The geology of Timor-Leste: a review

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Abstract: This article provides a general overview of the geology of Timor-Leste and history of the geological research in the country. Timor-Leste is located in Southeast Asia, approximately 700 km north of the northern Australian coast. The Island of Timor is part of the Outer Non-Volcanic Banda Arc that was formed from the collision between the Volcanic Banda Arc and the Australian Continental Crust, which occurred in Late Miocene. Consequently, the Island of Timor has an extremely complex geological setting, which has attracting many attentions from various experts worldwide since the early of 20th century. Generally, the history of geological research in Timor-Leste can be divided into three major phases: i) Period before 1975 (during Portuguese Colonization); ii) Period between 1975 - 1999 (Indonesian occupation); and iii) Period of 1999 - Recent (Post-Independence). In terms of tectonostratigraphy, the Island of Timor can be grouped into three distinct units: i) Allochthon/Banda Terrane (pre-collision Banda Forearc/Asian affinity); ii) Para-autochthones (Gondwana Megasequence and Australian Margin Megasequence); and iii) Autochthon (Syn-Orogenic Megasequence).

Keywords: Australian Margin Megasequence, Banda Forearc, Gondwana Megasequence, Geological research History, Tectonostratigraphy, Timor-Leste.

Resumo: *Este artigo fornece uma visão geral da geologia de Timor-Leste e da história da investigação geológica no país. Timor-Leste está localizado no Sudeste Asiático, aproximadamente 700 km a norte da costa setentrional da Austrália. A Ilha de Timor faz parte do Arco Externo Não Vulcânico de Banda que se formou a partir da colisão entre o Arco de Banda Vulcânico e a Crosta Continental Australiana, ocorrida no Miocénico Superior. Esta condição faz com que a Ilha de Timor tenha um cenário geológico extremamente complexo, que tem atraído muitas atenções de vários especialistas em todo o mundo, desde o início do século XX. Geralmente, a história da investigação geológica em Timor-Leste pode ser dividida em três períodos principais: i) Período antes de 1975 (durante a colonização portuguesa); ii) Período entre 1975 - 1999 (ocupação indonésia); e iii) Período de 1999 - Recente (Pós-Independência). Em termos tectonostratigráficos, a Ilha de Timor pode ser agrupada em três unidades distintas: i) Alóctone/Terreno de Banda (pré-colisão do Ante-arco de Banda/afinidade asiática); ii) Para-autóctones (Megasequência do Gondwanica e Megasequência da Margem Australiana); e iii) Autóctone (Megasequência sinorogénica).*

Palavras-chave: *Megasequência da Margem Australiana, Ante-arco de Banda, Megasequência do Gondwanica, História das pesquisas geológicas, Tectonostratigrafia, Timor-Leste.*

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Introduction

Timor-Leste (East Timor) occupies the eastern half of the island of Timor, located in Southeast Asia, approximately 700 km north of the northern Australian coast. Besides de mainland territory, it consists of Oecusse enclave and two small islands: Ataúro and Jaco.

The island of Timor is part of the Outer Non-Volcanic Banda Arc that is formed on the collision zone between the Volcanic Banda Arc and Australian Continental Crust (Carter et al., 1976; Barber et al., 1977; Audley-Charles, 2004). Banda Arc is a horse-shoe-shaped island arc, which forms 180-degree curve situated in Eastern Indonesia (Figure *1* 1), between three major tectonic plates - India-Australia, Eurasia, and Pacific (Hamilton, 1979; Vroon, 1992; Honthaas et al., 1998; Spakman & Hall, 2010). It consists of inner volcanic arc and outer non-volcanic arc settings. The inner volcanic arc consists of a volcanic island chain that has been active since the Late Miocene (Abbott & Chamalaun, 1981). The volcanic island arc can be divided into three parts; a southern inactive sector (Alor, Wetar, and Romang islands) related with the Sunda arc, a central active sector, and an inactive sector at the northern end (Vroon, 1992). The outer arc is composed of non-volcanic islands, including Timor as the largest island, Tanimbar, Seram and Buru (Hamilton, 1979; Vroon, 1992).

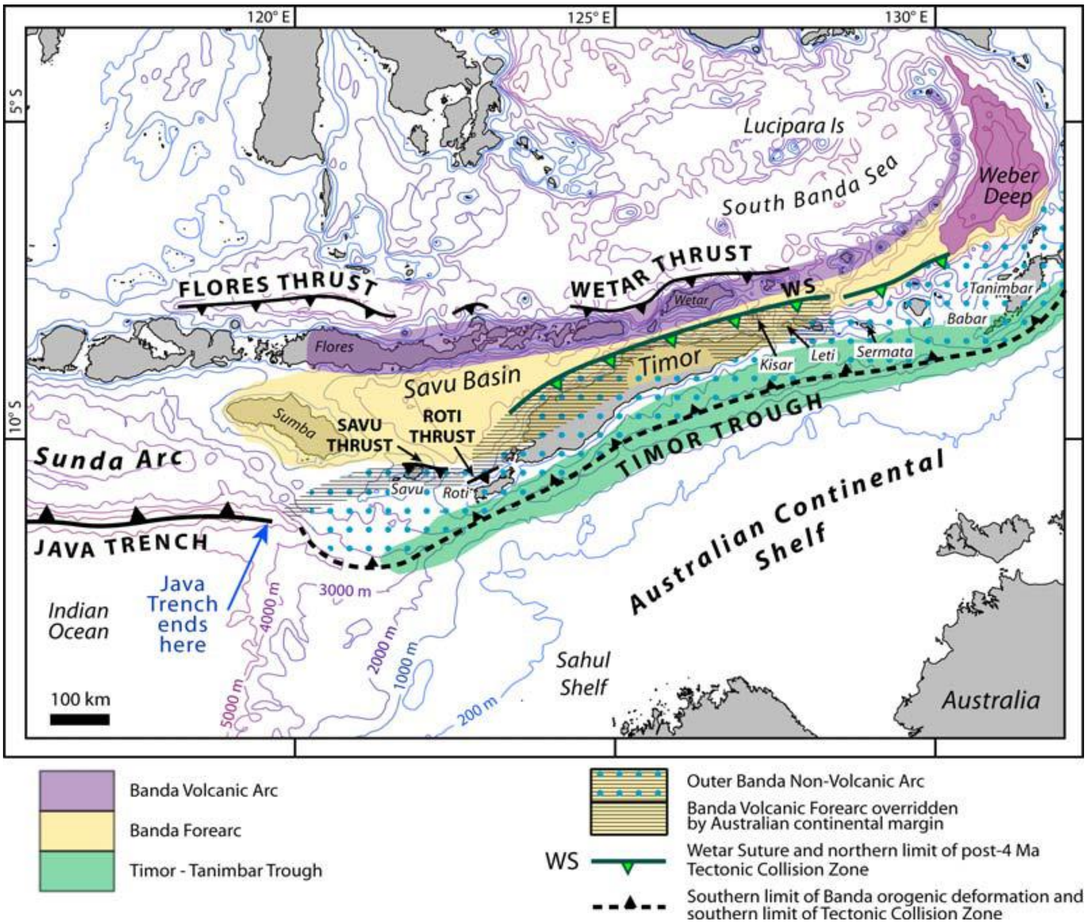

Figure 1 - Location of the Banda arc system [Source: adapted from Audley-Charles, 2011].

The origin and tectonic evolution of the Banda arc system has been the subject of much debate. However, it is widely accepted that Banda arc is the product of collision between a volcanic arc and the Australian continental margin (Spakman & Hall, 2010). According to Spakman and Hall (2010) and Hall

(2012), the Banda arc resulted from the collision between the southern margin of Sundaland with the Sula Spur, Indo-Australian continental promontory. This collision caused the Indo-Australian oceanic crust to tear apart and resulting slab roll back with south and eastward migration of the proto-Banda Arc into Banda embayment.

The arc-continent collision culminated at approximately 4 Ma. It was centered on the island of Timor and is recorded in the geology of the island via the complex intercalation of autochthonous sedimentary rocks derived from the northern margin of the Indo-Australian plate, and allochthonous rocks derived from the pre-collision Banda Arc (Abbott & Chamalaun, 1981; Audley-Charles, 2004, 2011 in Boger et al., 2017).

History of the geological research in Timor-Leste

The complexity of Timor geology has attracted many attentions from various experts worldwide since the early of 20th century. Therefore, the history of geological research will be divided into three major time intervals, here designated as the Period before 1975, the Period between 1975-1999 and the Period 1999-Recent.

Period before 1975

During this period there were several researchers that carried out reconnaissance studies in Portuguese Timor such as Hirschi (1907), Weber (field survey in 1910-1911), Kutassy (1930), Wittouck (1938), Bemmelen (1949) and Wanner (1956). More significant studies were carried out by Grunau, in 1953 and also by Gageonnet and Lemoine, in 1958. Grunau (1953) divided Timor into two tectonic units: autochthonous or pseudo-autochthonous and an alpine style overthrust/imbricated sheet. This study produces the very first reconnaissance geological map of Portuguese Timor that covers almost the whole part of mainland and the southern part of Ataúro Island. The Oecusse enclave was not included in this map.

Later in 1957, Gageonnet and Lemoine developed the work of Grunau and Wanner and produced a more detailed report, discussing the stratigraphy of the autochthon in Portuguese Timor, as well as the geological map of Portuguese Timor on a scale of 1:500,000, which includes the Oecusse enclave. This author applied the same tectonostratigraphic scheme proposed by Grunau (1953), with some additions. According to his research, the Portuguese Timor would be divided into three tectonic units, namely the autochthone unit, the thrust complex unit, and the neo-autochthone unit, which was not identified by Grunau in his previous work. From 1962 to 1968, the *Missão de Estudos Agronómicos do Ultramar* conducted regional reconnaissance mapping throughout the entire region of Timor-Leste in order to study the soil type and its agronomical characteristics. This was the first work related with the reconnaissance geological map covering the whole territory of Timor Portuguese region, including Oecusse enclave and Atauro Island (Leme & Coelho 1962; Leme, 1968).

At the same time, the British Geologist M. G. Audley-Charles, who has worked for Timor Oil Company, also published several publications from 1965-1967. In 1968, Audley-Charles published a reconnaissance geological map of Portuguese Timor on a scale of 1:250,000, together with the detailed description of each formation (Fm). According to this author, Timor is divided into two main tectonostratigraphic units, the autochthonous and the allochthonous one. Twenty-four formations (Fms) were identified, ranging from pre-Permian to Recent (Audley-Charles, 1968).

Period between 1975-1999

During Indonesian occupation from 1975 to 1999, the access to Timor were very limited. Only several authors were allowed to conduct their research in the area during 1975 until late 1980s. However, during this period, several authors managed to publish their work based on the data obtained before 1975. This was the case of Grady, Berry, Chamalaun, Abbot, Audley-Charles, and Barber, who published numerous papers related with the geology of Timor-Leste. By 1981, Berry published a new insight to the deformation and metamorphism of the Aileu Fm in Timor-Leste (Berry, 1979; Berry & Grady, 1981). This work was part of his PhD thesis at the Flinders University of South Australia. Alex E. Grady did an investigation on tectonic of Timor through Paleozoic and Mesozoic stratigraphy of the region and its structural relationship (Grady, 1975; Grady & Berry, 1977). Abbott and Chamalaun (1981) provided a detailed comprehension about the Banda Arc volcanic through the study of geochronology and identified volcanic extrusive rocks in Atauro and Oecusse.

From late 1980s until 1999 Timor was more accessible for research. Ron Harris made substantial contributions to the geology of Timor since 1989. Numerous papers were published from his research and provided a significant contribution for the understanding of the geological setting of Timor. He dealt mostly with the tectonic setting of Timor, arc-continent collision in the Banda arc, and Timor's ophiolite (Harris & Audley-Charles, 1987; Harris, 1991, 1992, 2006; Harris et al., 1998, 2000; Harris & Long, 2000).

During this period, a regional geological mapping was also carried out by the Indonesian Geological Research and Development Centre, which resulted in the publication of three quadrangles: Baucau (1994), Dili (1995) and Kupang-Atambua sheets (1996), on the scale of 1:250,000 (Bachri & Situmorang, 1994; Partoyo et al., 1995; Suwitodirjo & Tjokrosapoetro, 1996). During the 1990s, Hunter (1993) and Reed et al. (1996) were also able to work in Timor-Leste.

Period 1999 - Recent (post - independence time)

After the Indonesia occupation terminated in late 1999, Timor-Leste became much more accessible to geological research. The studies of Timor geology have been done in various areas. Haig & Keep and their colleagues from University of Western Australia conducted numerous fieldworks resulting in publication of several papers dealing with tectonics and biostratigraphy (McCartain et al., 2006; Haig & McCartain, 2007; Haig et al., 2007, 2008). Their immense works has greatly contributed in understanding the stratigraphic succession of Timor and their tectonic affinities.

Since 2004, a group from University of Melbourne carried out fieldwork in Timor-Leste resulting two PhD theses (Ely, 2009; Duffy, 2012) and several papers (Ely et al., 2010, 2014; Duffy et al., 2013, 2017; Boger et al., 2017). This group also produced the systematic geological maps of Laclo Quadrangle, Dili Quadrangle and Ataúro Quadrangle on the scale of 1:50 000.

Tim Charlton also did an extensive study of Timor geology since early 2000s. He conducted numerous fieldworks and produced many important papers regarding the geology of Timor Island. He dealt mostly with the stratigraphic and structural evolution of Timor, with emphasis on its tectonics, paleontology, and petroleum prospectivity (Charlton, 1989, 2000, 2001, 2002a, 2002b; Charlton et al., 1991, 2002, 2009; Charlton & Wall, 1994).

In 2010, a joint cooperation between the *Secretaria de Estado dos Recursos Naturais* (SERN) and the Polytechnique Geology and Mine (AGP) Indonesia, did a systematic geological mapping with scale 1:12 500 in Covalima Municipality. In 2011, a joint cooperation between the *Secretaria de Estado dos Recursos Naturais (*SERN) and the Korean Institute of Geosciences and Mineral Resources (KIGAM) conducted a geological mapping and produced a detailed geology map of Fohorem quadrangle, with the scale 1:25 000. *Instituto do Petróleo e Geologia (IPG)*, a state-owned geological institution also carried out several geological investigations in Hilimanu and Dili areas, respectively in the years of 2012 and 2013.

Stratigraphy of the Timor Island

As mentioned earlier, geology of the island of Timor is complex and has been the subject of much debate until now. Therefore, this part will present the summary of geological setting of Timor based on several researchers.

Based on tectono-stratigraphy perspective, the Island of Timor consists of three major units named Allochthon, Para-autochthon, and Autochthon (Audley-Charles, 1968, 1986, 2011; Carter et al., 1976; Barber et al., 1977; Barber, 1981; Charlton et al., 1991) (Fig. 2):

i) Allochthon consists of successions originated from pre-collision Banda forearc. The unit includes Mutis and Lolotoi Complex, Palelo Group, Same Fm, Barique Fm, Noil Toko Fm, Cablac Fm, Manamas Fm (Oecusse Volcanic), Miomaffu Tuff, Haulasi Fm, Dartollu Limestone, Metan and Aileu Fms (Charlton et al., 1991; Audley-Charles, 2011);

ii) Para-autochthon is the unit with the largest spread and is composed of materials similar to those from the Australia continental margin that thrusts back onto Australia (Barber, 1977 in Charlton et al., 1991). It is the bedrock of Timor and is characterized by the Atahoc Fm, Maubisse Fm, Cribas Fm, Niof Fm, Babulu Fm, Aitutu Fm, Wailuli Fm, Oebat Fm, Nakfunu Fm and Ofu Fm (Audley-Charles, 2011);

iii) Autochthon consists of raised coral reefs, Viqueque turbidite/Viqueque Fm/Noele Fm (Kenyon, 1974) and Batuputih Fm (Audley-Charles, 1986, 2011).

In addition, Harris et al. (1998) grouped the stratigraphy of Timor into five distinct lithotectonic units:

i) The Banda Terrane of Asian affinity, which is composed of fragmented basement blocks derived from the leading edge of the Banda forearc upper plate;

ii) The Gondwana sequence; and,

iii) The Kolbano sequence that together form the sedimentary cover of the Australian Continental Margin;

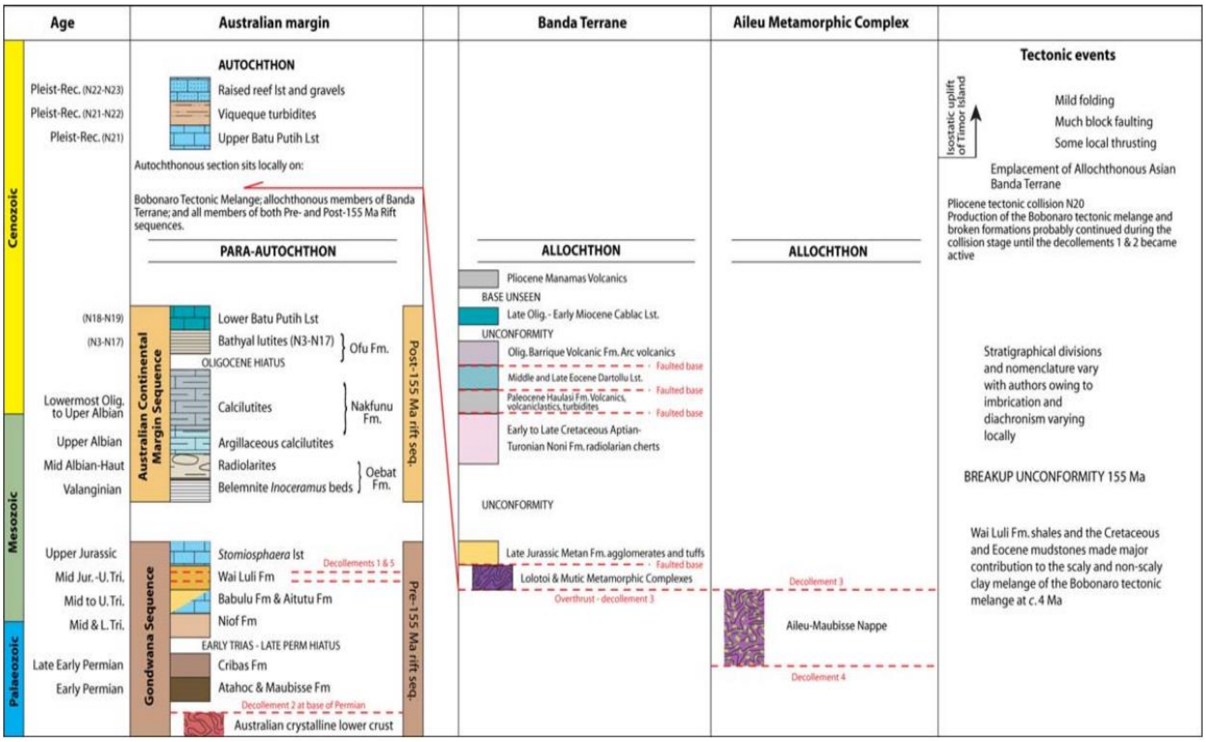

Figure 2 - Summary of Timor autochthonous, para-autochthonous and allochthonous stratigraphy [Source: adapted from Audley-Charles, 2011].

iv) The Bobonaro mélange, which is dominantly composed of clay from Gondwana and Kolbano sequences and marks the tectonic boundary between these two units;

v) The Synorogenic sedimentary sequence, which lies unconformably over all of the other lithotectonic units and are locally incorporated into the mélange (Fig. 3).

Haig and McCartain (2007) simplified Harris's scheme, divide the tectono-stratigraphy of Timor into a set of four units (Figure 4):

i) The Gondwana Megasequence composed by formations ranging from Permian to Middle Jurassic, and deposited in an intracratonic setting, after the continental breakup at about 155 Ma (Haig & McCartain, 2007);

ii) Australian Margin Megasequence: composed of shelf facies from the late Jurassic that are overlain by deep-sea pelagic deposits, until the late Miocene (Haig & McCartain, 2007). This revealed that the subsidence had occurred in the early Cretaceous period (Keep & Haig, 2010);

iii) Banda Terrane: composed of rock Fms from Jurassic to Early Miocene. It includes the Lolotoi-Mutis Metamorphic complex, associated with high degree metamorphism such as peridotite, siliciclastic sediments from Cretaceous-Eocene belonging to Palelo Group, shallow marine limestone and outer neritic mudstone of Eocene - Upper Oligocene and the Late Miocene (Keep et al., 2009);

iv) Synorogenic Megasequence, composed of rock Fms from Late Miocene to Pleistocene.

The collision process originated the Synorogenic Megasequence mélange through the diapirism process, derived from Jurassic and Triassic (Barber et al., 1986; Harris et al., 1998) and through the gravity sliding process (Audley-Charles 1965, 1968; Carter et al., 1976).

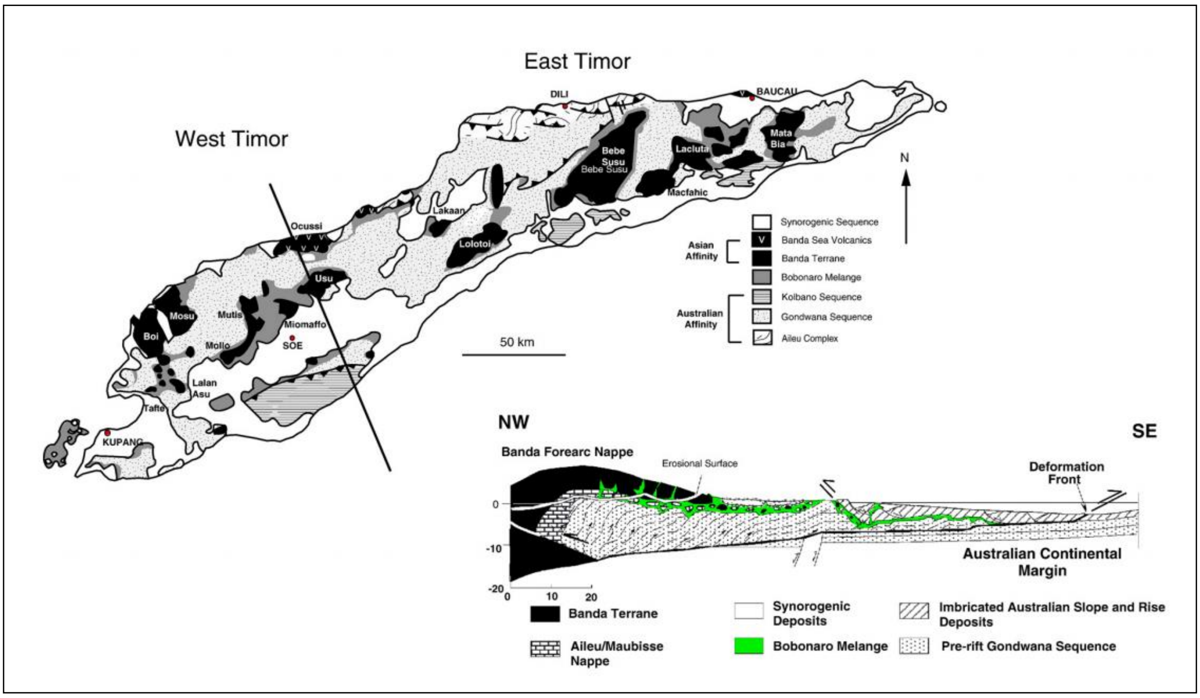

Figure 3 - Lithotectonic units of Timor [Source: adapted from Harris, 2006].

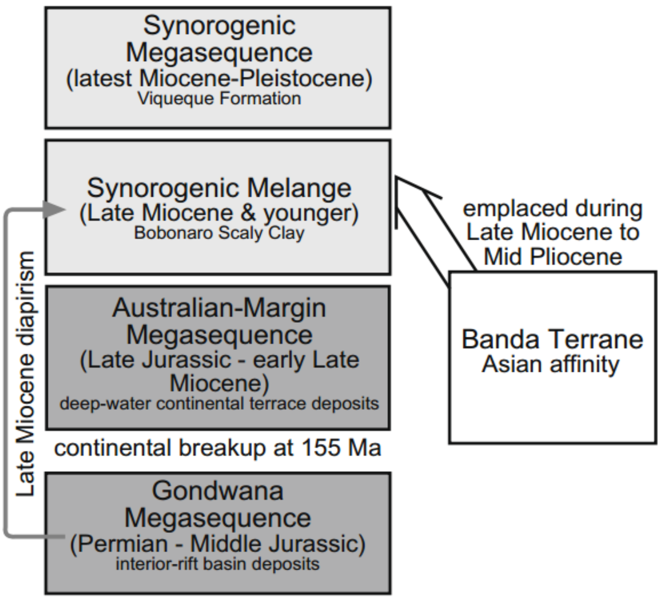

Figure 4 - Tectonostratigraphic divisions of Megasequence and Terrane of Timor. The dark-gray boxes are the para-autochthon, and the light-gray boxes are the autochthon and allochthon [Source: Haig et al., 2007 modified in Keep et al., 2009].

Tectonic setting of Timor Island

The Australian continental crust moves northward relative to the Southeast Asian plate with velocity 70 to 80 km/Ma (Minster & Jordan, 1978; Daly et al., 1987; DeMets et al., 1990; Smith et al., 1990). The subduction process occurred 12 - 3.5 million years ago, and was followed by the continental margin and Banda arc collision approximately 3.5 - 2 million years ago (Audley-Charles, 2004). Haig & McCartain

(2007) proposed a different timing of collision; they believed that it occurred in Late Miocene, prior to time proposed by Audley-Charles (Keep et al., 2009).

The uplifting of Timor began approximately 3.35 to 4.2 million years ago (Haig & McCartain, 2007). The emergence of Timor has a lot to do with Banda Arc, with its structure of double island, horseshoe-shaped arc located in the meeting point of the three plates: Indo-Australian, Pacific, and Eurasia (Hamilton, 1979). The Banda Arc is often called Banda Suture because it lies in the meeting-point zone (Hall & Wilson, 2000).

Regional and geological structures developed in Timor are the result of tectonic processes that have gone through a long period. The complex geology of Timor is a result of the collision between the Northwest Australian Continent and Banda Arc. It has been predicted that the collision occurred in the Late Miocene according to Haig & McCartain (2007) and continues until the present time. The collision process has caused folding and faulting of the pre-Pleistocene rocks. The tectonic occurrences taking place until today are characterized by active seismicity, mud-diapirs intrusion, and the uplift and subsidence of Timor Island. The main structures found, among others, are folds, thrust faults and left lateral strike-slip faults.

According to Charlton et al. (2001), fold structures emerge as the Aitutu Anticline with Southwest - Northeast direction and Cribas Anticline with West - East orientation. The three main faults of Timor are Semau Fault, Menamena Fault, and Belu Fault (Fig. 5). They are left lateral-strike slip faults facing Northeast - Southwest direction. In addition, there is also the Tunsip-Toko Fault, which is also a left lateral-strike slip fault but has Northwest - Southeast orientation (Fig. 5).

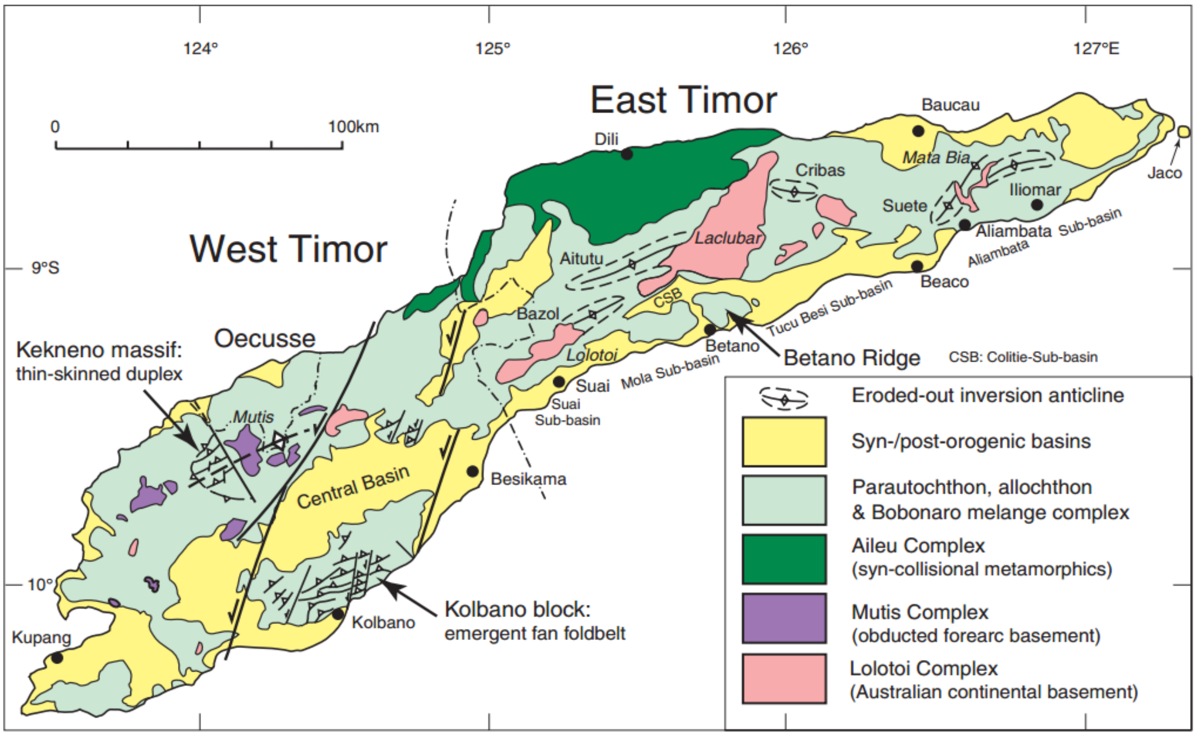

Figure 5 – Geological and structural map of Timor Island, showing the main faults of the territory [Source: adapted from Charlton, 2002b].

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