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Analogue Modeling of Oblique Convergent Strike-Slip Faulting and Application to The Seram Island, Eastern Indonesia

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Abstract - Unstable water table would lead to moist condition in the uppermost layer of the ombrotrophic peat, favoring fungi to grow. This is confirmed by the higher abundance of sclerotinite maceral in samples from the upper part of the coal core. Sandbox experiment is one of the types of analogue modeling in geological sciences in which the main purpose is simulating deformation style and structural evolution of the sedimentary basin. Sandbox modeling is one of the effective ways in conducting physically modeling and evaluates complex deformation of sedimentary rocks. The main purpose of this paper is to evaluate structural geometry and deformation history of oblique convergent deformation using of integrated technique of analogue sandbox modeling applying to deformation of Seram Fold-Thrust-Belt (SFTB) in the Seram Island, Eastern Indonesia. Oblique convergent strike-slip deformation has notoriously generated area with structural complex geometry and pattern resulted from role of various local parameters that control stress distributions. Therefore, a special technique is needed for understanding and solving such problem in particular to relate 3D fault geometry and its evolution. The result of four case (Case 1 to 4) modeling setting indicated that two of modeling variables clearly affected in our sandbox modeling results; these are lithological variation (mainly stratigraphy of Seram Island) and pre-existing basement fault geometry (basement configuration). Lithological variation was mainly affected in the total number of faults development. On the other hand, pre-existing basement fault geometry was highly influenced in the end results particularly fault style and pattern as demonstrated in Case 4 modeling. In addition, this study concluded that deformation in the Seram Island is clearly best described using oblique convergent strike-slip (transpression) stress system.

Keywords: sandbox modeling, oblique convergent, strike-slip, fold-thrust-belt

Introduction

Understanding internal deformation resulting from tectonic stress is very important for evaluating reservoir continuity and traps. For example, in many hydrocarbon exploration stage, available subsurface data (2D seismic) are mostly limited coverage with large spacing as a result structural interpretation particularly fault pattern and geometry often misleading and uncertain. One of the main problem is because of limited data can be used for 3D view of the internal deformation. In addition, in many cases conducting interpretation in structural complex area need support from analogue modeling in order to achieve high confidence level. Therefore, integrated 3D structural analysis supported by analogue modeling will contribute not only deformation pattern but also internal fault geometry.

This paper demonstrated result of integrated study using analogue sandbox modeling and supported with subsurface structural interpretation using existing seismic data for explaining deformation pattern in the Seram Fold-Thrust-Belt. The main purpose of this paper is to demonstrate the important of sandbox modeling in analyzing strain pattern distribution within the large deformation zone in order to understand their formation mechanism.

Geologic and Tectonic Setting of the Seram Island

Seram Island is located in the Eastern Indonesia geologic province. The study area is located in onshore of the Seram Island particularly within the main fold-thrust-belt (Figure 1). Eastern Indonesia is a highly complex geological region located in the zone of convergence between the Eurasian, Indo-Australian and Pacific Plates (Figure 2). The major geological feature is the Banda-Arc, which consists of an inner volcanic arc and an outer non-volcanic arc of islands formed of sedimentary, metamorphic, and some igneous rocks mainly of Permian to Quaternary age (Pairault *et al*., 2003). The inner volcanic arc is interpreted as a long-lived arc that has been active since the Late Miocene. On the other hand, the outer arc is interpreted as a recent zone of collision between the Australian continental margin and the Banda volcanic arc including thrust sheets, principally of Australian sedimentary rocks but associated in places with some igneous and metamorphic rocks, which have been elevated above sea level very rapidly since the mid Pliocene (Pairault *et al*., 2003). The Seram Trough is part of a long trough system, which runs almost 2,000 km from the Java Trench via the Timor Trough to join the Seram Trough, curving in a U-shape to enclose the deep Banda Sea.

The origin of the trough is still a growing debate. Some authors (*e.g.* Hamilton, 1979; Hall, 1997; Charlton, 2000) interpret it as a subduction zone separating the Australian and Eurasian Plates, whereas others suggest that it is a foredeep at the front of a developing fold belt. It has also

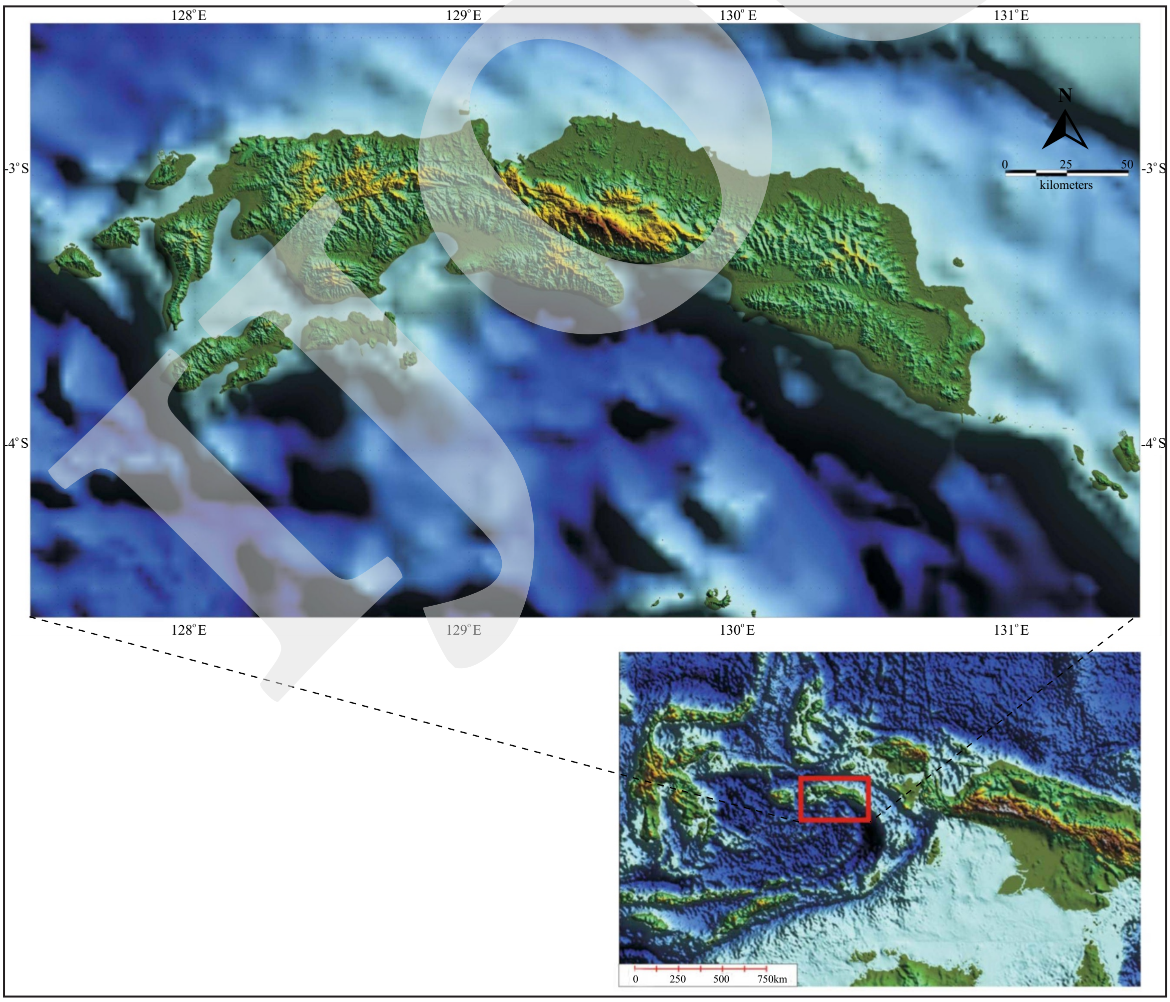

Figure 1. Location of studied area at Seram Island, eastern Indonesia bordered to by Banda Sea to south and Bird Head region to the north.

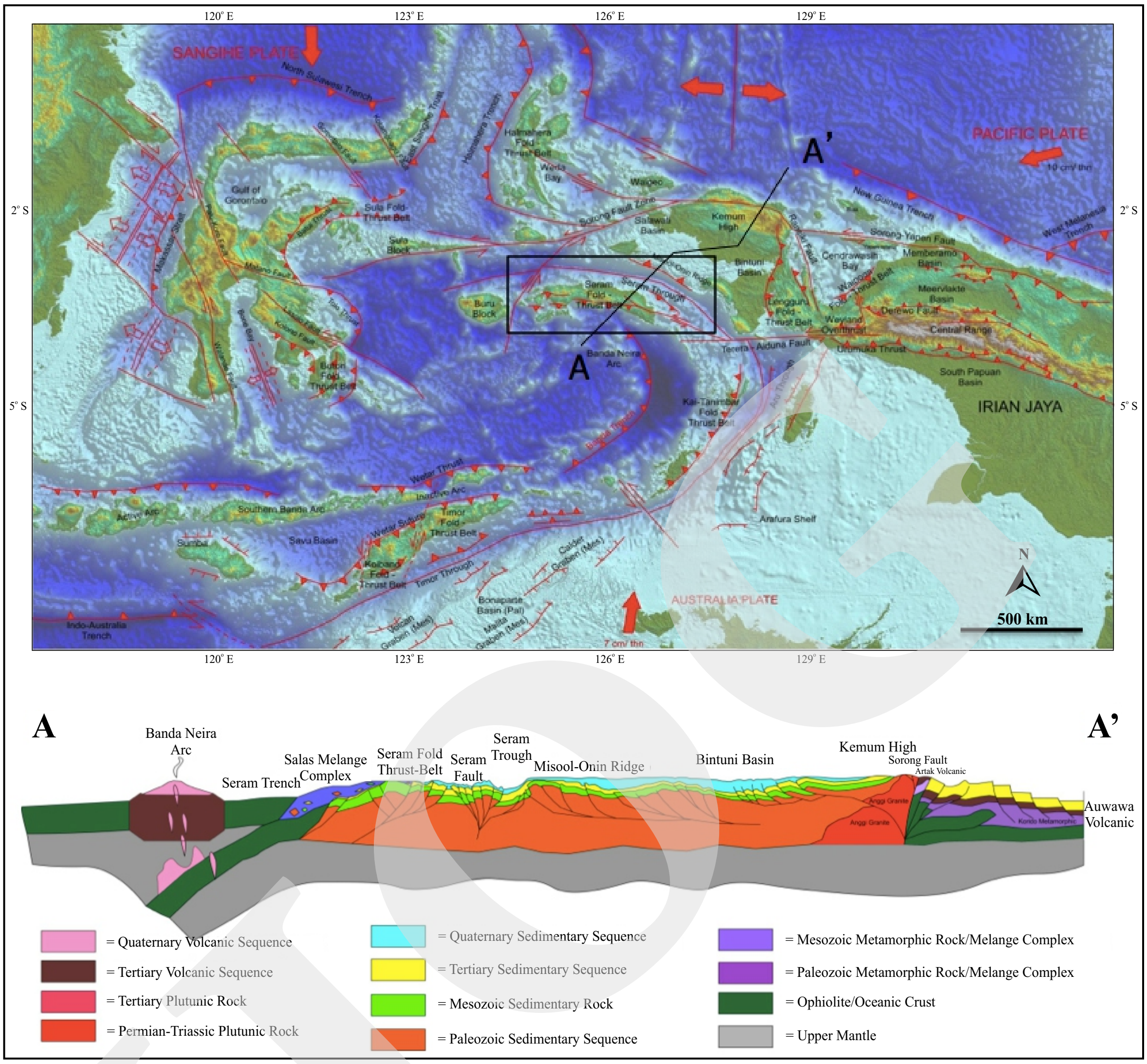

Figure 2. Tectonic setting of Eastern Indonesia region shows regional plate interactions including Seram Island structures and its surrounding boundaries. Lower diagram shows regional cross-section (NE-SW) indicating structural boundaries and relationship between Seram Island and Bird Head region (nomenclatures and boundaries is adapted from Sapiie *et al*., 2012).

been suggested that the Seram Trough might be a zone of strike-slip faulting (*e.g.* Linthout *et al*., 1991), but it is now generally agreed to be the site of southward underthrusting of the Bird's Head (northwest New Guinea) beneath Seram. However, the debate continues about whether it is a zone of intra-plate shortening or a subduction trench, and among those who argue for subduction which are supported by recent micro earthquakes and tomography studies, there is disagreement over whether there is a single slab which curves around the arc (Hamilton, 1979) or two separate slabs dipping in opposite directions (Cardwell *et al*., 1980).

Recent seismic interpretation work by Pairault *et al*., (2003) proposes that the Seram Trough is not a subduction trench but a foredeep produced in response to loading by the developing fold and thrust belt of Seram, with an associated peripheral bulge to the north. Therefore, the Seram Trough is interpreted to be a very young zone of thrusting within the Australian continental margin (Bailly *et al*., 2009; Pairault *et al*., 2003). However, the detail mechanism of the trough formation is still unclear. The most recent work was done using a detail interpretation of high-resolution bathymetry data (Teas *et al*., 2009). This work shows numerous evidence of strike-slip deformation within the Seram Trough (offshore part of SFTB), particularly in the eastern part. Changing deformation pattern within SFTB is interpreted as a result of transpression deformation due to the left-lateral movement of E-W trending Tarera-Aiduna Fault Zone. The fault is clearly seen in the bathymetry data and it also can be followed in the surface (onshore) to east using SRTM image data. However, subsurface data (2D seismic) are difficult to directly map this fault due bad image. Sapiie *et al*. (2012) proposed a mechanism of oblique convergent strike-slip deformation for explaining structural evolution of offshore Seram Trough. The onshore geology of Seram Island including fold-thrust-belt has been studied intensively in relation to hydrocarbon prospect by various authors since the early nineteen hundred's by the discovering the Bula and Oseil oil fields. However, the structural evolution as well as their mechanism still remains uncertain.

Methods of Study

This study was achieved using an analogue sandbox modeling. This technique has some strength, because it will give powerful methods in evaluating complex structured area. The main purpose is to have a better understanding in term of structural evolution and geometrical relationship among faults in 3D as well as their kinematics applied to SFTB.

Sandbox Modeling Apparatus

One of the problems in understanding deformation in the earth crust involves simulating structural development in the sedimentary basin. This can be achieved using analogue modeling. Sandbox modeling is one of the types of analogue modeling in geological sciences in which the main purpose is to simulate deformation style and structural evolution of the sedimentary basin (Sapiie and Hadiana, 2006).

The sandbox experimental method used in this investigation generally follows that described by Hubbert (1951) and Cloos (1968). The ITB sandbox apparatus used in this experiment is an open-topped glass box with fixed external walls and one or two moveable internal walls pushed by screw jacks driven at a constant velocity by a stepper motor. The dimensions of the box are sufficiently large to ensure that a large part of the model escapes boundary effects. The sand pack is made of thin alternating colors layers, which allow the identification of faults and folds on cross-sections. During experiments, photographs of the surface of models will be taken using a digital camera at regular time intervals to study the progressive evolution of structures. To check the consistency of the results obtained, the experiments will repeat several times.

In this study, two sandbox apparatus were designed for simulating various experiments and deformation of oblique convergent strike-slip tectonic setting. The first apparatus has dimensions of 1 m long, 0.5 m wide, and 0.5 m deep with open-topped glass box with fixed external walls and two moveable internal wall pushed by screw jacks driven at a constant velocity by a stepper motor (5 cm/hour). This apparatus is mostly aimed at a passive deformation setting in which one of the sides acts as a backstop or fixed point. The second apparatus is specially designed in this project for simulating strike-slip deformation experiment. It has dimensions of 1 m long, 0.5 m wide, and 0.5 m deep with open-topped glass box with fixed external walls and two moveable internal walls that can be rotated with a maximum angle of 45^{o} pushed by screw jacks driven at a constant velocity by a stepper motor. This apparatus is aimed at more active deformation setting in which two moveable plates move at a specific relative speed to each other (Figure 3).

Sandbox Modeling Apparatus

Deformation in a ductile rock depends on its rheological properties and strain rate that in turn depend on temperature, pressure and composition. On the other hand, a brittle deformation depends on the shear strength, and the coefficient of friction and cohesion. Therefore, to simulate the wide range of deformation styles actually observed in rocks, a range of different modeling materials needs to be used. Experimental and theoretical studies have shown that sand is a good analogue for brittle Mohr-Coulomb behavior during shallow (depth of 1 -10 km) deformation of sedimentary materials (McClay and Ellis, 1987; McClay, 1990;

Figure 3. Sandbox apparatus shows size and sand experimental box (a and c), electronics equipment (b) including stepper motor and control units. This apparatus specifically develops to simulate rotational strain.

Withjack *et al*., 1990; Davy and Cobbold, 1991; Dooley and McClay, 1996).

In this study, the authors used natural dry quartz sand with a Navier-Coulomb rheology and an angle of internal friction (φ) of about 30°, similar to many sedimentary rocks (Krantz, 1991). This natural granular quartz sand was collected from the Ngrayong Formation outcropping in the East Java area. It is composed of friable sands with sub-angular to well-rounded and well-sorted grains (Sapiie and Hadiana, 2006). Its bulk density is about 1.5 g/cm^3 and has a homogenous grain-size distribution with an average of ~< 0.5 mm obtained from sieving. For materials following the Navier-Coulomb failure criterion, an accurate scaling is required that the model and real earth cohesive strength should be scaled in the same proportion as the ratio of their unit thickness (Sapiie and Hadiana, 2006; Sapiie *et al*., 2012). Gypsum and kaolin are used in this experimental study for simulating more ductile rheology behavior such as limestone, clay or shale formations. Based on the previous laboratory work, these materials are the best of the kind for representing more ductile part of deformation. However, thick gypsum shows much more elastic behavior in which they tend to fracture in a high shortening number (Sapiie and Hadiana, 2006).

Geologic Boundary Condition for Sandbox Modeling

The stratigraphy and structural geologic interpretation used in this study is based on by Kemp, *et al*., (1995) modified from the previous works by Kemp and Mogg (1992).

The coverage area of the study lies within the Seram Island, approximately 600x180 km^2. The field consists of thick sequence of Pre-Tertiary (Paleozoic - Mesozoic) carbonate formations, from older to younger: Kobipoto Fm., Taunusa Complex, Tehoru Fm., Saku Fm., Kanikeh Fm., Saman-Saman Fm., Manusela Fm., Kola Shale, Lower Nief, and Upper Nief. For the scope of this work, Kobipoto, Taunusa Complex is considered as a crystalline basement (Figure 4). The experiment concentrates on the Mesozoic and Tertiary formations consisting mainly of interbedded limestone and clastics (mostly sandstone) units. The study area is controlled by a pre-existing fault system (representing graben of Early Mesozoic rift system) oriented N 300^o E (NW-SE) steeply dipping to the East. Convergent vectors will be set obliquely to the bounding fault (~ 30^o). The result of analogue modeling will be evaluated using provided published maps and 2D seismic interpretations.

Based on field data and limited 2D seismic data, structural pattern and styles of Seram Island is characterized by a series of fold-thrust-belt where in some part showing slightly en echelon pattern (Riadini *et al*., 2010.). It is interpreted that deformational setting of the Seram Island is

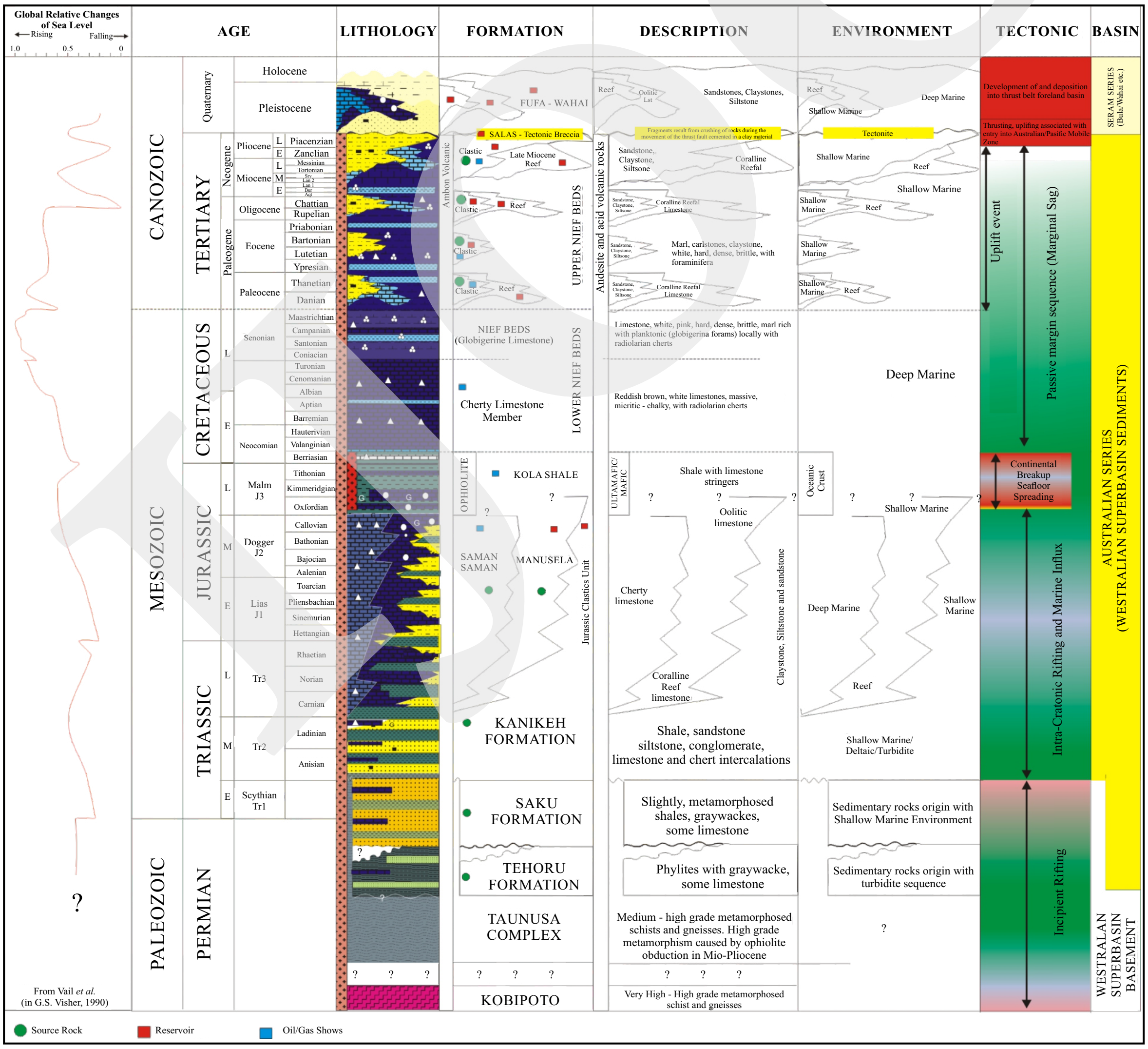

Figure 4. Regional stratigraphic column of the Seram Island showing vertical relationship of major rock units and formation generated based on a compilation of previous workers in the island (Nilandaroe and Barraclough, 2003).

controlled by strike-slip movement (transpressional tectonic setting) rather than by purely contractional deformation. Therefore, sandbox-modeling experiment is aimed at testing this tectonic interpretation.

Experimental Setting

Fold-thrust-belt (FTB) is one of the most complex deformation patterns. It can be formed by both pure and simple shear deformations. In most case, parallel fault pattern in FTB is a characteristic of pure shear deformation where en-echelon fault pattern commonly resulted from a simple shear deformation. Internal fault pattern and geometry vary significantly depending on their deformational setting. It can be controlled by basement known as thick-skinned FTB or along specific detachment surface usually within the thick shale unit known as thin-skinned FTB system. On the other hand, an oblique convergent strike-slip fault system will create combination shortening and strike-slip faulting and it has been known for generating complex and asymmetric deformation pattern. The main issue is to distinguish between FTB resulted from pure shear and oblique strike-slip fault system. In the most case, it is difficult to recognize them if only using their deformation pattern. Much field evidences indicate both thrust and strike-slip movements can act in the same fault plane.

In this study, four different deformational settings (case 1 to 4) were modeled including several sensitivity analyses to test and to simulate observed structural development within Seram Island. In most of the deformational settings, basin geometry is bound by two major faults in the basement forming a distinct NW-SE graben. Layers in the model followed basic stratigraphy of the area based on existing stratigraphy in which colored sand represents clastics unit and gypsum (white color) represents limestone formation or units (Figure 5).

Evaluation of each different modeling setting was done for several different increments of deformation, for example, during 5%, 10% or 23.5% shear displacement or shear strain (angular shear relationship). The geometry and timing relationship (*e.g.* between fold and fault) were evaluated by generating a series of cross-sectional view on the maximum shear strain (23.5%). In addition to geometry relationship (cross-sectional view), morphology or topographic development in each modeling setting was studied in great detail for understanding fault pattern and effect of defor-

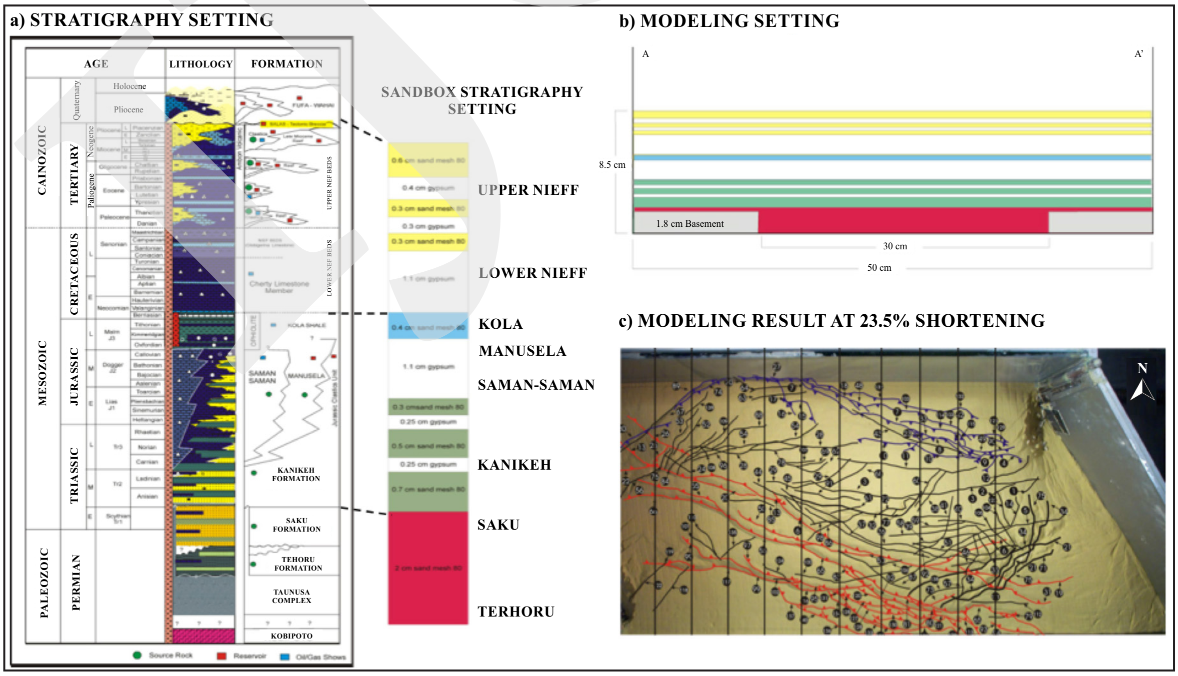

Figure 5. Example of modeling setting for case 3 showing a comparison of regional stratigraphy (a) and sandbox modeling including basement configuration (b). Result of modeling shows a structural map presenting fault pattern and types (c).

mation on the surrounding area. All of the steps above are very important particularly for evaluating structural development and deformational sequences. To obtain the best result, the final stage of the study should evaluate the modeling result using several detailed geological information, such as 2D seismic sections. This evaluation is the most important step to do, because in understanding deformational processes, all modeling results should match with what is observed in nature.

Result of Sandbox Modeling

The evaluation of sandbox modeling results generates several intriguing interpretations of internal structures and sequences resulting from oblique convergent strike-slip fault deformation (transpression). The results of sandbox experiments were evaluated using four different cases where is case representing specific geological boundary condition.

Case 1 modeling setting consists of two different materials: sand and gypsum. In the case of sand layer, it is observed that deformation is dominated by a series of low-angle thrust-faults. The orientation of major thrust-faults is gradationally changed from N-S trending to NW-SE trending faults starting approximately after 10% shortening. This evidence supported the theoretical prediction of rotational strain in the case of simple shear deformation. Sensitivity analysis supported the argument in which in thinner sand materials evidence of rotation was observed only after 20% shortening. On the other hand, experiment using pure Gypsum wasn't successful as expected in theoretical prediction.

Case 2 modeling setting comprises two rigid triangle-shaped basement blocks made of solid wood. One of the blocks is attached to moving wall, the other one act as a fixed wall. Total stratigraphic thickness is 8.5 cm, consisting of 4 layers of colored sand in which each has a specific thickness and grain size. The result shows an excellent development of NW-SE trending flower structures and pop-up morphology exactly as theoretically predicted. The flower structures are characterized by asymmetrical geometry toward the SE in which deformation on this side has more low-angle thrust fault geometry compared to the NE part of the model. A series of NNE and NE trending fracture systems were developed between major thrust-fault belts. These fracture systems are interpreted as Riedel's fractures (R and R'), which developed in the left-lateral strike-slip fault deformation as shown in the clay-cake modeling from Tchanlenko (1970). Overall observation suggests that the occurrence of Riedel fracture system and the dip of the thrust-fault are controlled by dip and dip direction of the basement fault (pre-existing structures).

Case 3 modeling is set exactly similar to Case 2 except in terms of stratigraphic unit. In this case, heterogeneous layers (interbedded sand and gypsum) are used for representing detailed stratigraphic units in the area. Similar settings of sensitivity tests in Case 2 were applied in Case 3. The results of Case 3 experiment show excellent development of fractures system in oblique strike-slip faulting as demonstrated in many literatures from both analog and field evidence. The stress distribution mostly occupies two main NW-SE trending thrust-fault zones (deformation zones) and forming pop-up morphology with asymmetry flower structures geometry (Figure 6). Riedel's fracture systems were well developed between two main deformation zones. These fractures are mostly dominated by NE-SW trending R (synthetic) type. Structural analysis at 23% shortening shows strongly dominant two major orientation of fracture: NW-SE thrust-fault and NE-SW Riedel's fracture system. The dip distribution shows that in average Riedel's fracture system more steeps than thrust-fault system (see stereographic analysis). Two sensitivity tests indicate that the dip of the basement fault controlled the total numbers and distribution of major thrust-faults (Figure 7). The Eastern verging basement fault generated less faults and joints compared to vertical and inward verging (opposite basement faults). It seems that the width of the deformation zone is very sensitive to the geometry of basement fault geometry. Thickness variation in the interlayer sand and gypsum seemingly controlled dip variation along the faults plane. Therefore, heterogeneous stratigraphic feature is the most representative setting for modeling rheology of Seram Island.

Case 4 experiments develop based on results from Case 2 and 3 above. In this case, the heterogeneous stratigraphic feature is used for representing modeling materials. Vertical dip of basement faults is chosen as representation of basement configuration. Case 4 experiments aimed to simulate field conditions surrounding the Oseil field based on interpretation of gravity data. Therefore, additional basement block is set in the middle of the basin representing structural high during deformation. Sensitivity analyses in this model consist of rheology (pure sand setting) and dip of basement high. In addition, a modification version of Case 4 is related to the setting in which a gypsum block is put on the top of basement high representing reef unit of Manusela Formation.

There are several differences and similarities in terms of styles and total number of faults oc-

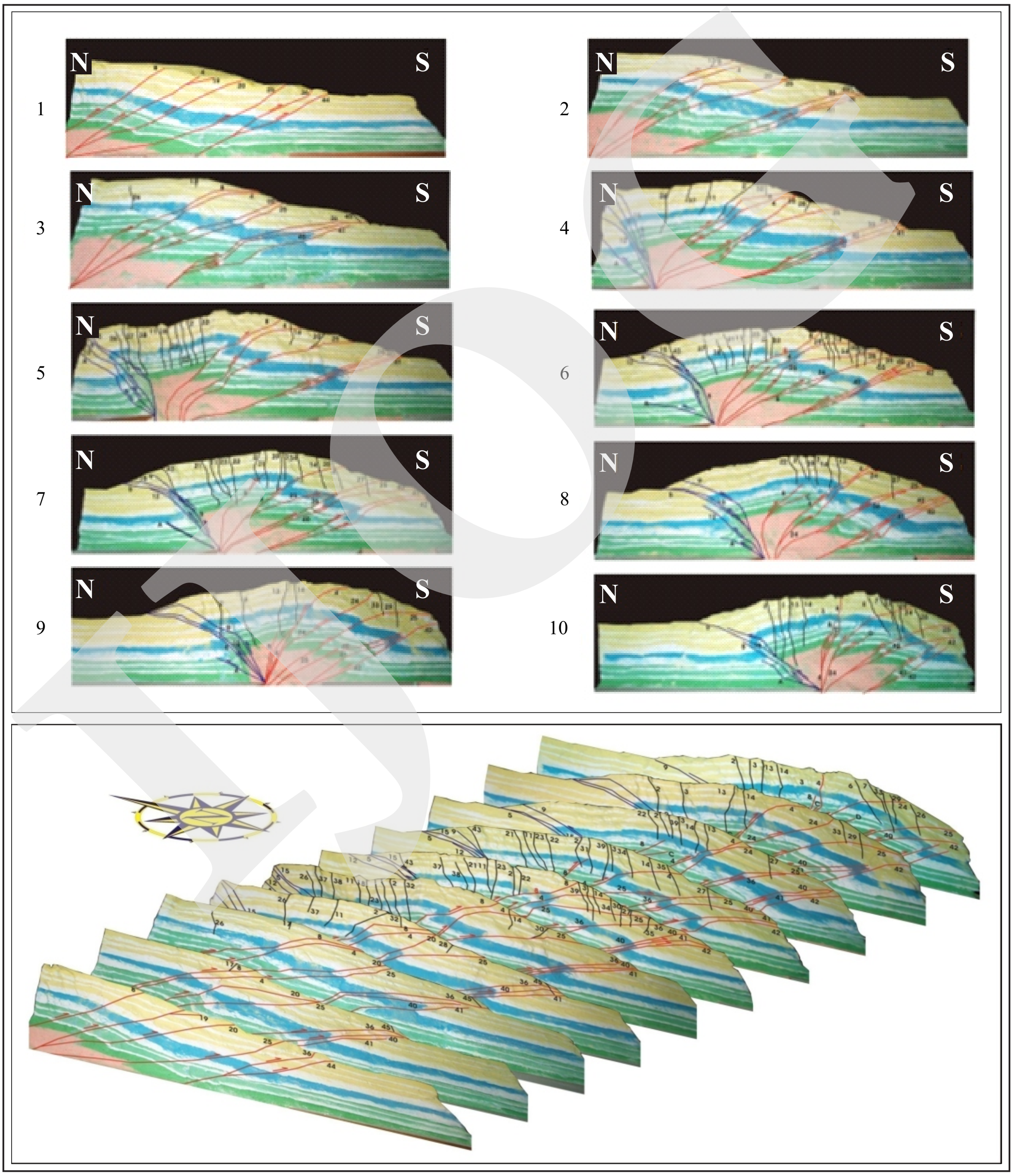

Figure 6. Cross-sectional view of sandbox modeling (Case 3) shows variation of fault style, pattern, and geometry. Note: significant changes in fault style from west to east (lower diagram) showing both thrust fault and flower structures geometry.

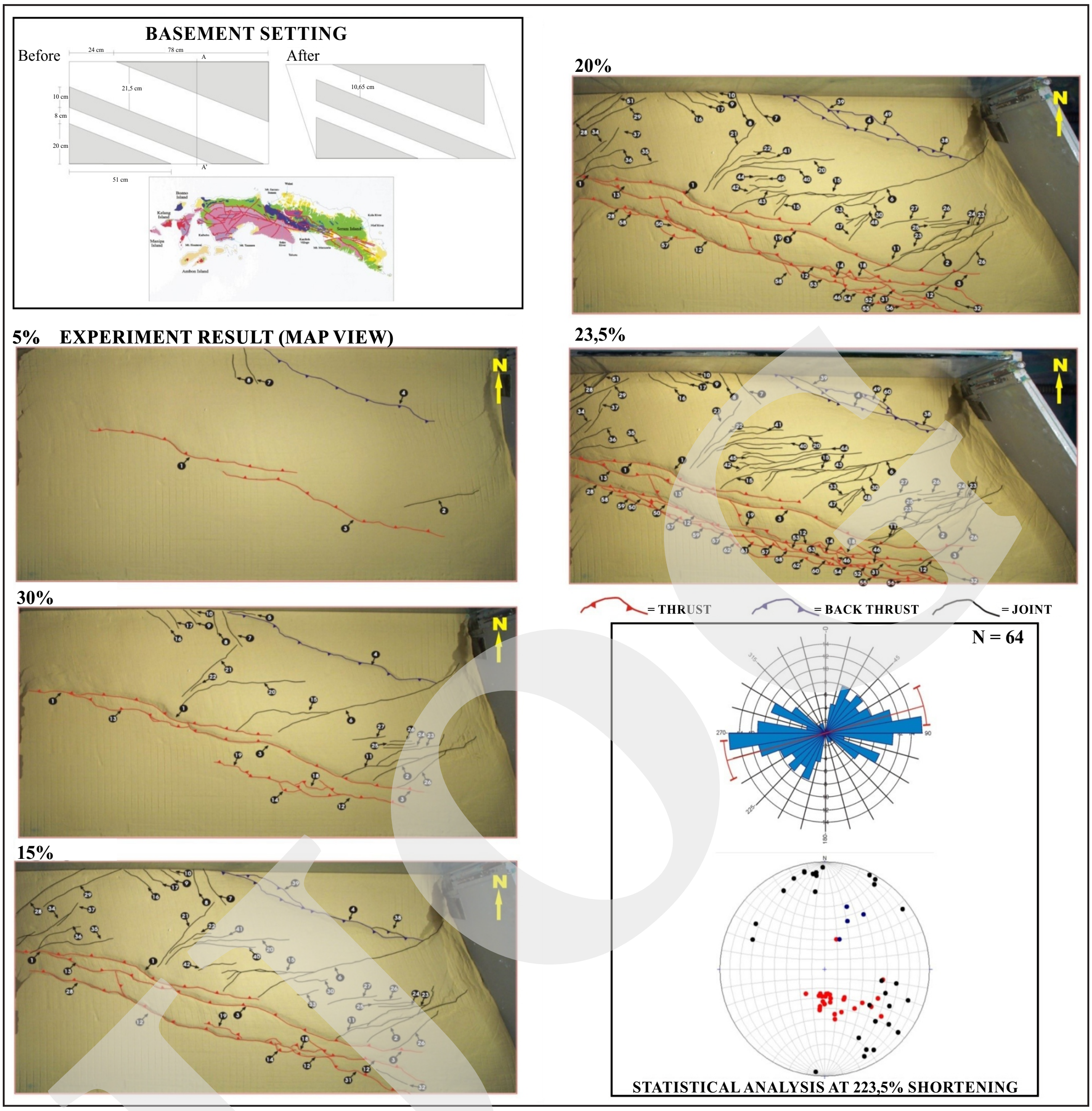

Figure 7. Example of modeling result of setting for Case 3 showing sequence of fault development as a result of deformation where in this case is represented by percentage of shear strain. Upper diagram show basement configuration setting and lower right corner diagram show structural distribution and orientation resulted from 23.5% of shear strain deformation.

curring in Case 1, 2, 3 and 4 modelling. All cases exhibit a similar result in which all generated asymmetry positive flower structures. The comparison results of all cases suggest several major conclusions concerning roles of modelling variables such as experimental materials (sand, gypsum or both) and basement configuration both geometry and positioning as pre-existing geologic boundary in the model. It has been demonstrated by all cases, those variables above were highly influenced in controlling detailed internal deformation of the sedimentary package. Variability in layering materials, meaning variability in rheology, will generate more complex internal deformation. The more complex basement geometry and setting generated, more complex faults and fracture systems. Therefore, choosing the right combination between those variables is the most important step in sandbox modeling. The error resulting from modeling can be reduced by intense evaluation of existing geological information and model. In the case of Seram Island modeling, it clearly shows that limestone block sitting in the top of basement high controls thrust-fault development in the basin.

The result of deformation in Case 4 shows a series of excellent developments of asymmetrical flower structures. The basement high geometry is highly influenced in the development of dip (*e.g.* low-angle *vs*. high-angle or ramp-flat-ramp geometry) and numbers of thrust-faults. These were clearly seen in the comparison of cross-sectional views from several different runs (Figure 8). In the modified Case 4, experimental results show an interesting conclusion in which deformation was clearly buffered by the presence of solid limestone block, although in some parts of the section, pieces of limestone was also involved in the thrust-fault system. Moreover, deformation is highly concentrated forming deformation bands in front of solid limestone blocks. Results from sensitivity test suggest that positioning basement in the basin is highly influenced in the total number of thrust-fault developed and location of deformation bands. The model indicates faults spacing, dips, and styles change rapidly along strike suggesting non-parallelism deformation involving rotation that is best describe as a simple shear rather than pure shear mechanism. Overall, our physical modeling results using analogue sandbox are able to demonstrate the roles of strike-slip faulting mechanism in the formation of SFTB. In addition, field example shows the development of low-angle thrust fault within the Kanikeh Formation which is similar to the sandbox modeling result (Figure 9).

Discussions

Fault pattern, geometry and style produced by the model are very similar to the pattern mapped in the SFTB. Therefore, it can be concluded that the oblique convergent strike-slip fault mechanism highly influenced the formation of SFTB. This type mechanism is known as transpression tectonics. However, there is still uncertainty concerning comparison with structures interpretation from 2D seismics. Because, most of the seismic data are very hard to interpret due to bad image and continuity reflectors, as results there are no good control in conducting interpretation. Hence, it will generate uncertainty in verifying modeling results. Moreover, it seems that deformation is more complicated in the middle structure domain compared to the west and southeast. These results suggest that the middle part of the SFTB is where coupling between shortening and translation occurred, and it was controlled by pre-existing structures such as strike of the bedding and pre-Jurassic structures (*i.e.* Permian rifting). Most of this information is limited due to lack of data, although, field evidences support the development of low-angle thrust fault system as observed within the Kanikeh Formation near Oseil-2 well (Figure 9). Result of deformation in the middle part is clearly supported by results from the surface and subsurface mapping which again supported the oblique convergent strike-slip model. But, a more detail and careful evaluation

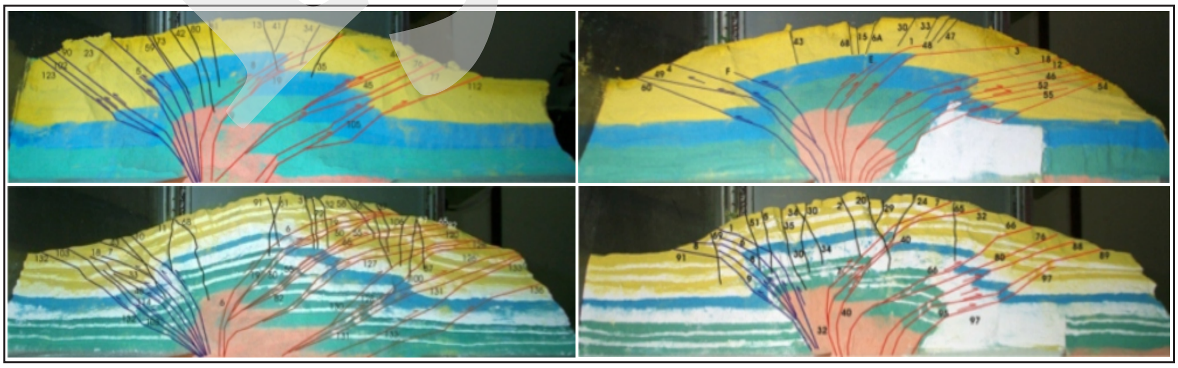

Figure 8. Cross-sectional view of sandbox modeling showing comparison of two different modeling setting: lithology composition (stratigraphy) and basin setting (basement configuration). Upper diagram show uniform sand grained with two different deformation setting without basement high (left) and with basement block representing by gypsum block (right).

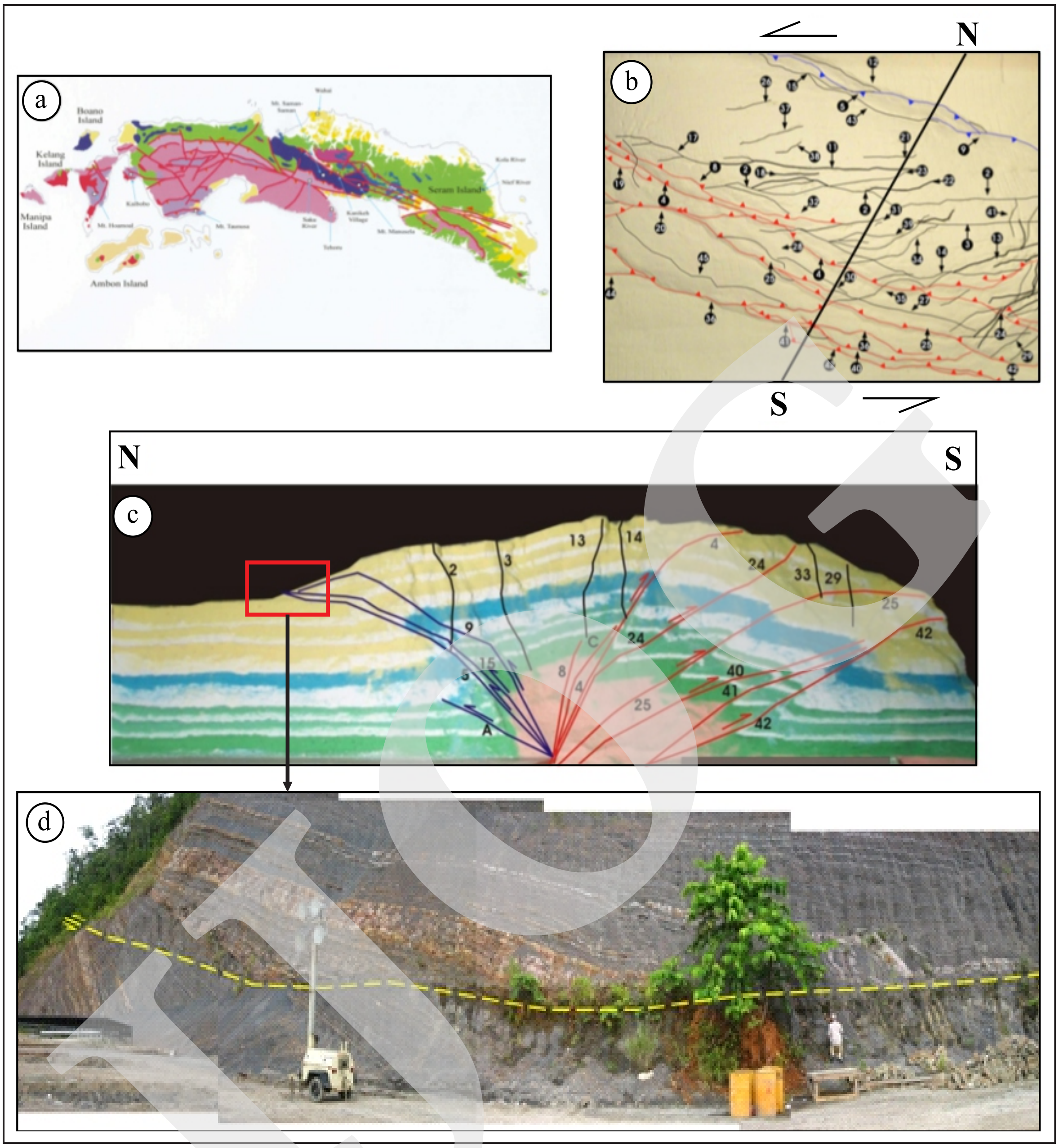

Figure 9. Examples of map and cross-sectional view of sandbox modeling (Case 3) exhibiting variation faults style, pattern, and geometry (a-d). Note: in c (middle diagram) significant changes in fault style representing field section of northeast to southwest show both thrust fault and flower structures geometry. Lower diagram (d) show field example in the Seram Island (close to Oseil-2 well) of low-angle thrust fault within Kanikeh Formation as indicated from sandbox modeling (red box).

in the future is needed for supporting this model. Since, the modeling results is mainly generated using simple basement configuration and constant sediment thickness where natural example may be not as simple as sandbox modeling setting. The main reason is due to limited and large spacing of existing seismic data. The geological boundary condition needs to be improved using more detail interpretation in particular in the middle part of the SFTB. In addition, some of the irregularity occurring in the model perhaps due to the scaling factor between thickness and area of the model. The scale factor is limited due to the capability of the sandbox apparatus in the laboratory. Future works will concentrate in improving capability of sandbox apparatus in supporting results from seismic interpretation particularly in term of scaling.

In addition, future works need to be done particularly in relation to sandbox modeling of different types of fold-thrust-belt geometry as calibrating of modeling results. Integrating approach using 3D palinspatic reconstructions (balancing cross-section) will help for developing better understanding relationship between stratigraphy and structures evolution. This knowledge is clearly very important in relation to hydrocarbon exploration and prospect in the fold-thrust-belt tectonic setting. Moreover, this study demonstrated that integrated detailed surface geology and subsurface structural analysis supported by sandbox modeling helps greatly in ramification the mechanism of the SFTB.

Conclusions

Based on integrated analysis of hard data using field geological map, 2D seismic interpretation, and analogue sandbox modeling generate several major conclusions concerning the development of SFTB as follow:

1. Sandbox modeling is a quick, cheap, and effective way to study and to understand the pattern and geometry of the deformed sedimentary basin as demonstrated in the Seram Island.
2. Variation in basement structures, thickness and rheology of the sedimentary package will control both structural pattern and geometry of the deformed sedimentary basin. This has been demonstrated in developing the model of Case 1, 2, 3, and 4 of Seram Island.
3. Sand from natural rock formation (*i.e.* the Ngrayong Formation in this case) is an excellent choice of materials to be used in modeling for representing silicic clastic sequences, where gypsum is an excellent material for substituting limestone formation (*i.e.* the Manusela Formation).
4. The results of sandbox modeling indicate that the Seram Island underwent oblique convergent strike-slip deformation (transpression) effected by strike-slip movement along the main bounded faults (Sorong Fault Zone and Tarera-Aiduna Fault Zone).
5. The results of sandbox modeling show that the deformation in the SFTB is strongly controlled by pre-existing basement configuration resulted in asymmetry strain distributions where basement configuration is represented by pre-Jurassic sequences as demonstrated in Case 4 modeling.
6. Integrated structural analysis using sandbox modeling, subsurface interpretation as well as a surface geological map is the best method in evaluating structural complex area.

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