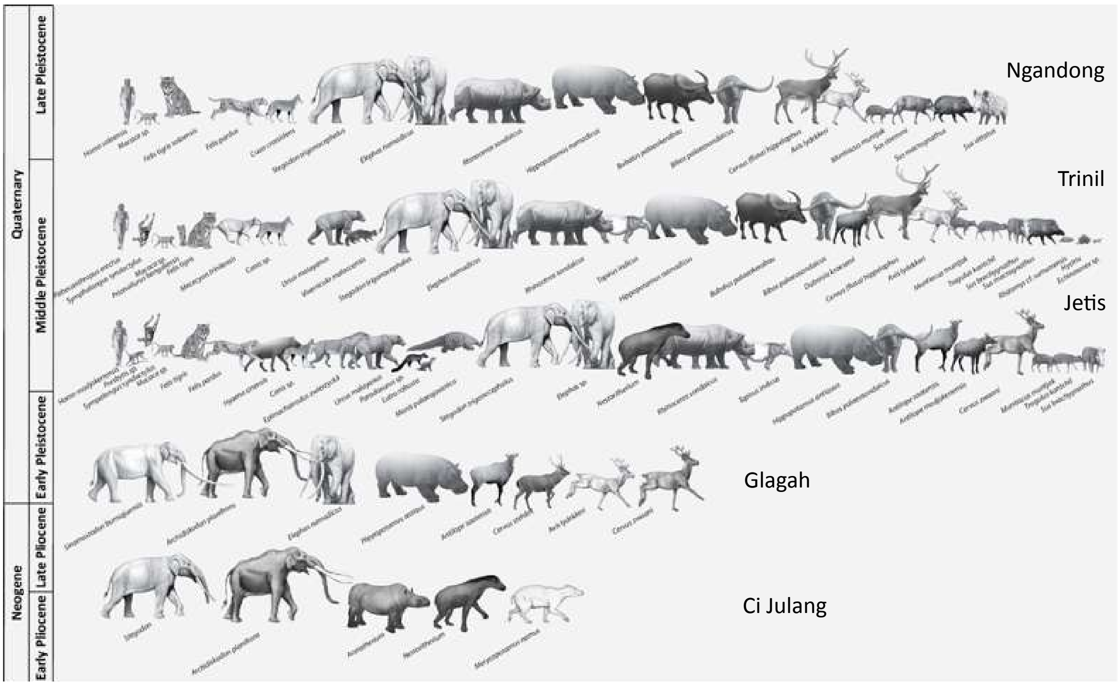


Figure 12. A vertebrate faunal succession for Java proposed by von Koenigswald (1934, 1935). In ascending order Ci Julang: *Archidiskodon praeplanifrons, Merycopothamus-nanus; Kali Glagah: Mastodon bumiajuensis, Hippopotamus simplex,* etc.; Jetis: *Cervus zwaani, Antilope modjokertensis, Leptobos cosijni,* etc.; Trinil: *Cervus (Axis) lydekkeri, Duboisis kroesenii;* Ngandong: *Cervus palaeojavanicus, Sus terhaari,* etc.; Ngandong: *Cervus palaeojavanicus, Sus terhaari,* etc., see Ingicco 2010.

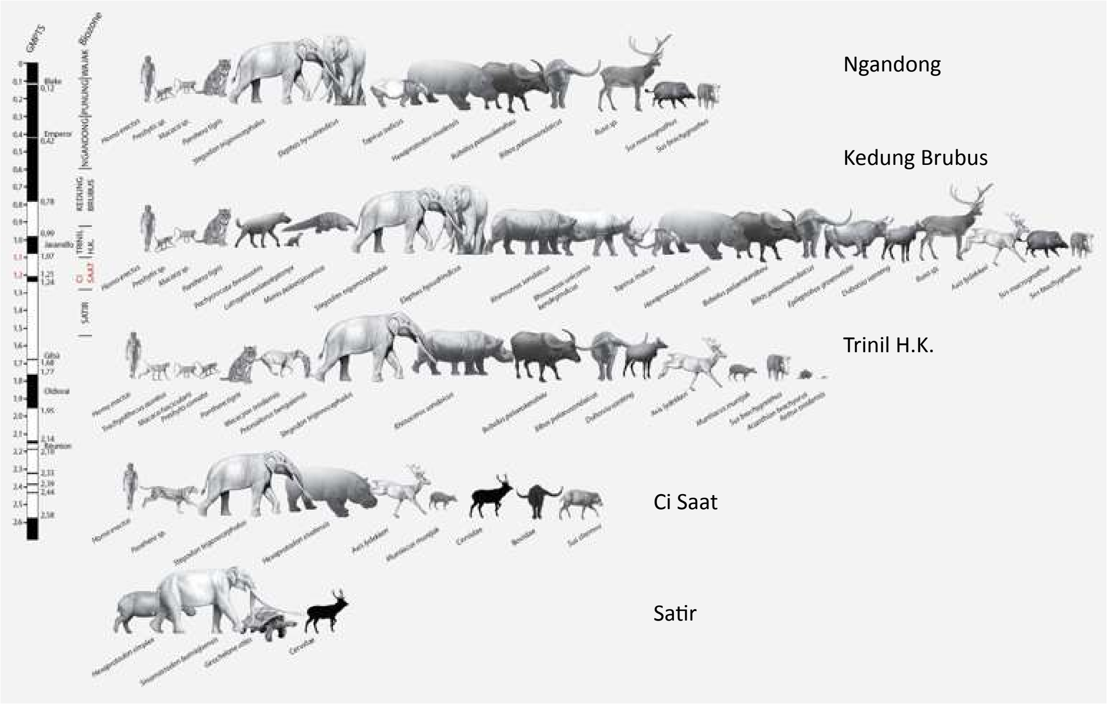


Figure 13. Faunal biostratigraphy of Java in the 1980s. In ascending order, a) the Satir: *Tetralophodon bumiajeunsis (SInomastodon sensu Saugusa, 1996), Hexaprotodon simplex, cervids, and Geochelone atlas; b)* the Ci Saat: *Stegodon trigonocephalus, Hexaprotodon sivalensis, Sus stremmi, Panther sp., bovids and cervids; c)* The Trinil HK*: Panthera trinilensis, Prionailurus bengalensis, Mececton trinilensis, Stegodon trigonocephalus, Rhinoceros sondaicus, Muntiacus muntjak, Cervus (Rusa) zwaani, Cervus (Rusa) hippelapus, Cervus (Axis) lydekkeri, Duboisa santeng, Bubalus palaeokerabau, Bibos palaeosondaicus, Sus brachygnathus, Trachypithecus cristatus, Macaca fascicularis, Acanthion brachyurus, Rattus trinilensis, Homo erectus and Meganthropus; d*) Kedung Brubus: *Hyaena brevirostris bathygnatha, Elephas hysudrindicus, Rhinocerus kendengicus, Tapirus indicus, Epileptobos groeneveldtii and Sus macrognathus; e)* Ngandong: *Homo erectus soloensis, Macaca fascicularis, Panthera tigris soloensis, Panthera tigris palaeojavanica, Stegodon trigonocephalus, Elephas hysudrindicus, Tapirus indicus, Bubalus palaeokerabus, Bibos palaeosondaicus, Sus macrognathus, Sus brachygnathus, Sus terhaari, Hexaprotodon sivalensis, Cervus (Axis) lydekkeri, Cervus (Rusa) hippelaphys, Cervus (Rusa) javanicus and Rhinoceros sondaicus* (Sondaar, 1984 and de Vos, 1982 and 1983), see Ingicco, 2010.

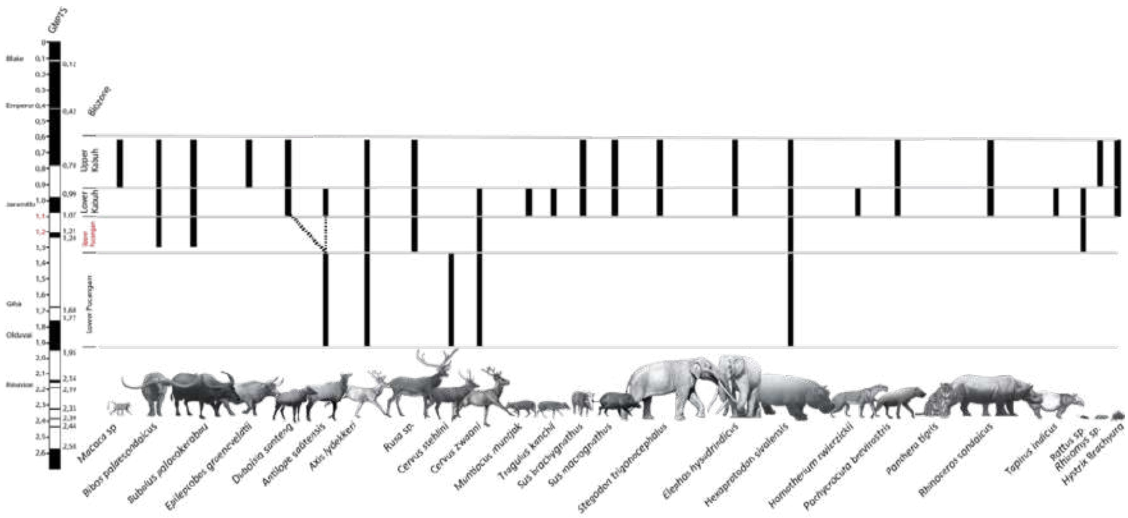


Figure 14. The biostratigraphic scheme of Sangiran dome. The Lower Lahar of lower Pucangan is the terrestrial base for Sangiran fauna succession ©Ansyori 2018

3. b. 2. Flora

Interpreting Quaternary flora and vegetation in the study of species-rich equatorial vegetation on pollen analysis proved to be applicable in Sangiran. History of vegetation, palaeoenvironments, and climates during the Quaternary and latest Tertiary for the Island of Java were mostly based from palynological evidence (Tokunaga et al., 1980 and 1985; Sémah AM, 1982a & b, and 1984). Palynological studies have been performed from latest Tertiary sediments, and early Quaternary shallow marine and fluvial from Central and East Java, in particular, the sections from Sangiran that become famous for their fossil skulls of *Homo erectus.*

The stratigraphic succession at Sangiran starts with Late Pliocene deposits of open water marine marls and is followed by blue clays in a shallow marine setting known as the upper Kalibeng at +/-2.6 Ma. Coastal facies and pollen records show a mangrove forest development during the beginning of the Early Pleistocene around 2.6-1.8 Ma. A tropical rain forest covered the emerged relief and mangrove forest began to extensively border the shoreline at 1.8 Ma. Likewise, a volcanic phase occurred and lahar flows accumulated in the Solo Basin. Complete filling of the Solo basin was due to the uplift of Kendeng hills in the north and mountains in the south leading to the non-marine environment. This phase disrupted the vegetation and indicated open grassland with a substantial presence of *Imperata cylindrica* and *Casuarina,* pioneer taxa that immediately recolonize the land after natural disruptions

(Sémah AM & Djubiantono, 2007). It was also reflected as the driest event in the palaeo-pedological profiles (Brasseur et al., 2015).

Palynological examinations in the Black Clay of Pucangan suggest a decrease of mangrove taxa except in diatomitic interbeds (Tokunaga et al., 1985; Sémah AM, 1982b and 1984). Pollen concentrations were characterized by fern spores, *Stenochlaena palustris*, and mangrove pollen*, Sonneratia caseolaris* suggested swamp forest. Followed by the Grenzbank layer, composed of specific pollen and spores, which reflect volcanic disruptions. The diversification of the flora with some trees (arboreal) indicates open vegetation with a relatively high percentage of non-arboreal taxa (Sémah, A.M. & Djubiantono, 2007).

Fluviatile environment revealed, supported with the predominance of non-arboreal pollen Gramineae, Cyperaceae, and abundant fern spores, in Kabuh deposits. The occurrence of Gramineae pollen throughout the sections in Kabuh indicated a strong seasonal climatic setting of savanna grassland during the Middle Pleistocene.

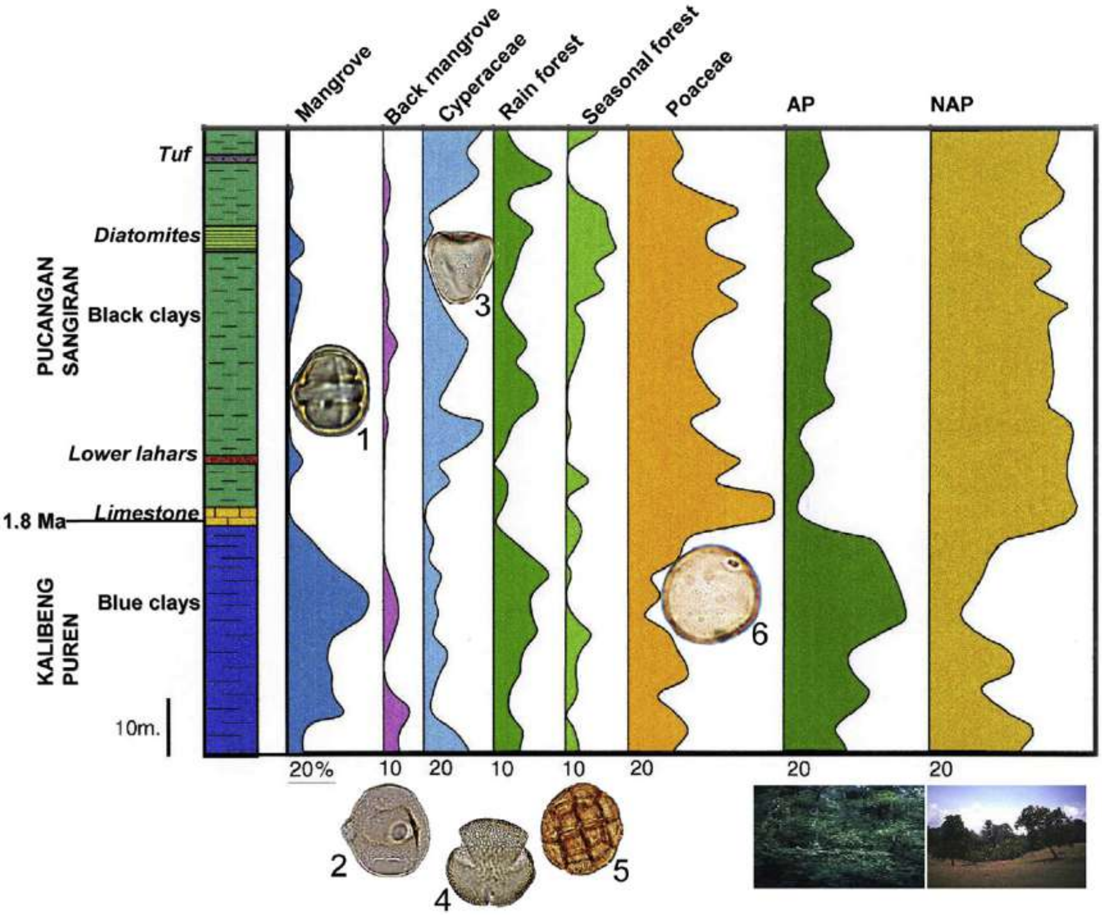


Figure 15. Synthetic pollen diagram of Kalibeng and Pucangan layers in the Sangiran dome. The diagram revealed, a) marine to continental environment and b) rainforest vegetation to a more open formation that corresponds to major climatic changes during glacial and interglacial periods in Central Java. © Sémah AM, 1986, Sémah et al., 2001 and Sémah AM et al., 2016.

4. Prehistory and archaeology

Unearthed lithic materials provided information on prehistory and archaeology in Sangiran (von Koenigswald, 1936; Semah et al., 1992; Simanjuntak and Sémah, 1996; Widianto et al., 2001). They pose the correlation of stone tools with the early man in Sangiran (Soejono, 2001). For example, the sources of raw materials to make the tools can tell how the stone was procured and perhaps even the trading patterns of cultures without a raw stone. The nature of the materials and the finished products help reveal their technological knowledge, skill base, and common learning. Artifacts that can be dated often provide insights to amend more accurately the chronological record.

The first lithic assemblage in Sangiran was discovered during exploration of von Koenigswald in 1934. These were flake tools, made of chalcedony, jasper or silicified tuff found on the surface of Kabuh deposits in Ngebung, the northwestern part of Sangiran. They were referred to as 'The Sangiran flake industry' and were attributed to the Middle Pleistocene culture (see von Koenigswald & Gosh, 1973; Widianto, 2006). Some scholars say otherwise, they came from a younger date (de Terra, 1943; Movius, 1944; de Chardin, 19565); ; Helmust de Terra) and based from several explorations concluded that tools might have been from the lower portion of the Notopuro bed, an Upper Pleistocene and might have been work of an early man (van Heekeren, 19721950s, 1968-?;, Bartstra, 1985).

Further excavations were carried out in Ngebung to reconcile the early lithic discoveries in Sangiran. The excavations were conducted at the ancient riverbank to the Kabuh unit from 1990 to 1994. They delivered numerous objects probably used by *Homo erectus* namely, pebbles, broken bones and a complete set with cleavers, bolas, polyhedras, choppers and chopping tool which are characteristics of the Acheulean-like assemblages in association with deer antler and fragments of other fauna (Semah et al., 1992; Simanjuntak & Semah, 1996; Simanjuntak et al., 2010).

More intensive excavations were conducted at Ngebung, Ngledok, and Dayu in the stratigraphic context in the Kabuh layer. Several massive tools like choppers, hand axes were found in these sites of the dome (Widianto et al., 1996). In Dayu, south of the dome, have flakes, scrapers, and borers found in the Grenzbank layer dating back to at least 800,000 years ago.

Pieces found in Sangiran especially in Ngebung both as surface finds and in the stratigraphic context, provided an a new understanding on the culture of *Pithecanthropus* (Sémah et al., 1992; de Lumley et al., 1993; Sémah & Simanjuntak, 1996). It implies that the stone technology was spread as far as Southeast Asian archipelagos and may be supported by the discovery of some isolated pieces (surface finds) in the Ogan riverbed in South Sumatra (Simanjuntak & Budiman, 2011) as compared with ancient artifacts found on Flores Island (Soa Basin). It also indicates the interconnectedness and mobility of *Homo erectus* and its response to environmental change reflected on material transport, technology, and behaviors during a glacial period where sea levels are low and have narrow cross-inlet (Moore &and Brumm, 2007).

5. Sampling sites

5. a. The study area

5. a. 1. Shells from the Upper Kalibeng to Lower Pucangan layers of Sangiran dome

The Plio-Pleistocene deposits in Sangiran dome on Solo depression are fundamental to understanding the palaeoecology and paleoenvironment in Central Java. Palaeoecological and palaeoenvironmental information from Java gave insights into the arrival and adaptations of hominins and fauna in Sangiran. The lithostratigraphy of hominid-bearing formations provides the connection between geology and palaeoecology in the site during the late Tertiary and early Quaternary. The geological and environmental contexts established wetland and fluvial deposits surrounded by volcanoes and non-volcanic uplands (REF Watanabe & Kadar, 1985; Semah et al., 2001; Bettis et al., 2004 and 2009; Hyodo et al., 2011). Moreover, climatic changes during glacial and interglacial episodes, and volcano- tectonic activity provide information on the environmental variations including aquatic environment evolution in Sangiran where it was still part of the Sundaland/arc during Pleistocene. The established diverse environmental landscapes (mangrove forests, swamp forests, rainforests, and disturbed forests as well as suggestions of more open vegetation) were supported by pollens, sediment deposits, terrestrial faunal and several chronological studies in Sangiran.

The hominid-bearing formations commonly contain marine and non-marine invertebrate fossils, such as molluscs and foraminifera. The invertebrate paleontology, bivalve and gastropod molluscs of Sangiran, may indicate a variety of physical and climatic settings to reflect the range of aquatic ecosystems and complement resources on which early hominins could have adapted and settled environment. Sampling focuses on thefocus study are the Kalibeng and Pucangan layers. These two formations have molluscs deposits. The Kalibeng has two parts, the lower and upper

Kalibeng. The Upper Kalibeng, located at the center of the dome, consists of sandy blue clays that have marine molluscs and foraminifera that shows a shallow marine environment (Sémah AM, 1986; Djibiantono & Sémah, 1991). It was followed by limestone and the *Corbicula* Bed with marine molluscs and numerous freshwater *Corbicula.* The latter indicates a change in the environment from full marine to lagoon landscape and initially presents in the overlying Pucangan layer.

The Pucangan layer is divided into the basal Lower Lahar and the Black Clay as the remaining part. The Lower Lahar discordantly overlies the Kalibeng deposits and consists of light gray unstratified andesitic tuff, fragments of tuff, pumice, calcareous nodules, molluscs, and corals. The Black Clay containing intercalations of silt, sand, molluscan shell enclosure, foraminifera sand, diatomite, peat, and tuff. Crocodiles were considered the most ancient vertebrates of Sangiran found at the lower Pucangan (van Es, 1931) until two continental vertebrates were identified from the Lower Lahar unit, *Cervus (Rusa) stehlina* and *Antelope sp.* (Ansyori, 2018).

5. a. 1. b. Sampled areas in Sangiran

Mollusc and sediment samples were taken from natural assemblage in the catchment areas of upper Kalibeng to lower Pucangan formations in the Sangiran dome. They are from exposures of natural cuttings and well-preserved outcrops in the areas of Pablengan and Krikilan along the Puren river and lower lahar deposits at Ngampon and Pondok. All samples underwent grain size analysis using laser granulomentry Mastersizer 2000® Malvern and infrared spectroscopy analysis for mineralogy identification using a Brucker Vector 22 device. Both analyses were performed at the laboratory of Musee de l'Homme, Paris.

Shell sampling sites were presented according to the stratigraphic sequence in Sangiran. Seven samples labeled as Puren River 1 and 3 (PR1 and PR3), Pablengan Kulon 2, 4 and 5 (PK2, PK4 and PK5), and Sangiran 1 and 2 (S1 and S2) belonging to the Blue Clay of Upper Kalibeng (Puren) and three sites were sampled in the Corbicula Bed, Pablengan 1 and 2 (P1 and P2), and Pablengan Kulon 1 (PK1). These areas were formerly sampled for palynology and sediment studies (Sémah AM, 1982a and 1982b, 1984, 1986; Brasseur, 2009). The Upper Kalibeng samples have fine sands consist of clay-loam aggregates, quartz, calcite, kaolinite, and smectite. Marine fossils observed were molluscs, whole and fragmented, foraminifera and spalls of echinoderms. The *Corbicula* Bed have fine sands and silts. Same minerals as the Upper Kalibeng were observed with aragonite and less quartz.

The Lower Lahar and the Black Clay, of the Lower Pucangan layer, were also sampled. Three sites sampled in the Lower Lahar, Ngampon (NPN), Pondok (PNK), and South of Museum Krikilan (SM). The Lower Lahar represents seminal marine regression, marking the transition between the underlying Kalibeng/Puren Formation made of blue marine clays and the overlying Pucangan/Sangiran Formation made of black mangrove swamp clays. Presence of several diatomite intercalations at the base of the Pucangan Formations marks the events of marine transgressions, evidences for the gradual land emergence at Sangiran (Sémah, 1982). The lower limit of the lahar deposits was dated between 1.9 (Bettis III et al., 2004) and 1.67 Ma (Sémah et al., 2000). The Lower Lahar has sand and silt sediments that were composed mainly of quartz, calcite, aragonite, kaolinite, and smectite. Notable fauna such as bovid, evidence of the earliest terrestrial fauna in Sangiran, retrieved in this layer (pers. comm. Sémah, 2016). Aquatic fauna includes an abundance of marine molluscs and benthic foraminifera, and rare freshwater forms, such as *Corbicula* molluscs.

Five sites were sampled in the Black Clay of Pucangan, Krikilan 1-4 (K1, K2, K3, and K4), and Pablengan Kulon 3 (PK3). Fine sands and silts are composed predominantly of quartz, calcite, kaolinite, and some smectite. Besides freshwater molluscs, fish bones and seeds were present. Most importantly, fossils of H. erectus were found in those clays (von Koenigswald, 1954; Jacob, 1981; Watanabe & Kadar, 1985; Widianto, 2001), ca. 1.6 and ca. 1 Ma (Nishimura et al., 1981; Suzuki & Wikarno, 1982; Saleki, 1997).

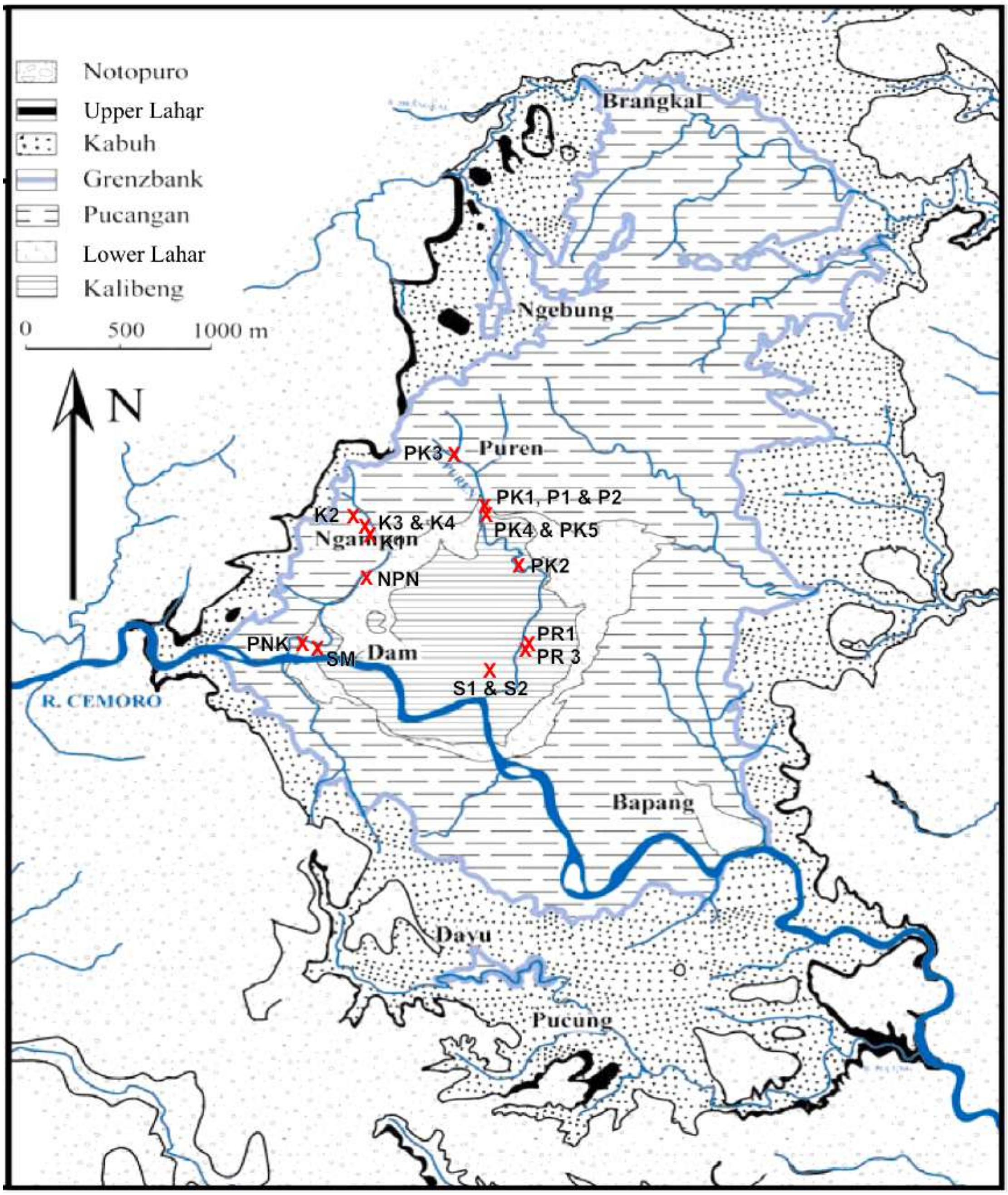


Figure 16. Shell sampled sites in Sangiran, marked in X, belonging to Upper Kalibeng and Lower Pucangan series underwent palaeoecological and palaeoenvironmental analyses. Geological map of Sangiran and its stratigraphy based on Von Koenigswald plan (1940) modified by Watanabe and Kadar (1985) and Sémah et al. (1992), see Brasseur et al., 2015.

CHAPTER 2:

PRESENTATION OF SANGIRAN FOSSIL SHELLS

1. Malacology: the study of shells in the context of archaeology and paleontology

Mollusc species are highly diverse and inhabit dynamic ecosystems. Paleontological and archaeological studies on fossil and excavated molluscs have proliferated in the last 50 years. As summarized by Thomas (2015a and b), scientific investigation on mollusc shells as resources for paleontological and archaeological research became diverse both in methods and practice. Owing to the morphology of mollusc shell, the various components of a mollusc shell can inform about the environment, chronology, subsistence, behavior and social contexts of people in the past.

Numerous compilations dealing with molluscs in archaeological and archaeological-relevant deposits were published in special issues of scientific journals, such as those edited by Szabó and Quitmyer (2008) and Verdùn-Castello & Colonese (2014) or introduced by the editors (e.g. Álvarez et al., 2011; Codding et al., 2014; Gröcke & Gillikin, 2008; Schöne & Surge, 2005; West, 2013) and in books (e.g. Antczak & Cipriani, 2008; Bailey et al., 2013; Bar-Yosef Mayer, 2005; Çakirlar, 2011; Claasen, 1998; Davies, 2008; Roksandic et al., 2014). These works present a state-of-the-art research on mollusc shells for environmental reconstructions and dating, and scientific investigations of molluscs and their shells as resources used by people in the past.

Molluscs and their shells became a medium in delivering a message in presenting the environment and past human activities namely, human behaviors, settlement patterns, territories and social structures. These are presented in the shell matrix site, which is common in archaeological and paleontological sites. In Island Southeast Asia, due to the archipelagic pattern, spectacular evolutionary and taxonomic diversification stemmed in crossing point between the sea and terrestrial environment in the region. Both have high species richness especially in complex tropical coastal environments (Bouchet, 2009; Ladd, 1960; Wells, 2002). There are several studies conducted on molluscs that employ a multi-disciplinary approach in the region exemplified by the work of Szabo and Amesbury (2011) and van den Bergh et al., (2009). Such work leads to questions on material preservation when molluscs were analysed to answer environmental reconstructions and dating or investigations deal on molluscs as resources used by people in the past.

Reconstructions of old environments using molluscs are based on the ecological and environmental background of shell species. This method shows how ecological data, pertaining to molluscs, may present biotic and temporal boundaries (King & Graham, 1981). It may be based on the relative or abundance of each taxon, as well as the diversity of taxa, in assemblages. Furthermore, it can be based on the habitat background of different species of mollucs that may be grouped into terrestrial, freshwater, estuarine, or marine environment. Examples are archaeological investigations conducted in Ilin Island of Mindoro (Pawlik et al., 2014) and Pasimbahan-Magsanib Site in Palawan Island (Ochoa et al., 2014) in the Philippines. These researches produced a human habitation and behavior sequence from shell middens in three rockshelter sites and reconstructed the landscape formation, sea levels and landmass during the terminal Pleistocene and early Holocene.

Besides describing old environments through molluscs' habitat and species richness, it can also produce time-series data from the evolving environment. This may be done through sclerochronology. It is the study of physical and chemical variations in the accretionary hard tissues of invertebrates, including molluscs, and the temporal context in which they formed (Rhoads, 1980). It focuses primarily on growth patterns reflecting annually, monthly, fortnightly, tidal, daily, and subdaily time increments of time. It analyses shell midden faunal remains or even an individual bivalve mollusc to study climate and environmental change in relation to human activity (Andrus, 2011). Mollusc shells have good preservation of accretionary calcium carbonate remains in comparatively well-dated contexts that are good source of sequential proxy records of past climate and environmental conditions. With these characteristics, sclerochronology may provide detailed pictures of human-environment interaction. However, Andrus (2011) also presented some concerns in studying the environment through molluscs and using sclerochronology. He enumerated the challenges in applying sclerochronology namely, the season of capture, reconstructing the history of anthropogenic environmental impacts and palaeoclimate/environment proxy reconstructions. In Asia-Pacific region, sclerochronology on fossil shells was initially employed in East Asia particularly in Japan (Kirby, 2000; Miyaji et al., 2007; Sato, 1999; Schöne et al., 2003 and others) and in Island Southeast Asia (Stephens et al., 2008; Faylona, 2010; Marwick & Gagan, 2011).

Shell chemistry of molluscs has also contributed significantly to the understanding of the past inhabitants. It provides environmental information from the mollusc species assemblages retrieved from the site. By analyzing the isotope composition of the shell growth increments, intra-seasonal information can be gained (Leng & Lewis, 2016). An example is the use of oxygen and carbon isotopes in molluscs for palaeoenvironmental reconstruction. Preservation, sampling and describing the $\delta^{18}O$ and $\delta^{13}C$ of a molluscan shell may provide information on seasonal climate, the season of collection as well as changes in global climate (McConnaughey & Gillikin, 2008; Prendergast & Stevens, 2014). Shell geochemistry of a mollusc has been applied in Island Southeast Asia. A study has already been conducted on shell-gathering from mangroves and the seasonality of the Southeast Asian Monsoon using a high-resolution stable isotopic analysis of the tropical estuarine bivalve, *Geloina erosa* from the Great Cave of Niah, Sarawak in Malaysia (Stephens et al., 2008). In Mainland Southeast Asia, late Quaternary climates are recorded in freshwater bivalves *Margaritanopsis laosensis* excavated from the Tham Lod and Ban Rai rockshelters in Mae Hong Son Province, northwest Thailand (Marwick & Gagan, 2011). The climate was described as wetter and prevailed relative unstable climatic conditions from 35,000-20,000 BP and became drier from 20,000-11,500 BP.

Another geochemistry of shell mollusc study is the strontium isotope analyses. Biological or climatological fractionation processes do not affect Sr isotope ratios of the fossils; they reflect condition in the host water in which they were growing (Faure, 1986). This method was applied to determine water provenance and water salinities of the aquatic environments at Trinil in Java, Indonesia (Joordens et al., 2009). The investigation concluded that hominins foraged with catchable aquatic fauna *Pseudodon* and *Elongaria* molluscs in a coastal habitat environment.

Other questions that can be answered using molluscs for analysis is chronology and dating. Marine shells are increasingly being used for radiocarbon dating and amino acid racemization dating, and samples have been calibrated (Thomas, 2015a). Establishing chronology is usually done to shell artifacts made from 'old' shells deposited in archaeological sites retrieved from palaeoshorelines. Shells selected for dating were ensured to reflect human activity along with the death of the shell that can be represented as a discarded shell (Rick et al, 2005). Recently, a *Tridacna* shell adze was dated in the Philippines (Pawlik et al., 2015). This is the first direct dating of a shell adze in Philippine archaeology. The date suggests that there have been significant implications of early human interaction between the Philippines and Melanesia in terms of chronology and distribution.

Study of mollusc shells has contributed greatly to understanding past human behavior and environmental change (Andrus, 2011). Shell bearing sites, archaeological or paleontological, provide good preservation technique for analysis. They posit questions and provide interpretations of the past- cultural and environmental histories. For these reasons, mollusk shells are considered good proxies in addressing research in the area of archaeology and paleontology.

2. Java fossil shells: the state of the art on mollusc study

Mollusc study in Indonesia started as reference collection, part of the early paleontological studies conducted by the Europeans particularly from the various scientific institutions in the Netherlands at the turn of the 20th century. Initiated by Dr. Johann Carl Ludwig Martin, a German geologist at the Leiden University in 1877, when he encountered the ‘Petrefacts from the Aachen region’ box from the Junghuhn collection at the mineralogical and paleontological collection of the Rijksmuseum van Natuurlijke History (de Groot, 1978). The box contained Tertiary molluscs from Indonesia and became the research focus of Martin (1910). This collection made him the foremost expert and his institution, Leiden, as a renowned center for research on Indonesian Cenozoic molluscs (Gerth 1944; van Regteren Altena, 1946). Martin mainly studied collections assembled by geologists/mining engineers of the “Dienst Minjwezen of the East Indies’. He used them to unravel the Cenozoic history of Indonesia using Lyellian statistics whereas the percentage of recent species in a sample was used to estimate its age (Gerth, 1944; see also Rudwick, 1978). He published numerous monographs and papers between 1879 and 1937, especially in Java, where he identified a total of 1,412 species of molluscs.

As mentioned, molluscs from Java was one of the research outputs of Martin. His work was included in the subchapters on marine and freshwater molluscs from the Tertiary and Quaternary beds in the book of LJC van Es (1931), The Age of Pithecanthropus. In the mollusc chapter, it was stated that Martin was able to summarize the mollusc present in Java from Upper Eocene to Quaternary and its corresponding beds that led to important results that demarcated the Pliocene from the Quaternary beds. Gustav Heinrich Ralph von Koenigswald assisted Martin on mollusc studies in Java and was included in this subchapter. They summarized and presented the mollusc shells, in the table, retrieved from different regions and periods in Java.

Martin work was continued by Dr. Cornelis Beets which produced several manuscripts on bivalves and gastropods from Indonesia (see Geological Publications by Dr. C. Beets in Prins et al., 1996). The Cenozoic mollusc collections of Dr. Martin from Java were re-examined by van den Hoek Ostende et al. (2002) and Leloux & Wesselingh (2009).

Woutera (Tera) Sophie Suzena van Benthem Jutting (1937, 1941, 1948a and b, 1950, 1952, 1959) was the first person to document and one of the few malacologists had given attention to the land and freshwater molluscs on the Indonesian molluscs at that time. She focused her research on the molluscan taxonomy and ecology of Indo-Australian archipelago.

Chistiaan Hendrik J. Oostingh (1923) started building more conventional mollusc biozonations of the Miocene-Pleistocene of Java, based on vertical ranges of species. His zones are based on species of the gastropod genus Turritella. Oostingh also studied the Pliocene fossil molluscs from Bumiayu (Boemiajoe) (1935) and Süd Bantam (1938) in Java.

On the other hand, some scientists studied the shells collected by other scientists who went to Java for exploration and were being stored in the Netherlands. One of them is C.O. van Regteren Altena (1945). He identified numerous fossil shells collected by Dr. Hans Heirich Gerth in Java in 1928-1929 and curated at the Geological Institution of the University of Amsterdam. From the collection, he identified 390 marine species belonging from different environments namely, beaches with coral reefs, mixed beach, sandy beach with dunes and sandy and muddy beaches with mangrove vegetation. He also did a systematic molluscan survey and recorded species from Family Muricidae, Magillidae, Pyrenidae, Buccinidae and Volemidae at the Kendeng Beds in Java (Altena, 1941, 1950).

Likewise, Eugene Dubois (1907, 1908) assembled extensive collections of early Pleistocene fossil shells from the hominid-fossil bearing site in Trinil, Java. His shell collections were considered historical and curated at Naturalis, Leiden. The collection was later examined by Joordens et al., (2009) for aquatic palaeoenvironment reconstruction. They were able to identify the possible dietary relevance of aquatic environments for hominins. Among the freshwater shellfish consumption by hominins, a shell toll and a shell with a geometric engraving around 500 Kyr were found from the Dubois collection (Joordens et al., 2014). Both resources were regarded as the earliest known raw material for tool production and inferring the ability of Asian Homo erectus for advance cognition.

Limited study has been conducted on fossil molluscs deposited in Sangiran at the turn of the 21st century. Research were conducted by Di Geronimo & Sartono (1990), Fae (1994, 1996) and Yudha & Suriyanta (2016). The molluscs that they studied were acquired several decades ago and part of the collection of Sartono stored in Bandung, Ing. Premonowati from University of Veteran (UPN), Yogyakarta and from the Sangiran Excavation Project in 1970-1980 stored at the Laboratory of Bioanthropology and Paleoanthoropoly, Faculty of Medicine, University of Gadjah Madha, respectively. While Resty Jatinungrum (2014), an International Master of Quaternary and Prehistory graduate student, collected and sampled the fossil molluscs for her thesis on shell isotope geochemical study.

Consequently, the existing shell collection in Java starting in the early 1900s show a mollusc-rich sites. They are distributed widely and abundantly across the island from different Tertiary and Quaternary beds. They occupied variety of habitats ranging from terrestrial, freshwater and marine. Research in all these areas is producing valuable evidence of environmental change.

3. Molluscan taxonomy of Sangiran bivalves and gastropods

One of the objectives of the thesis is to describe or cite all Sangiran fossil molluscs collected from Kalibeng and Pucangan (Plio-Pleistocene) deposits of Solo basin in Central Java. Most shell studies in Sangiran have either been conducted outside the area and others were documented as an overview of fossil molluscs in Java. Moreover, it comes after a gap of more than 50 years during which no papers have been published on Sangiran fossil molluscs. Thus, based on previous papers and of newly collected material, this study provided an up-to-date inventory of molluscan taxa and characterised the molluscan stage from Sangiran stratigraphic units of Kalibeng and Pucangan. Ecological background information on obtained fossil shells from Sangiran are discussed in Chapter 3.

The Sangiran fossil shells are composed of bivalves and gastropods from marine to freshwater environments. Bivalve shells are aquatic molluscs that show a fundamental bilateral symmetry. Their characteristic shell is composed of two calcified valves lying on the right and left sides of the body. Both valves are typically equally convex (equivalve shell), but they may differ in size and shape (inequivalve shell) as a result of an alteration of bilateral symmetry. Valves are articulated along a marginal process of the dorsal side called the hinge, and are connected by an elastic and poorly calcified structure, the ligament. Under the action of the ligament, the two valves tend to open along their anterior, posterior and mainly ventral margins. They are closed by the pulling action of one or two (sometimes three) adductor muscles. These are fixed to the inner side of valves by areas leaving well-defined imprints, the adductor muscle scars. Whereas, gastropod shells are torted, asymmetrical molluscs, usually with a spirally coiled shell. They produce a single coiled shell and many have a corneous or calcareous 'trapdoor', the operculum, that seals the opening of the shell. In some species, the shell may appear a simple conical or cap-shaped plate, or even may be absent.

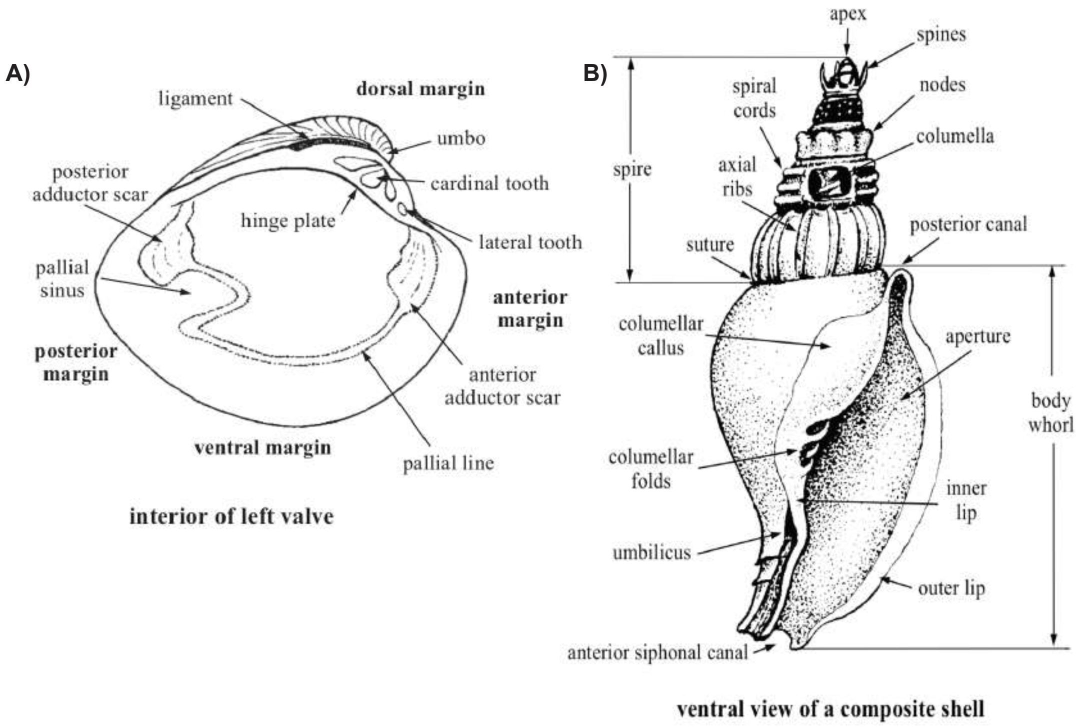


Figure 17. Diagnostic characteristics of A) bivalve and B) gastropod mollusc shell © Carpenter & Niem, 1998

Information on the environmental attributes and habitat preferences of each mollusc present in the sample were gathered from literature on modern molluscs from Indonesia (Dharma, 1988 and 1992), the Philippines (Lozouet & Plaziat, 2008; Poppe, 2008; Springsteen et al., 1986), Thailand (Robba et al., 2002 and 2005), Japan (Okutani, 2000) and Compendium of Shells (Abbott & Dance, 2000) and the living marine resources of the Western Central Pacific of UNESCO (Carpenter & Niem, 1998). MolluscaBase, World Register of Marine Species (WoRMS) and Ocean Biogeographic Information System (OBIS) Indo-Pacific Molluscan Database were consulted in verifying the accepted name of the taxon. They are the taxonomically oriented databases that provide account authority of all molluscan species. Conducted freshwater mollusc studies in Java, Indonesia, were also consulted: Jutting (1937, 1959), Köhler & Glaubrecht (2001), Marwoto & Isnaningsih (2012) and Robba (2013). All shell samples were also compared with the shell reference collection at the Biology Laboratory of Marine Invertebrates and Malacology, Muséum National d'Histoire Naturelle, Paris and Archaeozoology Laboratory of the University of the Philippines.

Freshwater and marine molluscs were obtained from stratigraphic sections in Kalibeng and Pucangan layers from several localities in Sangiran dome namely, Krikilan, Ngampon, Pablengan Kulon and Pondok. These assemblages are considered as the latest and updated fossil mollusc reference in relations with different stratigraphical units of Sangiran dome. Mollucs are present in Upper Kalibeng and Lower Pucangan. During our field work, carried out in November 2015 and June 2016, several species included in van Bethem Jutting and Oostingh's list were found along with several previously unrecorded ones. As a result, the Sangiran fossil molluscs are represented by 44 species of marine molluscs, 23 are bivalves and 21 are gastropods; and 16 species of freshwater molluscs, four bivalves and 12 gastropods.

Below is a list of Sangiran molluscan taxa reference. Most part of the species were identified at the generic level. The sampled material does not permit a more accurate determination. Shell diagnostic characteristics were mainly based on the books of Western Central Pacific of UNESCO (Carpenter and Niem, 1998) and Recent and Fossil Indonesia shells (Dharma et al., 2005) for marine molluscs and monographs on Pachychilidae (Köhler & Glaubrecht, 2001; Marworto & Isnaningsih, 2012), Thiaridae (Glaubrecht, 1999; Appleton et al., 2009); Viviparidae (Marwoto & Nurinsiyah, 2009) and Non Marine Mollusca from Fossil Horizons in Java with Special Reference to the Trinil Fauna (van Benthem Jutting, 1937) for freshwater molluscs.

The classification adopted in this account largely draws on that followed in the Treatise on Invertebrate Paleontology, Part I, Mollusca 1 (Moore R.C., Ed., 1960), with modifications according to more recently proposed changes (see Herbert, 1987; Hickman & McLean, 1990).

Table 1. List of mollusc taxa recovered from Kalibeng and Pucangan layers in Sangiran.

Taxonomy	Taxon and its description	Reference figure
CLASS GASTROPODA		
Order LEPETELLIDA Family FISSURELLIDAE	*Diodora* JE Gray, 1821 Outline ovate narrowing anteriorly from point of maximum diameter in posterior half of shell. Apical orifice subcircular, located slightly anterior to center. Exterior sculptured by fine radial ribs that become broader toward the periphery. Radial ribs beaded by a system of a closely spaced, fine concentric ridges. A few irregularly spaced concentric folds superimposed upon the finely beaded radial sculpture.	Figure 18b & 19
Order SEGUENZIIDA Family CHILODONTAIDAE	*Vaceuchelus* Iredale, 1929 Small, globular, turreted, stout, nacreous within, imperforate or narrowly umbilicate; columella without basal tooth; whorls convex, marked with strong spiral ribs crossed by well-developed axial lamellae that give ribs a beaded appearance and form deep pits in spaces between ribs.	Figure 18b

Order TROCHIDA Family CALLIOSTOMATIDAE	?*Calliostoma* Swainson, 1840 Shell moderately low, pyramidal. Whorls trapezoidal, regularly increasing in size. Initial sculpture of three equal and equidistant spirals, the anterior and posterior of which gradually become more prominent relatively and absolutely; intercalaries introduced on early whorls. Base flattened, sculptured with simple lirae, those nearer the axis the broader and the more irregular in size and spacing. Aperture somewhat broken, rudely rhomboidal; outer margin imperfect but obviously angulated at the periphery. Inner margin concave, reflected.	Figure 18b
Family SOLARIELLIDAE	*Solariella* SV Wood, 1842 Shape trochoid, whorls rounded or angular, suture impressed. Spire sculptured by strong cord on middle whorl forming, carinate shoulder. Aperture corneus, thin with central nucleus.	Figure 18b
Unranked clade CAENOGASTROPODA/SORBEOCONCHA Family ?PACHYHILIDAE P Fischer & Crosse, 1892	Shell forms almost globular to narrowly elongated and are either ornamented by axial and/or spiral ribs and/or spines or smooth except for growth lines and basal lirae are present. It has an oval multispiral operculum with whorls that increase rapidly in diameter.	Figure 20

	Sulcospira testudinaria (Köhler & Dames, 2009) Shell variable, turreted or elongately conic, solid, medium to large (22-40 mm), spire angle about 30°. Apex eroded. The sculpture consists only 2-3 spiral lirae near the suture, and 3-6 prominent spirals lirae at the base of the body whorl. Suture narrow and shallow. Suture narrow and shallow. Aperture oval, outer lip straight. Columella not thickened. Operculum oval with a sub-central nucleus.	
	Sulcospira Troschel, 1857 Shell rather conical, with spiral lirae but lacking axial lirae. Operculum with 4 to 6 whorls. Protoconch smooth and inflated, with up to two whorls possessing a fine granular texture or faint growth lines.	
Family THIARIDAE	*Tarebia* H Adams & A Adams, 1854 *Tarebia granifera* (Lamarck, 1822) *Tarebia aff. granifera* (Lamarck, 1822) The shell is turreted with the body whorl. The sculpture of rectangular knobs follows a spiral pattern. Sutures are distinct and the whorls are flat sided.	Figure 20

	Thiara Röding, 1798 *Thiara winteri* (von dem Busch, 1842) Shell large, solid, with a tall spire and a large body whorl; whorls are somewhat sdteeped; sculptured with weak axial folds which form a crown of short spines on the sharply angled whorl shoulder, some flat spiral ridges towards the body whorl base; aperture vertically ovate, pointed above and rounded below, the outer lip thin, lirate within and the columella heavily ridged.	
Unassigned CAENOGASTROPODA Family CERITHIIDAE	?*Cerithium* Bruguière, 1789 Shell elongate, thick and solid, sharply conical with a high many-whorled spire and small aperture. Sculpture variable, usually spiral or nodulosem and with axial ribs or varices. Umbilicus generally absent. Periostracum obsolete. Aperture with a distinct, anterior siphonal canal which may be drawn out, upturned and often laterally twisted. Outer lip somewhat expanded, usually notched posteriorly. Inner lip smooth or twisted. Operculum ovate, corneous, with a few spiral coils and an eccentric nucleus.	Undiagnostic
Family EPITONIIDAE	*Epitonium* Röding, 1798 Shells are high-spired, deep suture, imperforate, umbilicus narrow, fenestrate, peristome thick, axial ribs thick, partly or completely reflexed, often weakly or not coronated, intervals with axial and	Figure 18b

	spiral microstriae, more or less granulose at the intersection, forming a cancellate sculpture.	
Family TURRITELLIDAE	*Turritella* Lamarck, 1799 Shell elongate, sharply conical, with numerous whorls and a small, square to rounded aperture. Umbilicus usually absent. Sides of the whorls sharply keeled. Growth lines arched to sinuous. Outer lip of the aperture thin, often concave. Inner lip smooth. Anterior siphonal canal absent. Operculum corneous, rounded, with many spiral coils and a central nucleus; border of the operculum very thin, often with flexible bristles.	Figure 18b
	Turritella terebra Linnaeus, 1758 Shell large and solid, with an extremely long and tapering spire, with 25 or more whorls in mature specimens. Whorls strongly convex in outline, with impressed suture and up to six prominent spiral cords and weaker interstitials spiral threads. Apical end of spire invariably missing in adult shells. Aperture almost circular in outline. Margin of outer lip rather thin, forming a broad, very shallow sinus leaning backward with respect to the direction of growth, continued as a straight line across the base.	
Order LITTORINIMORPHA Family HYDROBIIDAE	Shell minute to small, usually 1-10 mm in height, dextrally coiled, planispiral to aciculate, phaneromphalous to cryptophalous, with	Figure 20

	about 2-8 whorls. Body whorl often loosened, shell sometimes partially uncoiling to assume a corkscrew or horn-like shape. Shell thin to fairly solid, transparent to white. Periostracum generally thin, rarely elaborated as hair-like or other projections. Aperture holostomatous, sometimes thickened, sinuous, deflected or flared, but without notches, canals, siphonal grooves, or denticulations. Shell usually smooth except for collaboral growth-lines, but occasionally with a sculpture of reticulations, carinae, spines or cords. Protoconch usually paucipsiral, rarely multispiral, usually dome-like, smooth or with sculpture of wrinkles, pits, or spiral lines. Operculum usually well-formed, rarely rudimentary, corneous, usually paucisliral, rarely multispiral or conical. Ventral (very rarely dorsal) opercular surface sometime with elevated corneous or whitened ridges or pegs.	
Family EULIMIDAE	*Melanella* Swainson, 1840 Shell turreted, white glossy, slippery, straight-sided and commonly slightly tilted. Spire tall with an acute apex. Aperture drop-like with posterior portion rounded. Outer lip completely convex, forming a symmetrical curve.	Figure 18b
Family NATICIDAE	*Polinices* Montfort, 1830 Thick and heavy, pear-shaped, distinctly longer than wide, with a moderately high conical spirem nearly flat-sided whorls and shallow sutures. Outer surface smooth and glossy with only fine lines of	Figure 18b

	growth. Umbilicus closed, entirely filled by a heavy callus (a slight umbilical groove occasionally present anterior to callus in juvenile specimens). Operculum corneous.	
Family RANELLIDAE	*Cymatium* Röding, 1798 Shell ovate to fusiform, thick and solid, with a raised spire and strong sculpture composed of nodules, spiral ribs and axial varices. Periostracum is frequently well developed and fibrous to hairy. Aperture with a short to long siphonal canbal anteriorly. Outer lip prominently thickened, often denticulate inside. Inner lip commonly wrinkled and with a columella callus. Operculum thick and corneous, rounded to trigonal.	Undiagnostic
Order NEOGASTROPODA Family ?MURICIDAE	Shell variably shaped, generally with a raised spire and strong sculpture with spiral ridges and often axial varices (3 or more in number on each whorl), frequently bearing spines, tubercles or blade-like processes. Periostracum absent. Aperture variable, ovate to more or less contracted, with a well-marked anterior siphonal canal that may be very long. Outer lip often denticulate inside, sometimes with a tooth-like process on margin. Columella is smoothish to weakly ridged. Operculum corneous, thin to thick, with nucleus near the anterior end or at about mid-length of outer margin.	Undiagnostic

Family COLUMBELLIDAE	*Mitrella* Risso, 1826 Shell generally small, fusiform to biconical in shape, with a conical, more or less elongate spire. Outer surface without axial varices, ribbed or smoothish. Periostracum variably developed to absent. Aperture long and narrow, with a rather short, anterior siphonal canal. Outer lip commonly thick, smooth or denticulate inside, sometimes with a shallow groove or slit posteriorly. Inner lip smooth or denticulate, but not folded. Operculum corneous, thin and small to absent with an apical nucleus.	Figure 18b
Family FASCIOLARIIDAE	*Fusinus* Rafinesque, 1815 Shell more or less elongate, fusiform, with a generally elevated spire and a well-developed, sometimes very long siphonal canal. Sculpture variable, often strong and nodular or composed of spiral threads and axial ribs. Periostracum is very thin to thich and fibrous. Aperture long and ovate. Outer lip smooth or with numerous inner spiral lirae. Columella often with a few low basal threads. Operculum thick and corneous, ovate to claw-shaped, with a terminal nucleus.	Figure 18b
Family MARGINELLIDAE	*Cryptospira* Hinds, 1844 Shell is oviform to spindle-shaped, with a rather elevated spira. The apertural lip is thin or only very slightly thickened, without	Figure 18b

	crenulations. The siphonal canal is superficial, not distinctly incised. There are four columellar folds, which are thin and narrow, and rather widely spaced. The two basal folds are very oblique, the two adapical ones are more horizontal.	
Family NASSARIIDAE	*Nassarius* Duméril, 1805 Shell squat and thick, with a fairly high, stepped spire and inflated body whorl. Early spire whorls with intersecting axial and spiral cords, a granulated pattern. Later whorls smooth, but for a row of prominently rounded nodules on the shoulder and a few spiral cords at the base of body whorl. Aperture lirate inside, outer lip thickened and often with a few small spines on its anterior outer edge in mature specimens. Inner lip with a prominent tooth-like nodule posteriorly. Columellar callus thick, forming a smooth shield wrapped around the ventral side of body whorl and posteriorly connected to the outer lip. Operculum with serrated margin.	Figure 18b
Family OLIVELLIDAE	*Olivella* Swainson, 1831 Shell thick and porcelaneous, elongate ovatem with a short spire, a large body whorl and usually deeply channeled sutures. Surface smooth, highly polished and often vividly coloured. No periostracum. Aperture elongate, with a wide and short anterior siphonal canal and an indistinct posterior notch. Outer lip slightly thickened in adult stage, smooth. Inner lip callus reaching almost to the posterior end of the aperture. Columellar callus usually	Figure 18b

	bordered posteriorly by a distinct, calloused spiral band. Operculum absent.	
Family TURRIDAE	*Drillia* Gray, 1838 Shell claviform, siphonal canal short, deeply notched, fasciole often strong; anal sinus moderately deep, U-shaped, spout-like, constricted by large parietal pad; and axial ribs strong.	Undiagnostic
	Gemmula Weinkauff, 1875 Fusiform in shape, with a high slender spire. Posterior notch of outer lip on shoulder. Outer surface composed of axial ribs and nodules. Periostracum often present. Aperture more or less elongate, siphonal canal well marked, short to long. Outer lip generally thin and sharp. A characteristic slit or notch along the posterior part of the outer lip, which is reflected in the growth lines made by the lip. Inner lip is mostly smooth. Operculum corneous.	Figure 18b
Order TROCHIDA Superfamily Trochoidea	*Trochoidea* Rafinesque, 1815 Shell conical to globose in shape, with a moderately large rounded body whorl with a flattened base. Sculptured spirally with tubercles. Periostracum sometime conspicuous. Aperture rounded, without a siphonal canal, nacreous inside.	Figure 20

Superorder PYLOPULMONATA Family PYRAMIDELLIDAE	*Chrysallida* Carpenter, 1856 Shape ovoid-conical, with fairly blunt top. Apex appears immerged in the following whorl. There are nearly three teleoconch whorls, of which the first adult is flat and the others are slightly convex. The body whorl forms more than half of the shell. The sutures are deep and wide; the lowest one is evidently oblique. The axial ribs, narrow and continuing to the base, are well marked and stronger than the spiral cords. The aperture is oval lengthened and there is a hardly visible tooth on the columella.	Figure 18b
Superorder RINGICULIMORPHA Family RINGICULIDAE	*Ringicula* Deshayes, 1838 Shell minute, ovate to subglobose, medium-height spire, convex whorls with seven incised spiral grooves, thickened outer lip with thick parietal callus, markedly curved inner lip with two folds, siphonal canal broadly open.	Figure 18b
Unranked clade CAENOGASTROPODA informal group ARCHITAENIOGLOSSA Family VIVIPARIDAE	*Bellamya javanica* (von dem Busch, 1844) The shell is conical and globular in shape, with a sharp apex and relatively higher spire and distant body whorls. The aperture is oval.	Figure 20

Unranked clade Heterobranchia/Euthyneura/Panpulmonata/ Hyrophila Family PLANORBIDAE	*Planorbis* Müller, 1773 Rounded body whorl. Whorls regularly increasing in size, suture deep with close transverse growth lines, aperture oval, body whorl rounded, first whorld on both sides depressed.	Figure 20
CLASS BIVALVIA		
Order ARCIDA Family ARCIDAE	*Anadara* Gray, 1847 Shell solid, inequivalve. Umbone in front of the midline, prosogyrate on top of a wide cardinal area. Ligament external, stretching across the cardinal area, with V-shaped grooves. About 28 radial ribs at each valve; radial ribs without a narrow median groove. Hinge elongate, almost straight, with numerous small transverse teeth which increase in size towards anterior and posterior ends. Interior of shell porcelaneous.	Figure 18a
	Arca Linnaeus, 1758 Subrectangular, markedly inequilateral outline. Ligamental area wide and almost flat, meeting the commissural plane of valves nearly at right angle with the hinge line. Posterior margin sinuates, beak at the anterior, broad dorsal area with evidence of anterior ligament, blunt umbonal keel, sculpture of numerous radial riblets made beaded by crossing commarginal ridges. Umbo non-ventral keep sharply angulated.	

Family ARCIDAE/NOETIIDAE	*Arcopsis* Koenen, 1885 Shell solid equivalve, subtrigonal trapezoidal to elliptical in shape, generally inequilateral and longer than high. Umbones often opisthogyrate, set apart from dorsal margin by a trigonal cardinal area. Ligament external, stretching across the cardinal area, with oblique grooves and transverse striations. Outer surface with radial sculpture. Periostracum conspicuous, generally pilose. Hinge elongate, straightish to slightly arched with numerous small transverse teeth which somewhat increase in size towards anterior and posterior ends. Interior of shell porcelaneous. Two subequal adductor muscle scars, with a ridge or a shelf present along the inner margin of one or both scars. Pallial line without sinus. Internal margins of valves smooth or crenulated.	Figure 18a
Family GLYCYMERIDIDAE	*Glycymeris* da Costa, 1778 Shell rounded-subquadrate in outline, moderately inflated slightly inequilateral with rounded anterior and obtusely pointed posterior margin. Umbones not very prominent, slightly opisthogyrate and in front of midline of valves. External sculture weak, with very low rounded radial undulations and fine grooves, crossed by numerous, small concentric marks.	Figure 18a & 19

Order OSTREIDA Family OSTREIDAE Rafinesque, 1815	Shell solid, often irregularly shaped, inequivalve, cemented to the substrate by the left (lower) valve which is generally larger and deeper. Right (upper)valve quite flat, often with thin, concentrically arranged, imbricating plates of horny material tending to make a protruding fringe beyond the shell margin. Outer surface commonly, at least on left valve, with radial folds or ribs which may affect the shell margin. Ligamental area with a shallow median groove and two lateral thickenings. Hinge without teeth. Interior of shell porcelaneous, sometimes with irregular chalky deposits or with a subnacreous tinge.	Figure 19
Order PECTINIDA Family PECTINIDAE	*Amusium pleuronectes* (Linnaeus, 1758) Shell thin, medium sized (commonly attaining 8 cm in length), laterally compressed, almost circular in outline, gaping anteriorly and posteriorly. Nearly smooth externally, but with distinct internal radial ribs.	Figure 19
	Amusium Röding, 1798 Shell more or less inequivalve, usually with one valve more convex than the other; ovate to subcircular in outline with median low, orthogyrate umbones and a straight dorsal margin forming wing-like ears at both ends.	Undiagnostic

	Mimachlamys Iredale, 1929 Shell solid, medium sized, higher than long and rounded-ovate in outline. Both valves are convex and subequal. Ears markedly unequal in size.	
Family PLACUNIDAE	*Placuna* Lightfoot, 1786 Shell thin and more or less translucent, almost circular in outline. Dorsal margin somewhat flattened to widely curved, sometimes faintly protruding anteriorly and posteriorly. Valves greatly compressed laterally, the lower (right) valve flat, the upper (left) valve with slight convexity. Commissural plane flat. Outer surface nearly smooth, excepting numerous, minute radiating threads forming tenuous wrinkles on the finely lamellate concentric lines of growth.	Figure 18a
Family PLICATULIDAE	*Plicatula* Lamarck, 1801 Valve small, ostreiform, slightly curved, equivalved, slightly inequilateral, with same degree of low convexity; right valve showing relatively large area of attachment in dorsal posterior beak region; shell sculpture of very broad fold-like radial ribs.	Figure 18a

Order CARDITIDA Family CARDITIDAE	*Cardites* Link, 1807 Shell subtrapezoidal in outline, not strongly expanded posteroventrally; sculpture of about 20 broad radial ribs.	Figure 19
Family CRASSATELLIDAE	*Bathytormus* Stewart, 1930 Small, elongate, sharply carinate. Sculpture of sharp relatively widely spaced concentric lamellae.	Figure 18a & 19
Order LUCINIDA Family LUCINIDAE	*Cardiolucina* Sacco, 1901 Outer sculpture of narrow, rounded radial ribs and concentric cords, forming distinct nodules at the points of intersection all over the surface of the valves; hinge with well-developed cardinal and lateral teeth.	Figure 18a
	Myrtea Turton, 1822 Shell ovate in outline and the surface is smooth and radial ribs forming a granulose surface. The umboneds are centrally located and anteriorly curved, the ligament external or partially internal, the hinge line smooth with weak cardinal and lateral teeth.	Figure 18a & 19

Order MYIDA Family CORBULIDAE	*Corbula* (Aniscorbula) Iredale, 1930 Shell small, thick, ovate, more or less rostrate; valves unequal, the usually smaller and flatter; umbones prominent, prosygrate or erect, the right usually higher than the left; hinge line of right valve fitted with a single prominent tooth in front of the resilial pit; left valve with a chondrophore and a deep cardinal socket; surface sculpture usually concentric; adductor scars distinct; pallial line indistinct; sinus feeble or obsolete.	Figure 18a & 19
	Varicorbula Grant & Gale, 1931 Shell trigonal, rather thin but sturdy, bluntly trunbcated posteriorly, strongly inequivalve; left valve smaller, flatter, less rostrate; right valve larger, more inflated. Both valves concentrically sculptured, but discreptantly so; right valce with coarser, higher ridges; left valve with finer concentric ridges, crossed by radial ridges. Umbones prosogyrous, higher and more inflated in right valve, without nepionic caps. Periostracum on the left valve forming overlapping foliations and radial lines, overhanging shell edge substantially. Right valve with large knob-shaped tooth, articulating with a deep socket in the left valve. Elongated plate posterior to the socket of left valve, including resilium-bearing chondrophore; complimentary right chondrophore on shelf within embayment posterior to tooth. Resilium oriented dorsoventrally; external ligament very small. Lateral teeth absent. Interior shell margins smooth. Deep interior groove running parallel to the ventral edge of right valve, and	Figure 18a

	continuing into lateral lamellae on either side of the hinge, into which margin of left valve inserts. Anterior muscle scar moderately large and crescent-shaped; posterior muscle scar oval and slightly larger. Pallial line entire; pallial sinus shallow but distinct.	
Order VENERIDA Family KELLIELLIDAE	*Alveinus* Conrad, 1865 Equivalved, smooth; anterior, posterior and ventral margins channeled within; hinge of right valve emarginated under the apex, and having one pyramidal tooth anteriorly; hinge of the left valve with a pit under the apex, and two compressed diverging teeth anteriorly; pallial line entire.	Figure 18a
Family VENERIDAE Rafinesque, 1815	Shell mostly solid, obliquely rounded in outline; with prominent umbones. Sculpture only concentric. Ligament external, behind the umbones, often inserted in a deep groove. Hinge with 3 usually radially disposed cardinal teeth in each valve. Interior of shell porcelaneous. Two or more or less equal adductor muscle scars. Pallial sinus usually present. Internal margins smooth to denticulate.	Undiagnostic
	Circe Schumacher, 1817 Shell is more roundly trigonal and lacks the roundly truncated antero-ventral margin. Very compressed laterally, about as long as high; umbones submedian and flattened. Pallial sinus very shallow hardly extending forwards beyond the posterior adductor scar.	Undiagnostic

	Timoclea T Brown, 1827 Shell very small, very inflated, obliquely trigonal. Anterior end broadly rounded, posterior one subangulate; ventral border broadly convex, somewhat being concave near postero-ventral corner. Beaks small and pointed. Hinge small and narrow consisting of two cardinal teeth and two thin lateral teeth on the right valve. Pallial sinus broad, shallow, triangular and pointed at the end. Surface sculptured with radial ribs and growth lines, and becomes weaker or absent at the anterior part.	Figure 18a & 19
	Venus Linnaeus, 1758 Trigonal-ovate, subequilateral, compressed shell, anterior side oval, posterior one truncate, flattened umbonal area, lunule and escutcheon narrow, lanceolate, the former bounded by a distinct angulation, hingle with 3 elongate, radiating cardinals and 1 approcimate, prominent anterior lateral in each vbalve, pallial sinus obsolescent, sculpture of even commarginal cords that are are weaker over the umbonal area.	Figure 18a
Order VENEROIDA Family CORBICULIDAE	*Corbicula gerthi* (Oostingh, 1935) Shell has a rounded triangular shell with a clear asymmetry. The shell umbo is very robust, situated above the ligament, slightly	

	rotated and directed to the front of the shell. The periostracum is glossy and covered with tightly spaced ribs.	Figure 20
	Corbicula pullata (Philippi, 1851) Shell is a trigonal, subequilateral species with the ventral margin greatly arched, rounded anteriorly and with a subtruncated posterior margin. Most single left valve is much higher than long and very inequilateral, while a few are more elongate. The sculpture consists of very regular, rather narrow but well impressed ridges.	
	Corbicula Megerle, 1811 Shell has an oval-triangular outline with prominent, more or less centrally located umbo. Sculpture is prominent with raised, regular concentric ribs.	
Order UNIONIDAE Family UNIONIDAE	*Elongaria orientalis* (Lea, 1840) Shell oval-elongated, rounded in front and often pointed behind. Striated concentrically according to the growth lines. The dorsal and ventral margin are almost parallel, rather accurate in the dorsal margin, particularly old shell, the lower margin straight or slightly concave. Ligament is between the apex and the meeting point between the dorsal and posterior margin. Muscle scars in the upper half of the shell, connected by a fine pallial line without sinus.	Figure 20

Superorder ANOMALODESMATA Family MYOCHAMIDAE	*Myochama* Stutchbury, 1830 Shell inequivalve, trigonal with small posteriorly inclined beaks, sculpture with strong rather widely spaced rounded concentric ridges, occasionally anastomosing. Pallial sinus of moderate depth. Hinge with a deep narrow wedge-shaped resilifer, flanked irregular ridges confluent with the hinge-plate.	Figure 18a
Superoder IMPARIDENTIA Family MESODESMATIDAE Gray, 1840	Shell equivalve, usually thick and heavy, more or less compressed laterally, inequilateral, elongate ovate or subtrigonal to wedge-shaped in outline. Umbones opisthogyrate. Outer surface smooth or mostly concentrically sculptured, with a well-developed and often glossy periostracum. External ligament short and not prominent, communicating with a strong internal ligament fitting in each valve in a deep pit of the hinge plate. Hinge with 1 or 2 cardinal teeth and more or less developed lateral teeth in each valve. Interior of shell porcelaneous. Two adductor muscle scars, subequal in size. Pallial line with a rather short sinus. Internal margins smooth.	Figure 19

3. a. Bivalves and gastropods assemblage in Upper Kalibeng formation (Figures 18a and 18b)

The Kalibeng layer is the oldest formation of Sangiran dome composed of volcanic materials namely, the bluish gray clay with *Balanus* limestone and *Turritella* beds from the Early Pleistocene, placed on top of the globerigina marls between the Late Miocene and Upper Pliocene. The molluscs are deposited in the upper part of the formation. From the samples, 20 bivalves and 21 gastropods were identified. All belongs to full marine environment, mostly in soft bottom sublittoral zone. Bivalve shells belong to two families Arcidae/Noetiidae and Veneridae, 18 to genus level (*Alveinus sp.*, *Amusium sp., Anadara sp., Arca sp., Arcopsis sp., Bathythormus sp., Cardiolucina sp., Corbula sp., Glycymeris sp., Mimachlamys sp., Myochama sp., Myrtea sp., Placuna sp., Plicatula sp., Timoclea sp., Varicorbula sp*. and *Venus sp.*). Gastropods identified are a species from family ?Muricidae, and 20 belongs to genus ?*Callliostoma sp., Cerithium sp., Chrysallida sp., Cryptospira sp., Cymatium sp., Diodora sp., Drillia sp., Epitonium sp., Fusinus sp., Gemmula sp., Melanella sp., Mitrella sp., Nassarius sp., Olivella sp. Polinices sp., Ringula sp., Solariella sp., Turritella sp.* and *Vaceuchelus sp*. and one species of *Turritella terebra*.

3. b. Bivalves and gastropods assemblage in the *Corbicula* Bed and Lower Pucangan (Figures 19 and 20)

The shell assemblages from the *Corbicula* Bed and in the Lower Pucangan were recovered from the topmost level of Kalibeng layer and the Lower Lahar and the Black Clay layers of Sangiran dome. There are 29 mollusc taxa, 16 bivalves and 13 gastropods from the marine and freshwater environments. Marine molluscs are present along with the freshwater molluscs in the *Corbicula* Bed. There are 12 marine bivalve taxa identified: *Cardites sp., Corbula sp., Bathytormus sp., Glycymeris sp. Myrtea sp., Amusium pleuronectes, Circe sp., Timoclea sp.*, and from the family Mesodesmatidae and Ostreidae (fragmented, juvenile and unidentified species). Two marine gastropods were found in this formation, a fragmented *Diodora sp*. and *Trochoidea s.l.* Freshwater mollusc taxa that are present both in the lower lahar unit and black clay layers have four bivalves and eleven gastropods. Freshwater bivalves are mostly composed of the Family Corbiculidae (*Corbicula gerthi, Corbicula pullata, Corbicula* *sp.*) and one from Family Unionidae, *Elongaria orientalis*. Gastropods in the Sangiran formation are represented by several taxa from the family Pachychilidae (*Sulcospira testudinaria, Sulcospira sp.* and ? Pachychilidae) and family Thiaridae (*Tarebia granifera, Tarebia aff. granifera, Tarebia sp. Thiara winteri and Thiara sp*.). The rest of the gastropods are *Bellamya javanica* and *Planorbis sp.,* and one from the family Hydrobiidae.

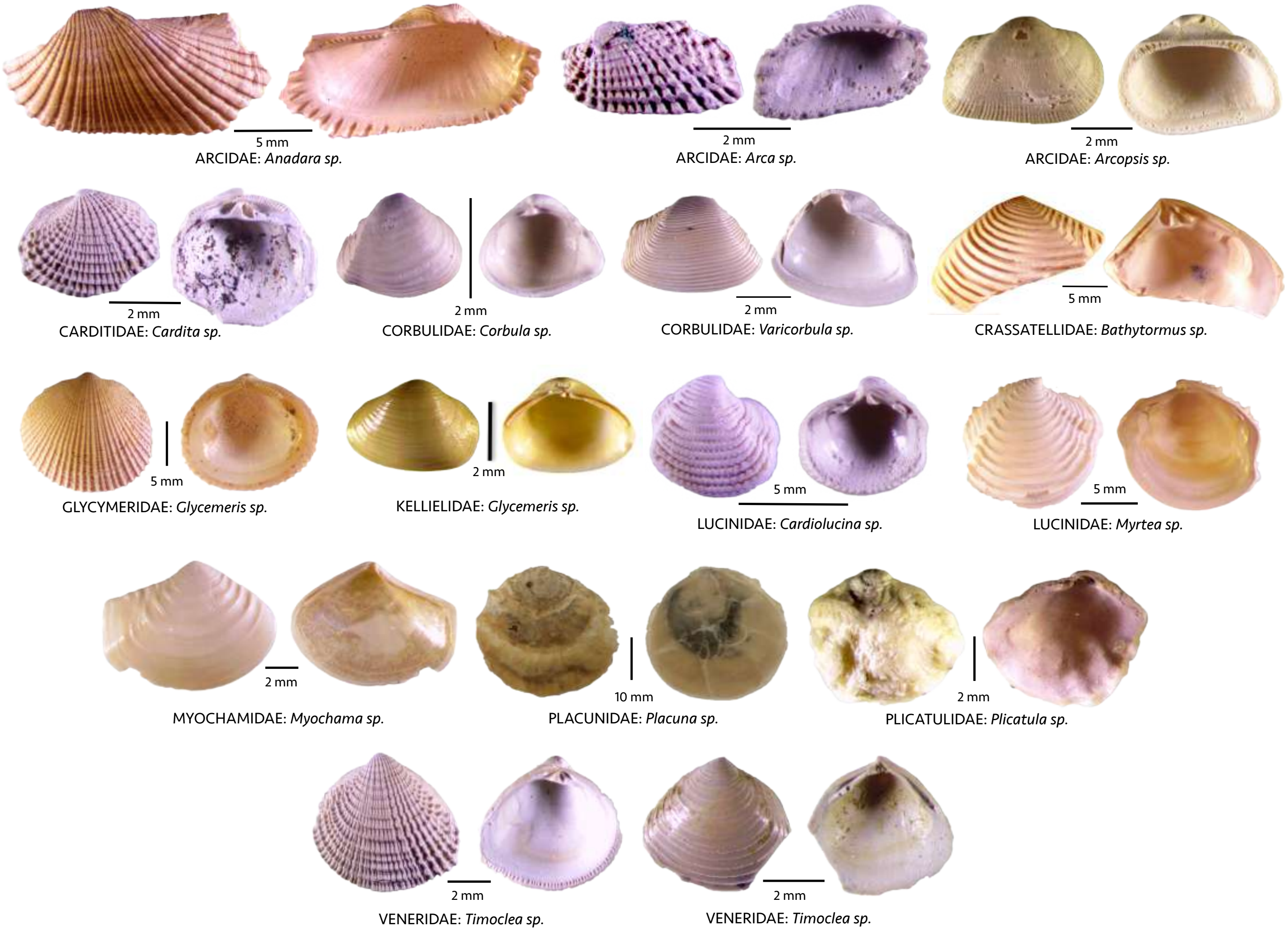
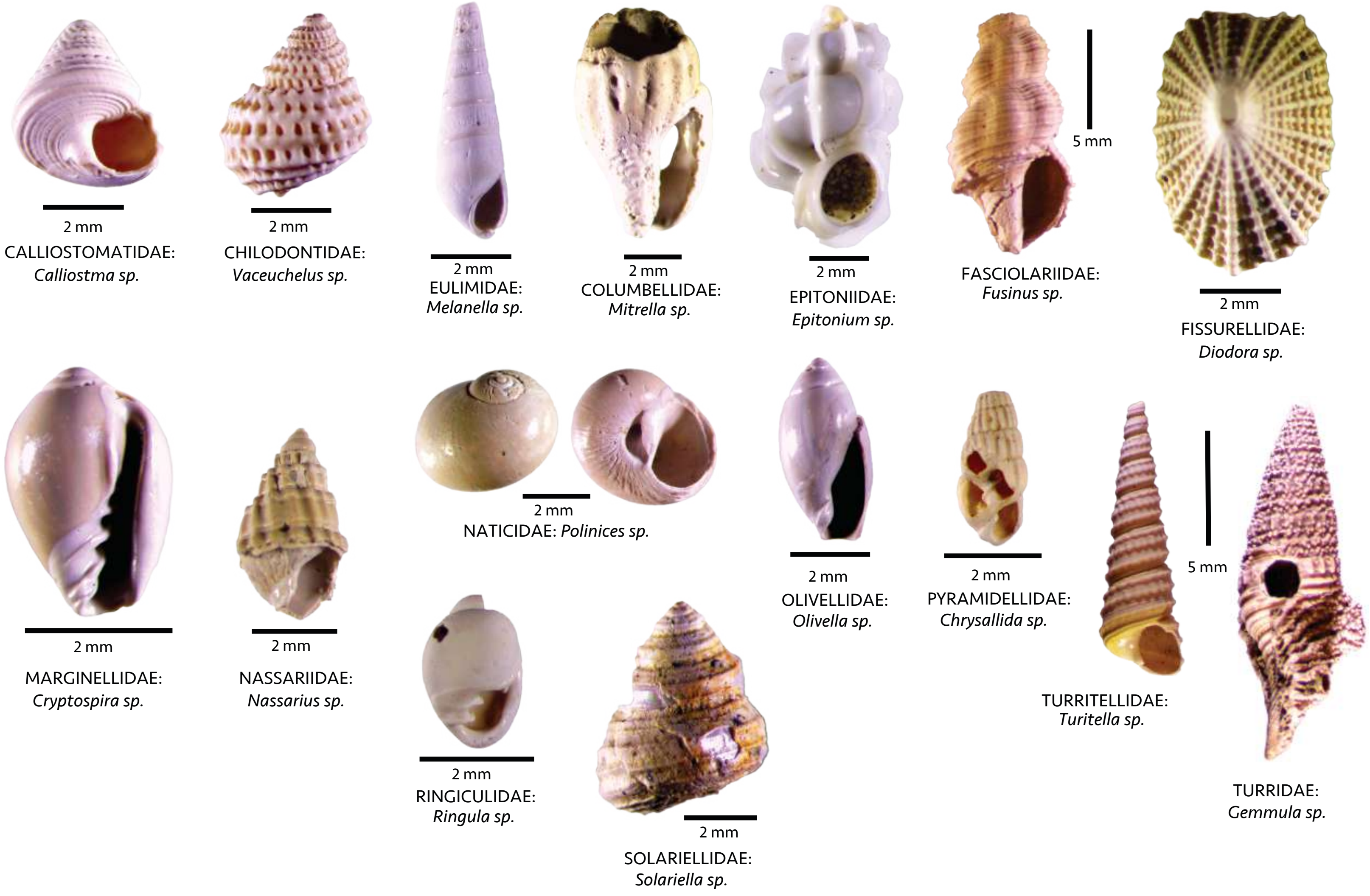


Figure 18a. Upper Kalibeng marine bivalves



CALLIOSTOMATIDAE: *Calliostma sp.*

CHILODONTIDAE: *Vaceuchelus sp.*

EULIMIDAE: *Melanella sp.*

COLUMBELLIDAE: *Mitrella sp.*

EPITONIIDAE: *Epitonium sp.*

FASCIOLARIIDAE: *Fusinus sp.*

FISSURELLIDAE: *Diodora sp.*

MARGINELLIDAE: *Cryptospira sp.*

NASSARIIDAE: *Nassarius sp.*

NATICIDAE: *Polinices sp.*

OLIVELLIDAE: *Olivella sp.*

PYRAMIDELLIDAE: *Chrysallida sp.*

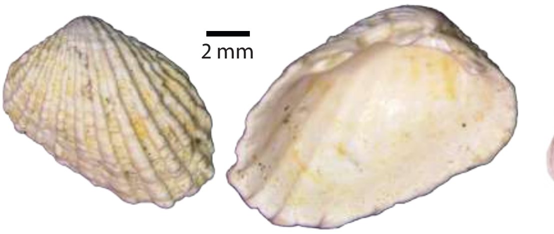
TURRITELLIDAE: *Turitella sp.*

RINGICULIDAE: *Ringula sp.*

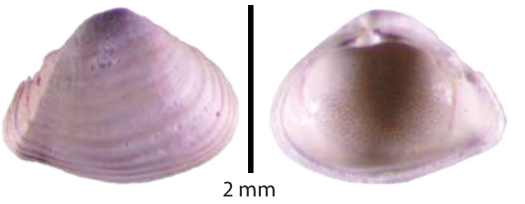
SOLARIELLIDAE: *Solariella sp.*

TURRIDAE: *Gemmula sp.*

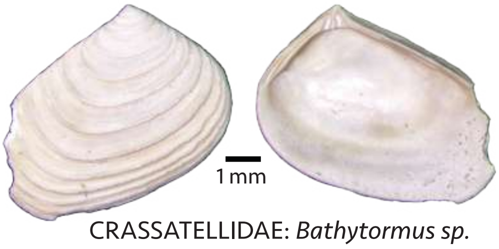
Figure 18b. Upper Kalibeng marine gastropod



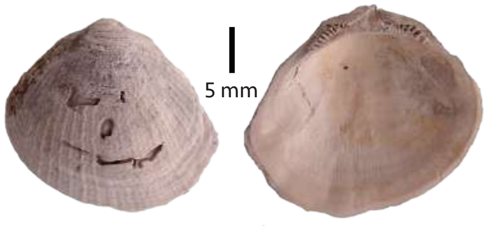
CARDITIDAE: *Cardites sp.*



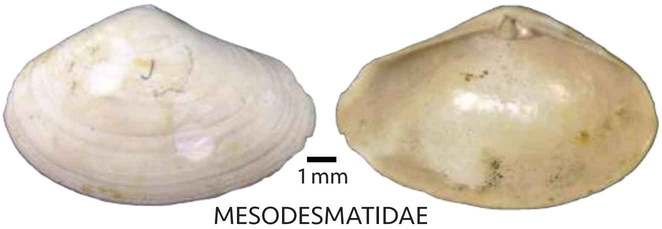
CORBULIDAE: *Corbula sp.*



CRASSATELLIDAE: *Bathytormus sp.*

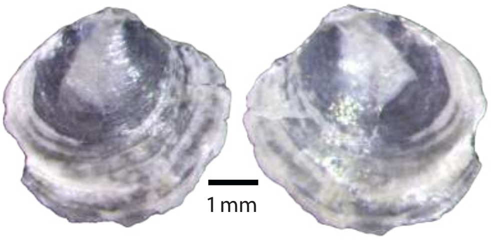


GLYCYMERIDAE: *Glycymeris sp.*

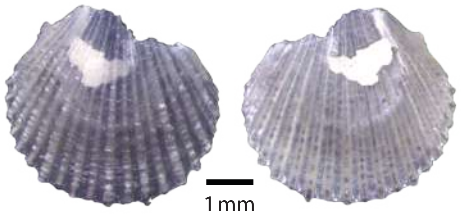


MESODESMATIDAE

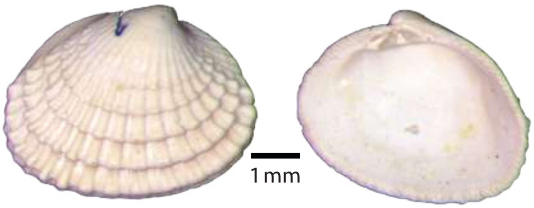
LUCINIDAE: *Myrtea sp.*



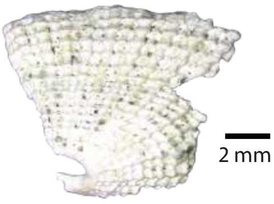
OSTREIDAE



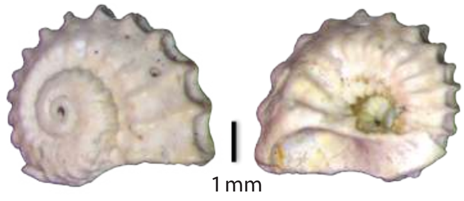
PECTINIIDAE: *Amusium pleuronectes*



VENERIDAE: *Timoclea sp.*



FISSURELLIDAE: *Diodora sp.*



TROCHOIDEA: *Trochoidea s.l.*

Figure 19. Lower Pucangan marine mollusc assemblage

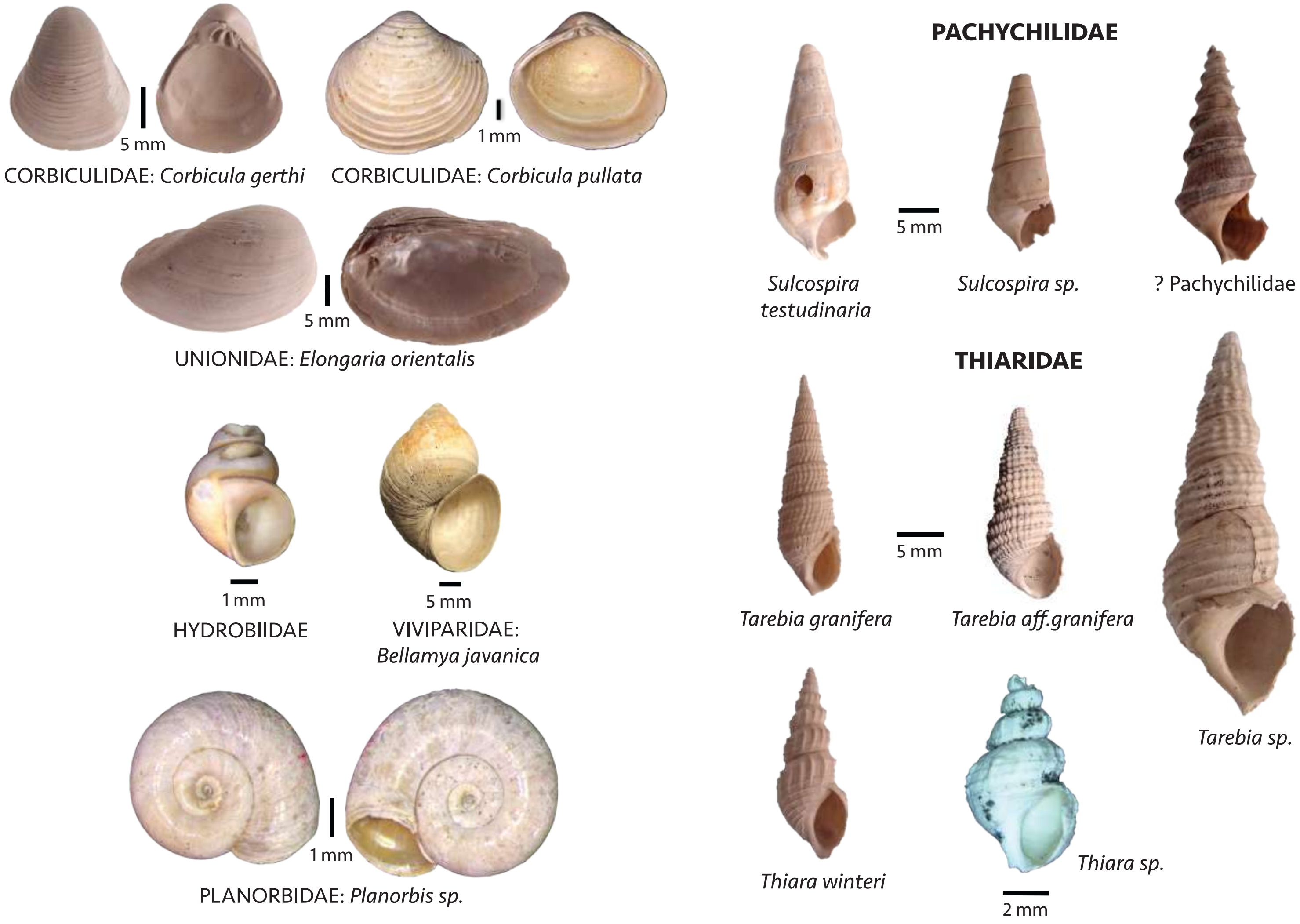


Figure 20. Lower Pucangan freshwater mollusc assemblage

CHAPTER 3:

THE PLIO-PLEISTOCENE MOLLUSC ASSEMBLAGES IN SANGIRAN DOME [1]

Mollusc shells in Quaternary fossil bearing formations produce paleontological records describing the ecology and evolution of environments. This information embodies in fossil shells of Sangiran Dome from Plio-Pleistocene period. In summary, 28 bivalves and 33 gastropod species were determined from the Upper Kalibeng to Lower Pucangan series in Sangiran. Within the mollusc association, various forms were detected: from facies and composed of sediments representing marine to swampy environments leading to continental development. Five lithofacies units were separated in the Upper Kalibeng to Lower Pucangan successions (old to young): a) massive marls and blue clays, b) layered clayey limestone, c) silty gray clay, d) volcanic breccia and lahars and e) black clays. From layers with greater concentrations of fossils, a rich community of shells was separated from the terrigenous fraction sample from wet sieving in 1.5 and 5 mm mesh and dried. All molluscs recovered were identified and counted to the lowest possible taxonomic rank, habitat description and underwent ecological statistics analysis.

The mollusc species and their abundance are determined by the geological and evolutionary history of the Sangiran area. Whole and diagnostic fragmented molluscs were quantified to establish the Number of Individual Species (NISP) of each taxon. The columella of gastropod was counted for one individual. This includes incomplete specimens and fragments. A valve of a bivalve was counted for one individual. The habitat was also identified.

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[1] Presented at the 13th International Conference of the International Council for Archaeozoology (ICAZ) held at the Cultural Convention Center at METU in Ankara, Turkey on 2-7 September 2018.

Standard statistical analyses were employed to present the ecology of the area. For each sampled site, the species richness (**S**), Shannon-Wienner diversity index (**H'**) and species evenness (**E**) were calculated (Magurran, 1988; Willis & Whittaker, 2002). These analyses were conducted to present the distribution of molluscs among sites sampled in Kalibeng and Pucangan layers. All these analyses were carried out with the computer program R. Tables and figures were prepared, showing the composition of the assemblage per sampled site.

This chapter presents a set of presence-abundance data for early Pleistocene bivalves and gastropods from the different lithofacies units of Upper Kalibeng to Lower Pucangan layers in Sangiran Dome (c. 2.2 to 1.5 Ma ago). Moreover, their significance is framed within the multidisciplinary research to reconstruct the palaeoenvironmental conditions in the transition from marine to continental development of Java Island by means of palaeoecological analysis.

1. Shell assemblages in the Sangiran dome

The stratigraphic succession of Sangiran dome with mollusc assemblages can be subdivided into four levels, along which 60 taxa of molluscs were identified. It deals with freshwater and marine taxa of gastropods and bivalves, which are distributed as distinct assemblages characterizing the different levels from a palaeoecological perspective. The relative abundance of the species is given in **Tables 3 & 6** and **Figures 24 & 30**.

1. a. 1. Shells from the Upper Kalibeng

Fossil shells were collected in seven areas of Sangiran Dome belonging to the Upper Kalibeng layers. They were labeled as PR1 and PR3 - Puren River 1 and 3, PK2, PK4 and PK5 - Pablengan Kulon 2, 4 and 5, S1 and S2 - Sangiran 1 and 2.

Sampled bivalves and gastropods present in the Upper Kalibeng layers in Sangiran are from the marine environment. All species are full marine and live in muddy sands. They are mostly found between near and offshore sections in the sublittoral zone. Shell sampled sites were presented according to Sangiran stratigraphic sequence and accurately fitted with the shell assemblage in each site.

The oldest sampled sites are Sangiran 1 and 2 (S1 and S2). S1 mollusc assemblage is a patch of coastal wetland more or less than 30 m in Sangiran palaeoshore. Molluscs present live in near shore of the sublittoral marine environment. Numerous bivalve fragments of *Amusium sp., Placuna sp.* and *Veneridae* shells are present from the shallow water of neritic zone. Heaps of *Turritella sp.* were also recovered. All mollusc shells uncovered in the site prefer soft substrates.

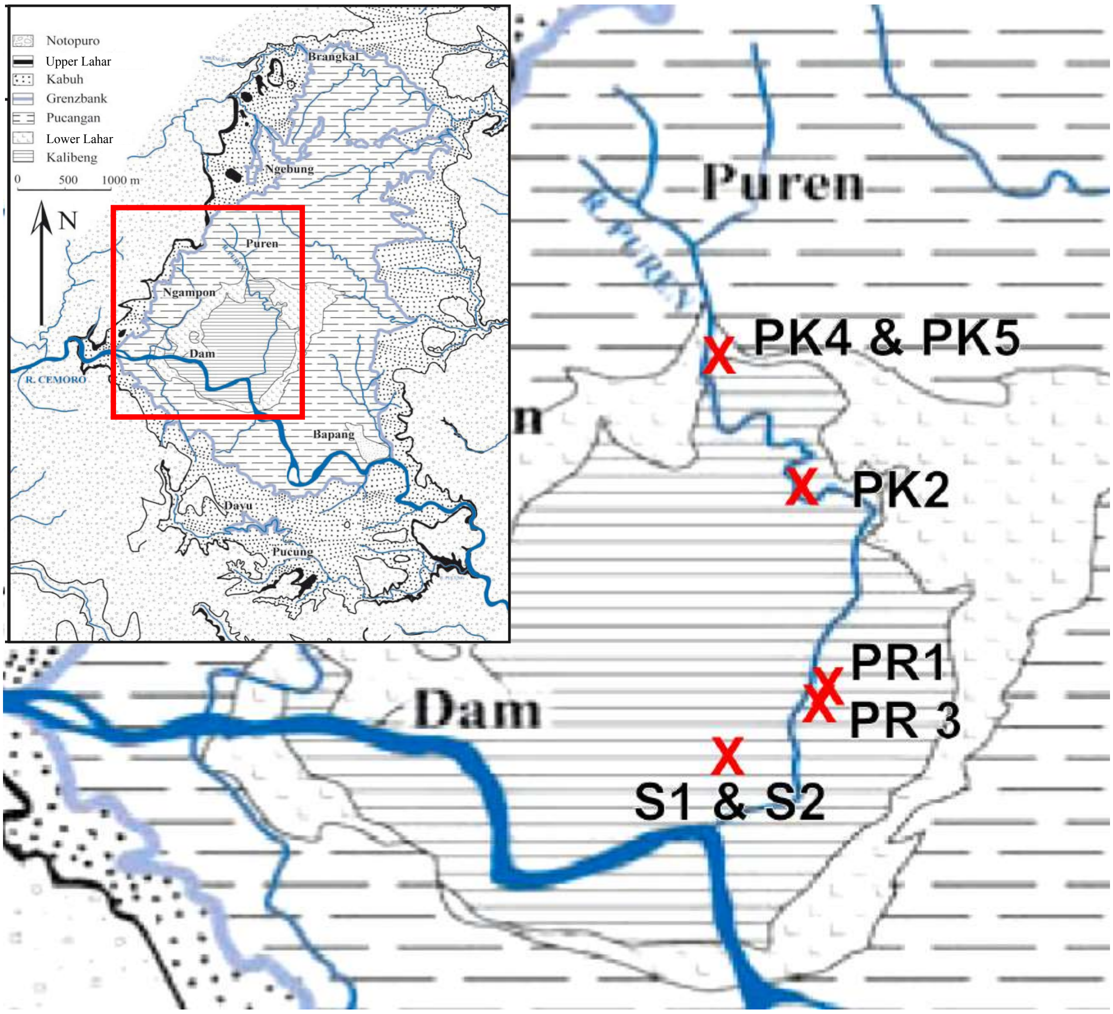

Figure 21. Location of shell sampling sites in Kalibeng layer. Geological map of Sangiran and its stratigraphy based on Von Koenigswald plan (1940) modified by Watanabe and Kadar (1985) and Sémah et al. (1992), see Brasseur et al., 2015.

Figure 22. Kalibeng sampled sites: A) Pablengan Kulon 2. B) Pablengan Kulon 4. C) Pablengan Kulon 5. D) Puren. E) Sangiran-Disun © MGPGFaylona November 2015/June 2016

S2 has a sublittoral marine environment based on the ecology of each shell in the sample. The mollusc assemblage inhabits shallow waters with muddy sand bottom. It also has a mass of *Turritella sp.*, as observed in S1. Bed of *Turritella sp.* in

Sangiran stratigraphic sequence overlaps the *Balanus* limestone where the marine regression is underlined by actual coastal facies.

Puren River 1 and 3 (PR1 and P3) sites are stratigraphically five meters apart from each other. The mollusc assemblages from these sites are different. PR1 features a near shore sublittoral environment with a muddy-sand bottom. PR3 reflects a mudflat shallow marine environment. The mollusc assemblage does not include gastropods as only one taxon is present, fragments of *Placuna sp*., while absent in PR1. Based on the species environmental background, this sector may be less than 50 meters away from coastal wetlands in Sangiran.

Following is the Pablengan Kulon 2 (PK2) site, which has a larger number of mollusc taxa dominated by the family Arcidae and *Varicorbula sp*. They live in near shore of sublittoral zone that is below the low tide line and extends all the way to the continental shelf. The site has muddy sand bottoms with fringing corals where sedentary molluscs are settled.

The last two shells sampled sites, Pablengan Kulon 4 and 5 (PK4 and PK5) are located in the Pablengan Kulon area at the meandering stream of Puren. PK4 and PK5 sample sites were adjacent to another as S1 and S2 and PR1 and PR3, and the fossil shell assemblages vary. PK4 has no gastropod shells and has the least mollusc distribution frequency and number of taxa. Both PK4 and PK5 show offshore assemblages and it is worth to note that they accumulated also hundreds of benthic foraminifera, e.g. *Operculina sp*. Molluscs present in this area lives in a shallow water environment with muddy sand bottoms.

1. a. 2. Relevance of species, species richness and diversity

The Kalibeng mollusc assemblage was dominated by seven taxa of bivalve namely, *Amusium sp., Anadara sp., Cardiolucina sp., Placuna sp., Glycymeris sp.*, *Varicorbula* sp. and family Veneridae and one for gastropod, *Turritella sp*. *Placuna* has the highest frequency among bivalves. *Glycymeris* was the most widely distributed shell in Kalibeng layers. Moreover, bivalves present in Kalibeng inhabited both the near and offshore of sublittoral marine environment. Unlike gastropods, the majority lived in a nearshore segment of the sublittoral zone. *Turritella* had the highest frequency among gastropods. However, gastropods in Kalibeng were not well distributed except in PK2. In addition, they are less represented.

Shells retrieved in PK2 have the most species richness. The least species richness is in PR3 where there is only one species abundantly present. Samples from S1 and S2 have the most abundance of species. However, their total abundance of different species does not make up for their species richness. Unlike in PK4 and PR1, they have relatively high abundance of different species proportional to the richness and evenness of the species. In addition, these two sites are the most diversified assemblages.

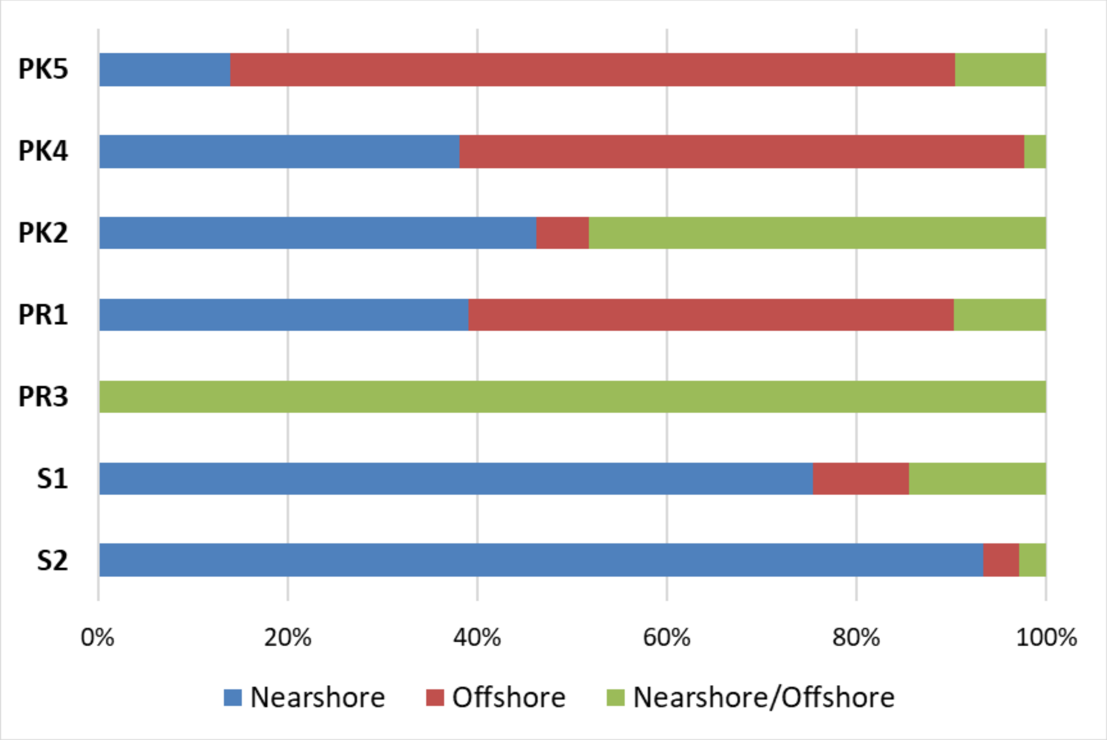

Figure 23. Kalibeng shell ecology. S1 and S2 have nearshore shell assemblage. PR 1 and 3 have both near and offshore shell assemblage. PK2 has near shore shell assemblage. PK4 and PK5 have offshore shell assemblage. All molluscs live in muddy-sand bottom.

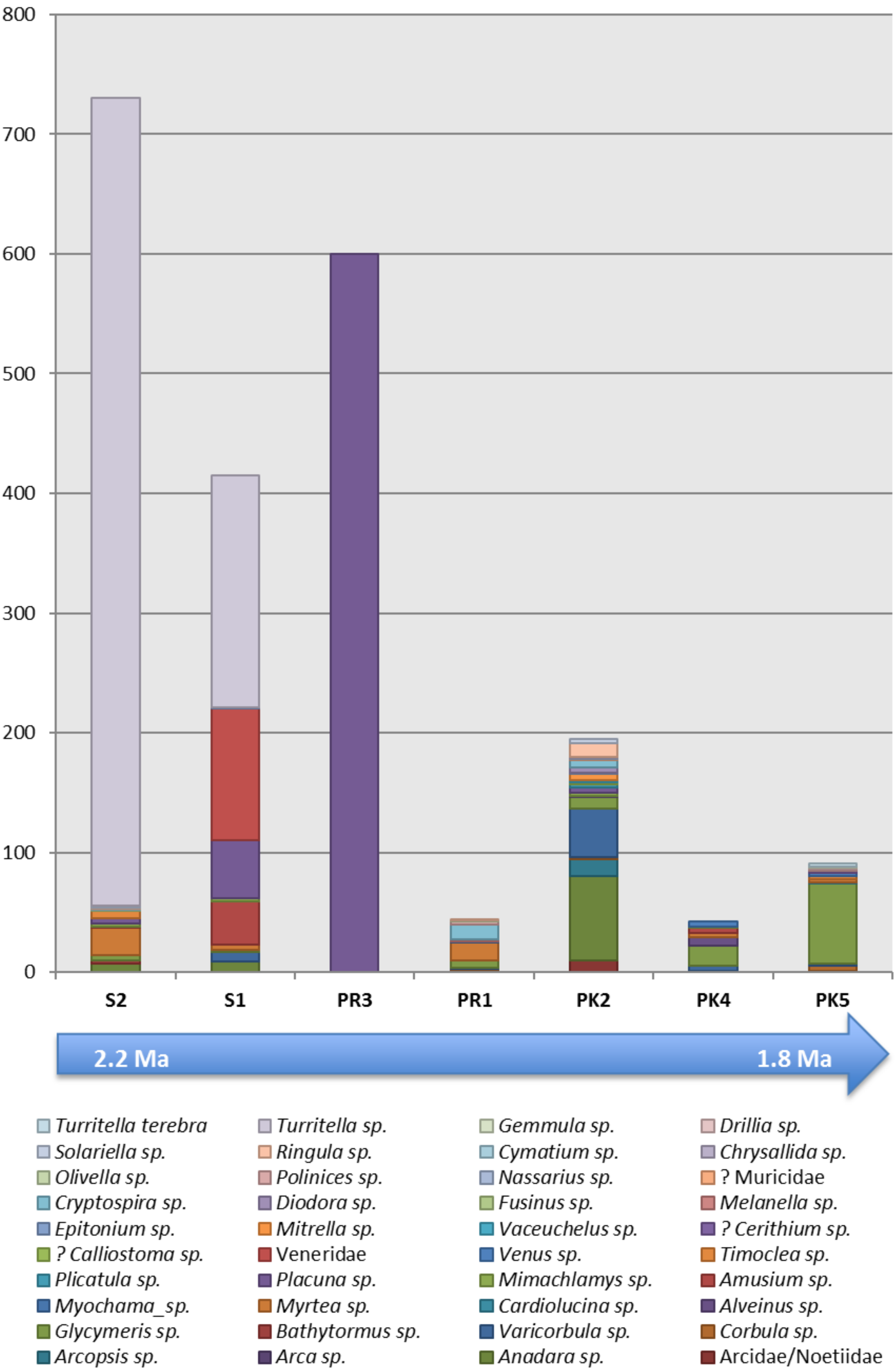

Figure 24. Kalibeng shell bivalve and gastropod frequency distribution, presented in chronology according from the oldest to youngest level of deposition in the blue clay layer of Sangiran dome.

Table 2. Ecological distribution and characteristic taxa recovered in Kalibeng layer

Table 2. a. The Kalibeng bivalve molluscs

FAMILY	**TAXON**	**Sublittoral zone**		**Substrate**		**Habitat**
CLASS BIVALVIA		**Nearshore**	**Offshore**	**Soft**	**Hard**	
Arcidae/Noetiidae		X		X	X	Sedentary animals, nestling in rock crevices, or unattached and more or less buried in soft bottom.
Arcidae	*Anadara* Gray, 1847	X	X	X		On muddy bottoms, intertidal and sublittoral to a depth of 25 m
Arcidae	*Arca* Linnaeus, 1758	X			X	Fixed on rocks, corals, or under stones. Littoral and sublittoral waters to a depth of 20 m.
Arcidae	*Arcopsis* Koenen, 1885	X			X	Shallow water, under stones. Littoral and sublittoral to a depth of 25 m.
Corbulidae	*Corbula* (Anisocorbula) Iredale, 1930	X	X	X		Lives on subtidal and intertidal mud flats, partially buried in soft sediment. Occasionally on the lower shore as well as in muddy sand and gravel and most are in abundant offshore.
Corbulidae	*Varicorbula* Grant & Gale, 1931	X		X		Shallow water
Crassatellidae	*Bathytormus* Stewart, 1930	X		X		Shallow water in littoral zone with soft and sand-mud bottoms.
Glycymerididae	*Glycymeris* da Costa, 1778		X	X		In sublittoral muddy-sand bottoms
Kellielidae	*Alveinus* Conrad, 1865	X		X	X	Sandy level-bottom in pelitic sample
Lucinidae	*Cardiolucina* Sacco, 1901		X	X		Buried in sandy bottoms, often in coral reef areas, from shallow sublittoral waters to a depth of 20 m.

Lucinidae	*Myrtea* Turton, 1822		X		X	Deep, offshore habitats with cohesive sandy mud (>20% mud)
FAMILY	**TAXON**	**Sublittoral zone**		**Substrate**		**Habitat**
		Nearshore	**Offshore**	**Soft**	**Hard**	
Myochamidae	*Myochama* Stutchbury, 1830	X			X	Intertidal sand flats to 20m, cemented to other shells or to rocks
Pectinidae	*Amusium* Röding, 1798		X	X	X	On sand and mud bottoms, sublittoral, from depths of 10 to 80 m.
Pectinidae	*Mimachlamys* Iredale, 1929	X	X	X		On sand or muddy-sand bottoms with gravel, coral rubble, shell debris or rocks. Littoral and sublittoral zones
Placunidae	*Placuna* Lightfoot, 1786	X	X		X	On the surface of soft muddy to sandy-mud bottoms, from low tide levels to a depth of about 100 m.
Plicatulidae	*Plicatula* Lamarck, 1801	X	X	X		Intertidal and shallow subtidal waters, off-shore on gravel bottom, 1 to 50 m, on hard substrates
Veneridae	*Timoclea* T. Brown, 1827	X	X	X		Intertidal. Found in sand, muddy-sand and gravel offshore, at depths ranging from 3 m to 180 m.
Veneridae	*Venus* Linnaeus, 1758	X		X		In shallow sandy areas
Veneridae		X		X		Inhabit muddy or sandy water just below the water surface, and live in shallow to deep water.
Calloistomatidae	? *Calliostoma* Swainson, 1840		X	X	X	Intertidal zone to mid-bathyal depths. Deep water, found mainly on hard substrates, although Japanese species have been found on sandy bottoms.

Table 2. b. The Kalibeng gastropod molluscs

FAMILY	TAXON	Sublittoral zone		Substrate		Habitat
CLASS GASTROPODA		**Nearshore**	**Offshore**	**Soft**	**Hard**	
Cerithiidae	? *Cerithium* Bruguière, 1789	X		X	X	Living on sandy to muddy bottoms of marine and estuarine environments, though small species may abound under rocks or on marine vegetation
Chilodontidae	*Vaceuchelus* Iredale, 1929	X			X	Intertidal, living on rocky substrate near shore
Columbellidae	*Mitrella* Risso, 1826	X			X	Among stones and weed, common in coral reef areas. Intertidal and shallow subtidal waters.
Epitoniidae	*Epitomium* Röding, 1798	X		X	X	Subtidal to 29 m
Eulimidae	*Melanella* Swainson, 1840	X		parasitic		Sublittoral, muddy sediments
	Fusinus Rafinesque, 1815	X		X		On sandy bottoms, intertidal and sublittoral zones
Fissurellidae	*Diodora* JE Gray, 1821	X			X	Subtidal on rocks
Marginellidae	*Cryptospira* Hinds, 1844	X		X		Shallow water, in mud
? Muricidae		X		X		On muddy littoral rocks
Nassariidae	*Nassarius* Duméril, 1805	X		X		On clean sand bottoms, often associated with coral reefs. Intertidal and shallow subtidal zones
Naticidae	*Polinices* Montfort, 1830	X	X	X		On sandy to muddy bottoms. Intertidal to shelf zones, to a depth of about 100 m.
Olivellidae	*Olivella* Swainson, 1831	X		X		Burrowing in sand bottoms, at shallow subtidal depths.
Pyramidellidae	*Chrysallida* Carpenter, 1856	X		X		Shallow water, sand

FAMILY	TAXON	Sublittoral zone		Substrate		Habitat
		Nearshore	Offshore	Soft	Hard	
Ranellidae	*Cymatium* Röding, 1798	X			X	In coral reef areas, low tide marks and shallow sublittoral waters to a depth of about 15 m.
Ringiculidae	*Ringicula* Deshayes, 1838	X	X	X		Soft bottoms
Solariellidae	*Solariella* SV Wood, 1842	X		X		Infralittoral and circalittoral and estuary
Turridae	*Drillia* Gray, 1838	X		X	X	Mostly living in soft substrates, but some species also occurring in rock and coral reef habitats. May abound in sublittoral and shelf zones.
Turridae	*Gemmula* Weinkauff, 1875	X		X		Deep water, mostly living in soft substrates, but some species also occurring in rock and coral reef habitats. May abound in sublittoral and shelf zones.
Turritellidae	*Turritella* Lamarck, 1799	X		X		On soft bottoms, from shallow sublittoral zones to a depth of about 30 m.
Turritellidae	*Turritella terebra* Linnaeus, 1758	X		X		On soft bottoms, from shallow sublittoral zones to a depth of about 30 m.

Table 3. Shell abundance, bivalves and gastropods, recovered from Upper Kalibeng layers in Sangiran.

Family	**Taxon**	**SITES**						
CLASS BIVALVIA		**S2**	**S1**	**PR3**	**PR1**	**PK2**	**PK4**	**PK5**
Arcidae/Noetiidae		0	0	0	2	10	1	0
Arcidae	*Anadara sp.*	7	9	0	0	70	0	0
Arcidae	*Arca sp.*	0	0	0	0	0	0	1
Arcidae	*Arcopsis sp.*	0	0	0	0	14	0	0
Corbulidae	*Corbula sp.*	0	0	0	1	5	0	5
Corbulidae	*Varicorbula sp.*	0	8	0	1	41	4	2
Crassatellidae	*Bathytormus sp.*	3	0	0	0	0	0	0
Glycymerididae	*Glycymeris sp.*	4	2	0	6	16	17	67
Kelliellidae	*Alveinus sp.*	0	0	0	0	1	7	0
Lucinidae	*Cardiolucina sp.*	0	0	0	0	0	0	1
Lucinidae	*Myrtea sp.*	23	4	0	15	0	4	3
Myochamidae	*Myochama sp.*	0	0	0	1	0	0	0
Pectinidae	*Amusium sp.*	1	36	0	0	0	4	0
Pectinidae	*Mimachlamys sp.*	3	3	0	0	3	1	0
Placunidae	*Placuna sp.*	4	48	600	0	4	0	0
Plicatulidae	*Plicatula sp.*	0	0	0	0	3	0	0
Veneridae	*Timoclea sp.*	6	0	0	0	3	0	3
Veneridae	*Venus sp.*	0	0	0	0	0	4	3
Veneridae	Veneridae	0	110	0	0	0	0	0

Family	Taxon	SITES						
CLASS GASTROPODA		**S2**	**S1**	**PR3**	**PR1**	**PK2**	**PK4**	**PK5**
Calliostomatidae	*? Calliostoma sp.*	0	0	0	0	2	0	0
Cerithiidae	*? Cerithium sp.*	0	0	0	0	0	0	2
Chilodontidae	*Vaceuchelus sp.*	0	0	0	0	1	0	0
Columbellidae	*Mitrella sp.*	0	0	0	0	6	0	0
Epitoniidae	*Epitonium sp.*	0	1	0	0	1	0	0
Eulimidae	*Melanella sp.*	0	0	0	1	0	0	0
Fasciolariidae	*Fusinus sp.*	1	0	0	0	0	0	0
Fissurellidae	*Diodora sp.*	0	0	0	0	4	0	0
Marginellidae	*Cryptospira sp.*	0	0	0	13	6	0	0
? Muricidae	? Muricidae	0	0	0	0	1	0	0
Nassariidae	*Nassarius sp.*	0	0	0	1	0	0	0
Naticidae	*Polinices sp.*	0	0	0	2	0	0	1
Olivellinae	*Olivella sp.*	0	0	0	1	0	0	0
Pyramidellidae	*Chrysallida sp.*	0	0	0	0	1	0	0
Ranellidae	*Cymatium sp.*	1	0	0	0	0	0	0
Ringiculidae	*Ringula sp.*	1	0	0	1	11	0	0
Solariellidae	*Solariella sp.*	2	0	0	0	4	0	0
Turridae	*Drillia sp.*	0	0	0	0	0	0	1
Turridae	*Gemmula sp.*	0	0	0	0	0	0	1
Turritellidae	*Turritella sp.*	674	194	0	0	0	0	0
Turritellidae	*Turritella terebra*	0	0	0	0	0	0	3

Table 4. Kalibeng relevance of species, species richness and diversity

SITE	S2	S1	PR3	PR1	PK2	PK4	PK5
Richness (S)	13	10	1	10	21	8	13
No. of Individuals (N)	730	415	600	44	195	42	91
Shannon-Wiener Index (H')	0.421	1.093	0.011	1.796	1.093	1.738	0.796
Evenness (E)	0.164	0.475	-	0.780	0.359	0.836	0.310

1. b. 1. Shells from the Lower Pucangan layers

Pucangan mollusc samples are from natural assemblage in the catchment areas of lower Pucangan layers. They are from exposures of natural sections and well-preserved outcrops along the Puren and Cemoro rivers. Shell diversity in Pucangan is presented according to the stratigraphic sequence of the study area. Faunal examination was made on eleven samples from the stratigraphic lower facies of Pucangan. The oldest deposit is the *Corbicula* Bed, with three shell samples: Pablengan 1 and 2 (P1 and P2) and Pablengan Kulon 1 (PK1). It is followed by the lower Pucangan layers with two sedimentary deposits: the Lower Lahar, Ngampon (NPN), Pondok (PDK) and South of Museum (SM), and the Black Clay with five sampled sites, Krikilan 1-4 (K1, K2, K3 and K4) and Pablengan Kulon 3 (PK3). The *Corbicula* Bed contains marine and freshwater bivalves and gastropods while the Lower Lahar and Black Clay have only freshwater shells. The abundant and widespread species were bivalves *Corbicula gerthi* and *Corbicula pullata,* orb-shell mussels, indicating the earliest development of continental environment in the area.

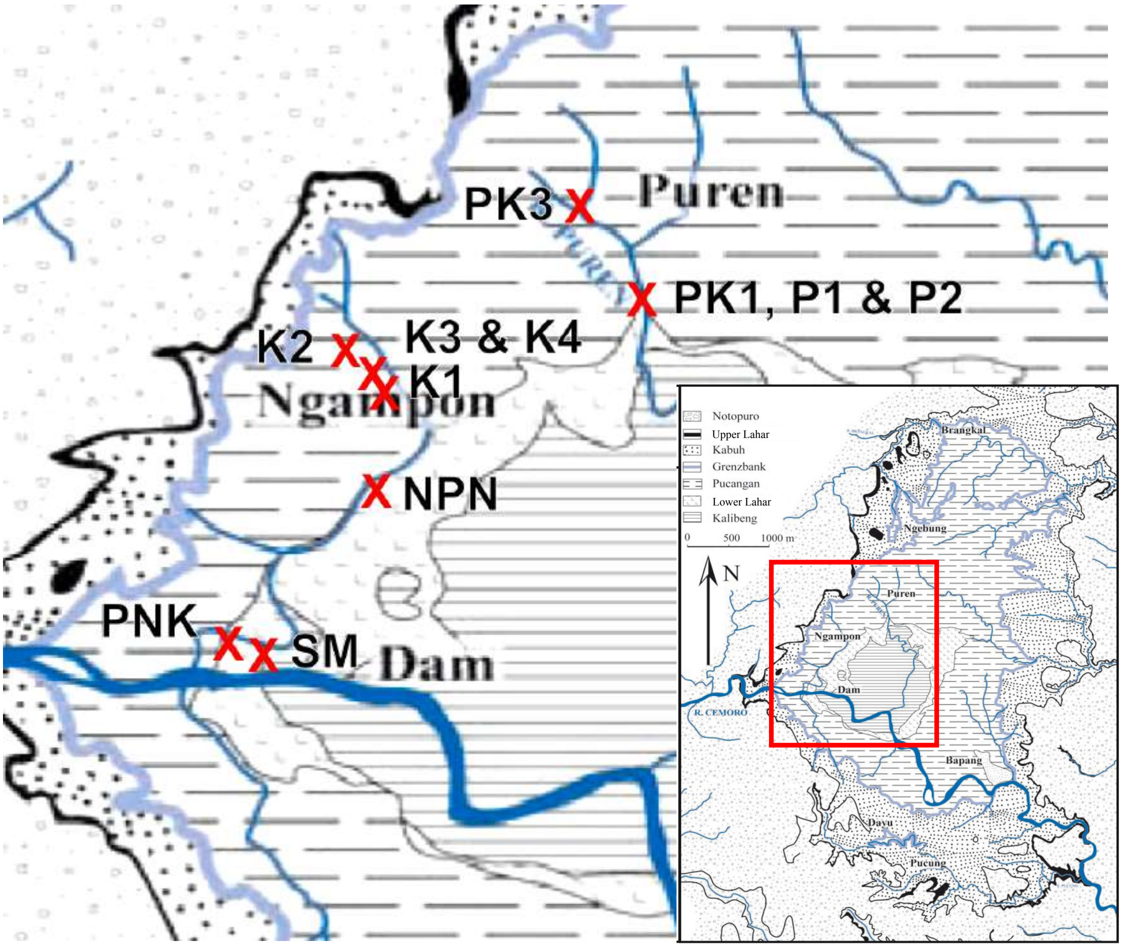

Figure 25. Location of shell sampling sites in the *Corbicula* Bed (PK1, P1 and P2), Lower Lahar (NPN, PNK and SM) and the Black Clay (PK3, K1-K4). Geological map of Sangiran and its stratigraphy based on Von Koenigswald plan (1940) modified by Watanabe and Kadar (1985) and Sémah et al. (1992) see Brasseur et al., 2015.

Mollusc assemblages from the *Corbicula* Bed, the Lower Lahar and the Black Clay picture developing landmass and freshwater basins along with near-shore marine environments. This is greatly supported by sampled sites from the *Corbicula* Bed that correspond, especially along the Puren river, to a transition facies between marine and continental deposits.

P2 had 12 species present, six taxa from both marine and freshwater environments. The composition of the marine species from this site has a near-shore environment living in hard substrate. Marine bivalve shells are well represented from the family Mesodesmatidae and genus *Glycymeris* in this sample. For gastropod, only genus *Diodora* was retrieved. Freshwater shells are only from families Corbiculidae and Thiaridae living in both lotic and lentic environments in fast flowing freshwater streams. Freshwater ecology was characterized and supported by having the most numerous *Corbicula gerthi* and *Corbicula pullata*.

PK1 has the most taxa present- eight marine and two freshwater bivalves, and five freshwater gastropods, in the *Corbicula* Bed. Numerous individuals of marine bivalves namely, species from family Mesodesmatidae, genus *Cardites* and *Circe* and a single gastropod, *Trochoidea s.l.* are present in this facies. The marine mollusc assemblage postulates a shallow water coastline on sandy and muddy bottoms with flowing water in swamps further inland. Corbiculidae and Thiaridae of freshwater molluscs dominated the area with limited *Bellamya javanica* and *Trochoidea* sp.

P1 has the least species present and individuals among the *Corbicula* Bed sampled sites. Moreover, there is only one marine species in the site, *Corbicula sp.* Freshwater bivalves show the largest number of individuals and gastropods. They are represented by *Tarebia granifera* and *Thiara sp.* All freshwater molluscs have lotic ecosystems in a low energy water movement SM site is located behind the Krikilan Museum where outcrops of volcanic sediments belonging to the Lower Lahar unit were found. The site is near the Cemoro dam.

SM has less representation of shell species, only family Corbiculidae for bivalves and Thiaridae for gastropods were observed. Additionally, this site had the least number of species deposited which reflects a lotic environment in the lahar deposits.

PNK is also located near the Cemoro dam. It has the most number of shell taxa present among sites from the lower lahar deposit. Bivalve species from family Corbiculidae still have a high number of species individuals and gastropod species from family Thiaridae have a relative equal distribution of species individuals in the shell sample. Besides these species from the two families, bivalve *Elongaria orientalis*, and gastropod species *Planorbis sp.* and *Sulcospira sp.* are also present. *Planorbis sp.* lives in very low salinity environments, and commonly associated with algae and macrophytes (Smith and Kershaw, 1979; Stanisic, 1998). Occurrence of these mentioned molluscs in Pondok denotes a change in the riverbed that entails a quiet shallow stream with riparian vegetation.

Ngampon (NPN) site is presently located near the Cemoro dam. It has a single species of Hydrobiidae and absence of *Bellamya javanica* among gastropods. In this sample, *Elongaria orientalis* for bivalves and *Thiara winteri* for gastropods have the most number of individuals among the sampled sites in the Pucangan formation. Based on the shell assemblage, they live mostly in lakes, ponds and streams and in fast flowing running water.

Figure 26. *The Corbicula* Bed and the Lower Lahar sampled sites: *Corbicula* Bed - A) Pablengan 1, B) Pablengan 2 and C) Pablengan Kulon 1; Lower Lahar – D) Ngampon, E) Pondok and F) South of Museum (SM) © MGPGFaylona November 2015/June 2016

Figure 27. Cemoro dam at the Sangiran dome

Overlying the Lower Lahar is the Black Clay, concentrated in the central part of Sangiran dome with intercalations of silt, sand, shell bed, foraminiferal sand, diatomites and eleven white tuffs (See in Fae, 1996). Black Clay deposits were sampled along the banks of Puren in Pablengan area. PK3 has the most number of individual species from family Corbiculidae among sites in the deposit. It has also a good representation of gastropod species from *Bellamya javanica* and families Pachychilidae and Thiaridae. These species stage a lotic environment from low to high-energy water flow in vegetated streams and shallow areas in lakes and rivers.

Shell beds in the Black Clay deposits, containing freshwater molluscs, is also evident in the eroded hill in the fields of Krikilan at the Pucangan formation. Four samples from the shell beds in Krikilan were taken from the vast clay deposit. The bivalve species present in Krikilan sampled sites have more or less similar mollusc assemblage with PK3.

Figure 28. Pucangan Black Clay sampling sites: A) Krikilan 1, B) Krikilan 2, C) Krikilan 3, D) Krikilan 4 and E) Pablengan Kulon 3 © MGPGFaylona November 2015/June 2016

Figure 29. Krikilan area in Sangiran dome © MGPGFaylona November 2015

K1 is above the stream bank of Puren where the shell bed is exposed. Shells from this site yielded the least number of species among sampled sites in Krikilan. Bivalves from the sample are well represented by family Corbiculidae and Unionidae. On the other hand, gastropods are dominated by species from family Thiaridae. Limited species individuals were found from family Pachychilidae and Viviparidae. This suggests a combined shallow quiet and fast flowing freshwater that may be attributed to the width of the river channel and landscape, which has ‘lowland and highland,’ in the area.

K3 is where the shell bed was sloped/inclined in the exposed wall of eroded hill. It has the most represented taxa among the Black Clay deposits, however, it did not accumulate thousand individuals as compared to other sampled sites from the same deposit. Species present has both lotic and lentic environment. Lentic environment was represented by *Bellamya javanica* and *Planorbis sp.* that mostly live at the vegetation-zone at the bottom of stagnant water.

Above K3 is the K4, where the exposed shell bed located at the foot of the eroded hill along the stream bank in Krikilan area of Sangiran dome. K4 has the most number of mollusc species among the sampled sites in the Black Clay deposit and the most number of individuals from family Corbiculidae. The shell assemblage is mostly from families Corbiculidae and Thiaridae that have a lotic freshwater environment.

Location of K2 is in the uppermost part of the eroded hill where the shell bed is visible. K2 has the same number of mollusc species as K1. However, the bivalves from family Corbiculidae and Unionidae are not highly represented in the assemblage as well as the gastropod from Pachychilidae. There is also a big drop in the number of individuals among Thiariade species as compared to K1. Moreover, sampled shells include the same species present as K3. The only difference is less species from families Pachychilidae and Thiaridae and more populated *Bellamya javanica.* Species presence from family Thiaridae establishes a lotic freshwater environment of shallow fast flowing rivers regardless of the drop number of species individuals.

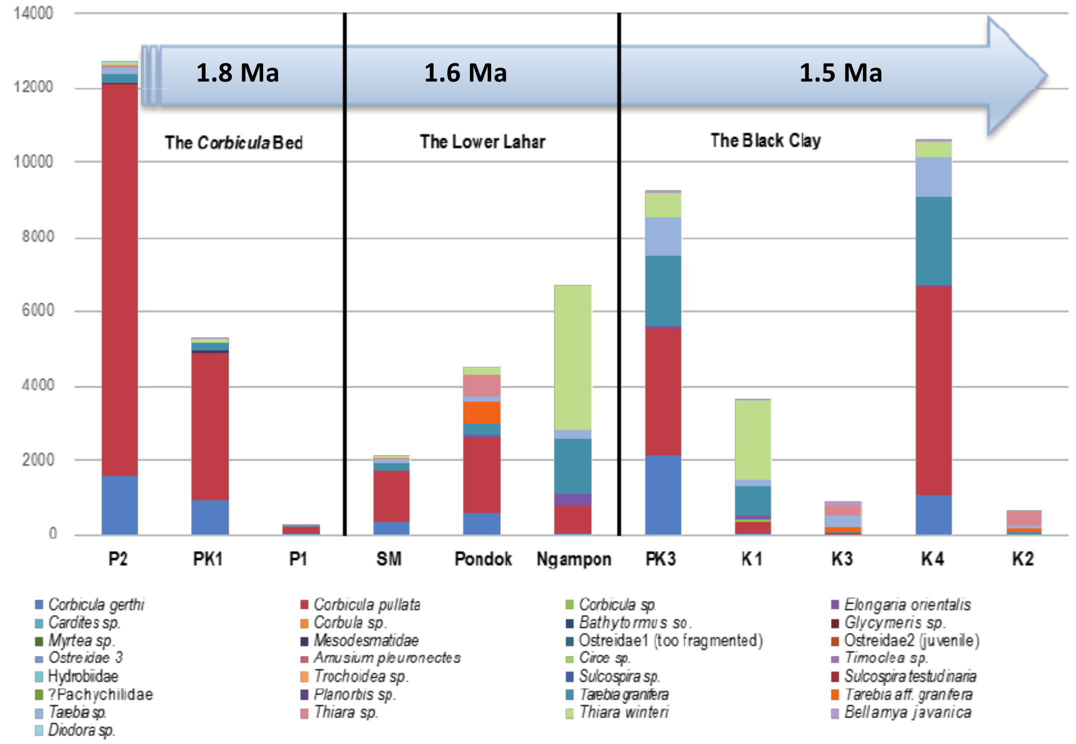

Figure 30. Pucangan shell bivalve and gastropod frequency distribution

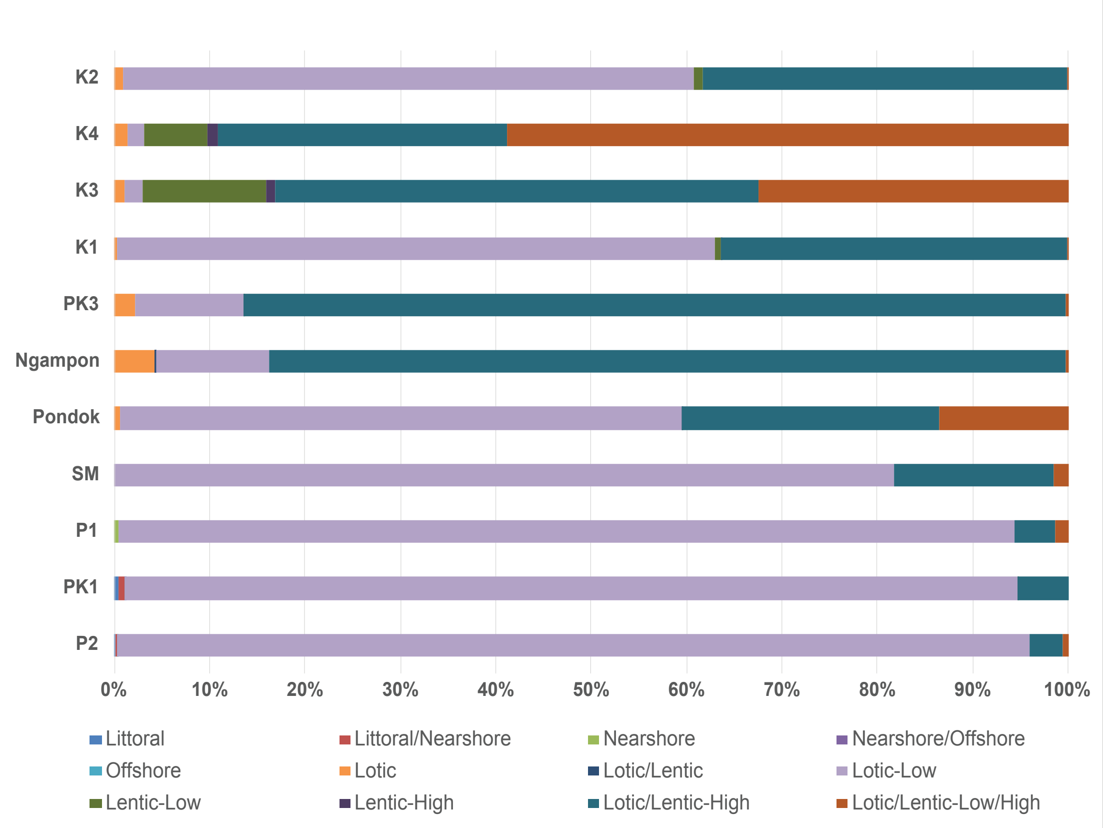

Figure 31. Pucangan ecology. Starting with mollusc assemblages living in lotic ecosystem with low energy water runoff in the *Corbicula* bed sampled sites, slowly replaced by a combined lotic and lentic ecosystem with high energy water runoff from the Lower Lahar mollusc assemblages. Afterwards, it begins to fluctuate from lotic to lotic/lentic ecosystems from the Black clay mollusc assemblages.

Table 5. Ecological distribution and characteristic taxa recovered in Pucangan layer

Table 5.a. Marine shells in Pucangan formation

FAMILY	**TAXON**	**Littoral zone**	**Sublittoral zone**		**Substrate**		**Habitat**
CLASS BIVALVIA			**Nearshore**	**Offshore**	**Soft**	**Hard**	
Carditidae	*Cardites* Link, 1807	X	X			X	On various littoral and shallow sublittoral bottoms.
Corbulidae	*Corbula* (Anisocorbula) Iredale, 1930		X	X	X		Lives on subtidal and intertidal mud flats, partially buried in soft sediment. Occasionally on the lower shore as well as in muddy sand and gravel and most are in abundant offshore.
Crassatellidae	*Bathytormus* Stewart, 1930		X		X		Shallow water in littoral zone with soft and sand-mud bottoms.
Glycymeridae	*Glycymeris* da Costa, 1778			X	X		In sublittoral muddy-sand bottoms
Lucinidae	*Myrtea* Turton, 1822			X		X	Deep, offshore habitats with cohesive sandy mud (>20% mud)
Mesodesmatidae Gray, 1840		X			X		Intertidal. In sandy bottoms and beaches.
Ostreidae Rafinesque, 1815		X	X		X	X	Intertidal and shallow subtidal water. Attached to various hard substrates or objects, and on soft bottoms
Pectinidae	*Amusium pleuronectes* (Linnaeus, 1758)			X	X	X	On sand and mud bottoms. Sublittoral, from depth of 10 to 80 m

FAMILY	TAXON	Littoral zone	Sublittoral zone		Substrate		Habitat
CLASS BIVALVIA			**Nearshore**	**Offshore**	**Soft**	**Hard**	
Veneridae	*Circe* Schumacher, 1817	X	X		X	X	Shallow water in low intertidal to subtidal depths. Active burrowers in various soft bottoms, sometimes nestling in rock crevices or among marine growths.
Veneridae	*Timoclea* T. Brown, 1827		X	X	X		Intertidal. Found in sand, muddy-sand and gravel offshore, at depths ranging from 3 m to 180 m.
CLASS GASTROPODA							
Fissurellidae	*Diodora* JE Gray, 1821		X			X	Subtidal on rocks
Trochoidea (Superfamily)	*Trochoidea* Rafinesque, 1815	X	X		X	X	Mostly littoral and shallow sublittoral, occurring in large number on hard substrates like rocky shores or coral reefs and in muddy-sand bottoms.
Mesodesmatidae Gray, 1840		X			X		Intertidal. In sandy bottoms and beaches.

Table 5.b. Freshwater shells in Pucangan formation

FAMILY	**TAXON**	**Ecosystems**		**Water Energy**		**Habitat**
CLASS BIVALVIA		**Lotic**	**Lentic**	**Low**	**High**	
Corbiculidae	*Corbicula gerthi* (Oostingh, 1935)	X		X		In inland quiet rivers and streams
Corbiculidae	*Corbicula pullata* (Philippi, 1851)	X		X		In inland quiet rivers and streams to occasionally brackish water
Corbiculidae	*Corbicula* Megerle, 1811	X		X		In streams and between sand and mud
Unionidae	*Elongaria orientalis* (Lea, 1840)	X				Forest streams and sandy, shallow areas in lakes and rivers

FAMILY	**TAXON**	**Ecosystems**		**Water Energy**		**Habitat**
CLASS GASTROPODA		**Lotic**	**Lentic**	**Low**	**High**	
Hydrobiidae Stimpson, 1865		X	X			In lakes, ponds, rivers and streams. Some found in brackish water or at the borders between freshwater and brackish water. A few occur in marine environments on sandy or muddy bottoms between algae and sea grass.
Pachychilidae	*Sulcospira* Troschel, 1857	X	X	X	X	Rapid waters, eurytopic (able to tolerate wide range of habitats or ecological conditions)
Pachychilidae	*Sulcospira testudinaria* (Köhler & Dames, 2009)	X	X	X	X	
?Pachychilidae P Fischer & Crosse, 1892			X		X	In fast-flowing oxygenated water on hard substrates
Planorbidae	*Planorbis* Müller, 1773		X	X		Vegetation-zone in stagnant water

FAMILY	**TAXON**	**Ecosystems**		**Water Energy**		**Habitat**
CLASS GASTROPODA		**Lotic**	**Lentic**	**Low**	**High**	
Thiaridae	*Tarebia granifera* (Lamarck, 1822)	X	X		X	Lakes, rivers, shallow fast flowing freshwater streams, ponds and swamps
Thiaridae	*Tarebia aff. granifera*	X	X		X	
Thiaridae	*Tarebia sp*	X	X		X	
?Pachychilidae P Fischer & Crosse, 1892			X		X	In fast-flowing oxygenated water on hard substrates
Thiaridae	*Thiara sp.*	X	X	X	X	In stagnant or running-water
Thiaridae	*Thiara winteri*	X	X		X	Fast-flowing rivers, small ponds
Viviparidae	*Bellamya javanica* (von dem Busch, 1844)		X	X		Bottom or plant dweller, lives in ponds and swamps, and tolerant of disturbance

Table 6. Shell abundance, bivalves and gastropods, recovered from lower Pucangan layers in Sangiran.

Class	Family	Species	THE *CORBICULA* BED			LOWER LAHAR			BLACK CLAYS					Habitat
			P2	**PK1**	**P1**	**SM**	**Pondok**	**Ngampon**	**PK3**	**K1**	**K3**	**K4**	**K2**	
Bivalves	Corbiculidae	*Corbicula gerthi*	1580	938	33	334	582	62	2105	32	6	1075	0	Freshwater
Bivalves	Corbiculidae	*Corbicula pullata*	10550	3954	183	1397	2059	739	3436	315	10	5592	11	Freshwater
Bivalves	Corbiculidae	*Corbicula sp.*	0	0	0	0	0	0	0	61	0	0	0	Freshwater
Bivalves	Unionidae	*Elongaria orientalis*	0	0	0	0	28	288	77	78	10	36	9	Freshwater
Bivalves	Carditidae	*Cardites sp.*	3	11	0	0	0	0	0	0	0	0	0	Marine
Bivalves	Corbulidae	*Corbula sp.*	0	0	1	0	0	0	0	0	0	0	0	Marine
Bivalves	Crassatellidae	*Bathytormus sp.*	0	2	0	0	0	0	0	0	0	0	0	Marine
Bivalves	Glycymerididae	*Glycymeris sp.*	11	0	0	0	0	0	0	0	0	0	0	Marine
Bivalves	Lucinidae	*Myrtea sp.*	5	0	0	0	0	0	0	0	0	0	0	Marine
Bivalves	Mesodesmatidae	Mesodesmatidae	16	25	0	0	0	0	0	0	0	0	0	Marine
Bivalves	Ostreidae1	Ostreidae1 (too fragmented)	0	2	0	0	0	0	0	0	0	0	0	Marine
Bivalves	Ostreidae2	Ostreidae2 (juvenile)	0	1	0	0	0	0	0	0	0	0	0	Marine
Bivalves	Ostreidae3	Ostreidae3	5	0	0	0	0	0	0	0	0	0	0	Marine
Bivalves	Pectinidae	*Amusium pleuronectes*	0	1	0	0	0	0	0	0	0	0	0	Marine
Bivalves	Veneridae	*Circe sp.*	0	11	0	0	0	0	0	0	0	0	0	Marine
Bivalves	Veneridae	*Timoclea sp.*	0	3	0	0	0	0	0	0	0	0	0	Marine
Gastropod	Hydrobiidae	Hydrobiidae	0	0	0	0	0	2	0	0	0	0	0	Freshwater
Gastropod	Pachychilidae	*Sulcospira sp.*	0	0	0	0	4	3	5	6	5	1	0	Freshwater

Class	Family	Species	THE *CORBICULA* BED			LOWER LAHAR			BLACK CLAYS					Habitat
			P2	**PK1**	**P1**	**SM**	**Pondok**	**Ngampon**	**PK3**	**K1**	**K3**	**K4**	**K2**	
Gastropod	Pachychilidae	*Sulcospira testudinaria*	0	0	0	0	3	0	8	5	10	8	0	Freshwater
Gastropod	?Pachychilidae	?Pachychilidae	0	0	0	0	0	0	0	0	6	0	7	Freshwater
Gastropod	Planorbidae	*Planorbis sp.*	0	0	0	0	3	0	0	0	3	1	0	Freshwater
Gastropod	Thiaridae	*Tarebia granifera*	198	203	10	178	273	1500	1861	798	19	2393	69	Freshwater
Gastropod	Thiaridae	*Tarebia aff granifera*	0	0	0	0	615	0	0	0	132	0	62	Freshwater
Gastropod	Thiaridae	*Tarebia sp.*	159	26	0	133	135	205	1054	157	306	1021	61	Freshwater
Gastropod	Thiaridae	*Thiara sp.*	76	0	3	32	604	1	0	0	278	0	374	Freshwater
Gastropod	Thiaridae	*Thiara winteri*	84	51	0	45	187	3910	617	2133	0	444	0	Freshwater
Gastropod	Viviparidae	*Bellamya javanica*	0	1	0	0	0	0	88	2	117	68	42	Freshwater
Gastropod	Fissurellidae	*Diodora sp.*	1	0	0	0	0	0	0	0	0	0	0	Marine
Gastropod	Trochoidea (superfamily)	*Trochoidea s.l.*	0	2	0	0	0	0	0	0	0	0	0	Marine

1. b. 2. Relevance of species, species richness and diversity

The analysis of the shells shows a predominance of bivalves over gastropods, especially freshwater molluscs, both in species richness and in total number of individuals. *Corbicula pullata* had the highest frequency among bivalves and was the most distributed shell in lower Pucangan layer. The marine shells present in the *Corbicula* layer are infaunal taxa where they live in the substrate of a body of water. They are mostly sandy bottom dwellers that inhabit the littoral and shallow sublittoral bottoms. They are also stenohaline species that cannot tolerate as range of salinity in the water. On the other hand, there are five freshwater gastropod species from family Thiariadae and consistently present in all lower Pucangan sites with a sole marine gastropod species, *Diodora sp*. in *Corbicula* Bed layer.

Statistics shows that the mean Shannon diversity index (H) ranges from 0.62 to 2.05 and evenness ranges from 0.25 to 0.82. Among the shell sampled sites in Pucangan, Krikilan 3 (within the Black Clay facies) have the Highest Diversity Index (H) of 2.05 and Evenness (E) of 0.82. Pablengan 2 (within the *Corbicula* Bed) had the lowest H and E but have the most number of shells. The Black Clay had the highest mean richness species, diversity index and evenness. It is followed by the Lower Lahar (H: 1.09-1.61 and E: 0.52-0.67) and *Corbicula* Bed layer (H: 0.62-0.77 and E: 0.25-0.42). Older layers had a less diverse assemblage with greater dominance in species richness. Diversity increased in the younger layers. Evenness in older Pucangan layers was lower than in the younger ones.

Table 7. Pucangan relevance of species, species richness and diversity

SITES	P2	PK1	P1	SM	PDK	NPN	PK3	K1	K3	K4	K2
Richness	12	15	5	6	11	10	9	8	12	10	8
No. of Individuals	12,688	5,231	230	2,119	4,493	6,720	9,251	3,587	902	10,639	635
Shannon-Wiener Index	0.62	0.77	0.68	1.09	1.61	1.19	1.56	1.21	2.05	1.32	1.54
Evenness	0.25	0.29	0.42	0.61	0.67	0.52	0.71	0.58	0.82	0.57	0.71

2. The Plio-Pleistocene aquatic palaeoenvironment of Sangiran Dome

The Sangiran Dome succession, particularly the Upper Kalibeng to Lower Pucangan layers, can be interpreted as a complex transgressive sequence deposited after a long period of emergence. It ranges from littoral marine sediments to freshwater lignitic seams. The facies succession is in good agreement with the existence of eustatic cycles and volcanic eruptions occurred in central Java Island.

Based on presence/absence data of articulated and/or complete specimens from Upper Kalibeng to Lower Pucangan mollusc assemblages reflect various aquatic ecology. This observation indicates that assemblage composition and variations in species abundances are relative to habitat, which are defined on the basis of Sangiran lithosgraphic and taphonomic interpretations (**Tables 3 and 6**; and histograms, **Figures 23 and 30**). These concentrations can be considered of autochthonous origin. The examined shells in Sangiran in their post-mortem condition were neither transported nor biologically altered. This interpretative approach explains the aquatic environment based on the assemblages and defines that habitat preferences of mollusc onthe Sangiran basin.

2. a. Palaeoecology of Upper Kalibeng

Mollusc assemblages comprise of shallow-living taxa, concentrated together with allochthonous elements such as deep-living taxa namely, *Myrtea, Amusium, Placuna, Plicatula, Timoclea* for bivalves and ? *Calliostoma, Polinices, Ringicula* for gastropods and hard bottom dwellers, *Arca* and *Arcopsis* of Arcidae, *Myrtea, Myochama, Placuna* for bivalves and *Vaceuchelus, Mitrella, Diodora* and *Cymatium* for gastropods. They are mostly characterized as a near-shore, shallow marine environment. The dominance of genus *Anadara sp.* and other taxa from family Arcidae suggests the development of a wetland environment. The assemblages also imply that some areas in Sangiran were submerged while other parts started to develop shores at that time.

The diversity and ecological requirements of taxa identified in Kalibeng indicate a sublittoral soft substrate. They all live underwater, which suggests a submersion event. High frequency deposition of *Placuna sp.*, *Varicorbula sp.* and shell fragments from family Veneridae confirm this point, which is also supported by the presence of numerous *Turritella sp.* They all lived in the neritic zone where the water is considered as shallow. Unlike the sole presence of *Placuna* species in PR3 sampled area, it may be attributed to a hydrological event resulting in an accumulation of single species.

2. b. Palaeoecology of Lower Pucangan

Molluscan associations were verified through taphonomic analysis that reveals changing environments within the Lower Pucangan formation, from near-shore marine environments to freshwater continental sedimentation with lahar-infilled lagoons. Analogous associations were supported by the vast *Corbicula* occurred in the *Corbicula* Bed.

Shell assemblages inhabited subsequent streams distributed in the central part of the dome during the early Pleistocene. The presence and abundance of shell species in lower Pucangan layers are positively correlated with the aquatic ecological diversity and habitat association. The layers show an open environment with *Corbicula*, consistently present in large numbers in all sampled sites. They are living in quiet streams and between sand and mud. The species richness of Pablengan Kulon 1 indicates a landscape transformation with marine and freshwater molluscs especially with the presence of *Trochoidea* that can live in different zones and substrates. Endemic bivalve, *Elongaria,* lives in forest streams and present midden-like characteristics in the Lower Lahar and Black Clay deposits that may posit an aquatic mollusc consumption. These two facies have also terrestrial mammals living in a coastal marine or freshwater habitat in Sangiran. With the richness of *Elongaria* in the assemblage, considered as medium-to large-sized shells and shell meat, and presence of terrestrial predators may lead to a symbiosis of aquatic exploitation (Joordens et al., 2009). On the other hand, species abundance and richness of Thiariadae in the layer depicts shallow fast-flowing streams. They are widely distributed in Java and eat algae, rotted plant parts, carrion, and diatoms. Diatoms are evident in the Pucangan layer in Sangiran. Massive incidence of diatoms was observed in the Pablengan area where thousands of Thiaridae were obtained. This suggests another symbolic relationship and supports the sediment pattern and shell deposits in Sangiran.

The studied samples contained neither mangrove shells nor marine molluscs, which is problematic to confer that the assemblage lived in an estuarine environment as compared to the previous studies conducted in Sangiran. Based on the pollen analysis in the first two lithographic units of Sangiran, the blue clay facies are dominated by mangrove forest and the black clay unit shows a decline of mangrove taxa (Sémah AM, 1982b, 1984, 1986). In the mollusc assemblages, they have a minimal representation of family Ostreidae, that can tolerate low salinities and subsequently inhabits brackish environments (Ruppert et al., 2004), in Pablengan Kulon 1. Moreover, the two individuals of Hydrobiidae, living between fresh and brackish water, were found only in Ngampon shell sample. With these assemblages, it is insufficient to verify that there was a mangrove environment from the study area of sampled sites in Sangiran. However, the shell habitat and substrates inform us that it was a wetland environment, a land consisting of marshes or swamps.

Distribution and abundances of molluscs within habitats are controlled by complexly interrelated physical factors namely, basin size, water depth, energy levels, substrate and sediment influx that varied in time and space during their deposition. The twenty-nine molluscan taxa in eleven samples from the *Corbicula* Bed and the Lower Lahar and Black Clay deposits in Lower Pucangan layer of the dome significantly picture low to high-energy flowing waters due to volcanic activity and oscillations that changed the hydrological courses, and to the nature of the basin that headed to landmass development. This is also in relation to elevation, highland or lowland, and the impact of sediment and water run-off in terms of gravity and soil contact to water movement at that time. Furthermore, the environment evolved into shallow, sublittoral lotic ecosystems that can tolerate disturbance in the environment concealed of emergent wetland vegetation.

CHAPTER 4:

PALAEOCLIMATE IN SANGIRAN DOME (CENTRAL JAVA) DURING THE PLEISTOCENE PERIOD [2]

1. Introduction

This chapter presents shell stable isotope analysis to interpret the palaeoclimate of the Early Pleistocene in Sangiran Dome located in Central Java. The site is of major importance for elucidating the Quaternary climate in Java in correlating the dispersal adaptation and evolution of hominins to their environment. Shells are commonly preserved in Quaternary sediments (e.g. Wiedemann, 1972; Holmes, 1996; Pigati et al., 2004; Pigati et al., 2013), therefore shells from these sediments have been used extensively in geological and palaeoenvironmental studies (e.g. Krantz et al., 1987; Romanek & Grossman, 1989; Goodfriend, 1992; Davis & Muehlenbachs, 2001; Gillikin et al., 2005**)**. Shells from this sediment contained many isotopic clues about the calcification physiology and environmental conditions that prevailed during shell formation (Keith et al., 1964; Gibson et al., 2001; Spiro et al., 2009). As such, stable isotopes as geochemical indicators provide biological and ecological information on shell species that may be able to use for palaeohabitat and palaeoenvironment reconstruction (Mook, 1971; McConnaughey & Gillikin, 2008; Leng & Lewis, 2016).

Sangiran underwent distinct changes in environmental conditions in the Early Pleistocene (Sémah et al., 2001). But the numerous studies that have been conducted on the old environment in Java Island (e.g. Urushibara-Yoshino & Yoshino, 1997; Verstappen, 1980 and 1997; van der Kaars et al., 2001; Sémah AM et al., 2004) and the interpretation on the palaeoenvironmental and palaeoclimatic conditions have been

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[2] Presented at the 11th International Conferene on the Application of Stable Isotope Techniques to Ecological Studies (IsoEcol 2018) held at Universidad Andrés Bello in Viña del Mar, Chile on 30 July – 3 August 2018.

based on hominin, mammalian fauna, sediments, and pollen records (e.g. von Koenigswald, 1940; Sémah AM, 1984; Simanjuntak et al., 2001; Bettis *et al.,* 2009; Bouteaux & Moigne, 2010; Sémah AM & Sémah F, 1998 and 2012; Brasseur *et al.,* 2015). The local quaternary climate of this region has not been characterized using shells, and stable isotopes on fossil shells have been scarce (Joordens et al., 2009 and 2014; Jatinigrum, 2014). Spearheaded in Trinil, neighboring area of Sangiran, where fossil shell isotopic values demonstrated an ecological perspective. It revealed that hominins are omnivorous who lived in a coastal environment and consumed shellfish as part of their diet (Joordens et al., 2009).

In this study, we employed stable isotope chemistry to determine the local climatic framework. Our study investigated the $\delta^{18}O$ and $\delta^{13}C$ values, and $^{87}Sr/^{86}Sr$ ratios obtained from the shell samples, which are abundantly present at the bottom layers of Sangiran Dome. This method determines the variation in isotope values among shell species in understanding climate variability at different time scales. Oxygen and carbon isotope data will be interpreted with the evolution of the palaeoclimate in the early Quaternary Sangiran. Variations in $^{87}Sr/^{86}Sr$ will be presented the strontium fluxes that determine water provenance and water salinities of the aquatic palaeoenvironments at Sangiran. Furthermore, we compared and correlated our interpretation from the isotope analysis with other established environmental datasets namely, the fossil pollen and sediment dynamics of the respective beds for reconstructing the palaeoenvironment of the site and the surrounding area. This study will contribute to the analysis of the climate and climate change that occurred in a pivotal area on the migration and adaptation of hominins in view of the palaeoclimatic evolution in Sangiran.

2. Shell isotope geochemistry

Isotope analysis is the identification of the isotopic signature, the distribution of certain stable isotopes and chemical elements within chemical compounds (Fry, 2006). It has become an essential tool for environmental sciences. It has provided clearly defined tracers of sources/provenance and information on the rates of environmental processes (Porcelli & Baskaran, 2012). According to Gillikin et al. (2005), isotopes are atoms of the same element that contain a different number of neutrons resulting in different atomic mass. Different atomic masses within the same element yield chemical and physical properties that produce variances in the abundance of heavy and light isotopes between the source and end products. This difference results in fractionation for the same element, which can be expressed as the *fractionation factor*, α:

$$\alpha = R_A/R_B \text{ (for A } \leftarrow\rightarrow \text{ B)}$$

Isotope fractionation comes from kinetic and equilibrium effects but mostly arises from equilibrium effects (Gillikin, 2005). Data on carbon and oxygen stable isotope analysis are presented as δ values, which is the isotopic ratio of compound A (R_A) relative to the isotopic ratio of a well-defined standard ($R_{standard}$):

$$\delta A = ((R_A/R_{Standards}) -1) * 1000 \text{ (in ‰)}$$

Biomineralization of element in shells can be used as a tracer of environmental changes. Stable isotope chemistry of carbonate in mollusc shell can reconstruct Quaternary climate (e.g. Mook, 1971; Krantz et al., 1987; Bonadonna & Leone, 1995; Freitas et al., 2005). Carbonates precipitate in shells that are in isotopic equilibrium with their surroundings. As the shell develop and grow, the biomineralized carbonates record any shifts in an environmental condition (e.g. Grossman & Ku, 1986; Leng et al., 1999; Schöne et al., 2005; Prendergast & Stevens, 2014). Changes in the physical and chemical environment of the mollusc during its development and growth throughout their lifetime (growth) are recorded. Analysis of the geochemical compositions can reveal the evolution of environmental conditions (temperature, pH, and salinity) and nutrient availability (Prendergast & Stevens, 2014).

2. a. Interpreting shell carbon and oxygen isotopes

Because both carbon and oxygen isotopes were measured simultaneously from one sample, the data are usually interpreted together. Evaporation and precipitation rates are two factors that heavily influenced the ratio of $^{18}O/^{16}O$ from which $\delta^{18}O$ was derived. The $\delta^{18}O$ of pristine (non-diagenetically altered) molluscan carbonate, if precipitated in isotopic equilibrium, is a function of the formation water $\delta^{18}O$ and the temperature at the time of shell formation (Leng & Lewis, 2016). Under such conditions, the relationship between water $\delta^{18}O$, shell $\delta^{16}O$, and the temperature of carbonate precipitation are constrained (Shanahan et al., 2005).

In marine shells, shell composition is controlled by the temperature and isotopic composition of seawater (Kenneth & Voorhies, 1996), whereas, for a terrestrial mollusc, the composition is controlled by the isotopic water (meteoric water) that was ingested by the snail (Leng & Lewis, 2016). For estuarine mollusc, the isotopic composition is controlled by the difference between isotope-salinity of marine and freshwater. This difference records variation in turbidity, temperature, and salinity (Leng & Pearce, 1999). In freshwater molluscs, the preserved isotope composition and values are based on changes in the water. For low latitude lakes, variations in the $\delta^{18}O$ are dominated by evaporation due to dry season (high $\delta^{18}O$) and recharge due to wet season (low $\delta^{18}O$). For open lake systems at high latitudes, variations in the lake water $\delta^{18}O$ are often controlled by the amount, source, and temperature of precipitation (Leng et al., 2001; Bar-Yosef et al., 2012).

On the other hand, carbon isotopic composition $^{13}C/^{12}C$ derived from $\delta^{13}C$ is collected alongside $\delta^{18}O$ from molluscan carbonate. In aquatic environment may it be marine or freshwater, CO_2, and the dissolved inorganic carbon (DIC) ion are often the main sources of carbon for mollusc shells. The inorganic carbon includes carbon dioxide, carbonic acid, bicarbonate anion, and carbonate. $\delta^{13}C$ of carbonate shells is controlled by the isotopic composition of DIC and the pH of the water, which reflect the variable state in the environment at the time of precipitation (Romanek et al., 1992).

Stable carbon isotope analysis of the shell carbonate precipitates in non-equilibrium state with the environment. Non-equilibrium effect can be attributed in part to metabolic effects or kinetic effects that are inherent in fast-growing shells, or certain areas within the shells. Non-equilibrium effect arising from metabolic and kinetic effects influences mainly the carbon isotope signature, which is reflected in the $\delta^{13}C$ values DIC when the carbonates precipitate (Keith et al., 1964; Swart, 1983; Tanaka et al., 1986; Klein et al., 1996; McConnaughey et al., 1997; Dettman et al., 1999; Lorrain et al., 2004; Gillikin et al., 2006; Gillikin et al., 2007; Gillikin et al., 2009).

Carbon isotopic composition $\delta^{13}C$ obtained from the carbonate shells of marine organisms are strongly influenced by photosynthesis, respiration, and upwelling of ocean waters. The process by which older, more ^{12}C-rich waters are brought from the bottom ocean to the surface. Shell is typically a few ‰ lower than ambient $\delta^{13}C$ DIC, which can reflect processes such as changes in salinity (in coastal and estuarine environments) (McConnaughey & Gillikin, 2008). In terrestrial molluscs, $\delta^{13}C$ will be influenced by carbon from several sources including ingested organic matter and carbonates as well as atmospheric CO_2.

Respired CO_2 and ambient inorganic carbon both contribute to the development of mollusc shells. Each source indicates whether $\delta^{13}C$ measured in shells records dietary $\delta^{13}C$ or ambient inorganic $\delta^{13}C$ (McConnaughey & Gillikin, 2008). McConnaughey et al. (1997) suggested that land snails and other air-breathing animals build their carbonates mainly from respired CO_2, while aquatic animals build their shells mainly from ambient inorganic carbon. These carbon sources impart the relationship between the shell carbonate $\delta^{13}C$ and $\delta^{13}C$ DIC values of ambient waters and produce biogenic $\delta^{13}C$ values that can serve as indicators of productivity, palaeo-pCO_2, or palaeoecology (Shanahan et al., 2005).

2. b. Interpreting strontium isotopes on shells

Application of strontium isotope analyses in well-preserved shells are unaffected by any diagenetic or climatological fractionation processes and reflect the Strontium isotope ratio of the host water in which they were growing (Faure, 1986). Strontium commonly occurs in nature and is soluble in aqueous solution as the Sr^{2+}. It has four stable isotopes, ^{84}Sr, ^{85}Sr, ^{86}Sr, and ^{87}Sr. ^{87}Sr is a radiogenic, being produced through the decay of ^{87}Rb. Natural variation in the abundance of $^{87}Sr/^{86}Sr$ ratio can be used to trace strontium sources to surface and groundwater. Hence, Sr ratios are good indicators of the original source of Sr. They may yield information namely, the provenance of a water, the relationships within bodies of water, the changes in the source history of a drainage or watershed (e.g. in lake sediments). Additionally, Sr ratios can be used to determine source contributions to water bodies, to trace nutrient pathways and availability of nutrient pools in ecosystems, to fingerprint and quantify the sources of salinity in river systems, and to indicate preferential flow paths within groundwater systems (Clark & Fritz, 1997). Strontium is generally incorporated in shell carbonates. ^{87}Sr/^{86}Sr ratio reflects the environment at the time of shell formation when they precipitate in equilibrium with the surrounding environmental conditions.

3. Materials and methods

3. a. Materials

Sixty-five unmatched left and right valves were chosen from Sangiran shell samples: eight *Glycymeris* sp. from the Blue Clay of Kalibeng layer, ten each of *Corbicula pullata* from the silty clay *Corbicula* Bed and Lower Lahar layers, and 37 individuals of *C. pullata* from the Pucangan layers. Freshwater *C. pullata* was found throughout the sequence of Pucangan. They are the most represented bivalve species in the *Corbicula* Bed, and in the Lower Lahar and Black Clay of the Lower Pucangan layer. Ten live *Lymnaea javanica* were collected and compared with the shell samples for isotope analyses (**Figure 32**).

Table 8. Bivalve shells from different facies of Sangiran that underwent isotopic analysis

FORMATION	SAMPLED SITE	TAXON
Kalibeng Blue Clay	PK5	*Glycymeris sp.*
The *Corbicula* Bed	PK1	*Corbicula pullata*
Pucangan Lower Lahar	SM	
Pucangan Black Clay	K1-K4 and PK3	
Modern		*Lymnaea javanica*

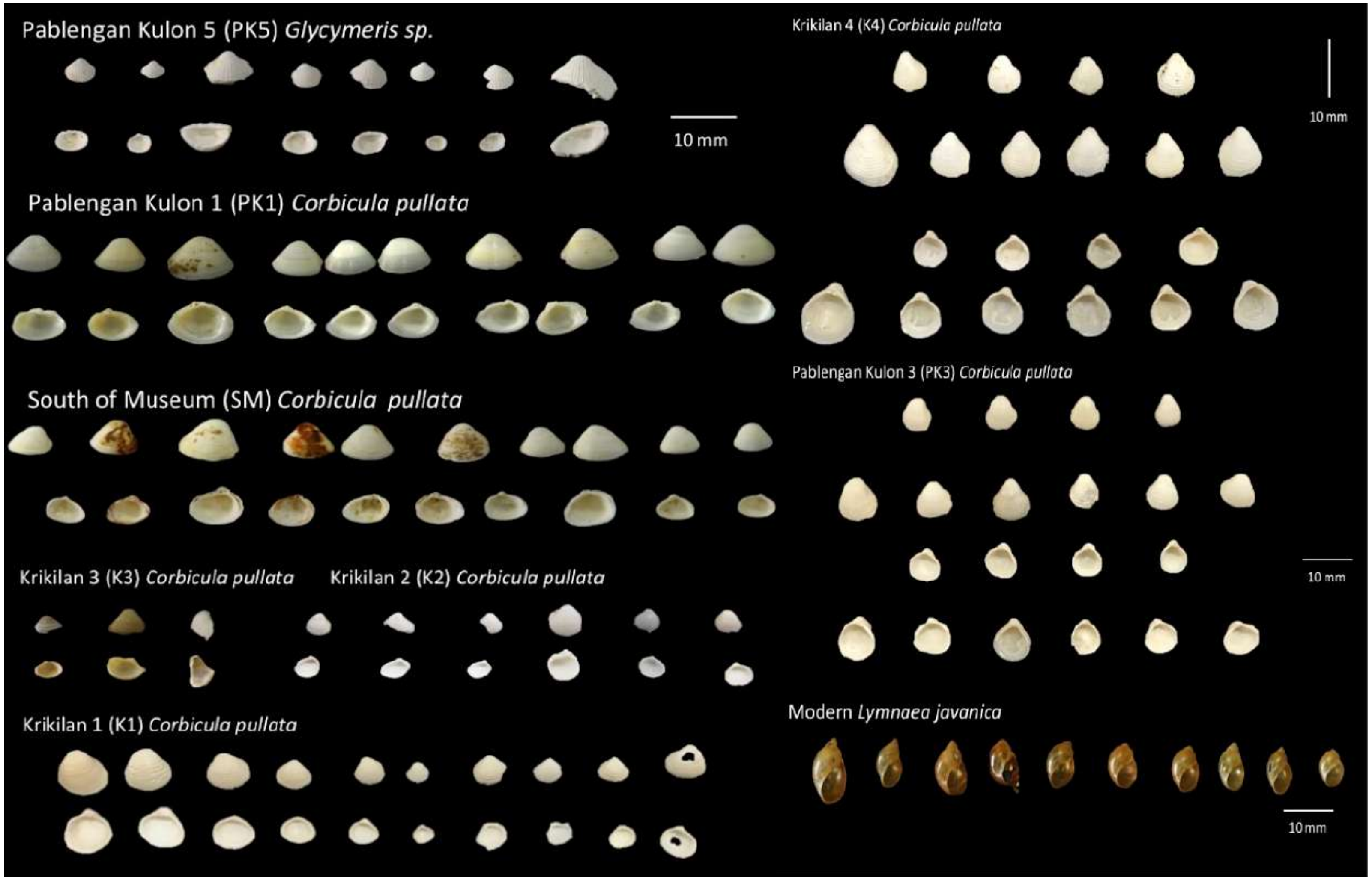

Figure 32. Shells underwent isotope geochemistry analyses © MGPGFaylona July 201

Glycymeris (da Costa, 1778) is a marine bivalve of the family Glycymerididae. They have a long lifespan of more than 20 years. This bivalve lives in a sand-mud bottom at 10 to 80 meters deep in the sea. This genus is distributed in Western Pacific, from Indonesia to Tonga Islands; north to Japan, and south to central Queensland and New Caledonia (Carpenter & Niem, 1998). *Corbicula pullata* (Philippi, 1851) is a freshwater bivalve and lives in streams, quiet-fresh to occasionally brackish waters. *Corbicula* is a native species of Java, especially in the Eastern part. Its distribution extends to Sumatra and Borneo islands of Indonesia. *Lymnaea javanica* (Mousson, 1849) is a freshwater gastropod that lives in vegetation zone of stagnant water, ponds and swamps (Whitten et al., 1996). The genus *Lymnaea* is widespread in Java. It is commonly present in the Puren river of Sangiran and is well distributed in the premises of Sumatra, Banka, Java, Lombok, Sumbawa, Flores, Sumba, Rotti, Semau, Timor, Borneo, Celebes, and Buru. *Lymnaea* occurs in a fossil state in the Pucangan Black Clay layer

3. b. Methods

Each shell was soaked in deionized and demineralized water, and then pretreated in a bath of 5% NaClO by volume at room temperature for two days to remove organic matter. The shells were rinsed three times with distilled water in an ultrasonic bath for five minutes then oven-dried at 50°C for 24 hours. After which, samples were ground to a powder using a mortar and pestle (**Figure 33**). The carbonate powder was placed in vials. All shell samples were submitted for X-ray diffraction analysis at the Analytical Testing Centers at Nanjing Normal University in China (Appendix I). Results revealed aragonite mineralogy (Appendix II). The results indicate that the modern gastropods and fossil bivalve shells were exposed to minimal diagenetic alteration and are likely to have preserved their primary isotopic signatures.

Oxygen and carbon isotope ratios were measured at the Isotope Laboratory at Nanjing Normal University. A subsample of approximately 0.4 mg was used for analysis. Measurements were run using an on-line automated carbonate preparation system (Kiel Carbonate Device) that was linked to a Finnigan MAT-253 mass spectrometer (Figure 33). The precision of δ^{18}O is 0.06‰ and δ^{13}C is 0.08‰ based on

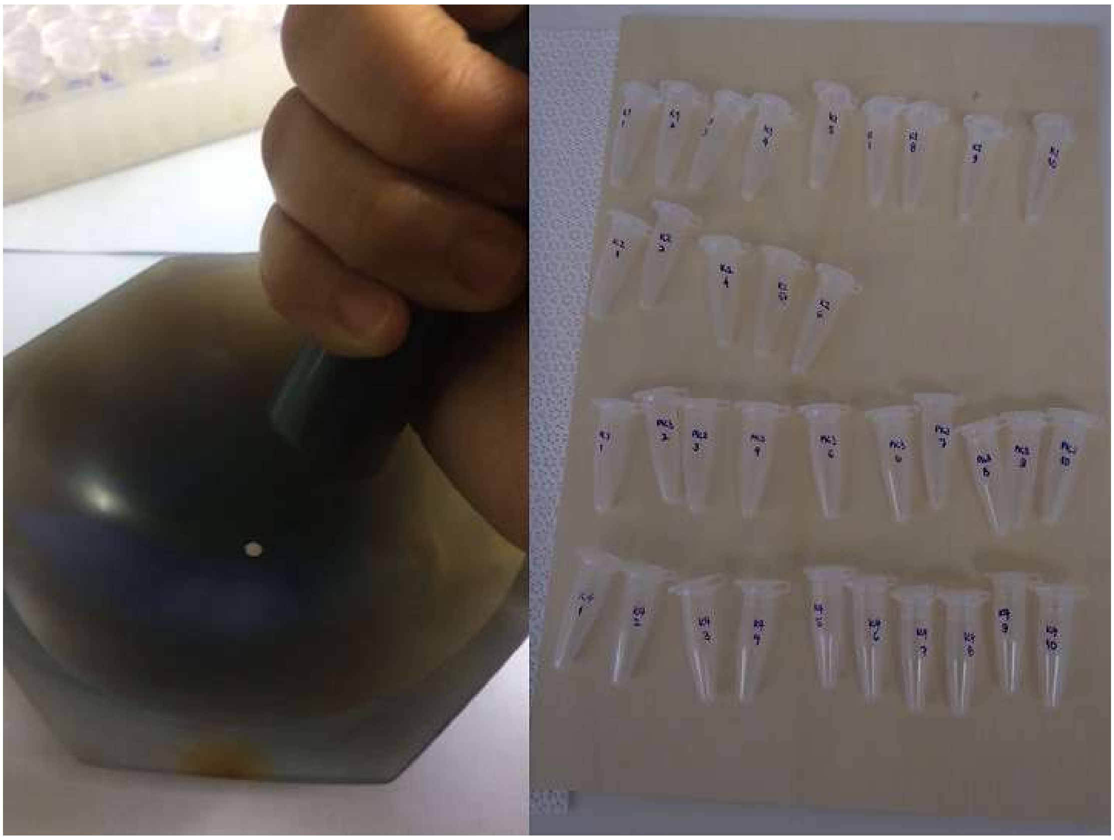

Figure 33. Sample preparation for isotope geochemical analysis © MGPGFaylona July 2017

replicate analyses of the laboratory standards. Another subsample was sent to Nanjing University for strontium isotope analysis.

All carbonate results are reported in per mil (‰) notation with respect to the Vienna Pee Dee Belemnite (VPDB), originally referred to as the Pee Dee Belemnite (PDB) as the international reference standard. VPDB is based on a Cretaceous marine fossil shell of an extinct organism called *Belemnitella americana*, which was from the Pee Dee Formation in South Carolina. The PDB was used to report the carbon and oxygen isotopic compositions of carbonate minerals such as shells expressed as δ (del) notation of isotope proportions (Allan & Wiggins, 1993; Miller & Wheeler, 2012). The original supply of this standard has long been exhausted; therefore, secondary standards have been introduced whose isotopic compositions have been calibrated relative to PDB. The isotope values relative to PDB now use the term VPDB to indicate that the data are normalized to the values of that standard as recommended by the Commission on Atomic Weights and Isotopic Abundances of the International Union of Pure and Applied Chemistry (Coplen, 1994 & 1996).

Figure 34. One of the on-line automated carbonate preparation system (Kiel Carbonate Device) linked to Finnigan MAT-253 mass spectrometer at the Isotope Laboratory of School of Geographical Sciences at the Nanjing Normal University. © MGPGFaylona July 2017

4. Results and Discussion

4. a. Presentation of data

4. a. 1. Shell $\delta^{18}O$ and $\delta^{13}C$

The results of isotopic analyses on shell carbonates from modern and fossil samples are presented in Table 8 and 9. Data are presented as frequency distribution plots (**Figure 35**). The $\delta^{18}O_{shell}$ of fossil *Glycymeris sp.* ranged from -

1.53‰ to -1.22‰ (mean= -1.40‰ ± 0.31‰, n=8), while $\delta^{13}C_{shell}$ ranged from 1.80‰ to 2.47‰ (mean= 2.18‰ ± 0.66‰, n=8). The $\delta^{18}O_{shell}$ of fossil *Corbicula pullata* ranged from -6.32‰ to 2.04‰ (mean= -1.56‰ ± 8.36‰, n=57), while $\delta^{13}C_{shell}$ ranged from -6.34‰ to 1.33‰ (mean= -3.25‰ ± 7.67‰, n=57). In comparison, the $\delta^{18}O_{shell}$ values of modern *Lymnaea javanica* ranged from -4.55‰ to -3.47‰ (mean= -4.17‰ ± 1.08‰, n=10), while $\delta^{13}C_{shell}$ ranged from -12.867‰ to -8.608‰ (mean= -11.1274‰ ± 4.259‰, n=10). This degree of covariation indicates that the incorporation of both elements during the biomineralization was not governed by some common controlling mechanism. Therefore, the sources of carbon that was incorporated into the shells were derived from DIC and not metabolic carbon.

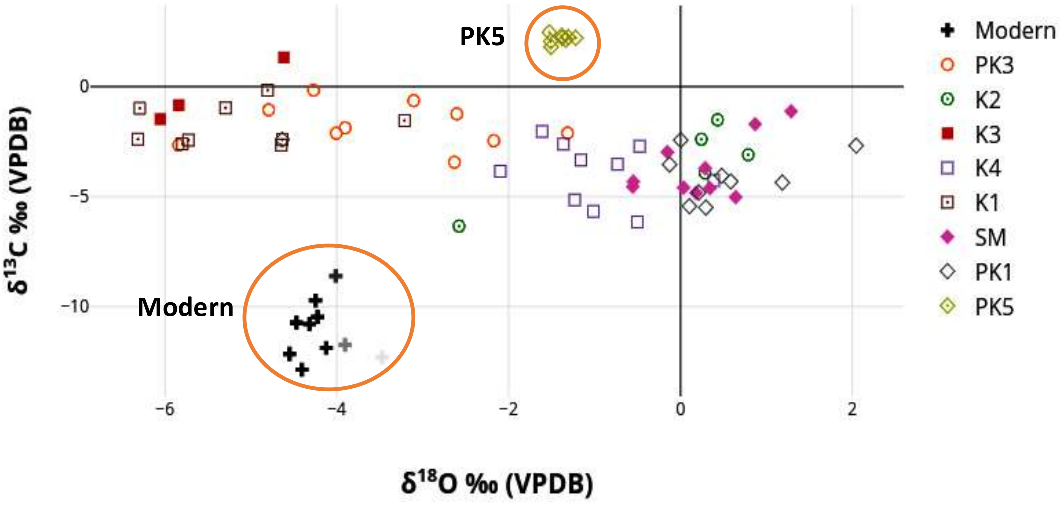

Figure 35. A scatterplot of carbon and oxygen isotopes in shells showing the distribution of values according to Sangiran stratigraphic sequence. Only modern shells and shells sampled in the Kalibeng layer present a constant $\delta^{18}O$ and $\delta^{13}C$ ‰, VPDB.

When the fossil shells were divided according to the Sangiran stratigraphic distribution, the highest mean $\delta^{18}O_{shell}$ was found in the layers associated with Lower Lahar near the base of Pucangan layer, (0.24‰, n=10), closely followed by the *Corbicula* Bed layer, the top of the Kalibeng layer, (0.01‰, n=10). While the lowest mean $\delta^{18}O_{shell}$ values occurred in the Pucangan layer (-2.48‰, n=37) (**Figure 36**).

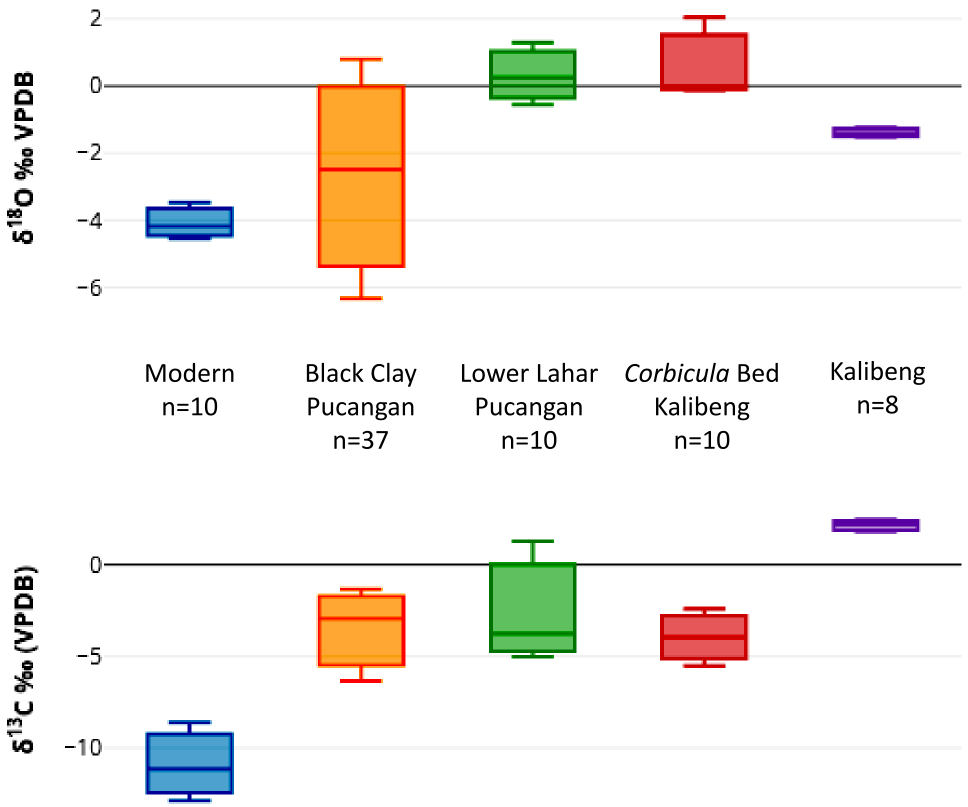

Figure 36. Boxplots of $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ normalized to Sangiran stratigraphic sequence. n= number of individual shells analyzed by layer.

The $\delta^{13}C_{shell}$ values were consistent throughout the sequence. All mean values are in negative values around -3.00 ± 4.00 ‰ except in Pablengan Kulon 5 (PK5), from the Blue Clay of Kalibeng layer, around 2.18 ± 0.66‰. Kalibeng mean $\delta^{13}C_{shell}$ value positive with minimal range isotopic value. Fossil mean $\delta^{13}C_{shell}$ values from the *Corbicula* Bed to the Lower Pucangan layer remained constant but exhibited a wide variability (mean= -3.25 ± 7.67‰). Modern shells exhibited a significantly lower mean of -11.13‰ ± 4.26‰. Their $\delta^{13}C_{shell}$ values were significantly ^{13}C-depleted compared with all fossil shells (**Figure 36**).

Figure 37 shows the correlation of each shell-sampling site to the Sangiran stratigraphic sequence. When the stable isotope results from each sampling site were considered separately, the highest mean $\delta^{18}O_{shell}$ value of 0.24 ± 1.84‰ occurred at the south of Krikilan Museum (SM) – Lower Lahar layer while the lowest $\delta^{18}O_{shell}$ value of -5.50 ± 1.44‰ occurred in Krikilan 3 associated to Pucangan layer.

The Lower Lahar and *Corbicula* Bed series are characterized by generally higher $\delta^{18}O_{shell}$ than the Pucangan layer (Krikilan 1-4 (K1-K4) and Pablengan Kulon 3-PK3) and Kalibeng (Pablengan Kulon 5-PK5) layers. However, within the Pucangan layers, there was a significant ^{18}O depletion of 3.41‰ between PK3 and K1. In the same facies, there was also a large and abrupt shift of $\delta^{18}O_{shell}$ value of 4.52‰ from K3 to K4 at the upper part of Lower Pucangan. Furthermore, isotope zones in different Pucangan layers show an inverse relationship between $\delta^{18}O$ and $\delta^{13}C$.

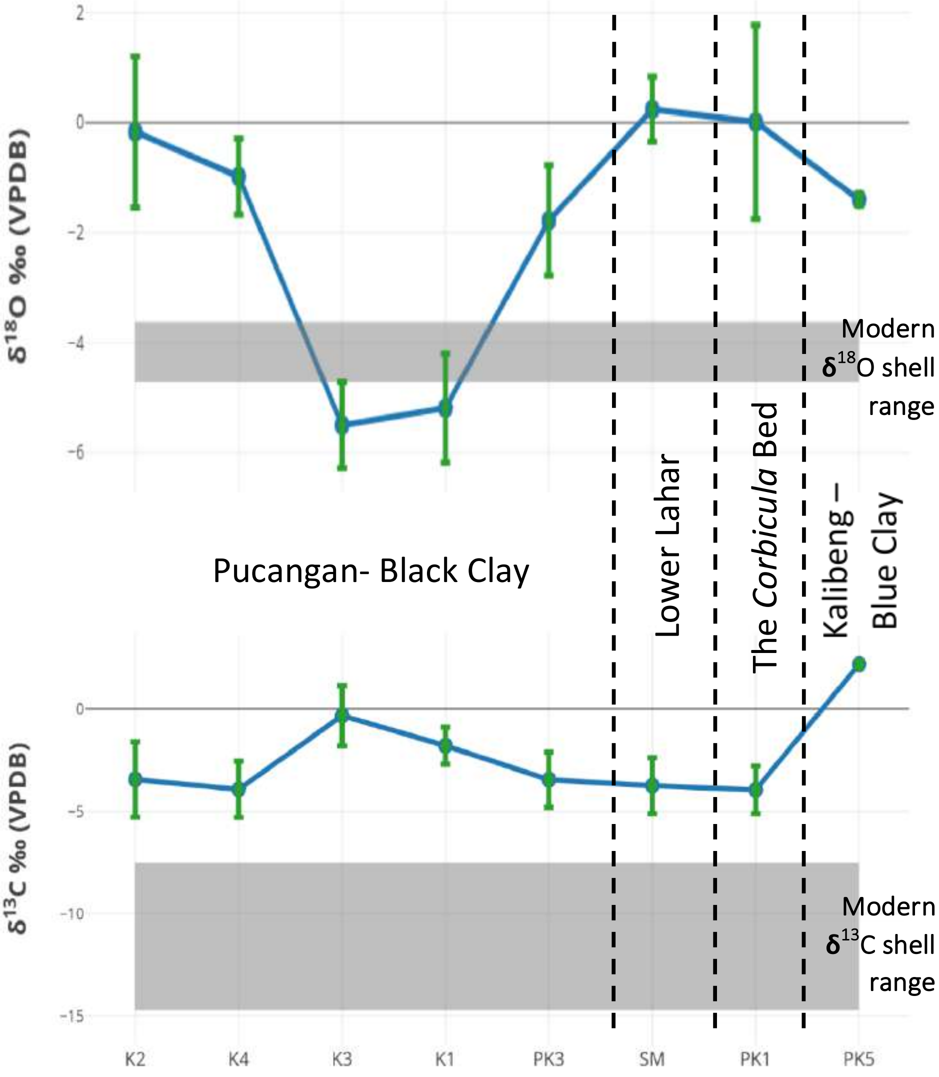

Figure 37. Shell carbon and oxygen stable isotopes from the stratigraphic sequence. The mean values from each site are plotted in relation to their corresponding layer. Error bars are one standard deviation of the mean. Vertical dashed lines show the division of the Sangiran stratigraphic sequence. The grey bars show the mean isotopic range of modern shells in comparison with fossil shells from the different geological context in Sangiran.

Table 9. Oxygen and carbon isotope values and descriptive statistics from Sangiran shells. Results are summarized according to the Sangiran stratigraphic sequence. All isotope ratios are in ‰ (VPDB). SD= standard deviation.

LAYER/ FACIES	**LOCALITY**	**TAXA**	**Habitat**	**Number**	**Shell $\delta^{18}O$**					**Shell $\delta^{13}C$**				
					mean	**range**	**min**	**max**	**SD**	**mean**	**range**	**min**	**max**	**SD**
Pucangan: Black Clay	Krikilan 2	*Corbicula pullata*	Freshwater	5	-0.17	3.37	-2.58	0.79	1.37	-3.45	4.83	-6.34	-1.51	1.84
	Krikilan 4	*Corbicula pullata*	Freshwater	10	-0.98	2.48	-2.10	0.39	0.69	-3.93	4.12	-6.16	-2.04	1.37
	Krikilan 3	*Corbicula pullata*	Freshwater	3	-5.50	1.44	-6.06	-4.62	0.78	-0.33	2.81	-1.48	1.33	1.47
	Krikilan 1	*Corbicula pullata*	Freshwater	9	-5.19	3.10	-6.32	-3.21	0.99	-1.80	2.49	-2.66	-0.17	0.91
	Pablengan Kulon 3	*Corbicula pullata*	Freshwater	10	-1.78	3.28	-3.44	-0.17	1.00	-3.46	4.53	-5.84	-1.32	1.35
Pucangan: Lower Lahar	South of Krikilan Museum	*Corbicula pullata*	Freshwater	10	0.24	1.84	-0.56	1.29	0.59	-3.75	3.90	-5.03	1.12	1.37
Kalibeng: *Corbicula* Bed	Pablengan Kulon 1	*Corbicula pullata*	Freshwater	10	0.01	2.17	-0.13	2.04	1.76	-3.96	3.07	-5.50	-2.41	1.16
Kalibeng: Blue Clay	Pablengan Kulon 5	*Glycymeris sp.*	Marine	8	-1.40	0.31	-1.53	-1.22	0.11	2.18	0.66	1.80	2.47	0.19

Table 10. Oxygen and carbon isotope values and descriptive statistics from sampled shells summarized according to stratigraphic sequence from the different geological context in Sangiran. All isotope ratios are in ‰ (VPDB). SD= standard deviation.

LAYER/ FACIES	LOCALITY	TAXA	Habitat	Number	Shell $\delta^{18}O$					Shell $\delta^{13}C$				
					mean	range	min	max	SD	mean	range	min	max	SD
Pucangan: Black Clay	Krikilan 2	*Corbicula pullata*	Freshwater	5	-0.17	3.37	-2.58	0.79	1.37	-3.45	4.83	-6.34	-1.51	1.84
	Krikilan 4	*Corbicula pullata*	Freshwater	10	-0.98	2.48	-2.10	0.39	0.69	-3.93	4.12	-6.16	-2.04	1.37
	Krikilan 3	*Corbicula pullata*	Freshwater	3	-5.50	1.44	-6.06	-4.62	0.78	-0.33	2.81	-1.48	1.33	1.47
	Krikilan 1	*Corbicula pullata*	Freshwater	9	-5.19	3.10	-6.32	-3.21	0.99	-1.80	2.49	-2.66	-0.17	0.91
	Pablengan Kulon 3	*Corbicula pullata*	Freshwater	10	-1.78	3.28	-3.44	-0.17	1.00	-3.46	4.53	-5.84	-1.32	1.35
Pucangan: Lower Lahar	South of Krikilan Museum	*Corbicula pullata*	Freshwater	10	0.24	1.84	-0.56	1.29	0.59	-3.75	3.90	-5.03	1.12	1.37
Kalibeng: *Corbicula* Bed	Pablengan Kulon 1	*Corbicula pullata*	Freshwater	10	0.01	2.17	-0.13	2.04	1.76	-3.96	3.07	-5.50	-2.41	1.16
Kalibeng: Blue Clay	Pablengan Kulon 5	*Glycymeris sp.*	Marine	8	-1.40	0.31	-1.53	-1.22	0.11	2.18	0.66	1.80	2.47	0.19

4. a. 2. Shell $^{87}Sr/^{86}Sr$ ratio

On the other hand, shell samples from the different facies have different $^{87}Sr/^{86}Sr$ level (Table 10). Marine *Glycymeris* shells from the Kalibeng layer are less radiogenic with starting $^{87}Sr/^{86}Sr$ ratios around 0.709091. It continuously decreases in the *Corbicula* Bed, Lower Lahar and Pucangan layers from the *Corbicula pullata* freshwater samples during the Early Quaternary. *C. pullata* shells contain relatively uniform $^{87}Sr/^{86}Sr$ values between 0.707479 and 0.708268 in the *Corbicula* Bed up to the Pucangan layers. The $^{87}Sr/^{86}Sr$ data presented in this study correspond to the binary mixing model of Palmer and Edmond (1989), Vonhof et al. (1998 and 2003) and McArthur et al. (2001) (see **Table 11**).

Table 11. Sr isotope ratios of molluscan fossil from the Sangiran Dome

LOCALITY	TAXA	Habitat	Sample	$^{87}Sr/^{86}Sr$ (± 1σ)
Pablengan Kulon	*Glycymeris sp.*	Marine	PK5-1	0.708913 ± 0.000058
			PK5-2	0.708945 ± 0.000079
			PK5-3	0.708910 ± 0.000078
			PK5-4	0.708903 ± 0.000082
			PK5-5	0.708905 ± 0.000090
			PK5-6	0.709091 ± 0.000199
			PK5-7	0.708915 ± 0.000075
			PK5-8	0.708949 ± 0.000074
Pablengan Kulon	*Corbicula pullata*	Freshwater	PK1-1	0.708181 ± 0.000064
			PK1-2	0.708123 ± 0.000045
			PK1-3	0.708087 ± 0.000038
			PK1-4	0.708156 ± 0.000060
			PK1-5	0.708135 ± 0.000042
			PK1-6	0.708154 ± 0.000061
			PK1-7	0.708120 ± 0.000038
			PK1-8	0.708204 ± 0.000051
			PK1-9	0.708123 ± 0.000047
			PK1-10	0.708175 ± 0.000043
South of Krikilan Museum	*Corbicula pullata*	Freshwater	SM-1	0.708142 ± 0.000040
			SM-2	0.708268 ± 0.000058
			SM-3	0.708179 ± 0.000036
			SM-4	0.708209 ± 0.000032
			SM-5	0.708179 ± 0.000038
			SM-6	0.708200 ± 0.000048
			SM-7	0.708157 ± 0.000047
			SM-8	0.708094 ± 0.000040
			SM-9	0.708177 ± 0.000043
			SM-10	0.708251 ± 0.000039

Krikilan	*Corbicula pullata*	Freshwater	K3-1	0.707673 ± 0.000130
			K3-3	0.707479 ± 0.000063
Puren River	*Lymnaea javanica*	Freshwater	Mod-1	0.707625 ± 0.000072
			Mod-2	0.707557 ± 0.000064
			Mod-3	0.707693 ± 0.000090
			Mod-4	0.707649 ± 0.000144
			Mod-5	0.707558 ± 0.000094
			Mod-6	0.707721 ± 0.000154
			Mod-7	0.707529 ± 0.000067
			Mod-8	0.707604 ± 0.000096
			Mod-9	0.707620 ± 0.000091
			Mod-10	0.707522 ± 0.000069

4. b. Climate interpretation

4. b. 1. Shell $\delta^{18}O$ and $\delta^{13}C$

Modern *L. javanica* shell $\delta^{18}O$ is used as a baseline value (-4.17‰) for comparison with the isotopic concentration of fossil shell samples in Sangiran. $\delta^{18}O$ values exceeding -4.17‰ reflect lower atmospheric precipitation rates relative to modern climate conditions while $\delta^{18}O$ values lower than the baseline reflect periods of increased atmospheric precipitation. The stable isotope record allows four phases of the sediment sequence to be distinguished. Characterized by the marine mollusc in the Blue Clay of Upper Kalibeng layer with inverse mean isotopic values of $\delta^{18}O$ and $\delta^{13}C$, in which the maximum isotope $\delta^{13}C$ values is recorded in this layer. The shell *Glycymeris sp.* of marine assemblage in a shallow marine environment is characterized by depleted $\delta^{18}O$ and enriched $\delta^{13}C$ values. Local environmental conditions may have influenced the $\delta^{18}O$ of seawater in the Solo Basin, leading to an even more reduced $\delta^{18}O$ values. Carbon and oxygen isotopic ratios of *Glycymeris* seem to indicate a shift in salinity of the aquatic system in Sangiran leading towards to wetland environments.

Followed by gradually increasing $\delta^{13}C$ values and a slight increase of $\delta^{18}O$ of freshwater shells over the transition from marine to continental development in the sediments of *Corbicula* Bed and Lower Lahar, respectively. Isotope records the maximum $\delta^{18}O$ in the Lower Lahar. The positive shift in $\delta^{18}O$ values of carbonates reflected a dry climate in the *Corbicula* Bed of upper Kalibeng and the Lower Lahar of lower Pucangan layers in the Early Pleistocene. Drier conditions were seen in the transition from marine to continental environment in Sangiran dome represented by shells from Pablengan Kulon 1-PK1 (*Corbicula* Bed layer) and South of Krikilan Museum-SM (Lower Lahar layer), 0.01 to 0.24‰. The dry climate in this stage of Early Pleistocene in Sangiran dome might have influenced $\delta^{18}O$ values by means of evaporative enrichment of water in ^{18}O. The shell $\delta^{13}C$ pattern in *Corbicula* Bed and Lower Lahar is flat. Intensifying shell $\delta^{18}O$ and $\delta^{13}C$ is the overall trend with strong depletion of $\delta^{18}O$ at the beginning and were restored at the end of lower Pucangan layer. Isotope phase in the Black Clay series of Pucangan layer began with a negative $\delta^{18}O$ value (PK3) in descending sequence, leaped highly in the middle (K3-K2) and ended with a near 0 $\delta^{18}O$ value (K2). The two notable dry periods were observed in the upper Krikilan sampled area of Pucangan layer, Krikilan 4 and 2, respectively. Pucangan started with increasing precipitation, $\delta^{18}O$ concentration shifted from -1.78 to -5.19‰ between PK3 to K1, followed by Krikilan 3 to 4, in which $\delta^{18}O$ values varied between -5.50 to -0.98‰. Marking the driest period in the Pucangan layer is at the topmost sampled site, K2 with -0.17‰.

The early Quaternary beds, *Corbicula* Bed, and Lower Lahar and Black Clay deposits of Pucangan layers, had a consistent mean shell $\delta^{13}C$ values around -3.0‰ at Sangiran dome (Table 8). Early Pleistocene (Upper Kalibeng layer) mean shell $\delta^{13}C$ value is 2.18 ‰. Changes in shell $\delta^{13}C$ may reflect the changing composition of the environment in the Early Pleistocene. The Solo basin was filled by volcanic deposits including the shallow lagoon in Sangiran that led to continental development and marine influence disappear. The $\delta^{13}C$ shell pattern at the bottom of the Sangiran stratigraphic sequence was almost constant, with minor ^{13}C enrichment in Pucangan layers, Krikilan 1 and 3, -1.80 and -0.33 ‰. Although this peak was not significantly different from surrounding layers, it is worth noting that it coincided with the lowest shell $\delta^{18}O$ peak, suggesting that the increase in humidity has affected the environment in Sangiran, as well as in Central Java during the late lower Pleistocene period. Moreover, higher $\delta^{13}C$ measured in shells ensues from lower atmospheric CO_2, which enriched the ^{13}C concentration in the environment during the Early

Pleistocene. Lastly, the fossil shells ^{13}C values were uniformly enriched compared with modern shells by -11.13‰.

In **Figure 37**, $\delta^{18}O$ were inversely related to $\delta^{13}C$. In general, these values oscillated at extended periods (K2-PK5). The deficit in $\delta^{13}C$ in shells, suggest the occurrence of rainfall events, which resulted in the dilution of the DIC present in aquatic systems and thus the amount of carbonates incorporated into the shells decreased. On the other hand, an increase in the value of $\delta^{13}C$ suggests a drier season, in which the DIC became concentrated due to loss of water in the aquatic ecosystem. Whether the increase in the amount of water deposited by rainfall events was due to increase prevalence of precipitation or increase in the magnitude of the amount of water cannot be deduced from our data and outside the scope of the study. Although these multiple factors may confound our interpretation of the palaeoenvironmental condition based on the isotopic measurements, our results are consistent with a highly productive environment that developed during warmer conditions.

Examined carbonate shells reflect the DIC present in the aquatic system during shell construction. The poor fit between the shell $\delta^{18}O$ and $\delta^{13}C$ values (Figure 34) resulted from the difficulty in apportioning the sources of carbon during shell formation. Difference between the trends of shell $\delta^{18}O$ and $\delta^{13}C$ is expected, especially in freshwater shells, since a major fraction of the dissolved carbon will reflect changes in the sedimentary basin and aquatic productivity because of an evolving landscape, volcanic deposits, and tectonic activities, of the Sangiran Dome in Central Java. The inverse correlation and high variability between $\delta^{18}O$ and $\delta^{13}C$ in Sangiran and the ^{13}C signature obtained from our measurement cannot clearly indicate the palaeoclimate conditions. Furthermore, the significant changes in shell $\delta^{18}O$ were independent of $\delta^{13}C$. Although the shell $\delta^{18}O$ trend suggests a higher occurrence of rainfall events, the rainy condition was not enough to alter significantly the environment in Sangiran Dome.

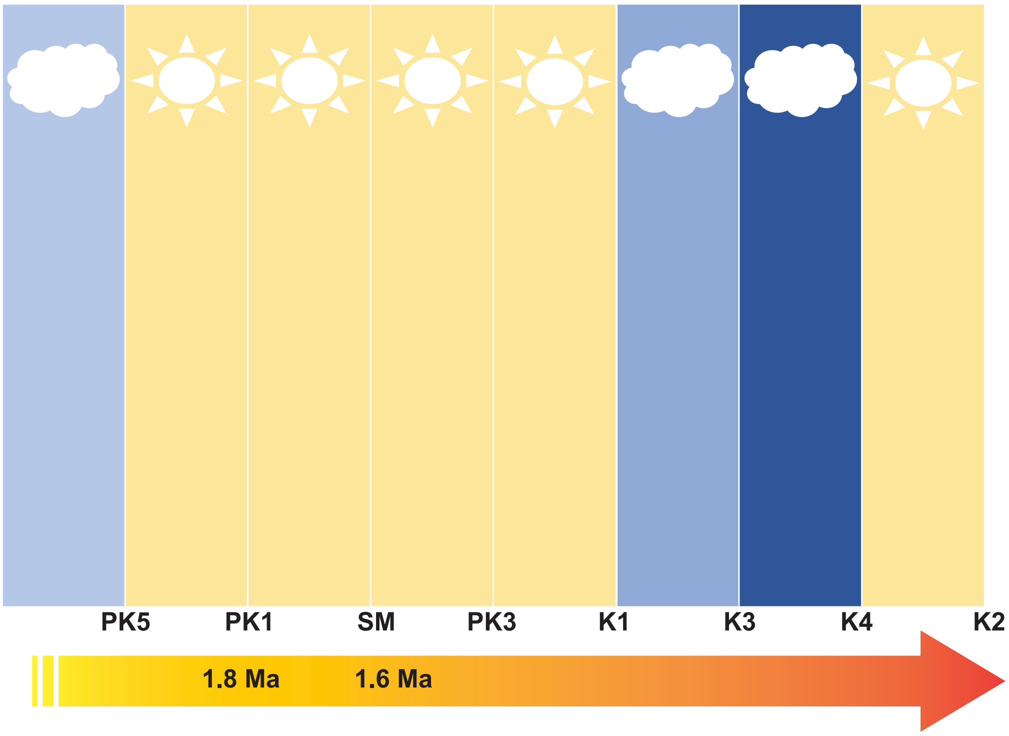

Figure 38. Reconstruction of the environmental condition in Sangiran as interpreted from the stable isotope values from aquatic shells. Sangiran climate oscillated between dry and wet environment conditions. The areas spanning the timeline colored in yellow are dry condition, whereas, those colored in blue are wet conditions. Darker colored indicates the magnitude and frequency of more rainfall events.

4. b. 2. Shell ^{87}Sr/^{86}Sr ratio

The Sangiran marine shell samples from the Upper Kalibeng layer have an average Sr isotope ratio lower than the values of early Pleistocene seawater, 0.709102 (McArthur et al., 2001). This indicates that the shells grew in an environment influenced by ^{87}Sr-rich river water. On the other hand, Sangiran freshwater shell samples, taken from the *Corbicula* Bed, Lower Lahar and Black Clay layers, confirm that the shells were living in a non-marine habitat. All freshwater shells yielded Sr isotope ratios above 0.706, the maximum value expected for Central-East Javan freshwater systems (Whitford, 1975; Carn and Pyle, 2001; Gertisser & Keller, 2003). These values suggest admixture of marine water into the Solo Basin freshwater system (Joordens et al., 2009). The low 87Sr/86Sr values for the Plio-Pleistocene marine fauna and higher 87Sr/86Sr values of freshwater bivalve shells present a picture of exchanging open waters and freshwater in Sangiran. Furthermore, the $^{87}Sr/^{86}Sr$ data present a strontium flux in Sangiran which can be correlated to the marine regressions and episodes of glaciation during the ice ages of the Pleistocene.

Table 12. Input for the Binary mixing model (Joordens et al., 2009)

[Sr] "anthropogenic" Javan freshwater	0.413 ppm (measured)
[Sr] "non-anthropogenic" Javan freshwater	0.079 ppm (inferred; Palmer and Edmond, 1989)
[Sr] seawater	7.8867 ppm (Vonhof et al., 1998)
Sr isotope ratio freshwater endmember	0.704946 (measured *Tarebia* 11422)
Sr isotope ratio Early Pleistocene seawater	0.709102 (McArthur et al., 2001)
Sr isotope ratio Middle Pleistocene seawater	0.709136 (McArthur et al., 2001)

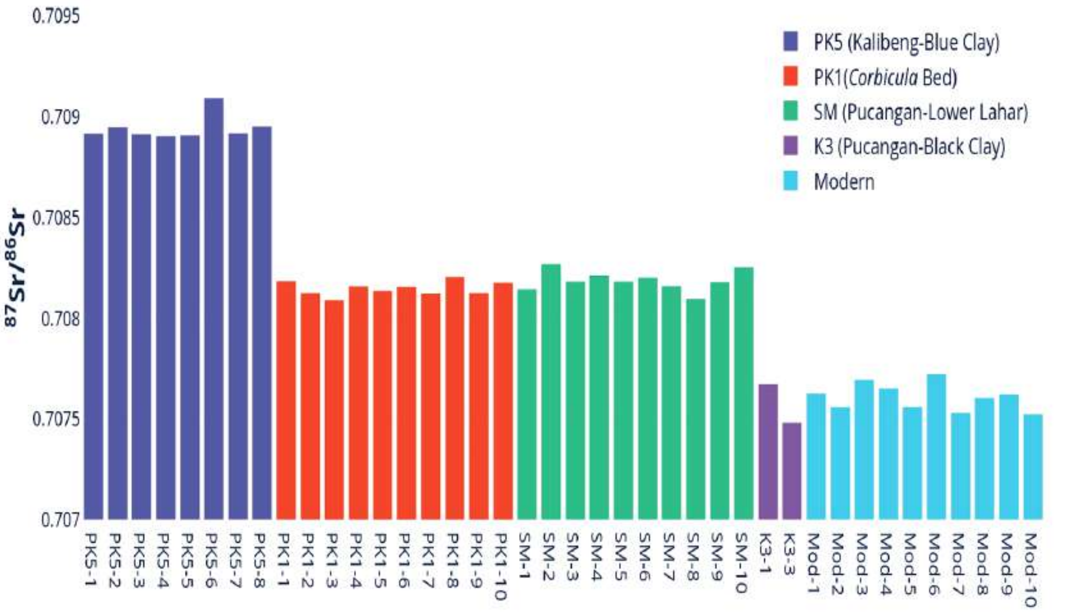

Figure 39. Sr isotope ratios of aquatic fossil shells from Sangiran and of a *Lymnaea javanica* from the present tributary in Pablengan Kulon from the modern Puren River. The ratios corresponding to a

brackish salinity range of 0.707-0.709 based on results of the mixing model using the "non-anthropogenic" freshwater Sr concentration. One sample, PK5-6, has a brackish-fully marine water.

5. Summary

According to van Es (1931:29), a thorough investigation of the species of molluscs in notable Quaternary sites in Java will lead to important results that can demarcate the Pliocene and Quaternary beds. In this study, the presence of a well-preserved of a marine bivalve *Glycymeris sp.* and the abundance of *Corbicula pullata* in the Upper Kalibeng until Lower Pucangan layers can be used as a proxy for climate fluctuation that transformed the Sangiran landscape from a sublittoral marine environment to the continental development. The approach adopted here, in which, where the shell stable isotope geochemistry was used to complement climatic data obtained from other environmental studies at the site.

$\delta^{18}O$ and $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ values from shell carbonate samples collected from different layers in Sangiran Dome show an oscillation of rainfall between 2.2-1.5 Ma. Dry conditions were observed between the boundary of late Pliocene and beginning of Pleistocene (early Quaternary) due to volcanic deposits filled Solo basin. In the lower Pleistocene, precipitation rates increased relative to climate variability. Afterward, precipitation trends toward modern values. The isotopic record compares closely with palaeoenvironmental records in Sangiran, reflecting specific conditions of relative humidity.

Investigation of Sangiran shells demonstrates the high potential of stable isotope analysis in obtaining palaeoclimatic information. Shell isotope analysis is one of the few methods for investigating climatic oscillations during the Quaternary that can provide information on the environmental effects on an area due to a changing climate. Our research is a work in progress; the isotopic information and our interpretation are preliminary. The significance and interpretations of the results are tentative and must be considered as a working hypothesis, which needs further tests and validation in future studies.

CHAPTER 5:

THE AQUATIC PALAEOECOLOGY IN CENTRAL JAVA DURING THE PLIO-PLEISTOCENE PERIOD: A SYNTHESIS OF SANGIRAN FOSSIL SHELL ASSEMBLAGES FROM KALIBENG AND PUCANGAN LAYERS [3]

1. Synthesis of Sangiran fossil shells

The molluscan content from the two quaternary beds, Kalibeng and Pucangan layers of Sangiran Dome included 61 molluscan taxa, 33 gastropods and 28 bivalves that were preserved in Solo Basin along Sragen province in Central Java. The Solo Basin is a low land formed by a modern volcanic belt of Java Island that extends to the Kendeng Zone. This zone is a rolling and hilly area that is composed of inverted deeper marine and Quaternary deposit, fluvio-volcanic sediments from nearby volcanoes since Pleistocene to recent caused by subsidence that led to marine and coastal-terrestrial conditions. Shifts in facies were triggered by oscillations, tectonic activities along the western margin of the basin and the changing courses of rivers and rivulets.

Evidence from our fossil molluscs found at Upper Kalibeng and Lower Pucangan molluscs of clearly indicate biotic and climatic responses or palaeogeographic effects during the long-term trends of climatic cooling and increasing glacial cycle amplitude during the Early Pleistocene period (Lisiecki & Raymo, 2007). Our interpretation agrees with the significant changes in the dynamics of the climate system as those observed with the Indonesian seaway restriction as documented by other researchers (Cane & Molnar, 2001).

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[3] Presented at the 18th Congrès d'Union Internationale des Sciences Préhistoriques et Protohistoriques (UISPP) held at the Sorbonne University (Paris 1) in Paris, France on 4-9 June 2018.

1. a. Kalibeng mollusc assemblages: Shallow marine environments

Kalibeng layer in Sangiran dome was formed by a complex interplay of a near-shore, shallow marine environment with marine marls at the bottom. The palaeogeography was mainly a result of sedimentary tectonics. Global oscillations of sea level and local triggers such as tectonics in the region were responsible for the deposition of materials in this layer. Mollusc assemblages from the samples in the upper part of Kalibeng indicates a shallow marine setting. The base of this layer is composed of bluish-gray clay and silty clay, followed by silty sand in the *Turritella* beds and *Balanus* limestone.

The dominance of *Glycymeris* in Pablengan Kulon sites reflects the establishment of littoral conditions. Laterally, infaunal bivalves from family Arcidae, Noetiidae, Placunidae and Veneridae colonized silty muddy bottoms. The occurrence of *Turritella* indicates a progression to a marine phase in Sangiran 1 and 2 of Upper Kalibeng. Scarce *Cardita* indicates strongly agitated, marine conditions. Pollen records reveal the establishment of coastal swamps and scattered mangroves (Sémah AM, 1982a and b 1984, 1986). However, the rest of the mollusc assemblages display strongly fully developed marine shells. This layer lacks mangrove shells and is dominated by Neogastropoda with representatives from diverse families: Muricidae, Columbellidae, Fasciolariidae, Marginellidae, Nasariidae, Olivellidae and Turridae.

The rest of bivalve assemblage of Kalibeng has numerous genus the family Arcidae, Noetiidae and Glycymerididae. This composition suggests typical marine near-shore conditions, with mostly sublittoral soft substrate, and shallow waters.

1. b. Pucangan mollusc assemblages: A pattern of fluvial and terrestrial environments

Marine and intra-continental molluscs were characterised by marked evolutionary processes of faunal changes and re-organisations in the course of:

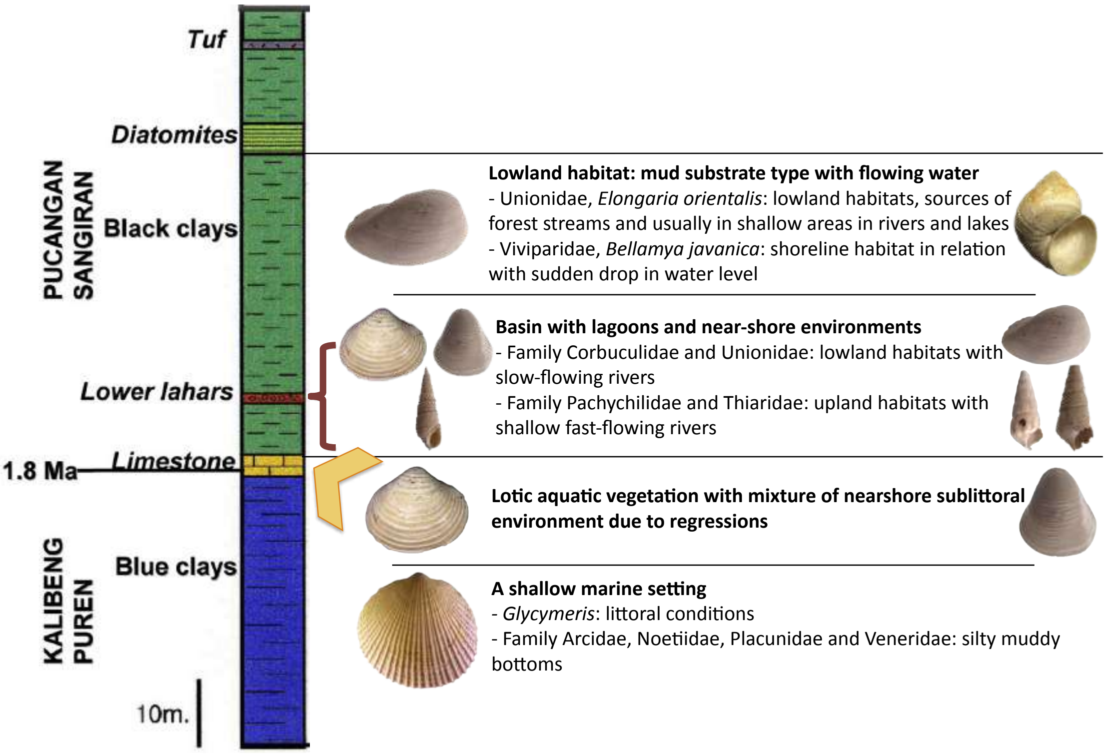
(1) The silty clay *Corbicula* Bed contained numerous *Corbicula*, a freshwater mollusc, at the overlying Pucangan. Processes of co-evolution of marine and estuarine and marsh environments and molluscs are evident in this bed. The mollusc assemblage shows lotic aquatic ecology with mixture of near shore sublittoral environment due to glacio-eustatic sea level regression.

(2) The Lower Lahar deposits developed terrestrial habitation from the basin with lagoons and near-shore environments triggered by the volcano-tectonic activity. Freshwater mollusc assemblage found in this facies decribes the Solo basin in Sangiran. Family Corbiculidae and Unionidae indicate lowland habitats with slow-flowing rivers while Pachychilidae and Thiaridae gastropods reveal upland habitats with shallow fast-flowing rivers. It is interesting to note that in this facies, two terrestrial mammalian taxa has been retrieved from the recent study on Sangiran faunal biostratigraphy (Ansyori, 2018). These two biostratigraphies were: *Cervus (Rusa) stehlini*, based on the nearly complete antlers; and *Antelope sp*. based on the atlas and radius bone found within a close range in the stratigraphy. The presence of these two species in Lower Lahar of the Lower Pucangan suggests the start of continental development in Sangiran and marks the earliest arrival of terrestrial fauna in the locality approximately between 1.9-1.6 Ma of the Early Pleistocene. This interpretation is consistent with those in the initial report by von Koenigswald (1940) on the occurrence of continental mammals (i.e., presence of cervid teeth in Sangiran) within the same facies.

(3) The Black Clay at the Lower Pucangan shows a freshwater ecosystem which bears abundant molluscs, foraminifera, diatomite and white tuff with silt intercalations. Lower Pucangan freshwater shells are generally characterized for lowland habitats. These freshwater molluscs prefer mud substrate type with flowing water. Bivalve Unionidae *Elongaria orientalis* is present in all sampling sites of Lower Pucangan. These molluscs are present in forest streams and in the shallow areas of rivers and lakes. The appearance of gastropod Viviparidae *Bellamya javanica* in this facies may suggests the existence of a shoreline habitat that experience a sudden drop in water level (Ashkenazi et al., 2010) as the shells reveal desiccation.

Evidence for the existence of marshy and lake-margin environments (Aimi & Aziz, 1985; Bettis et al., 2009; Ansyori, 2018) is consistent with occurrence of terrestrial vertebrate fossil taxa namely, *Hexaprotodon sivalensis, Bibos sp., Axis lydekkeri, Cervus (Rusa) sp.* and *Rattus aff. Tiomanicus,* which are well-adapted to these environments. The widespread occurrence of the mollusc genera *Corbicula* indicates terrestrial in the higher reaches and swamps or shallow lakes in the lower reaches in Sangiran.

The presence of freshwater molluscs is a clear evidence of an ecosystem that is evolving from transient waters towards a stable perennial lake. The initial transient water has low biodiversity but contained species that are highly tolerant to drought (presence of *Bellamya javanica, Planorbis*). Ultimately, it progresses to a perennial lake that has a high biodiversity (high abundance of *Corbicula*, and even forms adapted to the lotic conditions of perennial tributaries of Unionidae). A special situation is recorded in the Lower Lahar and the Black Clay of Pucangan layer, in which large freshwater gastropods are predominantly present as represented by juvenile Thiaridae. Its presence indicates initial unstable ecosystem relationships confined to a relatively well-watered regions of the continent, occurring in streams by moist grasslands with open woodlands in the driest landscape positions. It is then followed by large streams that filled the lake, and the landscape transformed into more riverine consisting of riparian forests, savanna, and open woodlands (Bettis III et al., 2009).



Lowland habitat: mud substrate type with flowing water
- Unionidae, *Elongaria orientalis*: lowland habitats, sources of forest streams and usually in shallow areas in rivers and lakes
- Viviparidae, *Bellamya javanica*: shoreline habitat in relation with sudden drop in water level

Basin with lagoons and near-shore environments
- Family Corbuculidae and Unionidae: lowland habitats with slow-flowing rivers
- Family Pachychilidae and Thiaridae: upland habitats with shallow fast-flowing rivers

Lotic aquatic vegetation with mixture of nearshore sublittoral environment due to regressions

A shallow marine setting
- *Glycymeris*: littoral conditions
- Family Arcidae, Noetiidae, Placunidae and Veneridae: silty muddy bottoms

Figure 40. Ecological shifts in Sangiran molluscan assemblages across Upper Kalibeng to Lower Pucangan @Sémah AM et al., 2016: Sangiran stratigraphy

2. Climate variability in Central Java based on Sangiran shell geochemistry

The 65 molluscan shells, marine *Glycymeris sp.* and freshwater *Corbicula pullata*, from representative sites of Kalibeng and Pucangan layers of Sangiran have been analysed for their oxygen, carbon and strontium stable isotope compositions. The investigated portion of the sampling covers the last 2 million years ago. The average of oxygen and carbon isotope data of freshwater is lower ($\delta^{18}O$ ~ 1.56‰/ $\delta^{13}C$~ -3.25‰) than of marine ($\delta^{18}O$ ~ 1.4‰/ $\delta^{13}C$~2.18‰). Shell $\delta^{18}O$ records show that the Early Pleistocene climate was dry with occasional periods of precipitation. The positive range in $\delta^{18}O$ suggests that hydrological conditions predominantly controlled the isotopic composition of the biogenic carbonate in Sangiran Dome. Samples from Sangiran show a marked ^{18}O depletion, which can be attributed to the onset of a wet climate, corresponding to the humidity and prevalent monsoons and marine regressions. Most of the shells show evidence of coincident negative anomalies in both $\delta^{18}O$ and $\delta^{13}C$ indicate reduced salinities related to the marine regressions and continental development in Sangiran. The carbon isotope variations within all studied shells (modern and fossil shells) were intermediate between carbonate and inorganic matter derived C. $\delta^{13}C$ records indicate a consistent mean shell $\delta^{13}C$ values around -3.0‰. $^{87}Sr/^{86}Sr$ ratios started with values between 0.70890-0.70909 in the marine layer of Sangiran and shift to a less radiogenic strontium isotope but relatively uniform values between 0.708268 to 0.707479 in the latter. This decrease in $\delta^{13}C$, is also attributed to the changing environment from a full marine to a constant surging riverine strontium in Sangiran.

The isotopic information provided is very preliminary. The climatic conditions that prevailed in Sangiran and Central Java during the Quaternary period have not been thoroughly studied. Isotopic analysis suggests onset of precipitation at the beginning of the Pleistocene followed by a sustained period of moisture (significantly above modern values) until the Pucangan Black Clay around 1 Ma.

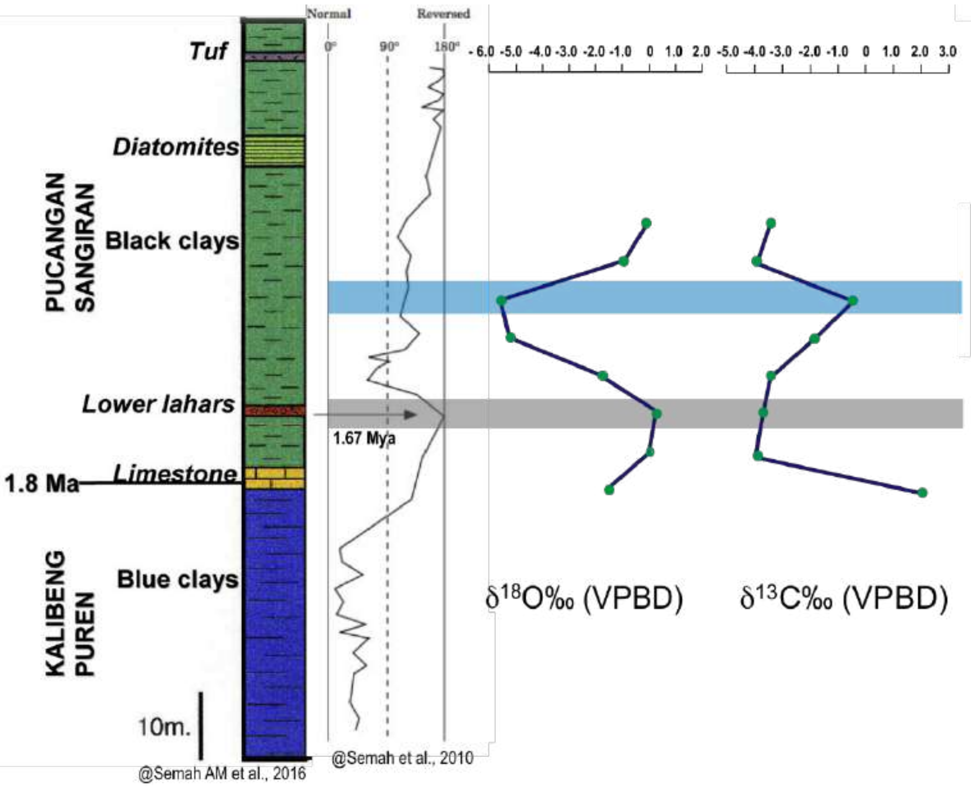


Figure 41. Comparison of climate records with palaeomagnetic results show that the lower lahar of 1.67 Ma to be of reversed polarity and near the end of a normal event and marks the emergence of the first relief at Sangiran (Sémah et al., 2000). Summary of oxygen and isotopic results by showing the facies from Upper Kalibeng and Lower Pucangan stratigraphy. Dark grey band indicates driest period and blue band indicates the wettest period.

3. Scientific outcome of Sangiran fossil shell analyses with palaeoenvironmental records from the Upper Kalibeng to Lower Pucangan

Reconstructing the aquatic palaeoecology at Sangiran 2 Ma based on shell ecology and isotopic results are in good agreement with pollen and faunal analyses. The evolution of the landscapes commenced in the boundary of blue clay facies where the shell assemblage and pollen spectra presented a shallow marine environment. The marine *Glycymeris* isotopic ratios is characterized by depleted δ^{18}O and enriched δ^{13}C values that may indicate a shift in salinity of the aquatic system in Sangiran leading towards to wetland environments. Whereas the pollen spectra were largely dominated by mangrove forest.

Increased shell concentrations of δ^{18}O in the *Corbicula* Bed and the Lower Lahar was coextensive when volcanic phase occurred in the Plio-Pleistocene period signified by lahar deposits filling the Solo basin in Sangiran. Shallow lagoons and coastal swamps were covered by volcanic deposits that may be coincident with a dry climate as suggested by the shell $\delta^{18}O$. This condition was reflected in the reduced precipitation at the beginning of 1.8 Ma, which is consistent with the oscillations between a tropical rain forest and seasonal open forest. These forests experienced a series of violent volcanic discharge, which is pervasive during the Quaternary.

Climate variability during the Lower Pleistocene in Sangiran assessed the pollen and the isotopic records. Isotope concentrations from shells of Krikilan in the lower Pucangan suggests wide shifts from wet to dry conditions. Low shell $\delta^{18}O$ values in Krikilan 1 and Krikilan 3 were regarded as wet condition and high shell $\delta^{18}O$ values in Krikilan 2 and 4 were regarded as dry condition. These shifts may be interpreted as the progression of continental environment and marine regression in more clayey deposits in the basin. Furthermore, the sharp decline in shell $\delta^{18}O$ signatures correlated to the massive sediment aggradation/sediment or water run-off in the Solo basin.

Moreover, vegetation shows a tropical rain forest with *Podocarpus*, Fagaceae, Dipterocarpaceae and *Altingia* on surrounding slopes and hills during ‘interglacials’, and a more open forest formation although not with the composition of an actual monsoon forest, during the ‘glacials’ throughout the Lower Pleistocene (Sémah AM 1986). These vegetal formations were developed from the volcanic cones and accumulated deposits, lahars and clays, in the shallow basins and lagoons as marked by continental stratigraphic transitions. They were noted by the arrival of continental vertebrates that able to cross the narrow straits of Central Java in 2 Ma (von Koenigswald, 1936; de Vos et al., 1994; Semah AM et al., 2016). These vertebrates were represented by *Cervus* and *Axis* found at the lower lahar in Sangiran (Ansyori, 2018).

The rain forest was replaced by drier and more open formations at the end of the lower Pleistocene. This may be associated with the increase in shell $\delta^{18}O$ at the end of lower Pucangan layer correlated to changes of littoral environments from estuarine to lacustrine environment. Peaty sedimentary facies taken in Pucangan layer contained pyrite mineralization and fossil biotas that may have developed a reducing aquatic environment (Brasseur et al., 2015). It is normally an area characterized by palustrine with reduced vegetal cover of *Phragmites*, rushes, *Typha,* and Cyperaceae herbaceous plants (Tokunaga et al., 1985; Sémah AM, 1986). The environment might have a closed forest nearby the water, probably a mangrove forest, as suggested by the presence of microfauna *Rattus aff. tiomanicus* (Ansyori, 2018). Furthermore, the lowest $\delta^{18}O$ value corresponded to the $^{87}Sr/^{86}Sr$ values, an indicating of warmer temperatures. This values suggests a shift to wet conditions with increasing precipitation as monsoon rains which can be characterized as the modern climate of Java.

4. Significance of Sangiran mollusc diversity and shell geochemistry in Kalibeng and Pucangan layers to the palaeoenvironment in Central Java during the Plio-Pleistocene period

The analysis of palaeobiodiversity and palaeobiogeography of Quaternary molluscan assemblages provide information on the environmental landscapes and climate in the Central Java. The huge amount of data derived from detailed malacological studies in the Solo Basin of Sangiran depicts a detailed picture of diverse environments during the Early Pleistocene in Central Java. In this study, patterns were presented in species richness, foundations of palaeoecological analyses were calculated as the number of species present. Shell isotopes analyses from each sampling site in Kalibeng and Pucangan layers suggest environmental changes linked to sea-level and volcano tectonics. The extent of which were large enough to modify not only the geography but also the existing biological associations, namely, flora and faunal compositions.

Combining environmental interpretations gleaned from studying Sangiran mollusc assemblages with other environmental proxies provide a robust reconstruction of the landscapes and environments occupied by *Homo erectus*, and migrations of continental mammals in to the southern part of the Sunda shelf during Quaternary glacials.

Table 13. Summary of Sangiran palaeoenvironment and palaeoclimate from upper Kalibeng to lower Pucangan layers.

LAYER/FACIES	**PALAEOENVIRONMENT**			**PALAEOCLIMATE**	
	Aquatic bivalves and gastropod molluscs	**Pollen (Sémah AM, 1982, 1984, 1986)**	**Fauna (Ansyori, 2018)**	**Aquatic bivalves and gastropod molluscs**	**Pollen (Sémah AM, 1982, 1984, 1986)**
Pucangan Black Clay	Lowland habitat with mud substrate type in a flowing water	Mangrove decreasing; rain and monsoon forest	Closed forest environment with nearby water	Started with series of wet climate and ended with dry climate periods; Increased precipitations	Wet and warm climate; Series of drier events due to volcanism
Pucangan Lower Lahar	Basin with lagoons and near-shore environments	Vegetation destroyed by volcanism	Closed forest environment	Driest period	
***Corbicula* Bed**	Lotic aquatic vegetation with mixture of nearshore sublittoral environment due to regressions	Mangrove rain forest		Dry climate with reduced precipitation	Wet and warm climate
Kalibeng Blue Clay	Shallow marine environment			Warm climate with wet conditions	

5. Conclusion

Molluscs are among the most diverse and abundant animal groups inhabiting many aquatic and terrestrial environments. Therefore, mollusc fossils are excellent proxies for palaeoenvironmental and climate change studies (Prendergast et al., 2013 and 2016; Schöne, 2013). They are well preserved in many archaeological and geological deposits, providing an excellent repository of the environmental conditions existing during their time (Mayer & Zohar, 2010; Çakirlar, 2011; Mannino & Çakirlar, 2012; Brockwell et al., 2013; West et al., 2018).

In this study, we provided additional evidence to support the Quaternary palaeoenvironment and palaeoclimate in Central Java. We used records that were encoded in the molluscan fauna as the environment in Central Java changes from marine to continental development. The Quaternary molluscan assemblages from Sangiran provided information on the habitat and environments during the Plio-Pleistocene period. This study is novel because it uses ecological data from mollusc fauna to extrapolate the ecological conditions in aquatic environments from the late Pliocene to Early Pleistocene in Sangiran. The analysis allowed us to postulate the palaeobiodiversity and palaeobiogeography since the Pleistocene based on the updated molluscan dataset, including comparisons of compilations gathered from an exhaustive search of literature and systematic bibliography.

Investigation of the shell geochemistry from Sangiran mollusc assemblage and demonstrates their great potential of palaeoclimatic information. Carbon and oxygen isotopes in the shells of the marine *Glycymeris* and freshwater *Corbicula* yield information on the isotopic composition of the water in which the shell was formed, allowing us to correlate climatic conditions prevailing during the bivalves' life span. Because *Glycymeris* and *Corbicula* were found in the Upper Kalibeng and throughout the sequence of lower Pucangan, respectively, climatic oscillations during the early Quaternary were recorded in these shells and provided information on the environmental effects on the area due to climate. Based on strontium isotope ratios of *Glycymeris* and *Corbicula*, aquatic salinities in Plio-Pleistocene Central Java were determined and were able to distinguish fluviatiles and lacustrine freshwater environments in Sangiran. The outcomes of the carbon, oxygen, and strontium isotope analyses have contributed of our understanding of the climatic and hydrological variations that may have influenced the central Java environment and adapted by hominins and fauna in Sangiran at the end of the Lower Pucangan.

Ecology and stable isotope data of the Sangiran molluscs allowed us to reconstruct the palaeoenvironment in Sangiran 2.2 Ma, which transformed from an initial coastal marine environment to wetland environments. The results from the molluscan assemblages from the Upper Kalibeng to the Lower Pucangan are critical in establishing palaeoenvironmental comparisons with other interdisciplinary interpretation involving faunal associations, pedosedimentary and palaeobotany conducted in Sangiran (Sémah AM et al., 2016). This study presents an overview of using molluscs in environmental and impact studies that can provide baseline data and in searching for other proxies in environmental reconstruction and climate change studies. Our work can provide a useful tool to compare and construct regional palaeoenvironmental models in Island Southeast Asia and the Pacific as well as in other Quaternary sites worldwide that may have been susceptible to intense climatic oscillations. Our methodology is a useful tool for future studies in interpreting taxonomic patterns that can be linked to environmental changes during the most recent past and for phylogeographic research. Ultimately, the methodology described in this study can provide a comprehensive palaeoenvironmental chronology and a better narrative for the emergence, migration, and adaptation of early humans.

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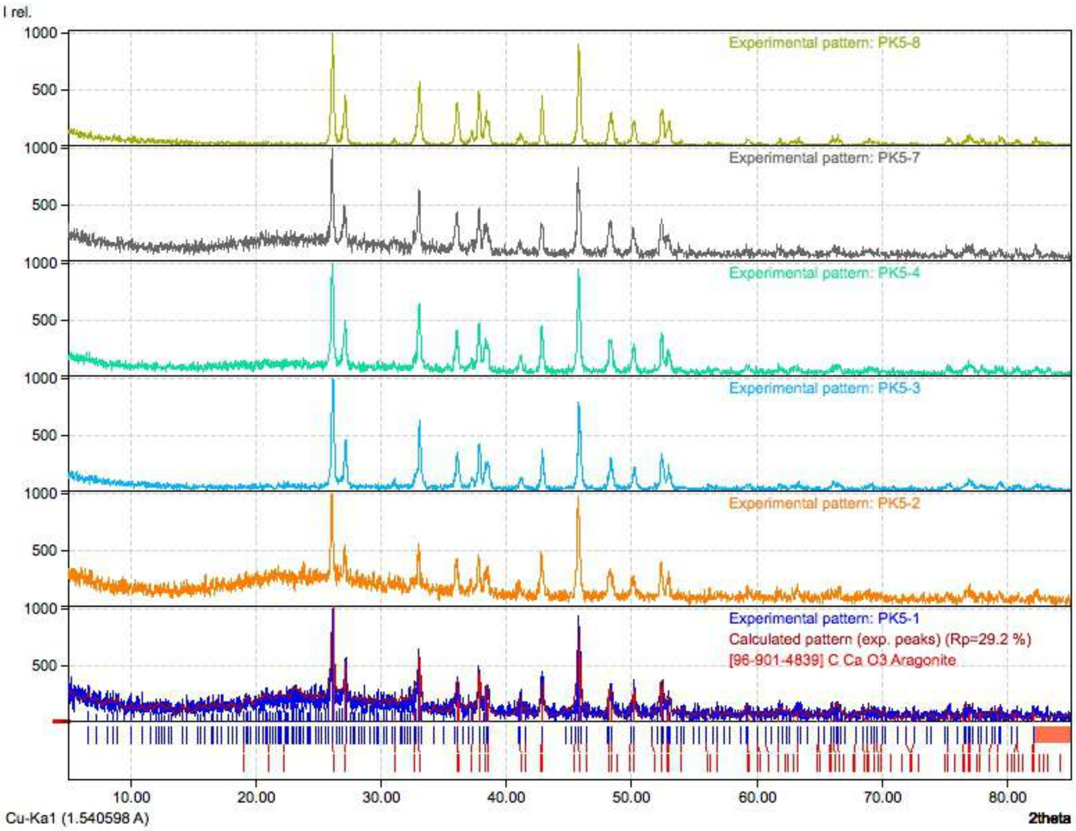
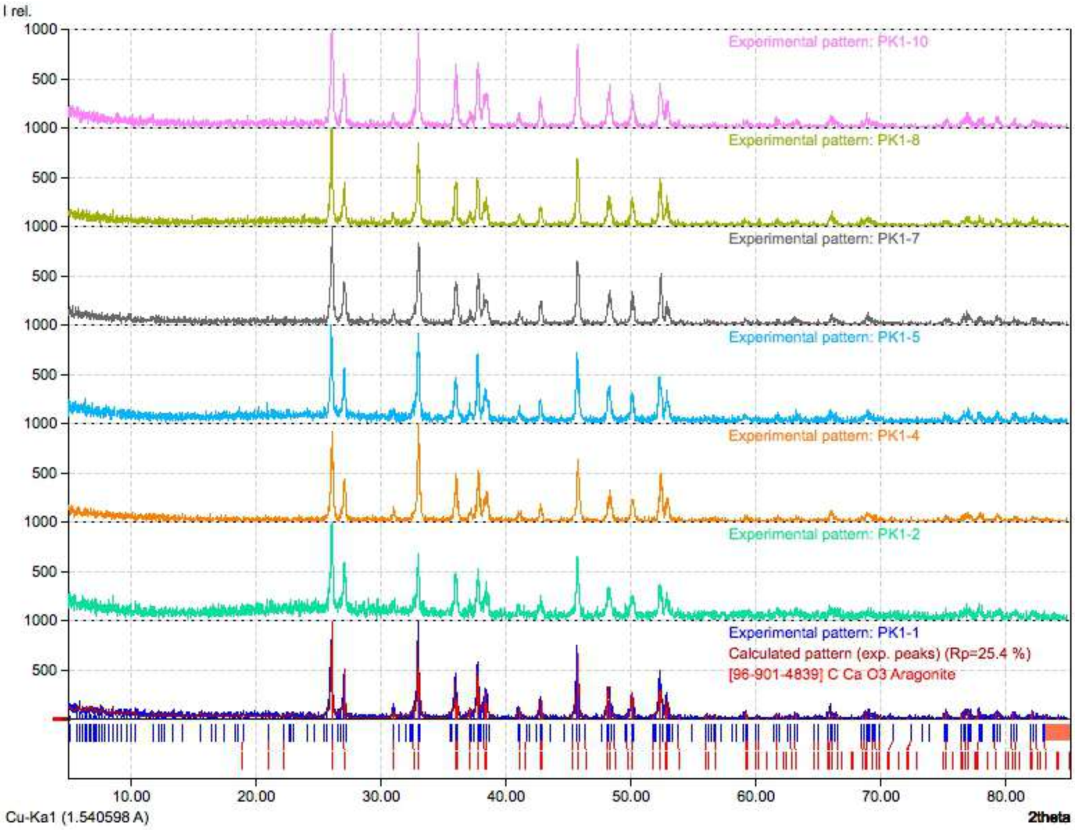
SUPPLEMENTARY DATA

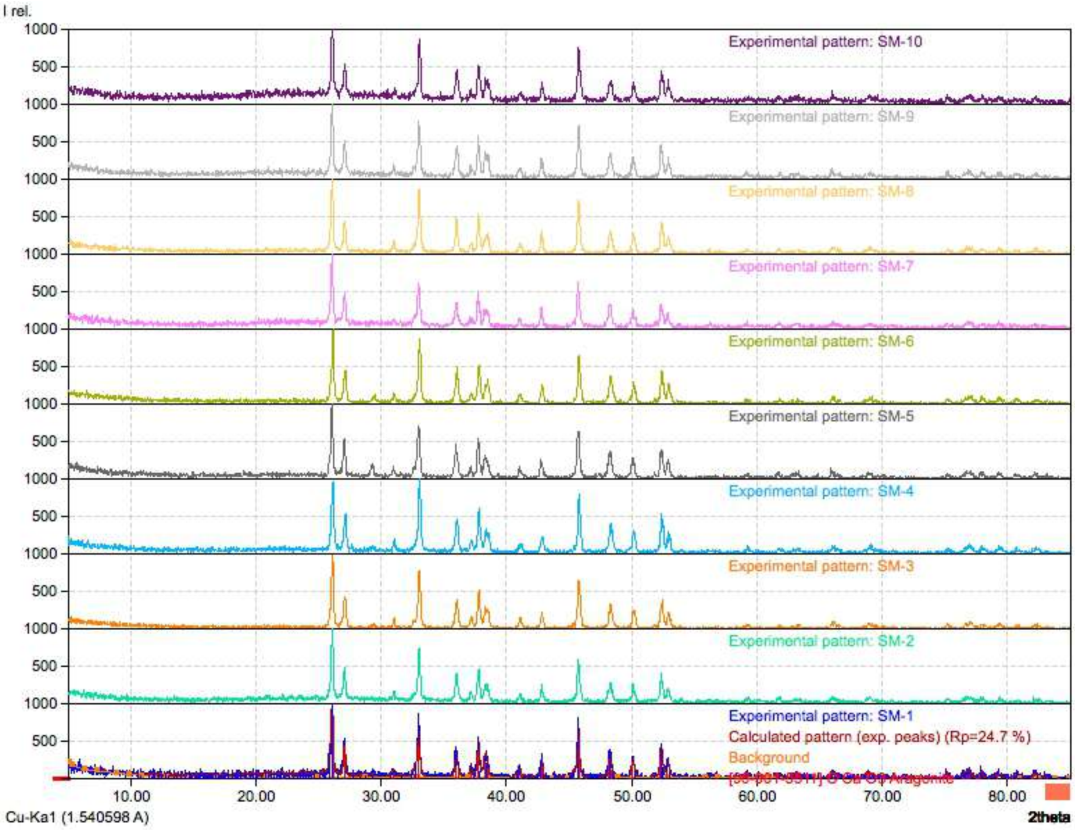
Appendix A: Xray diffraction patterns of sampled bivalve shells from different facies of Sangiran.



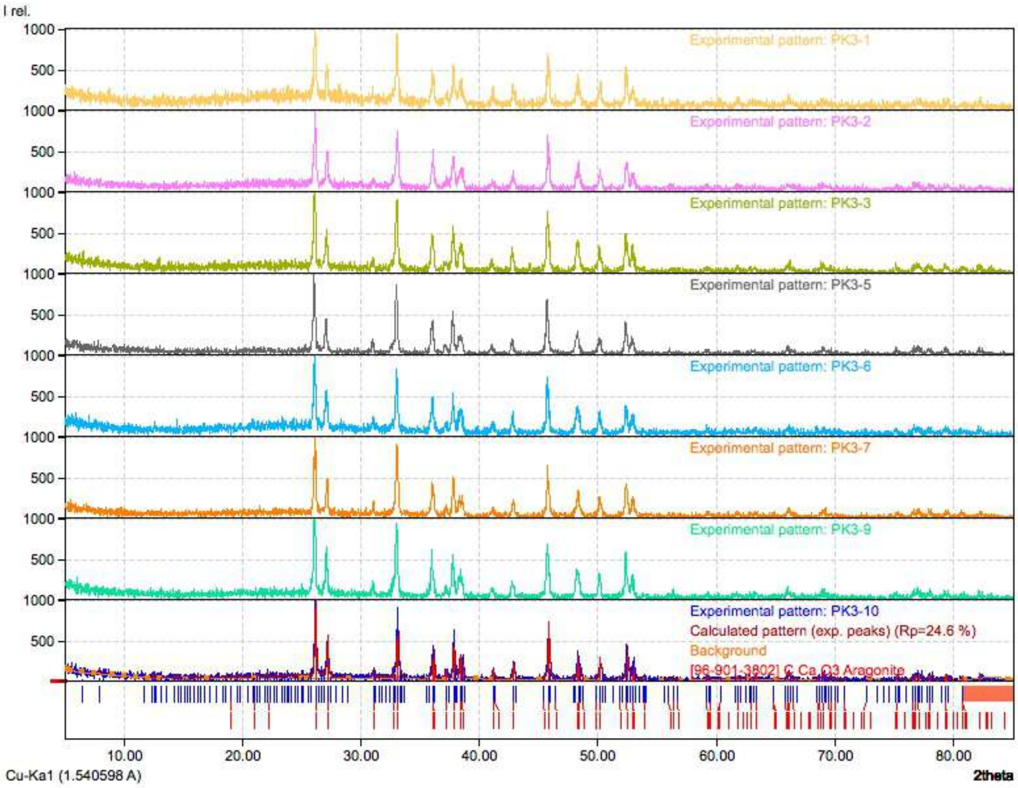
PK1


I rel.
1000
500
Experimental pattern: PK1-10
Experimental pattern: PK1-8
Experimental pattern: PK1-7
Experimental pattern: PK1-5
Experimental pattern: PK1-4
Experimental pattern: PK1-2
Experimental pattern: PK1-1
Calculated pattern (exp. peaks) (Rp=25.4 %)
[96-901-4839] C Ca O3 Aragonite
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
Cu-Ka1 (1.540598 A)
2theta

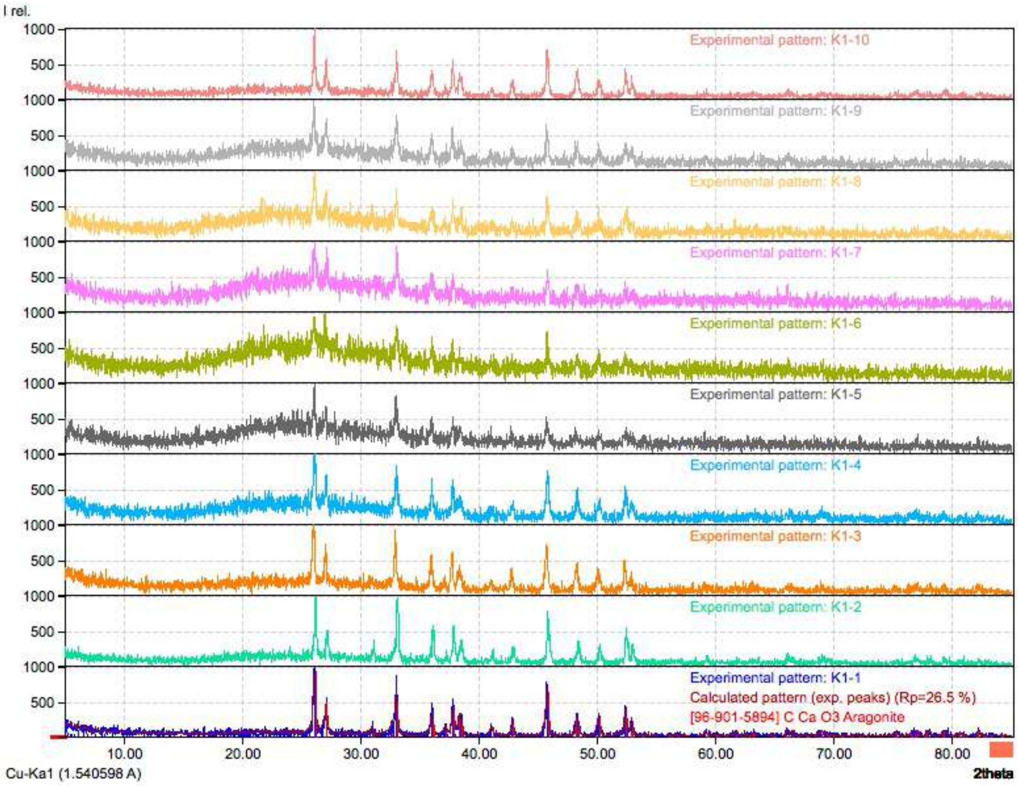
PK1


I rel.
1000
500
Experimental pattern: SM-10
Experimental pattern: SM-9
Experimental pattern: SM-8
Experimental pattern: SM-7
Experimental pattern: SM-6
Experimental pattern: SM-5
Experimental pattern: SM-4
Experimental pattern: SM-3
Experimental pattern: SM-2
Experimental pattern: SM-1
Calculated pattern (exp. peaks) (Rp=24.7 %)
Background
C Ca O3 Aragonite
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
Cu-Ka1 (1.540598 A)
2theta

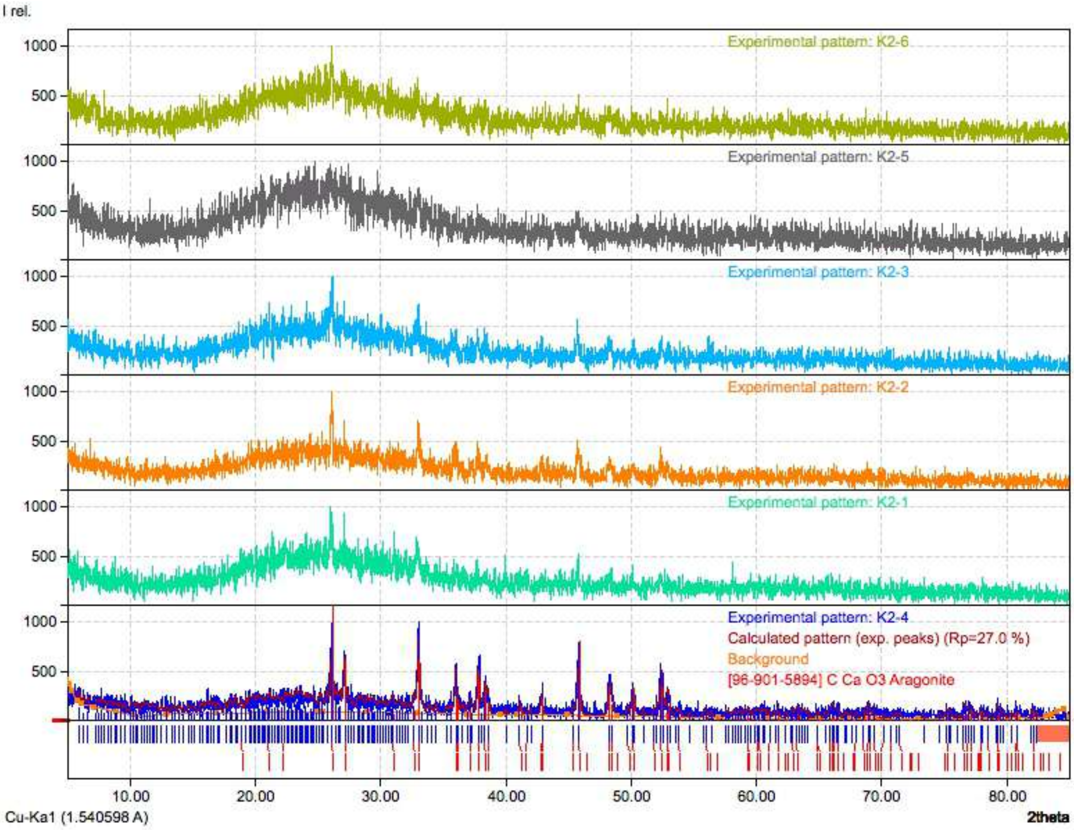
SM


I rel.
1000
500
Experimental pattern: PK3-1
Experimental pattern: PK3-2
Experimental pattern: PK3-3
Experimental pattern: PK3-5
Experimental pattern: PK3-6
Experimental pattern: PK3-7
Experimental pattern: PK3-9
Experimental pattern: PK3-10
Calculated pattern (exp. peaks) (Rp=24.6 %)
Background
[96-901-3802] C Ca O3 Aragonite
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
Cu-Ka1 (1.540598 A)
2theta

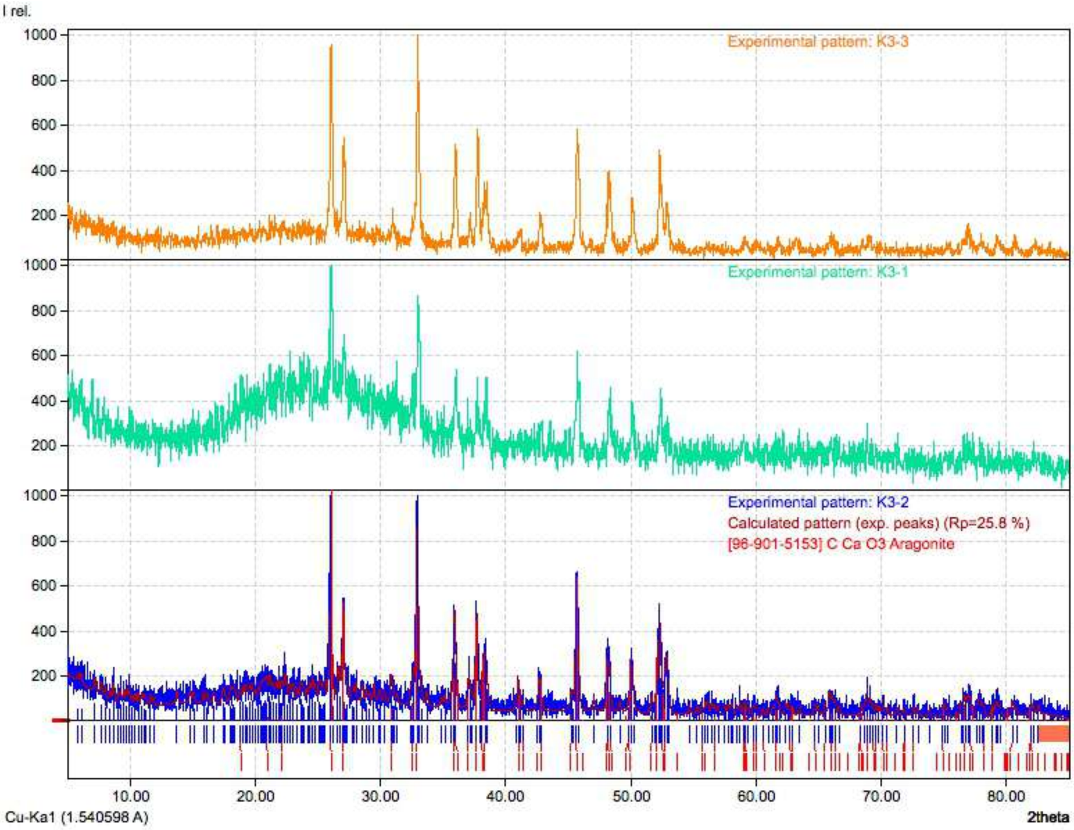
PK3


I rel.
1000
500
Experimental pattern: K1-10
Experimental pattern: K1-9
Experimental pattern: K1-8
Experimental pattern: K1-7
Experimental pattern: K1-6
Experimental pattern: K1-5
Experimental pattern: K1-4
Experimental pattern: K1-3
Experimental pattern: K1-2
Experimental pattern: K1-1
Calculated pattern (exp. peaks) (Rp=26.5 %)
[96-901-5894] C Ca O3 Aragonite
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
Cu-Ka1 (1.540598 A)
2theta

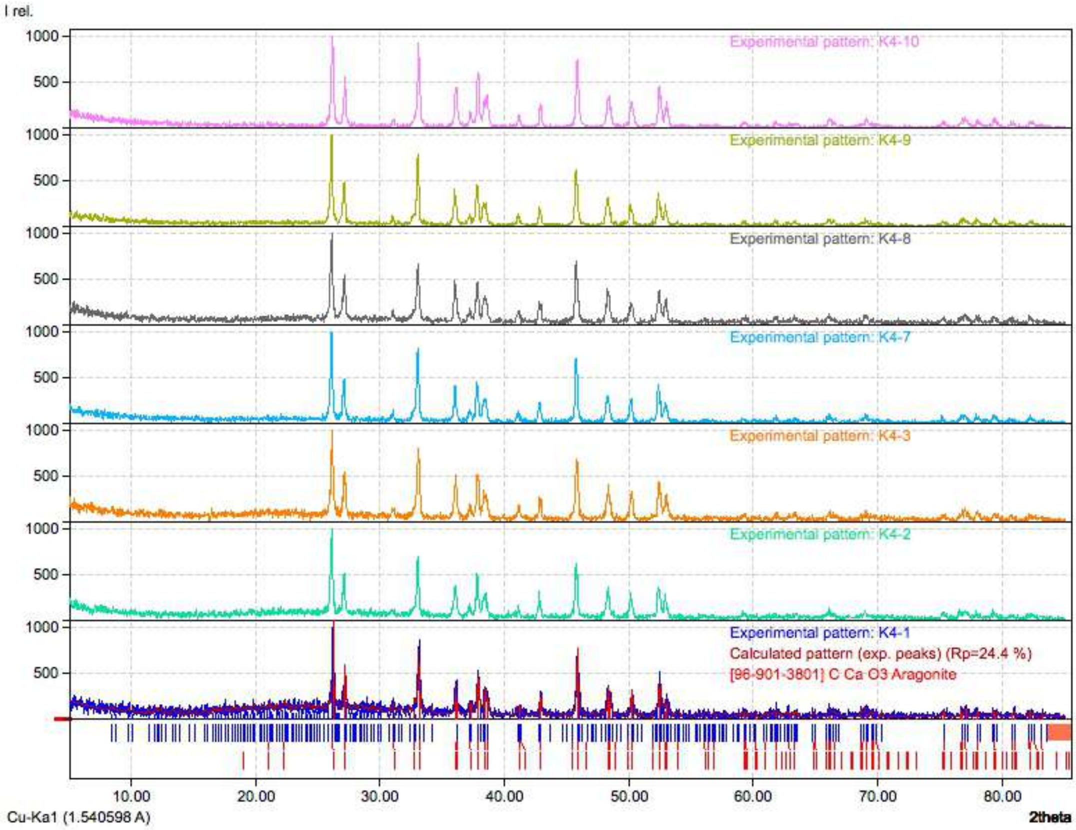
K1


I rel.
1000
500
Experimental pattern: K2-6
Experimental pattern: K2-5
Experimental pattern: K2-3
Experimental pattern: K2-2
Experimental pattern: K2-1
Experimental pattern: K2-4
Calculated pattern (exp. peaks) (Rp=27.0 %)
Background
[96-901-5894] C Ca O3 Aragonite
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
Cu-Ka1 (1.540598 A)
2theta

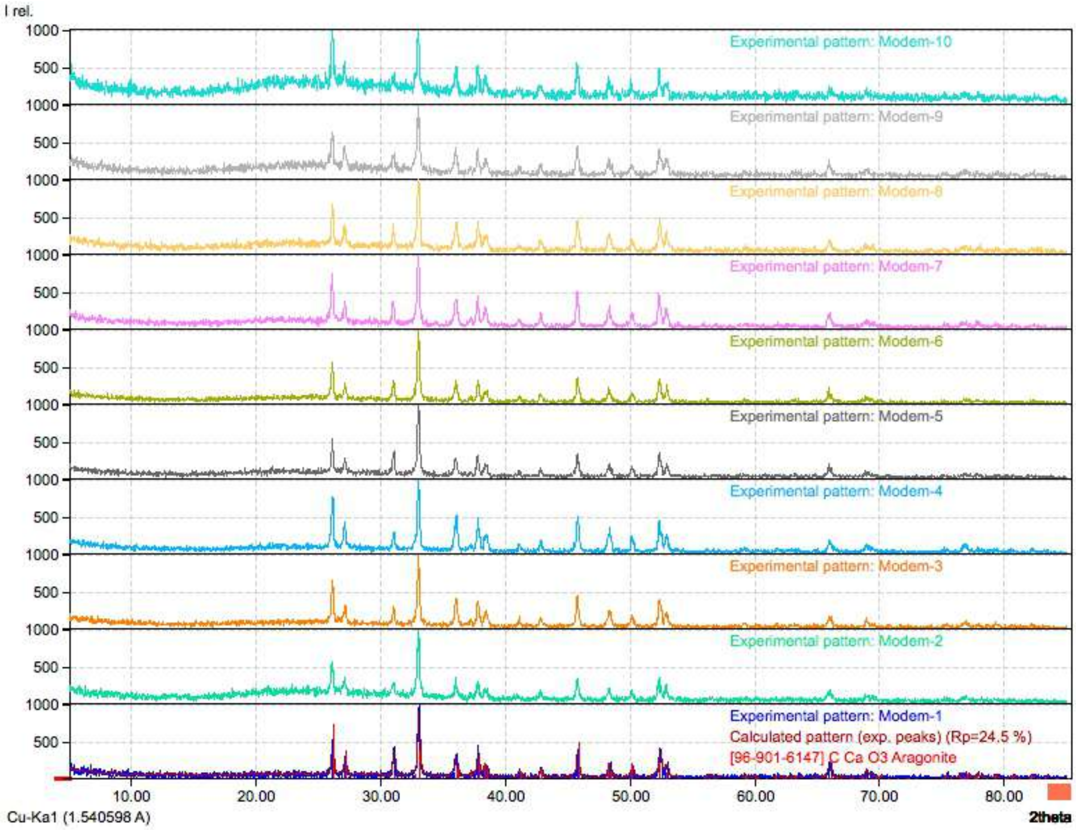
K2


I rel.
1000
800
600
400
200
Experimental pattern: K3-3
Experimental pattern: K3-1
Experimental pattern: K3-2
Calculated pattern (exp. peaks) (Rp=25.8 %)
[96-901-5153] C Ca O3 Aragonite
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
Cu-Ka1 (1.540598 A)
2theta

K3


I rel.
1000
500
Experimental pattern: K4-10
Experimental pattern: K4-9
Experimental pattern: K4-8
Experimental pattern: K4-7
Experimental pattern: K4-3
Experimental pattern: K4-2
Experimental pattern: K4-1
Calculated pattern (exp. peaks) (Rp=24.4 %)
[96-901-3801] C Ca O3 Aragonite
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
Cu-Ka1 (1.540598 A)
2theta

K4


I rel.
1000
500
Experimental pattern: Modern-10
Experimental pattern: Modern-9
Experimental pattern: Modern-8
Experimental pattern: Modern-7
Experimental pattern: Modern-6
Experimental pattern: Modern-5
Experimental pattern: Modern-4
Experimental pattern: Modern-3
Experimental pattern: Modern-2
Experimental pattern: Modern-1
Calculated pattern (exp. peaks) (Rp=24.5 %)
[96-901-6147] C Ca O3 Aragonite
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
Cu-Ka1 (1.540598 A)
2theta

MODERN