Structural Evolution of Banda Arc, Eastern Indonesia: As a Future Indonesian Main Oil and Gas Development*

Zaenal Holis[1], Agung Shirly Ponkarn[2], Agung Gunawan[2], Shinta Damayanti[2], and Brahmantyo K. Gunawan[2]

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[1]Exploration Division, BPMIGAS, Jakarta, DKI Jakarta, Indonesia (zholis@bpmigas.go.id)
[2]Exploration Division, BPMIGAS, Jakarta, DKI Jakarta, Indonesia

Abstract

In the last decade, exploration at Eastern Indonesia has seen rapid growth, as an impact of energy demand. Banda Arc is a result of the interaction of various plates as part of a complex geological history in Eastern Indonesia. The movement of the Australian plate relative to Banda Sea is to the NNE. Because Banda Arc is curved, the angle of plate convergence should be changed along the arc. It caused different implication for structural deformation along Banda Arc. It is high oblique compressional in the Timor area, low oblique transpressional to the east of Tanimbar, and changed from transpressional to transtensional in the area of Kai Islands.

The petroleum system is well developed in the Banda Arc area. It is shown by some discoveries, including: Abadi Field, Bayu-Undan, Elang-Kakatua, Seram, Salawati Basin, and Bintuni Basin. Those discoveries come from Jurassic Sandstone and Miocene Kais Limestone reservoirs. However, there are some unsuccessful exploration wells in the Banda Arc area, which indicate there are some misinterpretations of the petroleum system and structure. These unsuccessful exploration wells proved that structural restoration need to be conducted to explain the unique structural evolution related to the petroleum system development in Banda Arc. This research discusses the result of an integrated study of 2D seismic interpretation and balancing cross-sections, as part of the structural geology evaluation in Banda Arc which concentrates in finding and determining the kinematics relationship among different faulting events.

2D seismic interpretations were concentrated in recognizing structural pattern and kinematics. Balancing cross-sections were concentrated in the stable part area of Banda Arc where mostly successful exploration wells existed. Based on palinspatic models made from 2D seismic, it indicated that deformation in the stable area of Banda Arc shows a group of contrasting strain features: early extensional faults forming the syn-rift deposit, reactivated by latter extensional structural style. Inversion structure evidence can be observed just only in the thrust fault zone, unstable part area of Banda Arc. The strain axis consistently shows maximum NE-SW direction of shortening in the thrust fault zone, but does not show NW-SE direction of extension. Therefore, it concluded that both structures (extensional and shortening) were formed during different deformation phases. This interpretation would guide exploration well planning for a better success ratio in Banda Arc, Eastern Indonesia.

Regional Geology

Eastern Indonesia is one of the most dynamic areas in Indonesia since it is an interaction between three major plates, which are the Eurasian, Pacific, and Indo-Australian Plates. Banda Arc is a result of these interactions, the southern part of Banda Arc is a result of interaction between the Eurasian and Indo-Australian Plate, meanwhile the northern part of Banda Arc is a result of interaction between the Eurasian, Pacific, and Indo-Australian Plate. Banda Arc is one of the active examples for subduction between the island arc and continental crust (Indo-Australian Plate).

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. The inner volcanic arc has been active since the Late Miocene, the outer arc is widely regarded as a recent zone of collision between the Australian continental margin and the Banda volcanic arc and includes 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 Middle Pliocene (Pairault et al., 2003; Charlton, 2010).

The Banda Arc comprises paired volcanic and non-volcanic island chains extending in a loop 180^{o} from Sumba Island in the south to the Buru Island in the north. Banda Arc is a developing zone of arc-continent collisions, the deformation front of Banda Arc is the Timor Trough in the south, the Tanimbar Trough in the southeast, and the Seram Trough in the north. The Seram Trough in the north appears to be tectonically active, with continued underthrusting of Australian continental margin crust beneath the Seram forearc collision complex, but in the southern and eastern part the Banda forearc appears to be significantly less active (Charlton, 2010). Figure 1 presents the east Indonesia and northern Australia continental margin regional tectonic elements.

The structure of Timor has long been a controversial subject, with a number of strikingly different structural models to explain the island's tectonic complexity. These interpretations range from essentially thin-skinned to substantial involvement of Australian continental basement (Charlton, 2001). The thin-skinned model is the most prevalent for Timor, where two main structural levels are recognized, the upper zone of emergent fan imbricates, and a deeper under-plate zone. The emergent fan imbricate in Timor consist of the shallowest stratigraphic levels (mainly Late Jurassic - Neogene), repeatedly imbricated and complexly deformed by overprinting high angle reverse faulting, wrench faulting, and in the less competent stratigraphic section, by the formation of tectonic melange.

Seram Trough is located between the islands of Seram and Missol in Eastern Indonesia. The significance of the Seram Trough is still debated, some authors interpret it as a subduction zone separating the Indo-Australian and Eurasian plate, the others suggest it is the foredeep at a front of developing fold belt. It has also been suggested that the Seram Trough might be a zone of strike-slip faulting but it is now generally agreed to be the site of southward underthrusting of the Bird's Head beneath Seram (Pairault et al., 2003; Charlton, 2010). The debate continues about whether it is a zone of intra plate shortening or a subduction trench, and among those who argue for subduction there is a disagreement over whether there is a single slab which curves around the arc or two separate slabs dipping in opposite directions (Pairault et al., 2003; Charlton, 2010).

The Passive Margin area is composed of Paleozoic, Mesozoic, Tertiary, and Quaternary sedimentary sequences. Information concerning the overall stratigraphic succession is obtained from wells penetrating the Pre-Permian rocks. Figure 2 represents the regional stratigraphy of eastern Indonesia, which is analogous to the stratigraphy of the northwestern Australian continental margin. Paleozoic is the important period for grabens forming as an accomodation for source rock sedimentation. With the NW-SE trending pattern grabens, the dominance of the general environment of deposition is fluvial to deltaic, allowing the presence of fine coarse clastic rock deposition, even coal at several locations in the northern part of the Banda Arc. While Mesozoic and Cenozoic are the most important period for reservoir development, especially for Jurassic sands which are deposited in deltaic to marine environments and have good lateral distribution in the passive margin area, and also Oligo-Miocene carbonates which are deposited in a carbonate shelf and slope at the northern part of Banda Arc.

Method of Study

Most of the deformation histories in Banda Arc are characterized by complex structural geometries, so that available data are insufficient to constrain unique structural interpretation. Cross-section balancing has therefore become a powerful tool in constraining the structural interpretation in this area.

Deformation is assumed to neither create nor destroy rock volume; thus, reassembling the undeformed state from the deformed state is possible. Structures which involve oblique to strike-slip displacement, rotation about a non-horizontal axis cannot be successfully balanced by traditional techniques (i.e. 2D cross-section). Balanced cross-sections can be restored so that the beds are placed back into their depositional, pre-deformation position. Balanced cross-sections link the deformed and undeformed states; therefore, finite strain analysis can be performed, which can be used as a predictive tool for fracture distribution and orientation. Furthermore, a balanced structural model validates the geophysical interpretation and promotes a better understanding of the geological history of the area of interest.

The study includes several main goals as follow:

- To evaluate structural kinematics of interested areas by restoring its fault frameworks that form the prospect
- To analyze result of structural restoration to its petroleum systems
- To model structural development and strain distributions

Balanced geological cross-sections area drawn with the assumption that the area of section has not changed during deformation. It is assumed that an original sequence of flat-lying beds has been folded and faulted to form the present geological cross-section. The two main methods of balancing are the equal line-length and equal-area methods.

The equal-line-length method assumes that line lengths of all units in a cross-section are conserved during deformation, so that a geometrically correct structural interpretation shows equal line lengths of all units in the restored state. This method assumes that most of the deformation within the beds occurs by the flexural-slip mechanism and that variations in penetrative strain within the beds are relatively insignificant (Suppe, 1980; McClay and Price, 1981; Boyer and Elliot, 1982; Mitra and Namson, 1989).

Equal-area balancing methods can be classified into two types: (1) area restoration of beds to their undeformed state to ensure balancing and to determine the regional shortening, and (2) excess-area measurements to determine the depth to detachment or regional shortening. All methods that use the area-conservation principle assume plane strain, so that there is no loss of area either by movement out of the plane of the section or by volume lost (Hossack, 1979; Mitra and Namson, 1989).

In this study, the combination of equal-area restoration with line-length restoration of key beds is used because of significant thickness change in some units. There is a fundamental difference between the equal-line-length and the combined equal-area and key-bed restoration methods. In the line-length method, the balancing of a cross-section is tested by measurement of a single parameter which is the original length of the unit (l_o). However, in the combined equal-area and key-bed method, restoration of the area is dependent on two independent parameters, the original length and thickness (t) of the units as proposed by Mitra and Namson (1989) for contractional deformation. The assumption of plane strain or conservation of cross-sectional area can be applied to extensions as well as contraction.

In the geometry of listric normal fault systems is characterized by the development of rollover anticline. Rollover deformation commonly develops in the hanging wall of a listric normal fault. One of the problems is to construct listric normal fault geometry at depth based on the rollover shape in the hanging wall. There are several model to solve this problems including the constant heave (Gibbs, 1983), constant bed length (Davison, 1986), constant displacement and slip line (Williams and Vann, 1987), inclined shear (White and Yielding, 1991; Song and Cawood, 2001). The inclined shear model provides a relatively accurate technique for determining master fault geometry (Song and Cawood, 2001). The method critically depends on the amount of extension, heave, or displacement, and the bed shape in the hanging wall used for construction. In this study, structural restoration is conducted using flexural unfolding and inclined shear model (Figure 3 and Figure 4). The restoration techniques and strain calculation developed in this study is based on modified method from Gibbs (1983) (Figure 5). Each structural restoration of seismic sections is manually done. The results were digitized and graphically modified, combined using Coreldraw.

Result Summary

Based on palinspatic models made from 2D seismic, it indicated that deformation in the stable the area of Banda Arc shows a group of contrasting strain features: early extensional faults forming the syn-rift deposit (Permian-Jurassic time), which related with accommodation provision for source rock deposition. After those events, generally the whole area of Banda Arc was reactivated by latter extensional structural style which gave space for reservoir deposition both in the southern and northern part of Banda Arc. Inversion structure evidence can be observed just only in the thrust fault zone, unstable part area of Banda Arc. This inversion product generated some anticlines which give a good chance for trapping mechanism. The strain axis consistently shows maximum NE-SW direction of shortening in the thrust fault zone, but does not show NW-SE direction of extension. Therefore, it is concluded that both structures (extensional and shortening) were formed during different deformation phases. This interpretation would guide exploration well planning for a better success ratio in Banda Arc, Eastern Indonesia.

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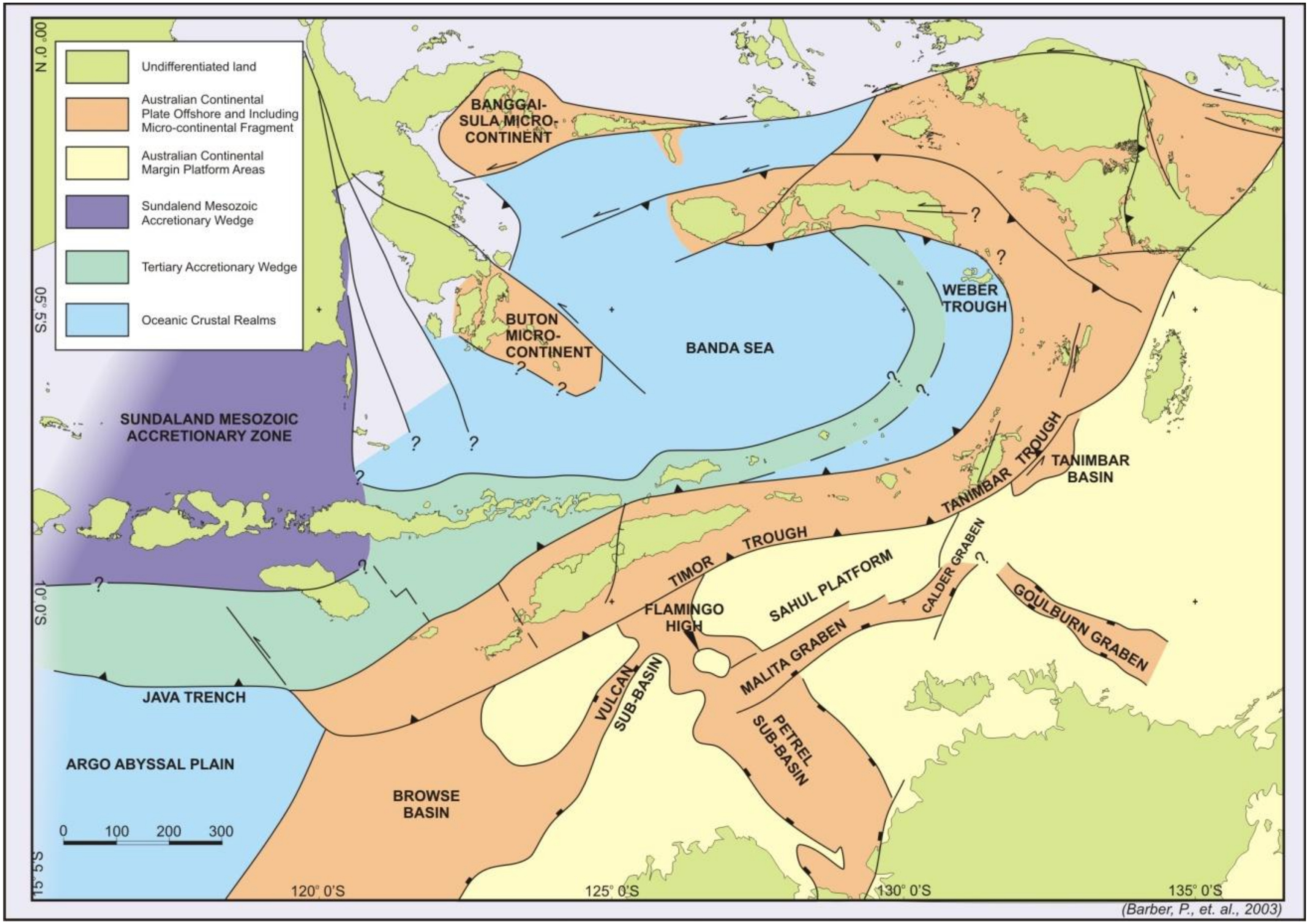


Figure 1. East Indonesia and Northern Australia Continental Margin Regional Tectonic Elements (Barber et al., 2003)

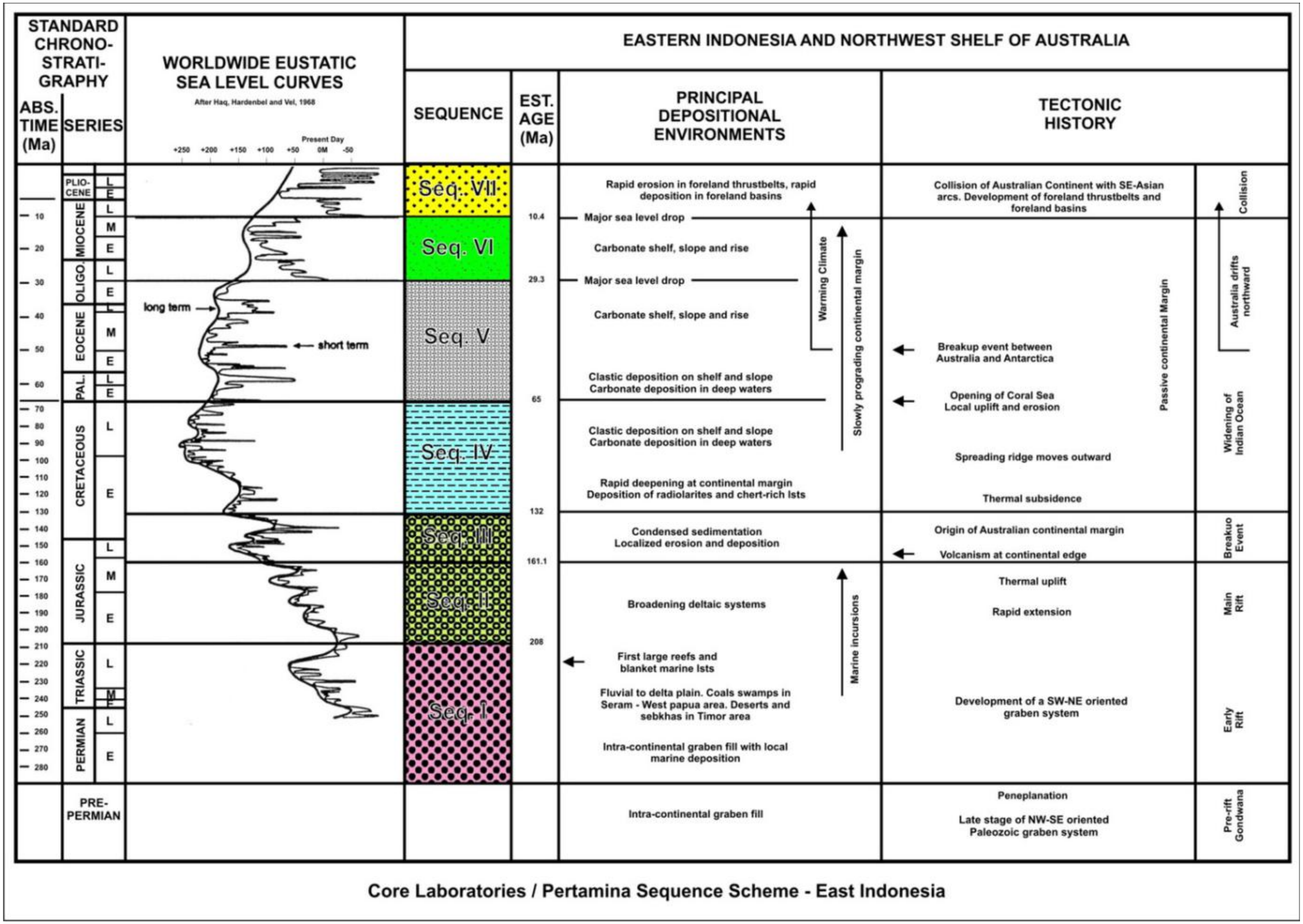
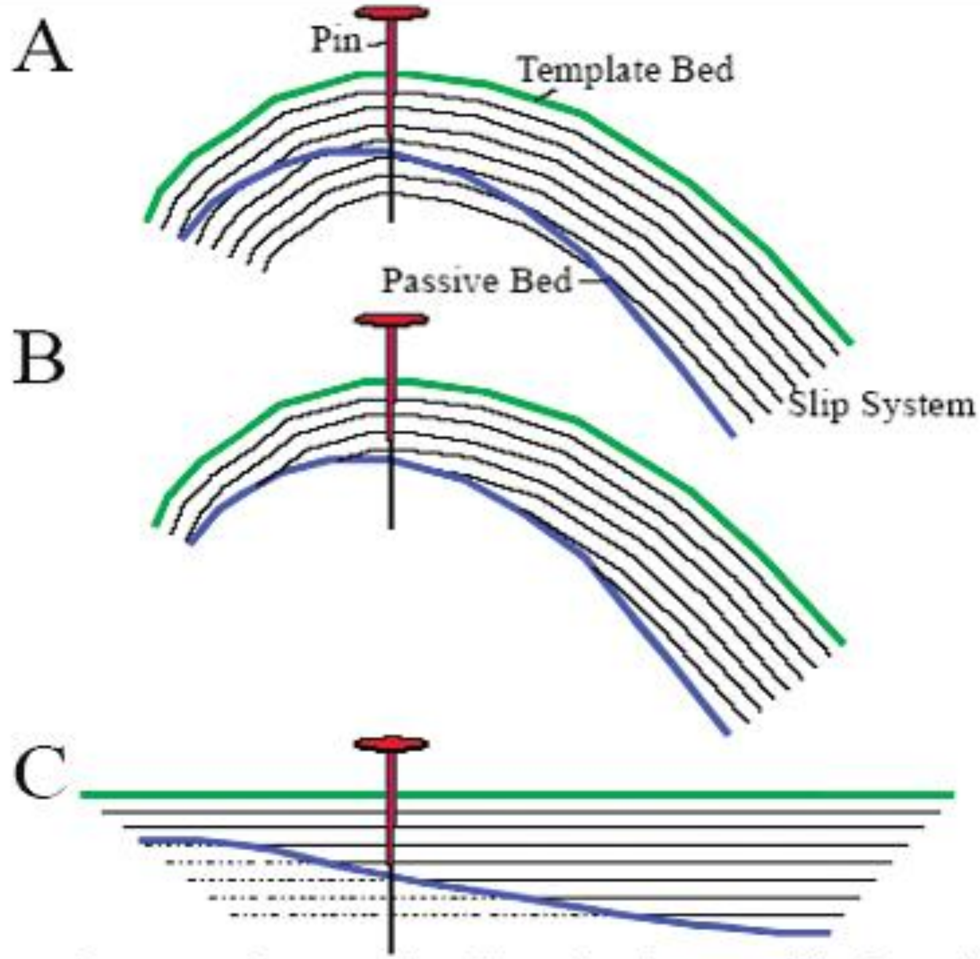
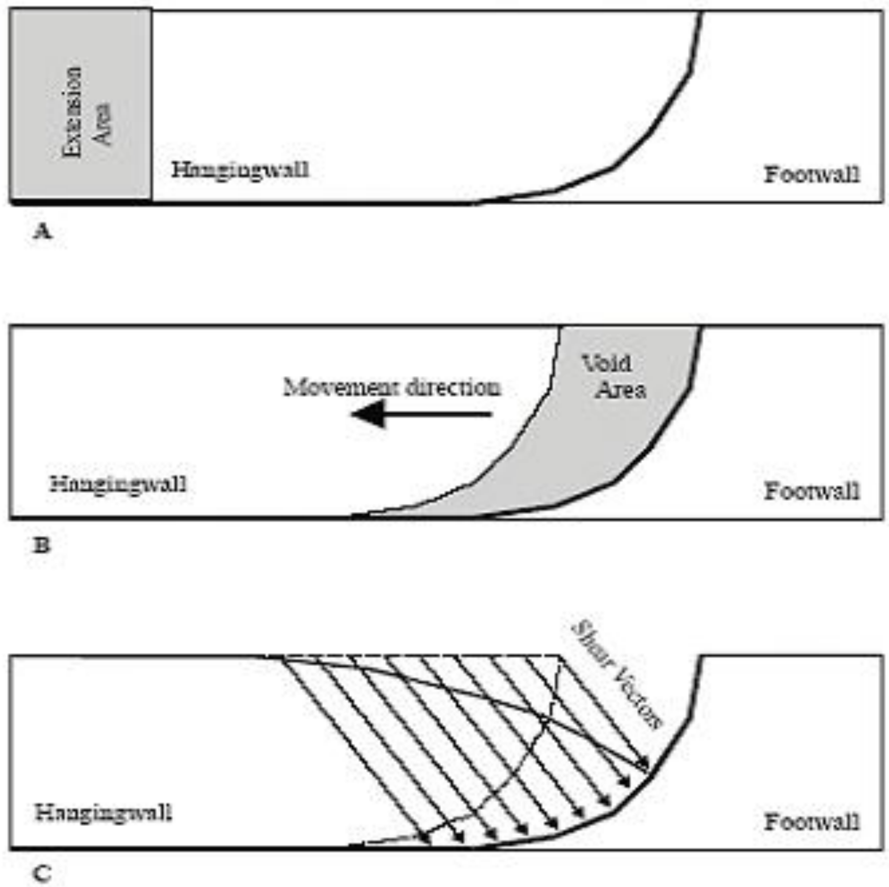


Figure 2. Regional Stratigraphy of Eastern Indonesia (CoreLab-Pertamina).



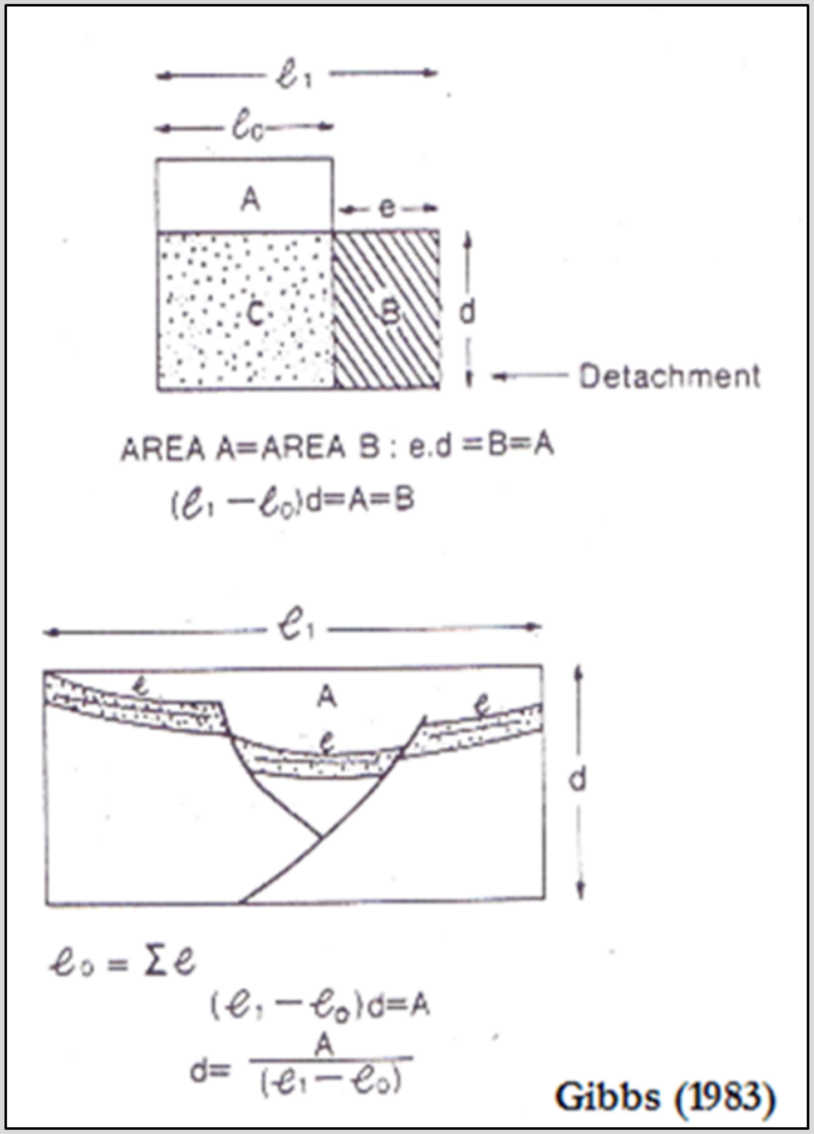
Sequence of cross sections illustrating the steps of the flexural slip unfolding algorithm. A) A fold with thickness variations to be unfolded. The slip system is constructed parallel to the template bed B) The intersections between the slip system and the passive bed record thickness variations. C) The template bed and the slip system are unfolded about the pin.

Figure 3. Flexural slip unfolding algorithm from Midland Valley (2001).



A series of cross-sections demonstrating how the Inclined Shear algorithm works. A) The initial state showing the amount to be extended. B) Extension creates a hypothetical void or gap between the hangingwall and footwall blocks. The area of extension equals the area of the void. C) The shear vector controls how hangingwall elements collapse down onto the fault plane, removing the void space. In this example, shear is oriented antithetic to the fault plane.

Figure 4. Inclined shear algorithm from Midland Valley (2001).



- l_0 is original length of section
- l_f is length in deformed state
- d is depth to detachment
- A is cross-sectional area
- e= extensional strain

Figure 5. Area balance for extension and depth to detachment calculation (Gibbs, 1983).