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MASS TRANSPORT COMPLEX IN EAST SUMBA: A REFERENCE FROM WORLD-CLASS OUTCROP AT WATUPARUNU COAST – MIO-PLIOCENE GRAVITY SLUMPS

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ABSTRACT

Watuparunu Coast in Southeast Sumba Island, Indonesia is composed of coastal cliff demonstrating excellent - world-class outcrop of deep-water mass transport complex (MTC) with complicated deformation related to gravity slumps. Seismic data (2D and particularly 3D) have recently enabled large MTC's of Recent to ancient deep-water basin to be described in considerable detail. However, the exposures of MTC's are scarce therefore, outcrop reference to examine seismic interpretation are seldom available. MTC outcrop of Watuparunu Coast recently accessible, could provide the reference.

MTC is subaqueous mass flow or landslide deposits that move downslope due to gravity sliding. It is important to study MTC's since these mass movement processes represent significant threats to the security of continental slope and deep-marine engineered installations, including deep-water exploration and development; geo-hazards for tsunamis to coastal communities; release of methane to atmosphere from frozen gas hydrates originally stored in slope areas but released upon MTC; the roles of MTC in deep-water petroleum system.

MTC's characterized the geology of East Sumba in Mio-Pliocene time. Within the period, East Sumba subsided to the north and east as response to the uplift of the Masu Mountains to the south and opening of the Savu Basin to the east. This caused gravity sliding from high to low areas. Volcano-clastic rocks eroded from the Masu Mountains and pelagic marls and chalks of Kananggar Formation were deposited and moved downslope forming slides, slumps, or debris flow and they continued into the Savu Basin.

Around 1 km long and 20-50 m high of the coastal cliff outcrop show the MTC at Watuparunu Coast. Slump structures dominate the MTC, forming very tight fold and thrust system. The top of the MTC is irregular erosional surface, its bottom is not exposed but it is considered as planar detachment surface where all faults ramp to. Internal facies consisting of: rotated blocks, pressured ridges, folded and thrusted blocks, and chaotic facies. This is the first publication and study of Watuparunu outcrop complex as MTC.

This excellent outcrop provide reference to study slump structures of MTC's which globally comprise up to 70% of the entire slope and deep-water stratigraphy. Exploring and developing petroleum in deep-water area should aware these deposits for the sake of engineering aspects and petroleum system. MTC's may act as both lateral and top seals for underlying hydrocarbon reservoirs and could create MTC-related stratigraphic traps.

INTRODUCTION

Mass transport complex (MTC) is subaqueous/ underwater mass flow deposits or landslide deposits that move downslope due to gravity sliding. Mass transport complexes (MTC's) in a marine environment commonly occur around the slope area, in the transition zone between the shelf and deep-water areas.

It is important to study MTC's since they are commonly large enough to be geo-hazards. Large MTC's can be tsunami-genic like that recently occurred in Palu area, Central Sulawesi (September 2018) triggered by mass failure due to strong earthquake; and in Banten and Lampung areas

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(around Sunda Straits, Sumatra-Java Islands) in December 2018 triggered by mass failure of part of Anak Krakatau volcano. These processes pose a significant hazard to near-shore navigation and coastal communities. These mass failure processes also provide significant threat to the security of continental slope and deep-marine engineered installations, including petroleum exploration and development in deep-water environments. Along similar lines, an interest in global warming has prompted a large number of climatologic researchers to consider catastrophic marine landslides and mass failures can themselves cause disruption of the pressure/temperature conditions that maintain methane clathrates in large portions of the world's continental margins, resulting in release of these gases (Maslin et al., 2004).

Ancient MTC deposits (slides, slumps and debris flows) also pose a problem for hydrocarbon exploration and development in deep-water facies. These units typically have low porosities and permeabilities (Shipp et al., 2004), and their episodic and recurrent nature in many basins of the world means that they can form significant baffles and barriers to fluid flow deep-water facies stratigraphic sections.

The MTC occurs in onshore East Sumba Island and continue into deep offshore Savu Basin (Fortuin et al., 1992; Roep and Fortuin, 1996). The Neogene slide masses in the Sumba Island were deposited in deep marine environments, within the reach of large amounts of clastics derived from a volcanic arc. We visited Sumba Island in April 2018 with "Geotrek Indonesia", a non-profit community dedicating for studying and appreciating geo-historical heritages of Indonesia, found new MTC outcrop in Watuparunu Coast, Southeast Sumba Island (Figure 1). The outcrop was not visited by previous researchers due to no access at the time they did field study. It is an excellent world-class outcrop, better than those investigated by previous authors, showing deformed MTC. The outcrop forms a sea cliff of around 1 km long and 20-50 m high.

The main goal of the paper is to record and inform the presence of an excellent MTC outcrop at Watuparunu, Southeast Sumba Island. This is the first publication describing this outcrop as an evidence of gravity-induced MTC related to subsidence of East Sumba. The outcrop is the sea cliff that is very prone to sea abrasion, few or many parts of the outcrop could be lost in the future due this natural process therefore, it should be recorded before we lose them.

DATA AND METHODS

The study is based on field study, some observations are conducted during the field visit, pictures were taken and interpreted. Description of the MTC outcrop here is based on sedimentary and structural features of MTC's previously defined by several authors which mostly based on seismic data (Dott, 1963; Nardin et al., 1979; Posamentier, 2005; Moscardelli and Wood, 2008; Debacker et al., 2009; Dykstra et al., 2011). Previous related papers were referred to compile the site of the outcrop to regional setting of subsidence of East Sumba (Fortuin et al., 1992; Roep and Fortuin, 1996). Data from field study and references are analyzed and synthesized as the content of this paper.

RESULTS AND DISCUSSIONS

Gravity Sliding-Tectonics

Gravity sliding (or gliding) is the mechanism whereby large masses of rocks move downslope under gravitational force producing folding and faulting of varying extent and complexity (De Jong and Scholten, 1973). Gravity sliding is the basic type of near-field stress driven deformation of a sedimentary wedge that progrades into deeper water (can also happen on land; landslides). Gravity gliding occurs by the rigid translation of a rock mass downslope (Morley et al., 2011). In a process, gravity sliding can combine with gravity spreading. Gravity spreading is also the type of near-field stress driven deformation of a sedimentary wedge prograding into deeper water. Gravity spreading is the flattening and lateral spreading of a rock mass under its own weight. Gravity spreading rarely affects the complete sedimentary section and is often limited to a thick mobile zone (usually either overpressured, undercompacted muds or salt) at the base of the gravity-driven system (Morley et al., 2011). Gravity gliding is usually associated with linkage of up-dip extension with a down-dip contractional toe region via a detachment zone and covers a wide range of temporal and spatial scales.

Deformation of rock layers in forms of folding, faulting, or structures like fold-thrust belts resulted from downslope movement of large masses of rocks under gravitational force (gravity sliding) is called gravity tectonics. Gravity-induced downslope movement has been invoked by structural geologists to explain an almost dizzying variety of phenomena on almost all geologic scales.

Mass Transport Complex (MTC)

When a submarine slope failure occurs, material is translated downslope above a basal shear surface which develops due to progressive shear failure (Varnes, 1978). Once failure initiates, the event may progress by means of a number of mass movement processes. This material which translated downslope by gravity sliding is called deep-water mass transport complex (MTC) or deposits. MTC undergoes some combination of creeping, sliding, slumping, and/or plastic flow in a marine or freshwater lacustrine environment (Moscardelli and Wood, 2008). In a deep-water environment, MTC's, products of mass transportation processes, often dominate the basin stratigraphy, and are intercalated with turbidite deposits (Dykstra et al., 2011).

Shanmugam (2016) distinguished MTC from turbidite deposits, this was based on Dott (1963) proposing the most meaningful and practical classification of subaqueous mass-transport processes. Dott (1963) broadly classified subaqueous processes into: (1) elastic, (2) elastic and plastic, (3) plastic, and (4) viscous fluid types based on mechanical behavior. The importance of Dott's (1963) classification is that mass transport processes (MTC) do not include turbidity currents. In short, mass-transport processes are composed of three basic types: (1) slide, (2) slump, and (3) debris flow. Shanmugam (2016) showed four common types of gravity-driven downslope processes that transport sediment into deep-marine environments (Figure 2). A slide represents a coherent translational mass transport of a block or strata on a planar glide plane (shear surface) without internal deformation. A slide may be transformed into a slump, which represents a coherent rotational mass transport of a block or strata on a concave-up glide plane (shear surface) with internal deformation. Upon addition of fluid during downslope movement, slumped material may transform into a debris flow, which transports sediment as an incoherent mass in which intergranular movements predominate over shear-surface movements. A debris flow behaves as a plastic laminar flow with strength. As fluid content increases in debris flow, the flow may evolve into Newtonian turbidity current. Not all turbidity currents, however, evolve from debris flows. Some turbidity currents may evolve directly from sediment failures. Turbidity currents can develop near the shelf edge, on the slope, or in distal basinal settings (Shanmugam, 2016).

MTC's are a common feature in many deep-water settings and have been well-described in the literature (Posamentier, 2005). They form a large stratigraphic component of many ancient and modern deep-water margins around the world. In some settings, up to 70% of the entire slope and deep-water stratigraphic column is composed of MTC's and associated deposits (Maslin et al., 2004). They can be observed both in slope as well as basin floor settings. Such deposits can occur in a broad range of shapes and internal geometries from massive to crudely bedded. The sizes of MTC are also in broad range. It can reach 150 m or more in thickness, greater thicknesses are observed where successive flows are amalgamated. Lateral reach of MTC in some instances can be as far as hundreds of kilometers across the basin floor. They can also be quite local in nature, such as those that form on the flanks of salt domes or mud volcanoes, or on the inner and outer flanks of turbidity-flow channel levees (Posamentier, 2005).

MTC slides are often triggered by short-term events e.g. storms, earthquakes and high rainfall. Gravity gliding systems on passive margins where the detachment is buried deeper (~1 km or greater), extending for tens of kilometers in the transport direction, develop as a result of long term geological processes (e.g. high sedimentation rates, uplift of the adjacent continental area resulting in tilting of the margin) (Morley et al., 2011). Large MTC's commonly originate on the mid to upper continental slope. The location of where these deposits originate largely determines the lithology of these deposits. The location where mass transport deposits originate can be 1) at or near the shelf edge, 2) the mid- to upper slope, and 3) locally, on the flanks of salt domes or mud volcanoes, or on the flanks of channel levees (Posamentier, 2005). Those flows that originate in the mid- to upper slope in particular are most likely to be mud prone, whereas those originating at the shelf edge stand a better chance of containing sand. However, even these deposits commonly have a mud matrix and from a hydrocarbon exploration perspective commonly are characterized by poor reservoir quality.

In recent years 2D, and particularly 3D, seismic data have enabled large MTC's to be described in considerable detail. One recent example of describing MTC in Indonesia using seismic data set was from Armandita et al. (2015) studying Pliocene MTC in slope area of the South Makassar Strait (Figure 3). The internal seismic expression of mass transport deposits can vary from transparent to chaotic, contorted internal seismic reflection character, and in isolated instances to convolute bedded, both in section and plan view (Posamentier, 2005). MTC's can assume a variety of shapes and sizes ranging from lobate to sheet to channel-form. Some of the larger deposits take the form of large excavated trenches where detachment and shearing at the base and sides of the deposits suggests a mechanism of substrate failure and sliding, providing distinctive aspect of the erosional scour that can commonly be observed at the basal contact.

Using three-dimensional (3D) seismic reflection data, Bull et al. (2009) proposed anatomy of MTC's from which kinematic indicators can be identified. Kinematic indicators are geological structures or features which may be analyzed to allow the direction, magnitude and mode of transport to be constrained. The various indicator types have been classified according to where they may typically be found within the MTC body exhibiting a typical 'tripartite' anatomy: the headwall domain, translational domain and the toe domain (Figure 2). Although there may be some overlaps among them. The imaging of kinematic indicators using seismic surveys which provide large areal coverage allows swift and confident evaluation of the direction of translation, and in many cases also allow the degree of translation of the displaced slide material to be constrained. Imaging of the basal shear surface, analysis of internal architectures and determination of transport direction are areas which are of particular benefit from the analysis of 3D seismic.

Geologic Setting of Sumba Area

Sumba Island belongs to Lesser Sunda Islands Group. Presently, the island is located in forearc setting in front of Quaternary Sunda-Banda volcanic arcs comprising mainly islands of Bali-Lombok-Sumbawa-Flores-Alor-Wetar. Sumba is tectonically important since it is located at the border of subduction and collision zones. To the west of Sumba, oceanic crust of the Indian Ocean plate subducts beneath the Sunda Arc. To the east of Sumba, there is collision zone where Australian continental crust underthrusts Timor Island. Sumba has been considered as micro-continent or continental fragment/ sliver (Hamilton, 1979) which detached from its provenance and transported to its present position as an exotic terrane. Satyana and Purwaningsih (2011) discussed the debates of previous authors of Sumba origin as a micro-continent and based on integrated data concluded that Sumba came from SE Sundaland in the area close to present Sulawesi. Gravity data show that Sumba has gravity anomaly of +160 to +200 mGal and is underlain by continental crust with a thickness of 24 km (Chamalaun et al.,1981).

The stratigraphy of Sumba covers rock complex of Late Cretaceous to Quaternary (Figures 4, 5). The pre-Tertiary basement of Sumba reveals faulting with rifted blocks. Recent seismic data in offshore Sumba prove this. Overlying this is the Late Cretaceous-Paleocene marine turbidites of the Lasipu Formation,accompanied by two major calc-alkaline magmatic episodes: the Santonian-Campanian episode (86-77 Ma) and the Maastrichtian-Thanetian one (71-56 Ma). During the Paleogene, Sumba was a part of a magmatic arc (Abdullah et al., 2000) characterized by calc-alkaline volcanic rock series (western Sumba) and shallow marine fossiliferous limestones and sandstones of the Paumbapa Formation and have an Eocene and Oligocene age (Effendi and Apandi, 1994). The corresponding deposits include tuffs, ignimbrites, greywackes, intercalations of foraminiferal limestones, marls, micro-conglomerates and claystones. Sumba contains typical Eocene low-latitude Sundaland larger forams of Assilina, Pellatispira, and Biplanispira and no Eocene high latitude Australian fauna of Lacazinella, showing SE Sundaland origin for Sumba, not Australia (Lunt, 2003).

In the early Miocene there is another period of volcanic activity (Wensink, 1994). This volcanism of the Jawila Formation, is restricted to western Sumba. Large areas are covered with tuff, tuff agglomerates, tuff-sandstones and lahars while rather fresh basalts and basaltic andesites occur as well. There are small exposures of the Middle Miocene Pamalar Formation with claystone and limestone, the latter both in lagoonal and in reef facies. An enormous mass of sediments with a thickness of at least 800 m covers large areas on Sumba. These sediments, which slightly unconformably overlie older rocks, belong to the Sumba Formation and have a late Miocene to early Pliocene age (Fortuin et al. 1992). The deposits show a general shallowing from east to west (Figure 6). The East facies of the Sumba Formation, often called Kananggar Formation, comprises basal conglomerates, overlain by volcanoclastic turbidites, sands, gravels and intercalated white, pelagic chalks. In East Sumba the formation contains many slumps, showing coeval subsidence (Figures 4 - 6). The western facies is mainly shallow marine; here, deposits of the Waikabubak Formation are found with carbonate platform sediments of reef and lagoonal origins. The Quaternary is represented by coral-reef terraces which fringe the island on the west, north and east coasts. These terraces comprise sandstones, conglomerates, marls and prominent reef limestones.

The Savu Basin to the east of Sumba is important to discuss in this study since the MTC observed in Sumba Island continued into this deep basin in Mio-Pliocene and also at the present day as revealed by seismic sections (van Weering et al., 1989; Roep and Fortuin, 1996; Tampubolon and Saamena, 2009; Toothil and Lamb, 2009) (Figures 7, 9). The Savu Basin extends over an area of 52,000 km2, at maximum water depth of 3470 m). The Savu Basin represents a complex forearc basin, situated at the western margin of the Banda Arc, and is affected by late Miocene and late Pliocene collisional events (van der Werff et al., 1994). The Savu Basin is underlain by series of east-west trending basement ridges. The ridge divides the Savu Basin into southern (South Savu Basin) and northern (North Savu Basin) structural basin. The thickness of basement rocks in the northern part of Savu Basin is 12-14 km, suggesting an oceanic crust (Beiersdorf and Hinz, 1980). The basement ridges that underlie the South Savu Basin have high density and may in part be related to an early-middle Miocene volcanic arc (van der Werff et al., 1994). Bathyal sediments of Middle to Upper Miocene are accumulated in this region during the period between 16 and 7 Ma when the Savu Basin was growing by extension. The basin was shortened after the Sumba Block ceased to move independently and related to the uplift of the outer-arc high, resulted in northward tilting since 7 Ma that has been accompanied by gravitational displacement of the sedimentary material northward into the southern part of Savu Basin (van Weering et al., 1989).

MTC in East Sumba

The presence of MTC in Sumba area was firstly identified by deformation style of the sedimentary rocks in East Sumba which cannot be explained by horizontal compressive stresses (far-field stress). Witkamp (1913) already noticed peculiar folding and faulting of the Neogene in East Sumba and assumed intra Neogene tectonic folding (Fortuin et al., 1992). Kinser and Dieperink (1941, quoted by van Bemmelen, 1949 as following sentences) reported in East Sumba the regional structure seems to be controlled by the Massu updoming. They do not believe that all folding in the Neogene series of Sumba is due to horizontal compressive stresses. The great irregularity of almost universally present folding, and the fact that regional lines of folding were not found, are reasons for this belief. It is believed that some of the structural features, especially the smaller ones, can best be explained by one or more of the following processes: original dips due to deposition of beds on a surface of much relief, differential compaction around buried ridges, local irregularities in the chalk beds due to solution and sliding. The larger structures are well-developed between Mauramba and Kananggar and between Kananggar and Kambaoni. This folding must have taken place while the beds were still plastic, as they have the same hardness as the low dipping beds and below and no secondary structures as cleavage and striae have developed. It is thought that these structures originated by contemporary folding caused by submarine land slip or creep. The thinning of the beds over the anticlinal axes points also to a plastic (flowage) folding of the yet unconsolidated sediments by the force of gravitation (van Bemmelen, 1949).

Later, submarine slide and slump of Kananggar Formation was discussed by von der Borch et al. (1983) when they reviewed the late Tertiary submarine fan sequences of Sumba, van Weering et al. (1989) discussing slumping and sliding in Recent and sub-Recent sediments of the Savu forearc, Fortuin et al. (1992) and Roep and Fortuin (1996) investigating slumping and sliding structures in Sumba based on field geology and compared to Neogene and Quaternary analogues in seismic profiles from the offshore Savu basin (Figures 7 – 9).

MTC requires subsidence to occur. Subsidence of northern to East Sumba started in the early Miocene when carbonate platforms (Waikabubak Formation) developed laterally on top of gradually subsiding Oligocene-Miocene volcanic eruption centers (Effendi and Apandi, 1994) (Figures 4 – 6). Increased subsidence later resulted in pelagic sedimentation. In East Sumba this started at the end of the Early Miocene. Sumba's Neogene sediments (Kananggar Formation, van Bemmelen, 1949) show in general an upward decrease of volcaniclastic turbidites and debrites, and an increase of pelagic oozes. In East Sumba fossiliferous pelagic chalky marls, rich in planktonic foraminifera are found both at the base of the series and towards the top. The pelagic muds in between have a chalky appearance, but the carbonate content appears to be very low and they are practically devoid of foraminifera, apart from foraminifera turbidites and reworked marl clasts. These sequences were considered to have been deposited below the CCD (Fortuin et al., 1992), stressing strong subsidence. These dissolution effects disappear in central Sumba, where subsidence must have been less strong. Here the strata overlying the pre-Neogene basement tend to be younger and the amount of intercalated volcaniclastic debris is limited compared to East Sumba. Slumping and sliding is less conspicuous in this part of the island (Fortuin et al., 1992).

The onshore Neogene slide masses of volcaniclastic debris flows, turbidites and interbedded pelites, and pelagic chalky marl sequences were deposited in deep marine slope environments The beds overlie a late Cretaceous basement-early Miocene volcanics (Massu Mountains), which underwent several episodes of block faulting prior to deposition of the Neogene. Since the Pliocene, uplift with slight N-NE tilting with consistent downthrow of the south coastal regions has taken place. This tectonically induced oversteepening is considered as a main cause of failure (Fortuin et al., 1992) (Figure 8). Fortuin et al. (1992) distinguished three types of slide masses, ranging from: mud clast-rich debris flows (type 1), elongate lenticular slumps (type 2), to over 100 m thick slide masses of intimately mixed and folded strata together with rafts of less deformed sediments (type 3). With proven lateral dimensions up to 10 km (but possibly more) and thicknesses up to 120 m, they are of moderate to medium size compared to present-day analogues described from continental margins (Fortuin et al., 1992). Large-scale slumping and sliding affected the middle to lower slope of the southern and southwestern Savu Basin (van Weering et al.,1989b). This area of nearly 4000 km^2 is the eastward continuation of the northern submarine slope of Sumba and is deeper than 1500 m. Near the westernmost extension of the offshore Sumba Ridge a giant blocky slide occurs. All slide masses are located on slopes with increasing gradients, due to differential vertical movements (Figures 7, 9).

MTC Outcrop of Watuparunu Coast, Southeast Sumba

Watuparunu Coast is located at the southeastern end of Sumba Island. It can be accessed by car, small bus, or motorcycles from Waingapu to the coast through Melolo town (Figure 1). The outcrop is coastal cliff, minimum 1 km long showing MTC (Figures 10 – 15).

MTC outcrop at Watuparunu Coast dominantly is composed of tuffs and marl to chalky deposits, and intercalations of claystones. Figures 11, 13, 16 show clear appearance of the lithology. The rocks are light gray, gray, and light crème in colors. Dissolution by sea abrasion occurs in some parts of the outcrop resulting in solution structures like holes, hollows, caves, and arches. The name of Watuparunu is given to these kind of solution structures (Figure 15).

The most striking view of the MTC outcrop at Watuparunu Coast is their complicated deformation and chaotic features. Figures 10 – 13 clearly show this complexity. The cliff is generally can be distinguished into two parts: lower and upper parts. The lower part is more complicated deformed with a series of folds and thrusts from south to north direction. The folds and thrusts are very tight, steeply dipping or recumbent. Some of the fold structures are complicated showing superposed folding (deformed fold structures). In part of synclinal limb of fold structure and anticlinal limb of fold structure which is deformed, an upward pressure ridge is observed, this is due to tectonic loading of the two fold structures compressing the area in between and buoyant sediments pierced upward forming pressure ridge structure (Figure 12). The vergency/direction of tectonic transport based on dip of thrusts are to NE (40° azimuth). The strikes of thrusts/faults are generally W-E (N285°E) (Figures 10, 11). The vergency of structures to NE and strike of structures W-E shows consistency with regional direction of MTC's in East Sumba and their gravitational structures (Roep and Fortuin, 1996) (Figure 7). All structures in MTC are thin-skinned with the presence of detachment surface as base of folds and thrusts. These thrusts are ramps that sole onto detachment surface which at these outcrop are not exposed, underground. Low angle thrust faults originating at the flow base and extending through to the top of the flow deposit are common features in MTC (Posamentier, 2005). These thrust faults are expressed near the surface of the deposit as arcuate fault traces oriented transverse to the flow direction. Some upper detachment is observed within MTC as base for upper thrusts (Figure 10). The upper part of the coastal cliff outcrop is not as complicated deformed as the lower one. Here there is no a series of fold and thrust observed except some faults considered formed as compensating faults as response to subsidence. The individual layers are generally thicker, this may be the reason why the rocks are deformed in other ways. The top of the cliff is erosional contact which is not in regular pattern, irregular top surface is usually a seismic character of top MTC. Different structural styles between the lower and upper parts of the cliff may show that the process of gravity tectonics of this MTC was multiple not a single history. The MTC at Watuparunu shows excellent outcrops of stages uplift, erosion, and deposition of younger sediments as shown by very striking angular unconformity in 3G geometry configuration due to sea abrasion. Here we can enter into the chamber of unconformity and see the bottom of unconformity surface (Figure 15).

In some instances, successive flows result in laterally directed compressional microstructures like convoluted beds commonly observed here (Figure 16), accompanied by internal deformation consistent with compressional fore shortening and subsidence.

Mass transport deposits commonly characterized by compressional structures like at Watuparunu Coast show the location of MTC near their termini/margins (Posamentier, 2005) or in the area of toe domain (Bull et al., 2009). The presence of compressional structures here does not mean that Watuparunu was the margin of MTC because the basin subsided to the north and northeast when the Kananggar sediments were deposited. The presence of fold and thrust system here is considered because of local high regionally, in this case was the Sumba Ridge located just east offshore of Watuparunu (Roep and Fortuin, 1996) (Figure 7).

The geometry and internal deformation of MTC's are consequences of the mechanism of failure and the morphology of the slope over which translation occurs. In addition, the mode of deformation will be influenced by the rheology of the rock and dependent on several factors including lithology and strain rate. It is therefore possible, through the characterization and analysis of the external geometry and internal distribution of deformational structures, to unravel the strain history of the MTC and formulate a kinematic model of emplacement (Bull et al., 2009).

Based on beds and structures observation at Watuparunu Cliff, the MTC here is dominantly composed of slump structures to distinguish it from slide, debris flow, and turbidite (Shanmugam, 2016). A slump is a coherent mass of sediment that moves on a concave-up glide plane (detachment surface) and undergoes rotational movements causing internal deformation. Slumps represent rotational shear-surface movements. Slumps are capable of transporting gravel and coarse-grained sand because of their inherent strength (Shanmugam, 2016).

To knowledge of the authors, there is no better MTC outcrop in Indonesia than the Watuparunu's, Sumba both in nature and dimension. Accordingly, we record the outcrop and publish this study for others to know the presence of this an excellent – a world-class outcrop. There is a need for better field study and understanding of this outcrop, processes and nature of this complex unit, and a hope for preservation of the outcrop as a geological heritage of Sumba and Indonesia.

CONCLUSIONS

1. Mass transport complex (MTC) compose the Mio-Pliocene stratigraphy and structure of East Sumba in forms of slides, slumps, and debris flow with deformation related to gravity sliding/ gliding. This was resulted from subsidence of East Sumba to the north, northeast, and east as a response to uplift of the southern and western part of Sumba and opening of the Savu Basin to the east of Sumba.

2. Excellent – a world-class outcrop of MTC is exposed at Watuparunu Coast, Southeast Sumba. The outcrop dominantly shows slump structures with tight fold and thrust system, rotated blocks, superposed folding, pressure ridge, in chaotic nature. The outcrop provides a good reference for slump structures of MTC that can be a guide for interpreting MTC in seismic data set.

3. Knowledge of MTC is important for various aspects, such as: geohazard related to submarine slides, exploration and development in deep-water environment, stratigraphic and structural history of sedimentary basin.

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Figure 1 - Above – Part of mass transport complex (MTC) outcrop at Watuparunu Coast, showing fold and thrust belt system of gravity slump structures, within yellow ellipse are people. Below – Google map of Watuparunu Coast, Southeast Sumba, road access is from Waingapu-Melolo-Watuparunu.

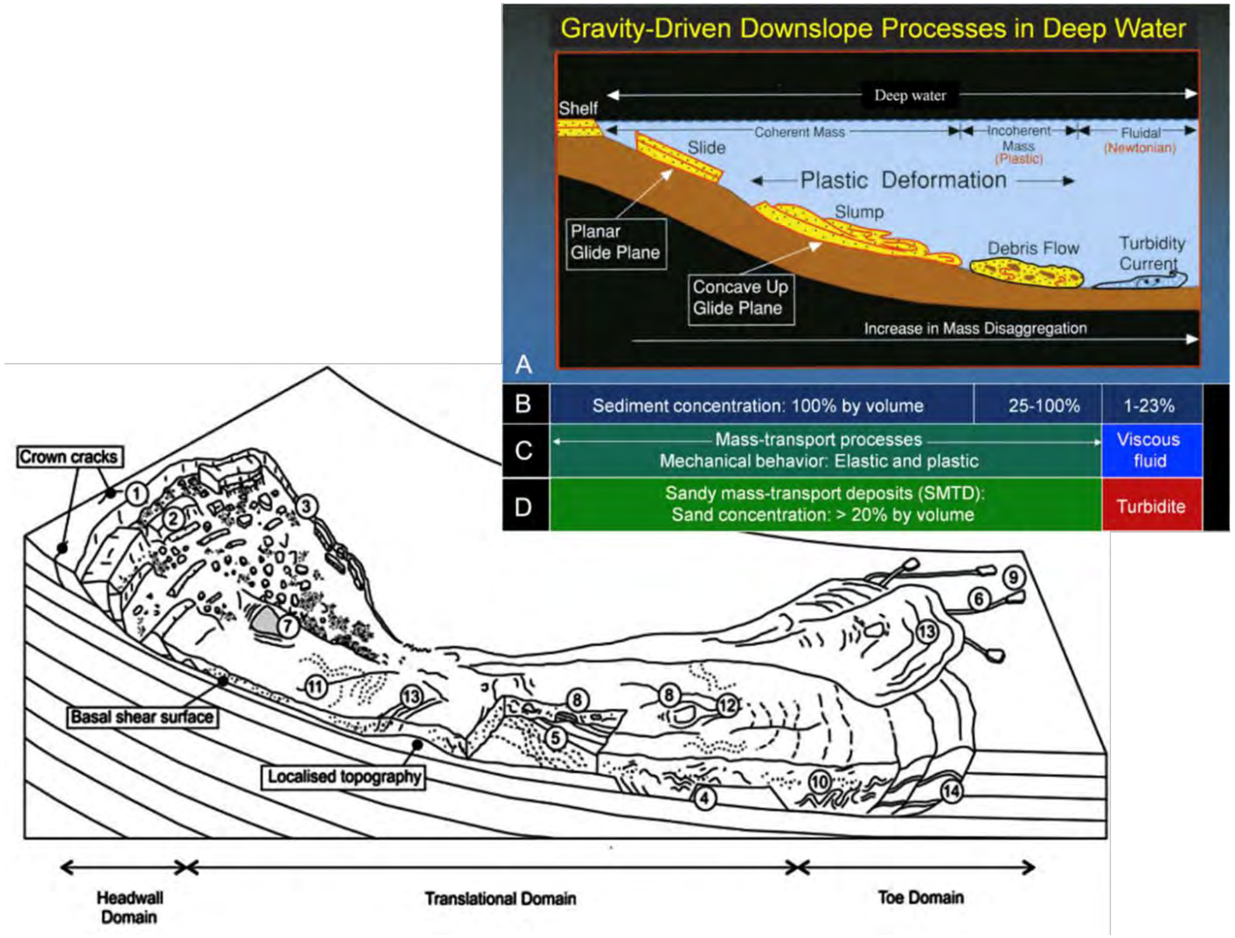

Figure 2 - Above - A-Schematic diagram showing four common types of gravity-driven downslope processes that transport sediment into deep-marine environments. A slide without internal deformation. A slump with internal deformation. A debris flow transports sediment as an incoherent mass. As fluid content increases, the flow may evolve into turbidity current (Shanmugam, 1996). Below - Schematic representation of a MTC and the likely occurrence and associations of kinematic indicators relative to the various domains. (1) Headwall scarp. (2) Extensional ridges and blocks. (3) Lateral margins. (4) Basal shear surface ramps and flats. (5) Basal shear surface grooves. (6) Basal shear surface striations. (7) Remnant blocks. (8) Translated blocks. (9) Out runner blocks. (10) Folds. (11) Longitudinal shears/first order flow fabric. (12) Second order flow fabric. (13) Pressure ridges. (14) Fold and thrust systems (Bull et al., 2009).

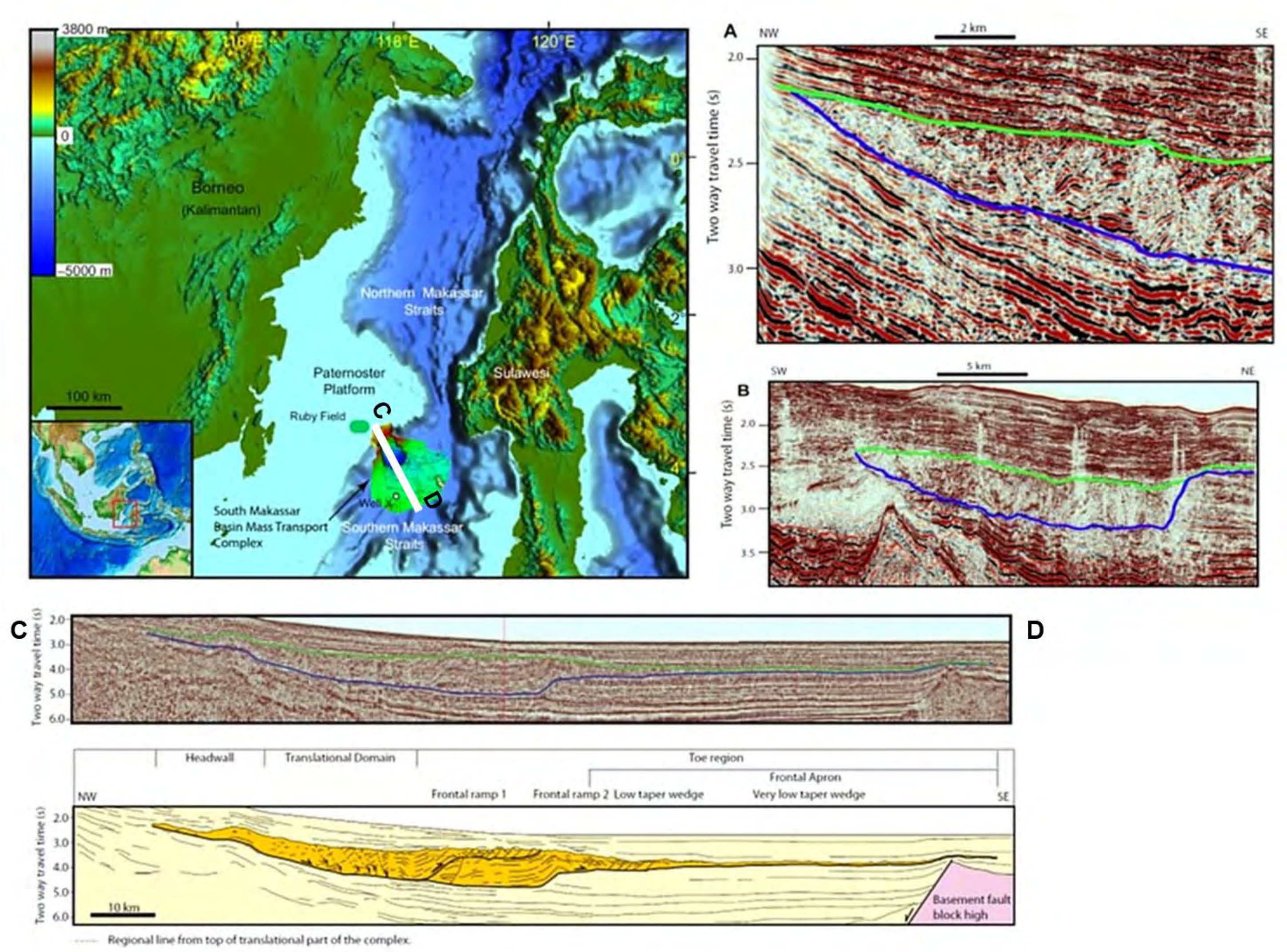

Figure 3 - Example of MTC (early Pliocene) in South Makassar Strait with seismic sections traversing the MTC. Lobe of MTC is plotted (based on seismic). Seismic sections A and B show detailed internal character of MTC, green line – top of MTC, blue line – base of MTC. Seismic section CD and its interpretation show regional line crossing parallel with direction of MTC (Armandita et al., 2015).

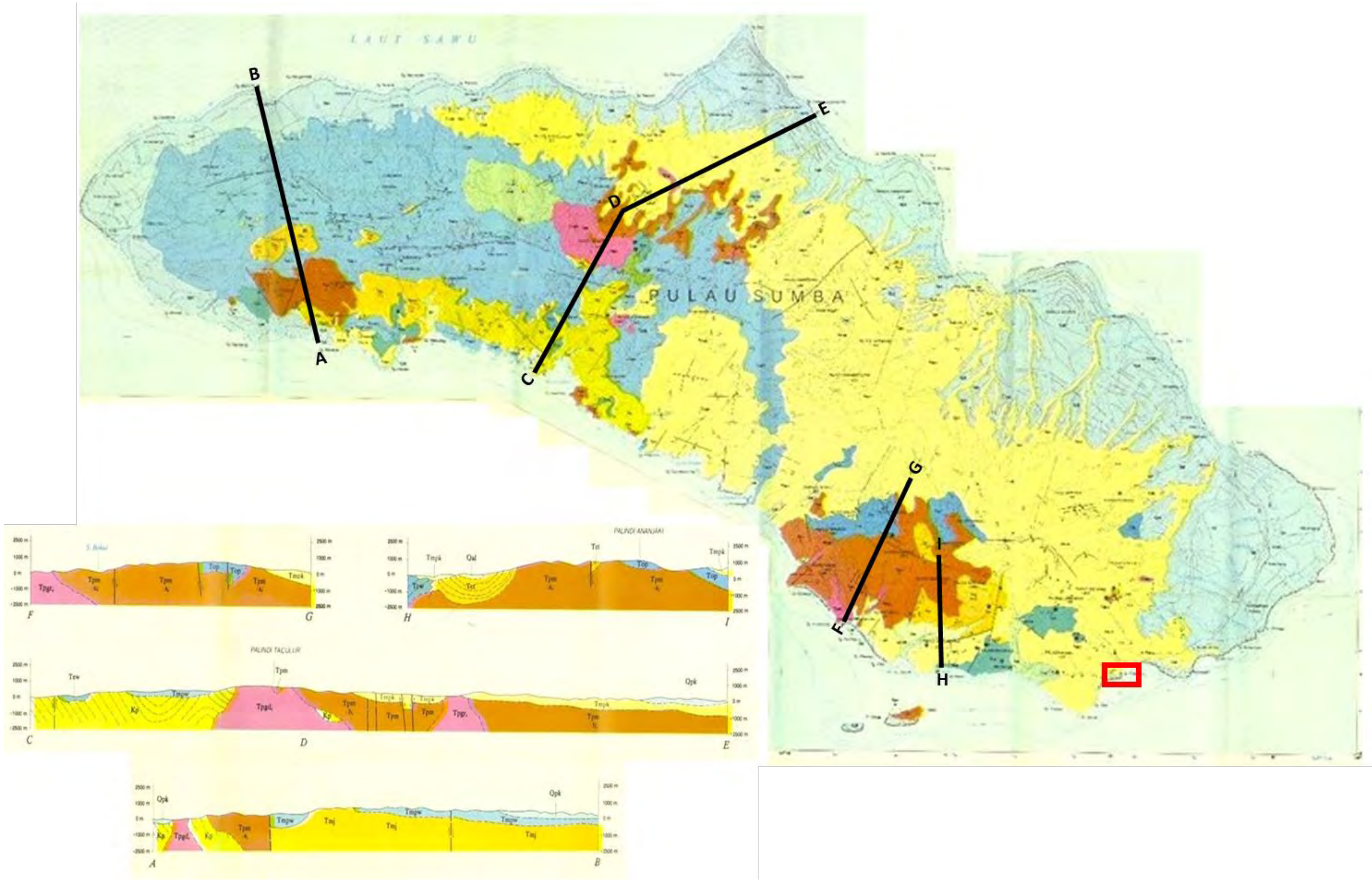

Figure 4 - Surface geological map of Sumba Island (Effendi and Apandi, 1994). Geological sections and their locations of section lines are shown. MTC of East Sumba occurs in Kananggar Formation (Tmpk) (Mio-Pliocene), light yellow in color, mostly distributed in East Sumba. Red box is the location of Watuparunu coast.

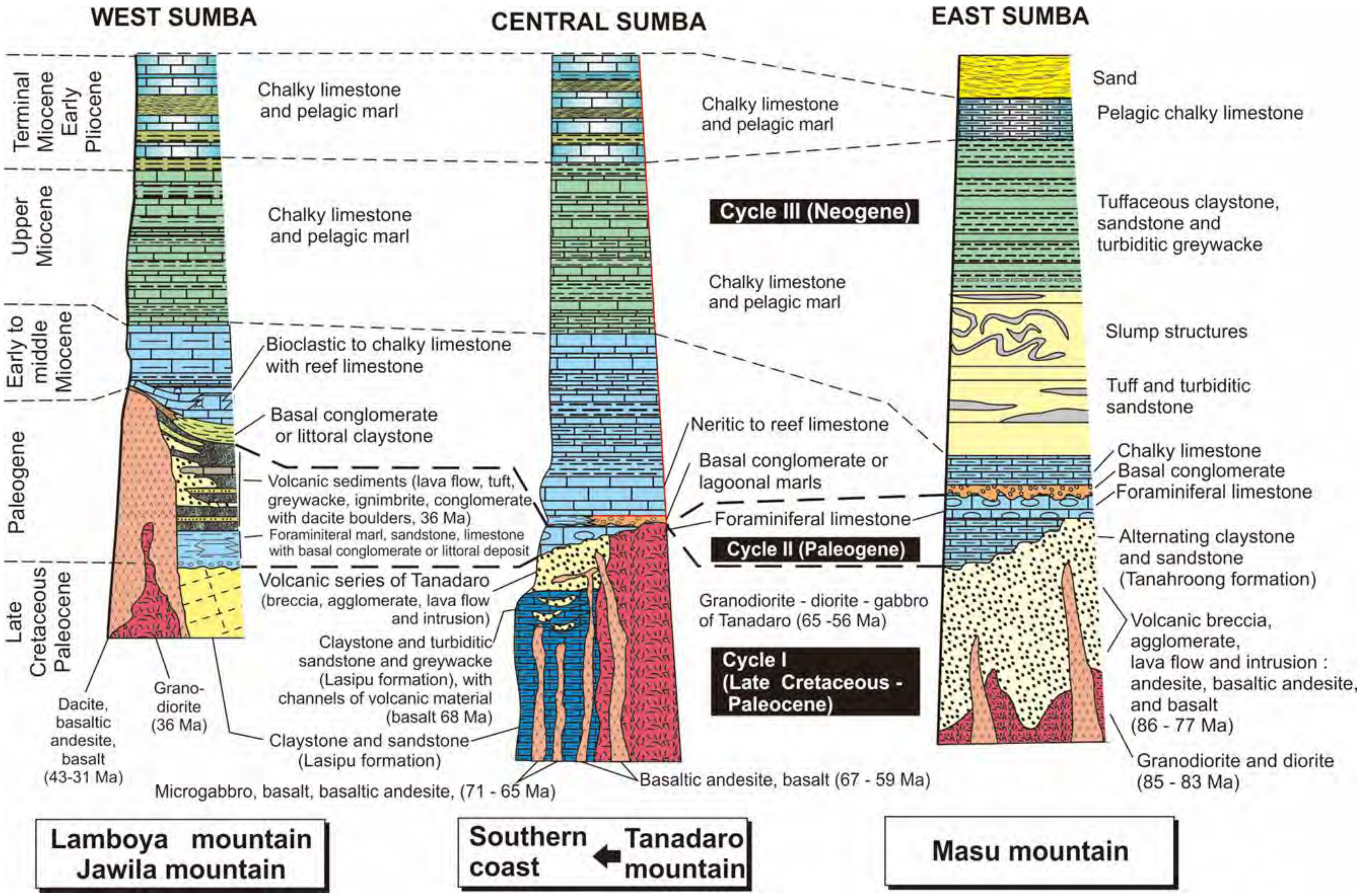

Figure 5 - Stratigraphic columns of Sumba at western, central, and eastern parts (Abdullah et al., 2000). Note in East Sumba the presence of stratigraphic sections of tuffs and pelagic carbonates triggering MTC as slump structures.

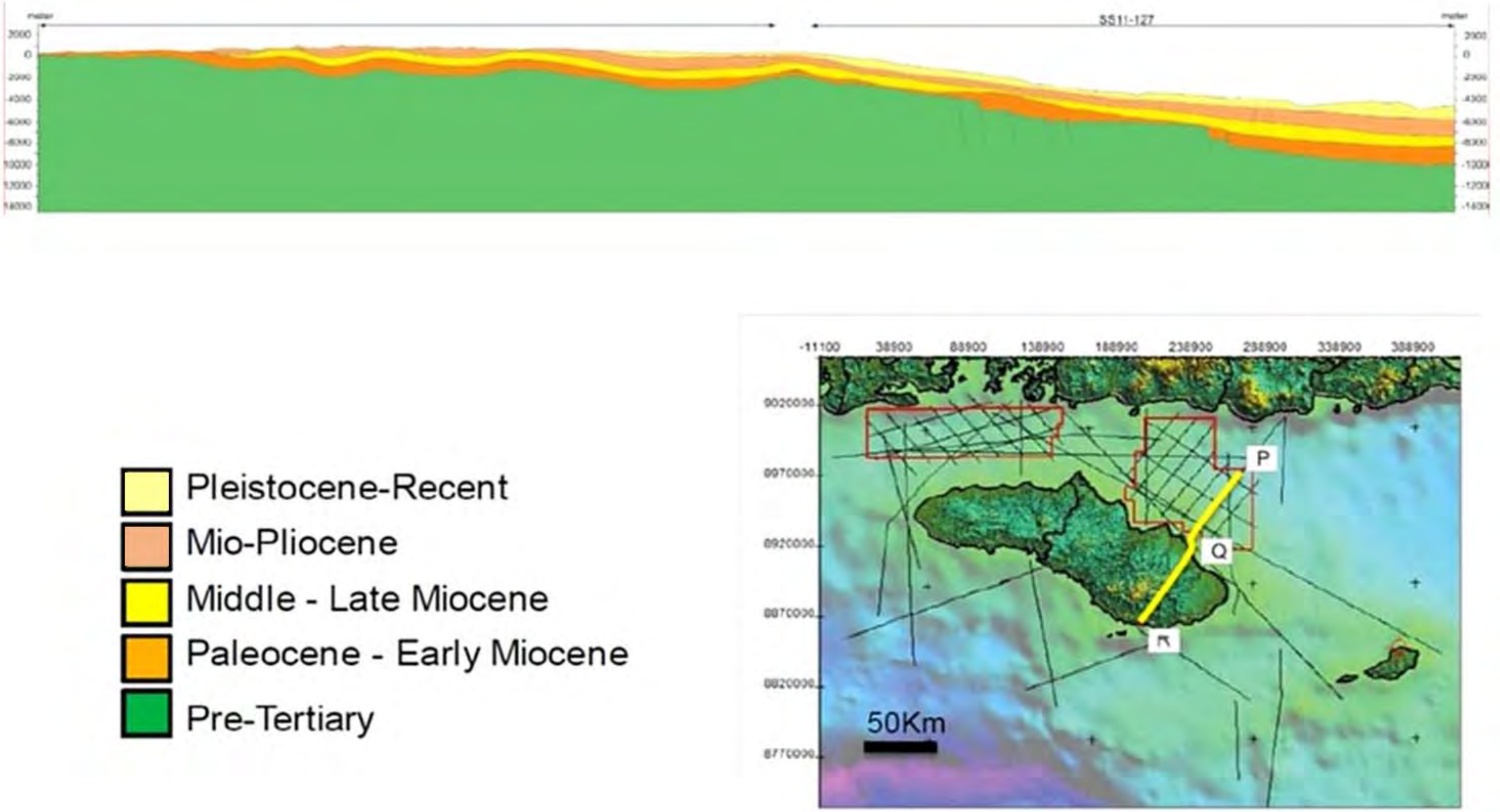

Figure 6 - Simplified section (onshore: based on geological map, offshore: based on seismic section) showing tilting and subsidence of northern and northeastern Sumba. This triggered MTC in Mio-Pliocene sediments.

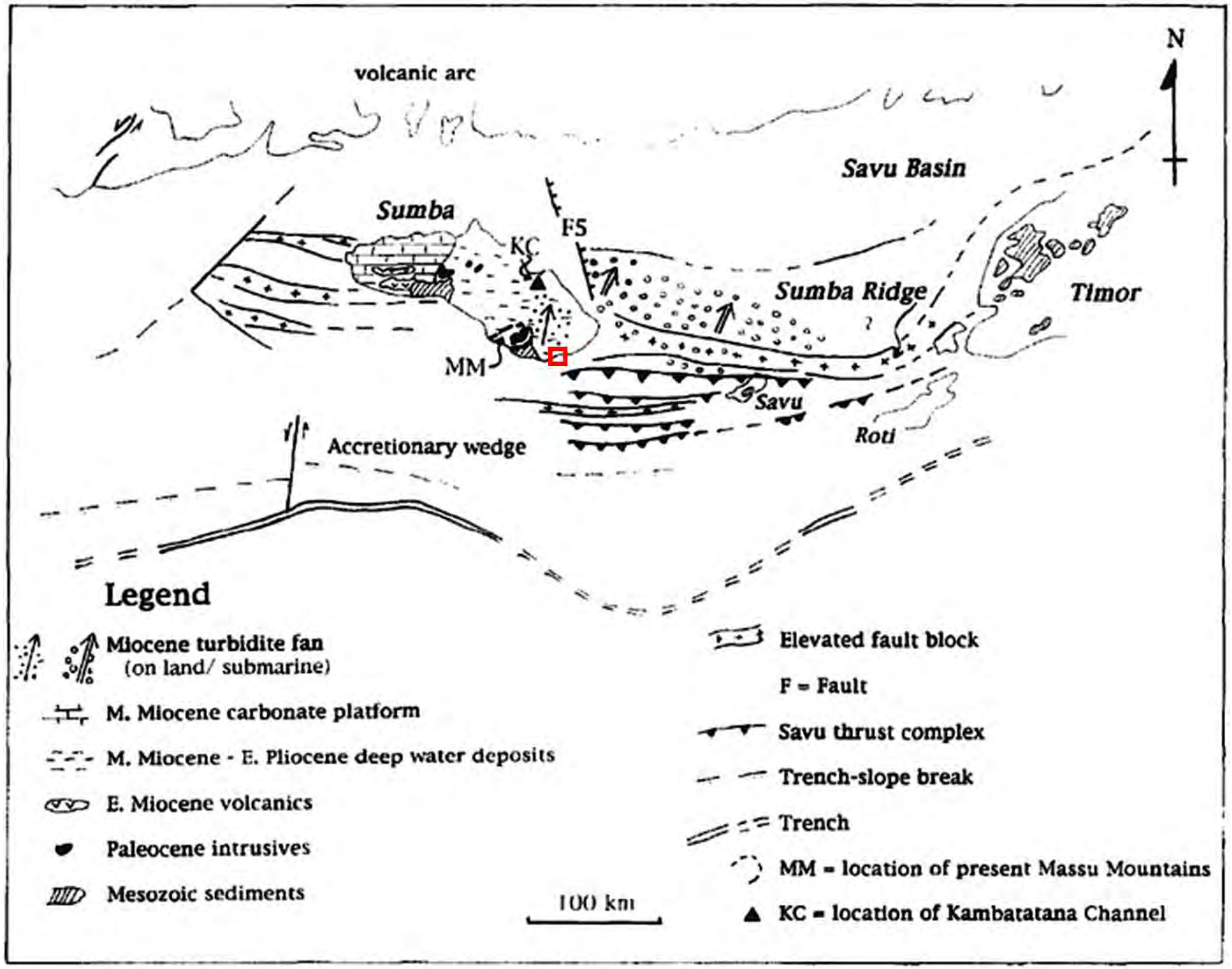

Figure 7 - Morphotectonic elements of Sumba and adjacent Savu Basin, showing the extent and direction of progradation (arrow) of the Miocene submarine fan. The arrows indicating the orientation of the slope and main palaeocurrent direction of the Neogene volcaniclastic turbidites of East Sumba. Fault F5 is interpreted as a growth fault between the position of the Pliocene Kambatana channel (triangle) and the main turbidite fan (Roep and Fortuin, 1996). Red box is Watuparunu Coast with the outcrop of slump structures showing northeastward transport, parallel with the regional trends.

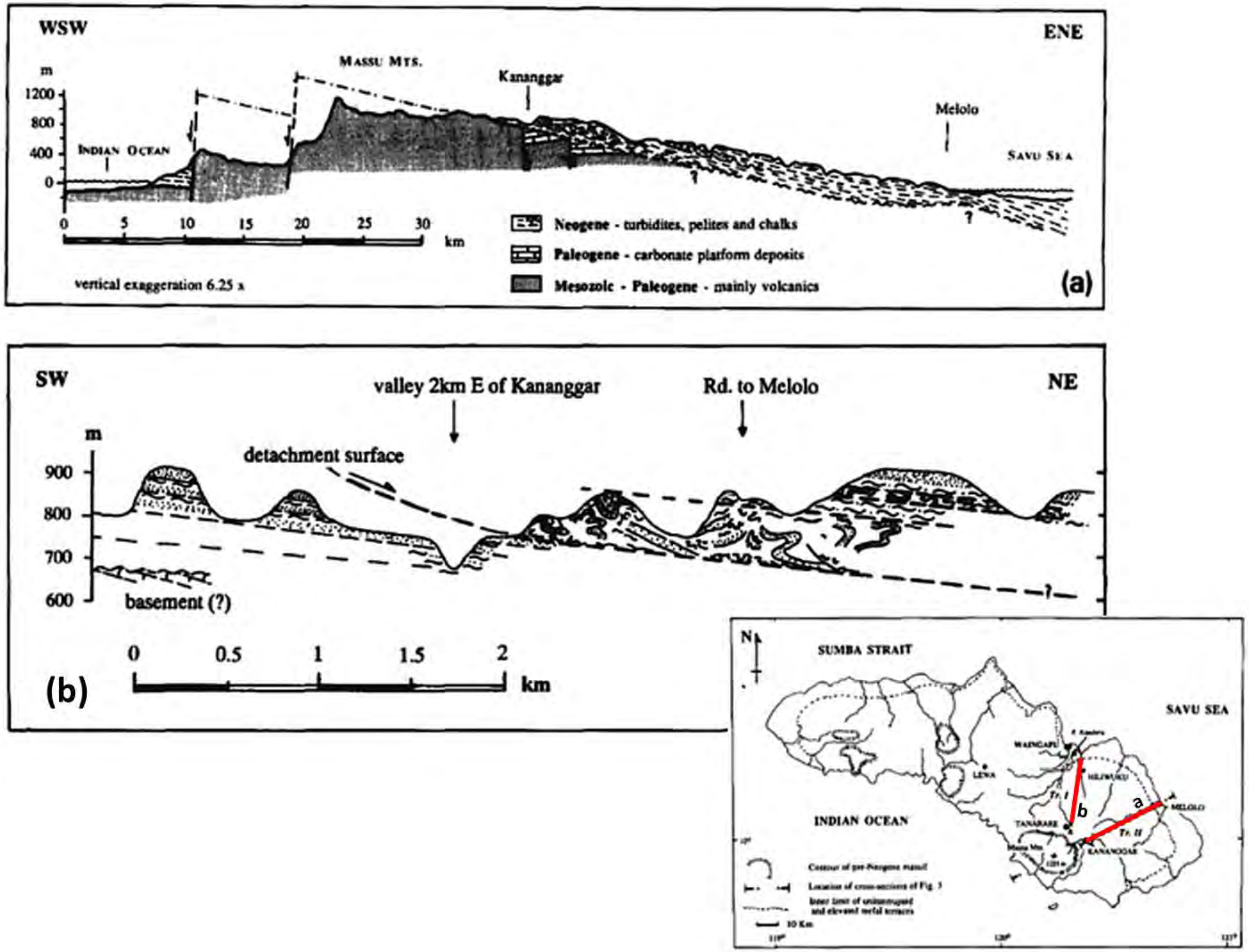

Figure 8 - (a) Schematic WSW-ENE structural cross-section of East Sumba across the line Melolo-Massu Mountains, transect II. Distorted levels within the Neogene indicate observed slides. (b) SW-NE cross-section through the Neogene Kananggar, located just east of Kananggar, slides and slumps are shown (Fortuin et al., 1992).

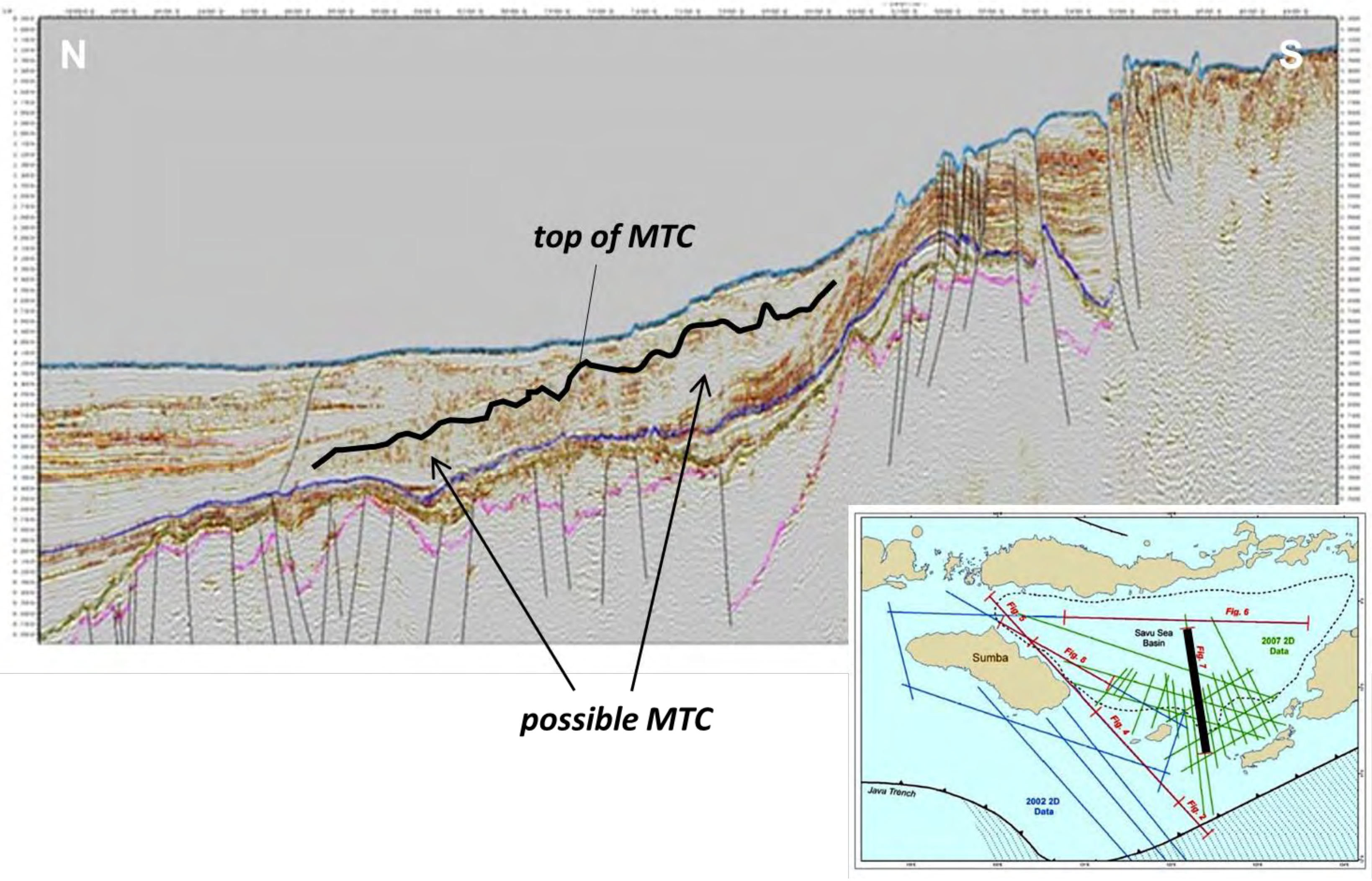

Figure 9 - Seismic section across the Savu Basin, showing possible presence of MTC, sourced from southern uplift moved downslope northward into subsided basin (seismic section after Toothill and Lamb, 2009).

Figure 10 - Part of the MTC outcrop cliff at Watuparunu Coast, SE Sumba, uninterpreted and interpreted pictures. Lithology are tuff and pelagic carbonates of Mio-Pliocene Kananggar Formation. The MTC show slump structures of fold and thrust system. Slump structure is a part of MTC representing a coherent rotational mass transport of a block or strata on a concave-up glide plane (shear surface) with internal deformation (Shanmugam, 2016). Detachment/shear surface is underground, upper detachment is observed in the middle of the outcrop into which some upper faults ramp to. Upper part of the outcrop is not as complicated as the lower one, indicating multiple history of MTC. Tectonic transport is 40°NE (direction of principal stress) with strikes of faults 285°NE, this parallel with regional trend of MTC in East Sumba (Fortuin et al., 1992; Roep and Fortuin, 1996). Note the dimension of outcrop compared with people of Geotrek Indonesia community.

Figure 11 - Coherent slump structures with fold and thrust system verging to the right (northeastward), at sea cliff of Watuparunu Coast, part of the MTC of East Sumba. Most of the structures are recumbent. The lithology are tuff and pelagic carbonates of Mio-Pliocene Kananggar Formation.

Figure 12 - Fold and thrust system of slump structures of Watuparunu Coast outcrop, SE Sumba with pressure ridge in between faulted folds. Left bottom inset shows in more detail the pressure ridge. Pressure ridge is created due to tectonic loading of the two fold structures compressing the area in between and buoyant sediments pierced upward forming pressure ridge structure, with some broken formation. Right bottom inset shows eroded fault plane by sea abrasion forming a sea cave. The sea cave was formed right at the weakness zone of the fault plane.

Figure 13 - Chaotic rotated blocks of tuffs and pelagic carbonates (marls and chalks) with internal deformation of Mio-Pliocene Kananggar Formation in slump structures of MTC of East Sumba at Watuparunu Coast outcrop.

Figure 14 - Sea cliff of Watuparunu Coast, SE Sumba, seen from top of the cliff. The cliff shows deformation of Mio-Pliocene Kananggar Formation related to gravitational slump structures of East Sumba MTC. Bottom insets show the observation of the cliff by the community of Geotrek Indonesia.

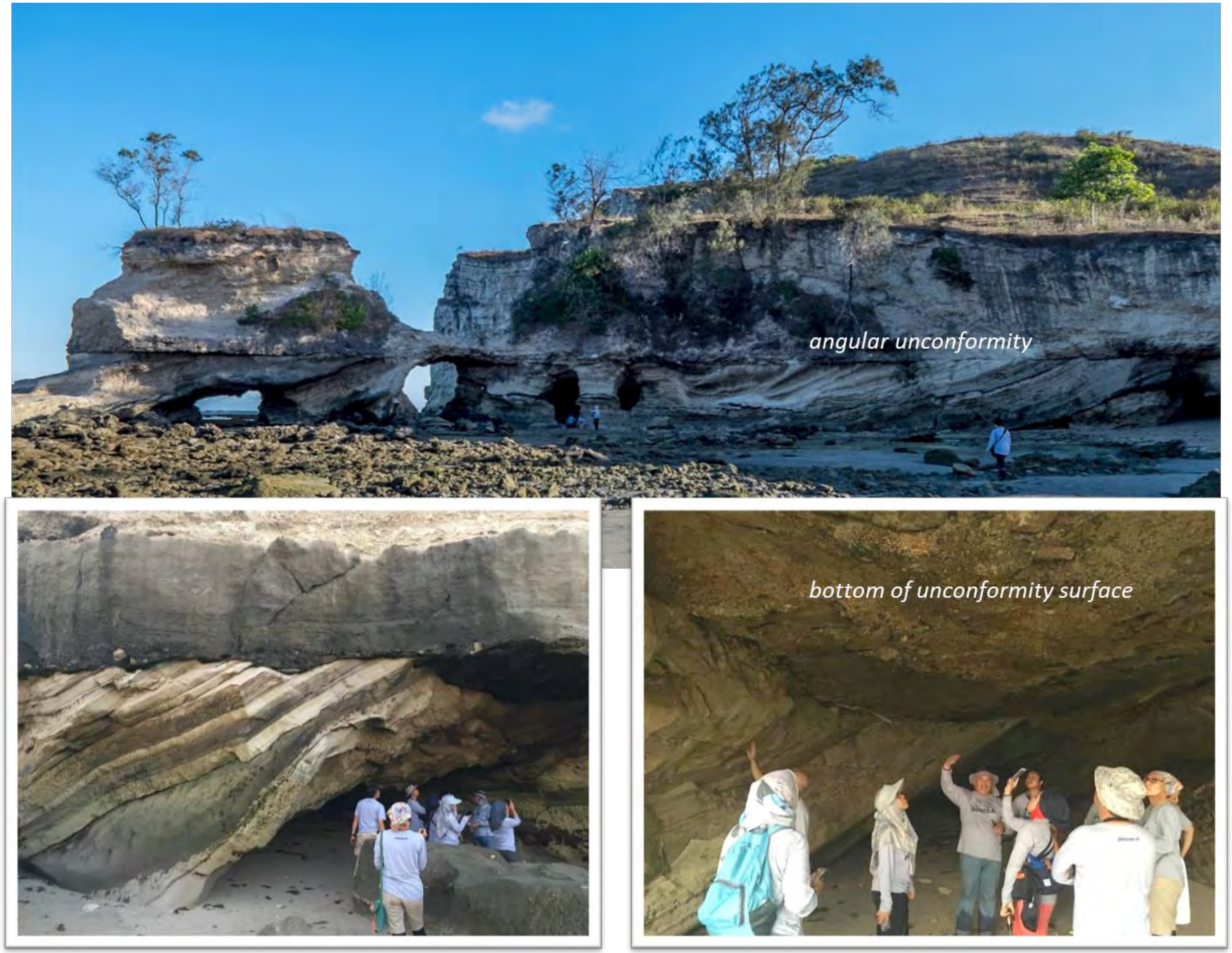

Figure 15 - Above – The karstified pelagic carbonates forming sea arches and caves of the Mio-Pliocene Kananggar Formation, the name of Watuparunu (means arched rock in local language) is due to these arches. Note the presence of angular unconformity, detailed in the bottom inset pictures. The surface of angular unconformity is eroded by sea abrasion in some places making the 3D geometry of the angular unconformity into which people can enter and observe the surface of unconformity from below.

Figure 16 - Successive flows result in laterally directed compressional microstructures like convoluted beds commonly observed in MTC outcrop of Watuparunu Coast, SE Sumba, accompanied by internal deformation which is consistent with compressional fore shortening and subsidence.