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GEOLOGICAL STRUCTURES AND TECTONIC RECONSTRUCTION OF LUWUK, EAST SULAWESI

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ABSTRACT

Luwuk at the eastern end of Sulawesi's East Arm has been recognized to be formed under obductional tectonic where the East Sulawesi Ophiolite Complex thrusted southward over the Banggai-Sula microcontinent during Late Neogene event. At the southern section, a gas field of Tomori has been developed with reservoirs distributed in the pre-collisional Miocene carbonates. To date, explorational work over the area has been incorporating collisional structures such as thrusts and wrench faults into the petroleum systems, e.g. hydrocarbon maturation and trap formation. Most of the structural concept based on the existing model of southeastward vergeance thick-skinned (ophiolitic basement involved) thrust-fold belt.

A geologic field work has been conducted transecting north-south section and east-west section of Luwuk. Satellite imagery interpretation and field observation suggest the existance of three structural compartments, i.e.: (i) the northern extensional, block-faulting, tectonic regime on the ophiolite complex, (ii) the central compressional, northwestward vergeance thrust-fold belt, tectonic regime on the Tertiary carbonates, and (iii) the southern, locally gravitational sliding, tectonic regime on the Pliocene molasse. Each compartment exhibits distinct structural style and diverse tectonic control.

The northern extensional compartment were controlled by rifting of Siuna Bay along the Late-Miocene right-lateral movement of Balantak Fault. The central compressional compartment were developed by the Late Pliocene northwestward shortening due to activation of Sorong Fault. The southern gravitational Molasse sliding were induced by the Late Pliocene uplift along the existing weak zone of north-south transtensional strike-slip fault. Implication of this research to petroleum exploration is a revision of Luwuk thrust-fold belt model, which is proposed to be thin-skinned (basement uninvolved) northwestward vergeance.

INTRODUCTION

Tectonic of eastern Indonesia is built upon convergence history between three major lithospheric plates, i.e. the Australian Plate, the Pacific Plate and the Eurasian Plate. One of the key area in understanding those plate interaction and its impact to geology and hydrocarbon resources is the East Arm of Sulawesi, where collision has been taking place since the Late Cenozoic between the North Sulawesi island arc and the Banggai-Sula microcontinent (Figures 1 and 2).

The East Arm of Sulawesi comprises a thrust-fold belt, consisting of disrupted and tectonized ophiolites, associated with Mesozoic to Cenozoic oceanic sediments (Rusmana *et al*., 1993; Surono *et al*., 1993). This belt is flanked by a cover of Neogene clastics, dominantly Pliocene sands and gravels, known as the Sulawesi Molasse. The thrust zone, called the Batui Thrust (Silver *et al*., 1983; Garrard *et al*., 1988), separates the ophiolites from the sedimentary formations with the NW block as upthrown part, suggesting a SE-vergent thick-skinned (basement-involved) thrust-fold belt (Figure 2). The Batui Thrust is also observed to be continued further eastward offshore (Watkinson *et al*., 2011).

Luwuk is a coastal town near the eastern tip of Sulawesi's east arm. This area is situated in the central portion of the arcuate thrust-fold belt where Quaternary reefs was utmost elevated.

It is speculated that the area had suffered maximum compression of Banggai-Sula microcontinent, as it is located at the frontal collisional zone. The distance to Peleng Island, the westernmost front of Banggai-Sula microcontinent, is just about 30

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kilometres as separated by a narrow Peleng Strait. The elevation of Luwuk uplifted reef terraces gradually decreases towards the east tip of the peninsula and towards the southwest of Batui Town (Rusmana *et al*., 1993a; Surono *et al*., 1993). Beyond Batui the Quaternary coastal development along the Gulf of Tolo is governed by subsidence, as indicated by the presence of a vast, swampy coastal plain and drowned reef platforms offshore.

Southwest from Batui down to Tomori Embayment along the shoreline, a major Tomori PSC gas field was explored and operated since mid 1980s (Davies, 1990). Hydrocarbon exploration in this area was supported by the above-mentioned tectonic concept, which was mostly derived from geologic observation in Luwuk area. This paper attempts to examine the existing concept, as a new finding during field mapping in crossing the East Arm of Sulawesi, from Luwuk to the north to Pagimana.

METHODOLOGY

This paper presents result of geologic mapping conducted by Department of Geological Engineering Universitas Gadjah Mada (UGM) with Pusat Survey Geologi (PSG, Center for Geological Survey). Particular research stages have been developed as: (i) desk study and satellite imagery analysis which produced tentative geologic map, (ii) field mapping where stratigraphic and structural data had been collected along selected key traverses, (iii) laboratory examination incorporated petrographic - paleontologic analysis and structural data analysis, and (iv) construction of geologic map and tectonostratigraphic synthesis. However, since this paper focuses on tectonic reconstruction, presentation and discussion on stratigraphic data are just adequately given in supporting structural aspects.

Satellite imagery used in this work was a composite image of Landsat and Digital Elevation Model (DEM), and several physiographic unit and major structural elements could undoubtedly be established. These physiographic delineation were intensively used in determination of lithologic unit and their coverage limit. Field traverse consist of one major north-south transect from Luwuk in the south to Poh in the north, perpendicular to the East Arm structural trend and covering most of the lithologic unit (Figure 3). Another east-west segmented transect was added in the northern area to cover extention of those major structural elements. Structural data collected in the field mostly composed of abundant minor faults along the major fault zone, where kinematic analysis were later performed in the laboratory.

GEOLOGICAL SETTING

Luwuk is considered to be located in a collisional belt between the Banggai-Sula microcontinent and the East Sulawesi Ophiolite complex. The Banggai-Sula microcontinent is interpreted to be originated from western Papua (Watkinson *et al*., 2011) and had been drifted westwards along the Sorong Fault (Garrard *et al*., 1988). Initial extensional phase on mid Mesozoic as represented by a transgressive phase of continental to shallow marine Jurassic clastics was followed by passive margin sedimentation through Cretaceous and early Tertiary during its drift.

A major regional unconformity separated the Mesozoic sequences with deposition of Oligo-Miocene carbonate. The collision of Banggai-Sula with Sulawesi probably took place from Middle Miocene (Garrard *et al*., 1988). It is commonly assummed that the collision responsible for overthrusting the East Sulawesi Ophiolite over the Banggai-Sula leading edge. This compressive period further have uplifted the eastern arm of Sulawesi, producing molasse deposition to its surrounding lower areas. This uplift is still taking place, as indicated by earthquakes and tremors (Watkinson *et al*., 2011). However, some Plio-Pleistocene normal faulting were observed, and tought to be caused by relaxation of the earlier compressive phase (Watkinson *et al*., 2011).

The collision of Banggai-Sula and obduction of East Sulawesi Ophiolite were assummed to be accommodated by the Batui Thrust zone, located north of Luwuk (Watkinson *et al*., 2011). They formed an arcuate thrust front eastwards towards Balantak, and imbricated further southeast, had caused this fault zone interpreted as SE-vergence (van Bemmelen, 1949; Hamilton, 1979). Based on seismic and gravity data, Silver *et al*. (1983) suggested that the Batui Thrust extended offshore to the east. However, with reexamination on new and better seismic dataset of similar line, Watkinson *et al*. (2011) had doubted their interpretation of a north-dipping thrust plane, and suggested new south-dipping normal faults developed in extensional system. Another seismic line yet suggested the Batui Thrust probably, though poorly understood, as a north-vergent thin-skinned thrust system (Watkinson *et al*., 2011). More amusingly, these north-vergent thrusts were overlying by undisturbed marine sediments, which expanding contradiction to arguments on south-vergent Batui Thrust as an active structures (Figure 4).

The eastern onland segment of Batui Thrust, that cut the Poh Head into the northern rugged mountainous area and the southern smoother topographic one, is also re-interpreted by Watkinson *et al*. (2011) as dextral strike-slip fault and named as Balantak Fault. Rusmana *et al*. (1993a) have named the Balantak Fault as Siuna Fault. Sigmoidal folds on seabed morphology suggest that this Balantak Fault was a transpressive fault (Watkinson *et al*., 2011).

RESULTS

Geologic mapping conducted in the study area had resulted on new finding on stratigraphy and geologic structures, as presented on the simplified geologic map in Figure 5.

However, since this paper is focusing on geologic structures and tectonic, then presentation on stratigraphy is briefly given, particularly to support discussion on basinal tectonic evolution.

Stratigraphy

Regionally, there are various kind of rock formation in the East Arm of Sulawesi, with their age ranging from Jurassic to Recent. The following description is given only for those found in the study area, which were identified into 8 formation (Figure 6).

1. **Ultramafic Complex**
   Most of ultramafic rocks were found in the northern part of study area, along the northern coast of East Sulawesi Arm. They consist of gabro, basalt, serpentinit, and few phyllite and schist. Their age was dated to be ranged from Middle Cretaceous to Late Oligocene, broadly known as Balantak Ophiolite and considered as part of a broader East Sulawesi Ophiolite belt (Simandjuntak, 1986; Mubroto *et al*., 1994; Kadarusman *et al*., 2004).

2. **Lamusa Formation**
   In the study area, this formation was found in Poh and Salodik, which mostly composed of cross-laminated calcareous sandstones that deposited in neritic environment during Middle to Late Cretaceous.

3. **Matano Formation**
   This formation composed of crystalline limestones, which found in Pagimana. They are intercalated with well-bedded reddish chert. Its age was Middle Cretaceous.

4. **Salodik Formation**
   This first Tertiary formation unconformably deposited over Mesozoic rock units. This research observed this formation probably deposited since Early Eocene, much earlier than previously mentioned by Rusmana *et al*. (1993a), which was Late Eocene. Three sedimentary facies were found, i.e. Nummulitic grainstone-rudstone, grainstone intercalated with calcareous sandstone, and rudstone intercalated with reefal limestones. Their depositional environments varied from reef to shallow marine.

   Nummulitic grainstone-rudstone facies was observed in the heart of Salodik anticlinorium. They are deposited in reef front environment during Early to Late Eocene, as characterized by large foraminifera as *alveolina*, *heterostegina, numulite,* and *austrotilina*. Grainstone intercalated with calcareous sandstone facies contains smaller nummulitic fossils. Rudstone intercalated with reefal limestones, which was identified to be deposited in Early Eocene to Middle Miocene, were characterized with fragments composed of coral, algae, mudstone, and grainstone containing nummulites. Reefal limestones mostly composed of framestone with few bindstone containing *acropora palmata, pelecypoda* and algae.

5. **Poh Formation**
   This formation was interfingered with Salodik Formation. Rusmana *et al*. (1993a) had estimated depositional age of Late Oligocene to Early Miocene, however this research found it initiated earlier and ceased later, that is Early Eocene to Middle Miocene. Depositional environments ranged from lagoon, neritic, to bathyal. There are two lithologic facies recognized for this formation, i.e. packstone-marls and calcareous sandstone-shales. Packstone-marls were grading to grainstone and rudstone, whereas marls contained few thin lenses of lignite. Calcareous sandstone-shale facies were found in Pagimana, both rock unit were in thick bedded.

6. **Kintom Formation**
   This formation was deposited unconformably over Poh Formation during Pliocene. It was observed in Luwuk and mainly composed of ultramafic conglomerates, and deposited in alluvial fan.

7. **Uplifted coral reef**

This unit consists of three facies, i.e. limestone breccias, limestone conglomerates, and rudstones. Limestone breccias were found in Pagimana, composed of limestone and coral fragments which embedded in mix silicic-carbonate coarse-sand matrix. They are deposited in planar cross bedding, probably in beaches to shallow platform environments. Their age is estimated of Pliocene.

Limestone conglomerates were observed in Luwuk, composed of loose allochemic conglomerates with thin layer of cross-bedded calcareous sandstones. It contents planktonic foraminifera *Globigerinoides extremus* Bolli of middle to late Pliocene, and bentonic foraminifera *Ephidium advenum* Cushman of dengan inner neritic environments.

Rudstone-reefal limestones were widely formed beach terraces, up to elevation of 400 m above sea level. They mostly consists of chalky framestone and rudstone, with approximate age of Pliocene to Holocene and deposited in shallow platform. Observable macro fossils such as nodular corals, *acropora cervicornus*, *acropora palmata*, and various molluscs.

8. **Alluvial**

It consists of sand, gravel, and mud. They are interfingered with rudstone-reefal limestone facies of coral reef unit. Their depositional environment are braided river and beaches.

Geologic structures

Remote sensing interpretation and field mapping have identified geological structures of faults, folds, and mass movement (Figure 5). There were three kind of faults, i.e.: thrust and reverse faults, normal block faults, and strike-slip faults. The most conspicuous major thrust fault is Salodik Thrust, that developed in the middle of study area and extending in ENE-WSW direction (Figure 5). The Salodik Thrust had deformed the Eocene-Oligocene reefal limestones of Salodik Formation and the Eocene-Miocene fine-grained marine sediments of Poh Formation. In fact, the Salodik Thrust actually is a name given to the well-known Batui Thrust which was applied in the study area.

Block faulting were developed in the northern part of the study area, collectively named as Poh fault zone and Bungawan fault zone (Figure 5). These block faulting oriented in E-W direction, each segment was curving northward, cutting both the Late Cretaceous-Paleogene ultramafic rocks and the Tertiary Poh Formation. Block faulting were also developed in the southern part of study area, aligned in NNW-SSE trend and collectively named as Biak fault zone (Figure 5). This fault zone cut Plio-Pleistocen molasse of Kintom conglomerates, limestone breccias, and uplifted reef terraces.

Strike-slip faulting was noticed in the south of Luwuk Town with left-lateral sense of displacement (Figure 5). This Luwuk sinistral fault trends NW-SE and cut almost all rock formation of the area, i.e. Plio-Pleistocene uplifted reef terraces in the south, Tertiary Poh Formation, Eo-Oligocene Salodik Formation, and Paleogene ultramafic rocks in the north. Another strike-slip fault but with right-lateral sense of displacement was observed in Salodik Village (Figure 5). This dextral Poh Fault was aligned NNW-SSE and in prolongation with Biak block faulting, thus it appears that these two fault system were linked in transtensional mechanism.

Folds are the most obvious geologic structures of the study area. Their geomorphic expression, such as elongated and warped ridges, as well as trellis drainage pattern, were evident in topographic map and satellite imageries. Folds were developed in the center of study area and prolonged in ENE-WSW, had deformed the Paleogene Salodik and Tertiary Poh limestones. As they consists of numerous smaller folds and the oldest strata were exposed in its center around Salodik Village, these folds were named as Salodik anticlinorium (Figure 5). To the north of Salodik Village, a minor parasitic S-fold were observed with its relatively horizontal axial plane, suggesting that the northern limbs of Salodik anticlinorium was overturned to the northwest (Figure 7). As arrangement of Salodik anticlinorium is sub-parallel to the adjacent Salodik Thrust that located its northern margin, hence both structures are thought to be connected each other in fold-thrust belt orogenic course.

Major mass movement were mostly developed in the southern part of studi area, between Kemumu to Biak villages (Figure 5). These surficial deformation were dominated by rock slides, as inferred from arcuate crown escarpment and the presence of minor toe-thrust faults at its terminus. The movement involved several rock formation, from the Paleogene Salodik limestones to the Plio-Pleistocene Kintom conglomerates and uplifted reef terraces. Distance across this Kemumu rock slides varies from 1 to 4 kilometres, and they are aligned in WNW-ESE to NNW-SSE. As their location just across the Biak block faulting, it is most likely that those two structures were genetically associated, where the Kemumu rock slides occurred as antithetic structures for the Biak block faulting in extensional tectonic regime.

DISCUSSION AND SYNTHESIS

Structural compartment

The field mapping and satellite imagery interpretation result on three structural or morphotectonic compartment, i.e. (i) the northern extensional, block-faulting, tectonic regime on the ophiolite complex, (ii) the central compressional, northward vergeance thrust-fold belt, tectonic regime on the Tertiary carbonates, and (iii) the southern, locally gravitational sliding, tectonic regime on the Pliocene molasse. Each compartment exhibit distinct structural style and diverse tectonic control.

Evidences for the northern extensional compartment were mostly observed in the Late Cretaceous – Paleogene Balantak Ophiolite complex. Beside of Poh and Bungawan block faulting which were determined from satellite imagery interpretation, other field data also strongly support the existance of extensional regime. Such as a kinematic analysis on a minor fault plane at Pagimana (Figure 8), which suggest a NE-SW extensional system had occurred on the area. The mechanism of extensional regime in this structural compartment is most likely to be controlled by rifting of Siuna Bay along the Late-Miocene right-lateral movement of Balantak Fault.

The involvement of Balantak strike-slip fault in this extensional tectonic regime have suggested from two indication, i.e. (i) similar rock distribution and coastline geometries around Bay of Poh, and (ii) structural geomorphic indicator and outcrop-scale data. There are so much resemblance of coastline around Bay of Poh, suggesting that they had been teared open to form the present embayment. This supposition is also supported by similarities of rock types, that is ultramafic complex, in both coasts of Poh embayment, suggesting that once they were same rock mass (Rusmana *et al*., 1993a). Geomorphic data along the northern escarpment of Siuna valley, as eastward extension of Poh embayment, showing triangular facets as indication of normal faulting (Figure 9). Various minor fault data found along the Siuna Valley also indicate a predominant NE-SW extension (Figure 10).

The central compressional compartment dictated almost all features of geomorphology and geologi structures in the study area, except the northern extensional compartment. It is characterized by the existence of Salodik anticlinorium, which involved almost all the sedimentary rock formation. The mechanism for compressional tectonic regime was developed by the Late-Pliocene northwestward drift of Banggai-Sula microcontinent due to activation of the regional Sorong strike-slip fault.

Apparently this compression of sedimentary rocks remarked the inversion of a sedimentary basin, in which at the southeastern side received significant shortening from Banggai-Sula approaching while at the northwestern side impeded by Balantak Ophiolite that influenced under completely different tectonic regime. Along the southern coast of East Arm of Sulawesi, the obvious evidence of this compressional uplift was the multi-level coastal terraces. Sumosusastro *et al*. (1989) have dated the 0.35 mya reefal terrace and calculated the rate of uplift might reached 1.84 mm/year, suggesting the Plio-Pleistocene uplift lasted to Recent.

The southern gravitational Molasse sliding, in this paper is named as the Kemumu rock slides, were also induced by the Late Pliocene uplift in which some strain were accommodated along the existing weak zone of Late Miocene north-south strike-slip fault. It appears that the southern section of the Poh strike-slip fault had triggered the transtensional regime and created Biak block faulting. The latter then induced the Kemumu rock slide. It means that this graviational sliding was local occurrence during the Luwuk uplift.

Tectonic development

From explanation above, those three structural compartment still have been looked as if they were three different mechanism. However, in author’s plain opinion, they have worked simultaneously together. It appears that the present-day morphotectonic distribution should be perceived from the tectonic uplift processes that brought all rocks to the surface. Thus, discussion in this part is limited to the responsible tectonic processes for the morphotectonic units. Further discussion on tectonic interaction processes in basin and regional scale of Banggai-Sula microcontinent and East Sulawesi Ophiolite complex is given in Husein *et al*. (in prep.).

The Balantak Ophiolite was uplifted first in the study area, during Late Miocene event. It was when the ophiolitic rocks were subjected to terrestrial erosion and producing initial Molasse deposit of

Kintom Formation. The mechanism of this first pulse of uplift was NW-ward compression of Banggai-Sula microcontinent as it had been pushed by North Banda Sea opening and spreading. It is deduced that in this period the activation of Balantak Fault had been initiated.

The second pulse of uplift, also the most influenced on the study area, occurred in Late Pliocene event. It was when the Banggai-Sula had another NE-ward pushed by the activation of Sorong Fault. This event inverted the Luwuk Basin, uplift its sedimentary rock formation into a major anticlinorium. The key structure in this inversion is Salodik fold-thrust belt, that consists of Salodik/Batui Thrust and Salodik Anticlinorium. This compressional compartment further had local gravitational regime of Kemumu rock slides as driven by the transtensional Poh strike-slip fault.

However, the Banggai-Sula approaching and NW-ward compression also made the Poh Head to be clock-wised rotated along the E-W weak zone of Balantak Fault. It could be occurred as Poh Head located in the right margin of outer rim of Banggai-Sula approach. These Poh rotation and right-lateral slip of Balantak Fault were responsible for the extensional regime over the Balantak Ophiolite exposures in the north of study area. Thus, it was the Late Pliocene event that brought the study area to the present-day morphotectonic arrangement.

Tectonic transport

Most of previous publication have speculated on southeastward tectonic transport of Luwuk Basin (Garrard *et al*., 1988; Davies, 1990; Parkinson, 1998). It is when the Balantak Ophiolite interpreted to be obducted southeastward over the sedimentary formation through a series of SE-ward vergent thrust faults. The main Batui Thrust was drawn with the NW block as upthrown part. This interpretation was derived from assumption that the Banggai-Sula microcontinent once separated from the East Sulawesi Ophiolite complex. The Late Miocene collision was thought to be responsible for NE-ward approaching and collision of Banggai-Sula to the East Sulawesi Ophiolite, obducted the ophiolite SE-ward over the sedimentary formation. In this viewpoint, the Luwuk Basin had experienced a significant shortening, as the Banggai-Sula microcontinent had drifted hundreds of kilometres from southeast.

However it is not the case observed in field. Salodik anticlinorium as the main compressional structure have shown normal anticline younging direction with minor indication of extreme recumbent or overturned bedding. In broader viewpoint, the Salodik anticlinorium is a portrayal of a typical asymmetric anticline, with a steep north forelimb and a gentle south backlimb. A field evidence of the presence an S-shaped parasitic fold in the northern limb of Salodik anticlinorium have suggested that the system was a NW-ward tectonic transport.

Indeed there is one outcrop just south of Poh Village that showing a structural contact of reverse faulting between the Balantak Ophiolite with Poh Formation, where the northern ophiolite is the upthrown block (Figure 11). However, looking at the structural compartment working in the study area, this particular reverse fault does fit into the local contact response between the northern extensional area with compressional belt regimes, and it does not represent the whole obduction scenario. Thus, this paper recommends a model of thin-skinned NW-vergent thrus-fold belts for the East Arm of Sulawesi.

Implication to hydrocarbon exploration

There is one report on the occurrence of hydrocarbon seepages in the study area, that is located in Lobu-Lobu Village, Pagimana. Rusmana *et al*. (1993a) put the seepage on the Balantak Ophiolite complex. Since it is most unlikely to have seepage from ophiolite rocks, this indication have been used to support the existence of subthrust sedimentary formation, which further also strengthened the occurrence of SE-ward ophiolitic obduction over the Luwuk Basin. However, this research have visited the outcrop site, and found out that the seepage was located in the Early Miocene Poh limestones. Thus, it does not necessary to evoke the SE-ward obduction scenario.

There are also several other reported hydrocarbon seepages around the Gulf of Tolo, that is located south of the study area. Most occurrences were observed near Batui Town (Surono *et al*., 1993; Figure 2), which was further have explored by the gas-producing well of Matindok-1 (Davies, 1990). In this area, those seepages were found on the Pliocene Kintom molasse that unconformably covered the Eosen Salodik limestones. The drilling revealed the existence of Early Miocene reefal limestones overlying the granitic basement. Measured depth to the granite was 9830 feet.

Further south to the Bay of Tomori, some seepages were also reported in the regional geologic map.

Another seepage was observed around Tokala Village just north of Bay of Tomori (Surono *et al*., 1993; Figure 2). This seepage was found on the indeterminated structural contact of the East Sulawesi Ophiolite with the Triassic Tokala limestone, one of the oldest sedimentary rock formation in the East Arm of Sulawesi. Offshore 20 kilometres to the east from Tolaka Village, a number of oil wells, Tiaka-1 (oil and gas), Tiaka-2 (oil-producing), Tiaka-3 (dry hole), Tiaka-4 (non-commercial oil) and Kalomba-1 (dry hole), have been drilled (Davies, 1990). Those wells penetrated the Early Miocene reefal limestones overlying the metamophic basement. Depth to the basement was 11,075 feet in Tiaka-2 and 11,219 feet in Tiaka-3.

In between Tiaka and Matindok fields at a distance of 45 kilometres SW Matindok along the shoreline, the first drilling in the area by Union Texas at 1983, known Mantawa-1, was located (Davies, 1990). It is a gas-producing well, penetrating the Miocene limestones that overlying granitic basement. Depth estimation to the top of the granitic is 8515 feet. Another well was drilled in between Mantawa and Matindok fields, at a distance 20 kilometres SW Matindok along the shoreline, and labelled as Minahaki-1 well (Davies, 1990). It was a gas-producing well from the Miocene limestones, and had penetrated the granitic basement at 8239 feet depth.

Another see page was found in the Lamona Village, south of Bay of Tomori (Simandjuntak *et al*., 1993a; Figure 2). It is located in the deep marine Cretaceous Matano limestones that probably being deposited at the same time with East Sulawesi Ophiolite magmatism. The Matano limestones and the ophiolitic complex were in structural contact with the Triassic shales-containing Tokala Formation that possibly to be source rocks potential for the seepage. About 30 kilometres further north of the seepage, two drilling have been conducted offshore, a dry-hole Tolo-1 and a gas-producing Dongkala-1 wells (Davies, 1990). The Dongkala-1 was penetrated the ophiolites at 3107 feet, which interestingly showing gas production from fractured reservoirs.

The petroleum exploration in the Gulf of Tolo and Bay of Tomori was targetting the Miocene limestones (Davies, 1990). The proposed source rocks were Middle Miocene shales, and its maturation time is put to be related with Plio-Pleistocene thrusting event and molasse depositional system. Some seismic data suggest that molasse deposits might attained 1.5 seconds thick, which is showing rapid sedimentation had occurred since Late Pliocene (Davies, 1990; Satyana, 2006). However, it is about thrust faulting that came to author's attention regarding this paper.

Davies (1990) have put several seismic lines in his publication. Two lines located in Minahaki Field and oriented NW-SE, capturing a gentle and relatifely undisturbed Miocene limestones and the overlying Plio-Pleistocene molasse. This field sit on the granitic basement that observed in 8239 feet depth. Davies (1990) have intepreted a positive flower structure of possibly E-W wrench fault in order to explain a gentle undulating reflectors (Line-4), which was strangely disappeared in the adjacent a kilometre south Line-3 although the gentle undulating reflectors were still identifiable.

Another seismic line crossed the Tiaka Field in WNW-ESE direction. Few indistinct SW-vergent thrusts were intepreted cutting the Miocene limestones (Davies, 1990). Comparable to the seismic lines in Minahaki Field, seismic reflectors pattern in this field also suggests a gentle and relatively undisturbed Miocene to Pleistocene section. It was reported that those thrust fault which identified at depth of 9100 feet, separated the overlying Miocene limestones with the underlying Plio-Pleistocene molasse (Davies, 1990), before Tiaka-3 encountered the metamorphic basement at depth of 11,219 feet. However, there was no further report on the subthrust clastic section that as thick as 2100 feet, thus it is demanding to be certain the nature of this 'molasse'.

The adjacent Tiaka-2 well that was located at 2.5 kilometres NE from Tiaka-3, had penetrated the metamorphic basement at 11,075 feet (Davies, 1990). These two wells were supposed to penetrate similar overthrust structure, however the Tiaka-2 had not encountered the thrust fault. In the Tiaka-2 well, the Miocene limestones overlaid the 60 feet basal clastic that unconformably covered the metamorphic basement. Therefore, is it possible that the 'subthrust molasse' of Tiaka-3 was essentially an Eocene basal clastic as found in Tiaka-2?

Another seismic line crossed the Dongkala-Tolo field, and few NE-ward vergent thrust faults were interpreted had cut the Miocene limestones and deformed the Plio-Pleistocene molasse (Davies, 1990; Satyana, 2006). The Dongkala-1 penetrated a thick Plio-Pleistocene molasse and encountered the ophiolites at 3107 feet, without any significant Miocene limestone section (Davies, 1990).

The Tolo-1 had penetrated a thick Miocene limestones and terminated at 11,000 feet depth without encountering basement. This substantial change of lithologic section in a distance of 3 kilometres between those two wells, suggesting that the controlling structures were not thrust faults, but major strike-slip faults.

Wrench tectonic is more plausible hypothesis than thrust-fold belts for Dongkala-Tolo field. This field is located perpendicular to NW-SE alignment of Tomori Bay, where the Manui Fault Zone existed and down SE offshore (Garrard *et al*., 1988). Numerous onshore geomorphic evidences have supported the presence of NW-SE wrench fault.

The NNW extension of Tomori Bay was a linear valley of Wekuli Fault that acting as a major structural contact between the East Sulawesi Ophiolite to the east with the high-pressure metamorphic Pompangeo complex, both were Cretaceous in age (Simandjuntak *et al*., 1997).

To the south of Dongkala-Tolo field, another major strike-slip of the WNW-ESE Matano Fault was unmistakably observed, although it was supposed to be kinematically right-lateral strike-slip in order to pull the Matano Lake apart, in opposed with a more well-known assumption of left-lateral strike-slip (Simandjuntak *et al*., 1993a,b; Moss & Wilson, 1998). The existing seismic line could also be intepreted of the existence of wrench faults, as the undulating reflectors might have been produced by some vertical movement in a transpression strike-slip faulting.

Since there were no compelling indication for SE-vergent thick-skinned (basement-involved) thrusts, both from surface mapping in Luwuk as presented by this paper as well as re-examination on published sub-surface data in Tomori PSC (Davies, 1990; Satyana, 2006), several points need to be considered as follows:

- Hydrocarbon system established in the East Arm of Sulawesi was not related with the SE-vergent thick-skinned thrust front that deduced from unconvinced assumption of tectonic obduction of East Sulawesi Ophiolite complex over Banggai-Sula microcontinent.
- Mesozoic source rocks need to be proposed and quested in order to provide an alternative for previous postulation that main source rocks were Miocene section which required sufficient overburden of Plio-Pleistocene thrust sheets (Davies, 1990). Mesozoic source rocks were not supposed to require thrust sheets emplacement for hydrocarbon maturation, as they had been subsided deep enough in the basin.
- Swelling anticlinal traps as shown in Tiaka and Minahaki fields (Davies, 1990) were not necessarily being produced by SE-vergent thick-skinned thrust nor E-W wrench fault as they could also be resulted from WNW-vergent thin-skinned thrust as proposed in this paper.
- Further assessment were needed to separate the hydrocarbon play system in the Tomori PSC, among the NE section (Matindok, Minahaki, and Mantawa fields), the central section (Tiaka and Kalamba fields), and the SW section (Tolo and Dongkala fields). They have different type of basement and structural control. The NE section exhibits gentle deformation over a granitic basement. The central section suggests gentle deformation over a metamorphic basement. The SW section denotes a strong influence of wrench fault tectonic over an ophiolitic basement. In regional perspective, this Dongkala-Tolo fields actually is not entirely located in the East Arm of Sulawesi, but in the SE Arm of Sulawesi, which is indeed vastly dissected by wrench tectonic (Simandjuntak *et al*., 1993a,c; Rusmana *et al*., 1993b).

CONCLUDING REMARKS

This geologic mapping program yields some new structural intepretation on Luwuk Basin, that are:

- The collisional event between Banggai-Sula microcontinent and the East Arm of Sulawesi had resulted in a thin-skinned NW-vergent fold-thrust belt, in opposite with the existing assumption on the SE-vergent fold-thrust belt.
- Three structural compartments were established in the East Arm of Sulawesi, i.e. (i) the extensional Balantak Ophiolite division that directed by the Late Miocene transtensional Balantak dextral fault as well as the Poh Head clockwise rotation, probably induced by North Banda Sea spreading, (ii) the compressional Salodik fold-thrust belt that forming the main section and produced by the Late Pliocene compressional event due to activation of Sorong Fault, and (iii) the gravitational mass movement in the southern limb of Salodik Anticlinorium as provoked by the Late Pliocene Poh strike-slip fault.
- Previous arguments on the structural and basinal relation of Luwuk to the Tomori Field

in the SW part of the East Arm need to be reviewed. There were no considerable compressive structures observed in sub-surface. Indeed there is compressive structures noticed in the Dongkala-Tolo fields, but they are more suitable in wrench tectonic regime rather than the classic fold-thrust belt. Furthermore, missing Mesozoic to Paleogene stratigraphic section in the Tomori Field might suggest that it was located at the basinal margin.

- Further study is recommended to examine the possible Mesozoic hydrocarbon source for the East Arm of Sulawesi, as a consequence of the absence of obduction scenario where Eocene-Miocene sedimentary formation might be shallower and less mature than previously thought.

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REFERENCES

Davies, I.C.(1990) Geological and exploration review of the Tomori PSC, Eastern Indonesia, Proceedings of 19th Indonesian Petroleum Association Annual Convention. p. 41-67.

Garrard, R.A., J.B. Supandjono, and Surono (1988) The Geology of the Banggai-Sula Microcontinent, Eastern Indonesia. Proceedings of the 17th Indonesian Petroleum Association Annual Convention. 88-11.01, pp. 23-52

Hall, R. (2012) Late Jurassic–Cenozoic reconstructions of the Indonesian region and the Indian Ocean. Tectonophysics, vol. 570–571, pp. 1–41.

Hamilton, W. (1979) Tectonics of the Indonesian region. U.S. Geological Survey Professional Paper, 1078. 345 pp.

Husein, S., D.H. Barianto, and M.I. Novian (in preparation) The Mesozoic to Cenozoic Tectonic Evolution of Luwuk Basin.

Kadarusman, A., S. Miyashita, S. Maruyama, C.D. Parkinson, dan A. Ishikawa (2004) Petrology, geochemistry and paleogeographic reconstruction of the East Sulawesi Ophiolite, Indonesia. Tectonophysics, 392, 55-83.

Letouzey, J., P. de Clarens, J. Guignard, and J-L. Berthon (1983) Structure of the North Banda-Molucca Area from Multichannel Seismic Reflection Data. Proceedings of 12th Indonesian Petroleum Association Annual Convention. p. 143-156.

McClay, K. (1987) The Mapping of Geological Structures. John Wiley & Sons, Chichester, 161 p.

Moss, S.J. and Wilson, M.E.J. (1998) Biogeographic implications of the Tertiary palaeogeographic evolution of Sulawesi and Borneo, in Hall, R. and Holloway, J.D., eds., Biogeography and Geological Evolution of SE Asia, Backhuys Publishers, Leiden, 133-163.

Mubroto, B., J.C. Briden, E.McClelland, and R. Hall (1994) Paleomagnetism of the Balantak ophiolite, Sulawesi. Earth and Planetary Science Letters, 125, 193-209.

Parkinson, C. (1998) Emplacement of the East Sulawesi Ophiolite: evidence from subophiolite metamorphic rocks. Journal of Asian Earth Sciences, vol. 16, no. 1, pp. 13-28.

Rusmana, E., A. Koswara, and T.O. Simandjuntak (1993a) Geological Map of Luwuk Sheet, Sulawesi, Geological Research and Development Centre, Bandung.

Rusmana, E., Sukido, D. Sukarna, E. Haryono, and T.O. Simandjuntak (1993b) Geological Map of Lasusua-Kendari Quadrangle, Sulawesi, Geological Research and Development Centre, Bandung.

Satyana, A.H. (2006) Docking and post-docking tectonic escapes of eastern Sulawesi: collisional convergence and their implications to petroleum habitat. Proceedings of Jakarta 2006 Geoscience Conference and Exhibition.

Silver, E. A., R. McCaffrey, Y. Joyodiwiryo, and S. Stevens (1983) Ophiolite emplacement by collision between the Sula Platform and the Sulawesi Island Arc, Indonesia. Journal of Geophysical Research, 88, 9419–9435.

Simandjuntak, T.O. (1986) Sedimentology and Tectonics of the Collision Complex in the East Arm of Sulawesi, Indonesia. Unpublished Ph.D. Thesis, University of London, UK.

Simandjuntak, T.O., E. Rusmana, J.B. Supandjono, and A. Koswara (1993a) Geological Map of Bungku Quadrangle, Sulawesi, Geological Research and Development Centre, Bandung.

Simandjuntak, T.O., E. Rusmana, Surono, and J.B. Supandjono (1993b) Geological Map of Malili Quadrangle, Sulawesi, Geological Research and Development Centre, Bandung.

Simandjuntak, T.O., Surono, and Sukido (1993c) Kolaka Sheet, Sulawesi Geological Map of Kolaka Sheet, Sulawesi, Geological Research and Development Centre, Bandung.

Simandjuntak, T.O., Surono, and J.B. Supandjono (1997) Geological Map of Poso Quadrangle, Sulawesi, Geological Research and Development Centre, Bandung.

Sumosusastro, P.A., H.D. Tjia, A.R. Fortuin, and J. Van Der Plicht (1989) Quaternary reef Record of differential uplift at Luwuk, Sulawesi East Arm, Indonesia. Netherlands Journal of Sea Research, 24 (2/3), 277-285.

Surono, T.O. Simandjuntak, R.L. Situmorang, and Sukido (1993) Geological Map of Batui Quadrangle, Geological Research and Development Centre, Bandung.

van Bemmelen, R.W. (1949) The Geology of Indonesia. Government Printing Office, Nijhoff, The Hague. 732 pp.

Watkinson, I.M., R. Hall, and F. Ferdian (2011) Tectonic re-interpretation of the Banggai-Sula–Molucca Sea margin, Indonesia. in: Hall, R., Cottam, M.A. & Wilson, M.E.J. (eds) The SE Asian Gateway: History and Tectonics of the Australia–Asia Collision. Geological Society, London, Special Publications, 355, pp. 203–224.

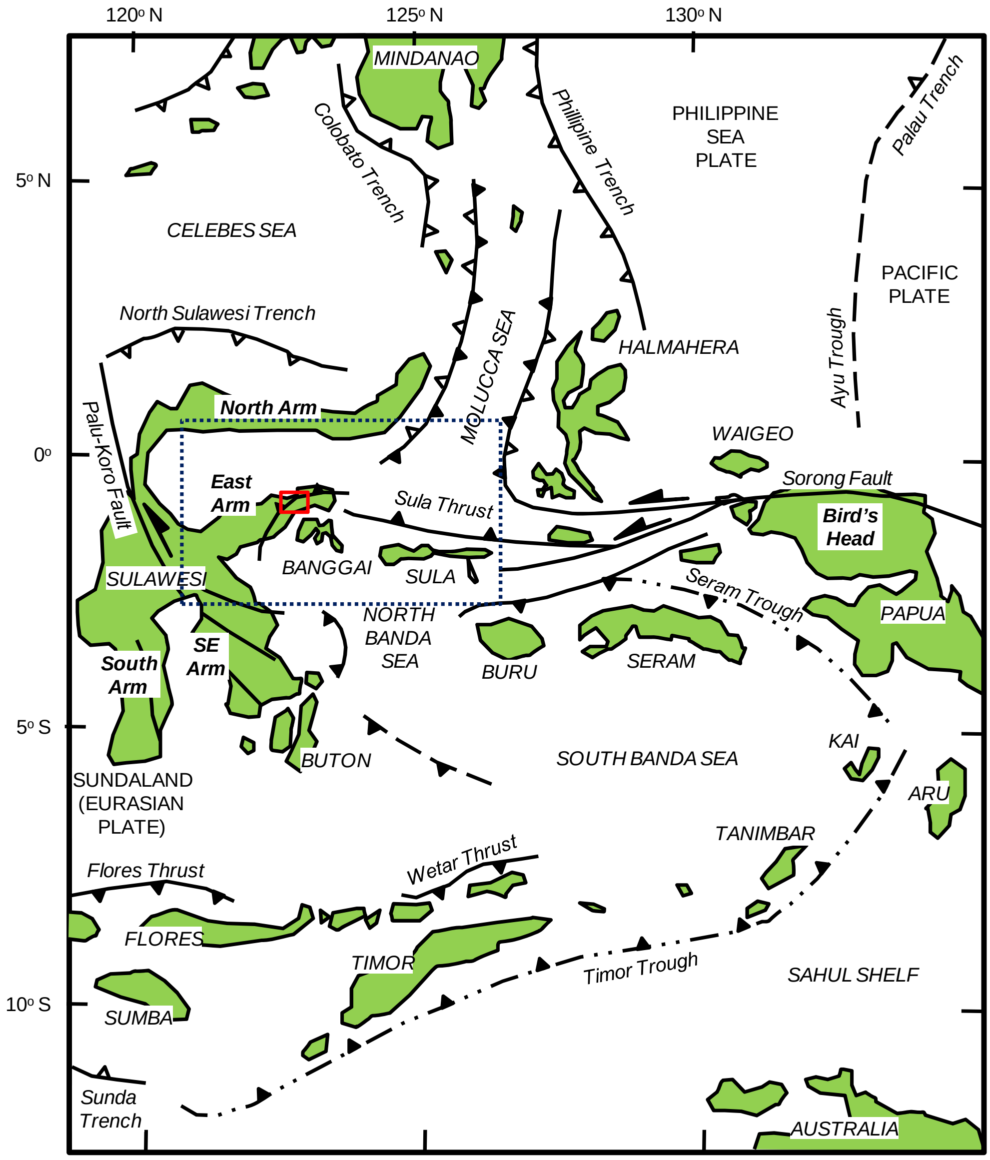

Figure 1 - Regional tectonic setting of East Indonesia (modified after Hamilton, 1979; Letouzey, 1983; Moss & Wilson, 1998; Hall, 2012). Red-line square is the study area, whilst the blue-dotted one is inset for Figure 2.

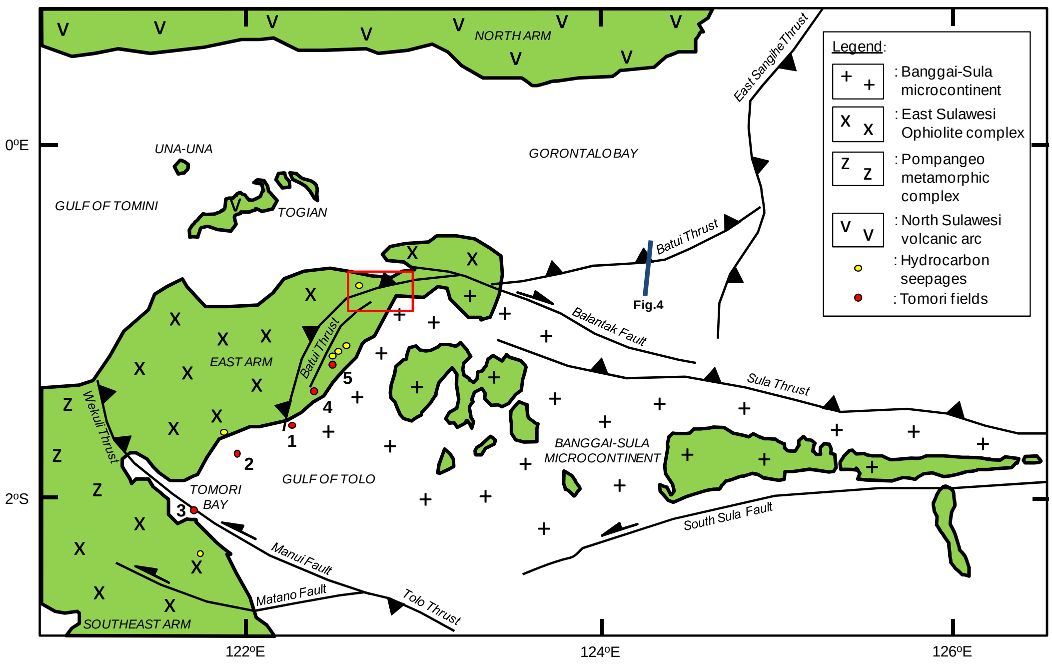

Figure 2 - Regional configuration of fundamental tectonic elements for the East Arm of Sulawesi and its hydrocarbon indication (modified after Garrard *et al.*, 1988; Davies, 1990; Rusmana *et al.*, 1993; Simandjuntak *et al.*, 1993; Simandjuntak *et al.*, 1997; Surono *et al.*, 1993; Moss & Wilson, 1998; Watkinson *et al.*, 2011). Exisiting hydrocarbon fields are marked by numbers: 1 - Mantawa, 2 - Tiaka Kalamba, 3 - Dongkala Tolo, 4 - Minahaki, and 5 - Matindok. Red-line square is the study area. Blue lines are location of seismic line in Figure 4.

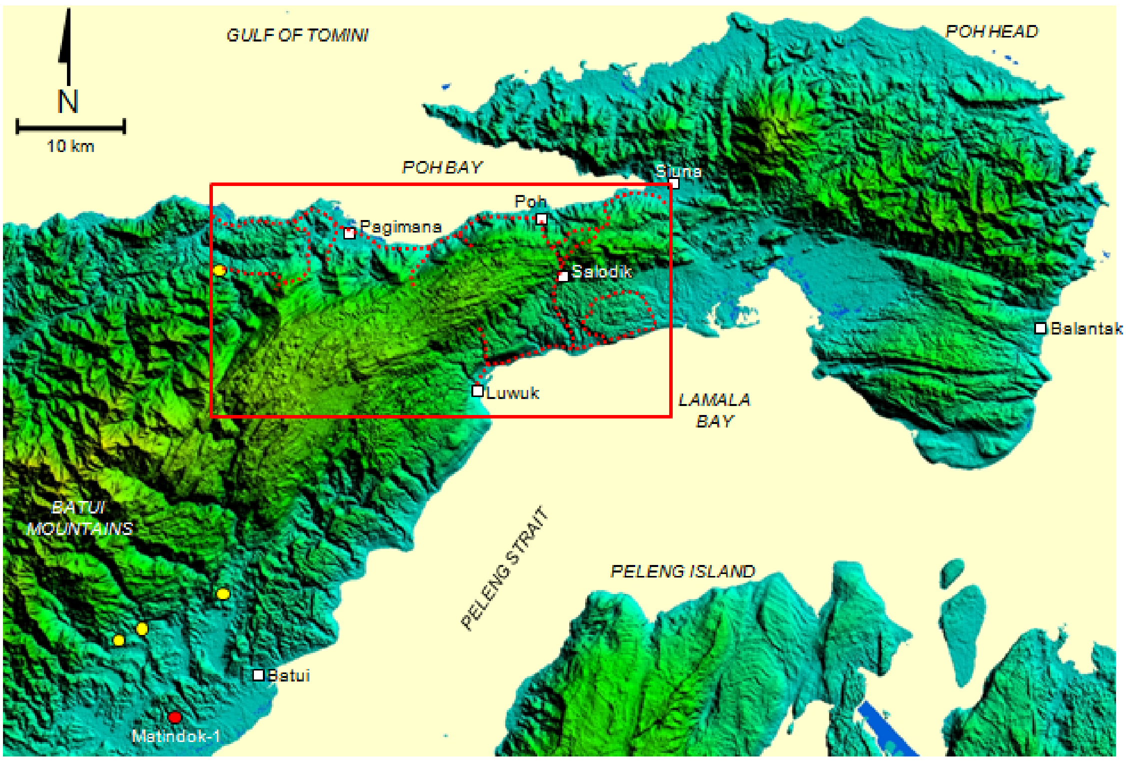

Figure 3 - Field traverse map on SRTM image. Red-line rectangle is the study area. Red-dotted lines are field traverse. Yellow circles are hydrocarbon seepages (after Rusmana et al., 1993; Surono et al., 1993). Red circle is gas-producing well of Matindok Field.

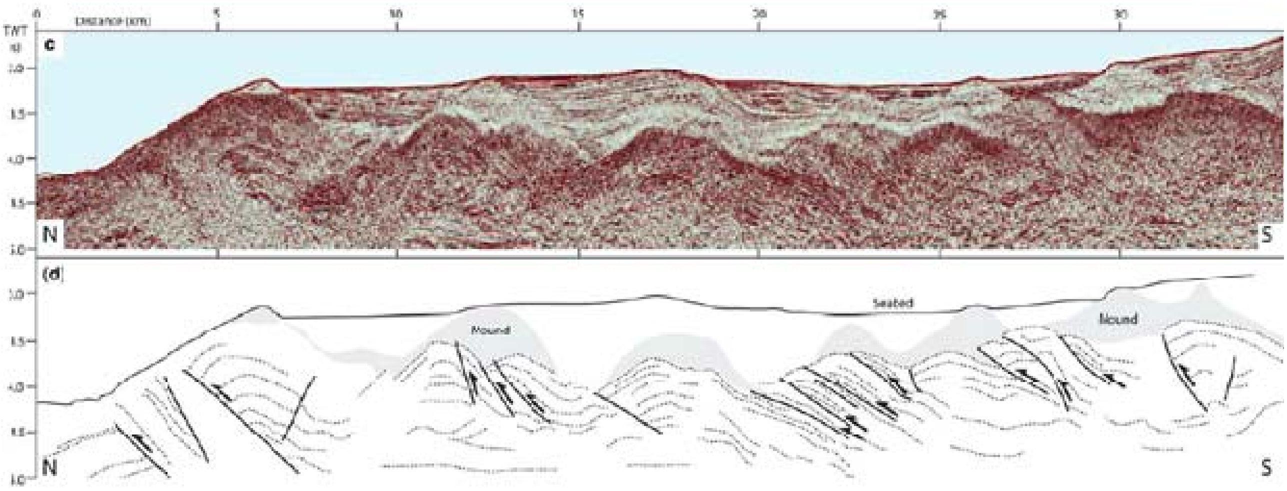

Figure 4 - Another seismic line of BS07-20 that crossing the extension of Batui Thrust offshore to the east (Watkinson *et al*., 2011). A series of north-vergent thrusts can be clearly observed. Location map is depicted in Figure 2.

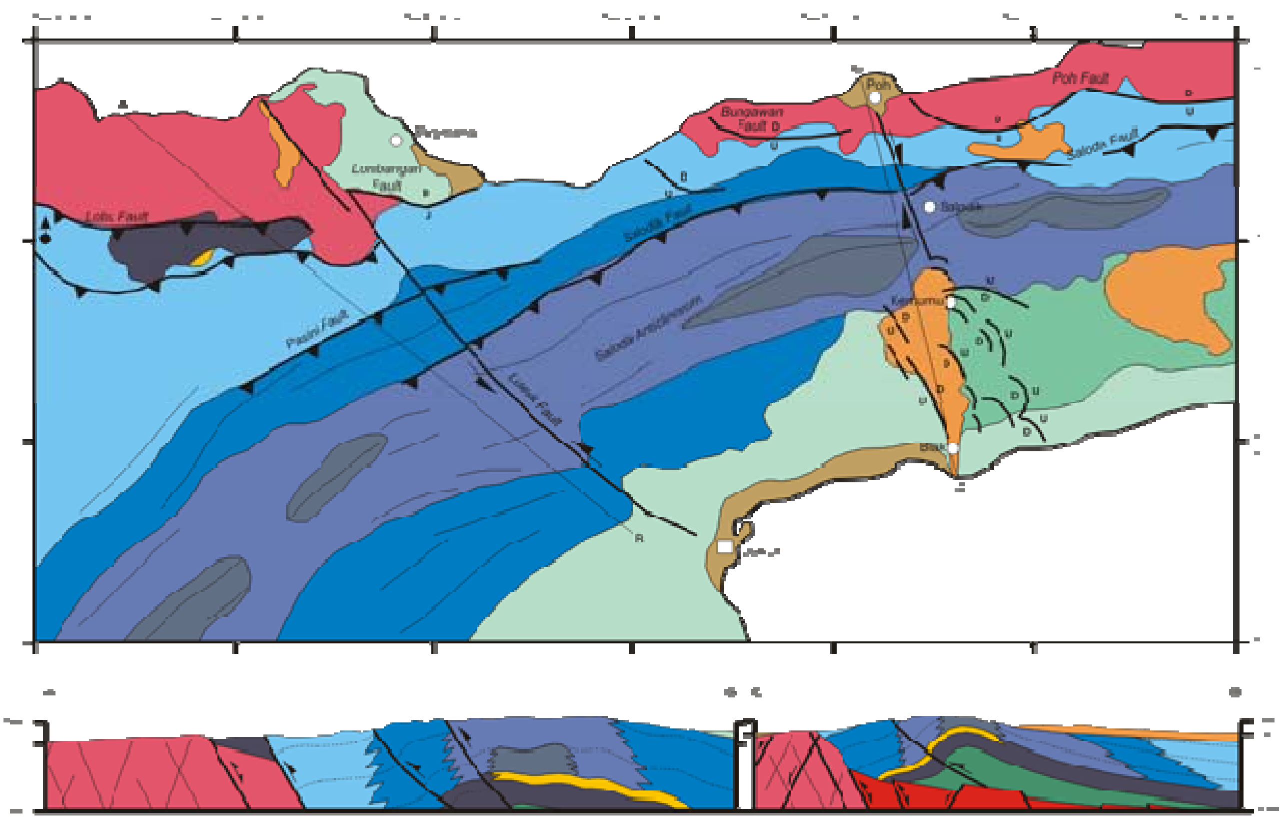

Figure 5 - Geologic map of Luwuk, resulted from this mapping program. Thin black lines are anticlinal axis of Salodik Anticlinorium. Stratigraphic legend is presented in Figure 6.

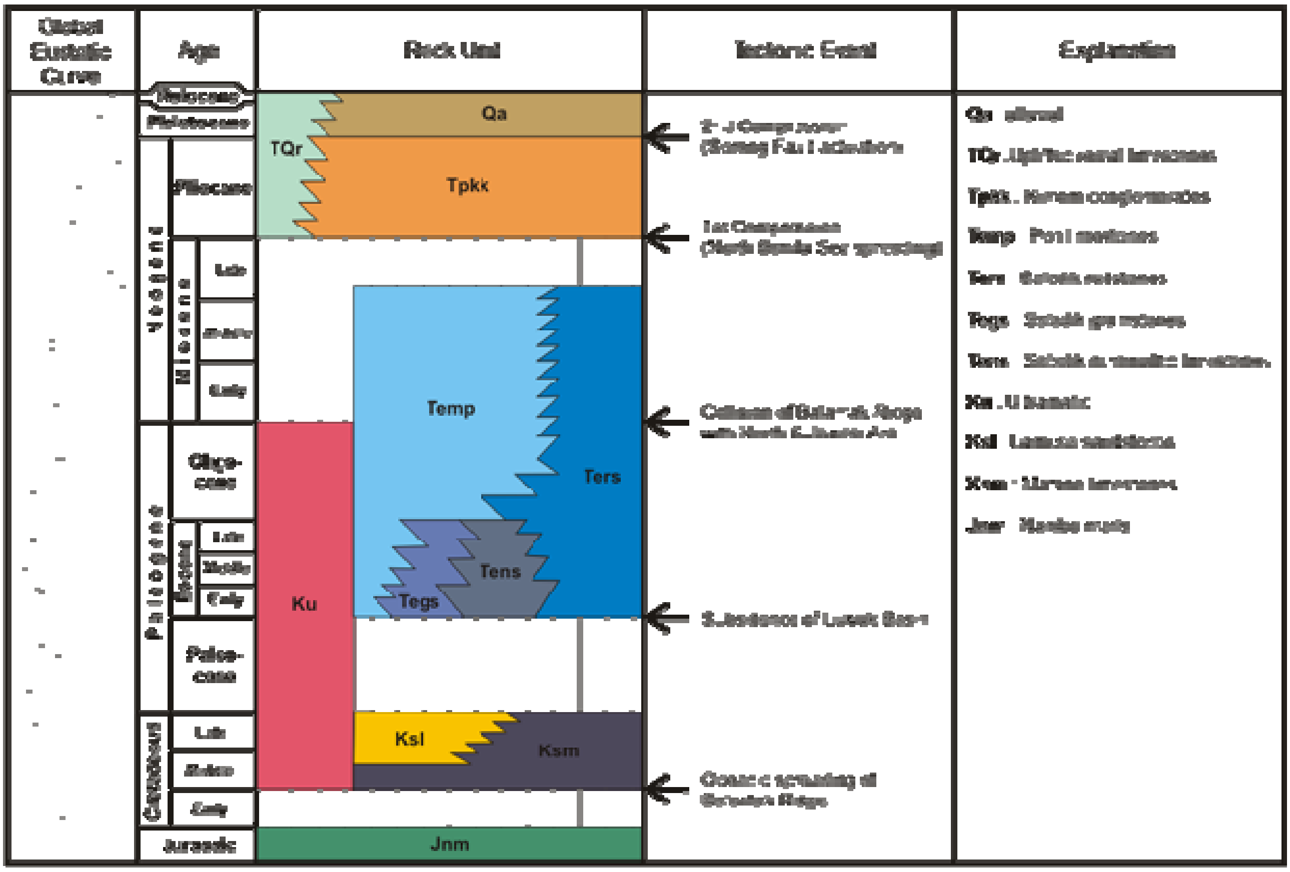

Figure 6 - Tectonostratigraphic chart of Luwuk. Comprehensive discussion on tectonic evolution is given in Husein *et al*. (in prep.)

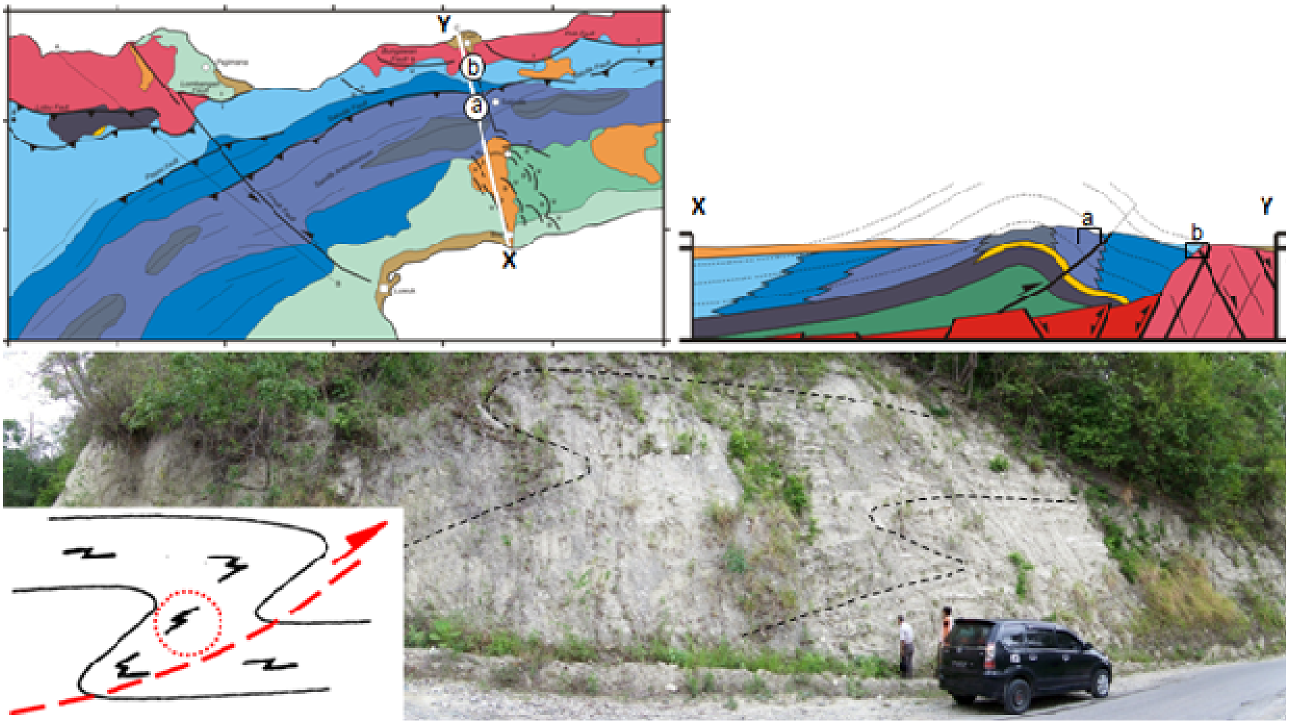

Figure 7 - S-shaped parasitic minor folds in the Tertiary Salodik grainstones, suggesting a major recumbent fold crest located to the south of the location (ref: McClay, 1987). A northwest-vergeance thrust is most likely located to the north of the location. Camera facing west, location is indicated by (**a**) on geologic map and cross-section.

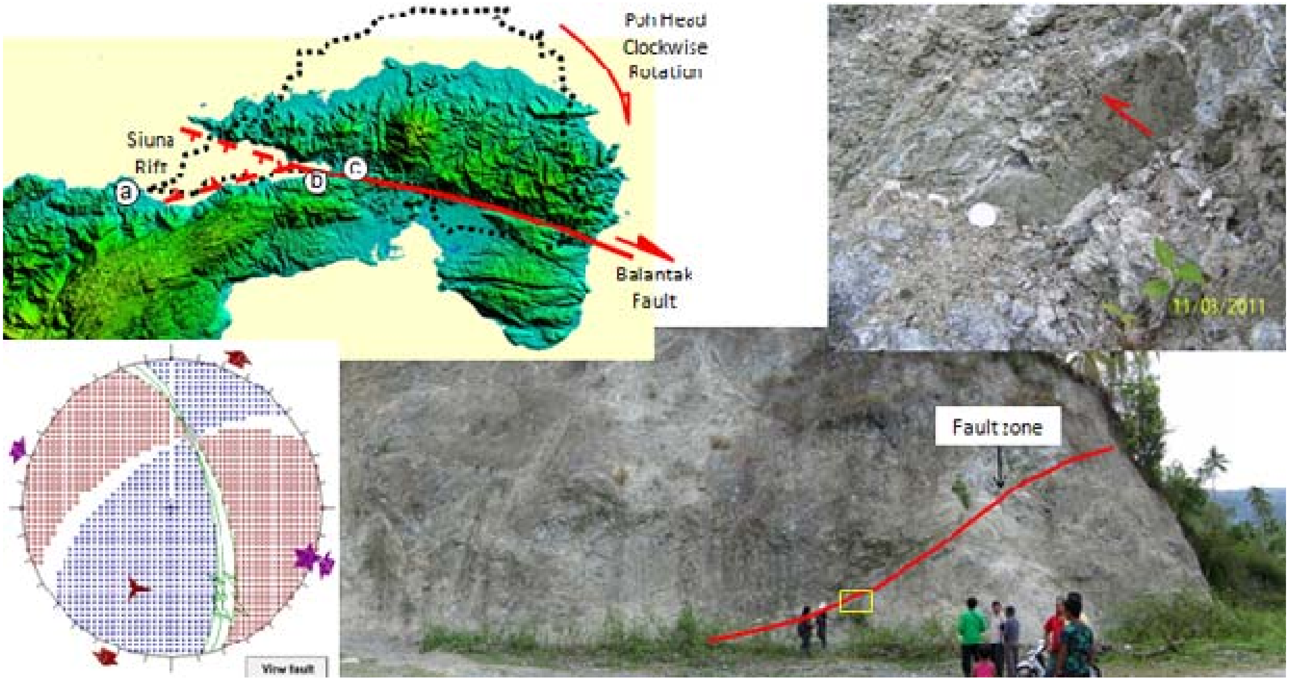

Figure 8 - Ophiolites outcrop at Pagimana, composed of highly sheared gabbro (white-green) and basalt (dark-green), with numerous magnesite veins mainly following existing fault planes. Kinematic analysis on an inverse fault (see inserted graph and photo) suggests a SE-NW compression and NE-SW extension once had working on the area. This fault zone might represents a NE extension of Siuna rifting along the western part of Balantak Fault. Camera facing south, location is indicated by (**a**) on SRTM image.

Figure 9 - Siuna Valley, with distinct triangular facets on the northern escarpment, suggesting a transtensional rift (large strike-slip fault with normal components created the triangular facets escarpment) had occurred along the Balantak Fault zone. Represents opening of the Gulf of Poh since Late Miocene (initial uplift of Luwuk). Camera facing north, location is indicated by (**b**) on SRTM image at Figure 8.

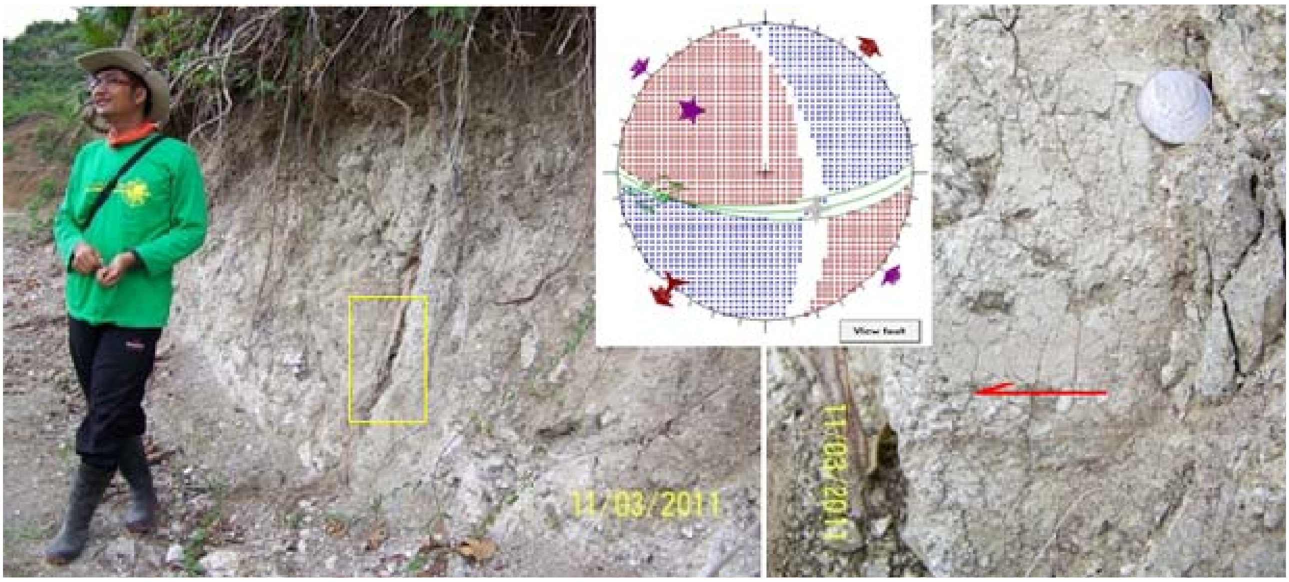

Figure 10 - Altered gabbro dissected by an E-W dextral fault, outcropped at Siuna Village. Kinematic analysis suggesting a NW-SE compression. Camera facing north, location is indicated by (**c**) on SRTM image at Figure 8.

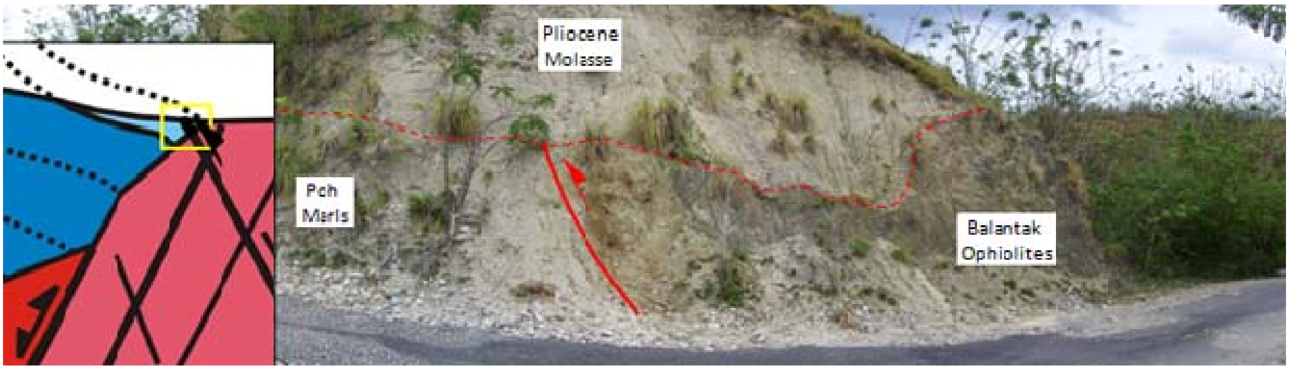

Figure 11 - Structural contact (high-angle reverse fault) between Balantak Ophiolites and the Tertiary Poh marls, both are eroded and covered by Pliocene molasse of Kintom Formation. This outcrop suggests aninitial inversion of the Balantak Ophiolites at Late Miocene. Camera facing west, location is indicated by (**b**) on geologic map and cross-section at Figure 7.