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West Timor: a key for the Eastern Indonesian geodynamic evolution

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Abstract . - Timor Island was at time considered as an example of “accretionary prism” linked to the collision between the Australian block and the Banda arc. However, its geological evolution is more complex. Five main superimposed structural units are distinguished in West Timor. The ~~today~~ structure is the result of three main tectonic events that occurred during the Late Oligocene, Late Early Pliocene and Late Pliocene-Early Pleistocene times, respectively. Our field investigations in the 1990 to 2000 decade completed with geochemical analyses and K-Ar datings (Jurassic and Miocene ages) of magmatism allow to precise the geodynamic evolution of Timor that can be summarized as follows: a first block was detached from Gondwana (unit 2) and drifted to the Asiatic margin until the Late Oligocene when it collided with the Asiatic active margin (unit 3). Then, the new block formed by ~~both~~ 2 and 3 ~~units~~ drifted to the South during the Miocene and the Early Pliocene until it collided with the Australian margin (ASM), by the Late Early Pliocene. Then, the Australian and Timor blocks moved together towards the North-North East during the Late Pliocene until they collided with the Banda fore-arc (unit 4). Later on (Pleistocene), Timor Island was capped by the “Autochthon” (unit 5) and then on (Quaternary?) by the Banda volcanic arc northward thrusted over the South Banda basin. Taking in consideration its close relationships with both the Australian plate and the Eurasian one~~.~~ Timor may be considered as a key area for building this geodynamical scenario of Indonesia.

Timor occidental : une clé de l’évolution géodynamique de l’Est Indonésien

L’ile de Timor ~~qui~~ a souvent été considérée comme un « prisme d’accrétion» lié à la collision entre l’Australie et le bloc de Banda. Mais son évolution est bien plus complexe. Nous avons distingué cinq unités structurales superposées dans Timor Ouest. Sa structure actuelle résulte de trois événements tectoniques principaux intervenus respectivement : à la fin de l’Oligocène, à la fin du Pliocène inférieur et à la fin du Pliocène ou au début du Pléistocène. Nos travaux de terrain effectués entre 1990 et 2000 complétés par des analyses géochimiques et des datations Ar/K sur différentes roches magmatiques (du Jurassique et du Miocène) nous ont permis de préciser l’évolution géodynamique de Timor.

Celle-ci peut être résumée ainsi : un premier bloc (Unité 2) s’est détaché du Gondwana au Jurassique et a dérivé vers le Nord-Ouest pour entrer en collision avec la marge active asiatique (unité 3), vers la fin de l’Oligocène. Ensuite, le bloc issu de la réunion des unités 2 et 3 a dérivé vers le Sud, du Miocène au Pliocène inférieur, grâce à l’ouverture des bassins de Banda (Nord puis Sud) et ce jusqu'à ce qu’il entre en collision avec la marge Nord du bloc australien (ASM), vers le fin du Pliocène inferieur. Puis l’ensemble formé par l’Australie et Timor se déplace en direction Nord-Nord Est durant le Pliocène supérieur jusqu'à ce qu’il rencontre le ~~fore-arc~~ de Banda (unité 4). Au Pléistocène, l’ile de Timor est partiellement recouverte par de dépôts de bassins (unité 5 autochtone). Enfin au Quaternaire, l’ensemble est charrié sur le bassin de Banda Sud qui commence à « subducter » sous Timor.

Ainsi l’ile de Timor qui contient des terrains appartenant à la fois au Gondwana et au bloc asiatique peut être considérée comme une des clefs géologique pour la reconstitution géodynamique de l’Indonésie orientale.

Mots-clés. **-**Indonésie, Timor, Sulawesi, Sumba, Nappes, Charriages, Collisions, Eocène, Oligocène et Pliocène, évènements tectoniques au Néogène, Reconstructions paléogéographiques.

INTRODUCTION

Timor Island is located in the southern part of East Indonesia [Fig. 1a] south of the Banda volcanic arc. This island is politically separated in two parts: the western part belong~~ing~~ to the Indonesian country and the eastern part ~~which~~ has been detached from the Portuguese colonial domain since 1976. Thus, these two parts were always geologically investigated separately. The study area, which corresponds to the current Indonesian province, extends over 170 km from Kupang, to the West, to Atambua, to the East, and 100 km from Wini, to the North, to Kolbano, to the South.

At first, the very complicated structure pointed out the island as a huge "tectonic melange" [Hamilton 1979]. But the Asiatic origin of some “terranes” [Villeneuve et al. 2004, Harris 2006]~~,~~ does not favour a simple “accretionary prism” between the Australian block and the Banda volcanic arc. Since the beginning of the 20th century, an “overthrust structure” has been evidenced by Dutch geologists and three different terranes have been distinguished: the “Allochthon”, the “Para-autochthon” and the “Autochthon” units.

Our geological investigations have been carried out in the frame of “French Indonesian programs” including studies both on land and sea basins over the eastern part of Indonesia including Kalimantan, Sulawesi and the “Banda” basins and islands. These “cooperative programs” lasted ten years, from 1990 to 2000 and bring a lot of new data recently summarized by Villeneuve et al. [2010], but the main results concerning the Western Timor area have not been published yet excepted the stratigraphic data [Harsolumakso et al. 1995, Villeneuve et al. 2005] and the origin of units [Villeneuve et al. 2004]. The structural framework and its geodynamical interpretation supported by new data, are the main topic of the present paper.

PREVIOUS WORKS

The first investigations in West Timor were conducted by Wanner [1913], Molengraaff [1915], Tappenbeck [1939] and De Waard [1955] which confirmed the "thin skin thrust structure" of "metamorphic massifs" over the sedimentary units. On the contrary, Fitch and Hamilton [1974] proposed a "tectonic mélange structure". On the other hand, Carter et al. [1976a and b] and Barber et al. [1977] favoured a “low angle thrust fault” on the Australian margin. Indonesian geologists from the GRDC [Research and Development Centre, Bandung] or from the ITB [Institute Technology Bandung] ~~work~~ there from 1974 to 1986 under control of Rosidi et al. [1979]. Many graduate students from the London University choose West Timor for their theses: Earle [1981], Charlton [1987], Bird and Cook [1991], Harris [1991] and Barkham [1991]. Australian geologists from the Flinders University also devoted their attention to the geology of West Timor as Chamalaun

[1977a], Hailé et al. [1979]. Harris [1991] provided a new tectonic model for the “overthrust” and Sawyer et al. [1993] published the “Amoseas Indonesia Inc.” geological researches. Other investigations were performed during the 1982 Snellius II Dutch-Indonesian program [Sopaheluwakan, 1990, De Smet et al. 1990 and Van Marle 1991] by the Santa Cruz University program and by the French-Indonesian cooperative program [Harsolumakso 1993, Villeneuve et al. 1999]. Since this time only Martini et al. [2000], Harris and Long [2000], Villeneuve et al. [2004 and 2005] and, Harris [2006] published some papers on West Timor.

A lot of papers dedicated to the geology of East Timor and its adjacent areas highlighted the Banda outer arc geodynamic model, such as: Gageonnet et Lemoine [1958], Lemoine [1959], Audley-Charles [1968], Carter et al. [1976b], Charlton [2002], Kaneko et al. [2007], Ishikawa et al. [2007], Haig et al. [2008], Standley and Harris [2009], Charlton et al. [2009], Rosmawati and Harris [2009], Kadarusman et al. [2010], Keep and Haig [2010]. Despite some ~~consequent~~ stratigraphic results a large discussion arose concerning the pattern and the chronological setting of the nappes, the timing of tectonic events, the origin of the different units and the integration in a geodynamic model.

Three geodynamic models have been proposed: an "imbricated model" [Fitch and Hamilton, 1974; Hamilton, 1979], an “overthrust model” [Wanner 1913, Carter et al. 1976a, Barber 1979, Harris 1991] and a “rebound model” proposed by Chamalaun and Grady [1978] taking into account a lot of vertical faults.

Our investigations performed in the framework of the "Geobanda group", lead to propose a different scenario for the West Timor evolution.

STRUCTURAL FRAMEWORK

New geological data and six new dating on Timor island ~~allows us~~ to present a new structural sketch map and an original North-South synthetic cross-section.

Geological scheme (fig. 1)

The geological scheme of West Timor (fig. 1b) modified from Rosidi et al. [1979] shows the main geological units together with the main thrusts. Three major geological structures have been distinguished:

1 The northern Banda terranes (“Manamas and Atapupu complex”) located in the northern part of the island and corresponding to the “Banda” formations, that were recently (Late Pliocene-Pleistocene) thrusted over the Island (T5, T6 and T7).

2 The “Timor belt” that comprises several sedimentary and metamorphic complexes ranging from the Permian to the Mid-Pliocene is strongly deformed and largely thrusted (T1, T2, T3, T4) at several periods. The geological scheme (fig. 1b) points out two sets of thrusts: the “Oligo-Miocene” thrusts (T3 and T4) and the “Plio-Pleistocene” thrust (T2). The East-West thrust (T2) ~~affects~~ both the Miocene and the Early Pliocene (possibly the Late Pliocene?) sediments, together with older units and thrusts (T3 and T4). T3 and T4 thrusts, cut by the Plio-Pleistocene thrusts (T5, T6 and T7), are older and likely of Late Eocene or Early Oligocene period.

3 The “Central basin” that covers a large part of the area is composed by ~~non~~ deformed ~~or locally slightly deformed~~ sediments deposited since the Late Miocene. Several unconformities have been distinguished between the deformed and the undeformed sediments.

North-South elongated fault, the “Beli fault”, ~~is limiting~~ the East and West Timor countries. Owing the geological map a sinistral strike-slip motion is suspected [Snyder et al. 1996].

Classically three main “terranes” have been distinguished in the Timor Island: the Autochthon, the “Allochthon” and the “Para-autochthon”. However, each “terranes” includes many other subdivisions named “units”. At least six lithostructural units, including nine groups and several formations, have been evidenced (see after).

The interpreted geological cross section (fig. 2)

The schematic cross section between Wini [to the North] and Kolbano [to the South] points out the main complexes, groups, formations and thrusts.

From North to South, we successively recognize: the “Manamas complex” thrusted over the “Mutis and Boi metamorphic complex” and the “Palelo” formations themselves thrusted over the “Maubisse and Kekneno–Tumu groups”. All these units are supposed to rest on an old metamorphic basement that does not presently crop out. To the South, the Maubisse and Kekneno-Tumu groups were thrusted over the Kolbano group. North of Kolbano (fig. 2c), a part of the Kekneno-Tumu group is thrusted over the Kolbano group and to the North, several gabbro-dioritic “plots” intruded the “allochthon” terranes.

In the Noil Toko (or Noetoko) river (fig. 2b), the “Noetoko” group of Lower to Middle-Miocene age is stressed between two metamorphic massifs: the “Miamoffo” and the “Booi” (Boie or Boii) massifs belonging to the “allochthon terranes”. Several post tectonic oolitic limestones klippen (Cablac limestones) set unconformably on top of the “allochthon terranes”.

Finally, outcropping between Niki-Niki and the Sabau River, the flat central basin (Autochthon unit) is limited by normal faults. This cross-section shows several “normal” faults likely related to the Timor trough and North Banda basin opening.

ADDITIONAL DATA

Geochronological data

Excepted five Neogene apatite fission tracks ages recorded from sedimentary rocks of the northern Kekneno inlier [Harris et al. 2000], only five radiometric data have been performed on West Timor previously (table 2). mainly on metamorphic rocks collected in the Booi and Mutis massifs.

According to Sopaheluwakan [1990] these results express an ophiolitic “obduction” or basement thrusting ages rather than the protolith ages.

K-Ar results which are listed in table 1 have been carried on six magmatic rocks collected:

in the volcanic complex in the Metan formation (sample BP 9);

in the Mutis massif (sample T 23);

south of Wini (sample T 109b from the Manamas basaltic complex and sample T 111from a gabbro-dioritic body, south of the volcanic formation of Oecusse);

and in the Atapupu ultrabasic complex (sample ATTP1 and sample ATTP2)

Finally, four groups of ages have been evidenced: during the Mesozoic (at 157 to 149 Ma and circa 118 Ma), in Late Eocene to Early Oligocene (37 to 32 Ma),in Middle to Late Miocene (14 to 10 Ma) and in Pleistocene (1.59 Ma).

Geochemical data

Geochemical analyses for major and trace elements by ICP except for Rb by AAS have been performed. One may note that all these magmatic rocks have a loss on ignition (wt. % LOI) varying between 1.6 % for the freshest ones (ATTP lavas) and up to 6 % for the most altered (T 23).

BP9: This basic lava (wt% SiO_2 at 56.2) is a normal CA andesite, which shows the typical negative niobium anomaly may be considered as the witness of an arc activity.

T 23: This basalt (wt% SiO_2 at 45.5) contains normative nepheline (13%) Its spidergram with a positive niobium anomaly may be interpreted as that of a “continental” alkaline basalt. These two “Jurassic” rocks show different affinities that can be related to probably two different geodynamical contexts.

T 109B: This basic lava (wt% SiO_2 at 52.0) contains normative quartz and hypersthene and is K_2O-poor (wt.% at 0.39). Its spider diagram shows a positive niobium anomaly.

T 111: This gabbro-diorite (wt% SiO_2 at 50.1) with normative quartz and hypersthene normative. is K_2O-poor (wt.% at 0.31). It shows a flat REE diagram and no niobium anomaly.

ATTP 2: This K_2O-poor (wt.% at 0.25) lava which is more differenciated (wt% SiO_2 at 57) than T 109 B or T 111 shows quite similar concentrations for trace elements.

ATTP 1: is a K-rich (wt.% at 3.88) CA basic lava (wt% SiO_2 at 53.3), rich both in strontium (1045 ppm) and baryum (1650 ppm), that can be classified among the shoshonitic lavas encounterd as in a arc or a back-arc framework.

Geochemical analyses indicate different geodynamical origins. Apart T23 most of them can be related to volcanic arc or back arc basins.

Metamorphic data

Most of the formations consist of sedimentary rocks and few of them were affected by metamorphism. Harris et al. 2000 applied the “vitrinite reflectance”, “Illite cristallinity, “conodont alteration” and “apatite fission track” to these sedimentary rocks. Most of them are in the diagenetic zone and do not exceed 100° in temperature that is consistent with the peak temperatures for the Gondwana sequences [100-150°]

So, only the allochthon massifs evidenced by Brouwer [1942] and Barber and Audley-Charles [1976] suffered a metamorphic event but only three of them: Booi, Miomaffo and Mutis were deeply investigated respectively by Earle [1981] and Sopahuluwakan [1990].

In the Booi massif: Earle [1980] reported a "basement" composed of pelitic and "mafic gneisses overlies by a dismembered "ophiolite" including peridotite and "metagabbros" stacked in reverse order. Barber and Audley-Charles [1976] reported a high proportion of pyrope in almandine garnets indicating a granulite facies.

In the Mutis and Miomaffo massifs main rocks are: metabasites and metatuffs (Amphibolitic to greenschist facies), metapelites (greenchist facies with staurolite and garnet zone), peridotite and granulite (or garnet-mica-staurolite –kyanite schists) with few gabbros. Bluechists are associated to these rocks. Due to numerous tectonic contacts, relationships between them are unknown. Sopaheluwakan [1990] considereded an inverted metamorphic zonation (albitic, chloritic, biotitic, garnet and staurolite zone) from the base to the top. Despite a lot of strong tectonic contacts, he concluded to a metamorphism generated by an obduction of peridotites (part of ophiolitic sheet) over metapelites or schists. Age of this "obduction" was around 37-32 Ma. But, the metamorphic age (118 Ma) recorded in gneisses of the Booi massif does not favoured the Sopaheluwakan [1990] interpretation. However, Barber and Audley-Charles [1976] favoured an Australian basement origin. They also talked of a possible "Sundaland" origin but previous hypotheses taking into account an Indian Ocean piece trapped in the Banda area prevented to consider a Sundaland origin.

Another high grade metamorphism was related to the emplacement of Atapupu complex by Helmers et al [1989]. After that, pelitic and mafic rocks located underneath the peridotite suffered a metamorphism to over 800°C at 6 to 7 Kbar. The lustrous slates in the Aileu massif (Maubisse group) in East Timor, dated by Berry and Mac Dougall [1986] between 8 and 5.5 Ma, are linked to the Atapupu peridotitic emplacement.

So there are, at least, three main metamorphic events: around 118 Ma in the Booi massif, around 37-32 Ma in the Mutis and Miomaffo massifs and around 8-5.5 Ma at the base of the Atapupu complex. The last two ones can be clearly associated to different "ophiolitic" obductions.

Paleomagnetical data.

Several paleomagnetic investigations have been carried out on Timor, by Wensink and Chamalaun.

Chamalaun [1977a] evidenced a paleoposition for the Permian Cribas formation [base of the Kekneno Tumu group] very consistent with the Permian Australian position. Then Chamalaun [1977b] found a similar paleopositon for the Permian part of the Maubisse group, which prevents the Audley-Charles hypothesis [1968] on the Sundaland origin for this group. Wensink et al. [1987] evidenced a paleopole located 1200km south of the present position for the Nakfunu formation [Lower Cretaceous part of the Kekneno-Tumu group]. That was also the location of the Northern Australian continent. Later on [Wensink and Hartosukohardjo, S., 1990] propose a paleoposition at 17° in the northern hemisphere for the Metan volcanics and finally an in situ paleoposition for the Late Miocene Manamas volcanics. In addition, this volcanic complex suffered a 40 to 60° counterclockwise rotation since the Late Miocene. Unfortunately they are the only paleomagnetic results known on West Timor.

THE MAIN LITHOSTRUCTURAL UNITS (fig. 3)

Most of the groups and formations mentioned above come from the literature. But there are a lot of non mentioned stratigraphic groups and formations bearing local names.

Accordingly, three main “terranes” have been distinguished, from North to South:

-The “Banda terranes” (BT) to the North including the Quaternary deposits (autochthonous deposits).

-The “Timor terranes” (TT) including all the others formations outcropping in Timor Island.

-The “Northern Australian terranes” (AT) also called Timor Gap (TG); never outcrop in the area are deduced from the geodynamic context. They belong to the current Australian margin which is currently “subducting” beneath the Timor Island and the Banda volcanic arc [Crostella, 1977]. The metamorphic basement of the Australian margin and its sedimentary cover are drawn in figure 3. The T1 thrust located on top of the Australian passive margin sedimentary cover can be considered as an equivalent of the “subducted” plane on top of the trench.

Five units (1 to 5) have been distinguished in the Banda and Timor “terranes”, each one including several groups and formations. A diagram (fig. 3) presents these main structural units with from the top to the base:

Unit 5 (Autochthon unit) is formed by 1500 m of marine and clastic sediments (the “Noele” group-G9**)** mainly deposited in the central basin (Soe basin) and along the coasts. It includes reefs limestones and Quaternary sediments.

Unit 4 (Sub-autochthon) which is separated from the unit 5 by the D4 structural unconformity, includes several groups, formations and complexes. Three “groups” have been distinguished:

The volcano sedimentary group (Viqueque group G8) including the “Viqueque formation” of Upper Pliocene age, which is locally deformed.

The northern volcanic and metamorphic group **(**Wini group G7), including the “Manamas basaltic complex” dated at 10.35 ± 2.20 Ma (basalt T109 B, table 1) (Upper Miocene) and the “Atapupu ultrabasic complex” dated at 14.10 ± 1.00 Ma (basalt AATP2 table 1) (Middle Miocene) and the “Aileu metamorphic complex” in East Timor. The latter includes material originated from the “Maubisse group” [Permian to Cretaceous deposits] but metamorphosed during the Lower to Middle Miocene [Berry and Grady, 1981]. The “contacts” between the different “complexes” belonging to the G7 group are tectonic (T6 and T7 thrusts).

The G6 group (“Batuputih group” includes the “Batuputih” formation consisting of white calcarenites, calcilutites and calcareous sandstones and the “Bobonaro” formation consisting of breccias and conglomerates that were deposited during the Upper Miocene to Lower Pliocene. This group is separated from the “Viqueque formation” by the D3 unconformity. The “Batuputih formation” is involved in the Middle Pliocene thrusts while the Manamas, Atapupu and Aileu complex were thrusted over Timor (T5) either during the Middle-Pliocene or at the end of the Pleistocene. The second hypothesis seems to be more valuable taking in consideration direct covering by the Quaternary group G9.

Unit 3 (Allochthon) is represented by two groups (G4 and G5) separated by the D1 angular unconformity.The Noetoko group **(**G5) is separated from the “Bobonaro breccias” and Batuputih calcilutites by the D2 unconformity. It includes the “Miamoffo” volcanic tuffs and the “Cablac” oolitic limestones. Barber [1979] included the “Cablac” limestones in the “Noetoko” sedimentary group (Lower to Middle Miocene). In fact, the “Cablac” name is properly inappropriate because it corresponds to “oolitic limestones” with different ages (i.e. Permian, Triassic or Lower Miocene) outcropping mainly in East Timor and firstly described by Gageonnet and Lemoine [1958]. Recently, Haig et al. [2008] ascribed the “Cablac” limestones from the “type area”, to the Upper Triassic or Lower Jurassic rocks. The G5 group is intruded by “dioritic” dykes (T111) displaying an Upper Miocene age (10.55 ± 1.60 Ma) (table 1).

The Palelo group (G4) includes several sedimentary and volcano-sedimentary formations as well as metamorphic complex. It is separated from the G5 by the D1 unconformity.

The sedimentary succession (i.e. Palelo, Haulasi and Noni formations) exhibits successively: Upper Cretaceous cherts, Paleocene to Eocene sandstones interbedded with Eocene lava-flows and Eocene Nummulitic limestones.

The volcanic complex (Metan formation) consists of basaltic lavas displaying a Late Jurassic age (BP9 dated at 149.7 ± 3.3 Ma, table 1).

The "metamorphic complex" well studied by Sopaheluwakan [1990] outcrops in the Mutis, Miamoffo and Booi massifs. The metamorphism is known as Middle Cretaceous [Earle, 1981] in the Booi massif, but basic rocks from the Mutis massif displays a Jurassic age (162 Ma) according to Harris [2006] and a basalt (T23) is dated at 157.4 ± 3.4 Ma (table 1). The main tectonic event (T4 thrusting) related to the "Mutis" massif "obduction" over the "Maubisse group" occurred at the end of the Eocene or during the Oligocene [Sopaheluwakan, 1990 and Villeneuve et al., 1999]. Harris [2006] delivers a lot of new ages which support an exhumation of these massifs, from 550 m (below surface) to the surface, between 36-28 Ma. This "allochthon" unit is sealed by the "Noetoko formation" belonging to the Batuputih group (G5).

Unit 2 (Para-allochthon) includes two groups (G3 and G2). The Maubisse group (G3) contains several sedimentary rocks (Permian and Triassic limestones, Jurassic and Cretaceous shales, radiolaritic and volcanic rocks). The Kekneno-Tumu group (G2**)** is characterized by Permian pelitic sandstones and Triassic shales associated with Cretaceous to Paleocene-Eocene radiolaritic rocks. G3 and G2 are separated by the T3 thrust.

Unit 1 (Para-autochthon) is represented by the Kolbano group which contains limestones, shales and calcilutites ranging from the Jurassic to the Lower Pliocene. It is tectonically overlain (T2 thrust) by the 2 and 3 units and parts of the 4 unit and sealed by the "Viqueque" group (G7)

Lithostratigraphic units (fig. 3) also reflect the geological evolution of Timor, and from the older to the younger one, successively: T4 (Oligocene), T2 (Late Pliocene) and T5 (Late Pleistocene) thrusts are displayed..

DISCUSSION and GEODYNAMIC EVOLUTION

Comparisons with adjacent areas (mainly Sulawesi) should be necessary to understand the origin of the different "terranes" that have built Timor Island.

Origin of Units

Apart the modern Australian margin and the unit 5 (Autochthon unit), other units were displaced with respect to the present position of Timor.

Unit 4 (Sub-autochthon)

The Viqueque group (G8) (Upper Pliocene) was deposited after the collision with the Kolbano group (G1, unit B). Taking into account a northward motion of the Australian continent, this deposition should occurred to the south of the Timor present position.

The northern volcanic and metamorphic group (G7) is related to the "Banda" terranes. The "Manamas basalts" T 109 B have been dated at 10.35 ± 2.20 Ma (table 1) and basalts from the "Atapupu ultramafic complex" display an whole rock age of 14.10 ± 1.00 Ma (table 1). Gabbro dioritic intrusions (T 111) dated at 10.55 ± 1.60 Ma (table 1) were piercing the Maubisse group (G3), thus indicating that a Late Miocene volcanic arc was operating there. Part of this volcanic arc was thrusted onto the Maubisse formations, at least after the "Viqueque formation" deposition (Upper Pliocene or Early Pleistocene?). Consequently, the "Manamas" basalts should be in a more northern position than presently but not so far from this latter, according to Wensink and Hartosukohardjo S. [1990]. Previous datings from Flinders University [Rosidi et al. 1979] and from Abbot and Chamalaun [1981] provide several ages between 6 and 4 Ma. These ages are consistent with a South Banda Neogene volcanic arc [Honthaas et al. 1998]. According to Berry and Grady [1981] similar formations in East Timor were thrusted on the mainland Timor around 5 to 4 Ma.

The 1.59 ± 0.07 Ma age for the ATT P1 basaltic dykes (table 1) postdate the thrusting.

The Batuputih group (G6) capping the Noetoko group, is involved in the tectonic event which affected the Kolbano group. Its location at the time of deposition is unknown.

Unit 3 (Allochthon unit).

The G5 group (Miocene), deposited before the Kolbano group deformation, is related to the southern Banda volcanic arcs and consequently should be in a northern position with respect to the Miocene Timor mainland.

The origin of the Palelo group (G4) has long been discussed, and specially its metamorphic complex. Most of the authors supposed a local origin [Tappenbeck 1939, Barber 1979] or a sub-local origin [Sopaheluwakan 1990]. Only Haile et al. [1979] pointed out a possible relationship between the Mesozoic "cherts" of Timor and Sulawesi. However, owing to a lack of information concerning the Banda Sea origin [first considered as an Indian Oceanic fragment by Lapouille et al. 1985] they were unable to link Sulawesi and Timor islands. Then, new dating [Réhault et al. 1994, Honthaas et al. 1998] on the Banda Sea floors [Upper Miocene to Pleistocene] allows us to propose a direct connection between West Sulawesi and Timor before the Banda seas opening [Villeneuve et al. 2004, 2005, 2010]. This hypothesis has then been enhanced by Harris [2006] and Standley and Harris [2009]. Therefore, taking into account:

1- the Neogene occurrence of Banda Sea basins [North and South Banda basins],

2- the similarities between the Western Sulawesi volcanic rocks and those of the Palelo group [G4], we again support an Asiatic origin for the G4 rocks.

The similarities to what we refer are:

-The "Booi" metamorphic complex [Earle 1981, Brown and Earle 1983] and the West Sulawesi metamorphic substratum [Sukamto 1975] which display comparable metamorphic ages, at respectively 118 Ma and 110 Ma

-The "Metan" volcanic formation in Timor (table 1) and the Lamassi-Bajo basaltic complex in Sulawesi [Priadi 1993] display a Jurassic age.

-The "Palelo" formation presents some close similarities with the Mesozoic succession of western Sulawesi.

-Finally, the Tertiary nummulitic limestones from the Timor "allochthon unit" [unit D] exhibits a terrestrial mammal [*Anthrocothere*] of Asiatic origin [Ducrocq 1996].

All these similarities enhance an Asiatic origin [close to Sulawesi] for the Timor unit 3 ["Allochthon"].

Unit 2 (Para-allochthon unit)

The origin of Maubisse G3 and Kekneno-Tumu G2 groups is more discussed. The G2 group presents a similar stratigraphic succession than the Australian margin, from the Permian to the Jurassic time. But, the post Jurassic stratigraphic successions of the two areas differ from the Cretaceous to the Eocene [Harsolumakso et al. 1995]. However, Chamalaun [1977a and 1977b] indicates palaeomagnetic accordance between Timor and the northern Australian margin [including the G2 and G3 groups] by the Permian and Triassic times. Moreover, a palaeontological [pollens] and sedimentological study of the Upper Triassic [G2 group] in Timor reveals its high latitudinal position at the depositional time [Martini et al. 2000]. This high latitude is consistent with the position of the Australian plate during the Upper Triassic time. It is important to be notice that Wensink [1987] pointed out the deposition of Early Cretaceous sediments in G2 in an area situated at 1200 km to the North of the Early Cretaceous Northern Australian margin palaeoposition. On the contrary, the palaeoposition of the Permian and Triassic rocks of the Maubisse formation was discussed. Audley-Charles [1968] supposed a more equatorial palaeoposition, according to the microfossils palaeoclimatic records, but the Chamalaun [1977b] palaeomagnetic data confirmed by Wensinck [1988] indicate high latitude consistent with the Triassic palaeoposition of the North Australian margin. Taking into account the lack of oceanic remnants between the G2 and the G3 groups, we favour the Wensink's conclusion and propose a common origin and evolution for the two groups. On the other hand, the trusting of this U 3 unit, of Asiatic origin, let us to suppose a strong connection between Timor Island and the Asian active margin at the thrusting time from Late Eocene to Early Miocene.

In conclusion, this part of Timor was first detached from the Australian margin (by the Jurassic time) and then connected to the Asiatic margin at least by the Early Neogene.

Unit 1 (Para-autochthon) (e.g. the Kolbano group G1) is considered as a part of the current Australian margin by Crostella [1977] even if the Australian margin sediments have likely incorporated the southern Timor Neogene accretionary prism. Anyway, it should not be far from the present position of Timor Island by the Mid-Pliocene time [Villeneuve et al. 1999].

Main stages of the evolution of West Timor

Taking into account the structure, the timing of events and the supposed origin of the units we confidently propose a new scenario for the West Timor evolution (fig. 4).

From the Permian to the Eocene (fig. 4a), the northern Gondwana margin (A1) splitted in several blocks by the Jurassic time. The Timor block, including the Kekneno-Tumu deposits (G2 group), the Maubisse sediments (G3 group), and the Triassic to Jurassic basaltic lavas drifted away from the Australian margin until it collided with the Asiatic margin (Unit 3 = Allochthon).

By the late Eocene to the Early Miocene (fig. 4b), the Unit 3 (Allochthon) was thrusted over the Maubisse group (G3), thrusted itself over the Tumu-Kekneno group (G2). According to Sopaheluwakan [1990] this thrust (T4) occurred around 37.5 Ma (Late Eocene). However, we cannot know if the thrust separating the Maubisse formation from the Kekneno–Tumu formation (T3) is contemporaneous with the T4 thrust. Then, the Timor area was covered by sedimentary rocks of the "Noetoko group" (G5) together with volcanism likely related to a Miocene volcanic arc. That probably has lasted until the Upper Miocene, when a set of calk-alkaline diorites (T 111 at 10.55 ± 1.60 Ma) intruded the new Timor block.

By the end of Early Pliocene (fig. 4c) the new Timor block, including the Unit 3 (Allochthon) collided with the Timor Gap formations (A2). Consequently, the whole new Timor block was thrusted (T2) over the Kolbano formation. As a result, the previous thrusts were rejuvenated and the Miocene and Lower Pliocene sediments were likely folded and thrusted during this collision.

By the Late Pliocene (fig. 4d) a period of extensive tectonic gave way to the central and marginal basins as exemplified by the "Savu" basin and the "Timor" trough which were filled by sediments of the "Viqueque" group G8.

By the Late Pliocene-Pleistocene boundary a new uplift was evidenced by Van Marle [1989]. This uplift should be related to the thrusting of the "Sub-autochthon unit" ("Manamas" and "Atapupu" complexes] over the contemporaneous Timor block (T6 and T7). The "Viqueque group" (G8) was likely deformed at that time, noticeably in the Mina area (West of Soe).

We notice that, during the Early Pleistocene, sediments were deposited in the central basin previously to the current Timor Island uplift [Jouannic et al. 1998].

Geodynamics

We attempt to illustrate the geodynamic evolution of Timor and adjacent areas since the Eocene to the present time. Because Timor can be considered as a "go between" for the Australian and Eurasiatic plates, it is a "masterpiece" in the east Indonesian "puzzle".

During the Eocene time (fig.5a), the northern part of the Indian Ocean [IO] was subducting underneath the Asiatic margin [AAM] until the collision between “Initial Timor” [tm1] and AAM, elsewhere south of Sulawesi and close to Sumba, by the Late Oligocene or the Early Miocene (fig.5b).

Then a new “subduction system” of the Indian Ocean skip over the new Timor Island given way to a Lower to Middle Miocene volcanic arcs (fig.5c), until the South Banda sea back arc basin (SBB) was opened in Late Miocene. Then a new volcanic arc took place to the South (fig.5e). In East Timor, Keep and Haig [2010] support a collision between the Banda arc and the Australian continent after 10.9- 9.8 Ma.

By the Middle Pliocene, Timor and the northern Australian margin were connected and then the southern part of the South Banda basin (SBB) was thrusted over the northern Timor (fig.5f).

Nowadays, according to Snyder et al. [1996], the whole Timor block, including the southern Banda arc, is thrusting over the Banda basin floor owing to the north-eastward motion of the Australian block (fig.5g).

Palaeogeography

A palaeogeographic reconstruction of eastern Indonesia since the Late Miocene is shown in Figure 6.

Late Miocene (fig. 6a). At that time Timor was incorporated to the Asiatic margin and new subduction zones were operating to the South (2 and 3 in fig. 6a). This volcanic arc was extended to the Tukang Besi and Lucipara blocks which have collided Sulawesi around 13 Ma [Silver et al. 1985]. However, the North Banda Basin (NBB) was opened by the Early Late Miocene (10-9 Ma) according to Réhault et al. [1994].

Late Miocene-Early Pliocene (fig.6b). This volcanic arc splitted and a new back-arc basin (the South Banda basin = SBB) opened and grew until the Middle-Pliocene [Honthaas et al. 1998]. The Late Miocene volcanic arc was operating in the southern part of the South Banda basin including the northern part of Timor. Another “subduction” zone was operating beneath the western margin of “Irian Jaya” (4 in fig. 6b). This time coincide, more or less, with the tectonic quiescent period (5-5-4.5 Ma) evidenced by Keep and Haig [2010]. The Banda volcanic arc migrated to the North separating the “Savu basin” from the “South Banda basin”. This event approximately coincides with the post 4.5 Ma phase of uplift evidenced by Keep and Haig [2010].

Late Pliocene (fig. 6c). The “Sahul shelf” [current Australian margin] joined the Timor mainland and the Indian Ocean slab collapsed providing a regional extensional trend underlined by several sedimentary basins within Timor. We suspect a new collisionnal event between the Timor block and the Southern part of the South Banda basin (SBB) by the end of the Pliocene, when the “Viqueque formation” was locally folded and the northern part of the U4 unit (G7) thrusted over the Timor mainland.

CONCLUSIONS

Timor Island includes at least five different lithostratigraphic “units”. Thus, apart the current Australian margin (A), the Pleistocene to Holocene sediments ascribed to the Unit 5 (Autochthon) and the Unit 3 (Allochthon unit) which includes some parts of the Asiatic margin, three others units have been evidenced: Unit 1 (Para-autochthon), Unit 2 (Para-allochthon) and Unit 4 (Sub-autochthon). This Timor “assemblage” results from a long and complex geological history.

At least three collisional tectonic events were involved in the Timor polyphased structure. Each one is sealed by volcanic or volcano-sedimentary rocks. Because Timor was a kind of “shuttle” between the Australian continent and the Asiatic margin, we consider this block as a geological “masterpiece” for the geodynamic evolution of Eastern Indonesia.

The Late Eocene-Oligocene tectonic event is linked to the collision of the “initial” Timor block (Unit 2, previously detached from the Jurassic Gondwana margin) with the active Asiatic margin (Unit 3).

The Mid-Pliocene event is linked to the collision of the enlarged Oligocene “Timor block” newly detached (Late Miocene) from the Asiatic margin, with the Northern Australian margin (A).

The third event (Late Pliocene / Early Pleistocene) may be linked to the collision between the Australian margin [including the new Pliocene Timor Island] and the southern part of the South Banda basin.

Nowadays, according to Snyder et al. [1996], the current Timor block, including the southern Banda arc, is thrusting over the South Banda Sea floor.

A further collision could be expected within the next millions years, between the present Timor block and the Northern Banda islands (Seram, Buru…) owing to the present north-eastward motion of the Australian block [Michel et al. 2000, Bock et al. 2003, Nugroho et al. 2009]. This motion allows us to forecast a “southward subduction” of the Banda basin floor beneath the Australian margin until the Australian block, including Timor, will collide with the northern Banda islands.

Finally, Timor Island has registered the main geological events that occurred in this part of Southeast Asia.

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FIGURES CAPTIONS

Figure 1.

1a- **Location of West Timor in eastern Indonesia.** NBB=North Banda basin, SBB=South Banda basin, SW=West Sulawesi, SE=East Sulawesi, HL=Halmahera, TB=Tukang Besi platform, LR=Lucipara Ridge, BA= Savu basin,

1b- **Geological sketch map of West Timor** [modified from Rosidi et al. 1979]

Legend: 1-Unit 5 [Autochthon unit], 2-Manamas and Atapupu complex [Unit 4, group G8], 3-Batuputih group [Unit 4, group G6], 4-Late Miocene dioritic intrusions [Unit 4], 5-Palelo Group [Unit 3, group G4], 6-Maubisse group [Unit 2], 7-Kekneno-Tumu group [Unit 2], 8-Kolbano group, 9-Oligo-Miocene thrusts, 10-Mid Pliocene and Late Pliocene thrusts, 11-vertical faults. D1, D2 and D3= main unconformities cited in Fig. 3, T2, T3, T4 and T5= main thrusts shown in Fig. 3. The underground D1 is not outcropping.

Man=Manamas, Bisn=Bisnain, ATP=Atapupu, ATB=Atambua, W=Wini, Kf=Kefamenanu, NK=Niki-niki, Kbb=Kolbano, TK=Takari, Cpl=Camplong, Kup=Kupang, Su=Suai,

Figure 2.

2a- **Crustal geological cross section of West Timor** (modified from [Villeneuve et al., 2005]). 1-Central basin (Unit 5, group G9), 2-Manamas complex (Unit 4, group G7), 3-Late Miocene dioritic intrusion (Unit 4), 4-Batuputih group (Unit 4, group G6), 5-Cablac formation (Unit 3, group G5), 6-Metamorphic complex (Unit 3, group G4), 7-Palelo group (Unit 3, group G4), 8-Kolbano group (Unit 1, group G1), 9-Maubisse group (Unit 2, group G3), 10-Kekneno-Tumu group (Unit 2, group G2), 11-Supposed Timor metamorphic basement, 12-Thrusts.

2b- **Geological section of the Noiltoko area**. 1-Quaternary deposits, 2-Miocene Noetoko group (G5), 3-Palelo group [G4], 4-Metamorphic complex [G4], 5-Maubisse group [G3].

2c- **The thrust within the Kolbano group**, 1-Lower Pliocene calcilutites (Batuputih group?), 2-black breccias, 3-Cretaceous or Eocene limestones, 4-Modern breccias.

Figure 3.-**Tectono-stratigraphic diagramm of West Timor**. 1-Plio-Quaternary deposits of the Noele group (Unit 5, group G9, Autochthon), 2-Reef limestones of the Noele group (Unit 5, group G9, Autochthon), 3-Manamas volcanic complex (Unit 4, group G7, Sub-autochthon), 4-Ultrabasic Atapupu complex (Unit 4, group G7, Sub-autochthon), 5-Aileu complex of East Timor (Unit 4, group G7, Sub-autochthon), 6-Viqueqe group (Unit 4, group G8, Sub-autochthon), 7-Dioritic intrusions (Unit 4, group G8, Sub-autochthon), 8-Batuputih formation and Bobonaro conglomeratic complex (Unit 4, group G6, Sub-autochthon), 9-Miomaffo formation (Unit 3, group G5, Allochthon), 10-Cablac formation (Unit 3, group G5, Allochthon), 11-Palelo group and Mutis metamorphic complex (Unit 3, group G4, Allochthon), 12-Maubisse group (Unit 2, group G3, Para-allochthon), 13-Kekneno-Tumu group (Unit 2, group G2, Para-allochthon), 14-Kolbano group (Unit 1, group G1, Para-autochthon), 15-Australian passive margin cover, 16-Australian metamorphic basement. T = Main thrusts, D = unconformity, G1 to G8: main groups cited in text. G1=Kolbano group, G2 = Kekneno-Tumu, G3= Maubisse group, G4 = Mutis complex and Palelo group, G7 = Atapupu and Manamas complex, G8 = G8 group including the “Viqueque formation”.

Stratigraphic ages: Gr1 = Jurassic to Early Pliocene, Gr2= Permian to Early Eocene, Gr3=Permian to Cretaceous, Gr4 = Jurassic to Eocene, Gr5 = Early to Middle Miocene, Gr6 = Late Miocene to Early Pliocene, Gr7 = Middle to Late Miocene, Gr8 = Late Miocene to Late Pliocene, Gr9 = Pleistocene to Quaternary.

Figure 4. **Cartoon depicting the geodynamic evolution of Timor in 4 main steps.**

4a- Triassic period: Extensive tectonic process on the Northern Gondwana margin. Aus (A1 and A2)-Australian block, G2-Kekneno Tumu group, G3-Maubisse group, AAM and G4-Asiatic active Margin.

4b- Oligo-Miocene period: Collision between the Timor Block and the Asiatic active margin (AAM). The Asiatic volcanic arc is thrusted over the Maubisse group and the Maubisse group is itself thrusted over the Kekneno-Tumu group. The Timor Block is separated from the Australia by the Indian Ocean; G4 = Part of the Asiatic volcanic arc thrusted over Timor, AAM = Part of the Asiatic volcanic arc remained at the border of the Asiatic margin.

Legend: IO = Indian Ocean, T3 = thrust between Kekneno–Tumu and Maubisse groups, T4 = thrust separating the G4 group (Mutis complex and Palelo group) from the U2 unit (Kekneno-Tumu and Maubisse groups).

4c- Middle Pliocene period: The Timor block collided with the Australian block. The Kolbano group contains formations of the Australian margin mixed with Neogene formations from the southern Timor accretionary prism, G7 = Manamas and Atapupu complexes are related to the south Banda volcanic arc; A1 = basement of the Australian margin, A2 =sediments of the Australian margin, T1 = thrust between the Kolbano group and the Australian block, T2 = thrust between the Kolbano and the Kekneno-Tumu group], T5 = thrust between the Aïleu complex and the "Maubisse group".

Legend: KTfm = Kekneno-Tumu group, Vqq = Viqueque group, TTr = Timor trough, Aus = Australian block.

4d- Late Pliocene period: The Manamas and Atapupu volcanic arc are thrusted over the Northern Timor and a new volcanic arc (the Banda arc) is setting North of the Savu basin.

1- Noele group (Unit 5, group G9, Autochthon), 2- Viqueque group (Unit 4, group G8, Autochthon), 3- Manamas complex (Unit 4, group G7, Sub-autochthon), 4- Atapupu complex, (Unit 4, group G7, Sub-autochthon), 5- Noetoko group (Unit 3, group G5, Allochthon), 6-Cablac formation (Unit 3, group G5, Allochthon), 7-Upper Miocene dioritic intrusions (Unit 4, group G8, Sub-autochthon), 8- Aileu complex (Unit 4, group G7, Sub-autochthon), 9- Palelo group (Unit 3, group G4, Allochthon), 10- Mutis metamorphic complex (Unit 3, group G4, Allochthon), 11- Maubisse group (Unit 2, group G3, Para-allochthon), 12- Kekneno-Tumu group (Unit 2, group G2, Para-allochthon), 13- Sedimentary prism of the Australian margin, 14- Kolbano group (Unit 1, group G1, Para-autochthon), 15- Gondwana basement, 16- Volcanoes, 17- thrusts. T6 = thrust between the Atapupu complex and the Maubisse group, T7 = thrust between the Manamas and Atapupu complexes, Kbfm = Kolbano group.

Figure 5. Cartoon illustrating the geodynamic evolution of Eastern Indonesia.

fig 5a- By the Eocene: Tethys ocean is subducting underneath the Asiatic margin. **fig.5b-** By the Oligocene: the Mutis complex is obducted over the Timor initial. **fig. 5c-** By the Early and Middle Miocene: the "subduction zone" skipped from North to South of Timor. **fig 5d-** By the Late Miocene: a volcanic arc arose in northern Timor. **fig.5e-** By the Early Pliocene: The South Banda basin developed. **fig.5f-** By the Middle

Pliocene: Australia collided with deformation of the Kolbano prism and by the Pleistocene: the Oecussi and Atapupu complexes obducted over the northern Timor. **fig. 5g-** Present time: Timor terranes obduct over the South Banda sea basin.

Legend: Aust = Australian block, TG= Timor gap, IO = Indian Ocean, Tm1 = Initial Timor, AAM = Asiatic active margin, MS = Makassar straits, K= Kalimantan, OP = Obducted part (Mutis complex), Tm2 = Timor initial + Allochthone, P.Aut = Para-autochthon (Maubisse and Kekneno-Tumu groups), All = (Allochtone), Kb1 = Kolbano group (Neogene accretionary prism), Kb2 = Kolbano group = part of the Australian sedimentary prism, Kb = Kolbano group (mix of Kb1 and Kb2), SBB = South Banda basin, BA = Banda volcanic arc, Ail = Aileu metamorphic complex (with blue schist minerals), Mc = Manamas complex, ATP = Atapupu complex, TmT = Timor through, Tm3 = Total Timor (Initial + Allochton + Banda arc).

Figure 6. **Palaeogeographic reconstructions of Eastern Indonesia [Late Miocene].**

6a- Late Miocene. Timor (Tm) is located on the Asiatic margin, south of Sulawesi and likely to the East of Sumba.

6b- Mio-Pliocene: The South Banda basin (SBB) is opened by migration of the Timor-Tanimbar volcanic arc (Tm-Tan).

6c- Pliocene-Pleistocene: Following the collision between the Timor-Tanimbar (Tm-Tan) volcanic arc and the Australian block, the Banda volcanic arc is setting north of the Savu basin. The Weber trough is opened on the Eastern part of the South Banda basin.

WS-West Sulawesi, **ES**-East Sulawesi, **Sb**-Sumba island, **KL**-Kalimantan, **MS**-Makassar straight, **Bs**-Banggai-Sula, **Sb**i-Sulabesi, **Hl**-Halmahera, **Pap**-Papouasie, **NBB**-North Banda basin, **Bu**-Buru, **SR**-Seram, **TB**-Tukang-Besi platform, **LuR**-Lucipara ridge, **Fl**-Flores, **Sb**-Sumba island, **Fl**-Flores island, **SBB**-South Banda basin, **WB**-Weber trough, **Tm**-Timor, **Tan**-Tanimbar, **TT**-Timor through.

Legend: **1**-Asiatic Volcanic arc, **2**-Kolonodale Timor Block, **3**-Lucipara block, **4**-Emerged islands**, 5**-Volcanoes (Miocene- Pleistocene), **6**-Main subduction zones: (1)-Central Sulawesi subduction thrust, (2)-North Banda subduction thrust, (3)-South Banda subduction thrust, (4)-Seram-Buru Subduction thrust, **7**-The Australian block, **8**-Marginal basins, **9**-Miocene–Pliocene metamorphic formations, **10**-Marine escarpments, **11**- Basins and troughs.

Table 1. K-Ar ages carried on West Timor samples. (Ages were performed in Brest University at UMR CNRS 6538 “Domaines océaniques”).

Geographical coordinates: in column 2.

Table 2. K-Ar dating on the Western arm of Sulawesi and on the Timor allochthon and sub-autochthon units. Legend: NRD=New radiometric dating, np = sample number and time error bracket not precised, M =dating on mineral, Horn = Hornblende, wr = K-Ar ages were performed on whole rock.