From the Solo to the Madura Strait: Quaternary geology, vertebrate palaeontology and hominin chronology of eastern Java and submerged Sundaland

Berghuis, H.W.K.

SUMMARY

The vertebrate fossils of eastern Java have fascinated the world for more than a century. The area holds some of the richest hominin sites of the world and yielded the type specimens of *Homo erectus*. What makes this area so rich in Pleistocene fossils? This is a question I often get from an interested audience. For sure, Java must have had a rich and diverse vertebrate community throughout the Pleistocene. But the chance that bones of terrestrial species end up as fossils is very small. What helped, is that most of the time eastern Java had a relatively dry climate, with low bone weathering rates. There was a pronounced rainy season, washing scattered bones into river channels. A high supply of volcanic sand caused efficient burial in fluvial sediment. Eastern Java is also a tectonically active zone, with local subsidence, which makes that such fluvial deposits were preserved. In later time, this same tectonism resulted in local folding and uplift, exposing the ancient deposits and their fossil content. And finally, it is helpful that eastern Java is, also today, relatively dry, which provides more or less open exposures, and it makes that there is no tropical weathering, which would quickly reduce embedded bones to clay.

The fossils from eastern Java give an interesting insight into the evolution and dispersal of species over Southeast Asia. The islands of western Indonesia, which include Java, are part of the Sunda Shelf. In the past, the shelf has been subaerially exposed, forming a wide continental zone that connected western Indonesia to the Asian mainland. We call this lost continent Sundaland. Stages of Sundaland exposure have been linked to ice ages, also known as glacials, by the mechanism that large volumes of water get stored in ice caps, resulting in a lower global sea-level. *Homo erectus* may have reached Java under such glacial conditions.

Against this background, the discovery of the Madura Strait vertebrate site was very exciting news. It is the first sub-sea fossil site of the Sunda Shelf, offering a unique window to the vertebrate community of the lowland plains of Sundaland. The fossils were excavated from the seabed during a sand extraction work. The extracted sand was transported to a coastal site in Gresik, where it was used to develop a new harbour terrain. In 2015, just after its completion, this site was a 100 ha-wide sandy plain, completely desolated and baking in the sun. Upon inspection, its surface appeared to be strewn with vertebrate fossils. It took me several months to pick them all up, collecting a total of 6372 specimens.

Collecting the fossils was only the beginning. The subsequent analysis and interpretation of the geology and the fossils proved to be difficult within the accepted geological and palaeontological models for Java. The stratigraphy of Java, which subdivides the depositional record of the island in larger units, was rather simple and seemed to ignore the complex landscape setting of the island, subject to volcanism, tectonism, sea-level fluctuations and changing drainage systems. Moreover, there appeared to be no connection between the island stratigraphy of Java and the off-shore stratigraphy of the shelf. The island has been the domain of palaeontologists and archaeologists, whereas the shelf sea has been the domain of oil companies searching the area for hydrocarbon reserves. Their seismic surveys revealed a sub-seabed geology with cyclic build-up, of stacked sea-level related marine sequences, pointing to repeated stages of submergence and intermittent stages of shelf exposure. But a similar cyclicity was unknown from the depositional record of Java. This is strange, even more so because palaeontologists refer to such alternating stages of shelf submergence and shelf emergence to explain changes in the fossil record of Java.

To solve these matters, I started, together with colleagues from the Netherlands and Indonesia, a re-investigation of the geology of eastern Java and its vertebrate sites. Indeed, the depositional record of the island appeared to be much more complex than previously understood. It contains significant hiatuses and has considerable lateral variation. The previous use of regional chronostratigraphic units is largely incorrect. Instead, we defined local units. Units that follow major lithological changes and reflect important changes in the local depositional landscape. The units do not infer unproven regional age relations. Nevertheless, we did our best to place them in a chronological context, referring to available numerical ages. How do you know these ages? This is another frequently asked question. There are several ways to date deposits, but they usually come with uncertainties. For marine deposits we may refer to dated ranges of specific microfossils. For terrestrial deposits in a volcanic terrain, we may use radiometric dating techniques, but these determine crystallization ages, which are not necessarily the same as depositional ages, certainly not for fluvially re-deposited material, which is generally what we work with on Java. Another option is OSL-dating. This method determines the time that has passed since a mineral grain was last exposed to light. This gives an age of actual deposition, but the technique only works for specific sediment types, and for ages below around 450 thousand years. There are more techniques, such as measuring the magnetic polarity of sediment and linking this to dated reversals of the earth's magnetic field. Altogether, such ages only form pieces of the puzzle. It is important to also take into account other chronological information, such as major eruptions or a change of volcanic style, tectonic events, a changing climate, or a change of river behaviour. All these things left their traces in the depositional record and sometimes even in the present-day landscape, and can be used for correlations and age estimates.

One of the most important patterns in the geological record is a cyclicity related to sea-level fluctuations. It allows for correlations, and in combination with a few reliable numerical ages, forms a good framework. Most of all, it provides the long-sought connection with the off-shore geology. However, the situation proved to be a bit different than previously assumed. Recent studies have shown that the Sunda Shelf is not a tectonically stable surface, but instead has been subject to subsidence. The shelf was widely exposed during the Early Pleistocene, and only came within the reach of sea-level fluctuations in the course of the Middle Pleistocene. On eastern Java, this was the period in which the two large drainage systems developed, the Brantas and the Solo. These days, the rivers were much longer than they are today and extended eastwards all the way to the shelf edge, over what now is the seabed of the Madura Strait. Each time their lower reaches became flooded, the rivers responded by sedimentation in their higher reaches. And as the sea retreated again, the rivers incised new valleys. Depending on the tectonic situation, this process of alternating sedimentation and incision may have formed river terraces (under uplift conditions) or stacked and buried valley-fills (under conditions of subsidence). Both can be observed on eastern Java. In the subsiding plains area around Jombang and Mojokerto, the Brantas formed stacked fluvial sequences, buried below the surface of the plains. Interestingly, these have locally been pushed up in a series of young folds, providing beautiful exposures of these fluvial deposits, which contain the hominin-bearing bone beds of Perning and Jetis. In the uplifted plains around Trinil and Ngawi, the Solo formed a unique series of fluvial terraces, with fossil-bearing fluvial deposits of various ages. The terraces can be traced to the Kendeng traverse valley, where we find the famous hominin-bearing terrace of Ngandong. North of the Kendeng ridge, these terraces continue as stacked valley fills, buried in the coastal clays of the subsiding plains of the Randublatung Valley. For both rivers, the incision and aggradation cycles could be linked with the sea-level curve, forming a reliable age framework. The fluvial sequences of the Brantas and the Solo finally made it possible to establish a link between the stratigraphy of Java and the stacking of marine sequences of the central part of the shelf, by the principle that both are linked to sea-level highstands.

The buried Pleistocene valleys of the Solo can be traced eastwards to the Madura Strait seabed. The Madura Strait vertebrate site is one of the ancient valleys. Based on our reconstructions of incision-aggradation cycles and shelf subsidence, the valley might have been cut during the second last glacial. This was confirmed by OSL-datings of the sandstone fill, which gave an age of around 140 thousand years. This age slightly postdates the glacial maximum, and links the valley fill to the subsequent stage of rising sea level.

The skeletal elements in this fluvial sediment are the remains of fluvial vertebrates, such as river sharks, crocodilians, turtles and hippopotamids, mixed with the remains of terrestrial vertebrates, such as bovids, cervids, elephantoids, rhinos, and suids. A total of 36 different species could be identified, which makes the assemblage extremely rich in species. Altogether, the assemblage represents a lowland community, populating the grass-dominated terrain along a large, slow-moving river. Several species of stingrays, sharks and turtles were previously undescribed from Java. Other species are extremely rare within the Javanese fossil assemblages, such as macaques and Komodo dragons. The latter species was an important predator of the lowland plains of Pleistocene Sundaland, indicating that its current territories on Komomo, Rinca and Flores are a relict of a much larger geographic range. Species such as *Duboisia santang* and *Epileptobos groeneveldtii* were previously assumed to have gone extinct earlier in time, but were shown to have survived on the Sundaland plains up to at least 140 thousand years ago. A valuable feature of our faunal studies is that all identified remains have been measured in detail, which gives an interesting insight into size ranges and evolutionary trends per species and provides a reference for future identifications.

Among the identified fossils are two hominin skull fragments. The material dates from a period of great changes of the hominin population in Asia. On the mainland, the older *Homo erectus* population was replaced by invading more modern hominins, amongst which were Denisovans and Neanderthals. On Java, *Homo erectus* appeared to have survived as a relict population. But does this also account for the lowland plains of Sundaland? After all, Sundaland was openly connected to mainland Asia most of this time. To get a better grip on this interesting question, we carried out a detailed metric and morphological comparison of the new skull fragments with all relevant Pleistocene skulls from China, India, Java and Flores. This showed that the Madura Strait skull fragments have a great affinity with the late *Homo erectus* from Java and not so much with the contemporary, more modern populations from the Asian mainland. It shows that the Javanese *Homo erectus* had a larger territory, which extended over the lowland plains of Sundaland. Instead of Java Man, we may better speak of Sunda Man. This, however, brings up the question: why didn't the late Middle Pleistocene mainland hominins penetrate into Sundaland? This question is not so easy to answer. A possibility is that the Sundaland savanna only covered the southeastern part of Sundaland, and that it was shielded from the plains further to the north by a dense equatorial forest, which formed a barrier for species more adapted to an open terrain.

Cutmarks on fossil bones show that the Madura Strait hominins foraged on river turtles and bovids. Bovid limb bones were broken for collecting bone-marrow. Interestingly, the death assemblage of bovids is dominated by young adults. This is not what you would expect under natural conditions and points to selective hunting by hominins, aiming for the most fat-rich prey. In Europe and mainland Asia, this behaviour is generally linked to relatively modern populations such as Neanderthals. Possibly, Sunda man developed this behaviour independently. But it may also be possible that Sunda man copied this behaviour from invading more modern groups. This makes that we still cannot rule out that the late *Homo erectus* from Java, and from the Madura Strait, did already carry some genes of these mainland populations.