The Manusela Limestone in Seram: Late Triassic age for a 'Jurassic' petroleum play

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ABSTRACT

A well-known Mesozoic hydrocarbon exploration target in eastern Indonesia is the 'Jurassic Limestone Play', validated by the Oseil oilfield in NE Seram. However, there is no biostratigraphic evidence to support a Jurassic age for the Manusela Limestone that forms the reservoir in this play, while numerous paleontological studies on outcrops and wells instead document only Late Triassic faunas and microfloras.

We here review the paleontological literature on Seram and suggest that the Manusela Limestone is of latest Triassic (Late Norian-Rhaetian) age, while the Early-Middle Jurassic interval is condensed or absent over the structural highs established as a result of the Manusela Limestone accumulation. This revised (but in reality >100 years old) age model fits well in Tethys-wide trends where sponge- and algae-dominated reefs blossomed during the Norian-Rhaetian from the Alps to NW Australia-Papua New Guinea, while a major extinction event at the end of the Triassic caused a collapse of carbonate reef systems globally, leading to a virtual absence of reefal limestones during the Early-Middle Jurassic.



Outcrop of massive Upper Triassic Manusela Limestone along the north coast of Central Seram between Sawai and Saleman (photo courtesy of Guido Baroncini)

INTRODUCTION

The Mesozoic Manusela (or Asinepe) Limestone is a striking geological element of Seram island, forming prominent morphological features such as the Nief Gorge in NE Seram, and the summit of Gunung Binaia, at 3019m the highest point in the Banda Arc (Figure 1). These massive shallow marine limestones also form a proven hydrocarbon reservoir in NE Seram, with minor oil production from the 1913 BPM wells at Nief (Zillman and Paten 1975), the 1988 East Nief 1 well with significant oil shows, the 1993 Oseil oil discovery (now in production) and the recent (2012) Lofin discovery. The Manusela Limestone is the primary reservoir target for wider petroleum exploration in Seram, and this is commonly, but we suggest incorrectly, referred to as the 'Jurassic carbonate play'.

The view that the Manusela Limestone is of Late Triassic to Middle Jurassic age is common not only in oil industry literature (e.g. O'Sullivan et al. 1985, Price et al. 1987, Kemp 1992, Kemp and Mogg 1992, Pertamina/BPPKA 1996, PND 2006, Dradjat and Patandung 2012, Lopulisa et al. 2012, etc.), but is also shared by the Geological Survey (Harahap et al. 2003) and academic groups working on the regional geology of the area (e.g. Sukamto and Westermann 1992, Milsom 2000, Carnell and Wilson 2004, Hill 2005, Pownall et al. 2013). However, a (partial) Jurassic age for the Mesozoic limestones on Seram is not supported by any paleontological evidence, whereas numerous historic and modern studies have identified only Late Triassic-age fossils.

The present article re-iterates the evidence in favour of a Late Triassic age for the Manusela Limestone, as most convincingly argued by Wanner (1907), Wanner, Knipscheer and Schenk (1952) and Martini et al. (2004).

TRIASSIC-JURASSIC STRATIGRAPHY OF SERAM

Observations on the Mesozoic stratigraphy and paleontology of outcrops on Seram and nearby Buru island date back to the early twentieth century, with significant contributions by geologists including Martin (1901-1903), Wanner (1907, 1923), Verbeek (1908), Deninger (1918), Brouwer (1919) and Rutten (1919-1920, 1927). Subsequent important contributions to the Mesozoic stratigraphy and paleontology of Seram include studies by Valk (1945), Germeraad (1946), Van der Sluis (1950), Van Bemmelen (1949), Audley-Charles et al. (1979) and Tjokrosapoetro and Budhitrisna (1982). Modern contributions with microfaunal/microfloral information include Al-Shaibani et al. (1983, 1984) and Martini et al. (2004), as well as papers from oil company staff operating on Seram (O'Sullivan et al. 1985, Price et al. 1987, Kemp and Mogg 1992, Nilandaroe et al. 2002). Unfortunately, due to the complex fold and thrust belt structure and poor outcrop on the island, the vast majority of faunal/floral data are from isolated samples rather than from continuous stratigraphic successions.

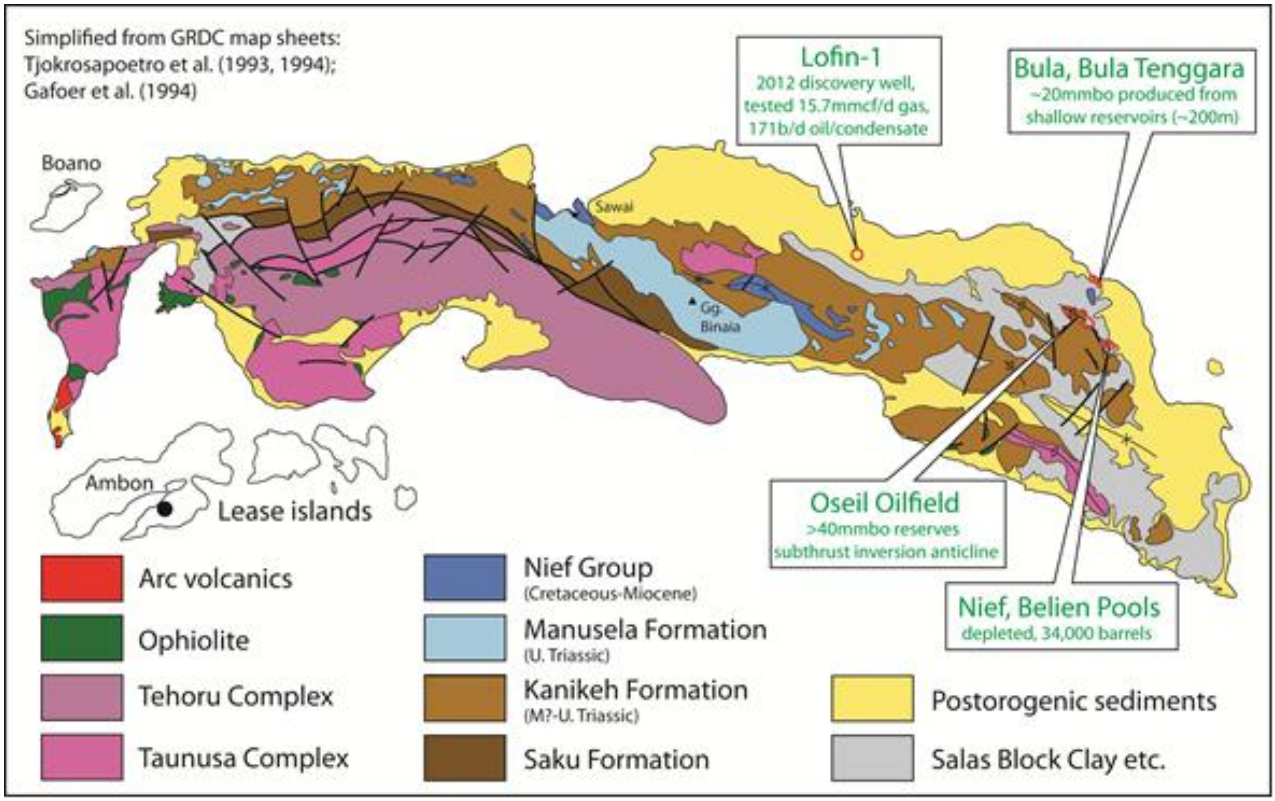


Figure 1. *Geology and location map of Seram, showing outcrop distribution of the Late Triassic Manusela Limestone from the NW coast to central and eastern Seram, and the principal oil discoveries in NE Seram.*

The main stratigraphic elements recognised in the Triassic- Jurassic of Seram are, from old to young (Figure 2): (1) a Late Triassic marine clastic unit (Kanikeh Formation); (2) a Late Triassic limestone-dominated package (Manusela and Saman Saman Formations); (3) a very thin Early Jurassic marine transgressive interval and hiatus; (4) a more widespread Late Jurassic marine shale (Kola Shale). The paleontological content of these units is summarized below and in Table 1.

Audley-Charles et al. (1979), recognizing close geological similarities between Seram and Timor, proposed a model of 'para-autochthonous' and 'allochthonous' nappes for Seram, as then also interpreted for Timor (Carter et al., 1976; Barber et al., 1977). They placed the Triassic deeper marine, thin-bedded Saman-Saman facies in a para-autochthonous/'Australian' tectonic unit, while the more massive, oolitic Asinepe (=Manusela) facies was placed in an allochthonous/'Asian' terrane, thrusted over the para-autochthon from the S/SW. In Timor there is now overwhelming evidence for the Triassic shallow to deep marine clastic and carbonate successions having accumulated in a single connected sedimentary system, and given the very strong similarity of Triassic successions in the two islands, this single-terrane interpretation must also apply to Seram. This is the structural/stratigraphic framework that we adopt in the present study.

1. Triassic clastics: Kanikeh Formation

This is a predominantly or perhaps entirely marine clastic succession, often described as greywacke, mainly in 'flysch-type' facies, micaceous, with locally common plant remains and rich in metamorphic rock detritus. Following Deninger (1918) it is now generally known as the Kanikeh Formation. Thickness estimates range from ~400m (Wanner 1907) to ~1000m or more (Audley Charles et al. 1979; Tjokrosapoetro et al. 1993). It contains undisputed Late Triassic bivalves such as *Monotis salinaria* and *Halobia* and the brachiopod *Halorella*. *Halorella amphitoma* (Plate 1, Fig. 3) is a well-known marker species for the Norian in the European Alps.

The vast majority of fossils reported from the Kanikeh Formation are of Late Triassic age, mainly Norian. Krumbeck (1923) distinguished three zones in the Kanikeh Formation: (1) Carnian *Halobia* shale; (2) Lower Norian *Myophoria-Trigonia-Protocardia* shale; and (3) probably Middle Norian *Monotis salinaria* beds.

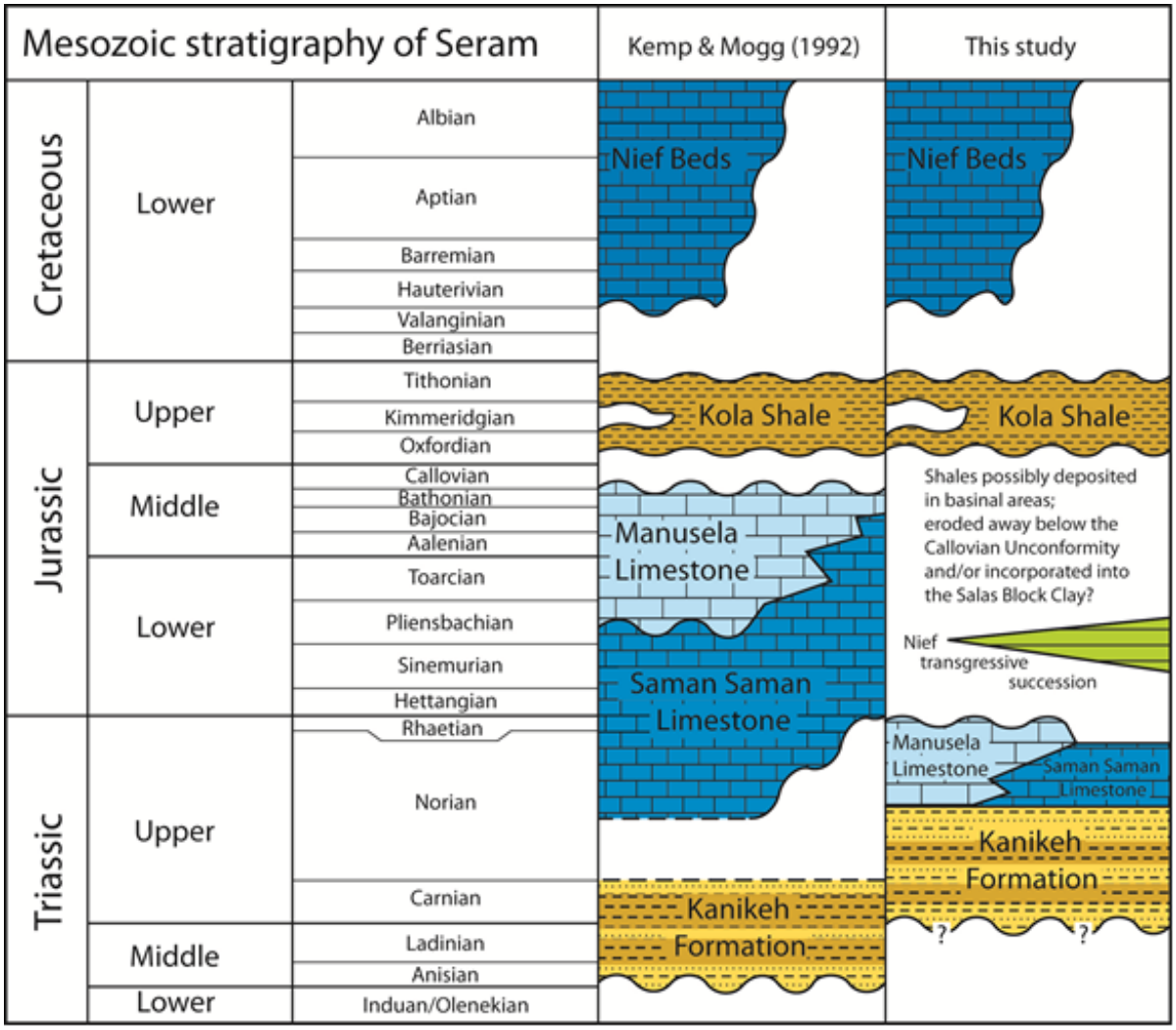


Figure 2. *Mesozoic stratigraphy of Seram. Dark Blue= deeper marine limestone, Light Blue= shallow marine, reefal or platform limestone*

The Carnian-Norian age range established by these early studies agrees well with more recent palynological analyses as reported by P.T. Geoservices (1991; in Kemp and Mogg, 1992), who placed the Kanikeh Formation samples in the *Samaropollenites speciosus* to *P. crenulatus* palynozones. These zones were believed to represent Ladinian to Norian age range, but more recent calibrations place the *S. speciosus* zone in the (Late) Carnian-earliest Norian and the *Minutosaccus crenulatus* zone in Middle-Late Norian (Brenner et al. 1992, Nicoll and Foster 1998, Cirilli 2010, Riding et al. 2010). Dinoflagellate genera *Sverdrupiella*, *Heibergella* and *Suessia* were reported from the Kanikeh Formation of Seram by Helby et al. (1987) and interpreted as most likely Middle-Late Norian in age.

No Middle Triassic macrofossils were found by the early explorers (Wanner et al. 1952). One study on outcrop samples of the Kanikeh Formation suggested the presence of Middle Triassic-age palynoflora (Price 1976, unpublished report; quoted in Kemp and Mogg 1992). Anisian age was believed to be indicated by the occurrence of *Falcisporites* and *Lunatisporites noviaulensis* in one sample and a Ladinian-Carnian age by gymnosperm taxa such as *Ovalispollis* sp., *Ellipsovelatisporites* sp., *Rimaeosporites* sp. and *Patinasporites* sp. in another sample. However, in our opinion this evidence for Middle Triassic section in Seram remains inconclusive, as these taxa are long-ranging and most of them actually also occur in assemblages of Carnian-Norian 'Onslow-type' warm-temperate palynological assemblages of the region.

2. Manusela - Saman Saman Limestone

The Mesozoic carbonate-dominated succession of Seram can be subdivided into different facies:
1. Shallow marine, massive, locally oolitic reefal/carbonate platform facies (Manusela or Asinepe Formation; older names include Bula Limestone, Pharetrone Limestone). Fossils in the reefal facies are often rare or difficult to recognize due to dolomitization and karstic diagenesis, but wherever present they are dominated by calcareous sponges with subordinate calcareous algae, hydrozoans and corals.
2. Deeper marine, cherty limestone facies (Saman-Saman Limestone; older names include *Misolia* Limestone, etc.
3. Thin-bedded bituminous limestones. These do not outcrop extensively on Seram, but bitumen-impregnated limestone was observed at the base of a Late Norian limestone on the south coast of Seram (Weber, unpublished report 1926, quoted in Price et al. 1987). These are probably moderately deep marine deposits, and are presumed to be the principal hydrocarbon source rock in Seram (cf. Livsey et al. 1992, Peters et al. 1999).

In its type area in the Manusela mountains of central Seram (Figure 1) it appears that the Manusela Formation is many hundreds of metres stratigraphic thickness (Rutten 1927), with Audley-Charles et al. (1979) estimating 1000-1500m thickness and Tjokrosapoetro et al. (1993) up to 1000m. With a structurally massive limestone such as this, and considering the enormous mass of virtually uninterrupted limestones exposed in the Manusela Mountains, these are probably genuine stratigraphic thicknesses rather than structural repetitions of thinner stratigraphic sections duplicated by cryptic thrusts. The Manusela Mountains probably comprise massive accumulations of Late Triassic shallow marine limestones, presumably accumulating in rapidly subsiding rift sedimentary basins (cf. Price et al. 1987; Kemp and Mogg 1992). In northern Seram, in contrast, Wanner (1907) and Rutten (1919) found that lithologically similar limestones occur as lenses within the Upper Triassic 'flysch' succession. In these areas stratigraphic thicknesses are substantially reduced: Wanner (1907) estimated 80-100m, and Deninger (1918) and Martini et al. (2004) about 150m.

Kemp and Mogg (1992) interpreted the deeper water Saman Saman Limestone as underlying, and partly interdigitating with, the shallow marine, reefal Manusela Formation, an interpretation followed here (Figure 2).

The most likely interpretation for the age of faunas in the carbonate interval of Seram is Late Triassic, and more precisely Late Norian-Rhaetian (e.g. Wanner 1907, Wanner et al. 1952, Flugel 1981, 2002, Martini et al. 2004). Fossil evidence for this is compiled in Table 1 and discussed further below. However, as already mentioned, most oil-industry and academic studies routinely extend the top of the Manusela Limestone into the Early-Middle Jurassic (Pliensbachian-Callovian; e.g. Kemp 1992). This results from an erroneous interpretation of a Jurassic age for the sponge-like fossil *Lovcenipora* (Van Bemmelen 1949, Van der Sluis 1950; see further discussion below), combined with a near-absence of Early-Middle Jurassic sediments in the area.

3. Early- Middle Jurassic condensed succession and/or hiatus

Early and Middle Jurassic faunas are poorly represented in Seram. The only well documented fauna of this age is from a ~60 cm thick glauconitic-sandy limestone from the Nief Gorge area of East Seram, where it overlies (weathered?) massive oolitic limestones (Wanner and Knipscheer, 1951). The fauna is composed of a relatively rich diverse assemblage of Early Jurassic ammonites, brachiopods (*Spiriferina* spp., *Rhynchonella* spp.) and gastropods (Table 1). Faunas and lithology suggest an open marine shelf environment with a very low sedimentation rate. This fauna is closely related to middle Liassic European Tethys faunas, but is not known from anywhere else in Indonesia.

While there is no additional evidence on Seram for Jurassic fossils in limestones, there are some indications for the possible presence of Early Jurassic-age shales in the Bula area of NE Seram. These shales may form part of the matrix of what Rutten (in Van der Sluis 1950) described as a 'soup of shales with (Triassic) limestone blocks', and is now known as a Neogene melange described as the Salas Block Clay. Jurassic fossils from this unit include:

1. An *Ichthyosaurus* vertebra, possibly of the Liassic genus *Eurypterygius* (Von Huene 1931). Comparable ichthyosaur fossils have been found in Timor and Tanimbar, with the Tanimbar example from a basinal grey shale facies equivalent to the Lower-Middle Jurassic Wai Luli Formation of Timor (Charlton et al. 1991);
2. An ammonite of the Hettangian-Sinemurian genus *Ectocentrites* (Wanner et al. 1952).
3. Unspecified Early Jurassic palynological age determinations from blocks of 'Kanikeh Formation' (i.e. flysch) within the Salas Block Clay (Price, unpublished report 1976, quoted in Kemp and Mogg 1992).

4. Late Jurassic Kola Shale

The Kola Shale is found immediately above the Triassic limestones in exploration wells in NE Seram, but has only rarely been found at outcrop. The Kola Shale contains a characteristic Late Jurassic assemblage of brachiopods (*Malayomaorica malayomaorica)*, pelagic bivalves (*Inoceramus haastii* group) and belemnites (*Belemnopsis gerardi* group) (Wanner et al. 1952). This open marine faunal assemblage is typical of the Oxfordian-Kimmeridgean of the Gondwanan Tethys margin ('Maorian Province'). In the Oseil 1 well this shale interval was characterised by the dinoflagellate species *Omatia montgomeryi,* which in recent calibrations is usually placed in Kimmeridgean- Early Tithonian time.

TABLE 1 **TRIASSIC- JURASSIC FAUNA OF SERAM**

FOSSIL GROUP	KEY SPECIES	AGE	REFERENCES
KOLA SHALE ('FATJEH SHALES'; Late Jurassic)			
Brachiopods	*Malayomaorica malayomaorica,*	Oxfordian-Kimmeridgean	Krumbeck 1923, Wandel 1936
Belemnites	*Belemnopsis gerardi* group	Oxford-Kimm.	Wanner et al. 1952
Bivalves	*Inoceramus haasti group*	U? Oxfordian	Wandel 1936
Dinoflagellates	*Omatia montgomeryi*	Kimm- E Tith.?	Oseil 1 well
Calcispheres	*Stomiosphaera moluccana, Cadosina fusca*	Malm	Wanner 1940
E-M JURASSIC CONDENSED SECTION			
Brachiopods	*Rhynchonella* spp., *Spiriferina rostrata, S. alpina, S.* spp., *Terebratula*	Liassic	Wanner and Knipscheer 1951
Ammonoids	*Oxynoticeras, Phylloceras, Echioceras, Lytoceras, Dactylioceras, Coeloceras,*	Liassic	Wanner and Knipscheer 1951

	Brodiceras		
MANUSELA/ SAMAN SAMAN LIMESTONE			
Corals	*Montlivaltia molukkana, Thecosmilia aff. clathrata, Retiophyllia cf. wanneri, Oedalmia norica, Isastrea seranica*	Late Norian-Rhaetian	Wanner 1907, Wilckens 1937, Wanner et al. 1952, Martini et al. 2004
Hydrozoa/ Demosponge	*Lovcenipora vinassai*	Norian	Wanner 1907, Gerth 1910
Calcisponges ('Pharetronen')	*Molengraaffia regularis, Blastochaeta intabulata, Peronidella moluccana, Deningeria camerata, D. miriabilis, Seranella, Cryptocoeliopsis gracilis*	Late Norian-Rhaetian	Wilckens 1937, Germeraad 1946
Brachiopods	*Misolia pinajae, M.aspera, M. misolica, Halorella rectifrons, H. amphitoma*	Late Norian-Rhaetian	Wanner 1907, Krumbeck 1923
Bivalves	*Oxytoma inaequivalve intermedia, Pecten* cf. *acutauritus, Monotis salinaria?*	Late Norian	Krumbeck 1923
Calcareous Algae	*Solenopora triasina, Cayeuxia, Bacinella*		Pia 1924, Germeraad 1946, Martini et al. 2004
Foraminifera	*Triasina hantkeni, Aulatortus sinuosus, A.* spp., *Agathammina austroalpina, Galeanella, Tetrataxis inflata, AIpinophragmium perforatum, Piliammina sulawesiana, Duotaxis birmanica, Gandinella falsofriedli*	(Late Norian?-) Rhaetian	Al-Shaibani et al. 1983, 1984; Martini et al. 2004
Calcareous Nannofossils	*Prinsiosphaera triassica, Archaeopontosphaera primitiva*	(Late Norian?-) Rhaetian	Oseil 1 well
Dinoflagellates	*Rhaetigonyaulax rhaetica, Beaumontella* spp.,	Rhaetian	Martini et al. 2004
Palynomorphs	*Corallina* spp., *Falcisporites australis, Minutosaccus crenulatus, Taenisporites rhaeticus, Semiretisporites gothae*	Late Norian-Rhaetian	Oseil 1 report, Martini et al. 2004

KANIKEH FM ('Triassic Graywacke-Flysch')			
Ammonoids	*Juvavites ceramensis, Cycloceltites appiani, Sirenites, Halorites macer*	(Early?) Norian	Wanner 1928, Wanner et al. 1952
Pelagic hydrozoa	*Heterastridium conglobatum*	Norian	Gerth 1909, 1942
Brachiopods	*Halorella amphitoma, H. plicatifrons, H. rectifrons, Misolia asymmetrica*	Norian	Wanner 1907
	Koninckina alfurica, Spirigera moluccana, Retzia bulaensis	Carnian?	Wanner 1907, 1952, Hasibuan 2010
Bivalves	*Monotis salinaria, Amonotis rothpletzi*	Late Norian	Wanner 1907, Krumbeck 1923 , Wanner et al. 1952, Hasibuan 2010
	Myophoria seranensis, Cardita, Palaeocardita buruca, Trigonia seranensis, Serania seranensis, Krumbeckiella, Aequipecten, Hologyra timorensis	Early Norian	
	Halobia deningeri, H. comata, Posidonomya gibbosa	Carnian	
Calcareous Algae	*Macroporella sondaica, Sestrosphaera*	Norian	Pia 1924
Dinoflagellates	*Sverdrupiella, Heibergella*	Norian	Helby et al. 1987
Palynomorphs	*Samaropollenites speciosus-Minutosaccus crenulatus.* zones	Carnian-Norian	Geoservices 1991 in Kemp 1992

PALEONTOLOGY AND AGE CONTROL OF THE MANUSELA LIMESTONE

A significant number of paleontological publications exist on Triassic fossils from Seram, starting with Wanner (1907) on material from the Bula area of NE Seram. Key subsequent studies on Seram Triassic faunas include Krumbeck (1923; molluscs), Pia (1924; algae), Wilckens (1937; corals, sponges), Wanner et al. (1952; general), Al-Shaibani et al. (1983, 1984; foraminifera) and Martini et al. (2004; foraminifera, corals, palynology). Most of these authors recognised the 'Tethyan' character to the Late Triassic faunas of Seram, and many of the species identified are the same as those from the Northern Calcareous Alps, Oman, Iran, etc. and also from Timor.

From Table 1 it is apparent that most of the fossils described have been assigned Late Norian ages, but Rhaetian marker fossils are also present:
1. Corals: *Retiophyllia* is the dominant coral in Rhaetian reefs in the Alps and other areas;
2. Bivalve mollusks: *Oxytoma inaequivalve intermedia,* reported from massive *Misolia* limestones of Seram by Krumbeck (1923), is also present in beds assigned to the Rhaetian of Timor and in the Rhaetian Kossen Beds of the Alps (Gazdzicki et al. 1979);
3. Foraminifera: *Triasina hantkeni, Tetrataxis inflata, Gandinella falsofriedli* and

AIpinophragmium perforatum reported by Martini et al. (2004) are generally placed in the Rhaetian (e.g. Gazdzicki et al. 1979, Zaninetti et al. 1992);
5. Dinoflagellates: *Rhaetigonyaulax rhaetica*, is a generally recognized marker for Rhaetian age (Riding et al. 2010);
6. Calcareous nannofossils: *Prinsiosphaera triassica*, reported from core section from near the top of the Manusela Formation (Oseil 1 well report), is the dominant nannofossil species in the latest Triassic of the (Meso-)Tethys Ocean and ranges in age from Late Norian to Rhaetian (Bralower et al. 1991, Gardin et al. 2012). The well report also reported the presence of *Archaeopontosphaera primitiva*, a species originally described from the Rhaetian of Austria. These occurrences emphasises that the top of the Manusela Limestone is also latest Triassic in age in well penetrations, not Jurassic.

As noted by Wilckens (1937), Martini et al. (2004) and others, calcareous sponges are the dominant reef builders in the Manusela Limestone, with corals generally representing less than 20% of the fauna. This is the normal pattern in Late Triassic reefs of the Tethys, although regionally corals become dominant in the Rhaetian (Flugel 2002, Payne and Van de Schootbrugge 2007). For Seram the dominance of calcareous sponges may be due to facies control, but may also point to an age that is primarily Late Norian rather than Rhaetian.

From the paleontological information presented above and in Table 1, it is safe to conclude a Late Norian-Rhaetian age range for the Manusela/Saman Saman limestone complex, as also suggested by Martini et al. (2004). The underlying Kanikeh Formation probably spans a Carnian to 'Middle' Norian age range.

Significance of Lovcenipora

As already mentioned, the erroneous change from the previously established Late Triassic age interpretation for the Seram limestones to a Jurassic age interpretation was first suggested by Van Bemmelen (1949) and Van der Sluis (1950). They based this on the occurrence of *Lovcenipora* in the Seram limestones, which they believed to signify a Jurassic (indeed Late Jurassic) age. Wanner, Knipscheer and Schenk (1952) were quick to point out that this was incorrect, and listed the faunal groups of undisputed Late Triassic age within the Seram limestones. Unfortunately, however, this publication was written in German and published in a Swiss journal at a time of limited interest in eastern Indonesian geology, and so remained unnoticed by many subsequent workers.

Lovcenipora Giattini 1902 is a calcareous sponge or coral-like creature, originally described from the Upper Triassic *Megalodon* Limestone of Lovcen, Montenegro. The exact taxonomic position of this fossil is still debated, but it is now usually classified as a chaetetid sponge (Demospongiae). The first record of *Lovcenipora* from Seram was by Wanner (1907) (Plate 1, Figure 1), who described it as a new species of tabulate coral, *Pachypora intabulata*. Gerth (1910) and Vinassa de Regny (1915) correctly identified this Seram fossil as *Lovcenipora vinassai*.

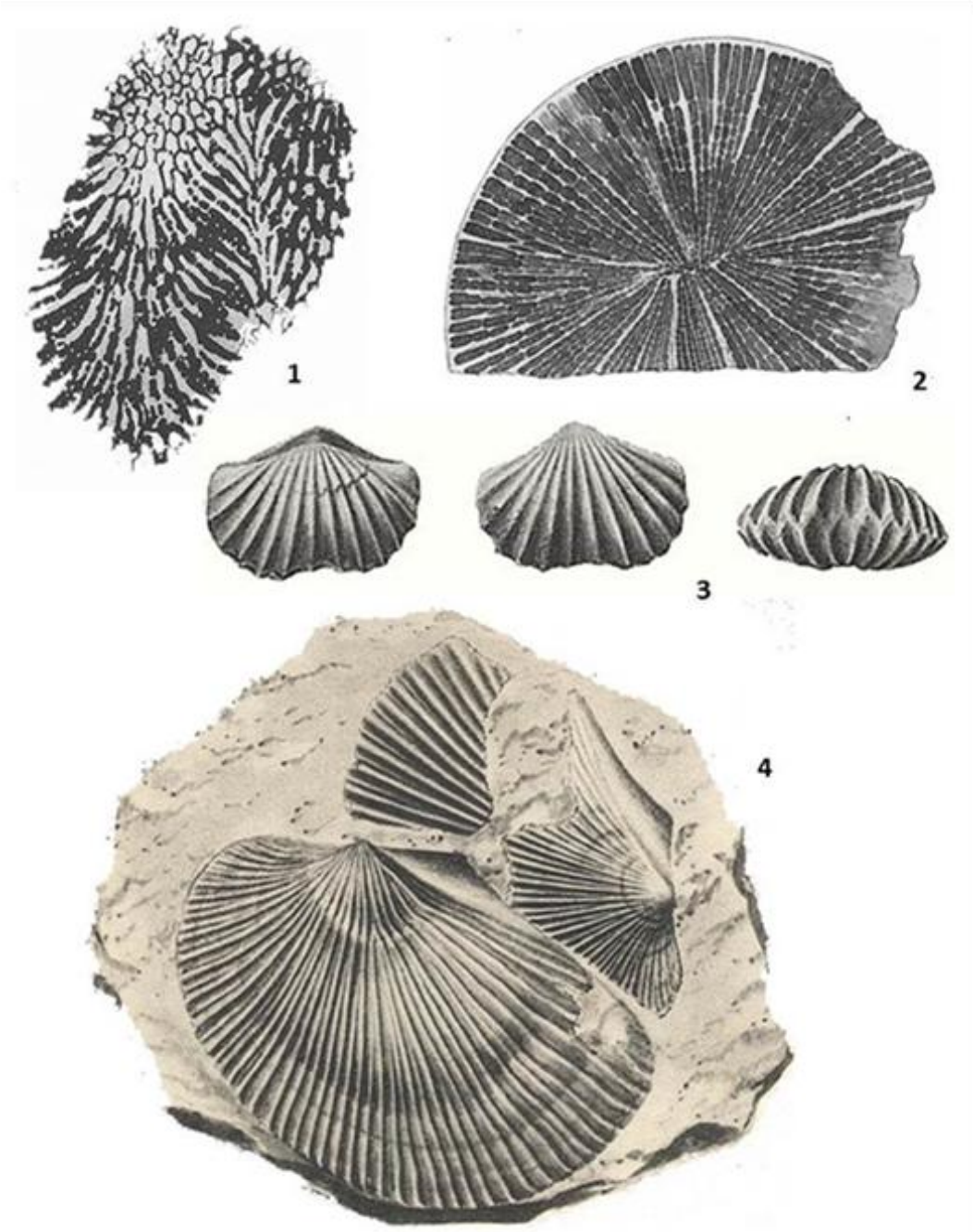


PLATE 1*- Late Triassic fossils from Seram (Wanner 1907)*
1. *Section of Lovcenipora vinassai from breccious Manusela Limestone near Bula, NE Seram. Initially described as a coral (Pachypora intabulata) by Wanner, but now viewed as chaetetid calcareous sponge.* ***2.*** *Montlivaltia molukkana, solitary coral from Bula Limestone of East Seram* ***3.*** *Halorella amphitoma, a Norian rhynchonellid brachiopod from Bula area, NE Seram* ***4.*** *Monotis salinaria, Norian pelagic bivalve mollusks from the Kanikeh Formation.*

Typical *Lovcenipora* are most common in Late Triassic limestones across the Tethys realm, from the Northern Calcareous Alps to Oman, UAE, Iran and the NW Australian margin (Wombat Plateau), as well as in Panthalassan terranes now in British Columbia and Japan. *Lovcenipora vinassai* is also known from Timor and Buru islands, always in limestones with Late Triassic faunas (Wanner and Knipscheer 1951). For instance:
- West Timor: in >15 'Fatu Limestone' localities where it is associated with undisputed Late Triassic brachiopods (*Misolia, Halorella*), and corals (*Montlivaltia*, etc.) (summarised in Wanner et al. 1952);
- East Timor: Fatu Limestone near Tutuala; with Triassic *Halobia* and *Misolia*. (Grunau 1957, p. 84);
- Buru: associated with Triassic algae *Macroporella* (Gerth 1910, Pia 1924).

Although *Lovcenipora*-like fossils have also been described from limestones of Jurassic and Cretaceous age, most of these are probably misidentifications. For instance, *Lovcenipora* described from the Early Cretaceous Saling Limestone in the Gumai Mountains of South

Sumatra by Vinassa de Regny (1925) are different from true Triassic *Lovcenipora*, and should instead be assigned to *Cladocoropsis miriabilis* (Yabe, 1946).

TETHYAN TRIASSIC REEF PATTERNS AND END-TRIASSIC EXTINCTIONS

The presence of latest Triassic reefal limestones in Seram (and similar occurrences on Buru, Misool, Timor, East Sulawesi, Papua New Guinea and the Wombat Plateau of the NW Australian margin) closely follows reef development trends observed across the Tethys (e.g. Flugel, 2002; Payne and Van de Schootbrugge, 2007). Reefal carbonates are very rare in Early and Middle Triassic, but Early Carnian and particularly Late Norian- Rhaetian were times of widespread development of reefal/carbonate platform limestones along the margins of the Tethys.

The well-known end-Triassic mass extinction event eliminated over 90% of all coral, sponge and other species around 200 Ma (e.g. Hautmann, 2012). It is believed to be associated with a global eustatic sea level drop. It caused a collapse of the Late Triassic carbonate reef ecosystems, which then led to a global virtual absence of reef systems in the Early Jurassic (e.g. Leinfelder et al., 2002). This is therefore another reason why the presence of Early-Middle Jurassic-age reefal limestones in Seram is unlikely.

CONCLUSIONS

In summary:
(1) As suggested by Wanner et al. (1952), Martini et al. (2004) and many others, all paleontological information from the Manusela Formation limestones of Seram supports a Late Triassic age, while there is no evidence for any fossils characteristic of a Jurassic age in this limestone;
(2) The Manusela Limestone formation is of Late Norian-Rhaetian age, demonstrated by multiple fossil groups;
(3) The underlying Kanikeh Formation clastics are of Carnian-Norian age, demonstrated by the biostratigraphy of ammonites, brachiopods, bivalves, palynomorphs and other groups;
(4) The Manusela Limestone appears to be overlain directly by the Late Jurassic Kola Shale in petroleum exploration wells, demonstrating that the Early and Middle Jurassic is either absent or very thin, at least on the structural highs on which the Manusela Limestone accumulated in northern Seram. The absence or incomplete Early-Middle Jurassic section may be due to erosion at the time of the Triassic-Jurassic boundary global fall in sea levels; at a tectonically-driven relative fall in sea levels associated with Middle Jurassic continental rifting; to an unusually thin, condensed and generally unrecognized stratigraphic record; or to a combination of all of these;
(5) The Late Triassic flourishing of reefal limestone on Seram, followed by the end-Triassic collapse of the reef/platform carbonate system, fits with the pattern observed all along the Tethys margins, including nearby localities in eastern Indonesia, the NW Australia margin and Papua New Guinea.
(6) Faunas and lithofacies of the Late Triassic succession and the Norian-Rhaetian limestones in Seram are remarkably similar to those in the western Tethys (Northern Calcareous Alps, Oman, etc.). Numerous studies on faunal taxonomy, biostratigraphy, biofacies and carbonate sedimentology undertaken in those areas should be very useful for more detailed comparison with the Late Triassic of eastern Indonesia;
(7) The Manusela Limestone is a proven hydrocarbon reservoir. The change in the age of the principal reservoir unit suggested here has potentially significant implications for regional hydrocarbon exploration:
- The Late Triassic was a time of reefal limestone development in eastern Indonesia and surrounding areas, and carbonate reservoirs of this age may also be a potential target outside Seram. However, known regional occurrences are sponge-algal dominated systems that, except for the oolitic shoal platform facies, tend to have poor primary porosity. Adequate reservoir quality will therefore probably depend primarily on secondary diagenetic porosity and/or fractures;
- The Late Triassic limestones are probably genetically associated with deep marine bituminous platy limestones and marls, such as those in the Winto Beds of Buton and the 'Fogi Beds' (Ghegan Formation) of Buru and the Aitutu Formation of Timor. The syn-rift character of the Late Triassic sedimentary environments in Seram and other areas of eastern Indonesia should place potential source and reservoir successions in close juxtaposition.

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