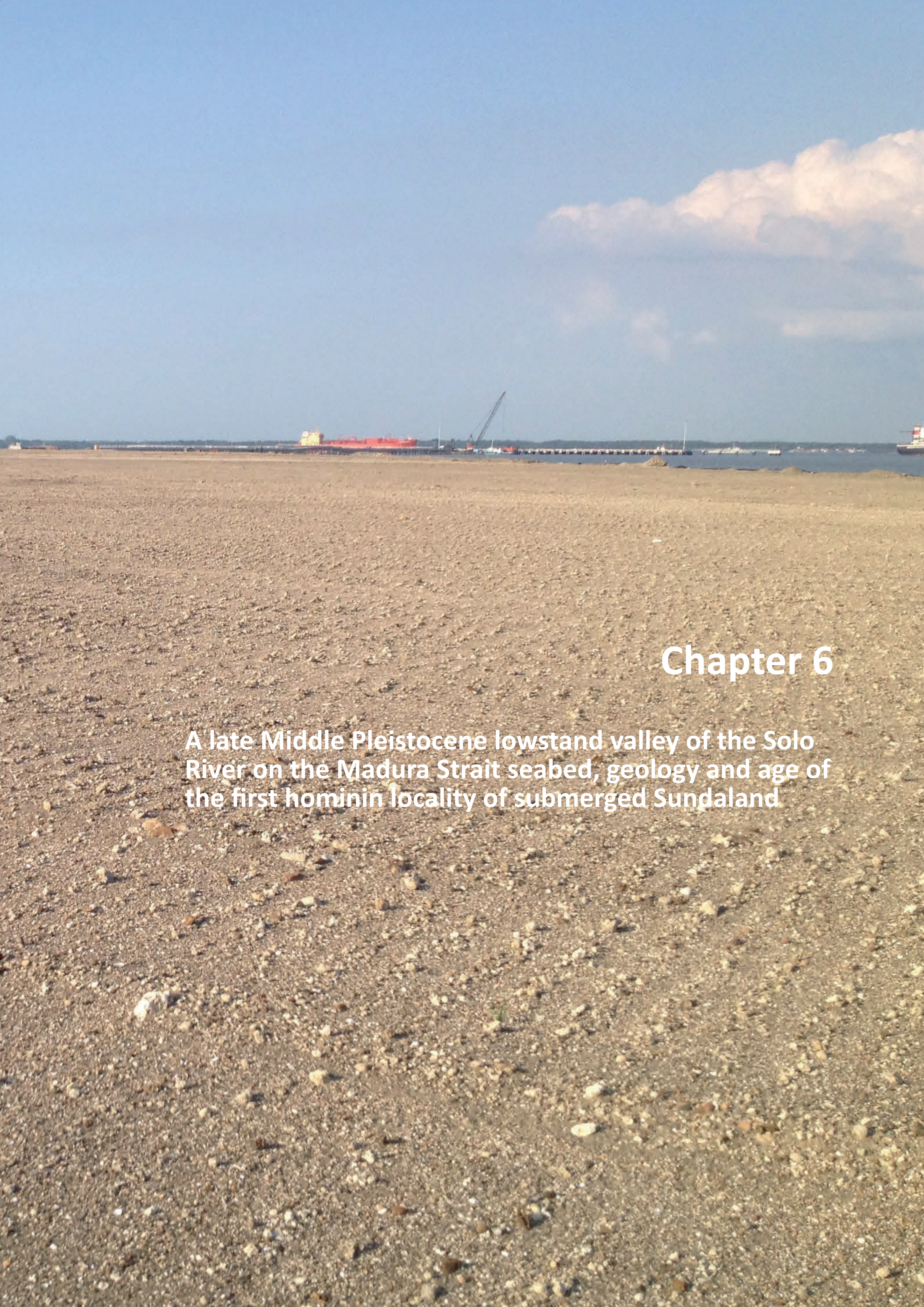
From the Solo to the Madura Strait: Quaternary geology, vertebrate palaeontology and hominin chronology of eastern Java and submerged Sundaland

Berghuis, H.W.K.

The BMS land reclamation shortly after its completion in 2015. View to the east.
On the background, ships are passing by, on their way to the port of Tanjung Perak (Surabaya).



Chapter 6

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H.W.K. Berghuis, A. Veldkamp, Shinatria Adhityatama, Tony Reimann, Alice Versendaal, Iwan Kurniawan, Eduard Pop, Thijs van Kolfschoten, Josephine C.A. Joordens

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Abstract

The island of Java (Indonesia) is renowned for its Pleistocene hominin-bearing vertebrate fossil sites. Recently, a marine sand extraction work in the Madura Strait, off the coast of Surabaya, hit upon vertebrate-rich sandstones. More than 6,000 vertebrate fossils have been retrieved from the dredged sand, amongst which are two skull fragments ascribed to *Homo erectus*. The fossils form the first vertebrate record from submerged Sundaland, the lowland plains that connected the great islands of western Indonesia to the Asian mainland during Middle and Late Pleistocene lowstands. Here we present the results of a comprehensive study of the age, depositional background and landscape setting of the subsea fossil locality. The fossiliferous sandstones form the fill of a lowstand valley of the Solo River. The material was OSL-dated to 162 +/- 31 and 119 +/- 27 ka, which links the valley to the lowstand of MIS6. Fluvial backfilling was probably related to the stage of rising sea in the run-up to MIS5. The top of the valley fill consists of marine sandstones, pointing to valley drowning and a change to estuarine conditions, probably during peak highstand conditions of MIS5e. The Madura Strait submerged valley is of similar age as the Solo terrace of Ngandong, one of the richest *Homo erectus* sites of Java and regarded as yielding the youngest record of this species.

1. Introduction and aims

In 2014 and 2015, a total volume of >5 million m3 of sand was extracted from the Madura Strait seabed north of Surabaya (Indonesia) and used for the development of a land reclamation along the coast of Gresik **(Fig. 1B and C).** The extracted sand appeared to be rich in vertebrate fossils. Over 6,000 specimens were collected from the surface of the reclamation site, representing a diverse vertebrate fauna of fish, reptiles and mammals (Berghuis et al., 2025b), including two *Homo erectus* skull fragments (Berghuis et al., 2025d).

The fossils provide a rare and unprecedented insight into the Pleistocene vertebrate fauna of submerged Sundaland **(Fig. 1A)**. This area, the largest drowned shelf of the world, was widely exposed during Pleistocene glaciations, connecting Borneo, Sumatra and Java to the Asian mainland (Voris, 2000). It formed an important habitat for Pleistocene species (Louys and Turner, 2012) and provided a pathway for faunal dispersal to Java (Salles et al., 2021; Van den Bergh et al., 2001; Van Den Bergh, 1999; De Vos et al., 1982), which included *Homo erectus* (Louys and Kealy, 2024; Kaifu et al., 2008; Antón, 2003).

Recent insights emphasize the evolutionary complexity of the Pleistocene hominin fossil record of eastern Asia (Kaifu and Athreya, in press), which besides *Homo erectus* includes several forms of ‘post-*erectus* grade’ archaic *Homo* such as Neanderthals and ‘Denisovans’ (Liu and Wu, 2022; Athreya and Hopkins, 2021; Athreya and Wu, 2017; Reich et al., 2010) and the diminutive *Homo luzonensis* and *Homo floresiensis* (Détroit et al., 2019; Brown et al., 2004). Sundaland must have played a central role in this complex evolutionary pathway and insight into its fossil record is essential.

This paper presents the results of our study of the geological setting of the subsea site. The study aimed for an analysis of the depositional conditions and age of the fossil-bearing strata. Moreover, the study aimed to place the Madura Strait subsea site in a wider landscape framework, by correlations with the on-shore geology of Java and with the off-shore geology of submerged Sundaland, as known from seismic data.

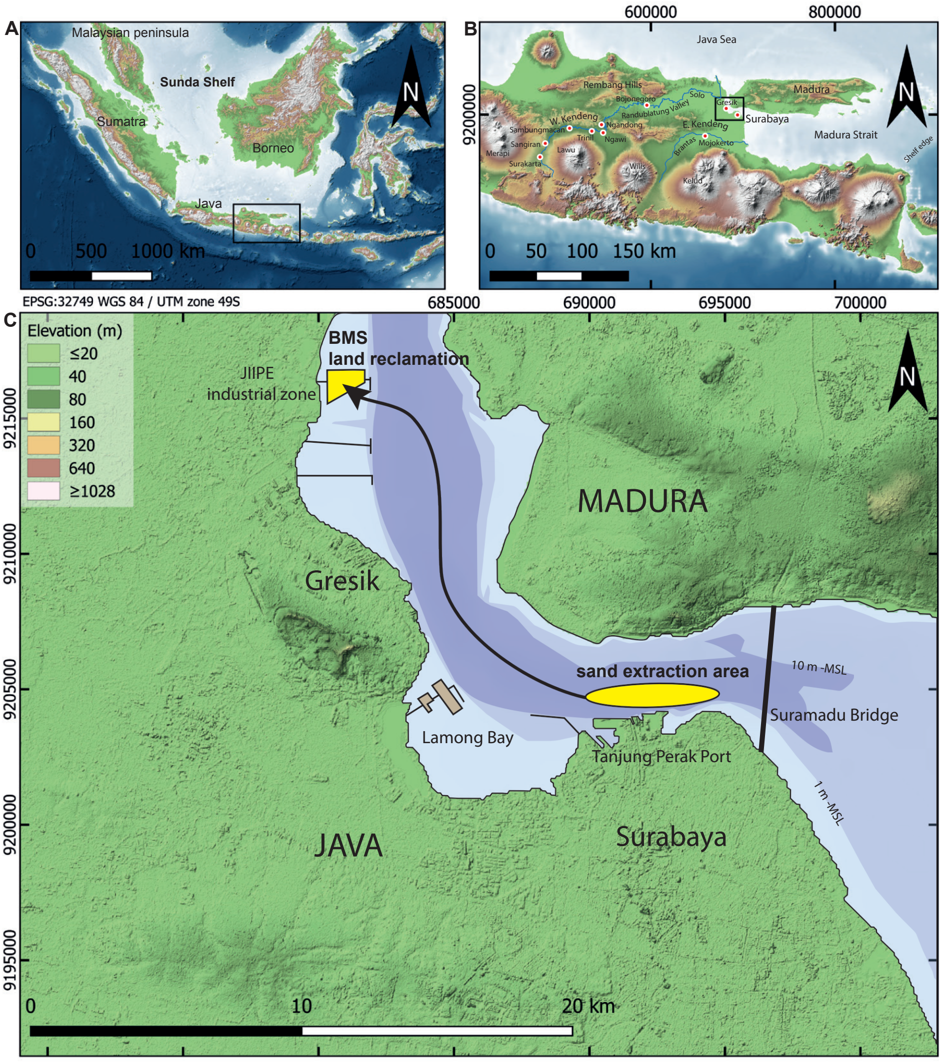

Fig. 1. A: The Sunda Shelf of Southeast Asia, with the Indonesian archipelago. Box indicates the position of map B. **B:** Eastern Java, the Madura Strait, the Solo River, Surabaya and other sites mentioned in the text. Box indicates position of map C. **C:** The Madura Strait north of Surabaya, with the sand extraction area and the BMS land reclamation. Map data: GEBCO and ALOS.

2. Sand extraction and land reclamation

The Madura Strait shores around Surabaya form a mud-dominated coastal lowland, with wide intertidal mudflats. In the Surabaya port, nautical depth is provided by a tidal channel running through the sea strait between the islands of Java and Madura. During earlier marine construction activities, patches of sandstones and conglomerates were found below the seabed of this tidal channel. Sand is a much sought-after resource in this urbanized region and is used for land reclamations along the shallow coast. In 2013, it was decided to use the material for the development of an artificial island along the coast of Gresik, west of Surabaya **(Fig. 1C).** The work was assigned by Berlian Manyar Sejahtera (BMS), a local port company that today uses the island as a port logistics site. The work was carried out in 2014 and 2015 by the marine contractor Van Oord Indonesia and involved the extraction of >5 million m3 of sand and sandstones. Use was made of a trailing suction hopper dredger, a vessel that collects bottom sediment by dragging a suction pipe over the seabed **(Fig. 2A)**. The suction pipe was mounted with a drag head, penetrating and loosening the sandstones and mixing the loosened material with water. The drag head included a 30 by 30 cm grid that prevented the uptake of larger rock fragments. The loosened and water-saturated material was sucked up and stored in the vessel's hopper **(Fig. 2B)**. When fully loaded, the vessel sailed to the land reclamation site and connected with a floating pipeline to discharge the sand to the site **(Fig. 2C)**, where the material was redistributed by shovels **(Fig. 2D)**.

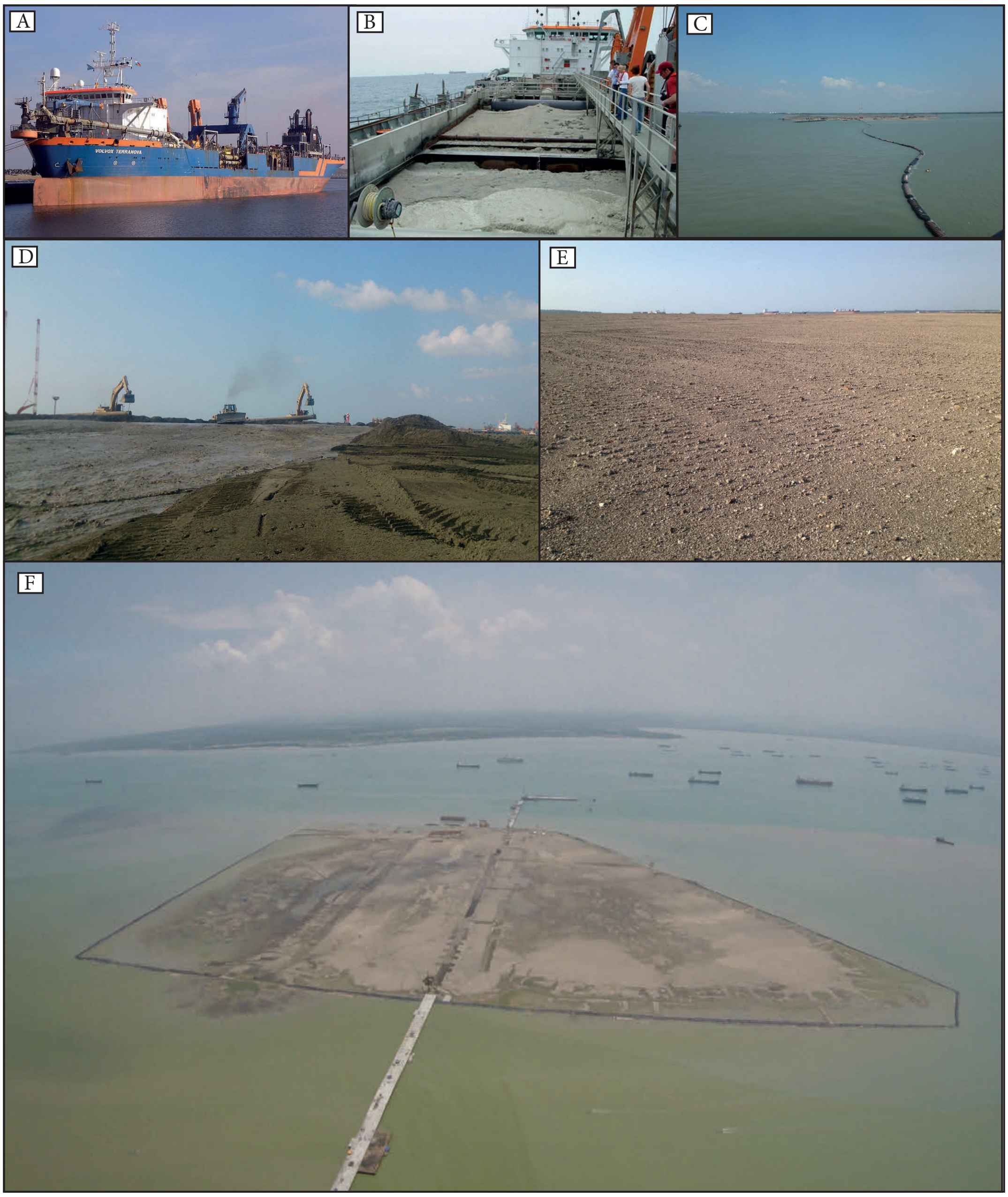

Fig. 2. Selected photographs of the 2014-2015 sand extraction and land reclamation work. **A:** The Trailing Suction Hopper Dredger Volvox Terranova. **B:** Fully loaded hopper of the Volvox Terranova. **C:** Floating pipeline for discharging the hopper load to the BMS reclamation site. **D:** Pipeline handling and sand redistribution at the reclamation site. **E:** Surface of the reclamation site after dewatering. **F:** Aerial view of the BMS land reclamation after completion. View to the east. All pictures: courtesy of Van Oord Indonesia, BMS, Sealand Coastal Consultancy and Pelindo III.

Prior to the work, average water depth at the dredging site was ~20 m -MSL (local reference level, see **Section 4**). Dredging was carried out in east-west trails and proceeded down to a depth of 32 m –MSL, not reaching the base of the sandstone body. By April 2015, the artificial island was completed **(Fig. 2E and F)**, with a total surface of ~100 ha and a height of over 4 m +MSL. The island was left for dewatering and compaction and was safely accessible by July 2015.

3. Geological setting

Java lies along the southern margin of the Sunda Shelf **(Fig. 1A)**, directly north of the line where the Indian-Australian oceanic plate subducts under continental Sundaland. A volcanic arc forms the mountainous core of the island. To the north, the foot of the volcanoes gradually changes into a lowland plain, which stretches out to the Java Sea coast. In eastern Java, this lowland has been subject to Pliocene compression, which formed east-west trending uplift zones, the Kendeng and Rembang Hills (**Fig. 1B**), both of which are made up of folded Miocene to Pliocene marine strata.

The Rembang Hills continue to the east as the island of Madura, leaving the Madura Strait as a semi-enclosed shelf sea. The southwestern shore of the Madura Strait, around the city of Surabaya, is a subsiding coastal plain. Fine terrestrial sediment is supplied by tidal currents and by the Brantas River. The build-up of the subsoil of Surabaya is roughly known from penetration tests related to construction works (Satrya, 2014). It consists of an unconsolidated muddy surface layer with a thickness of ca. 20 m, overlying more consolidated marine clays. Analogous to similar mud-dominated subsiding shorelines worldwide (Zagwijn, 1989), the unconsolidated surface layer probably represents Holocene coastal progradation. At a depth of around 200 m there is a transition to Pliocene calcareous mudstones.

A more detailed insight into the geological build-up of this lowland zone is provided by several gentle anticlines rising up from the coastal plains west of Surabaya, known as the eastern Kendeng Hills **(Fig. 3A)**. Folding reflects local compression and dates back to the Middle Pleistocene (Genevraye and Samuel, 1972). From west to east, the anticlines become lower and younger, and consequently incorporate younger material. Duyfjes (1938a and b) studied outcrops in these anticlines, which he presented as a several hundred meters thick stratigraphic section, of calcareous mudstones, overlain by marine clays, deltaic sandstones and fluvial sandstones. He interpreted this section as an uninterrupted record of coastal progradation. Moving eastward along the anticlines, toward Surabaya, he noted that the deltaic and fluvial sandstones wedge out in the marine clays, which according to him demarcated the maximum reach of Pleistocene coastal progradation.

Until recently, Duyfjes' interpretations remained uncontested. However, there is a substantial problem involved in his model of uninterrupted coastal progradation, namely that it does not take into account Pleistocene sea-level fluctuations. Sarr et al. (2019) demonstrated that the Sunda Shelf was widely exposed during most of the Early Pleistocene. The shelf became subject to regional subsidence in the Middle Pleistocene (Husson et al., 2020), which gradually brought its surface within the range of sea-level highstands, causing intermittent and progressive stages of submergence. Seismic profiles of the central zones of the Madura Strait show a stacking of four to five marine sequences, overlying a basal unconformity (Susilohadi, 1995), indicating that the Madura Strait Shelf followed the same tectonic trend as the larger Sunda Shelf (Berghuis et al., 2022).

Clearly, the sub-seabed stratigraphy of the central Madura Strait is inconsistent with Duyfjes' (1938a) model of uninterrupted sedimentation and coastal progradation. In the past years, we re-investigated the eastern Kendeng exposures, paying special attention to sea-level-related cyclicity (Berghuis et al., 2022, 2019). This resulted in a revised stratigraphy **(Fig. 3B)** and a new model of the Pliocene and Pleistocene development of this coastal area. The transition from calcareous mudstones to marine clays is gradual and could be dated to ~3 Ma by planktonic foraminiferal markers. The facies change probably relates to the emergence of the Rembang Ridge, which created a sheltered embayment along its southern border, cut-off from the supply of calcareous matter from the north. The clays that were deposited in this embayment have a characteristic, massive facies and contain benthic foraminifera that reflect water depths of around 200 m. A thick, red-colored weathering profile overlies these marine clays, showing that the embayment eventually emerged. Referring to planktonic markers and an estimate of sedimentation rates, emergence may roughly be dated to ~1.8 Ma. The weathering profile is overlain by bedded clay-sand alternations rich in shell fragments with shallow-water benthic foraminifera, representing a new transgression, presumably still during the Early Pleistocene. This series has a cyclic build-up of stacked coastal progradation sequences, reflecting sea-level fluctuations. The preservation of these sequences indicates that the area must have been subject to subsidence. The material is conformably overlain by clinoform-bedded ash layers, representing a stage of explosive volcanism, during which the coastal area was overrun by ash-rich deltas. The clinoforms are sharply overlain by fluvial conglomerates and sandstones, which, in contrast to earlier interpretations (Huffman et al., 2005; Duyfjes, 1938a) are not part of the underlying record of deltaic progradation, but form a younger unit that erosively overlies the older clinoform-bedded series (Berghuis et al., 2023, 2022, but see Huffman and Zaim, 2023 for a different interpretation). Well-rounded

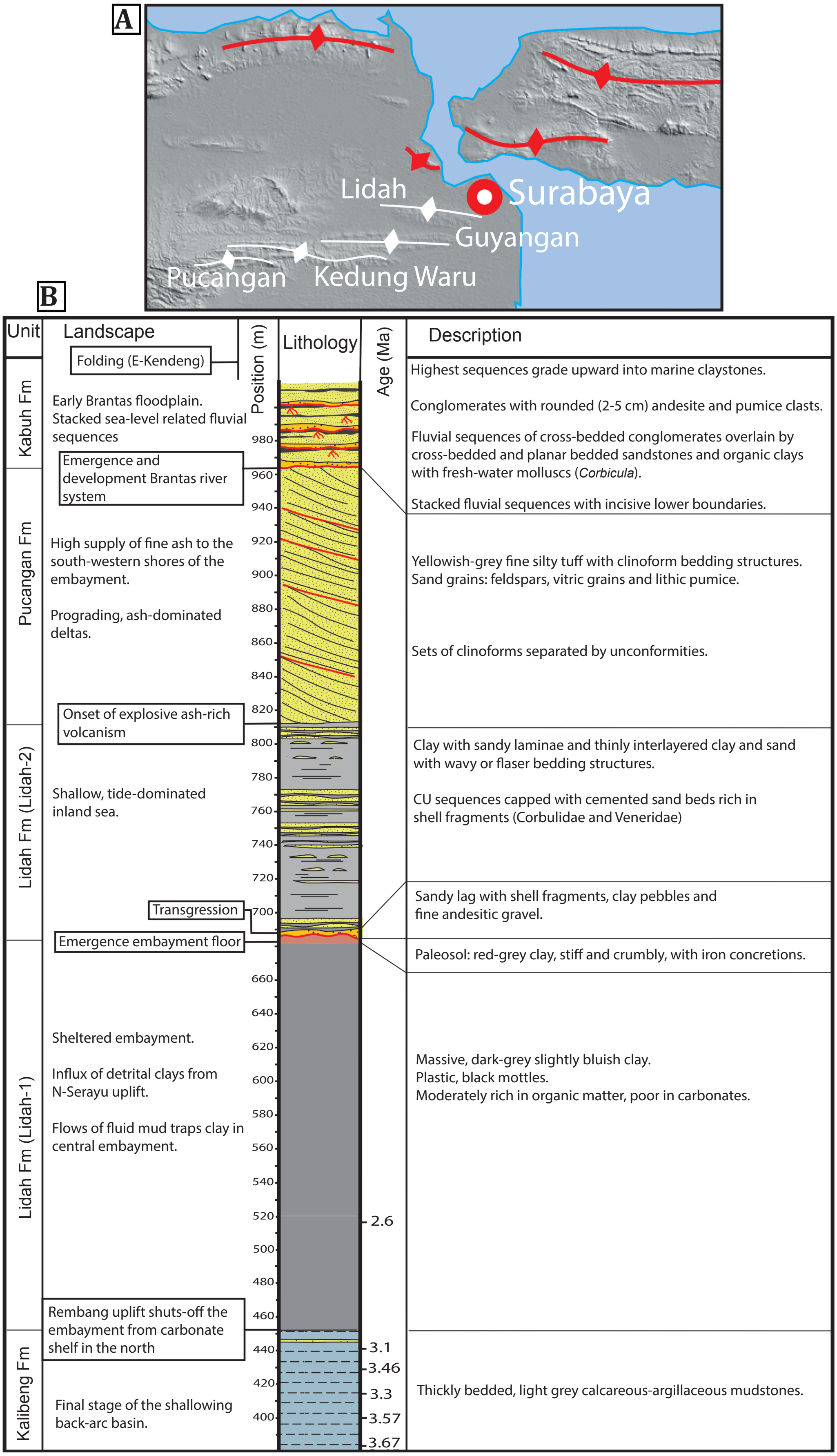

Fig. 3. A: Fold zones eastern Java. In white: the Middle Pleistocene to recent anticlines of the eastern Kendeng in the coastal zone of Surabaya. In red: the Pliocene anticlines of the Rembang Hills. **B:** Stratigraphic section of the Pucangan anticline (from: Berghuis et al., 2022; 2019). Stratigraphic units have local significance only. Ages based on planktonic foraminiferal markers. See mentioned papers for details.

andesite pebbles link these younger fluvial strata to a large and stable river system, which is regarded as the ancient Brantas. The strata form several stacked fluvial sequences, each with an erosive base. The repeated incision and aggradation cycles probably primarily reflect sea-level fluctuations in the river's lower reach. Several of the higher fluvial sequences grade upward into marine claystones and sandstones with shell fragments, reflecting drowning of the river valley during peak highstands.

In Berghuis et al. (2022) we proposed a revised stratigraphy for the eastern Kendeng Hills, based on Duyfjes (1938a), but with local significance only **(Fig. 3B)**. In this revised stratigraphy, the marine clays are subdivided into two members: Lidah-1 consists of the basal, massive marine clays, deposited in the relatively deep Late Pliocene embayment. Lidah-2 consists of the overlying shallow marine clay-sand alternations, which we associated with local subsidence, probably also dating from the Early Pleistocene. The conformably overlying clinoform-bedded ash is referred to as the Pucangan Formation. The fluvial sequences that unconformably overlie the marine strata at the top of the eastern Kendeng section form the Kabuh Formation, a unit which is linked to the Middle Pleistocene Brantas drainage system.

4. Material and methods

Our study of the geological build-up of the seabed of the Madura Strait north of Surabaya has been based on available research data, deriving from various construction projects in the port area.

A relevant data source is the pre-dredge survey, carried out in 2013 by Van Oord Indonesia as a preparation for the sand extraction work. During this study, the seabed was surveyed by sub-bottom profiling, using a Parametric Sediment Echo-Sounder (SES-2000 standard, Innomar), and by placing 48 shallow penetration (max. 5 m) vibro-cores. Penetration depth of the sub-bottom profiler depends on sediment texture and may reach 10 to 20 m in clay-dominated subsoils. The interpretation of sub-bottom profiles has been based on Damuth (1980).

Other relevant data sources are core logs of deep drillings, which provide insight into the sub-seabed geology down to depths of 60 to 100 m. The core logs derive from three infrastructure works: the Suramadu Bridge construction (2003-2009), the construction of jetties and bridges in Lamong Bay (2013-2016), and the Maspion jetty expansion (2012). The Suramadu Bridge connects Java to Madura and the deep drillings related to its construction form a unique cross-section over the sea strait.

The reclamation material was only partly crushed during the dredging process, leaving abundant intact sediment blocks and chunks on the reclamation site, which were studied with a hand-held lens and photographed at the site. Representative samples were collected and stored at the Geological Museum Bandung. Based on a comparison with the core logs of the Suramadu Section, it was possible to reconstruct the original position of individual facies in the sub-seabed stratigraphy.

Three sediment samples were selected for Optically Stimulated Luminescence (OSL) dating. Sample preparation and dating was carried out at the Netherlands Center for Luminescence Dating and at the Cologne Luminescence Laboratory (Germany). Based on previous experiences with OSL-dating of similar sandstones from Java (Hilgen et al., 2023; Berghuis et al., 2021; Rizal et al., 2020; Joordens et al., 2015), we applied the elevated temperature post-IR IRSL measurement protocol $pIRIR_{290}$ (Joordens et al., 2015; Buylaert et al., 2012) for sand-sized, potassium-rich feldspar extracts. Each sample was crushed and sieved. K-rich feldspars were extracted and purified from the samples using the preparation procedure as described in Kars et al. (2014).

All used geotechnical reports have kindly been made available by PT Pelindo III, the operator of the port of Surabaya, and by Van Oord Indonesia, the contractor of the sand extraction work. All studies on the reclamation site have been carried out under kind permission by BMS, owner and operator of the site.

Depths have been presented in meters below mean sea-level (MSL), which is the average sea level in the Surabaya port over a 14-days tidal cycle, regardless of wind or swell. Maximum tidal amplitude in Surabaya is 1.8 m.

5. Results

5.1 Sub-bottom profiling

Section A (locations: see **Fig. 4**) is a north-south profile over the Madura Strait, right in front of the Surabaya port **(Fig. 5A)**. The northern half of the profile, toward the Madura coast, shows a deep penetration of the acoustic signal, pointing to clay-dominated sediment. The top layer, from the seabed down to a depth of ca. 18 m -MSL, shows parallel bedding structures, pointing to interbedded layers of higher reflection, probably sandy laminae. Toward the axis of the sea strait, these bedding structures become oblique, which suggests slumping of large clayey blocks. This area has been subject to nautical deepening, which may have caused the slumps. Below 18 m -MSL, the sedimentary structures disappear, while the acoustic signal still has a reasonable penetrating capacity, pointing to a fine-textured, more massive subsoil, which may be either fine sand or clay. In the southern half of the section, toward the Java coast, penetration is very low, pointing to a coarse-textured subsoil. This is confirmed by three shallow test-drillings, which contain cemented, medium to coarse sand and conglomerate. Section B **(Fig. 5B)** is an east-west profile of the seabed in front of the port. In the eastern part of the section, penetration is moderate to low, with dispersed reflection, indicative of fine or medium sand. Again, this is confirmed by test-drillings. Note that the structures deeper in the profiles are harmonic reflections of the seabed. Toward the western part of the section, the sandy material becomes covered by several meters of bedded clays. Section C **(Fig. 5C)**, located in front of Lamong Bay, shows again a top layer of several meters of clay-dominated sediment with horizontal bedding structures. At a depth of ca. 25 m -MSL this material is underlain by more massive sediment with moderate penetration, which may be either fine sand or clay. In the eastern part of the section, the bedded top layer appears to thin abruptly. A test drilling shows that the top layer continues to consist of marine mud with sandy laminae. Possibly the signal is blurred by gasses in the muddy topsoil (gas blanking).

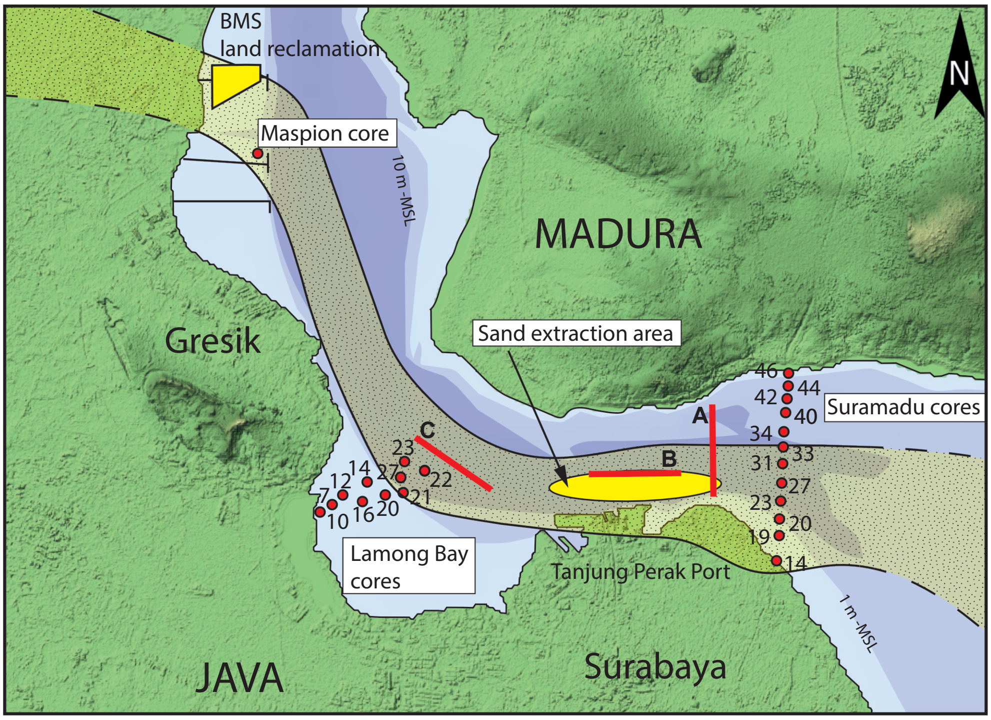

Fig. 4. The Madura Strait north of Surabaya, with positions of the sub-bottom profiling sections (red lines, A-C) and the deep drillings (red circles) as used for this study. Dotted zone: Inferred position of the sand-filled paleovalley.

5.2 Deep drillings of the Suramadu Bridge

Description

The Suramadu cores form a cross-section over the Madura Strait, only a few hundred meters east of seismic profile A **(Fig. 4)**. The cores show a deeper subsoil made up of grey, massive and firm clays **(Fig. 6A)**. The material is poor in admixed fine sand and forms a uniform and, as it appears from the core logs, uninterrupted unit. Along the Madura shore, these clays continue upward to ca. ~20 m -MSL, with at the top several interbeds of cemented, clayey sand with shell debris.

The series is capped by a ca. 5 m thick weathering profile of stiff, reddish-brown, sandy clay with iron concretions. The weathering profile is sharply overlain by grey, unconsolidated mud with interbeds of loose fine sand with shell fragments, which continues upwards to the intertidal zone and makes up the mudflats along the Madura shore. This part of the Suramadu Section correlates well with the northern part of sub-bottom profile A **(Fig. 5A)**. The bedded top layer of this acoustic section can be tied to the unconsolidated top layer of coastal mud. The underlying material with the dispersed acoustic signal is the massive clayey subsoil.

Moving toward the axial part of the sea strait, the clay series with its weathered top becomes steeply incised by a large, sand-filled channel structure, cutting down to a depth of ~ 50 m –MSL. The base of this channel is covered by several meters of brown, cemented conglomerate. This conglomerate grades upward into yellowish-grey sandstones with occasional thin conglomerate interbeds. Upward, at a depth of around 30 m -MSL, the sediment changes into grey, cemented sandstones with shell fragments, containing interbeds of grey, sandy claystones, also containing shell debris. In most of the cores, the transition to shell-bearing sandstones is marked by a well-cemented conglomerate bed with coarse shell fragments. The shell-bearing sandstones continue upward to the present seabed, which in the axial part of the sea strait is blanketed by 1 or 2 m of unconsolidated sand with shells and city waste, forming mobile

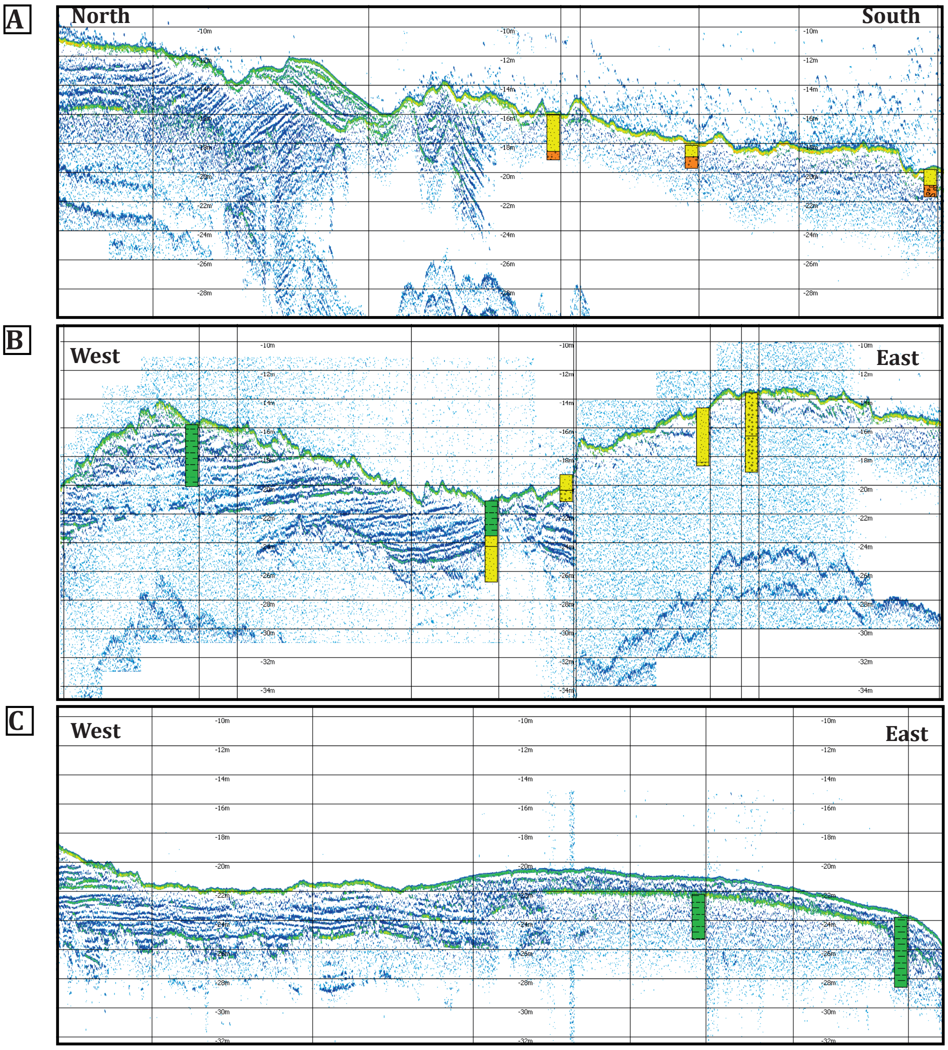

Fig. 5. A-C: Sub-bottom profiling sections over the Madura Strait seabed North of Surabaya. Locations of the sections indicated on **Fig. 4.**
Color code test drillings: Green = clay or mud; yellow = sandstone or loose sand; orange = conglomerate. Data: courtesy of Van Oord Indonesia.

tidal bars. Further toward the Java coast, the cemented sandstones are covered with mud and loose fine sand with shell debris, forming a similar tidal mudflat as along the Madura coast. Again, this part of the Suramadu Section compares well with the corresponding part of sub-bottom profile A **(Fig. 5A)**, which also shows the presence of sandy material directly below the seabed.

Interpretation

The Suramadu cores show the extracted sandstone body at the Madura Strait seabed as a large sand-filled channel, deeply cut into the clayey substrate. We regard this incision as a Pleistocene river-valley, related to a past sea-level lowstand. Molengraaff and Weber (1921) already pointed at the presence of such ancient river courses on the Sunda Shelf. More recently, stacked lowstand channels were described from seismic profiles of the Java Sea (Albab and Aryanto, 2017). The sandy fill of the incision follows the standard sequence of transgressively-filled valleys (Bowen and Weimer, 2003). The basal conglomerate, currently at a depth of 50 m -MSL, forms a fluvial lag that probably relates to the incision of the valley, during a stage of falling sea level. The overlying sandstones represent fluvial back-filling during the subsequent stage of rising sea level. Occasional conglomerate interbeds reflect a stacking of flow channels during this aggradation stage. The upward change to shell-bearing marine sandstones and clays indicates that eventually the valley drowned and changed into an estuary. Marine conglomerates, found at the transition from fluvial to marine shell-bearing sandstones, reflect increased energy conditions during this change to estuarine conditions, as a result of tidal currents.

A relation with Pleistocene sea-level fluctuations suggests that the area may have been subject to repetitive fluvial incision and aggradation cycles. An indication for the presence of stacked incised valleys is found in the base of cores 19 and 23, where sandstones rich in shell fragments are found below the incisive base of the large paleovalley. The facies of this material contrasts with the surrounding massive marine clays and also with the overlying fluvial sandstones and conglomerates. Possibly, this material represents the estuarine top of an older valley fill.

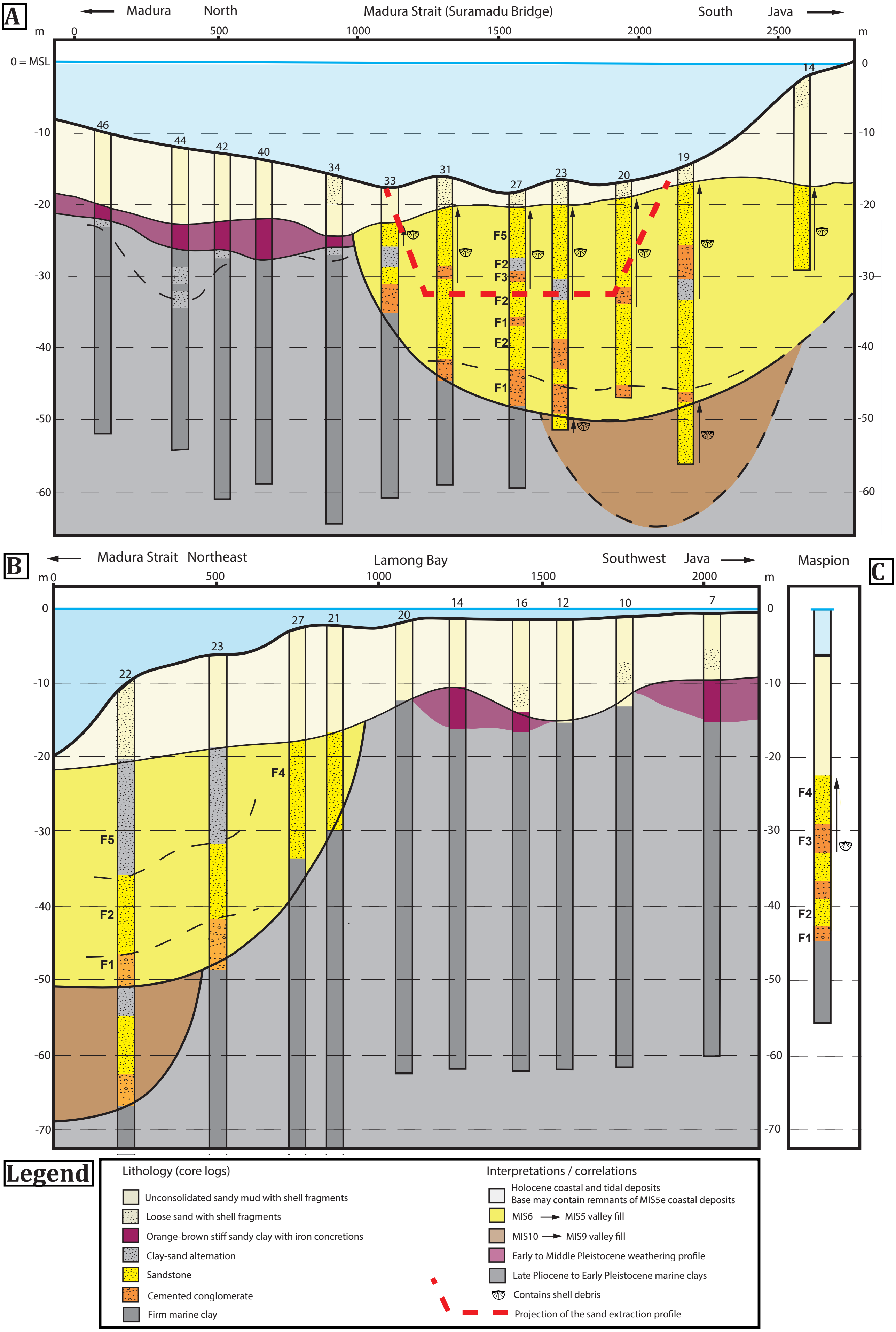

Fig. 6. Deep drillings in Madura Strait north of Surabaya, with correlations and interpretations. Drilling locations indicated on Fig. 4. **A:** Suramadu cores and section. **B:** Lamong Bay cores and section. **C:** Maspion core. Data: courtesy of Pelindo III.

Although the sand-filled valley is the focal point of this study, it is valuable to have a closer look at the clayey substrate in which the valley was cut. The massive and uniform facies of these clays suggests a relation with the Late Pliocene to Early Pleistocene marine clays from the base of the eastern Kendeng exposures **(Fig. 3B)**. The occurrence of this material so close to the surface is unexpected, as in the eastern Kendeng anticlines it is covered by more than 200 m of shallow marine clays and deltaic sands. Conclusive evidence for this relatively old age of the clayey subsoil north of Surabaya can only be based on an analysis of its foraminiferal fauna, which could not be carried out in absence of samples. However, the correlation is confirmed by the weathering profile capping the massive clays in the Madura Strait cores, which was found at the same stratigraphic position in the eastern Kendeng Section **(Fig. 3B)**. Its red color and abundant iron concretions are indicative of ferralitic weathering processes under humid tropical conditions. On eastern Java, humid conditions prevailed during the Early Pleistocene, whereas the Middle Pleistocene climate was relatively dry (Sémah and Sémah, 2012; Sémah et al., 2010; Polhaupessy, 1990). Middle Pleistocene paleosols on eastern Java are therefore usually vertisols, whereas ferralitic paleosols are only known from the Early Pleistocene and are usually older than ~1 Ma (Berghuis et al., 2021; Brasseur et al., 2011). This points to an Early Pleistocene age of the thick weathering profile in the Suramadu cores and a correlation with the Early Pleistocene paleosol of the eastern Kendeng Section.

5.3 Deep drillings of Lamong Bay and Maspion

The Lamong Bay cores derive from the south coast of the Madura Strait, directly west of Surabaya **(Fig. 4).** Again, the cores show a deeper subsoil of firm, massive clays **(Fig. 6B)**, which can be traced down to a depth of at least 100 m -MSL (maximum penetration). Upward, these massive clays continue to ca. 15 m -MSL, where we see again the red weathering profile and a top layer of unconsolidated coastal mud. Moving off the coast, the firm clays become steeply incised by a large channel structure with a fill of cemented sandstones. The base of this incision lies ~ 50 m -MSL, similar to the base of the large paleovalley of the Suramadu cores, strongly suggesting that we are looking at the same valley system. Also the valley fill is similar, with a base of fluvial conglomerates and sandstones and a marine top of shell-bearing sandstones and claystones. In core 23, the paleovalley was cut directly into the massive clayey subsoil. However, in core 22 sandy clays and sandstones continue below the valley base. This material grades downward into a cemented conglomerate bed, which sharply overlies the firm clayey subsoil at a depth of 68 m -MSL. We regard this as an erosion remnant of an older incised valley, preserved below the 50 m -MSL paleovalley. Probably, the sandstones that were found in the base of cores 19 and 23 of the Suramadu Section represent the top of the fill of this same valley system. The shell-bearing sandstones and claystones that form the top of this older valley fill show that also this lowstand valley eventually drowned and changed into an estuary.

The cores of Lamong Bay only hit upon the southern margin of the large 50 m -MSL paleovalley. The remaining part of the paleovalley must be located below the seabed of the deeper sea strait, north of Lamong Bay. The clayey top layer of sub-bottom profile C **(Fig. 5C)** may be a layer of younger mud covering the valley fill, or it may be the claystone facies of the marine top of the valley-fill.

The Maspion core **(Fig. 6C)** shows again the incised valley, cut into the deeper subsoil made up of massive clays. The base of incised valley was found at a depth of 45 m MSL. The height difference with the valley base in the Suramadu Section may reflect the ancient river-gradient, suggesting eastward flow. However, care must be taken with this interpretation, as deformation and compaction of the clayey subsoil may have affected the vertical position of valley base.

5.4 Extraction profile

The sand extraction was carried out directly north of the port of Surabaya. The work followed the trace of the large paleovalley **(Fig. 4)** in an area where the targeted material is found directly at the seabed. The dredging work proceeded to a depth of 32 m -MSL, removing a sand-dominated top layer with a thickness of ~12 m. The extraction profile has been projected against the Suramadu Section **(Fig. 6A)**, which lies directly east of the extraction zone. This shows that the extracted material consists mostly of the marine sandstones that make up the top of the valley fill. Excavation also penetrated several meters into the underlying fluvial sandstones and conglomerates.

5.5 Facies of the extracted material

The uncrushed sediment blocks on the reclamation site (BMS-island) have been subdivided into five genetically significant facies **(Table 1 and Fig. 7)**. A comparison with the core logs of the Suramadu Section provides a valuable insight into the original stratigraphic context of these facies.

The fluvial conglomerate (Facies 1) forms a fluvial channel deposit. The sand extraction work did not reach down to the basal channel lag of the paleovalley at ca. 50 m -MSL. Therefore, the conglomerates at the reclamation site must derive from interbedded channel deposits within the overlying sandy valley fill, representing aggradation and stacking of flow channels. The fluvial sandstones (Facies 2) also derive from this same part of the valley fill, shortly below the transition to marine strata. The material was probably deposited as a stacking of channel bars during fluvial aggradation. The marine conglomerates (Facies 3) are regarded as a tidal lag deposit. In the Suramadu Section, this facies occurs at the transition from fluvial to estuarine deposits and forms a transgressive lag. The gravel clasts may represent direct fluvial supply to the estuary, or they may have been reworked from the underlying fluvial beds by tidal scour. The shell fragments represent taxa that are common in shallow coastal waters and estuaries. The marine sandstones (Facies 4) derive from the upper part of the valley fill and represent estuarine depositional conditions. The material was deposited as bars in aggrading, laterally mobile tidal channels. The marine sandy clays (Facies 5) represent tidal depositional conditions and were probably deposited in shallow tidal channels or on subtidal flats between the main tidal flow paths. In the Suramadu cores, such sandy clays form interbeds within the marine sandstones.

Description	*Interpretation*
Facies 1. Calcite-cemented, massive or coarsely bedded conglomerate with moderately to well-rounded gravel (diameter 2-6 cm). Coarse sandy matrix made up of monocrystalline (feldspars, pyroxenes, hornblendes) and lithic (pumice, andesite) grains. Gravel consists of andesite, dacite and pumice, with scarce non-volcanic clasts (sandstones or mudstones).	Fluvial channel deposit
Facies 2. Calcite-cemented, medium to fine-grained sandstone with planar laminae or cross-bedding structures. Sand made up of monocrystalline (feldspars, pyroxenes, hornblendes) and lithic (pumice) grains.	Fluvial channel fill
Facies 3. Calcite-cemented, massive, poorly sorted conglomerate with moderately to well-rounded gravel (diameter 2-6 cm) and shell fragments. Sandy matrix made up of shell debris and volcanic grains. Gravel composition as in facies 1. Rich in shell fragments (Pectenidae, Verenidae, Gastropoda and Balanidae).	Tidal lag
Facies 4. Calcite-cemented, medium to fine-grained sandstone with planar laminae or cross-bedding structures. Sand made up of shell debris and volcanic grains. Veneers of larger shell fragments.	Estuarine channel fill
Facies 5. Firm clay or claystone with sandy laminae. The sandy laminae are parallel or wavy and may form lenticular and flaser bedding structures. Sand is fine to medium-grained and rich in shell debris.	Estuarine inter-channel deposit

Table 1. The five facies of the extracted material, based on uncrushed sediment blocks from the BMS reclamation site; descriptions and interpretations. For photos see **Fig. 7**.

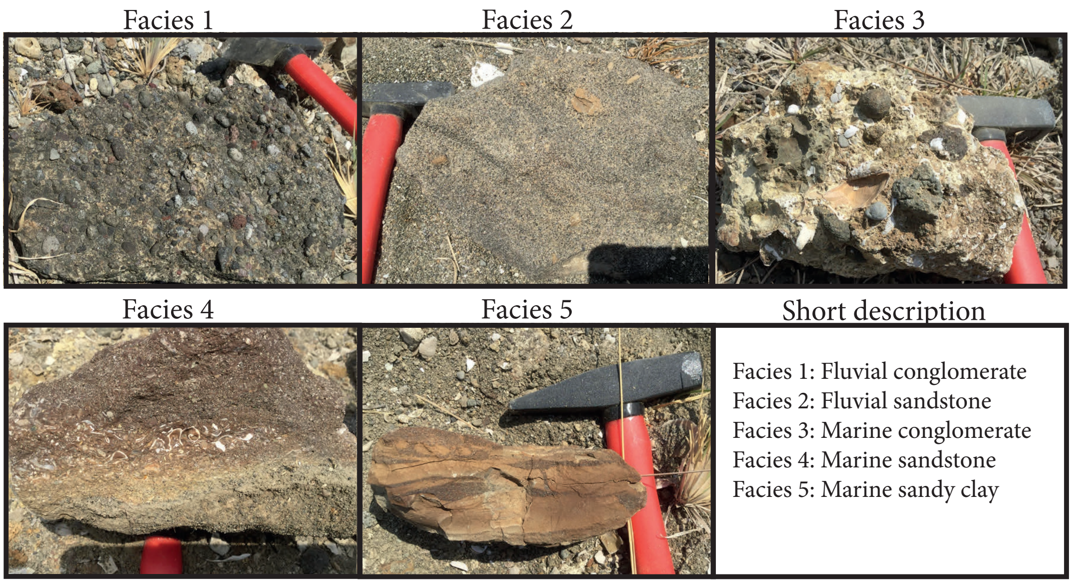

Fig. 7. The five facies of the extracted material, based on uncrushed sediment blocks from the BMS reclamation site; selected photographs. For detailed descriptions see **Table 1**.

5.6 Provenance of the vertebrate fossils

Bone fragments are frequently found in Facies 1 (fluvial conglomerates), Facies 2 (fluvial sandstones) and Facies 3 (marine conglomerates), but not in Facies 4 and 5. Interestingly, the marine conglomerates form the most fossil-rich facies. Almost all blocks of this material contain fine bone debris and larger bone or tooth fragments. This makes Facies 3 a rather exotic mixture of volcanic and marine sand, rounded andesite gravel, large fragments of marine shells and fragmented fossils of terrestrial vertebrates.

5.7 OSL-dating

Three sediment samples from the reclamation site were selected for OSL-dating **(Table 2)**. Unfortunately, no suitable sample could be obtained from the marine conglomerates with its abundant fossil fragments, due to a dominance of shell fragments and low feldspar content. However, a more feldspar-rich sample (Sample 1, CLL-Sura1) was taken from a block of uncrushed, medium-grained marine sandstones (Facies 4), which presumably derives from the same estuarine sequence. Sample 2 (CLL-Sura 2) derives from a block of fine-grained fluvial sandstone (Facies 2), which contained an unidentified fragment of mineralized bone. Sample 3 (NCL-1320099) was prepared from the sandstone fill of the neural arch of a fossil cervid vertebra. The material consists of fine-grained, cemented sandstone lacking shell fragments and is regarded as Facies 2 (fluvial sandstones).

Test measurements showed that the natural $pIRIR_{290}$ OSL signal of sample 1 is in saturation. Therefore, for this sample only an estimate of the minimum palaeodose could be determined, based on the 2*D0 threshold (Wintle and Murray, 2006). The natural signals of samples 2 and 3 are well below the onset of OSL signal saturation. To test the performance of the $pIRIR_{290}$ protocol for these samples, we carried out dose recovery tests. Dose recovery ratios, corrected for residual doses, were 1.00±0.10 (n = 4) and 1.03 ± 0.09 (n = 2), respectively, confirming the suitability of the $pIRIR_{290}$ protocol for the samples. For the two samples, $pIRIR_{290}$ equivalent doses were measured on 18 and 5 aliquots respectively. The corresponding palaeodose was calculated as the arithmetic mean and the 1-sigma standard error of the equivalent dose distributions. Finally, the palaeodoses were corrected for a remnant dose of 30±15 Gy, as proposed by Joordens et al. (2015) for comparable deposits measured with the feldspar $pIRIR_{290}$ protocol.

For determining the dose rates, the activity concentrations of Uranium, Thorium and ^{40}K were measured by high-resolution gamma spectrometry. For sample 3, which is the sandstone fill of the cervid vertebra, it was not possible to retrieve sufficient material for gamma spectrometry. As this sample has a similar composition as sample 2 and probably represents the same vertebrate-bearing fluvial sandstone unit, we assumed that the gamma spectrometry measurements of sample 2 are also applicable for sample 3. The conversion from activity concentrations to dose rates has been carried out with the dose rate calculator DRAC (Durcan et al., 2015). For the water content attenuation, we assumed a gravimetric moisture content of 15 ± 5 % for all samples. For the internal dose rate we assumed an effective K-content of our K-rich feldspar of 12.5 ± 0.5 % (Huntley and Baril, 1997). The cosmic dose rate was calculated in DRAG, based on geographic latitude and altitude of the sampled units, as well as a reconstruction of the thickness and density of the overburden. The latter must have varied over time, mostly in relation to sea-level changes. Referring to sampling depth (excavation depth) and sea-level reconstructions, we estimated the average thickness of the overburden to ~35 m.

With the obtained dose rates, the paleodoses could be converted to OSL-ages, which yielded OSL ages of 162±31 and 119±27 for samples 2 and 3 (fluvial sandstones). For sample 1 (marine sandstone), only a minimum age (≥462±71 ka) could be given. Laboratory fading tests have been conducted on aliquots of samples 1 and 2, following the approach of Auclair et al. (2003). No significant fading trend was observed for the $pIRIR_{290}$ signal of both samples and thus no fading correction was applied to the final ages.

Sample	Lab-ID	Description	Palaeodose (Gy)	Uranium (ppm)	Thorium (ppm)	Potassium (%)	Total dose rate (Gy)	Age (ka)
1	CLL-Sura 1	Marine sandstone	>1390±73[a]	9.38±0.64	1.49±0.14	0.34±0.01	3.01±0.34	≥462±71
2	CLL-Sura 2	Fluvial sandstone	216±31[b]	1.08±0.08	1.91±0.16	0.61±0.02	1.33±0.16	162±31
3	NCL-1320099	Fluvial sandstone *	158±31[b]	n/a	n/a	n/a	1.33±0.16[c]	119±27[c]

* Sandstone fill of fossil vertebral centre.
[a] Minimum dose estimate based on the 2*D0 threshold.
[b] Palaeodose is corrected for a remnant dose of 30±15 Gy according to Joordens et al. (2015).
[c] Too little material for gamma spectrometry. Dose rate estimate taken from lithologically similar sample 2.

Table 2. OSL dating of 3 sandstone samples, Madura Strait subsea site. Summary of results.

6. Discussion

6.1 Age of the paleovalley, its sandy fill and its vertebrate fossils

The OSL-ages of the two fluvial sandstone samples (samples 2 and 3), of 162±31 and 119±27 ka, provide an age frame for the stage of fluvial backfilling of the submerged valley. It links fluvial aggradation to the lowstand of MIS6 and the subsequent stage of rising sea level toward the highstand of MIS5e. Consequently, the valley was probably cut during the preceding stage of falling sea level, in the run-up to the lowstand of MIS6. The overlapping interval of the two OSL-ages (and their margins) is 146 – 131 ka, which we regard as the 'most likely age range'. This range fits well with the proposed model of valley-aggradation and drowning, as it covers the stage of rising sea-level in the run-up to MIS5. The estuarine strata that form the top of the valley fill in that case represent peak MIS5e highstand-conditions, which implies an age of around 123 ka. Unfortunately, the latter could not be confirmed by OSL-dating. The sampled marine sandstone (sample 1), which was expected to be representative of this estuarine top of the valley fill, has a minimum OSL-age of 462±71 ka. Possibly, the sample derives from a block of older sediment which was hit upon by the sand excavation work, or which had become reworked in the valley fill. It may for example derive from the marine sandstones of the older channel system, that was found underlying the large MIS6 paleovalley in drillings 23 and 19 of the Suramadu Section and drilling 22 of Lamong Bay **(Fig. 6)**.

Fluvial fossil localities often have a complex accumulation history, which may include exhumation and reworking of fossils from older accumulative cycles (Rogers et al., 2010). However, if we consider the valley fill as a single, uninterrupted aggradational sequence, the vertebrate fossils may very well be contemporaneous to the surrounding sediment. Reworking of older fossil material may rather be associated with incisive conditions. During the MIS6 downcutting stage, fossils may have been exhumed from older fluvial cycles. Such reworked fossils would in that case be expected in the basal lag deposit of the MIS6 paleovalley. This basal channel lag lies ca. 20 m below the depth reached by the sand extraction work **(Fig. 6)**. In the top of the valley fill, the occurrence of reworked older fossil is unlikely. We therefore provisionally regard the 'most likely age range' of the excavated fluvial sandstones, of 146-131 ka, to be representative for the vertebrate fossils. Note however that the occurrence of older marine sandstones among the reclamation material (sample 1) shows that the situation may be more complex. In a taphonomic study of the Madura Strait assemblage (Berghuis et al., 2025c) we will go deeper into the process of fossil accumulation and into the age and homogeneity of the Madura Strait fossil assemblage.

6.2 The paleovalley as an ancient course of the Solo

Based on the available drilling data and sub-bottom profiles, the position of the MIS6 paleovalley can be traced from the Suramadu Bridge, along the sand extraction area to the northern margin of Lamong Bay and subsequently to the Maspion core in Gresik **(Fig. 4)**. West of Lamong Bay, south of Gresik, uplifted Pliocene limestones form an isolated hill, which was formed during the same Late Pliocene compression stage that uplifted the Rembang ridge. The position of this bedrock outcrop, as well as the absence of the paleovalley in the southern cores of Lamong Bay, indicates that the MIS6 paleovalley must have had a more northern course, roughly following the current sea strait between Surabaya and Gresik. This gives an impression of an ancient river draining the Java Sea Shelf and flowing eastward to the Madura Strait Shelf, or vice versa. This, however, is an unlikely drainage pattern, connecting two subsiding shelfs. More importantly, a river draining one of these vast subsiding alluvial plains cannot have supplied the volcanic sand and andesite gravel that make up the valley fill. The composition and texture of the valley fill points to a large river with its origins in the central volcanic highland of Java. Today, there are two of such rivers in proximity of Surabaya **(Fig. 1B)**. The Brantas reaches the Madura Strait south of Surabaya, whereas the Solo flows to the Java Sea, north of Surabaya. The present course of the Solo is the result of canalization in the early 20th century. Originally the river debouched in the Madura Strait directly north of Gresik. The paleovalley at the Madura Strait seabed lies in the direct extension of this original course of the Solo, strongly suggesting that it is a Pleistocene lowstand valley of this river. This points to an eastward flow direction, which is in line with the gradient of the valley base between the Maspion and Suramadu cores. A relation with the Solo is interesting, as it connects the Madura Strait subsea locality with the on-land hominin sites of the Solo valley, such as Trinil and Ngandong **(Fig. 1B)**.

6.3 Reconstructing Solo incision and aggradation cycles on the Madura Strait Shelf

The origin and Pleistocene development of the Solo is well-known from studies of its fossil-bearing terraces (Berghuis et al., 2021; Lehmann, 1936). The river system originated in the Middle Pleistocene, when headward erosion cut a passage through the western Kendeng Hills, draining a previous lake basin south of this hill range and eventually capturing a pre-existing southward-directed drainage system **(Fig. 8A and B)**. The oldest terraces of this newly formed river system were OSL-dated to ~350 ka (Rizal et al., 2020), which suggests that the transverse valley through the Kendeng was cut during the lowstand of MIS10. If this is correct, lowstand paleovalleys of the Solo on the Madura Strait Shelf cannot be older than MIS10.

The incision and aggradation cycles of the Pleistocene Solo on the shelf surface, such as recorded in the Madura Strait north of Surabaya, may be regarded as responses to alternating stages of emergence and submergence in the river's lower reach. Referring to Sarr et al. (2019) and Husson et al. (2020), the regime of intermittent and progressive shelf submergence goes back to the Middle Pleistocene. Seismic profiles of the central zones of the Madura Strait show a sub-seabed stratigraphy consisting of four to five stacked marine sequences (**Fig. 9A)**, overlying a basal unconformity (Susilohadi, 1995). This basal unconformity currently lies at a depth of ca. 200 m –MSL and may be regarded as the Early Pleistocene land surface of Sundaland. A graphic representation of the subsiding Madura Strait Shelf against the sea-level curve (Bintanja and van de Wal, 2008) illustrates the process of progressive shelf submergence during Middle Pleistocene highstands **(Fig. 9C)**. Under a regional subsidence rate of 0.2 mm/a (Sarr et al., 2019), the first Middle Pleistocene stage of extensive Madura Strait submergence probably relates to MIS11. The graph also shows that, after this first large-scale flooding stage, there was a dramatic base-level fall of > 100 m in the period toward MIS10. Possibly, this quick regression initiated the strong wave of headward erosion that cut the traverse valley through the Kendeng, marking the origin of the Solo drainage system.

In order to reconstruct the incision and aggradation cycles of the Pleistocene Solo, we simulated the river's equilibrium profile **(Fig. 9B)**, referring to the similarly-dimensioned longitudinal profile of the Meuse (Tebbens et al., 1999). The inland plains of Surakarta and Ngawi form the river's uplifted middle reach. The northern margin of the Kendeng traverse valley forms a hinge line, marking the transition to the river's subsiding lower reach, which during lowstands extended eastward to the shelf edge, ca. 200 km east of Surabaya.

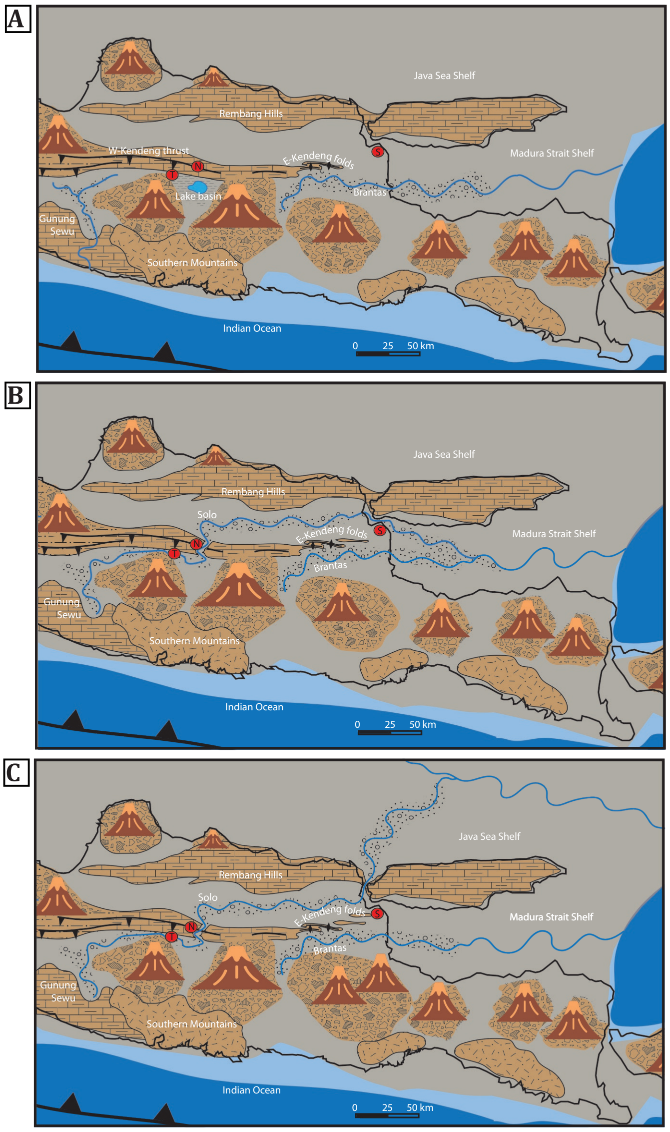

Fig. 8. Pleistocene paleogeography of eastern Java, the Madura Strait and Java Sea shelf area (part of the Sunda Shelf) and the Solo drainage system. Sea-level lowstand situations. Red circles indicate locations of Trinil (T), Ngandong (N) and Surabaya (S). **A:** Middle Pleistocene around 400 ka (MIS12?). The Brantas river system has already developed. The inland plain around Trinil, between the volcanoes Wilis and Lawu is a poorly drained lake basin. More to the west, a southward-directed drainage system exists. **B:** Middle Pleistocene between 350 and 140 ka (MIS10, MIS8, MIS6). Strong headwards erosion, presumably during MIS10, cut the Kendeng traverse valley and drained the lake basin south of the Kendeng. Eventually, also the existing drainage more to the west was captured, forming the large, eastward-directed Solo drainage system. The Madura Strait shelf area, exposed during lowstands, now holds two large perennial rivers, which possibly merge in their downstream reaches. **C:** Late Pleistocene (MIS4, MIS2). Headward erosion of northern rivers may have created a passage through the Rembang Ridge, possibly after MIS5, capturing the Solo and forcing a new course of the Solo towards the Java Sea shelf area.

Projecting the Madura Strait vertebrate site on this simulated equilibrium profile gives an altitude of around 60 m above base level. This makes it possible to estimate local incision levels, assuming that that during each lowstand, Solo downcutting reached the equilibrium state of 60 m above base level. As base level we used the altitude of the subsiding shelf edge or, when sea level did not drop below the shelf edge, lowstand sea-level. This effective lowstand base-level has been indicated by red bars in **Fig. 9C**. For each lowstand, the corresponding valley incision around present-day Surabaya, has been indicated. We tied the incision of the vertebrate-rich paleovalley to MIS6, referring to the OSL-age of the valley fill. The graph nicely illustrates the process of valley-filling during the subsequent stage of rising sea-level towards MIS5 and shows that eventually the valley drowned. The graph also shows that, under a subsidence rate of 0.2 mm/a, the base of the MIS10 incision is preserved below the MIS6 incision, while the MIS8 incision is overprinted by the deeper-reaching incision of MIS6. The remains of an older valley system, locally found below the base of the MIS6 paleovalley, therefore probably relate to MIS10, reflecting the earliest stage of the river's existence. An MIS8 paleovalley has probably not been preserved in this area. OSL-sample 1, with an age of ≥462±71 ka, possibly derives from the sandy fill of this MIS10 channel.

The position of the paleosol, which we regard as the ancient land surface in which the Solo incised, has been added to **Fig. 9C** (purple line) by taking the vertical distance of 35 m between the base of the MIS6 incision and the top of the paleosol. In section 4.2 we noted that the paleosol may reflect prolonged subaerial exposure, dating back to the Early Pleistocene. This implies that it may be the equivalent of the basal erosion surface of the seismic profiles of the deeper Madura Strait. **Fig. 9C** shows that the peak highstand conditions of MIS5e not only drowned the Surabaya paleovalley, but also the surrounding plains, represented by the paleosol. The unconsolidated sediment that in the present situation covers the paleosol is therefore not necessarily only of Holocene age, but may contain remnants of coastal sediment from this earlier flooding stage.

It is remarkable that we found a prominent MIS6 paleovalley north of Surabaya, whereas there appears to be no trace of Solo valleys related to MIS4 and MIS2. **Fig. 9C** gives a predicted incision depth of 65 m -MSL of the MIS2 paleovalley near Surabaya. Under an unchanged course, MIS2 Solo incision would therefore have removed most of the previous lowstand valleys and their sandy fills. Possibly, the river took a more southern course during MIS4 and MIS2, which implies that the remains of these younger paleovalleys must lie below the city of Surabaya. We have no detailed core data of metropolitan Surabaya, however, available soil charts and foundation reports from the city area point to a clay-dominated subsoil and do not mention the presence of a significant sand body (Satrya, 2014). Therefore, in case the subsoil of Surabaya contains the traces of MSI4 or MIS2 paleovalleys, their valley fill must be dominated by clays. Clayey valley fills may relate to the more humid climate conditions that have prevailed on Java since the Late Pleistocene (Van der Kaars and Dam, 1995).

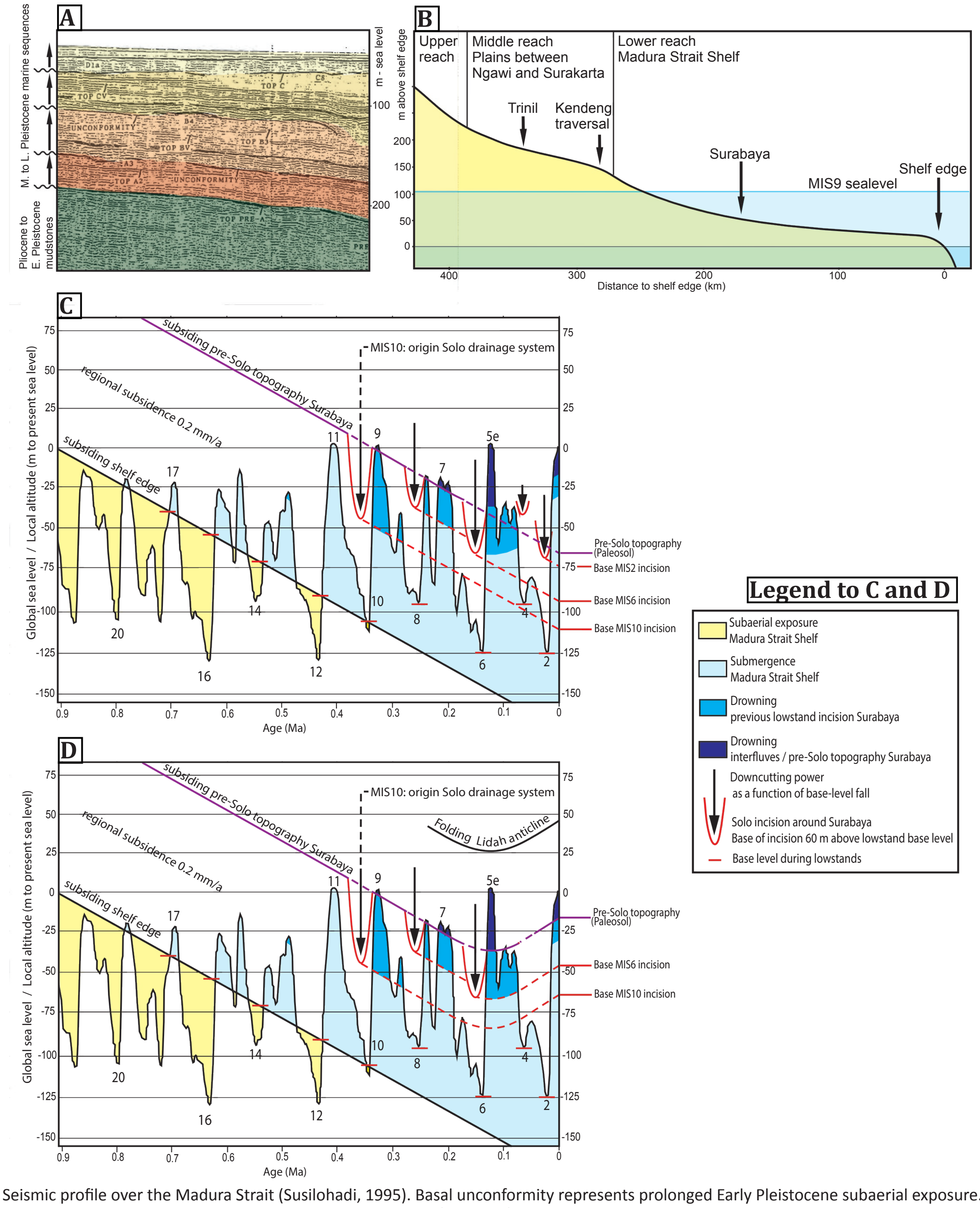

Fig. 9. A: Seismic profile over the Madura Strait (Susilohadi, 1995). Basal unconformity represents prolonged Early Pleistocene subaerial exposure. Overlying marine sequences with incised top represent intermittent submergence of the shelf during Middle Pleistocene highstands, under regional subsidence. First stage of large-scale submergence probably relates to MIS 11. **B:** Simulated longitudinal equilibrium profile of the Solo. Situation during sea-level lowstands, with sea level below the shelf edge. Position of present-day Surabaya is ~ 60 m above lowstand base-level. During highstands such as MIS9, flooding of the Solo valley reached beyond Surabaya. **C:** Reconstruction of the subsiding shelf edge in relation to sea-level fluctuations and subsidence and reconstruction of successive fluvial cycles of the Solo around present-day Surabaya. Sea-level curve based on Bintanja and van de Wal (2008), regional subsidence based on Sarr et al. (2019). **D:** Idem, but with the addition of local, fold-related uplift as a result of local compression and folding of the Lidah anticline. This provides an explanation for the current depths of the MIS10 and MIS6 incisions in the subsoil. MIS4 and MIS2 incisions were not found and have been left out.

Another and possibly more plausible explanation for the absence of MIS4 and MIS2 paleovalleys of the Solo around Surabaya is the development of a northern passage through the Rembang Ridge. Today, this opening in the hill range forms the connection between the Java Sea and the Madura Strait **(Fig. 1B)**, but it may very well have an origin as a fluvial valley. Similar to the earlier development of the Kendeng traverse valley, the stage of rapid sea-level fall associated with MIS4 may have initiated strong headward erosion of local rivers along the margin of the Java Sea Shelf, eventually cutting a passage through the Rembang Ridge and capturing the Solo around present-day Gresik. Moreover, it is possible that during peak MIS5e highstand conditions, the local saddle in the hill range became drowned. This might have generated strong tidal currents, widening and deepening the sadle, paving the way for the development of a new, northward directed river course over the Java Sea Shelf during MIS4 **(Fig. 8C)**.

6.4 Recent upwarping

The graphic representation of incision and aggradation cycles of the Solo, under a regime of sea-level fluctuations and shelf subsidence **(Fig. 9C)**, nicely explains the occurrence of the two superimposed paleovalleys at the Madura Strait seabed north of Surabaya. However, under a continued regional subsidence of 0.2 mm/a (red dotted lines in **Fig. 9C**), these incisions project at depths below their actual depths. The current vertical position of the ancient valleys may relate to recent upwarping. As explained in **Section 3**, the coastal zone is subject to compression, which is expressed by the eastern Kendeng folds southwest of Surabaya. From west to east, the folds become progressively younger. Folding of the Kedung Waru anticline **(Fig. 3A)** probably dates back to ~350 ka (Berghuis et al., 2022) and involved a change from regional 0.2 mm/a subsidence to local uplift of around 0.3 mm/a. The Lidah anticline, which continues eastward into urban Surabaya, is the youngest and most eastern fold, pushing up the surface to an altitude of ~25 m +MSL. The Surabaya coastline lies on the northern flank of this anticline and must have been affected by this uplift. In **Fig. 9D**, we added local warping-up of the clayey subsoil to our graph, assuming fold-related uplift of 0.3 mm/a, similar to the Kedung Waru anticline. With respect to the timing of this uplift, we applied a 'best fit scenario', using the current position of the MIS6 incision and the paleosol as a reference. This suggests a gradual change from regional subsidence to local, fold-related uplift at ~125 ka.

6.5 Correlations with the Solo terraces

In the Kendeng traverse valley, at least 4 terraces have been distinguished **(Fig. 10)** which were dated by Rizal et al. (2020). A correlation with the Madura Strait paleovalleys is interesting, but it is important to note that the upstream terraces and downstream paleovalleys are not necessarily direct and contemporaneous landscape equivalents. There may for example have been differences in timing of the response to degradation or aggradation events along the longitudinal river profile (Bull, 1990). Moreover, degradation and aggradation on different river stretches may have been regulated by different processes. On the Madura Strait Shelf, this fluvial behaviour was probably primarily a response to sea-level fluctuations, but higher-up along the longitudinal river profile, factors such as varying volcanic supply and local uplift may have been more important.

Nevertheless, a provisional correlation has been made, in the first place based on the available dating results **(Fig. 10)**. Comparing the ages of the Kendeng terraces to the sea-level curve **(Fig. 9)**, it seems that also in this area the main downcutting stages may have been responses to sea-level fall. Note that with the exception of the higher terrace, which is a gravelly strath terrace, the OSL-ages of the Kendeng terraces refer to the terrace fill, which overlies the basal erosion surface and postdates downcutting.

The upper terrace contains the oldest known Solo deposits and probably represents the earliest stage of the river system, shortly after the development of the Kendeng traverse valley. Erosion remnants of this oldest terrace can also be found south of the Kendeng (Berghuis et al., 2021). This earliest incisive stage of the Solo, which we linked to MIS10, is probably the equivalent of the lowest, partly preserved paleovalley of the Madura Strait north of Surabaya.

The middle and lower terrace of the Kendeng traverse valley have OSL-ages that overlap with the valley-fill of the large, fossiliferous paleovalley of the Madura Strait, but the lower terrace clearly gives the best age fit. The terrace sediment was dated by a combination of OSL, Ar/Ar and U-series techniques, yielding a Bayesian-modelled age of 140 – 92 ka (Rizal et al., 2020). We provisionally linked downcutting of this terrace and incision of the largest Madura Strait paleovalley to the stage of falling sea-level related to MIS6. The middle terrace of the Kendeng traverse valley is older and its downcutting is possibly related to MIS8.

6.6 Relation between the Madura Strait subsea site and the upstream hominin sites along the Solo

The proposed correlation between the fossiliferous valley fill of the Madura Strait and the lower terrace of the Kendeng traverse valley is of great interest, as this terrace yielded the rich vertebrate fossil assemblage of Ngandong, including 11 partial skulls and 2 tibiae assigned to *Homo erectus* (Huffman et al., 2010; Weidenreich, 1951; Oppenoorth, 1932), which is regarded as the youngest record of this hominin species on Java (Rizal et al., 2020).

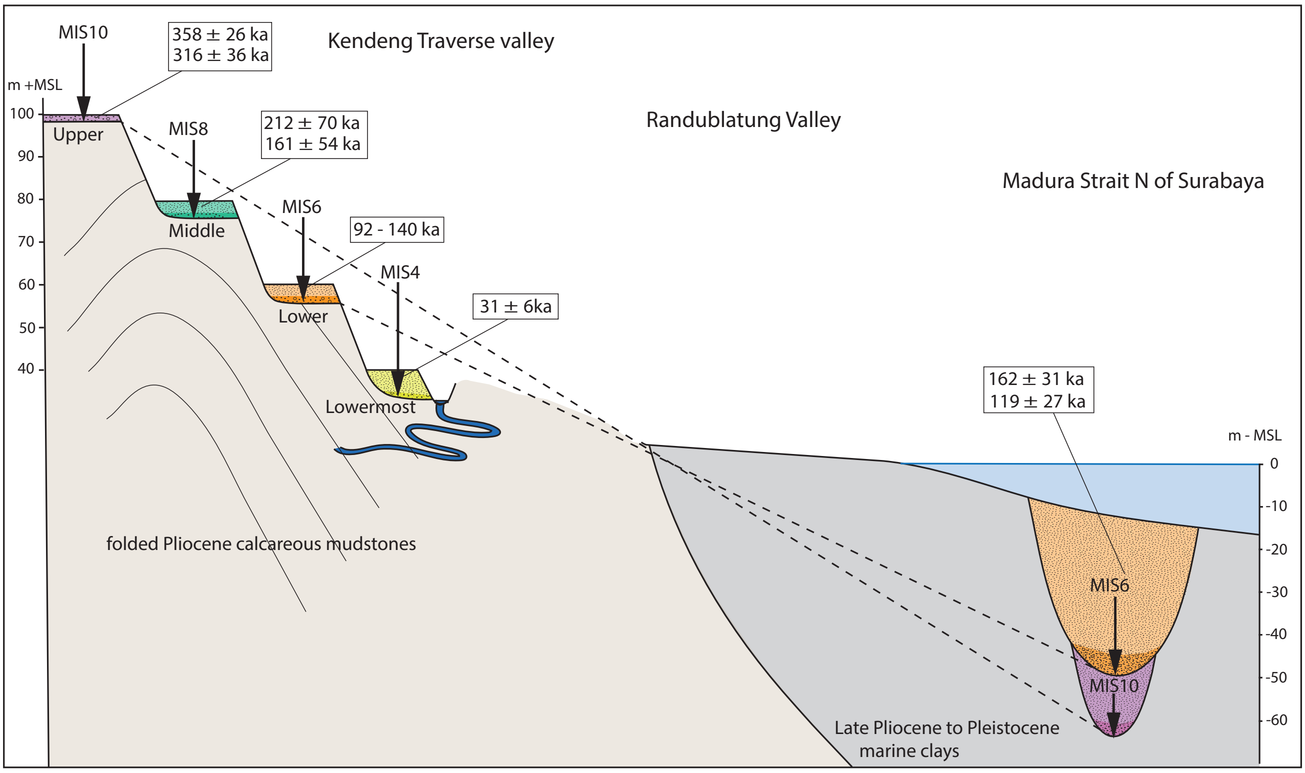

Fig. 10. Provisional correlation between the Solo terraces of the Kendeng traverse valley and the incised valleys of the Madura Strait north of Surabaya. Terrace ages from Rizal et al., 2020. These ages are OSL-ages or, for the lower terrace, Bayesian-modelled of OSL, U-series and Ar/Ar ages. Dated material of the upper terrace is a lag that probably relates to downcutting. For the other terraces, the dated material is probably the terrace fill, postdating downcutting. The proposed correlations are the downcutting stages and their inferred relation to sea-level lowstands. The lower terrace of the Kendeng traverse valley is the hominin-bearing Ngandong terrace.

Not only are the Ngandong and Madura Strait sites of similar age, they are also tied to the same river valley. Yet, there may have been relevant landscape differences. Ngandong represents a setting along the uplifted middle reach of the Solo, whereas the Madura Strait site represents a setting along the river's lower reach, surrounded by lowland plains **(Fig. 10)**. Stream velocities around Ngandong were probably higher. Moreover, Ngandong was probably not invaded by the sea during peak-highstand conditions of MIS5e, although the shoreline may have come close to the Kendeng traverse valley and a salt-water wedge may have reached further upstream, especially during periods of low discharge. Another important difference is that the highland of Java probably had more rain than the lowland plains, which must have had an effect on vegetation types and faunal communities. An analysis of the Madura Strait assemblage and a comparison with the Ngandong assemblage may shed a better light on these matters (Berghuis et al., 2025b).

Further upstream, south of the Kendeng traverse valley, the Solo terrace landscape continues. Lower uplift rates make that individual terrace levels are more difficult to recognize. Moreover, fluvial behaviour of the Solo has been strongly influenced by sediment supply, with ash-rich fill-terraces reflecting eruptive stages of the nearby Lawu (Berghuis et al., 2021). The hominin skulls Ngawi 1 and Sambungmacan 1-3 were found in this area and may very well derive from the Solo terraces. Unfortunately, details on their age and stratigraphic provenance are not available (Kaifu et al., 2015; Delson et al., 2001). The skulls may also derive from the Trinil Formation, which forms the local substrate and consists of fluvially reworked ash, deposited in a local lake basin shortly before the development of the Solo drainage system **(Fig. 9A)**. This unit, which is highly fossiliferous, is often difficult to distinguish from ash-dominated fill terraces in isolated outcrops (Pop et al., 2023b).

The skullcap from Trinil (Dubois, 1896), today regarded as the type specimen of *Homo erectus* (Pop et al., 2024; Mayr, 1950), was also excavated in the Solo valley south of the Kendeng, but certainly predates the origin of this river. At the find site, there are two superimposed bone beds, which were dated to 830 – 773 ka and around 450 ka respectively (Hilgen et al., 2023). Referring to the ancient morphology of the skullcap, it probably derives from the oldest bone bed, and may even have been reworked from older layers. Interestingly, also an intact hominin femur was discovered in Trinil. It was originally associated with the skull cap (Dubois, 1896), but is today commonly regarded as a younger specimen, deriving from the Solo terrace deposits that erosively overlie the older deposits (Pop et al., 2023a; Ruff et al., 2022). This terrace, locally referred to as T2 (Berghuis et al., 2021), is probably the equivalent of the vertebrate-rich terrace of Ngandong and thus may be of similar age as the Madura Strait site. Further upstream along the present Solo valley, Sangiran is the richest *Homo erectus* site of Java. The local fossils are probably of late Early to early Middle Pleistocene age and predate the origin of the Solo (Matsu'ura et al., 2020; Kaifu et al., 2008).

6.7 Correlation with the eastern Kendeng stratigraphy

In **Section 5.2** we correlated the massive clays that make up the deeper subsoil of coastal Surabaya with the Late Pliocene to Early Pleistocene massive marine clays (Lidah-1) of the eastern Kendeng section **(Fig. 3B)**. The transgressively-filled incised valleys of the Madura Strait are comparable to the fluvial incision and aggradation cycles that make up the top of the eastern Kendeng section, both forming a record of fluvial response to Middle Pleistocene sea-level fluctuations and progressive submergence of the Madura Strait Shelf. However, the fluvial records represent two different river systems. The fluvial to estuarine top of the eastern Kendeng section relates to the Brantas drainage system and is referred to as the Kabuh Formation. The valley-fill sequences of the Madura Strait relate to the Solo drainage system. In Berghuis et al. (2021) we proposed to refer to all (terrace-related) deposits of this river system as the Solo Formation.

The ca. 260 m thick series of coastal, partly deltaic deposits (Lidah-2 and Pucangan Formation), which in the eastern Kendeng section lies between the massive marine clays and the fluvial top, is absent in the coastal area around Surabaya. The accumulation and preservation of this shallow marine series in the eastern Kendeng area point to significant, local subsidence, and to a connection with the sea. Possibly, the occurrence of local subsidence zones relates to vertical movement along basement faults, a process that was described by Lunt (2013) for the wider eastern Java area.

6.8 Landscape setting of the Madura Strait paleovalleys

The Madura Strait paleovalleys north of Surabaya are lowstand valleys of the Solo, cut in an ancient land surface that had been stably exposed since the Early Pleistocene. Valley incision in this area probably dates back to MIS10, when the Solo developed as a large eastward-directed drainage system. If we regard the paleosol of the Madura Strait stratigraphy as the ancient land surface in which the valleys incised, then the MIS10 valley of the Solo had a depth of 50 m compared to the surrounding lowland. MIS6 incision was less pronounced, cutting a valley of around 30 m. During intermittent highstands, the valleys drowned and changed into estuaries. During peak highstand-conditions of MIS5e also the surrounding plains submerged.

The ferralitic paleosol in which the valleys were cut, had originally formed under humid conditions. However, by the time the surface was incised, climate conditions had changed to more arid, leaving the ferralitic soil properties as a relic of passed climate conditions. This is confirmed by the valley fill of monocrystalline sand and rounded andesite gravel, which points to sediment supply from a hinterland subject to physical abrasion under arid or semi-arid climate conditions rather than chemical weathering under humid, densely vegetated conditions.

7. Conclusions

The subsea vertebrate locality of the Madura Strait north of Surabaya is a submerged lowstand valley of the Solo. Valley incision relates to MIS6. Two samples from the fluvial valley fill were OSL-dated to 163+/- 31 ka and 129 +/- 27 ka, which links fluvial aggradation to the stage of rising sea-level between MIS6 and MIS5. The top of the valley fill consists of shell-bearing marine sandstones, reflecting drowning of the river valley and a change to estuarine conditions during peak MIS5e highstand conditions.

Vertebrate fossils of the valley fill are associated with fluvial sandstones and conglomerates, and with a marine conglomerate bed that marks the transition between fluvial and estuarine sandstones. Most of the available fossils derive from this transitional bed, which is regarded as a tidal or transgressive lag.

The late Middle Pleistocene age of the site is of great interest in terms of hominin evolution, as this period is characterized by a great morphological diversity and mobility of hominin populations in the region (Kaifu and Athreya, in press). The subsea site is of similar age as the Ngandong terrace of the Kendeng Hills and terrace T2 of Trinil, both of which yielded hominin fossils, which are generally regarded as the last occurrence of a long-standing, isolated *Homo erectus* population. Although of similar age and tied to the same river, the landscape context of these find sites was probably different. The Trinil T2 terrace and the Ngandong terrace were formed along the river's middle reach, at the foot of the volcanic highland of Java. The Madura Strait submerged valley represents a lowland setting. The lowland plains probably had a lower precipitation rate, which may have affected vegetation and faunal communities.

Under the relatively dry Middle Pleistocene climate of eastern Java, herds of herbivores and groups of hominins on the lowland plains were probably dependent on large perennial rivers, providing drinking water and terrestrial as well as aquatic food sources. These drainage systems may very well have formed important dispersal routes for hominins and other species. The Middle Pleistocene Madura Strait Shelf had two of these rivers, the Brantas and the Solo, which must have made the area an attractive habitat.