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Deformation zone 'jumps' in a young convergent setting; the Lengguru fold-and-thrust belt, New Guinea Island

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A B S T R A C T

The Lengguru fold-and-thrust belt in West Papua (Indonesia) has all the characteristics of a young orogen involved in a rapidly changing tectonic setting. The analysis of the young wedge shows however that its internal shortening has ceased recently, and that it is nowadays suffering severe extension. Recent topographic data, marine industrial seismic lines and drilling, were used with field observations and measurements to create detailed cross-sections and a new structural map. The study allows us to distinguish two superimposed prisms composed of stacked Mesozoic marine sediments of the Australian margin against a crustal buttress. The construction of these two wedges is younger than 11 Myr. The structures of the Lengguru belt external zones are sealed by an unconformable clastic series, indicating that the construction of the Lengguru prism had aborted suddenly due to a change in the way the Australian and Pacific plate convergence was accommodated. At that time, the internal zones probably started to exhume and the tectonic regime became extensional. Nowadays the internal part of the Lengguru fold-and-thrust belt is undergoing an active east–west extension. We believe that the extension observed in the Lengguru wedge is coeval with a transition from a compressive to a transtensional regime illustrated in the Central Range of Papua, and the onset of the Tarera-Aiduna and Paniai left-lateral faults. The structure of the Lengguru belt therefore results from events occurring over a very short time span; a previous Late Miocene northeast–southwest compression linked to the subduction process, a second from Middle Miocene to Early Pliocene and a Late Pliocene-Quaternary global extension in the whole range. The evolution is compared with that of the Seram wedge and the Misool–Onin–Kumawa continental ridge to the west; where deformation is accommodated at a localized zone which jumps as convergence between Australian and Pacific plate proceeds. This evolution of the belt reflects rapid changes in the accommodation oblique shortening, with the isolated orogenic wedge of Lengguru fold-and-thrust belt left to collapse.
This example illustrates the way a long-lasting subduction terminates. At the lithospheric scale, the deformation remains rooted at the suture zone. However at the surface, the shortening is suddenly widespread over a large area during a very short time span (formation of the Lengguru belt) prior to being transferred to another plate boundary.

1. Introduction

South East Asia is characterized by active and often fast plate motion which allows us to illustrate various examples of rapidly changing geodynamic settings. In these settings, many interesting discoveries have been made to illustrate magmatic processes such as slab detachments, subduction of large asperities, adakitic and Nb-enriched basalt provinces or complex subduction patterns. Examples like the consumption of a piece of oceanic crust by two opposite vergence subductions have been described in the Molucca Sea (Moore and Silver, 1982) and in the Solomon Sea (Cooper and Taylor, 1987), and have brought a lot of understanding of the behavior of basins when shortening becomes intense. In these examples however, it is difficult to unravel the variations of convergence parameters and to establish the timing of deformation.

Papua New Guinea Island is involved in a very rapid oblique plate convergence between the Caroline and Australia plates (Charlton, 2000; Hall, 2002). The movement of the Caroline plate relative to fixed Australia is in the order of 11 cm/yr (Puntodewo et al., 1994; Rangin et al., 1999; Michel et al., 2001; Cloos et al, 2005). The strong obliquity of the convergence induces the development of Tarera and Paniai faults with high strike-slip rates (Stevens et al., 2002; Pubellier and Ego, 2002) that individualise the continental Bird's Head microblock from the rest of Papua New Guinea (Fig. 1). However, while this configuration indicates that the rapid convergence between the plates shifts from the Mamberramo Range and New Guinea Trench in the

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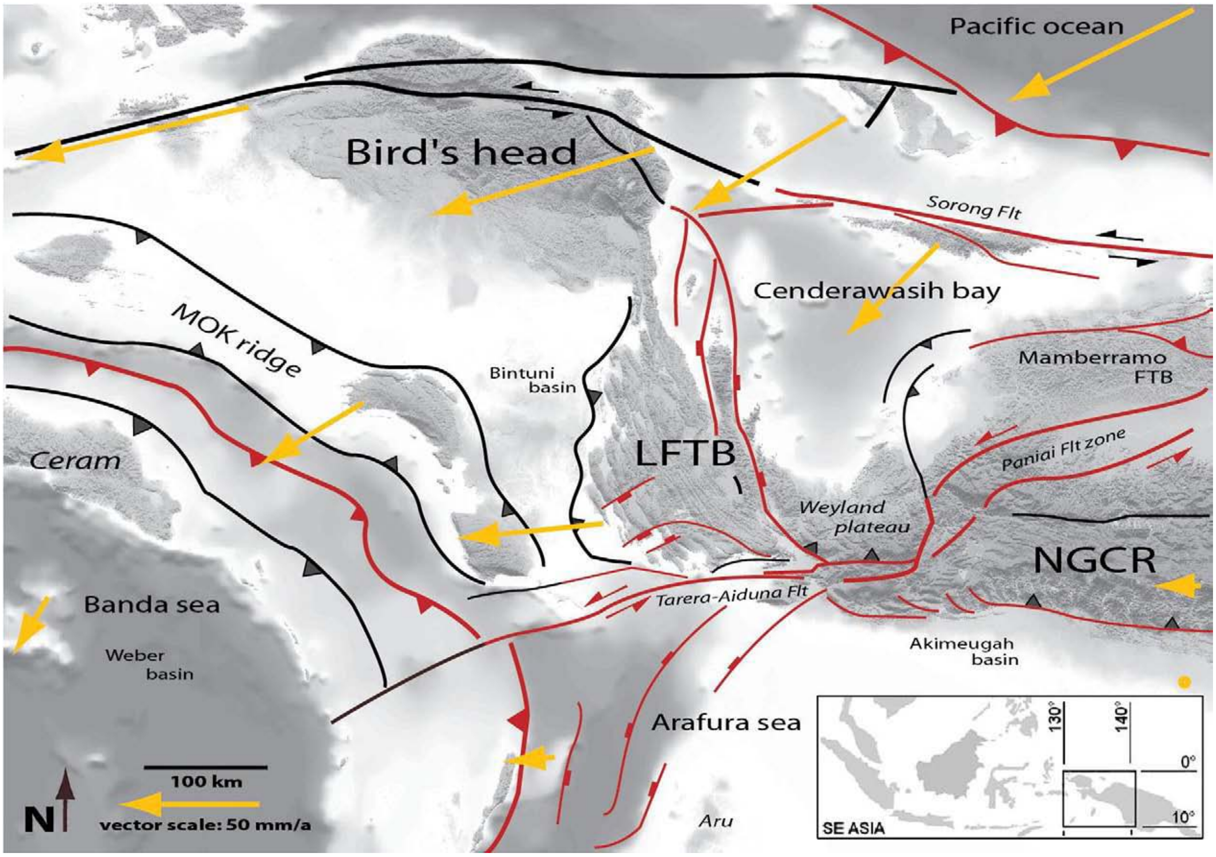


Fig. 1. Simplified regional structural map (SRTM onshore and predictive bathymetry offshore). Main plate boundaries and faults are in black. Active structures are in red. GPS data are in yellow, motions relative to Australian plate (adapted from Puntodewo et al. (1994), Michel et al. (2001), Stevens et al. (2002), Cloos et al. (2005)). MOK ridge: Misool, Onin, Kumawa ridge. LFTB: Lengguru fold-and-thrust belt. NGCR: New Guinea Central Range. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

northeast, to the Seram Trench in the southwest, it fails to explain the formation of the very recent Lengguru fold-and-thrust belt. GPS data indicate that the Bird's Head and Lengguru fold-and-thrust belt move as a single block toward the southwest relative to fixed Australia.

Most of the deformation observed in West Papua took place during the Late Neogene (Pigram and Panggabean, 1981; Dow et al., 1988; Robinson, et al., 1988; Pigram and Symonds, 1991) with rapid changes in geodynamic context and strain style during the past 5 Myr (Pubellier et al., 2004, 2003). The western part of the Belt, the Lengguru belt, is characterized by its curved shape which links the high elevation Central Range of Western Papua to the moderately high mountains of the eastern coast of the Bird's Head (Fig. 1). The shortening in the Central Range has ceased very recently (<2 Myr) causing the convergence to be transferred mostly to the Seram Trench via the Tarera and Paniai wrench faults (Pubellier et al., 1999, Stevens et al., 2002).

2. The Lengguru fold-and-thrust belt; stratigraphy and rheological implications

The stratigraphic units involved in the wedge exhibit strong rheologic contrasts, which have direct implications on the structure of the Lengguru fold-and-thrust belt. Above a basement composed of metamorphic and Paleozoic sediments, we observe a Mesozoic series consisting of incompetent terrigenous shaly material at the base, grading upward to more calcareous and massive resistant units. The Tertiary lithologies are dominated by the thick Eocene to Miocene New Guinea Limestone, overlain by Middle Miocene to Present, fine-grained turbidites and Molasse deposits. For convenience, from top to bottom, three major sequences are distinguished in the belt (Fig. 2):

- The post 11 Myr sequence shows two clastic formations (Dow and Sukamto, 1984). We hereafter consider the lower one as synchronous to the Lengguru fold-and-thrust belt formation and the upper one as post-formation. The Pliocene to recent Steenkool Formation, defined by Visser and Hermes (1962) covers most of the southern part of the Bird's Head from Seram Island to the Lengguru belt. Encountered in many industrial boreholes in the Bintuni Basin, this formation can exceed 3000 m at places (Pieters et al., 1983). Lateral facies changes from micaceous clay to coarse material are common. It is occasionally covered by Quaternary alluvial deposits. The Upper Miocene to Lower Pliocene Klasafet Formation (Fig. 2), as defined by Visser and Hermes (1962), outcrops rarely in the study area. Composed of grey micaceous marls interbedded with calcareous siltstone turbidites and rare micritic fine limestone beds; the Klasafet Formation is typically syntectonic and records the Lengguru fold-and-thrust belt construction. With a maximum thickness in the foreland reaching 2000 m, it is also found inside narrow piggy-back synclines in the midst of the range.
- The lower Tertiary group of the New Guinea Limestone arms the main part of the Lengguru belt. It is composed of the Lengguru Limestone Fm. (Fig. 2), exposed in the south of the range and the Imskin Fm. which outcrops more to the north (Robinson et al., 1988; Brash et al., 1991; Thery et al., 1999). Both formations are Paleocene to Middle Miocene and correspond to a lateral variation of depositional environment. The first formation is a very competent layer of thick grey to brownish platform limestone. Also present in the Lengguru wedge and the Misool–Onin–Kumawa ridge, it is known by boreholes in the bottom of the Bintuni Basin. With a maximum thickness of 2000 m in the range,

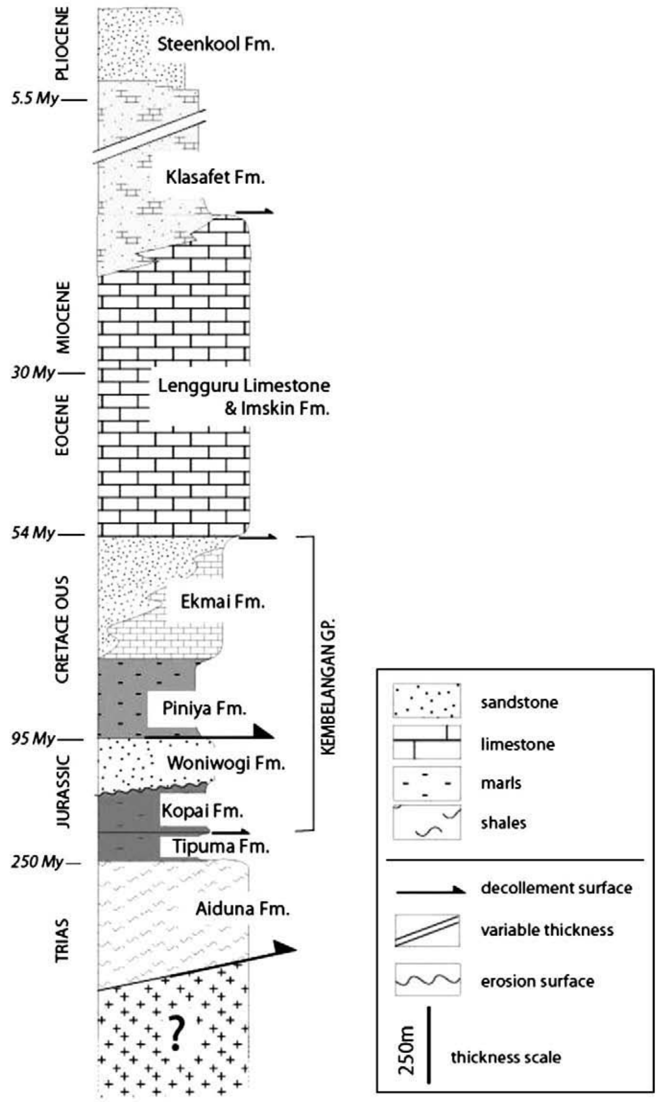


Fig. 2. Lithological and mechanical stratigraphy of the Lengguru FTB (modified from Visser and Hermes (1962), Pieters et al. (1983), Cloos et al. (2005)).

it had a key role in geomorphology and the mechanical behavior of the sedimentary cover during Pliocene shortening. The second unit, the Imskin Fm. (Fig. 2), is a thinner fossil-rich pelagic calcareous series with a maximum thickness of 1500 m, less affected by karstic weathering. Its thickness decreases quickly toward the northeast, until a complete disappearance caused by either total erosion or non deposition.

– The Permian to Paleocene deposits are typical of the North Australian Margin. Because of their mechanical properties, they serve as the main decollement levels in the Lengguru belt. They are composed of six formations.

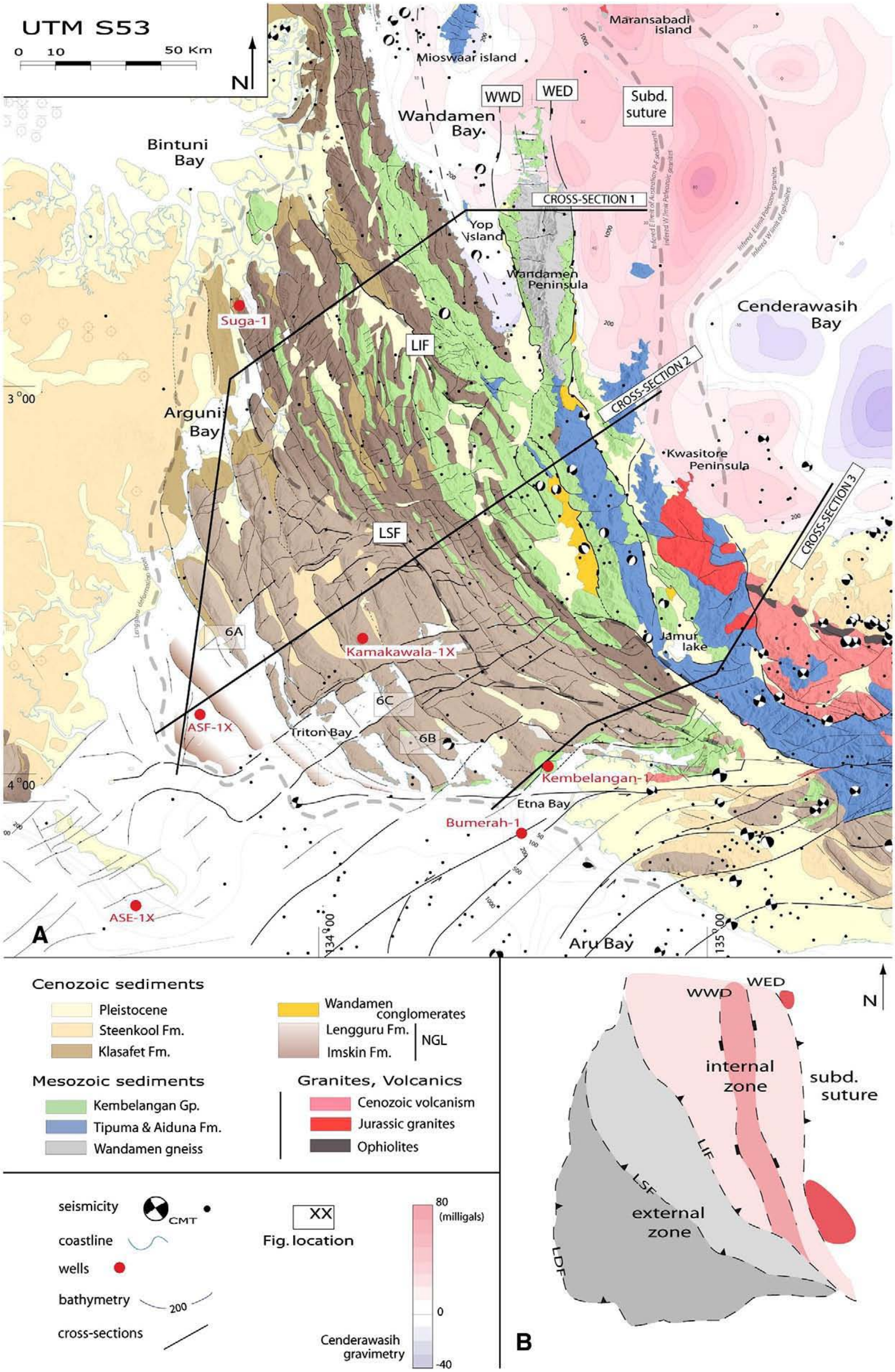
The Ekmai Formation (Fig. 2), dated from the Late Cretaceous to the Paleocene, belongs to the Kembelangan group defined by Pigram et al. (1982) which also includes the Piniya, Woniwogi and Kopai Formations. A general metamorphism increasing toward the northeast is observed in this group across the belt. The Ekmai Formation is exposed mostly in the eastern part of the belt, in the eroded cores of New Guinea Limestone anticlines. Composed of sandstone, greywacke and a few marly layers in the south of the range (Pieters et al., 1983), it appears to be progressively calcareous to the north. With an average thickness of 100 m at the front of the Lengguru belt, it increases to the northeast up to over 500 m. The Piniya Formation (Fig. 2), Middle Cretaceous, is mainly composed of black mudstone, little sandstone and red clay layers (Pieters et al., 1983). Like the previous overlying formation, its thickness increases drastically toward the northeast from 400 m at the front of the belt, and it served as an efficient decollement level in the range. The Woniwogi Formation, Lower Cretaceous, is present in the northeast of the Lengguru belt and is composed of thick pure sandstone layers overlain by thin dark clay. This unit varies in thickness from 100 m in the frontal part of the range to 500 m to the north. Underneath is the Kopai Formation (Fig. 2) which is dated from Middle to Late Jurassic and which forms the lowest formation of the Kembelangan group. It is composed of a fine sandy conglomerate layer overlain by thick clay and black limestone beds (Pieters et al., 1983). It does not outcrop in the foreland of the Lengguru belt but thickens up to 2500 m and serves as the main decollement level in the eastern part of the range. The Tipuma Fm. (Fig. 2), from Triassic to Lower Jurassic in age, was described previously by Visser and Hermes (1962), and is composed of greywacke, sandstone and black shales. This formation is very thick in the eastern part of the belt (over 3000 m) but is almost inexistent in the front of the range. This formation, ubiquitous in the West Papua province, is in fact exposed sporadically and is generally metamorphosed. Along the Cenderawasih Bay, the strong metamorphic conditions due to a deep burial and proximity with highly metamorphosed gneiss, have transformed the lithologies into marbles and slate. The Aiduna Fm. (Fig. 2), dated Permian, is the only formation of the Aifam group defined by Visser and Hermes (1962) which is actually known in the belt area, although only through drilling. It is composed of micaceous lithic sandstones, a few fossil-bearing biocalcarenite and intercalated fossiliferous coal beds (Pieters et al., 1983). We estimate its thickness around 3000 m. Considering that the other Mesozoic deposits increase their thickness toward the northeast, we assume that it is also the case for this formation. The overall stratigraphy of the Lengguru belt consists of a young fine-grained clastic series overlying a competent layer of carbonates. This assemblage rests upon a thick pile of marls and clay layers providing good decollement surfaces.

3. The Lengguru fold-and-thrust belt; internal units

As mentioned above, high grade metamorphic rocks outcrop in the northeast of the Lengguru fold-and-thrust belt. In these rocks, we distinguish two main units both showing lithologic similarities with the surrounding sediments. They are considered hereafter as metamorphics derived from the Mesozoic formations described above:

– The first unit has little thermo-barometric control, as no metamorphic minerals, except some chlorites and white micas are observed. It outcrops on Yop and Mioswaar islands in the middle of the Wandamen Bay, in the south and along strike on the Wandamen Peninsula next to the Jamur lake (Fig. 3A). We will show that this unit underwent moderate metamorphic conditions.
– The second one, located in the Wandamen Peninsula is referred to as the Wandamen gneiss by Pieters et al. (1983) and may correspond to the gneiss mentioned by Dow et al. (1988). This second author also described high grade metamorphic rocks such

Fig. 3. Structural map of the Lengguru fold-and-thrust belt with geology and SRTM superposed onshore, gravimetric contours in Cenderawasih Bay and last 20 yr of seismicity (adapted from Tobing et al. (1990a,b), Henage (1993), Sutriyono and Hill (2001), Hill et al. (2004); seismicity from Engdahl et al. (1998) (last database); gravimetry from Total E&P Jakarta and cenozoic volcanism location from PT Freeport Indonesia). LDF, Lengguru Deformation Front, LSF, Lengguru Shallow Front, LIF, Lengguru Internal Front, WWD and WED are respectively the West and East Wandamen detachments. The LSF correspond to the front of the first prism and the LDF to the second.


UTM S53
0 10 50 Km
N
Bintuni Bay
Wandamen Bay
Mioswaar island
Maransabadi island
WWD
WED
Subd. suture
CROSS-SECTION 1
Yop island
Wandamen Peninsula
Cenderawasih Bay
Suga-1
LIF
3°00
Arguni Bay
CROSS-SECTION 2
Kwasitore Peninsula
CROSS-SECTION 3
LSF
6A
Kamakawala-1X
Jamur lake
6C
ASF-1X
Triton Bay
6B
4°00
Kembelangan-1
Etna Bay
Bumerah-1
ASE-1X
134°00
135°00
Aru Bay
A
Cenozoic sediments
Pleistocene
Steenkool Fm.
Klasafet Fm.
Wandamen conglomerates
Lengguru Fm.
Imskin Fm.
NGL
Mesozoic sediments
Kembelangan Gp.
Tipuma & Aiduna Fm.
Wandamen gneiss
Granites, Volcanics
Cenozoic volcanism
Jurassic granites
Ophiolites
seismicity
CMT
coastline
wells
bathymetry
200
cross-sections
XX
Fig. location
80 (milligals)
0
-40
Cenderawasih gravimetry
WWD
WED
N
internal zone
subd. suture
LIF
LSF
external zone
LDF
B

as amphibolites and suggested that these rocks could be retrograded eclogites. The peninsula is mainly composed of metasediments, metabasalts, paragneiss and leucogranite (de Sigoyer et al., 2007). The existence of these rocks provides pressure, temperature and age indications on the deeper part of the orogen, considered as the result of subduction at great depth of the sediments. These levels were then exhumed. Maximum estimated temperatures on co-existing chlorite and muscovite are around 700 °C and above 7 kbar (Dow et al., 1988).

At the easternmost part of the range, granites outcrop in the Kwasitore Peninsula and small islands such as Maransabadi (Fig. 3A). These granites are Triassic to Lower Jurassic in age (Dow et al., 1988; Permana, 1998) and are connected to each other by a strong positive gravity anomaly (Fig. 3A). They did not suffer metamorphism and were considered to belong to the backstop of the Lengguru belt indicating the location of the subduction suture.

4. The Lengguru fold-and-thrust belt; morphology, structure and metamorphic conditions

With its triangular shape, the Lengguru fold-and-thrust belt is atypical. The length is 250 km at the centre; the width is 200 km, and its average elevation is less than 1000 m. Only in the internal zone does the metamorphic dome of Wandamen Peninsula exceed 2000 m. The belt has preserved both external zones, most of which are above sea level and unmetamorphosed, and internal zones which bear the characteristics of a mature orogenic wedge. These internal zones show exhumation of deeply buried sediments and probable crustal thrust. Detailed mapping and previous work on the Lengguru belt area (Tobing et al., 1990a,b; Henage, 1993; Sutriyono and Hill, 2001; Hill et al. 2004) allowed us to distinguish several tectonic domains (Fig. 3A and B), which will supply information about the way the accretionary wedge has evolved through recent times.

4.1. The external zones; a belt resulting from compression and extension

The external zone, to the west and southwest (Fig. 3B) between the Lengguru Deformation Front and the Lengguru Internal Front, consists of two distinct superimposed wedges (Figs. 5 and 7).

A superficial prism, situated in the middle of the Lengguru fold-and-thrust belt at the present time, is rooted on a 4–5 km deep decollement layer. It is generally composed of Kopai Formation and locally of Ekmai Formation. The bulk of this wedge is composed of southwest trending folds and thrusts with a period of 5 km. The arcuate shape of the range originated with this prism.

A second thicker prism consists of thrusted anticlines above a 7–8 km deep decollement layer located in the Aiduna Formation. The contact between the two prisms, the Lengguru Shallow Front is illustrated by either a thrust or a fold which preserves the formal front of the first wedge (Fig. 3A). It is therefore oblique to all the other thrusts of the Lengguru belt. This difference in trend may be due to various causes such as variations of friction or structural inheritance. Along the Lengguru Shallow Front, we can see tilted short period anticlines above larger ones, showing that the shallow prism was in place before the thicker one.

This second prism is expressed over the entire external part of the range, and thus reactivated the first wedge as a passive roof. It is composed of in-sequence 10 to 20 km period northwest–southeast linear folds and thrusts trending southwest (Fig. 5). This deep decollement creates large anticlines at surface rising up to 800 m (Fig. 4A). All of these anticlines are protected by the massive Tertiary New Guinea Limestone Group. The thrusts generally overlap the synclines, thus giving a typical morphology where anticlines step on each other in a manner similar to the “break-thrust folds” of Willis (1893) (Fig. 5). Thus, the structural surfaces often face each other (Fig. 4B). Folding is Late Miocene to Pliocene, as recorded by syntectonic clastic deposits in few piggy-back basins onshore and in the foreland. The prism is presently partly offshore (Figs. 5 and 4A), as a result of the loading associated with the important sedimentation in the Bintuni Basin. In a map view (Fig. 3A), the front of the wedge has characteristic northwest–southeast steps interpreted as transfer zones. The offsets are either marked by cross-cutting strike-slip faults or sharply rotated periclines, suggesting varying basal friction on the decollement (Fig. 3A). The age of the second prism is well constrained. Some seismic lines correlated to the ASF-1X well in the offshore Lengguru wedge show that the area was under deformation between ~10 and ~3 Myr (Fig. 6). We believe that the two superimposed prisms of the external zone were formed in an in-sequence continuum between Middle Miocene and Middle Pliocene.

Both prisms have been recently affected by post-thrusting block-faulting tectonics. These structures represent collapses along northeast–southwest trends, with vertical displacements reaching 1000 m (Fig. 4C). We observe the same phenomenon in the offshore part of the range (Fig. 6) and is dated from ~3 Myr to the present day. These trends are all parallel to each other and are not radial to the range. Since this northeast–southwest orientation does not appear on field measurements (e.g., in the Triton Bay), we assume they are controlled by underlying structures. Large northeast–southwest tilted blocks with a period of 25 km, separated by severely collapsed zones have been identified. As the relaxation event post-dates the formation of the Lengguru belt, we interpret these structures as the result of gravitational collapse of the wedge exaggerated by a major left-lateral drag along the Tarera fault zone. It is likely therefore that recent extensional and strike-slip deformation during the last 3 Myr has reactivated the previously formed structures in the basement.

4.2. Internal zone; deep part of a subduction complex exhumed

The internal zones, in the eastern part of the Lengguru fold-and-thrust belt (Fig. 3B), constitute a pre-Lengguru wedge and are mostly constituted of metamorphic units. This internal domain connects with the western extremity of the New Guinea Central Range (Dow and Sukamto, 1984; Dow and Robinson, 1985). Presently, the area is undergoing active extension (McCaffrey, 1996; Pubellier et al., 1999; Pubellier and Ego, 2002; Stevens et al., 2002). In this area, the syntectonic Klasafet Formation, of Middle Miocene age (Robinson et al., 1988) is older here than in the front of the range. It was deposited in the foreland of an advancing prism. Locally, some patches have been isolated and transported in piggy-back basins. This formation therefore records the activity of a previous prism providing a maximum age of Middle Miocene. The oldest new datings of the underlying Imskin Formation based on nannoplankton indicate Middle Miocene ages. As it was deposited during a period of quiescence, we assume that this prism started to be active around 15 Myr and is responsible for the non deposition of the Imskin Formation in the eastern part of the range.

We also suggest that the internal part of the Lengguru fold-and-thrust belt is composed of two metamorphic units. They are mostly exposed in the Wandamen Bay and Peninsula (Fig. 3A and B). Oriented northeast–southwest, they are approximately parallel to the thrusts of the early subduction prism structures and to the drowned granites interpreted as the upper plate.

The first metamorphic unit outcrops in two places but constitutes a single unit. It outcrops in the Wandamen Bay and in the southern trend of the Peninsula. It is therefore located between the Lengguru Internal Front and the Wandamen West Detachment in the north and between the Wandamen West Detachment and the Wandamen East Detachment in the south.

The Wandamen unit forms a north–south elongated antiform bounded by two roughly north–south detachment faults, the Wandamen West Detachment and the Wandamen East Detachment (Figs. 3 and 7). Each detachment is actually made of a series of high-angle

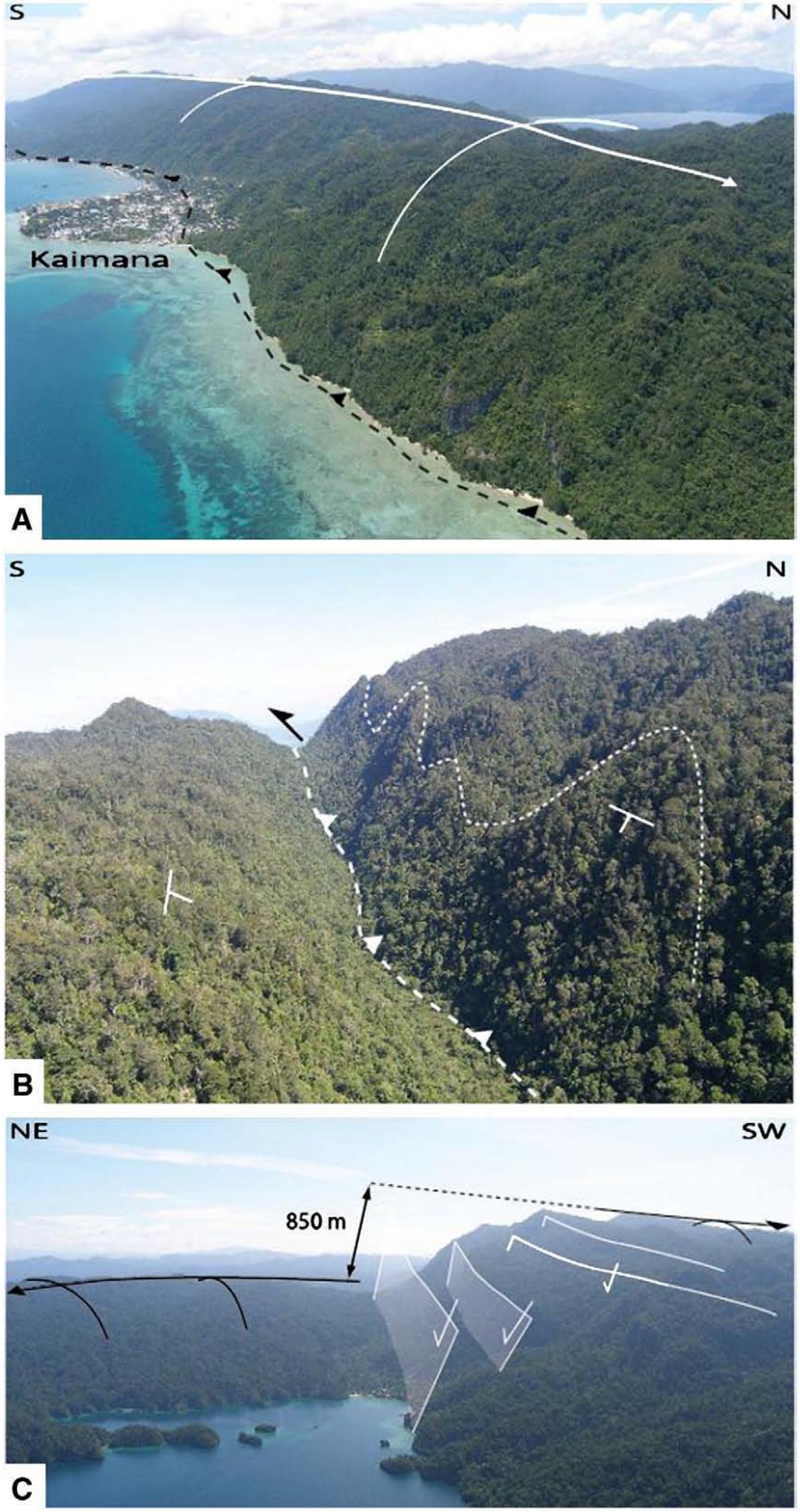


Fig. 4. (A) View on a large anticline armed by the Lengguru Limestone at the onshore/offshore transition. (B) Overthrust of the syncline in the SE part of the LFTB illustrated by two structural surfaces facing each other separated by a southward thrust. (C) South ending of the Triton Bay. View on a set of large normal faults cross-cutting through a pre-existent anticline.

normal faults at the surface connected to a low angle detachment as commonly observed in most gneissic domes. On the east side of the units, a large thickness of Plio-Pleistocene sediments lies in the bottom of the Cenderawasih Bay as evidence of a large amount of eroded material.

Except in the heart of the Wandamen Peninsula, index metamorphic minerals are lacking in the Lengguru fold-and-thrust belt, while carbonaceous material is ubiquitous all around the belt. To explore the thermal structure of this area we used the Raman Spectroscopy on Carbonaceous Material, RSCM. During diagenesis and metamorphism,

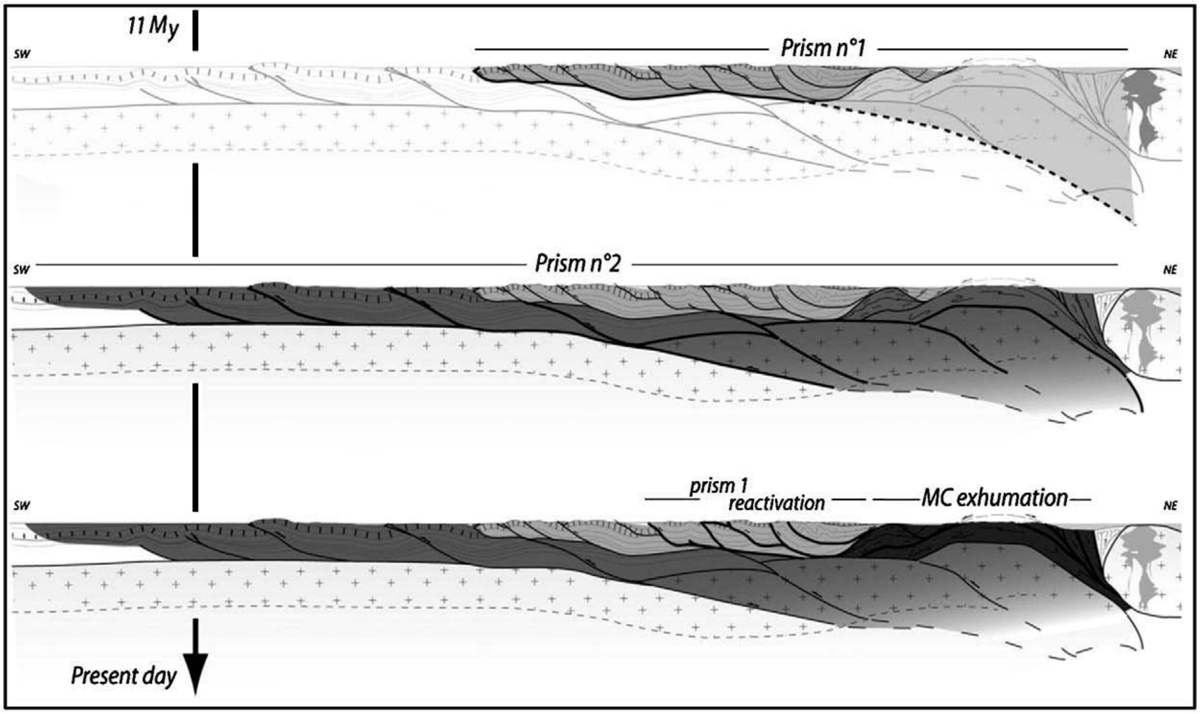


Fig. 5. Sketch cross-sections of the central Lengguru fold-and-thrust belt showing the two superimposed prisms and the metamorphic core on a static present day view of the range. Time scale showing the chronology of the structures. Each shading zone corresponds to the deformed area of a prism. Prism 1 corresponds to the shallow prism and prism 2 corresponds to the present day LFTB prism.

the carbonaceous material present in the initial sedimentary rock progressively transforms into graphite. The corresponding progressive degree of organization of the material is considered to be a reliable indicator of metamorphic grade, especially of temperature (Rietmeijer and Mackinnon 1985; Wopenka and Pasteris 1993). 14 estimations of maximum temperatures were determined using this method. The range is 330–650 °C (Beyssac et al., 2002) and the maximum temperature is interpreted as a proxi of the burial. Here, a good consistency is observed within the main structural sub-units as well as sharp jumps of 100 °C between them (Fig. 8). With these estimations, we are able to better define the metamorphic units of Fig. 3B. We can distinguish, zone one and zone Umar as two low metamorphic grade areas (Fig. 8). The two opposite detachments localized by the morphological study and temperature estimations occur within the pre-Lengguru wedge (subduction wedge in the internal zone) leaving low-grade metamorphic sediments on each side while reactivating some of the earlier thrusts. The Yop-Mioswaar unit and the Jamur unit were certainly a previous single unit as their lithologies and temperatures are similar: between 400 and 500 °C (Figs. 7 and 8). In the core of the internal zone (Wandamen Peninsula), the temperatures obtained with the Raman Spectroscopy on Carbonaceous Material method are around 650 °C. This means that the carbonaceous material has been transformed into graphite and that the method is inadequate for these rocks. Nevertheless, these results are consistent with our preliminary multi-equilibrium estimations and therefore the maximum temperature undergone by the rocks is over 650 °C. The last unit, the int. zone 3 with temperatures around 450 °C, corresponds to the last unit to the east before the unmetamorphosed Triassic granites but remains little known. The granites belong to the upper plate and constrain the location of a subduction suture (Figs. 3B and 7).

In the core of the Wandamen Peninsula, fresh eclogitic boulders were sampled. They consist of a garnet–omphacite–quartz–rutile–Na–Ca amphibole paragenesis. We estimate temperatures based on the Fe/Mg exchanges between garnets and omphacites, using Krogh-Ravna (2000) of about 630 °C for a minimum pressure (based on jadeite content in omphacite) of 14 kbar (de Sigoyer et al., 2007). We also suspected the crystallisation of coesite in these eclogites as inclusions of quartz in garnets of omphacites are surrounded by many cracks. The estimation of pressure would be greatly improved if this suspicion is confirmed.

On the northern part of the peninsula the eclogites and the associated metasediments were overprinted by high temperature paragenesis. In the metasediments the paragenesis biotite–sillimanite–garnet overprints a high pressure assemblage of kyanite–garnet–muscovite. Migmatites and anatectic leucosomes (which contain two micas, garnet and tourmaline) are the highest metamorphic evidence on the Wandamen peninsula. Temperatures over 700 °C were estimated for the high temperature event on the base of Fe/Mg exchanges between garnets and biotite .Temperatures in the range of 730 °C and 790 °C. (Bailly et al., 2008) were estimated using the Zr contents in rutiles (Zack et al., 2004). All the metamorphic rocks presented in the Wandamen peninsula bear a north–south mineral or stretching lineation. This orientation may correspond to a strong strike-slip deformation during the exhumation of the metamorphic units. Unfortunately, the age of the eclogite occurrence in the core of the peninsula is still unknown.

Dating using the conventional K/Ar method on biotite, muscovite and hornblende carried out on the Wandamen unit is very young, ±4 Myr (Pieters et al., 1983), and 2 to 8 Myr (Dow et al., 1988). We attribute these young ages to the penetrative north–south fabric and the overprinting warm event which post-dates the subduction-related first prism. One age of 89 Myr was obtained on a possible amphibolite by Dow et al. (1988). This age could be the proof of a previous metamorphic event responsible of the eclogitisation. If the early ages obtained by previous authors were corresponding to the eclogite paragenesis on which we estimated the pressure and temperature conditions, then the exhumation would have been rapid, between 0.7 and 2.5 cm/yr. But as the second high temperature event is very penetrative, especially on the side of the peninsula where the dated samples come from, we believe that the previous estimated ages do not correspond to the deep pressure and temperature conditions which we estimated but to the second warm event associated to a strong north–south shearing.

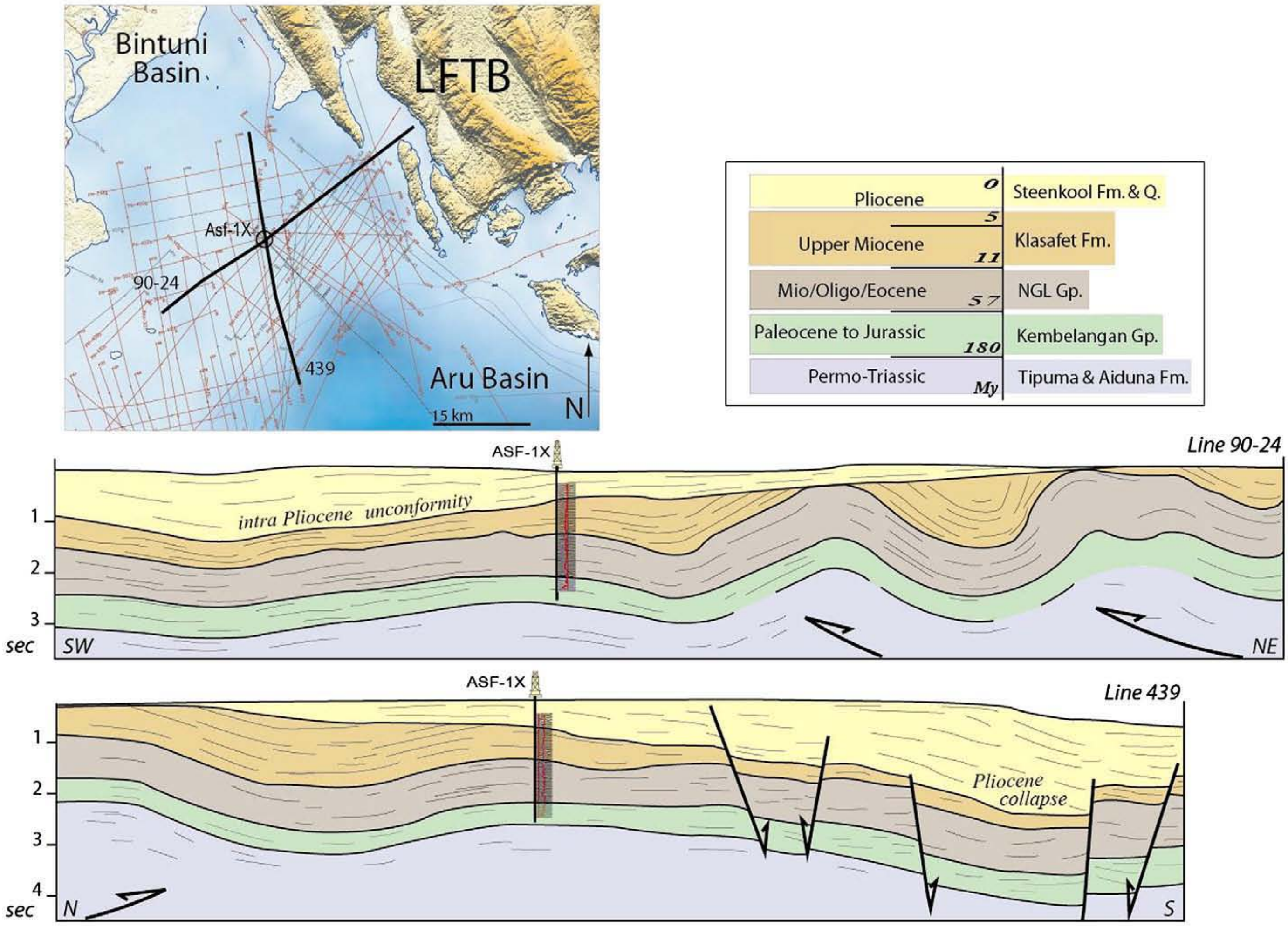


Fig. 6. Line drawing of two seismic lines showing the front of deformation of the LFTB. The NE–SW Mobil line 90–24, shows the offshore thrusts and the folds of the LFTB with a remarkable intra-Pliocene unconformity around 3 Myr dating the end of the LFTB construction. The second Mobil line shows a considerable Pliocene collapse post-unconformity affecting the LFTB.

The parallel orientation of the metamorphic units to the thrusts of the early prism and to the backstop of the range provides a proof of the origin of the deep material in the subduction wedge. The large amount of material found in the Cenderawasih basin favours an exhumation process by staking. We do not know the exact amount of vertical displacement due to crustal thrusting within the compression regime and to the late extensional process but the present dome shape of the Wandamen unit coincides with the active tectonic regime.

5. Discussion

The Lengguru belt, due to its young and partly submarine evolution, allows us to identify accurately a relative chronology of events from Late Miocene to Present. The principal morpho-structures of the belt were controlled by a northeast–southwest compression during Late Miocene to Early Pliocene against a composite arc/ophiolitic crustal backstop. As a result, thin-skinned thrusting of various thicknesses of mesozoic and tertiary sediments over a previously structured basement took place and was later followed by thick-skinned thrusting. At Present and probably since the last dated deformation about 3 Myr ago (Pubellier and Ego, 2002), shortening has ceased in both the Lengguru fold-and-thrust belt and the Central Range of West Papua. Geodetic, seismicity and structural data show that the Lengguru wedge is intersected by the major left-lateral Tarera Fault zone, whereas we observe a strike-slip along the Central Range (Abers and McCaffrey, 1988; Puntodewo et al., 1994) and extension and denudation at the junction between the Central Range and the Lengguru belt (Pubellier et al, 1999).

In order to have a global picture of the zone along which shortening is accommodated, a correlation has been carried out including the structures and succession of events described by Pairault et al. (2003), and Sapin et al. (2009) over a larger transect from the Seram wedge to the Lengguru fold-and-thrust belt (Fig. 9). The simplified section shows a crustal continental block (Bird's Head) overthrusted on both sides by converging wedges of opposite polarities. At the latitude of our transect, the block is thus in the process of being covered by tectonic belts. Its remnant undeformed part is occupied by the Bintuni basin.

Sapin et al. (2009) have similarly proposed a succession of events due to changes of the detachment levels in the Seram Wedge. Starting from Messinian times, shortening constructed an early Seram wedge which affected the western edge of the Bird's Head. During the Pliocene, the deformation became thick-skinned, thus creating a large crustal pop-up known as the Misool–Onin–Kumawa ridge. Finally from Pleistocene to Present, the shortening on the Seram wedge probably accelerated due to the incipient Tarera fault (Pubellier and Ego, 2002; Stevens et al, 2002).

The correlation between these events, all taking place within a narrow time bracket, is summarized in Fig. 9A and B. Toward the east, in the internal zone, the Lengguru belt wedge (prism 1) initiated by

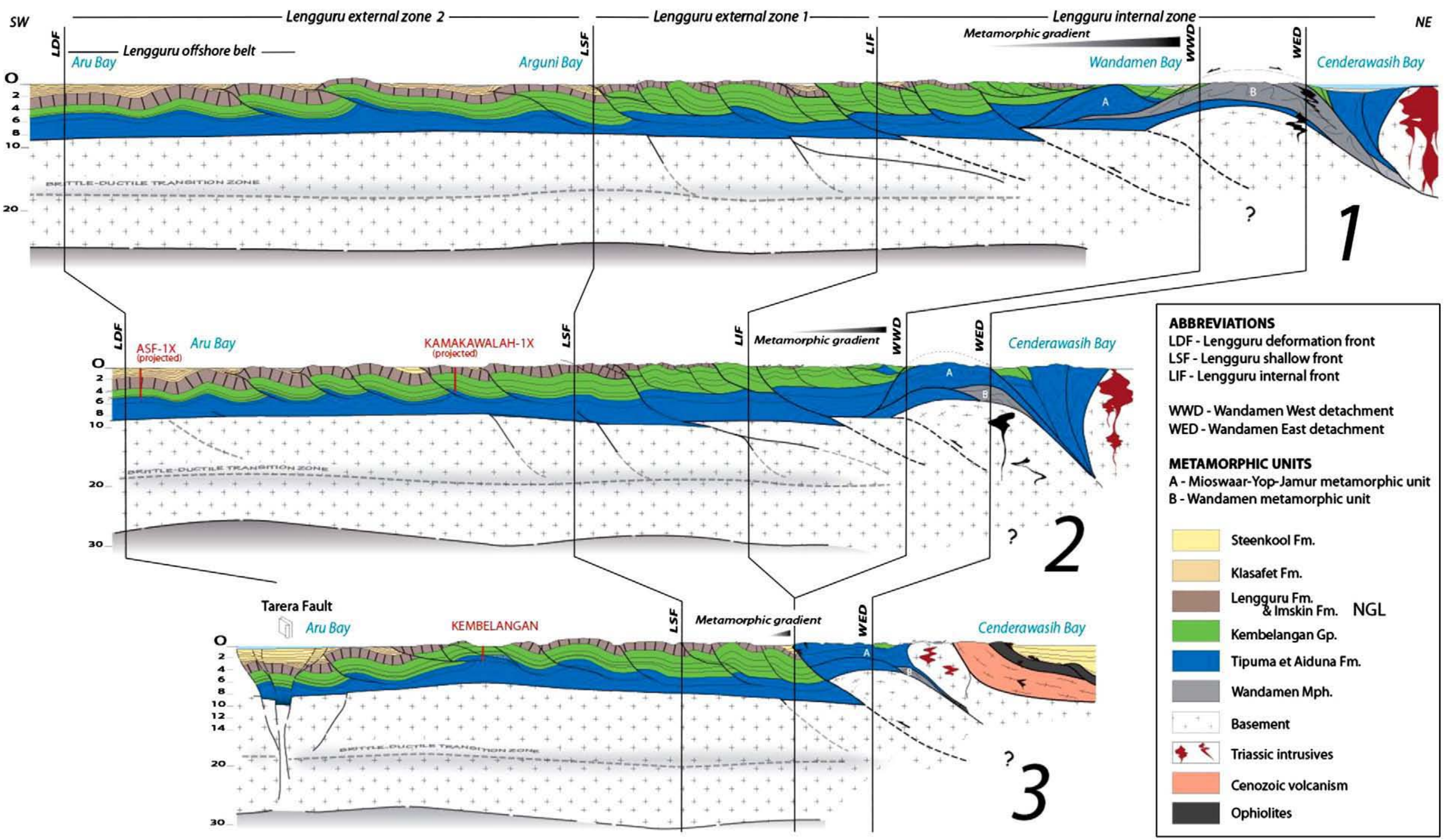


Fig. 7. NE–SW cross-sections through the Lengguru fold-and-thrust belt showing the different fronts and the lateral differences of the range. Location of the cross-sections on Fig. 3A.

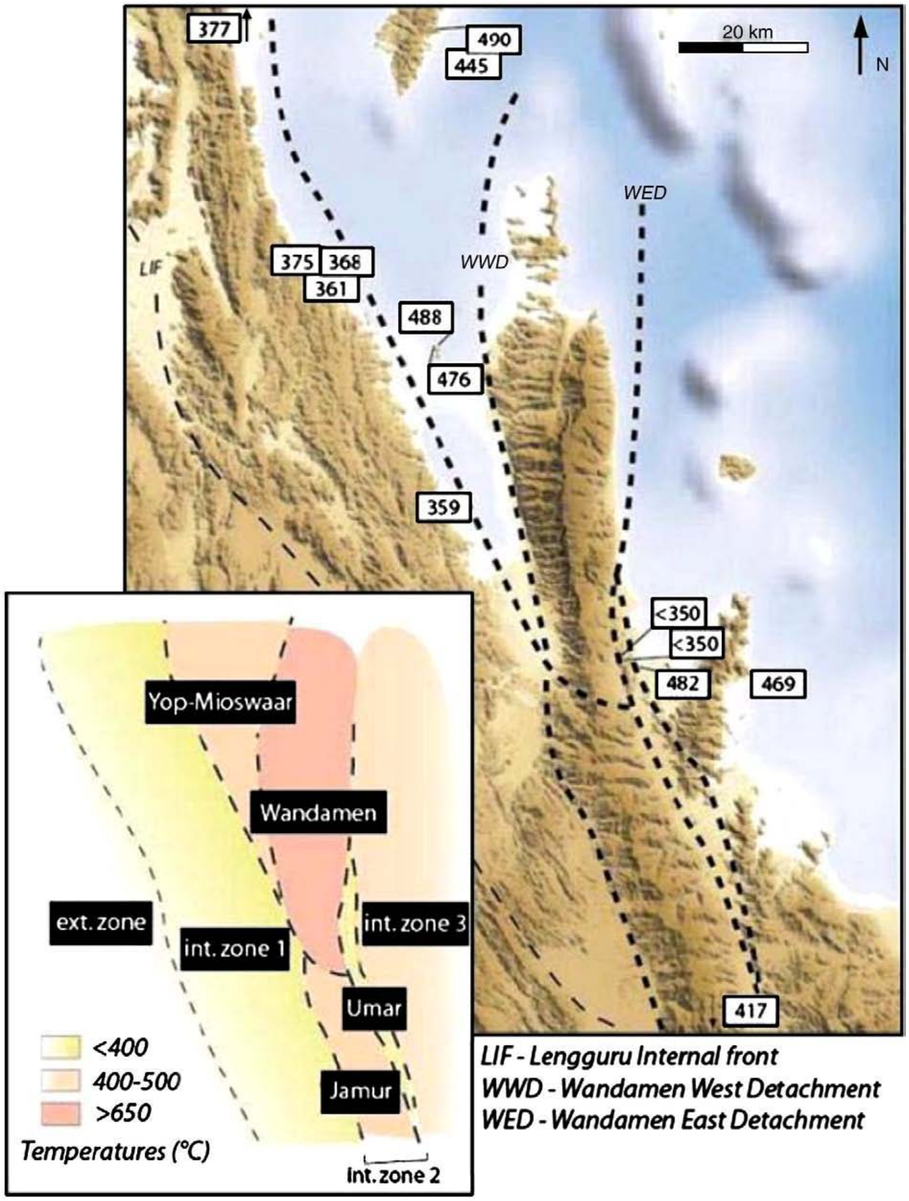


Fig. 8. Location and interpretative sketch of the temperatures estimated by RSCM method into the internal part of the LFTB. We distinguish 3 zones: the int. zone 1, the int. zone 2 composed of 4 units (Yop-Mioswaar, Wandamen, Umar and Jamur) and the int. zone 3. The Wandamen Peninsula temperatures estimated are out of range and not shown here.

the end of Miocene, after the deposition of the stable shelf limestone. The cross-sections presented in this paper (Figs. 5 and 7) show that this wedge is followed by a second wedge (prism 2) developed in the external zone which coeval with the incipient crustal stacking in the internal zones of the Lengguru belt (Fig. 5). This shortening period underwent during the construction of the “old” Seram prism (Fig. 9).

We propose that the following cessation of activity on the Lengguru fold-and-thrust belt, possibly because of increasing friction due to the large development of the wedge, corresponds to a ‘jump’ of the shortening via the Tarera-Aiduna fault. This situation then triggered the crustal thick-skin deformation to the opposite (western) side, on the Misool–Onin–Kumawa ridge during Early Pliocene, which in turn marked the beginning of the strong subsidence in the Bintuni basin (Fig. 9).

Finally, from 2 Myr ago to Present, the tectonic regime became very different on both sides of the Bird's Head block. Meanwhile the present day Seram wedge was becoming the major convergence zone, with a shallow thrust covering the previous structures and approaching sea level in places. The Lengguru wedge underwent a drastic extension which unroofed the sedimentary cover of the Wandamen Peninsula in the internal zone. The extension also caused the Cenderawasih and the Wandamen basins to collapse, and is associated with spectacular extension in the external zone such as the Triton Bay and other similar basins which sliced off the recent conformal anticlines.

The Lengguru fold-and-thrust belt, the Seram wedge and the Misool–Onin–Kumawa continental ridge have accommodated a continuous convergence between Australia and the Pacific since Late Miocene. However the location of the shortening was accommodated at localized zones which jumped through time. When the shortening on the Lengguru wedge ceased, the isolated orogenic wedge started to collapse. Therefore the belt, despite its young age, illustrates and summarizes the whole evolution of a mountain belt.

This example illustrates the way a major and long lasting subduction ends up. The deformation still rooted at the suture zone (east of the belt internal zone) is suddenly widespread and develops the Lengguru fold-and-thrust belt via large decollement layers. The decollements use rheologic contrasts both in the sediments and in the

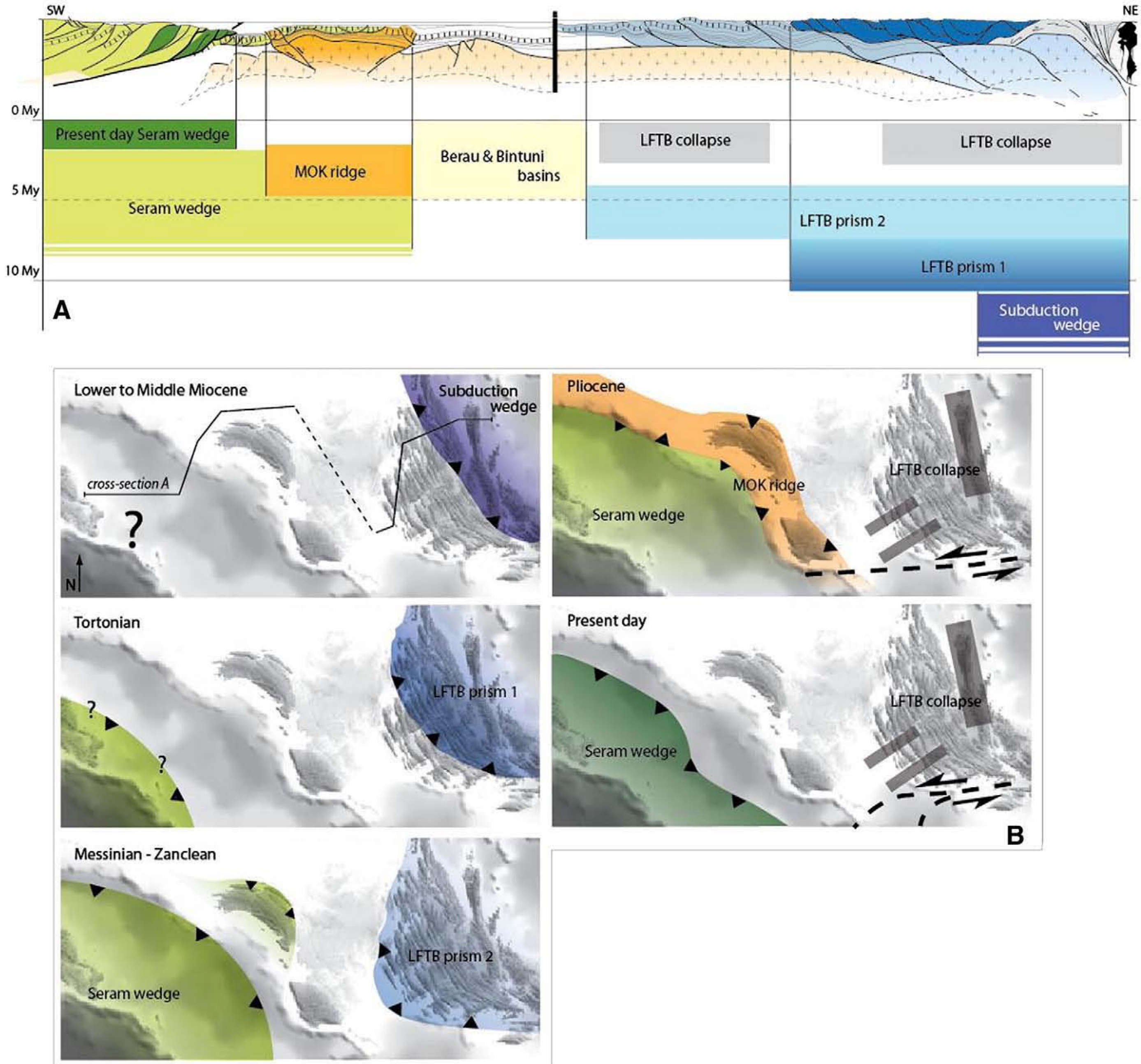


Fig. 9. (A) SW–NE simplified cross-section (location on B) from the Seram wedge to the LFTB with underneath time scale since lower Miocene time. (B) Successive sketches from lower Miocene to present day showing the location of the active structures. Both show the activation age of each structure through space and time but also the style of deformation (MOK, Misool–Onin–Kumawa, ridge and Seram prism are modified from Sapin et al. (2009)).

crust. This deformation occurs during a very short time span until the shortening is forced to another location.

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