

Origin and age of carbonate clasts from the Lusi eruption, Java, Indonesia

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Deep stratigraphic constrains below the Indonesian Lusi mud eruption are currently lacking due to the absence of deep wells and good quality seismic data. A collection of carbonate clasts has been sampled from the Lusi site, active since its birth in 2006. These specimens are part of a large variety of lithotypes erupted from the main crater. The carbonates analysed comprise scleractinian coral and bivalve shell fragments, probably shallow-water in origin, and clasts consisting of planktonic foraminifera-bearing mudstone, from pelagic deposits. Selected rocks were analysed using planktonic foraminifera and $^{87}\text{Sr}/^{86}\text{Sr}$ dating with the aim to constrain their age and to improve the understanding of the, so far unknown, sequence of limestone deposits inferred at this site.

Based on biostratigraphy using planktonic foraminifera, one group of samples reveal to belong to the Planktonic Foraminifera Zone M5b, with an age comprised between 16.29 and 15.10 Ma (Miocene, Latest Burdigalian to Langhian). The Sr isotope-based ages of clasts analysed for $^{87}\text{Sr}/^{86}\text{Sr}$ cover a larger time window spanning from Pliocene (Zanclean and Piacenzian), Miocene (Messinian) down to Eocene (Priabonian). The Pliocene and Messinian ages are unreasonably young from what is known of the local geology and one sample provided an $^{87}\text{Sr}/^{86}\text{Sr}$ age that is ~ 8 My younger compared to that obtained from the planktonic foraminifera assemblage occurring in that sample. The discrepancy suggests that this and the other unduly young samples have possibly been contaminated by geological materials with radiogenic Sr isotope composition. The minimum age of 37.18 Ma obtained by $^{87}\text{Sr}/^{86}\text{Sr}$ from a well-preserved oyster shell indicates that some of the clasts can be attributed to the deep seated Ngimbang Formation.

The dating has been combined with the interpretation of seismic profiles to investigate the stratigraphy of inferred carbonates below Lusi and the PRG-1 well located some kilometres to the north east. PRG-1 borehole data are also integrated and discussed in this study.

The obtained results reveal multiple implications: a) the Tuban and Kujung Formations are overlapping at Lusi site; b) the Lusi feeder conduit brecciated and mobilized to the surface carbonate lithologies buried as deep as possibly ~ 3.8 km as well as even older and deeper seated lithotypes from the Ngimbang Formation; c) since the deeper carbonate samples erupted in 2006 belong to the typically not overpressured Kujung Formation, an additional overpressure generated from deeper units (Ngimbang Formation) would be required to force these fragments to surface.

1. Introduction

The current stratigraphic scheme of east Java is based on several studies largely based on information acquired through industry seismic surveys and wells for hydrocarbon exploration (Matthews and Bransden, 1995; Kusumastuti et al., 2002; Satyana, 2005; Sharaf et al., 2005; Ardhana, 1993). The general stratigraphy may vary depending on the selected location as sedimentation can be affected by the presence of e.g. neighbouring volcanic complexes, extension of carbonate

platforms, localized reefal buildups and lacustrine deposits. Seismic acquisition is typically arduous due to the logistics occurring in densely populated areas such as the NE Java. In addition the signal in seismic profiles is often buffered by the presence of carbonate units that absorb large part of the energy. This results in poor resolution of the internal structures of numerous onshore carbonate units and formations, as well as limited or no details about the overlaid formations. Similarly the available well data is restricted to shallow depths (i.e. sand reservoirs < 1 km) or reach the top of the reefal carbonates that are the

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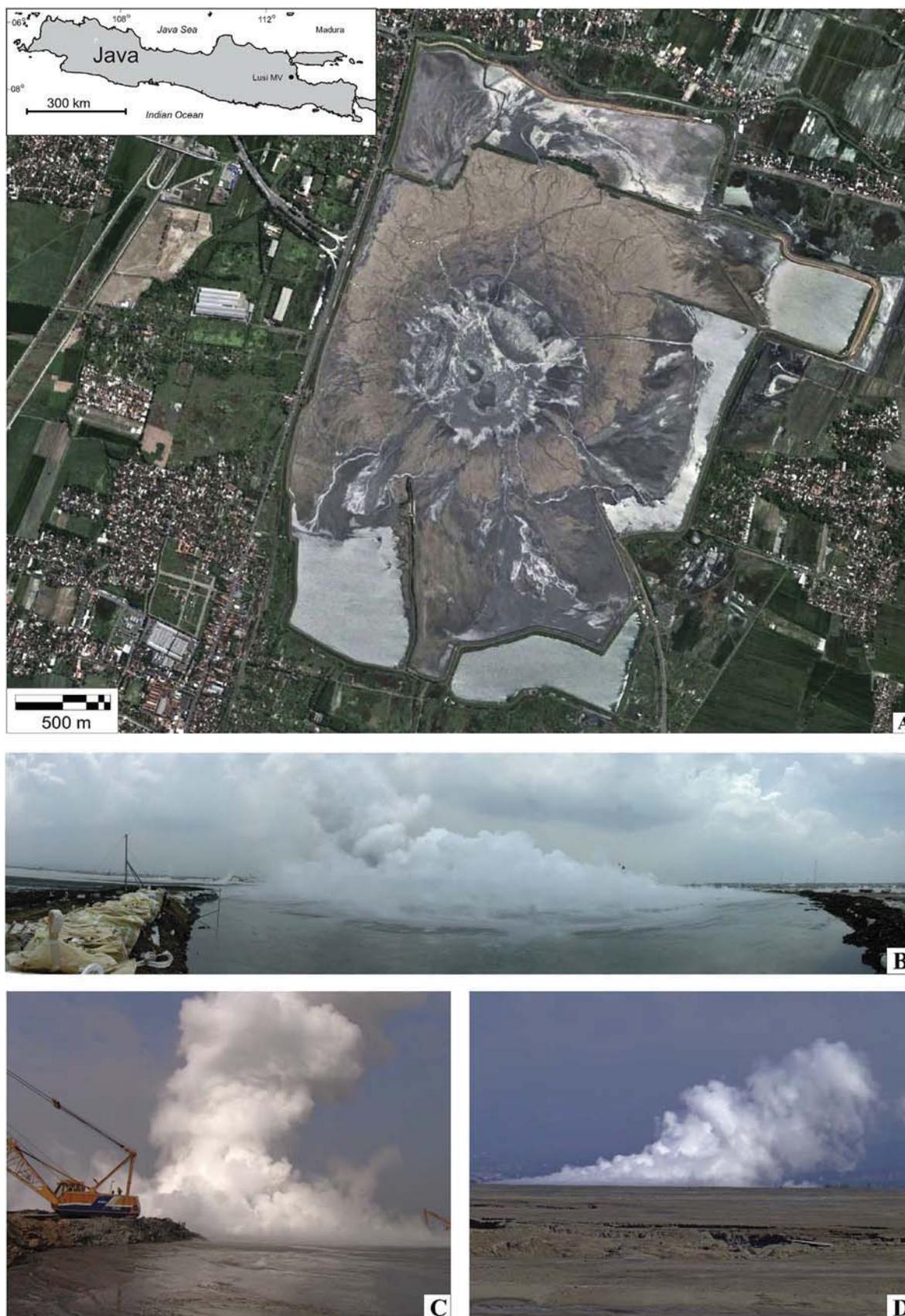


Fig. 1. Setting.

Inset map of Java Island, Indonesia with the marked position of the Lusi eruption site in northeast Java. (A) Satellite image of the Lusi eruption site showing the two active vents in the central part and the vast area covered by erupted mud breccia framed by a tall embankment wall. In brown colour the dry mud breccia zone that is today accessible. Field images of the Lusi crater framed by an artificial berm (B) that allowed the direct use of excavators for fluids and clasts sampling. (C) Sampling using an excavator in 2006. (D) Since 2009 the Lusi crater remained isolated inside a 7 km² embankments zone surrounded by a vast area of erupted mud breccia that is dry on the outskirts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

common reservoir units in the NE Java Basin (e.g. Kusumastuti et al., 2002). The approach proposed in this paper is to obtain information about deeply buried strata exploiting the available piercement structures. These localities may be considered as “free wells” since during their growth and eruptive activity, piercements brecciate the formations intersected by the feeder channel and ultimately expel to the surface a mix of the different lithologies. The study of erupted mud breccia clasts, collected at mud volcano craters, was successfully used to reconstruct the pierced stratigraphic column. Examples of such studies are reported in the literature (e.g. Premoli Silva et al., 1996; Akhmanov et al., 2003; Giresse et al., 2010; Gennari et al., 2013). This technique may be also used at the Lusi locality in the north east Java. Lusi is one of the most spectacular geological phenomena currently active on Earth. This clastic-dominated geysering-like system started the 29th May 2006 in the Sidoarjo regency and has been active since, erupting a current average of 80,000 m³ of mud breccia per day (Mazzini et al., 2007, 2012; Karyono et al., 2016) (Fig. 1). A collection of the clasts erupted at Lusi reveals the presence of organic-rich shales, volcanoclastic rocks, and carbonate specimens. These lithologies correspond to the known stratigraphy present below Lusi. Here the section up to ~2833 m depth is constrained by drilling results (e.g. see drilling details in Lupi et al., 2014), and consists of:

- 1) Recent Holocene alluvial sediments (intercalated sands and clay) between 0 and 290 m.
- 2) Pleistocene alternating sandstone and shale of the Pucangan Formation, between 290 and 900 m.
- 3) Pleistocene bluish gray clay of the Upper Kalibeng Formation, between 900 and 1871 m. This unit is strongly illitized and partly organic rich.
- 4) volcanoclastic deposits between 1871 m and at least up to ~2833 m, but likely deeper.
- 5) inferred Miocene-Oligocene carbonates of the Tuban and Kujung (including the upper Prupuh unit) Formation assumed to be as deep as 3800 m.
- 6) Eocene - Early Oligocene (?) black shale of the Ngimbang regional source rock deeper than ~3800 m (Mazzini et al., 2007, 2012; Istadi et al., 2009; Sawolo et al., 2009).

The stratigraphy below 2833 m has not been penetrated and it remains under investigation. So far, the exact depth of the boundary between the volcanoclastic deposits and the overlaid carbonates is not constrained by direct data. Similarly, the age of the carbonates remains unclear. The knowledge of East Java carbonates is inferred from data obtained from the northern part of the basin (Kendeng Deep to the north, including present East Java Sea) where most petroleum companies have operated. Porong-1 well (PRG-1), as well as KE-11C, KE-11E BD-1 wells are the only sites/wells penetrating carbonates of East Java located to the south of Kendeng Deep (Kusumastuti et al., 2002). Therefore, new samples from carbonate formations, such as those collected at Lusi, may provide additional information to constrain ages and to better understand the regional paleogeography. Interpreting the information from other localities, the carbonate underneath Lusi have been ascribed to a) the platform limestones of the Oligocene Kujung Formation, similarly to those present in the offshore East Java Basin, and/or b) to the younger early middle Miocene reefal Prupuh Unit or c) even younger carbonates occurring on top of the Tuban Formation (and their slope and basinal equivalent). The presence of the Tuban Formation is suggested based on Sr dating of one red algae fragment recovered from the inferred structurally similar carbonates drilled in the Porong-1 well (located in the same region). Results from PRG-1 well indicate a numerical age of approximately 16 Ma (late early Miocene) (Kusumastuti et al., 2002). The only dating that has been completed at Lusi so far is reported in Mazzini et al. (2007) and in Sawolo et al. (2009) that compared the dating of foraminifera and nannofossils from the mud erupted at Lusi site during its initial activity with side well cores from the BJP-1 exploration well located in the vicinity. Results revealed that large part of the mud originates from the Kalibeng Formation between 1.2 and 1.8 km, although a deeper source was never excluded. Since the initiation of the Lusi eruption no further attempts

have been made to date the mud or the clasts present in the erupted mud breccia.

Since the Lusi birth in 2006 we have conducted a systematic collection of different lithologies of mud breccia clasts erupted from the Lusi crater site. These include also specimens of carbonate samples that are the primary focus of this study. The aim of this paper is to date the clasts selected from the collection of carbonate lithologies and to a) constrain the stratigraphy and the local basinal history and b) improve our understanding of the Lusi plumbing system discussing how the obtained ages fit the current stratigraphic scheme of the area obtained from available seismic data, outcrops and cores.

2. Setting

The eruption site in East Java nicknamed Lusi is an active sediment-hosted hydrothermal system that has been active since the 29th of May 2006 (Mazzini et al., 2012; Miller and Mazzini, 2017). It is located in a Cenozoic-aged back-arc basin of NE Java (Kusumastuti et al., 2000). Currently a surface of nearly 7 km² is covered by erupted mud breccia (Fig. 1). This area is framed by a 10 m tall embankment that prevents additional floods in the surrounding villages. The vast walkable area inside the Lusi embankment zone is filled by erupted dry mud breccia consisting of a fine grained sediments (from clay up to sand) and clasts of different sizes (up to 15–20 cm) and lithologies.

3. Methods

3.1. Field sampling

The eruption of mud breccia characterized the Lusi activity after its birth in 2006. Since then we have conducted sampling of erupted mud breccia clasts of different lithologies. During the first years we collected sediments from the scoop of excavators that could access and collect material directly from the crater area. Later we handpicked specimens from the vast area of walkable dry mud breccia that surrounds the central active zone.

From this collection, we selected 12 samples for dating (Table 1) using ⁸⁷Sr/⁸⁶Sr ratios and for thin sections used for microfossil identification.

3.2. Sample preparation

Samples for Sr isotope analyses were recovered by micro-drilling targeted portions of rock slabs made from carbonate specimens. About 10 mg of powdered carbonate material were dissolved in 2.2 M high purity acetic acid during 1–2 h at room temperature in conical shaped 2 ml vials. The solutions were centrifuged and the supernatant was recovered and transferred to Teflon vials, where it was dried down on a hot plate. The residue was re-dissolved in a few drops of 14 M HNO₃ and dried down again before Sr separation from the matrix using Sr-Spec resin. The Sr separate was dissolved again in 5 ml of ~2% HNO₃ solutions and ratios were measured using a Thermo Neptune PLUS Multi-Collector ICP-MS in static mode. The ⁸⁸Sr/⁸⁶Sr (8.375,209) ratio was used to monitor internal fractionation during the run. Interferences at masses 84 (⁸⁴Kr), 86 (⁸⁶Kr) and 87 (⁸⁷Rb) were also corrected in-run by monitoring ⁸³Kr and ⁸⁵Rb. The SRM987 standard was used to check external reproducibility, which was 10 ppm (1SD) on the long-term (more than 100 measurements during one year). The internally corrected ⁸⁷Sr/⁸⁶Sr values were further corrected for external fractionation (due to a systematic difference between measured and a nominal standard ratio of the SRM987 of ⁸⁷Sr/⁸⁶Sr = 0.710248: McArthur et al., 2001) by a value of -0.039‰ per amu.

Thin sections of all samples were made for petrographic studies, particularly for screening of possible diagenetic alteration.

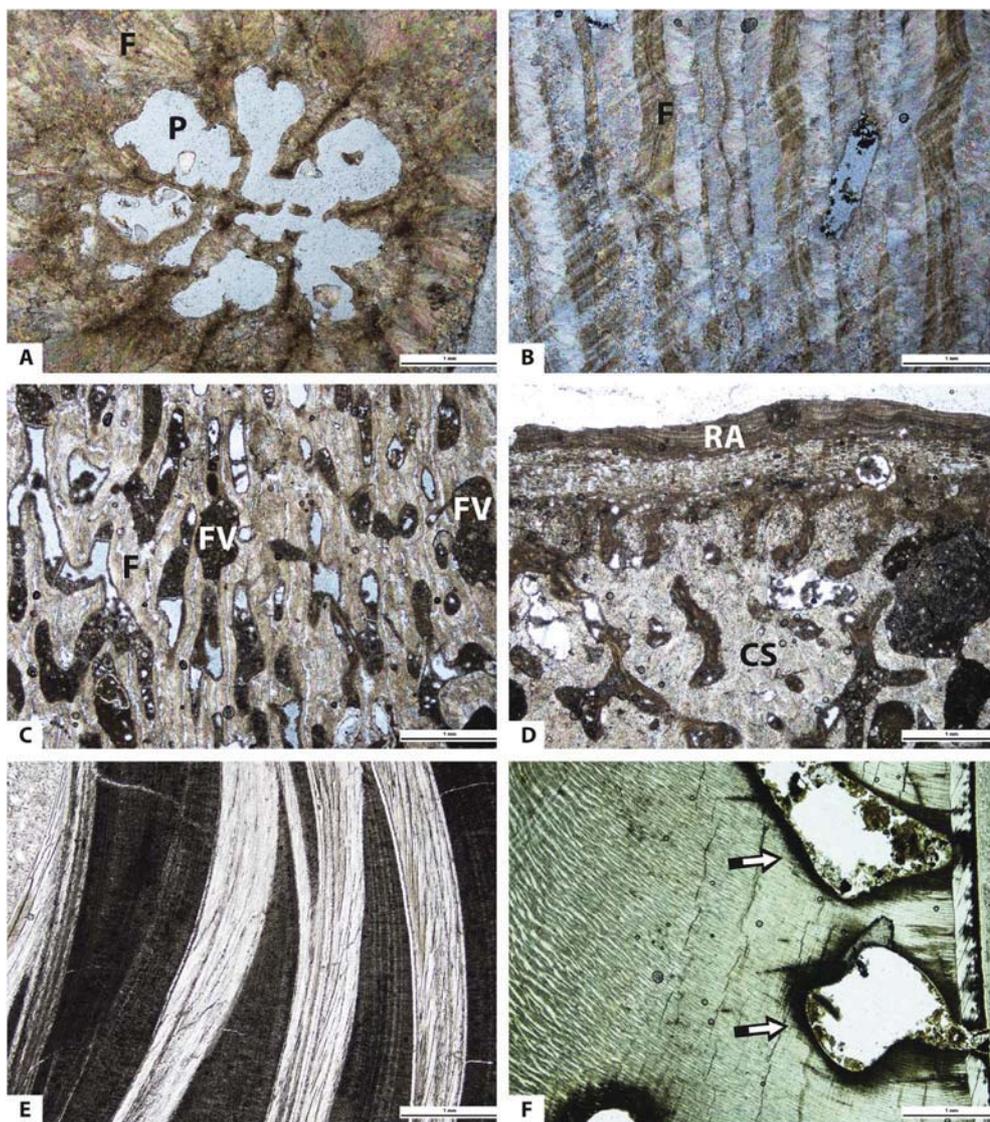


Fig. 2. A- B.: Finger-like scleractinian corals with well-preserved fibrous fans (F) and open pores (P) cut perpendicular to the direction of growth in A and parallel in B. C. Section parallel to direction of growth of the coral skeleton with filled pores (FV). D. Coral skeleton (CS) encrusted by coralline red algae (RA). E. Well-preserved multi-layered bivalve (oyster) shell. F. Oyster shell exhibiting borings with micritized walls in dark (arrows). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Additionally, a series of thin sections from three limestone samples were used for biostratigraphy. Only one of these yields planktonic foraminifera. Therefore, a total of five thin sections were analysed from that specific sample (JVIII-F). The stratigraphic chart of Wade et al. (2011) was used to derive ages.

3.3. Seismic profiles

Time migrated 2D seismic lines passing in proximity of the BJP-1 and Porong-1 wells were interpreted in detail using Petrel platform (Schlumberger) in order to investigate the detailed stratigraphy surrounding the Lusi area. Access to e-logs and check shots data allowed to develop a velocity model and calibrate wells to seismic and calculate the depths of key stratigraphic horizons (for more details see Moscardiello et al., 2017). Note that the seismic acquisition was done during the 80s and 90s, hence well before the occurrence of the Lusi eruption.

4. Results

4.1. Petrography

The analysed corals show overall a well-preserved skeleton, with visible fibrous fans (Fig. 2A, B and 2C). The pores are empty in some of the corals, and filled with fine-grained material in others (Fig. 2C). In some cases the corals exhibit encrustation by coralline red algae (Fig. 2D). The coral skeleton is too thin to be sampled separately for Sr dating, implying that some matrix and/or sediment from pore infills were included in the analysed micro-drilled powder.

Except for one ripped form, all the studied bivalves consist of oysters. The shell fragments are well preserved, with distinct alternating layering characteristic of oysters (Fig. 2E). Some of the shells have borings, partly with micritized walls (Fig. 2F). Shells are thick enough and were sampled without matrix. Dark areas, likely impregnated, pore infills and micritized zones were avoided during micro-drilling.

Multiple gastropods were collected. However, the shells of the specimens are too thin to be micro-drilled for Sr isotope analyses.

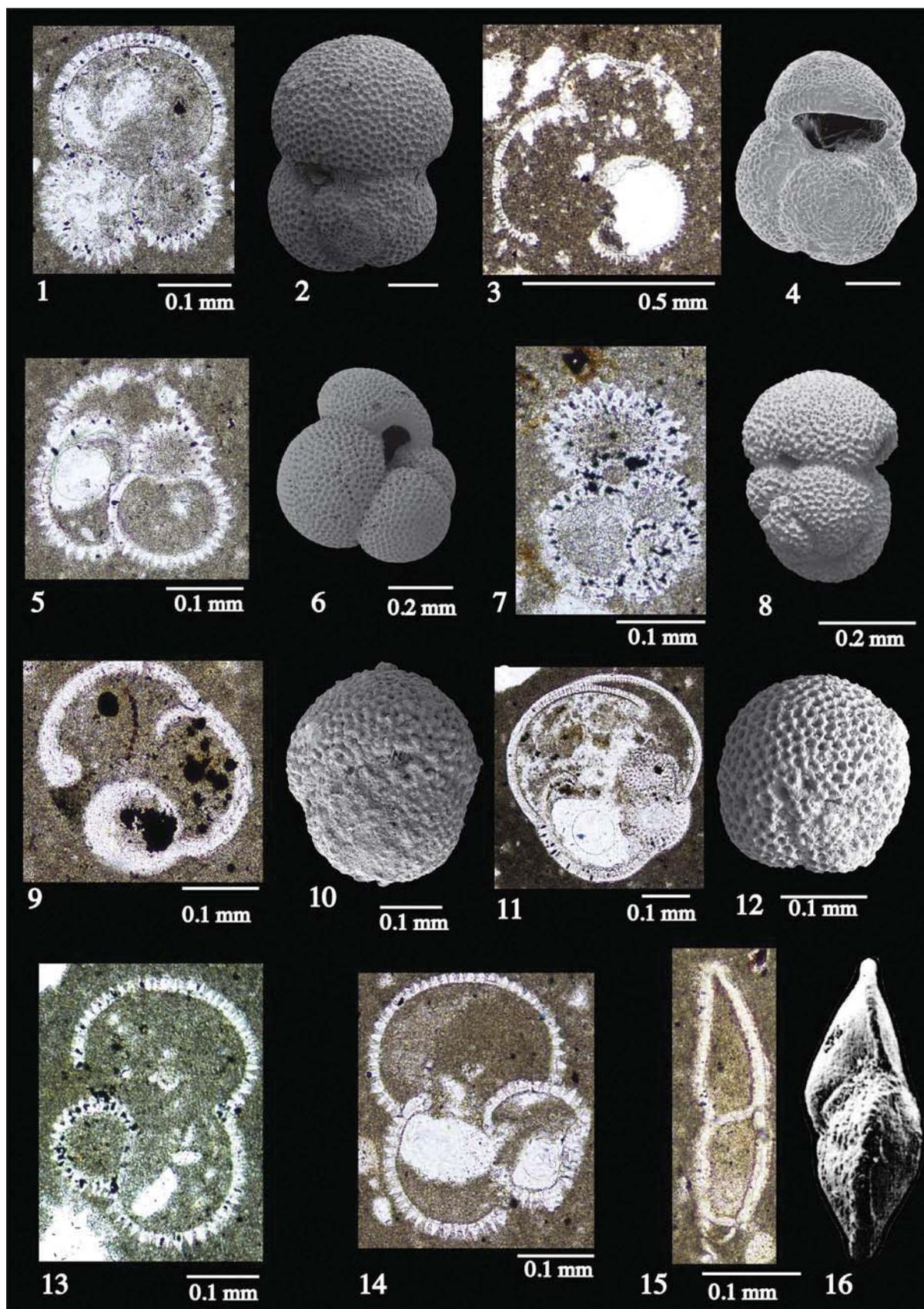


Fig. 3. Planktonic foraminifera from thin section JVIII-F and comparison with whole specimens of the identified species. A. *Trilobatus trilobus*, sample JVIII-F; B. *Trilobatus trilobus*, image of the neotype from Rögl (2012); C. *Globigerinoides obliquus*, sample JVIII-F; D. *Globigerinoides obliquus*, image of the holotype from Spezzaferrri et al. (2017); E. *Trilobatus sacculifer*, sample JVIII-F; F. *Trilobatus sacculifer*, sample BC3441, Alboran Sea; G. *Globigerinoides ruber*, sample JVIII-F; H. *Globigerinoides ruber*, sample BC3441, Alboran Sea; I. *Trilobatus sicanu*, sample JVIII-F; J. *Trilobatus sicanus*, sample IODP-359-36-4-68-70 cm, Maldives K. *Praeorbulina glomerosa*, sample JVIII-F; L. *Praeorbulina glomerosa*, sample IODP-359-36-4-68-70 cm, Maldives; M. *Globigerinoides* cf *ruber*, sample JVIII-F; N. *Globigerinoides* cf *ruber*, sample JVIII-F; H. *Globigerinoides ruber*, sample JVIII-F; O. *Globorotalia* sp. belonging to the *G. menardii* group, sample JVIII-F; P. image of the neotype of *G. menardii*, from Ellis and Messina (1949).

4.2. Biostratigraphy

Sample JVIII-F (Table 1), consisting of mudstone, yields planktonic foraminifera (Fig. 3). The assemblage contains rare specimens of *Globigerinoides* and *Trilobatus* together with specimens that can be attributed to the *Globorotalia menardii* group. The presence of *Trilobatus sicanus* and *Praeorbulina glomerosa* and the absence, in all the investigated thin sections, of specimens that could be clearly attributed to the genus *Orbulina* (the first occurrence of *Orbulina suturalis* marks the lower boundary of Zone M6) allow to restrict the age attribution to the interval spanning Zone M5b of Wade et al. (2011). The lower boundary of this Zone is dated as old as 16.29 Ma and its top as old as 15.10 Ma (Wade et al., 2011). The generic attribution of the planktonic species follows Spezzaferri et al. (2015), a purely taxonomic research, based on a robust coupling of fossil and genetic evidence. In particular, the species “*sicanus*” here attributed to *Trilobatus* was previously attributed to the genus *Praeorbulina* (*P. sicana* in, e.g., Wade et al., 2011) or *Globigerinoides* (Turco et al., 2011). However, according to the International Code of Zoological Nomenclature-ICZN (Ride et al., 2012), the tentative generic combination of a genus with a species name does not

affect the availability of the specific name, meaning that a species name remains valid even if the generic name is tentatively changed. Additionally the ICZN consider the principle of homonymy for species name having the same spelling (e.g., the species “*sicanus*” and “*sicana*” are homonyms and the one-letter difference is only due to the association with the genus name).

4.3. Strontium isotope dating

Table 1 includes $^{87}\text{Sr}/^{86}\text{Sr}$ data of the samples analysed, along with the nature of the material used for measurements. Results reveal a wide time window spanning from 37.18 to 3.14 Ma (Fig. 4). The oldest age was recorded from an oyster shell that gave mean value of 37.18 Ma (Eocene, Priabonian). The other measured shells (Miocene) vary in age from 20.38 Ma (Aquitanian) to 6.10 Ma (Messinian). The foraminifera-bearing sample JVIII-F dated with planktonic foraminifera, and another carbonate clast showed an Sr isotope age of 6.1080 and 6.84 Ma respectively. The scleractinian corals revealed the youngest Pliocene ages (from 4.99 to 3.14 Ma, Zanclean and Piacenzian).

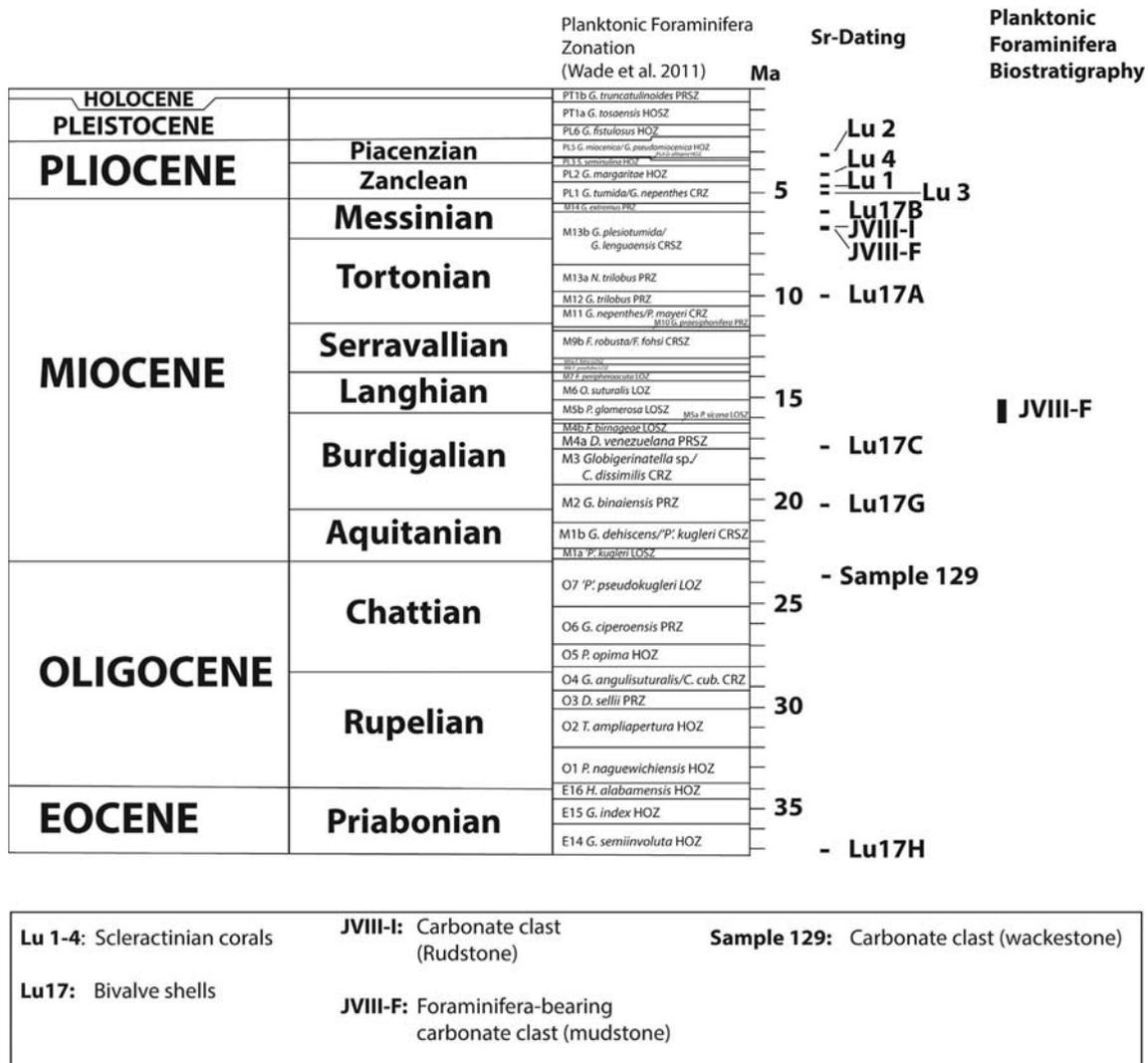


Fig. 4. Stratigraphic position of dated samples on the chronostratigraphic chart. Planktonic Foraminifera Zonation is based on Wade et al. (2011). Sr ages are calculated using McArthur et al. (2001).

Table 1

$^{87}\text{Sr}/^{86}\text{Sr}$ data. Sr ages are calculated using McArthur et al. (2001). Note that the samples indicated as scleractinian corals may include matrix and/or sediment infills. Samples originating from bivalves were micro-drilled from shells only and, thus, can be considered pristine (see text for details and Fig. 2).

Sample	Nature of sample	$^{87}\text{Sr}/^{86}\text{Sr}$	1 SE	Age in Ma		
				min.	mean	max.
Lu1	Scleractinian coral	0.709043	0.000002	4.62	4.74	4.84
Lu2	Scleractinian coral	0.709060	0.000002	2.88	3.14	3.46
Lu3	Scleractinian coral	0.709036	0.000003	4.91	4.99	5.08
Lu4	Scleractinian coral	0.709051	0.000002	3.92	4.23	4.47
129	Carb. clast (wackestone)	0.708214	0.000002	23.60	23.77	23.93
JVIII-I	Carb. clast (rudstone)	0.708960	0.000001	6.69	6.80	6.94
JVIII-F	Carb. clast (mudstone)	0.708959	0.000004	6.72	6.84	6.98
LU17A	Bivalve (oyster shell)	0.708885	0.000002	9.85	10.03	10.24
LU17B	Bivalve (ripped, underm.)	0.708990	0.000001	6.01	6.05	6.10
LU17C	Bivalve (oyster shell)	0.708634	0.000002	17.33	17.44	17.54
LU17G	Bivalve (oyster shell)	0.708416	0.000002	20.22	20.38	20.56
LU17H	Bivalve (oyster shell)	0.707745	0.000003	36.59	37.18	37.95

5. Discussion

5.1. Strontium isotope dating and biostratigraphy

The planktonic foraminifera assemblage of sample JVIII-F provided clear dating results (Zone M5b, between 16.29 and 15.10 Ma, topmost Burdigalian to early Langhian). This time window agrees with the current Sr-isotope age of 15.34 Ma (Langhian) obtained from the topmost limestone of a formation interpreted to be Tuban (cf. Sharaf et al., 2005; their Fig. 3) (Fig. 4). The mudstone texture and the presence of planktonic foraminifera indicate a pelagic depositional setting. A comparable depositional setting is reported from the underlying Formation for, e.g., the Prupuh Unit, representing the slope facies equivalent to the shallow-water reefal facies of the Kujung Formation (Satyana, 2005) (Fig. 5). Sharaf et al. (2005) reported a “chalk facies” rich in planktonic foraminifera from the Tuban Formation, likely the equivalent of the planktonic foraminifera-bearing mudstone in our study. Kusumastuti et al. (2002) used a red algal fragment from a sidewall core in the Porong-1 (PRG-1) well (depth of 2586 m) to calculate strontium isotopic ages. This sample was collected within 2 m of the interpreted lithological discontinuity and the results indicated an absolute age of 16 Ma (late early Miocene). This implies that the planktonic foraminifera-bearing sample interpreted to originate from the Tuban Formation in the present study may represent the slope or basinal facies contemporaneous to the shallow-water facies interpreted as Tuban in the Porong-1 well (PRG-1). Another important piece of information is provided by the dating of a sidewall core at 2584 m in the same PRG-1 well. These samples were collected less than a couple of meters above the sample dated at 16 Ma, and were dated biostratigraphically as middle–late Pliocene, about 3 Ma. This clearly indicates that this site area was exposed to substantial erosion and/or non-deposition for about 13 Ma (Fig. 5). It is worth noticing that Plio-Pleistocene volcanoclastic deposits were observed in the BJP-1 well from 1871 and at least up to 2833 m (Fig. 5). These deposits are absent at the PGR-1 well where presumably the Kalibeng Fm (i.e. dated at 3 Ma) caps directly the thin Tuban and the Kujung Fms. We suggest that the lateral discontinuity of the volcanoclastic deposits is probably ascribed to a laharc (?) event (i.e. from the Arjuno-Welirang volcanic complex) that does not extend further to the NE where the PRG-1 well is located.

The age of sample JVIII-F as derived from Sr isotopes is unrealistic because the planktonic foraminifera assemblage of the same sample indicates an age that is more than 8 My older (Fig. 3). No evidence of species older than Zone M5b has been found and, therefore, reworking of planktonic foraminifera in sample JVIII-F can be ruled out. A possible

reason for this discrepancy is contamination of the investigated carbonate samples by geological material with more radiogenic Sr isotope composition (e.g., Israelson and Spezzaferri, 1998), which would result in a shift towards younger Sr isotope-based ages. Taking this into account, we estimate that the pristine carbonate material with Sr isotope composition in equilibrium with that of seawater at the Miocene (i.e. time of its precipitation as indicated by the planktonic foraminifera assemblage) would range between 0.708,776 (15.10 Ma) and 0.708,702 (16.29 Ma) (McArthur et al., 2001). Since the investigated sample has an $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.708,959, the contaminant material is expected to have a higher $^{87}\text{Sr}/^{86}\text{Sr}$ value. The various clasts entrained in the Lusi feeder conduit form a mud breccia mixture including various lithotypes and multiple fluids from different units and formations. This cocktail of fluids and crushed sediments may indeed alter the isotopic analyses. The bluish gray shales of the Kalibeng Formation (Fig. 4) have $^{87}\text{Sr}/^{86}\text{Sr}$ values $> 0.710,129$ (Mazzini et al., 2017) and are the likely candidates to contaminate the Sr isotopic values of the unduly young samples. The $^{87}\text{Sr}/^{86}\text{Sr}$ values of magmatic rocks of the Sunda arc (Java, east of longitude 111°) are between 0.704 and < 0.706 with a main mode at 0.7045. These values are much lower than the $^{87}\text{Sr}/^{86}\text{Sr}$ values measured in Lusi (> 0.708) and, therefore, cannot be responsible for a “younging” of the ages, which must be due to a contaminant with more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (see Appendices).

Samples Lu 1 to 4 are all fragments of scleractinian corals, originating from coral-bearing carbonates widely reported from the Java Sea Basin. Strontium dating of these samples indicates Pliocene age (4.99–3.14 Ma Zanclean and Piacenzian). To our knowledge there is no reefal carbonates documented during the Pliocene time. In addition, the Pliocene sediments at the Lusi site consist of volcanoclastic deposits that cannot contain corals (Fig. 5). This implies that the dated corals are in fact older than the Sr-derived Pliocene time. Assuming the same contamination parameters described earlier on, we consider a Sr-isotope shift to younger values and can assign these coral fragments to the Tuban Formation (Figs. 4–5). In theory, however, the Kujung Formation from which coral fragments are also reported (Sharaf et al., 2005) is a potential candidate, too. It is important to notice that potential contamination (from younger sediments) may be exacerbated in particular for coral samples that display higher porosity and may thus facilitate the entrapment of exotic particles (Fig. 2; see also the section on petrography above).

Having established that we have to invoke contaminations for some of the samples, it remains so far unclear if a similar situation is likely for the other carbonate clast samples that reveal Eocene-Priabonian, Oligocene-Chattian and Miocene-Messinian. Contamination appears unlikely in the other dated shells, from which was easier to drill pristine samples.

The overall ages indicate that the carbonates deposits extend for a period including the carbonate platform of the Oligocene Kujung Fm, as well as Miocene reefal upper part of the Kujung Fm, including also the Miocene Tuban Fm characterized by marly shales and limestones.

Of particular interest are the oysters of sample Lu17H, which exhibits the oldest Sr-based age obtained in the present study and that is dated as Priabonian. This stratigraphic level coincides with the depth of the organic-rich Ngimbang Fm. Indeed, lacustrine and marine deposits, including carbonates, were reported from the Ngimbang Formation (Satyana and Darwis, 2001; Mudjiono and Pireno, 2002). Further research is needed to provide more details on facies of this Formation.

5.2. Insights from seismic profiles

The findings of the carbonate dating and facies identification have been incorporated in the interpretation of the 2D seismic profiles intersecting carbonates above and in the proximity of the Lusi area. The detailed seismic facies analysis in Lusi region was implemented using composite seismic lines intersecting Lusi and the BJP-1 well and connecting the region pierced by the PRG-1 well, where the seismic signal

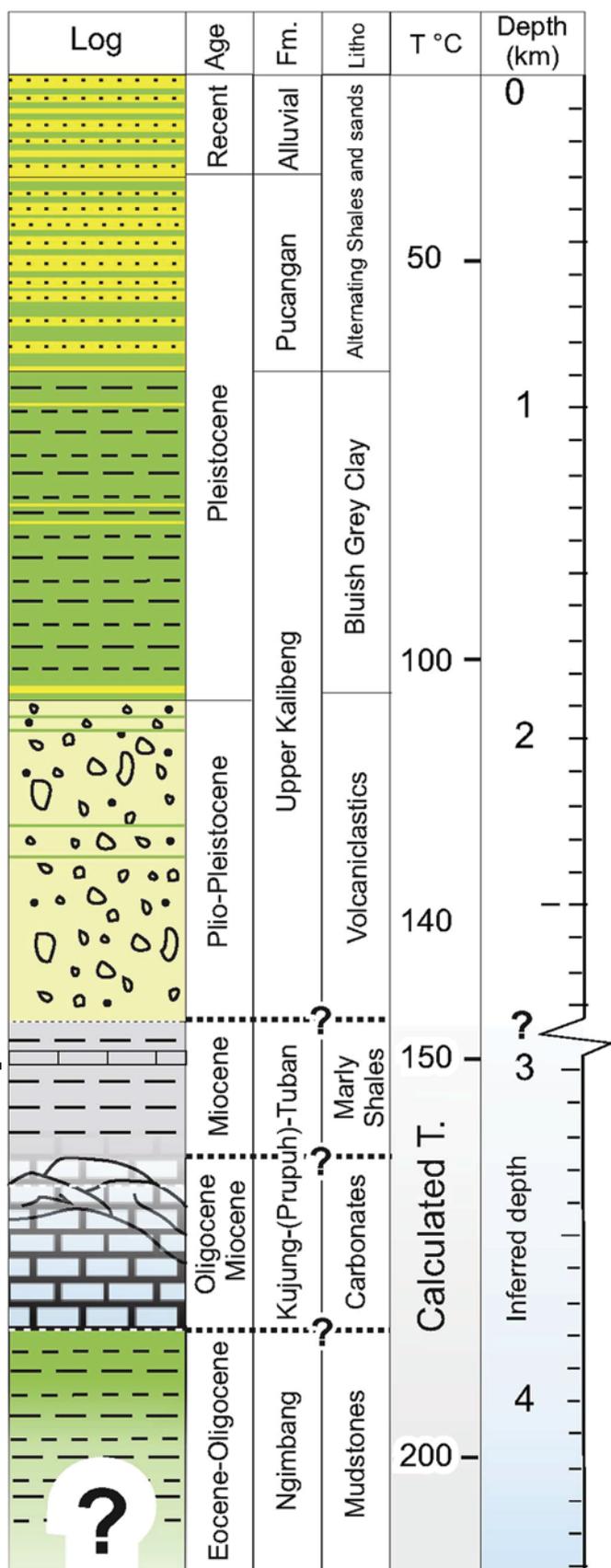


Fig. 5. Schematic log summarising the stratigraphy at Lusi site. The thin carbonates in the Tuban Formation could represent the youngest samples consisting of scleractinian corals of our collection and correspond to reefal facies reported in the literature (e.g., Sharaf et al., 2005). The scheme is adapted from Mazzini et al. (2012) and updated using data from the present publication. Question marks and dashed lines refer to uncertainties to locate the boundaries between the formations that have not been drilled (unlike the top 2833 m). See more info in the introduction. These boundaries are inferred based on seismic data interpretation.

is of much better quality. Below Lusi the seismic signal is in fact disturbed with discontinuous and chaotic reflectors which impair the immediate stratigraphic interpretation of the units not penetrated by the BJP-1 well. However, by using the proposed composite line through PRG-1 well, several horizons defined using seismostratigraphic criteria (facies and geometry such as onlaps and truncations) can be traced back to the Lusi region with relatively high level of confidence. Overall, this allowed us to recognize a stratigraphic unit sandwiched between the volcanoclastic deposits of the Upper Kalibeng Formation and the Oligo-Miocene carbonates. This has been interpreted as the transgressive shales of the Tuban Formation (Fig. 6) onlapping and partly blanketing the underlying carbonate buildups structures. The surface separating the Upper Kalibeng Formation and the Tuban Formation is marked by a clear angular unconformity of seismic reflectors (Fig. 6) indicating its erosional nature. Above the carbonate structure in correspondence of the BJP-1 the preserved thickness of Tuban Formation is ca. 420 m while it reaches only few meters (< 10–15 m) above the structure penetrated by the PRG-1 well. This interpretation is consistent with the finding of shallow-water red algal remains dated at 16 Ma in the PRG-1 well (Kusumastuti et al., 2002) above the carbonates. Based on our seismic interpretation, the Tuban Formation thins towards the ENE. These data also suggest a syn-tectonic deposition, possibly related to a tilting of the carbonate platform ridge which induced its uplift in the ESE (i.e. in the Porong region) and subsidence to the WSW (i.e. at Lusi locality). The shallow-water deposits recorded in the Tuban Fm in the PRG-1 well is consistent with the finding of coeval planktonic foraminifera-bearing deposits described in this study, attesting the progressive transgressive (i.e. deepening) of the depositional environment recorded by the Tuban Formation. Below this unit, the top of Oligo-Miocene carbonates, as well as their inferred base can be traced from one well to the other, showing most likely the presence of the Prupuh Unit (Early Miocene) resting on the more laterally continuous Oligocene Kujung carbonates. Below the carbonates, transparent seismic facies resting on a high-amplitude tabular reflector are interpreted as the continental shales and possibly lacustrine and marine carbonates associated with the Ngimbang Formation as reported to be present in the region by various authors (Mudjiono and Pireno, 2002; Lelono and Morley, 2011; Satyana and Purwaningsih, 2003).

We compared the available regional stratigraphic information with the 2D seismic calibrated with check-shot derived velocity data. The depths of the formations below Lusi are estimated as follow: top Tuban Formation ~2840 m, top Kujung Formation (including the Prupuh Unit) ~3260 m, top Ngimbang Formation ~3850 m true vertical depth. The seismic data examined do not allow for confident identification of the base of the Ngimbang Formation in the area of the BJP-1 well.

6. Implications and conclusions

The dating of carbonates within the Lusi erupted mud breccia and the interpretation seismic profiles reported herein have several implications. These can be summarized as follows:

- 1) Our findings provide additional information regarding the regional stratigraphy indicating that the volcanoclastic sediments are overlying a succession of carbonates, which age spans from Miocene to Eocene.

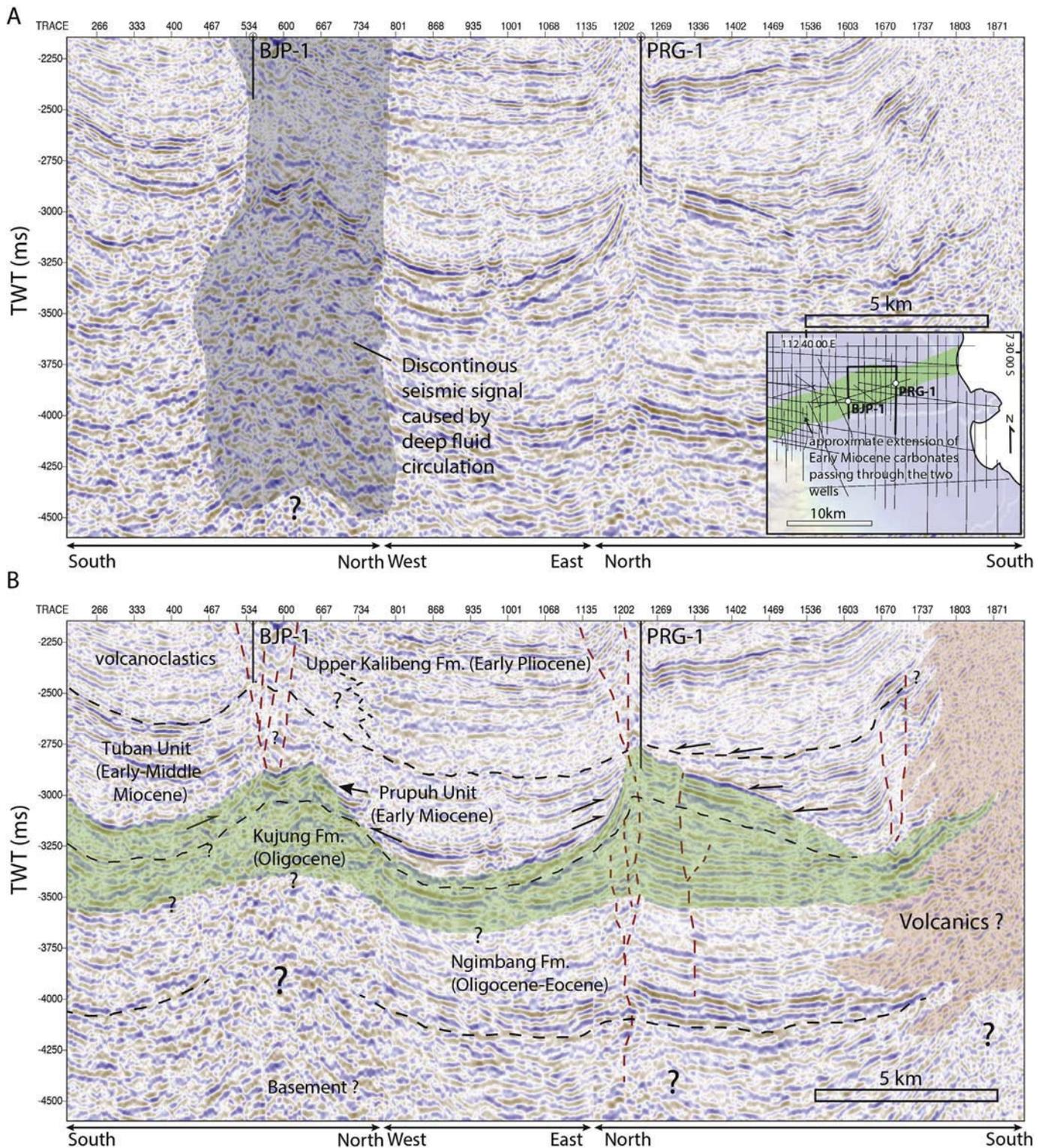


Fig. 6. A) Composite 2D seismic line crossing the wells PRG-1 and BJP-1 (for location of the seismic line see inset map) showing the architecture of the deep sedimentary succession in the area immediately above and below the Oligo-Miocene carbonates. In the BJP-1 area, corresponding to the gray zone, is visible the highly-disturbed seismic signal likely caused by the effect of deep fluid circulation associated with the predisposing conditions resulted in the Lusi eruption. B) The composite section allows the stratigraphic correlation between the two wells. Even when the signal is disturbed (BJP-1 area) it is possible to recognize (based on reflector geometries and seismic unit architecture) and to extrapolate the key stratigraphic units which, from top to bottom include: the Upper Kalibeng Formation, Tuban Formation, Kujung Formation (including the Prupuh Unit), the Ngimbang Formation. The basement is likely present at the base of the section. Note the important thickness change of Tuban Formation in the two areas indicating a possible topographic and tectonic control during the deposition of this unit.

2) These carbonate clasts were brecciated through the Lusi conduit and brought to the surface during the eruptive activity. Indeed the occurrence of carbonate clasts with a minimum age of 23.77 Ma

indicates that the source of some of components extends to the base of the Kujung Formation (Late Oligocene to Early Miocene)(e.g., Ardhana, 1993; Satyana, 2005; Sharaf et al., 2005), This finding

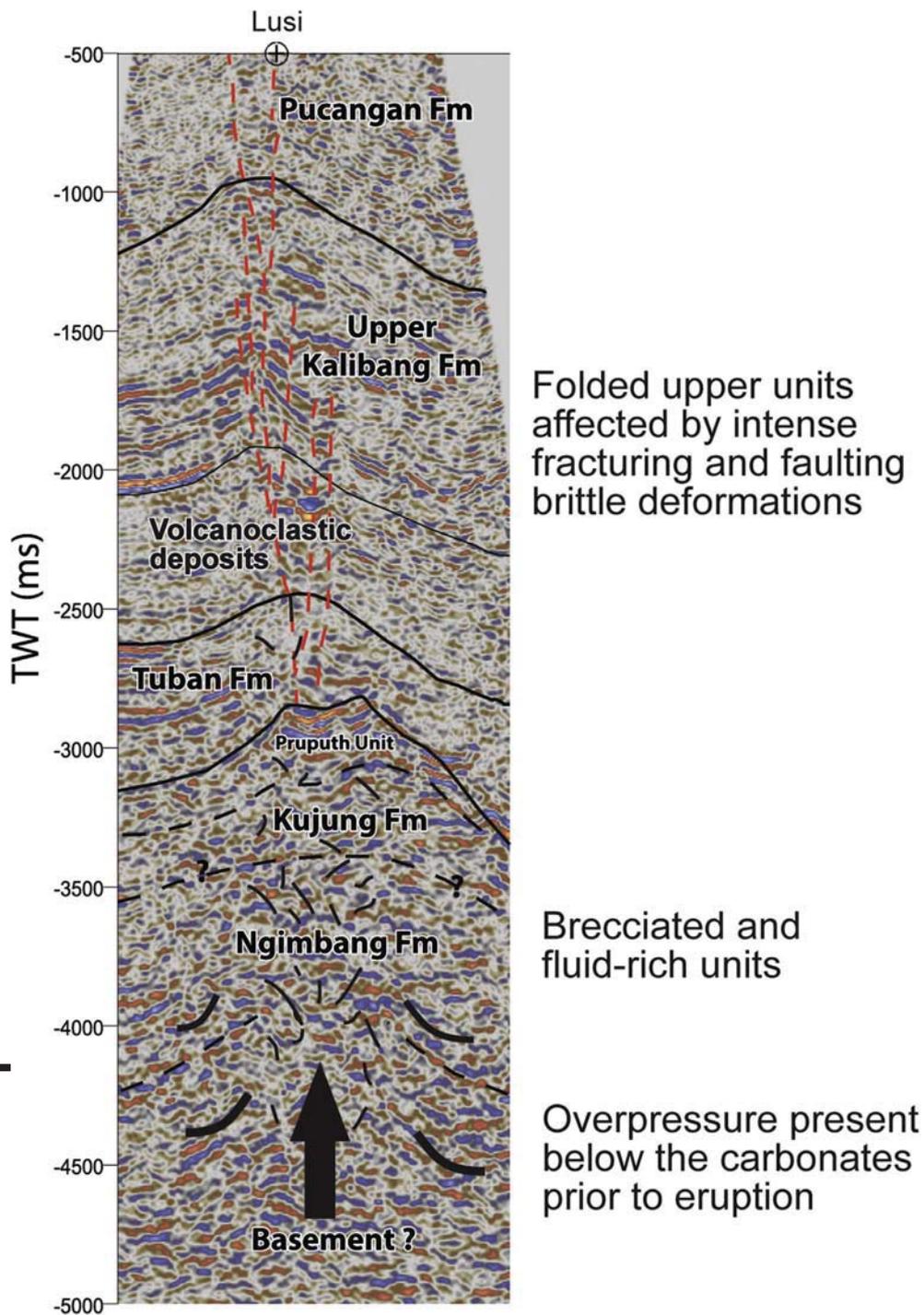


Fig. 7. Seismic line collected in the 80's below the Lusi eruption site with schematic formations boundaries. Some of the features observed inside the formations are included. The image highlights that before the eruption occurred significant overpressure had to be present at great depth (e.g in the Ngimbang Formation). This would be indispensable to bring to the surface clasts of deep platform carbonate from the Kujung Formation that, at this depth, is typically not overpressured, and also clasts towards the surface were already present at the time of the seismic data collection. Modified from [Moscardiello et al. \(2017\)](#). "?" indicates uncertainty in interpretation.

supports previous geochemistry results ([Mazzini et al., 2012](#)), which indicated that the fluids source and the Lusi plumbing system are indeed deeper than the Kalibeng formation. Results support a scenario where fluids and rock fragments are moving from great depth since the very beginning of the eruption. This implies that not only the Kalibeng Formation plays a key role in sourcing sediment and fluids but also deeper units are part of the plumbing system.

- 3) The presence of both the Oligocene Kujung Formation and the Miocene Tuban Formation at the same site provides insights into the paleogeography of the area. Facies encountered in the older clasts indicates an off-reef, pelagic depositional setting, whereas the clasts exhibiting younger ages are from a shallow-water, reefal depositional environment. This result implies a superposition of two

lithologies denoting different depositional conditions, confirming progradation and/or facies transitions that are possibly fault controlled ([Matthews and Bransden, 1995](#); [Sharaf et al., 2005](#)).

- 4) The interpretation of seismic data indicates that the bottom part of BJP-1 well is within the volcanoclastic deposits of the Upper Kalibeng Formation. Further, this unit is overlying a 420 m thick marly-shale package of the Tuban Formation. The (reefal?) carbonates (supposedly Purpuh Unit, as part of the Kujung Formation) are encountered at a depth of 3260 m. Ultimately the bottom part of the Kujung Formation is encountered at 3850 m, overlaying the Ngimbang Formation.
- 5) The deposits close to the bottom of BJP-1 well have been commonly associated with the carbonates encountered at the bottom of the PRG-1 well. Our seismic data provide a new interpretation of the

carbonate stratigraphy below Lusi and the PRG-1 well. Results show that the formation at the bottom of PRG-1 well, interpreted here to belong to the Kujung Formation, is not stratigraphically equivalent to that commonly believed to be just below the bottom of BJP-1 well where 420 m of Tuban Formation are suggested to be present before finally reaching the Kujung Formation.

6) The presence of Eocene carbonates gives hints about the Lusi dynamics. The Kujung carbonates are the common reservoir units in the prolific offshore East Java Basin. The lower and older portions of Kujung Formation are typically not overpressured (Kusumastuti et al., 2002; Sharaf et al., 2005; Ramdhan et al., 2013). Since these rock fragments are present at Lusi site from the early stages of the Lusi eruption, we can infer that additional overpressure was required from deeper units (likely in the Ngimbang Formation) to eject these clasts all the way to the surface (Fig. 7). The scenario is also consistent with the model depicted by Mazzini et al. (2012) that highlighted the presence of mantle fluids expelled at Lusi (hence the definition of sediment-hosted geothermal system) likely migrating through the deeply sited Ngimbang Formation below 3.8 km. Corroborating results have been recently published by Fallahi et al. (2017) where tomography studies clearly highlighted that the Arjuno-Welirang neighbouring volcanic complex is connected with Lusi at ~4.5 km depth.

The finding of early clasts of an age equivalent to that the Ngimbang Formation, recorded in the present study, provides further evidence for this scenario.

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Appendix A. Supplementary data

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