The Pemali Formation of Central Java and equivalents: Indicators of sedimentation on an active plate margin

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ABSTRACT

The Pemali Formation is revised from being the oldest known sedimentary unit in north Central Java to being almost the youngest. This, and a new examination of its composition, has implications for regional geological models and petroleum geology. The Pemali Formation was originally interpreted as “early Miocene” but is now shown to be latest Miocene through Pliocene in age, and characterised by both very high rates of sedimentation and a particularly high degree of reworking. The mid-Late Miocene tectonic event that initiated deposition of this formation created a new series of basins that were filled by erosion of new structural highs. Continuing constriction of the basins resulted in the uplift of older Pemali sediments on the basin margins, being reworked into the youngest Pemali strata.

Neither the Pemali Formation nor the associated uplift and erosion are seen in the basins in the Java Sea a short distance to the north. Both the severe effects of the mid-Late Miocene tectonism and the Pemali-type sediments are restricted to a particular geologic zone, which is roughly the same as the modern island of Java. This may be above lithosphere of mixed terranes that forms a rim to the sialic Sunda Plate. The onshore Java area has a history of severe tectonism through the Tertiary and consequently a stratigraphy that greatly contrasts with that of the present-day Java Sea.

The localised and thick Pemali deposition affected the burial history and the generation of hydrocarbons around the mid-Late Miocene basins, whilst the uplifted areas may include hydrocarbon traps. If base ment composition influenced the location and thickness of the Pemali Formation then it is also likely to have fundamentally controlled deposition of older formations, including the unknown source rock for surface oil seeps. Likewise, these controls appear to contrast strongly with the better known rift-sag basins of the Java Sea.

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1. Introduction

The Pemali Formation (ter Haar, 1935; Pemali Series or Pemali Beds of some workers) is distinguished from the more common tuffaceous sediments of Central Java as it is a clay-rich unit with common Globigerina, and frequent sandstone beds containing metasedimentary quartz. This distinct lithological composition was previously thought to be related to its position as the oldest known sedimentary strata in the area, however this paper suggests a very different geological setting and age.

New analyses are reported from the type location and surrounding outcrops of the Pemali Formation (see Figs. 1–3. Table 1 details the analyses). In addition exploration well and seismic data extends our understanding of this sedimentary unit and allows a new geological model to be proposed. The implications of the new model to petroleum geology are discussed.

Note that the term “Tertiary” is used here instead of the ICS recommended Cainozoic (which is the Tertiary plus the Quaternary) as the term is included in several still widely used stratigraphic schemes in Asia, including the Letter Stages (T.a to T.h) used in this report.

2. History of the formation

To understand the context of the new work and the changes proposed, a review of the history of the Pemali Formation is required. The original work was in Dutch but translations are given in Appendices.

2.1. Definition and subsequent application

The Pemali Formation was defined by the concurrent mapping work of Hetzel on Sheet 54 and ter Haar on Sheet 58 of the Dienst van den Mijnbouw in Nederlandsch-Indië (Survey and Mining Bureau of the Netherlands Indies; both 1935), see Figs. 1 and 2. Both...
reports were published at the same time but Hetzel’s work is in front of ter Haar’s in the publication records of the Survey and therefore has priority. However the Stratigraphic Lexicon of Marks (1957) considered that “The most complete section is exposed in the Cibabakan (river) from Sahang to nearby Cikeusal”, which is in the second report (ter Haar’s) and consequently he selected this as the type location. Hetzel and ter Haar’s reports describe numerous outcrops assigned to this formation, and thrust faults were mapped where the Pemali Formation, considered to be the oldest sediments in outcrop, was found on top of the Late Miocene Halang “Series” (cf. Fig. 3). Note that the Kali Pemali is the traditional border between the Javanese part of Java, east of which rivers are called “Kali”, and the Sundanese area where river names are prefixed with “Ci” (“Tji” in the original reports).

At the time of van Bemmelen’s (1949) review of the Geology of Indonesia the Pemali Formation was still considered the oldest outcropping sedimentary unit in north Central and north-west Java. The uncertainty over the degree of reworking in the formation, as reported by ter Haar and Hetzel (see Appendix) was not considered, and the index fossils Eulepidina and Spiroclypeus were used to suggest the lower part of the Pemali Formation may have been as old as basal Miocene (Letter Stage T.e).

Marks (1957) moved back to the position of the original workers, preferring to interpret an age close to the Early to Middle Miocene boundary, based on Lower T.f Letter Stage markers rather than the rarer T.e fossils. He also emphasized an observation of van Bemmelen correlating the quartz-bearing Pemali with the quartz-bearing Merawu Beds of older Miocene age some 70–100 kms to the east (Fig. 1). The Merawu Beds were mapped to overly “Eocene” (van Bemmelen, 1937) and Marks suggested that the presence of reworked Eocene in the type Pemali indicated that the “Eocene deposits . . . cannot be far down below the lowest known parts of the Pemali Beds.” (However recent work by Lunt and Sugiatno (in press(a)) has shown the “Eocene” south of the type Merawu Beds is actually Early Oligocene with olistoliths of older material.)

In 1974 Sumarso and Suparyono suggested that Pemali Beds were much younger than previously thought, within planktonic foraminiferal zones N16 to N18. This work was not used, or cited by later studies.

The concept of the Pemali Formation as an older Miocene sediment, apparently the oldest in the area, was not changed by later workers (e.g. Muchsin et al., 2002; Ratman and Robinson, 1996, p. 11–12; Suyanto and Roskamil, 1977). Oil exploration work in south Central Java added new, local formation names that were stated to be equivalent to the Pemali Beds to the north. The most widely cited of these was the Penanjung Formation (Mulhadiyono, 1973) which the author said was equivalent to the Pemali Beds and ranged in age from Oligocene to early Middle Miocene. No type location or faunal list was given for the Penanjung Formation. No rocks of such old age are found in outcrop or well samples in the general area indicated by Mulhadiyono.

Several oil seeps are associated with the type and other locations of the Pemali Formation (Hetzel, 1935; ter Haar, 1935 cf. Fig. 3 here) and the first well drilled for oil in Indonesia, by Reerink in 1872 (see van Bemmelen, 1949, p. 654 and Fig. 1 here) was from seeps in Pemali Beds near Maja that are still active today.

2.2. The studies of Sumarso and Suparyono

In 1974 Sumarso and Suparyono were the first to apply the newly developed planktonic biostratigraphy of Blow (1969) to the Pemali Formation and adjacent sediments. They studied the Pemali Formation at a site close to or possibly the same as the Larangan site described in this report (their “Pamulian (Kali Rambatan)” site). Sumarso and Suparyono found a fauna with Globorotalia tumida (Brady), Globorotalia tumida flexuosa (Koch), species of Pulleniatina and Sphaeroidinellopsis

![Fig. 1. Map of Central Java. For regional location see Figs. 6 and 7.](image)
Blow. It is not stated why they dated this stratigraphically very short section as "zone N16 to zone N18" when it contains the definitive N18 and younger markers *G. tumida* and *G. tumida flexuosa*. Sumarso and Suparyono's work remains a useful first application of planktonic biostratigraphy to the area, but these workers did not re-interpret the lithostratigraphy and produced a stratigraphic column with Pemali Formation interpreted as the oldest beds in the area. Since the Halang and Rambatan "Series" contain Late Miocene planktonic microfossils they were therefore forced to draw these beds as lateral equivalents to the older beds in the area, since the Halang and Rambatan "Series" are also considered a separate formation with Pemali Formation interpreted as the older beds in the area.

Fig. 2. Locations in mapping sheets 54 and 58 and the locations mentioned by field geologists.
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<th>Sample</th>
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<tr>
<td>P-1 (Catalog No. 2K3/06/3)</td>
<td>Pemali-type location: 108.78998'E, -7.030671'S, Close to contact with Halang Beds</td>
<td>All three samples: soft claystone with silt. Fauna contains: 90%+ planktonic foraminifera. Common Globorotalia tumido and variety flexuosus, Pulleniatina, frequent and always sinistrally coiled rare Sphaeroidinella delicosus (small apertures) – Dentoglobigerina alatipira, Rare Globorotalia margaritae (sinistral), frequent Neogloboquadrina acostmans and N. deustretri, plus common Orbulina universa, Globorotalia menardii, Sphaeroidinellopsis spp. Gaudryinoides inc. C. obliquus as well as species of Globigerina. Scarce benthics include Lenticulina spp., Hoeglundina elegans, striate Uvigerina, Planulina spp. Martinitiella communis, Osangalaria cultus, Sphenocerita bulboides rare Melonis sp. and rare abraded Amphistegina</td>
</tr>
<tr>
<td>P-2 (Catalog No. 2K3/06/4)</td>
<td>Pemali-type location: 108.884184'E, -7.016557'S, Close to contact with Halang Beds</td>
<td>Soft claysstones with fair to good faunas; Orbulina, G. tumida, Sphaeroidinellopsis, sinistrally coiled Pulleniatina, N. humerosa, Globorotalia aff. unguilata, absence of G. venezuelana, with both striate and hispid Uvigerina, Globocassidulina, Gyroidina, Melonis, Eggerella/Gaudryina</td>
</tr>
<tr>
<td>P-3 (Catalog No. 2K3/06/6)</td>
<td>Pemali-type location: 108.885707'E, -7.018365'S, Close to contact with Halang Beds</td>
<td>Soft claysstones with fair to good faunas; Orbulina, G. tumida and G. t. tumida flexuosus Sphaeroidinellopsis, sinistrally coiled Pulleniatina, N. humerosa, Globorotalia margaritae (sinistral), with Lenticulina, Hoeglundina elegans, Gaudryina types, Uvigerina, Pullenia bulloides, Cibicidoides, Bulimina, Globocassidulina. Nannofossils indicate an age restricted to NN14-15 based on concurrence of Gephyrocapsa spp. (small forms), Sphenolithus abies, Pseudoemiliania lacunosa and Discoaster asymmetricus</td>
</tr>
<tr>
<td>Larangan (Catalog No. BWS01-1012-1013)</td>
<td>Ciracambatan, 1.9 km south of Larangan village at 108.9450'E, -7.022110'S</td>
<td>Soft claysstones with fair to good faunas; Orbulina, G. tumida, Sphaerooidinellopsis, sinistrally coiled Pulleniatina, N. humerosa, Globorotalia aff. unguilata, absence of G. venezuelana, with both striate and hispid Uvigerina, Globocassidulina, Gyroidina, Melonis, Eggerella/Gaudryina</td>
</tr>
<tr>
<td>Cisenti – Cibeureum (Catalog No. BWS-1016-1021)</td>
<td>Near Cisenti – Cibeureum river sections and sample location of Hetzel in Sheet 54, multiple samples spaced over some 450 m centered on 108.7121'E, -7.05179'S</td>
<td>Soft claysstones with fair to good faunas dominated by planktonics (90%+). Orbulina, G. tumida and G. t. tumida flexuosus Sphaeroidinellopsis, sinistrally coiled Pulleniatina, N. humerosa, Globorotalia margaritae (sinistral), with Lenticulina, Hoeglundina elegans, Gaudryina types, Uvigerina, Pullenia bulloides, Cibicidoides, Bulimina, Globocassidulina. Nannofossils indicate an age restricted to NN14-15 based on concurrence of Gephyrocapsa spp. (small forms), Sphenolithus abies, Pseudoemiliania lacunosa and Discoaster asymmetricus</td>
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<tr>
<td>H-1 (Catalog No. 2K3/06/7)</td>
<td>NW side of G. Ciganggajung, Halang Beds, c. 300 m and stratigraphically below contact with Pemali Fm.</td>
<td>Moderately hard, well cemented tuffaceous sands and mudstones. Limited fauna includes mostly planktonic foraminifera Orbulina universa, Neogloboquadrina acostmans, and N. humerosa, Globobuquadrina venezuelana, Dentoglobigerina altipira, Globorotalia menardii, with a few striate Uvigerina and indeterminate arenaceous species</td>
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<tr>
<td>Lawak (Catalog No. BWS-1005-1011)</td>
<td>NW side of G. Ciganggajung, Halang Beds, c. 300 m and stratigraphically below contact with Pemali Fm.</td>
<td>Moderately hard, well cemented tuffaceous sands and mudstones. Limited fauna includes mostly planktonic foraminifera Orbulina universa, Neogloboquadrina acostmans, and N. humerosa, Globobuquadrina venezuelana, Dentoglobigerina altipira, Globorotalia menardii, with a few striate Uvigerina and indeterminate arenaceous species</td>
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3. Emended definition of the Pemali Formation

The Pemali Formation can be defined as a field-mappable, lithostratigraphic unit that contrasts strongly with the underlying strata. It can also be defined as a sequence, with a highly unconformable basal event.

Composition: gray-green, locally dark gray-blue mudstones with minor sands. The mudstones are calcareous, usually with planktonic marine microfossils. The sandstones are varied in composition and grain size, with medium and coarse grades common. Tuffaceous clasts are usually present, but it is the metasedimentary quartz, which can be the dominant grain type in some sandstones that distinguishes the coarse clastics of the Pemali Formation from other stratigraphic units in the area. Sandstones sometimes contain bioclastic material to several millimeters. In outcrop the Pemali Formation is at least 900 m thick. The Pemali Formation contains a high level of reworking of micro- and nannofossils, especially in the sandy beds. Underlying sediments, such as the Halang Fm., have negligible reworking, and this contrast is also an important feature of the formation.

Subsurface data identifies a major angular unconformity at the base of the Pemali Formation. The thickness of the Pemali Formation away from the area varies relative to its structural position, but is estimated from seismic data to reach at least 2500 m in the area around Purbolinggo and Bobotsari. The basal beds in this formation have an angular, down-lapping, relationship onto the underlying strata, visible on seismic but not seen in the field.

The Pemali Formation grades up into Pleistocene sediments showing a gradual transition to non-marine sediments with various local names reflecting local fluvial facies. Type locality: following Marks (1957), the type location is a section along the Cibabakan (Babakan River), long. 108°52'57"E, lat. 7°15' in the NW corner of sheet 58, Geol. Map of Java, 1/100,000 (Fig. 3 here). The name comes from the nearby Kali Pemali (Pemali river) which runs west and north of Bumiayu, south of Cirebon, C. Java.

Geographical distribution: in outcrop, from the area west of Maja, continuing along the northern area of old mapping quadrangles 54 and 58, from the south-west flank of Gunung Ciremai, south past the town of Kuningan to the area north of Bumiayu. East of Bumiayu covered by the volcanic cone of Gunung Slamet but occurring again in the area between Sukaraja and Purbolinggo and a little to the east of this. Present below thin alluvium in the Citandui Basin on the southern side of the Banyumus Antcline, north-west of Sidareja (rare outcrops on the flanks and in oil company seismic shot-hole samples). May continue south-east, offshore from Citandui.

Diagnostic fossils: Planktonic foraminifera are common in many beds and include Globorotalia tumida, species of Pulleniatina, and in the middle to upper part Sphaerooidinella dehiscens dehiscens. For most of the formation the high ratio of planktonic to smaller benthic foraminifera, and the benthic assemblage, suggests an open marine, fairly deep marine environment of deposition. There are rare occurrences of larger foraminifera in sandstones, many reworked from older strata.

4. The Pemali Formation in the subsurface

The Pemali Formation is recognized in the Pertamina KRG-1 well (Fig. 1) and on seismic data in the surrounding area (e.g. Fig. 5), which allows correlation with surface outcrops. Microfossil and nannofossil analysis of well samples confirms that the Pemali Formation was rapidly deposited here, being no older than mid-Pliocene and over 1500 m thick, and also that it contains diverse reworking. An important data point is the basal Pemali Formation mudstone at around 1530–1552 m in the well, just above the Tapak limestone. This mudstone yields a microfauna far more abundant than any sample higher in the well, and a casing point at 1050 m rules out any caving of sample material from above that depth. This acme of microfossils is therefore considered in situ, and it is probably from a hemipelagic draping over the Tapak reefal limestone, deposited while coarser Pemali clastics onlapped areas below the reef-capped high. This fauna contains Globorotalia tumida and Sphaerooidinella dehiscens dehiscens. The former has a very well developed secondary aperture like the types that appear later in the Early Pliocene; the datum of N19 types with very small secondary aperture (cf. Bolli and Saunders, 1985). This late Early Pliocene age is supported by Pulleniatina specimens being almost exclusively dextrally coiled (Berggren et al., 1995; Berggren et al., 1985).

It is hard to make definitive biostratigraphic observations in the upper part of the KRG-1 well due to the high degree of reworking and the presence of caving in drill cuttings samples (no other type of samples are available from this well). Nannofossil analyses record Eocene, Late Oligocene, lower to middle Miocene and probable late Miocene reworking throughout the Pemali section in this well. No Pleistocene forms such as large Gephyrocapsa species or foraminifera such as Globorotalia truncatulinoides or the ancestral G. tosaensis are recorded in the well. Outcrop samples at Kedungrandu, on strike with the well location (Fig. 1), can be correlated to a set of seismic events that are seen in the well at about 2788 feet (850 m). Four out of five field samples yield nannofossils, all of which give an age at the top of zone NN11 (roughly 3.3 Ma, cf. Berggren et al., 1995; Berggren et al., 1985), with much reworking, as also seen in the well. The top of NN15 (top Sphenolithus abies) is seen at 850 m (2788 ft) in well samples. Therefore the age of the Pemali Formation in the KRG-1 well ranges from about 4 Ma to no younger than 2 Ma.

No corrections for compaction have been made, but it can still be seen that the rate of sedimentation of these five thousand feet of clastics (substantially thicker down-dip on the line shown in Fig. 5, and deeper still on other lines to the north-west) is exceptionally high. Approximately 8000 ft or 2500 m of clastics in no more than 2 million years. Such high rates of sedimentation are

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<td>H-2 (Catalog No. BWS01-1005-1011)</td>
<td>Cirambatan, c. 1.5 km NE of Pamulian village, on strike with G. Ciganggajung, 108°52'57&quot;E, 7°04'19&quot;S</td>
<td>BWS-1005, 1009 and 1010 both have moderate faunas of Globigerinoides, Orbitolina, Sphaerooidinella, Densothyridina altispina, N. acostaensis, rare N. humerosa, G. mendardi. Arenaceous benthics including Martinotiella communis, Glomospira and Bathysiphon, calcareous species include Orbulina umbonatula, Planoconus, Globigerina bulloides. Nannofossils include Upper Miocene NN11 [1r] forms Discoaster berggrenii, D. quinqueramus D. neohamatus, Helicosphaera orientalis. Larger foraminifera in samples 1007 and 1008 dominated by Cyclocyclus and L. (Trybliolipidina), Amphistegina, but also some deeper water benthic species in the same samples</td>
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Table 1 (continued)
comparable to those seen in tectonically active Eastern Indonesian basins such as east Sulawesi, Salawati and Bintuni (the last two have up to 20,000 ft deposited in about 7 Ma; unpublished industry data).

A seismic line passing through the KRG-1 well can also be tied to nearby outcrop data (Fig. 5, location on Fig. 1). This seismic shows clear southerly onlap onto the ridge or slope upon which a Tapak Formation reef grew. This onlap surface is the northern flank of the newly formed Banyumas Anticline. The large reverse fault, the uplift and angular truncation of Pemali Beds (and underlying Tapak/Bodas limestone) and the folding of the intermediate Pemali reflectors, demonstrates that since initiation of the Bobotsari Basin there has been continual compressional shrinking of this basin while it was being rapidly filled. Some of this younger sediment fill is cannibalised from earlier parts of uplifted Pemali Formation.

Seismic and outcrop data indicates that the Citandui Basin on the SW flank of the Cipari Anticline trend and a small but deep basin just south of Majenang are Pemali Formation sub-basins created by the same latest Miocene uplift and folding (Fig. 1).

5. Regional synthesis

The island of Java is located on the southern edge of the Sunda continental plate (Sundaland), where oceanic crust below the Indian Ocean has been subducting to the north, under Java, since mid-Eocene times (cf. Hall, 2002). Java contains an arc of generally andesitic volcanoes produced by subduction melts, yet also many outcrops of non-volcanic marine sediments, estimated as 3/5ths of the island area by Junghuhn (1854). These frequently deep marine sediments range in age from Eocene to Pleistocene (cf. van Bemmelen, 1949; Netherwood, 2000) and their frequent presence in outcrop indicates that the island of Java is a relatively young feature, with relatively recent (and on-going) uplift after sediment fill of old basins (cf. van Bemmelen, 1949, p. 25–31, 592 and elsewhere). The onset of deposition of the Pemali Formation appears to be linked to this change from being a long-standing deep marine basin and volcanic island-arc fringe around southern Sundaland, to becoming a large, contiguous island.

The historical and new field observations discussed here show how the Pemali Formation was rapidly deposited into sub-basins between newly uplifted structures, with high levels of older Tertiary reworking. This depositional sequence was initiated in middle Late Miocene times, with continuing compression further constraining the sub-basins. This eventually resulted in the reworking of lower Pemali sediments into the final phase of basin fill.

The effects of the mid-Late Miocene uplift and erosion are observed in southern Central Java where a coarse-grained equivalent of the Pemali Formation was originally mapped under the name “the Third Breccia Unit” by Harloff (1933), in the area from Karang-sambung to near the Menoreh Hills (Fig. 6). These sediments have been shown to be of later Late Miocene and younger age by Kadar (1986), who found the base of the unit to have been deposited just prior to the intra Late Miocene evolution of Pulleniatina, and for the unit to range through the latest Miocene and Pliocene. This formation was noted by Harloff to differ from any of the previous Neogene sediment in the area by being composed of the erosional products of older strata, including Eocene material and “for the
first time the erosion products include rounded fragments of gabbro-diorite, dolerite and serpentine derived from the pre-Tertiary massif" (p. 24 op. cit.). This dates the uplift and exposure of the nearby Lukulo basement complex (Fig. 1) as being due to this mid-Late Miocene tectonism.

The Pemali Formation can be correlated to other phases of accelerated clastic sedimentation across Java following widespread mid-Late Miocene tectonism. In eastern Java the equivalent is the Ledok to Mundu succession (cf. Marks, 1957; cf. Marks, 1957). The initiation of the Ledok Formation has been dated by the senior author in a field traverse north of Jojogan (north of Cepu, E. Java, Fig. 6) where the seismic sequence boundary crops out and is dated as within the lower part of zone N17, just before the evolution of Pulleniatina, based on examination of shot-hole and outcrop samples. The Ledok Formation, including the type formation, often has reworked quartz sands in its lower part (Pringgoprawiro, 1983, also cf. the lower part of the Terang-1 well to the east, Fig. 6). van Gorsel and Troelstra (1981) located a single, thin olistostrome deposit at the base of the Lower Kalibeng Formation, within zone N17, just before the evolution of Pulleniatina, in the Solo River near Ngawi. This seems to be a distal expression of the initiating unconformity in deep marine conditions. To the north-east this event is the uplift of the Tuban Plateau and island of Madura where there was erosion of several thousand feet of sediments down to mid-Oligocene levels near the Kujung-1 well site (cf. van der Vlerk and Postuma, 1967). This zone of uplift extended west past the town of Rembang, and further east to the island of Kangean. This uplift is recognised by Bransden and Matthews (1992) in offshore area between Madura and Bali. These workers identified a sequence of roughly Early Pliocene age that had one of the shortest time-durations of any of their post Eocene lithostratigraphic units (cf. Fig. 5 op. cit.). However in the low area south of Madura and Kangean their seismic data shows this “T65” sequence to be one of the thickest units, with a much higher rate of sedimentation than any of the underlying Miocene sediments, and with reworked quartz sands seen in the Terang-1 well in the basal part of this new sedimentary unit.

A common feature immediately overlying the mid-Late Miocene unconformity in central and north-east Java is a thin, but widespread, shallow marine limestone. Age-dating this carbonate has previously been difficult as it occurs in the Upper Tj Letter Stage; a period noted to have minimal diversity of age-diagnostic larger foraminifera (cf. Adams, 1984). In north-easternmost Java and Madura this unit is called the Karren limestone, to the east towards Semarang it is the Kapung limestone, further west near Wonosobo it is the Bodas limestone and, in the area of the Pemali type location, it is called the Tapak limestone. Reefal bioherms can be recognised both in the field outcrops and on seismic (e.g. Fig. 5). In all cases this limestone occurs above a distinct angular unconformity and is now consistently dated by strontium isotope stratigraphy as between about 7$^{12}$ and 5$^{12}$ Ma (see Table 2).
In the area south of Semarang, a “submarine folding” unconformity was recognised by van Bemmelen (1949, p. 573) based on his unpublished mapping in 1941. Van Bemmelen’s field reports and original samples at the Indonesian Geological Survey in Bandung, including those from the location where he mapped the angular contact, show that this unconformity is in fact the mid-Late Miocene, base Pemali event. The samples below the event are from foraminiferal zone N16 or the lower part of N17, before the evolution of *Pulleniatina*, and above this event are from foraminiferal zone N16 of the lower part of N17. Below the event are from foraminiferal zone N18 of the Lower Miocene. The samples below the event are from foraminiferal zones N16 and N17, before the evolution of *Pulleniatina*. The samples above the event are from foraminiferal zones N18 and N19, after the evolution of *Pulleniatina*. The event was recorded by van Bemmelen (1949, p. 573) based on his geological survey in Semarang, a submarine folding unconformity.

![Diagram](image.png)

Figure 5. Line 91-BMS-05 across the Bobotsari Basin (Fig. 1): a depocentre produced in mid-Late Miocene times (about 7.5 Ma) and showing late-continued compression and continued uplift of the basin margin.
contact samples are N18 and younger with both *Pulleniainia* and *Globorotalia tumida* (Lunt, in preparation). Below this event are the tuffaceous, plankton-rich marls of the Cipluk Beds, and above it are Pemali-equivalent mudstones called Kalibiuk Beds in the north and Kalibeng in the south.

Other historical work, on Javanese mollusc assemblages, highlights the mid-Late Miocene as the outstanding stratigraphic break of the later Tertiary. The "Kalibiuk Beds" (type location in the Pemali Formation north of Bumiayu) contain mollusc faunas assigned to the Cheribonian mollusc stage of Oostingh (1938). Oostingh noted a significant change between the Cheribonian Stage and the preceding Ciodeng Stage and he suggested a hiatus on his summary chart (redrawn in the summary on p. 82 of van Bemmelen, 1949). Further west, around Ceribon (Fig. 6), more mollusc sites have been studied and considerable contrast in both lithostratigraphy and mollusc faunas have been noted either side of an event datable as mid-Late Miocene. The formations here are the volcaniclastic-rich Cidadap Formation below the unconformity, and the mixed mudstones and silty sands of the Kaliwangu or Cijurei Formation above. As long ago as 1940 the foraminifera specialist LeRoy (pers. comm. to Oostingh, April, 1940, cf. van Bemmelen, 1949, p. 650) noted: "the microfaunal break between the Kailwangu and Cidadap Beds is of great magnitude, suggesting a major hiatus in this part of the section".

In western Java field mapping has shown the existence of a major uplift and unconformity within the Late Miocene. van Bemmelen (1949, p. 620) summarised this event in SW Java in the following way: "After the formation of the Cimandiri Complex, that is at the end of the Middle Miocene, the zone of the Southern Mts was arched up. The highest part of this uplift was presumably formed by the eruption centers of the Jampang Series, such as the Pasawahan Plateau, south of Lengkong which was subject to tensional stresses (fissures and faults). At this time the young gold- and silver-bearing quartz veins were formed. The area north of Lengkong occupied already the northern flank of this intra-miocene geanticline and here some compression phenomena (folding) may be observed. The intensity of this folding increases northward. It is still weak near Lengkong, but along the northern margin of the southern Mts and in the Cimandiri Valley some rather complicated northward compression phenomena are found. Especially the acid

### Table 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{87}$Sr/$^{86}$Sr</th>
<th>2 SEM (%)</th>
<th>Age (Ma)</th>
<th>Precision and error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tapak limestone in outcrop. (T1: Catalog No. BWS-1252) 109.04188°E, 7.422191°S</td>
<td>0.708911</td>
<td>0.0016</td>
<td>5.4</td>
<td>4.8–5.78 Ma (whole rock analysis)</td>
</tr>
<tr>
<td>Bodas limestone in outcrop B-1 (Catalog No. Bodas W-8), 109.80008°E, 7.364167°S</td>
<td>0.708599</td>
<td>0.0013</td>
<td>6.21</td>
<td>5.98–6.86 Ma (whole rock analysis)</td>
</tr>
<tr>
<td>Karen limestone (NE Java) in outcrop Karen-1 (BG-2)112.5703°E, 7.0435°S</td>
<td>0.709912</td>
<td>0.0012</td>
<td>5.46</td>
<td>5.12–5.75 Ma (whole rock analysis)</td>
</tr>
<tr>
<td>Karen limestone (NE Java) in outcrop Karen-2 (TA-15) 112.23705°E, 6.940205°S</td>
<td>0.708922</td>
<td>0.0018</td>
<td>7.56</td>
<td>6.61–9.16 Ma (whole rock analysis)</td>
</tr>
<tr>
<td>Kapung limestone above Cipluk Beds SW of Semarang. 10.18145°E, 7.08133°S</td>
<td>0.7089</td>
<td>0.0014</td>
<td>5.93</td>
<td>5.69–6.15 Ma (whole rock analysis)</td>
</tr>
</tbody>
</table>

$^{87}$Sr/$^{86}$Sr ratios normalized to $^{87}$Sr/$^{88}$Sr = 0.1194.

$^{87}$Sr/$^{86}$Sr ratios normalized to NBS987 $^{87}$Sr/$^{88}$Sr = 0.710235.

Measured NBS987 $^{87}$Sr/$^{88}$Sr = 0.710247 ± 0.000015 (95% confidence limits) 2 SEM – 2 standard errors of the mean (2cWn). Modern seawater (Mobil) $^{87}$Sr/$^{86}$Sr = 0.709168.

Ages calculated from McArthur et al. (2001). Precision and error figures are a guide to an acceptable range of ages based on machine precision to standard deviation correlated to high and low values within the robust range of data in the McArthur et al. correlation curve.
tuffs of the Jampang Series near Baros (south of Sukabumi) shows complicated structures, which are separated from the Nyalindung Beds near Nyalindung by a northward upthrust. This uplift caused some strong erosion and base leveling of the eroded parts.”

This erosional unconformity is overlain by the Bentang Beds which contain the age index *Lepidocyclina (Trybliolepidina)*, showing that the event occurred before the extinction of this taxon at about the Mio-Pliocene boundary (cf. Adams, 1970).

In the same uplifted area of south-west Java, apatite fission track data (Table 3) from outcropping Early Oligocene sands shows populations of grains that were buried just into the fission track annealing window (both sites 0.60–0.62% Ro on abundant vitrinite data) and then uplifted to give re-set fission track ages of 7.55 ± 4.11 Ma in the Rajamandala area, and at 7.12 ± 1.29 Ma at Gunung Walat slightly west.

In the Bayah area of south-west Java Late Miocene sediments are not known, but a thick Pliocene succession (Cimanceuri Beds, *Koolhoven, 1993*) unconformably overlies Middle Miocene beds. The Pliocene clastic sediments have lenses of larger foraminifera, such as the *Cyclcopyleus* studied by Tan Sin Hok (1932, his Tijdjen-\(^\text{kol},\) *Koleberes location*), which may be dated as Pliocene based on negative evidence, specifically the absence of the Miocene marker *Lepidocyclina* in facies where this form would normally be expected. However older workers such as Koolhoven dated the sediments as Pliocene based on extant mollusc percentages. The specialist Oostingh (verb. comm. to Tan Sin Hok, p. 75 op. cit. and in Koolhoven op. cit.) determined a value of 56% extant forms, which was regarded to indicate a Pliocene age. Seismic data to the south of Bayah shows this Pliocene mudstone unit to be over 7000 ft thick in places (unpublished Amoco data). In far west Java, offshore from Labuan to Aher, the Aminoli (1971–76) B-1-SX, C-1-SX and D-1-SX well drilled 1526 m, 3005 m, and 2448 m, respectively, and all these terminated in sediments no older than Late Pliocene. Seismic data shows that these very thick, young clastic sections were deposited in new basins created in Late Miocene times.

All the above data shows that across Java, from the area around Krakatoa in the west to the Madura Straits and south of Kangean in the east, there was a major unconformity, characterised by the formation of new basins and highs, with erosion of these highs causing rapid fill of the new lows. The expression of this tectonism in Central Java was the initiation of the Pemali Formation and the un-capping of the basement complex at Lukulo. There were negligible structural events at this time in the simple extensional basins to the north (Sunda/Asri, Arjuna, Muria, Central Deep basins, etc., Fig. 6; cf. *Netherwood, 2000*). There is no evidence for significant uplift and erosion, nor accelerated deposition in these present-day offshore areas. The available accommodation space there had been mostly filled, and sediments throughout the Java Sea, both before and after the mid-Late Miocene event, contain shallow marine environmental indicators, with fluctuations mostly the result of eustatic sea level changes. However one minor effect on sedimentation in the offshore area can be recognised as being due to the mid-Late Miocene event. It was at this time, as parts of onshore Java were uplifted and eroded, that a new river system developed that has long been recognised on bathymetric data (*Umbrgk, 1949*) and modern seismic data (e.g. Fig. 10 of *Bransden and Matthews (1992)*). During eustatic low-stands this river system drained north from the uplifted north-east Java margin (Semarang, Rembang, Tuban, Madura to Kangean) then it turned east and south-east to debouch on the east and west sides of Kangean Island.

This considerable contrast in stratigraphy between onshore and offshore Java in the Late Miocene is thought to have existed in the older geological record as well, and this long-standing contrast between the two areas reflects a fundamental geological divide. For instance there are many instances of thick, older Tertiary sediments onshore Java that are not found in the simple extensional basins to the north. These include the thousands of meters of Eocene quartz clastics at Bayah and Ciletuh, the Nanggulan Eocene, and traces of Paleocene known from Central Java (*Sukendar Asikin in Hamilton, 1979; Lunt, in preparation*). In West Java thick and deep marine Early Oligocene siliciclastics are overlain by the Late Oligocene, in situ reeal Rajamandala limestone, which is itself overlain by thick, deep marine Citarum Beds (*Lunt and Sugiatno, in press[b]*). This indicates active tectonism onshore Java that is outside the simple rift-sag-inversion model commonly used to describe the Java Sea basins.

The apparent absence of older Tertiary or Mesozoic sedimentary basins over Sundaland has long been considered an indication that the main Sunda Plate was an eroding land mass during this time. The fringing areas of Java would have been the site of much siliciclastic sedimentation from the large Sunda land mass. The boundary between this rim zone and the main sialic plate appears to be abrupt, located at the limit of the old Sunda Craton (Fig. 7). The north Central Java area around the outcrops of the Pemali Formation provide some of the best examples of this contrast. Field outcrops (marked as “x” in Fig. 6) are not only much older than any sediments known over the Sunda Plate, but they also are of very much deeper marine facies than any of the younger sediments found in Sunda type well sections only 20 km to the north (NCJ-A to C wells, Fig. 6) and also traceable on seismic data into the offshore Java Sea.

Zircon ages from onshore Java (*Smyth et al., 2005*) show there are very ancient crustal fragments under parts of Java, while strontium ratios of volcanic rocks (*Whitford, 1975*) show that recently erupted andesitic melts have included some assimilation of sialic crustal material. However the outcrops of basement at Lukulo, Ciletuh and Jiwo (Fig. 6) show a mixture of sialic and mafic components, with much ultrabasic material having ophiolitic affinities. This basement contrasts with the suspected composition of the Sunda Plate under the Java Sea, occasionally sampled by oil exploration wells, which is dominantly sialic and effectively a young continental craton.

---

**Table 3**

Apatite fission track data on the age of uplift in western Java

<table>
<thead>
<tr>
<th>Sample</th>
<th>ρs (10⁶ tracks cm⁻²)</th>
<th>ρp (10⁶ tracks cm⁻²)</th>
<th>Ni (tracks)</th>
<th>Grains</th>
<th>Dpar and Dper (u.m.)</th>
<th>Pooled FT age (Ma)</th>
<th>Mean FT age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sands below the Rajamandala limestone,</td>
<td>0.067</td>
<td>2.963</td>
<td>311</td>
<td>8</td>
<td>1.80, 0.59</td>
<td>5.07 ± 1.94</td>
<td>7.55 ± 4.11</td>
</tr>
<tr>
<td>Bandung, (107.35824E, 6.865613S)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sands at Gunung Walat (106.780806E, 6.922846S)</td>
<td>0.222</td>
<td>6.501</td>
<td>115</td>
<td>9</td>
<td>1.78, 0.47</td>
<td>7.66 ± 1.28</td>
<td>7.12 ± 1.29</td>
</tr>
</tbody>
</table>

Early Oligocene sands from western Java.

Stratigraphic age about 33 Ma; vitrinite reflectance at both sites between 0.60% and 0.62% Ro for young population only, in samples with mixed populations. Many values are greater than the sediment age (un-annealed at this borderline thermal maturity for apatite) and a few values are isolated outliers (?diagenetic apatite).

“Pooled age” = average of values in modal, 0–10 Ma, group. “Mean age” includes some values from the young population in the small 10–15 Ma set.

It is probable that the lithosphere under Java is a mixture of rock types, mainly an old accretionary wedge that also includes small continental microplates, forming a rim around the southern edge of the main Sunda Plate. Such a zone might be a continuation of the Woyla Terranes described for Sumatra (Barber, 2000; Fig. 7).

This considerable contrast in underlying basement could explain the very different tectono-stratigraphic histories through the Tertiary.

6. Petroleum geology

The oil seeps from the Pemali Formation (particularly the most active, and least biodegraded seep at Maja, Fig. 1) are of a thermally mature character, occurring in sediments with vitrinite reflectance showing very little burial (<0.3% Ro). Therefore the oil must have migrated from much deeper in the section. Seeps of the same type of oil are also known from sediments older than Pemali (e.g. Cicabe or Margamukti seep on Fig. 2, see Hetzel, 1935), and hence the Pemali Formation itself is not suspected to be the source rock. The Pemali Formation in the outcrops studied had far too low organic carbon content to be considered a hydrocarbon source facies (<1.5% TOC). The association of the seeps with the Pemali Formation is thought to be a result of the fill of the Late Miocene to Pliocene sub-basins with thick Pemali sediments burying deeper source rocks into the oil generation window. Hydrocarbons produced at this time will move to the flanks of the sub-basins, particularly in the north – the type Pemali area – where there is much faulting.

The source of these hydrocarbons is not known. The scenario described above in the regional synthesis, of contrasting stratigraphic styles between the Java Sea petroleum basins and the onshore Java area, will probably have affected the distribution of the source rock facies. The history of major tectonic unconformities onshore Java (such as that of the Rajamandala Lst. given above, and Lunt, in preparation), contrasts with the “rift-sag-inversion” model used by the oil industry to summarise the simple extensional basins to the north. While in the simple extensional basins the source rock is invariably in the early “rift” phase, onshore Java there is evidence that source rocks can occur at much higher levels, after a tectonic event changes basin configuration (Lunt, in preparation, on Early Oligocene paralic hydrocarbon source rocks overlying thick, deep marine Eocene strata in oil wells in NE Java). Similarly it can be expected that reservoir rocks, both sands and limestones, will have their occurrence controlled by this active tectonic history.

The giant Pagerungan gas field, the Terang gas field (& adjacent small fields), and the recent Jeruk and Banu-urip oil discoveries all lie in this tectono-stratigraphic zone (Fig. 6).

7. Conclusions

The history of the concept of the Pemali Formation is reviewed to explain why a major revision of its age and geologic setting is required. The previous age of generally “early Miocene” can be shown to be based on reworked coarse, bioclastic material, found in sandy facies. New microfossil and nannofossil analyses in the clays clearly demonstrate these sediments are of latest Miocene and Pliocene age.

The distinct, mixed clastic composition of the Pemali Formation contrasts with the underlying volcaniclastic sediments, which had been the dominant sediment type in the area since
at least Early Miocene times. The contact between these volcanics and the basal Pemali Formation can be shown to be a marked angular unconformity, and that the Pemali Formation is restricted to newly formed sub-basins. On the flanks of these sub-basins are biohermal limestones, dated using strontium isotopes, and which in Central Java were the first shallow marine sediments after tens of millions of years of very deep marine sedimentation. Age-equivalent limestones, occurring above a major tectonic unconformity, can be identified over many parts of central through eastern Java. In western Java such limestones are rarer, but the major mid-Late Miocene tectonic event can still be identified by field mapping and fission track age-dating. While this mid-Late Miocene tectonic event stands out as one of the fundamental tectonic divisions in the stratigraphy of onshore Java, over a thousand kilometers from west to east, it had negligible effect just 20 km to the north in the multiple, well studied, back-arc basins of the Java Sea.

The stratigraphy of south and western Sumatra is not as well understood as onshore Java, however there is a striking tectonic correlation between the zone on Java with the mid-Late Miocene event and the resulting Pemali Formation, and the zone of the Woyla Terranes proposed by Barber (2000) for western Sumatra. Field mapping on Java and recent zircon provenance work by Smyth et al. (2005, see also Smyth et al. 2007) shows that basement in Java includes both Mesozoic ultramafic 2ophiolites as well as ancient continental microplates of probably Australian origin. On current data it seems reasonable to conclude a link between basement type and the zone of severe mid-Late Miocene tectonics; namely that an outer zone of mixed basement terranes is tectonically much less stable than the sialic basin under the Sundaland plate. This new geological model has direct implications for hydrocarbon exploration in a zone that hosted the first drilling for oil in Indonesia as well as several recent, large, oil and gas discoveries.

Better stratigraphic understanding of western Sumatra, the islands east of Bali and southern Sulawesi should help develop the plate tectonic model along the collision zone between Sundaland and the Australian plate.

Acknowledgements

We are grateful to Lundin Banyumas b.v., ConocoPhillips and BPMigas for permission to publish this report. The strontium dating was carried out by T. Allan at CSIRO, who advised on the conversion of all data to a common GPTS. Bernhard Seubert collected the samples in the Larangan and Cisenti – Cibeureum and Kedungrau areas. Peter Pieters translated many original Dutch documents. The Museum of the Geological Survey in Bandung, especially Didik Kosasih and Pri Sanyoto helped in locating and providing the archived samples of the Lawak and Tapak beds.

Appendix A. Definitions of the Pemali Formation

The following definitions are published in English for the first time. The original taxonomy and place names are unchanged.

A.1. Original description of the Pemali Facies

Sheet 54 Majengang, Hetzel, 1935.

A.1.1. Pemali series

This series is best accessible for study in the north-east part of the Sheet area. It is a monotonous unit of brittle gray Globigerina marlstone and bedded Globigerina clayey marlstone with minor claystone, marly claystone, limestone and marly limestone with Globigerina. The base of the series is not exposed, and it is directly overlain by the Halang series, so that the Rambatan and Lawak series are missing in this part of the Sheet area. Near the boundary with the Halang series occur thin sandstone beds between the marlstone, for example in the Cijangkelok at Candawadak, and therefore the contact between the two series is gradational. In the marlstone near the upper boundary, corals were found at a few places in the Cipondok along the road west of Candawak.

Along the horse track from Kampung Cipondok to Cijankelok in the west outcrops of coral and foraminiferal limestone (781). Tan Sin Hok determined the following foraminifera from one of these limestones:

Cycloclypeus sp. with six rings, Tryblinepidina sp. 1 aff. Rutteni V. d. VI., Tryblinepidina radiata Martin, Amphistegina, Miliolidae.

The fauna, with the presence of Tryblinepidina and the absence of Spiroclypeus and Eulepidina, indicates a Tertiary age (according to the division of Van der Vlerk and Ubbegrove), or a Middle-Early Miocene age (n2–n3, according to De Jongh in the introduction of the Explanatory Note on Sheet 14, Bayah, of the Geological Map of Java). As the fauna is stratigraphically below the Middle Miocene (n2) lower part of the Halang series it must also belong to the Middle Miocene. However, it is possible that the lower part of the Pemali series, for reasons mentioned later, falls in the Early Miocene (n1).

The marly and associated rocks of the Pemali series are widely exposed in the surrounds of Ciniru, in the north-west part of the Sheet area. In this area, marlstone and clayey shale are dominant, but beds of limestone, calcareous sandstone and volcaniclastic (andesite) sandstone are also present. The minor lithologies show some similarities with the Rambatan series, but, because of the close association with marlstone and clayey shale, they are also assigned to the Pemali series. One of these packages is exposed in the Cipendak, downstream of Ciniru; it is made up of steeply dipping dark grey clayey shale and marly shale with several, 5–15 cm thick, beds of dark grey limestone and calcareous sandstone. The limestone contains Amphistegina and Operculina. Sandstone and thin beds of fibrous limestone occur sporadically. Near the boundary with the overlying Halang series, the marlstone along the Cipendak includes a brecciated bed of foraminiferal limestone with clearly rounded calcareous fragments. The limestone bed contains the following fauna (determinations by Tan Sin Hok):

Lepidocyclina sp., Miogypsina sp., Spirolocycus sp., Carpentaria sp., Gypsina sp.

These fossils are mostly damaged and rounded.

North of Ciniru, along the road, foraminiferal limestone crops out between brittle clayey shale; loose blocks of this limestone occur slightly farther north, that is, nearby the triple junction about 800 m north of Ciniru. The thickly bedded limonitic limestone contains Katakoclypeus sp., Miogypsina sp. (microspheric and megalo- spheric), Lepidocyclina sp., Spirolocycus sp., Gypsina sp., Amphistegi na sp., Miliolidae.

Both in these rocks and in the rocks of Cipendak the Spirolocycus is a rare foraminifera. The high stratigraphic position of the Cipendak limestone in the section of the Pemali series, and also the clastic character of this rock suggest that the fossils are derived. The somewhat rounded form of the Spirolocycus in the limestone of Ciniru also points to reworking. Therefore, it is doubtful that these rocks belong to the Early Miocene (n1). In the upper course of the Ciawi, upstream of Cibunut, the marlstone contains locally frequent thin beds of calcareous sandstone, and at the same place occurs an intercalation of andesite breccia. Thickly bedded, gray reefal limestone without foraminifera is exposed south-east of Rambatan, along the road to Ciniru.
South and south-east of Ciniru, the marlstone and shale are well exposed in the Cipedak, Citapen, Cijamaka and Cileunghi. The dark gray fine-grained rocks are mostly carbonate-poor or carbonate-free, and Globigerina are rare or are absent. Limestone and calcareous limestone are also rare; volcanioclastic (andesite) sandstone is mostly uncommon, although locally it is moderately developed. Characteristic of this area are fine-grained sills that caused contact metamorphism of the adjacent clayey shale and marlstone. In the area the clayey shale and marlstone contain some interbeds of quartz-bearing sandstone. A sandstone from Cipedak is composed of fragments of strained quartz that are cemented by calcite; about 850 m to the north-east of Citapen, light brown quartzite (13) was found, and a similar sandstone was located along the road to Cipedes. Some muddy sandstone beds also contain quartz detritus.

The thickness of the Pemali series is not known, as the base of the unit is not exposed in this Sheet area. In the north-east part of the Sheet area (section A–B) the exposed (minimum) thickness is about 550 m, and in the Cijamaka in the north-west it measures about 1200 m.

A.2. Sheet 58 Bumiayu, ter Haar, 1935

The Miocene is made up of the following series: (a) Pemali series; (b) Rambatan series; (c) Lawak series; and (d) Halang series.

A.2.1. Pemali series

The widest distribution of the Pemali series is in the north-west part of the Sheet area where it occupies a wide marginal zone of the Neogene and extends far to the south from south of Cikeusal. The unit also occurs in the surrounds of Sindagheula and north of Bantarkawung; along the Kali Lenggerang, the Kali Glagah and nearby Kali Bakung in the north-east part of the Sheet area it is mostly covered by erupted material of the Sla- gerina, Rotalia, Lithothamnium, algae.

The range of large foraminifera from the rocks at Cisadap suggests that the fossil assemblage is partly reworked. The occurrence of the first six foraminifera indicates a Middle Miocene (n2) age for the Pemali series, while the Eulepidina and particularly the Camerina were probably derived from an older rock unit.

The Pemali series contains in a few places beds of shelly limestone, that is two beds along the Ciseureuh (tributary of the Cirambatan) about 1 km downstream of Karanganyar, one bed at the left bank of the Ciruntuh (tributary of the Cirambatan) about 650 m downstream of the walking track Karanganyar-Jamash, and along the Kali Lenggerang (tributary of Kali Glagah south of Bligo). The shelly limestone beds at these places are completely identical, however, they have no stratigraphic significance as the shells are only represented by poorly preserved stone casts of Unio. The beds accumulated in situ as the shells are closed and show no signs of transport; some shells show the effects of boring by a marine snail.

Sedimentation of the Pemali series was partly in a shallow sea near the coast, but towards the end of deposition gentle crustal movements caused a temporary regression and the formation of local fresh water basins. This also explains the lenticular character of the Rambatan and Lawak series, and the minor unconformity between the Rambatan and Pemali series.

The base of the Pemali series is unknown and therefore only a minimum thickness could be estimated. In the steeply deformed anticline of Sindangheula the thickness is at least 900 m.

Appendix B. Full names of species cited in the text

B.1. Foraminifera

<table>
<thead>
<tr>
<th>Species Name</th>
<th>Author(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycloclypeus annullatus</td>
<td>Martin, 1880</td>
</tr>
<tr>
<td>Lepidocyclina (Nephrolepidina) ferreroi</td>
<td>Provale, 1909</td>
</tr>
<tr>
<td>Lepidocyclina (Trybilepidina) rutteni</td>
<td>van der Vlerk, 1924</td>
</tr>
<tr>
<td>Nummulites djokdjokartae</td>
<td>Martin, 1883</td>
</tr>
<tr>
<td>Dentoglobigerina altispina</td>
<td>Cushman and Jarvis, 1936</td>
</tr>
<tr>
<td>Globigerinoides obliquus</td>
<td>Bolli, 1957</td>
</tr>
<tr>
<td>Globoquadrina venzuelana</td>
<td>Hedberg, 1937</td>
</tr>
<tr>
<td>Globorotalia margaritae</td>
<td>Bolli and Bermudez, 1965</td>
</tr>
<tr>
<td>Globorotalia menardii</td>
<td>Parker and Jones, 1865</td>
</tr>
<tr>
<td>Globorotalia plesiotumida</td>
<td>Blow and Banner, 1965</td>
</tr>
<tr>
<td>Globorotalia scitula</td>
<td>Brady, 1882</td>
</tr>
<tr>
<td>Globorotalia tumida</td>
<td>Brady, 1877</td>
</tr>
<tr>
<td>Globorotalia tumida flexuosa</td>
<td>Koch, 1923</td>
</tr>
<tr>
<td>Neogloboquadrina acostaensis</td>
<td>Blow, 1959</td>
</tr>
<tr>
<td>Neogloboquadrina deutertrei</td>
<td>d’Orbigny, 1839</td>
</tr>
<tr>
<td>Neogloboquadrina humerosa</td>
<td>Takayanagi and Saito, 1962</td>
</tr>
<tr>
<td>Orbulina universa</td>
<td>d’Orbigny, 1839</td>
</tr>
<tr>
<td>Sphaeroidinella dehiscens</td>
<td>Parker and Jones, 1865</td>
</tr>
<tr>
<td>Hoeglundina elegans</td>
<td>d’Orbigny, 1826</td>
</tr>
<tr>
<td>Martinitella communis</td>
<td>d’Orbigny, 1846</td>
</tr>
<tr>
<td>Melonis pomplioides</td>
<td>Fichtel and Moll, 1798</td>
</tr>
<tr>
<td>Oridorsalis umbonatus</td>
<td>Reuss, 1851</td>
</tr>
<tr>
<td>Oxygularia culveri</td>
<td>Parker and Jones, 1865</td>
</tr>
<tr>
<td>Planulina wuelsterofii</td>
<td>Schwager, 1866</td>
</tr>
<tr>
<td>Praeglobobulimina ovata</td>
<td>d’Orbigny, 1846</td>
</tr>
<tr>
<td>Pullenia bulboides</td>
<td>d’Orbigny, 1846</td>
</tr>
<tr>
<td>Sphaeroidina bulboides</td>
<td>Deshayes, 1832</td>
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</table>
References


Duyfjes, J., 1938. Toelichting bij Blad 110 (Modjokerto), Geologische kaart van Java 1:100,000, Bandung, Dienst van den Mijnbouw in Nederlands-Indië.


Harloff, C.E.A., 1933. Toelichting bij Blad 67 (Bandjarnegara), Geologische kaart van Java 1:100,000, Dienst van den Mijnbouw in Nederlands-Indië.


Ter Haar, C., 1935. Toelichting bij Blad 58 (Boemulaejo), Geologische kaart van Java 1:100,000, Dienst van den Mijnbouw in Nederlands-Indië.


van Bemmelen, R.W., 1937. Toelichting bij Blad 66 (Karangkcedur), Geologische kaart van Java 1:100,000, Dienst van den Mijnbouw in Nederlands-Indië.

van Bemmelen, R.W., 1941. Toelichting bij Blad 73/74 (Semarang/Oengaran), Geologische kaart van Java 1:100,000, Dienst van den Mijnbouw in Nederlands-Indië.

van Bemmelen, R.W., 1937. Toelichting bij Blad 66 (Karangkcedur), Geologische kaart van Java 1:100,000, Dienst van den Mijnbouw in Nederlands-Indië.

van Bemmelen, R.W., 1941. Toelichting bij Blad 73/74 (Semarang/Oengaran), Geologische kaart van Java 1:100,000, Dienst van den Mijnbouw in Nederlands-Indië.


