A STRUCTURAL MODEL FOR NORTH SUMATRA

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ABSTRACT

The geological evolution of North Sumatra has been controlled by strike slip tectonics troughout most of the Tertiary. The area experienced extensional and transtensional regimes during the Paleogene, rift basins opened up between major wrench faults, and rates of subsidence and sedimentation were rapid.

Structures in North Sumatra were inverted by a phase of post - Mid Miocene compression and transpression, and the extensional faults were reactivated and modified. Plio- Pleistocene strike slip faulting caused major dextral wrench faulting mainly along northwest-southeast and north- south fault trends.

A structural model for North Sumatra has been developed using data both from publised geological maps and from seismic sections. In this model fault systems linked to flower srtuctures that control the horizontal displacement of structural blocks are due to the stresses from a largely dextral strike slip system. The srtuctural blocks root down to depths of about 10 km and are often bounded by listric faults that shallow out to a basal decollement at this depth. Deformation at the decollement horizon corresponds to a brittle/ductile transition in the upper crust, and it controls structures in the Sumatran Fault System, and within the forearc and back arc basins.

I. INTRODUCTION

I.1. General

This report represents the first attempt to interpret the geology and tectonic evolution of North Sumatra in terms of the structural models developed by Gibbs (1983, 1985). The models were originally developed for the evolution of extensional basins, and emphasise the control of basement faults and shallow dipping decollement horizons on the geometry of shallower fold and fault systems.

According to Gibbs (1983, 1985) basins develop on linked fault systems that have dip-slip or strike-slip displacements. As basins develop, deformation in the upper brittle crust occurs on linked arrays of low angle listric faults, on steeper planar (domino) faults, or on combined fault systems linked by strike-slip movements. Fault systems with compatible strain must be geometrically linked by detachments or ductile shear zone with both steep and shallow dipping faults (Fig. 1); these factors have been taken into account for this interpretation of the tectonic evolution of North Sumatra during the Tertiary.

This model has been used to interpret the geological structure of North Sumatra using data form geological maps and a limited number of seismic sections. It should be regarded as a first interpretation, and a more refined model can be developed as more structural information becomes available for North Sumatra. The ideas need to be applied to a series of regional seismic sections that are available for the basinal area, in order to improve the model.

I.2 Data base and previous work

The structural evolution of North Sumatra (north of 3^{o}N) has been studied for many years but remains poorly understood. Oil companies have tended to work in isolation within their concession areas and interpretations of petroleum geology are often inconsistent across the basin. The geological maps produced by the BGS/DMR team provided a

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valuable data base for North Sumatra, but the reconnaissance nature of the maps means that there is still a great deal more work to be done. The new stratigraphy proposed by the BGS/DMR team is not widely accepted and a satisfactory stratigraphic classification for the basin has yet to be proposed.

II. GENERAL TECTONIC SETTING OF NORTH SUMATRA

II.1. General

At the present day, Sumatra forms part of the Sunda Arc, where the Indian Ocean Plate is subducting below the Eurasian Plate at a rate of 6-7 cm/yr in a NNE direction. Oblique plate convergence at the Sunda Arc is accommodated by subduction at a shallow Benioff Zone lies about 100 km below Sumatra, and by dextral strike-slip movements, largely along the Sumatran Fault System (SFS). Active sea floor spreading in the Andaman Sea also has a major effect on Sumatra and is accomodated by compression in North Sumatra and possible underthrusting below the northern coast of Aceh. (Hamilton, 1979, Cameron et al., 1980).

Sumatra forms part of the Sundaland cratonic core of Southeast Asia. Three microplates have been distinguished in western Sundaland, namely the Mergui, Malacca, and East Malaya microplates. These microplates stabilised in the late Triassic; additional terranes have been accreted since the late Mesozoic, including the Woyla Terranes, and the Natal and Sikuleh Continental fragments (Pulunggono & Cameron, 1984, Fig. 2).

The Tertiary basinal areas of Sumatra north of 3^{0}N may be devided into the North Sumatra Basin (NSB) and Sibolga Basin. The North Sumatra Basin (NSB) is the main area of interest for this study.

II.2. Geological History of North Sumatra

Sumatra has been at or near an active subduction zone since the Late Permian (Cameron et al., 1980). Convergence vectors between the plates have a major influence on deformation processes at the arc. Highly acute angles of plate convergence produce the greatest strike-slip deformation, with subduction processes at a minimum, for example at the Andaman-Nicobar Ridge where plate convergence occurs at an angle of 20^{0}. Less acute convergence vectors cause subduction processes to dominate, for example south of Java, the plate convergence angle is 90^{0}. However, to the SW of Sumatra, the angle of plate convergence lies between these two extremes (55^{0}) and a combination of strike-slip faulting and subduction processes, with compression, occur at the Sunda Arc.

Variations in sea floor spreading directions in the Indian Ocean, and rotation of microplates within Sundaland may have caused changes in plate convergence vectors at the Sunda Arc with time. These changes have strongly influenced the tectonic evolution of the region. For example, N-S spreading in the Indian Ocean during the Eocene-Early Oligocene produced plate convergence at about N 10^{0}E at rates of 18 cm/yr and caused major dextral wrench faults in western Sundalnd (Davies, 1984). The Indian Ocean Plate approached Sundaland at 5 cm/yr in a NE direction from 44 Ma until the Late Miocene, and the region was in extension. Since the Late Miocene (9-10 Ma) the convergence vectors have remained at 5-7 cm/yr in a N 20^{0}E direction, and this change produced compression in western Sundaland, deformation along the SFS, and sea floor spreading in the Andaman Sea (Johnson, 1976, Karig et al., 1979).

The Tertiary basins of Sumatra began to evolve during Eocene-Lower Oligocene times. Rifting and subsidence occurred at this time and the basins evolved in an extensional regime throughout the Early Tertiary (Davies, 1984, Cameron et al., 1980). Crustal thinning may be related to the displacement of crustal blocks along major strike-slip faults in Southeast Asia as a result of the collision of India with Asia in the Oligocene (Tapponnier et al., 1982, Tapponnier et al., 1986). These early rifts may have developed between major strike-slip faults as pull apart basins, and have later experienced a component of strike-slip movement.

A major change from an extensional regime to a compressional regime occurred during Middle Miocene times, and Sumatra was deformed by compression and strike-slip faulting during the Neogene (Davies, 1984). This change may have been due to increased rates of subduction and steeper angles of plate convergence. The area was also deformed by active sea floor spreading in the Andaman Sea (initiated in the Middle Miocene).

Subduction at the Sunda Trench was ob-lique during Plio-Pleistocene times (N 20^{0}) and major strike-slip movement occurred, especially along the Sumatran Fault System (SFS), often reactivating older faults. This NW-SE structural trend dominates the present geology of Sumatra, but major N-S trending faults were also reactivated with wrench movements (Situmorang & Yulihanto, 1985) possibly as synthetic faults (Fig.3). The SFS and the volcanic arc both occur within the Barisan Mountains, and extend the whole length of Sumatra. The SFS forms part of a transform fault in the Andaman Sea to the north, and extends into the Sunda Strait in the south.

III. STRUCTURAL MODELS FOR NORTH SUMATRA BASIN

Gibbs (1983, 1985) discusses many techniques to calculate the depth to detachment of listric faults in extensional regimes. These methods use the geometry of roll over anticlines and excess area calculations to construct the faults and interpret the depth to detachment. Although these techniques can be aplied to extensional regimes, probles arise in areas of strike-slip tectonics, where volume changes out the plane of the section cannot be accounted for. Calculations may be possible if the data has very good three dimensional control, but the present data for North Sumatra certainly does not support such techniques of balancing cross sections.

In developing structural models for the NSB the importance of the change from a Paleogene tensile regime to a Neogene compressive regime is emphasised. Both phases have elements of strike-slip displacements that may be considered as transtensional and transpressional respectively.

Basin inversion during compression would reactivate old fault trends but he steeper part of the footwall may be breached and a new shallower fault developed (Gibbs, 1985, Fig. 4). As wrenching continues, positive or negative flower structures may develop in areas of transpression and transtension within the fault system (Harding, 1985). Pull-apart basins or thrust faults may also form, depending on the overlap and curvature of the wrench faults.

Many structural models have been published for the evolution of North Sumatra, e.g. Cameron et al. (1980), Davies 1984). This study attempts to consider the geometry and genetics of fault systems down to depths of about 10 km where a transition from brittle to ductile deformation occurs withins the crust. It is proposed that many the dip-slip faults become listric at depth and shallow out to a common decollement level at about 10 km.

The NSB was initially formed by Eocene-Oligocene rifting that may have been related to major strike-slip faults active in Southeast Asia (Tapponnier et al., 1982). Rift faults related to wrench tectonics may show little evidence of strike-slip movement during the early stages of rift development (Kingstone et al., 1983). Listric normal faults may develop during extensional phase, and the faults are later reactivated by inversion and strike-slip displacements. This interpretation is consistent with Songpope Polachan's (Pers. Comm. 1986) structural models developed from his interpretations of seismic reflection profiles and geophysical well logs for the Mergui Basin.

Major N-S strike-slip faults have controlled the tectonic evolution of the NSB throughout much of the Tertiary (Situmorang & Yulihanto, 1985), but Plio-Pleistocene wrench faulting, mainly along the SFS, now dominates the geology of Sumatra.

A general model for the geology of North Sumatra is presented in this report. The SFS forms a series of flower structures with listric faults dipping steeply near surface and shallowing out at a detachment level of approximately 10 km. The stems of the major flower structures continue deeper into the crust but they may also flatten at a ductile zone somewhere near the Moho, at depths of about 30 km. The benioff Zone below Sumatra occurs at shallow depths of about 100 km.

The depth to detachment has been calculated at 10 km for the Andaman Sea by Songpope Polachan (Pers. Comm. 1986) using seismic and well log data from the Mergui Basin. The Mergui Basin is an offshore extension of the NSB and both areas have similar stratigraphies (Nakanart & Mantajit, 1983). The Mergui Basin was formed by extension between major strike-slip faults and is underlain by thinned continental crust (Curray et al., 1979).

IV. GEOLOGICAL CROSS SECTIONS ACROSS NORTH SUMATRA

IV.1. General

Using the BGS/DMR 1:250,000 geological maps, three geological cross sections have been drawn across Sumatra, using this structural model. Figure 5 provides a general geological map for North Sumatra, showing the cross-section locations. The cross-sections are shown in Figs. 7, 8 & 9, the symbols refer to formation names used for BGS/DMR geological maps and the cross-sections are drawn at a scale of 1:250,000, with no vertical exageration. The stratigraphy of North Sumatra is summarised in Fig. 6.

The SFS has been divided into 3 major fault zones, i.e. the Western, Central, and Eastern Zone and each of the sections will be described in detail.

IV.2. Section 1 :

Tapaktuan-Kutacane-Batang Sarangan (fig. 7)

The SFS is about 100 km wide in this section, and is divided into fault bounded blocks with rock units of different age and lithologies. The stratigraphy used for these sections is given in fig. 9. The blocks are 10- 25 km wide, 150 km long, and 8-10 km deep (?), and they occur as lensoid tectonic units oriented parallel to the axis of the SFS.

Pre-Tertiary basement rocks of the Woyla Group (Mult) extend to the west coast of Sumatra, and intermediate volcanics with a limestone member form a high between the Sibolga Basin (approximately 3000 m deep). The Western Fault Zone is interpreted as a positive flower structure with associated thrust and reverse faults shallowing out at depths of approximately 10 km. This fault is considered to accomodate major displacement along the SFS.

Between the Western and Central Fault Zones two main structural blocks of Tapanuli group metasediments are bounded by reverse faults, where an area of Tertiary sediments (m thick) was deposited unconformably on the basement. These basement rocks consists of Kluet Formation (Puk) metasediments and Alas Formation (Ppal, Ppa) limestones and metasediments.

In the western part of the section, the Kluet Formation is intruded by granites (Mpibp) of mid-Permian to late Triasic age. The intrusion does not appear to be related to major faults, but outcrop locations in Sumatra have been displaced by the wrench tectonics, so original relation ships between igneous activity and tectonics have often obscured (Rock et al., 1982).

The line of cross section shows the Kutacane graben in the Central Fault zone. The graben is about 6-7 km wide and 75 km long and represents an active extensional regime within the SFS.

East of the central zone the basement is composed of pebbly mudstones and metawackes of the Bohorok Formation (Pub.). The Eastern Fault Zone forms the western margin of the North Sumatra Basin, and the complex faulting is suggested to relate to a positive flower structure.

Folding and faulting within the NSB is possibly related to ramps and flats in the basal decollement. The basin is divided by a series of sub- basins separated by basement highs, that may be explained in terms of strike-slip related compressional and extensional regimes. Wrench related displacements within the basin are suggested to be accommodated by movement of fault bounded blocks along a shallow dipping or horizontal basal decollement, approximately 10 km deep.

IV.3. Section 2 :

Kutabahagia-Kutapansang-Lokop (fig. 8)

Section 2 is 100 km further north and the major structures seen in Section 1 can also be observed here. Section 2 includes the northern tip of the lensoid blocks of Woyla Group, Kluet Formation, and Bohorok Formation, lithologies as described for Section 1.

The Western Fault Zone strongly deforms the local geology by a series of reverse faults and thrusts that may be linked at depth to form a positive flower structure. The rock units consist of Woyla Group and Kluet Formation metasediments and volcanis, with a sequence of Tertiary sediments deposited unconformably on the basement. The Western fault Zone is the eastern margin of the Sibolga Basin (forearc basin), with approximately 3000 m of Tertiary sediments (Cameron et al., 1980).

The central Fault zone is slightly wider than in Section 1 (i.e. 10 km and forms a bifurcated section of the anastomosing fault system. The fault zone is part of the extensional Kutacane Graben.

The Eastern Fault Zone intersects the N-S trending Lokop-Kutacane wrench fault zone. Structures are highly complex and may be linked to a flower structure, with displacements along the fault zone estimated at 15-20 km (Bennet et al., 1981).

Folds and faults within the NSB may be controlled by ramps and flats in the basal decollement level, and faults are interpreted to shallow out at this level within the basin. The western margin of the basin is deformed by the Simpang Kanan Monocline, a complex series of wrench related folds and faults trending NW-SE (Bennet et al., 1981).

IV.4. Section 3

Krueng Woyla-Takengon-Lhok Sukon (fig. 9)

Section 3 trends NE-SW across North Sumatra cuts through the Sibolga Basin, the Barisan Mountains, and the northern North Sumatra basin. It lies 100 km north of sec tion 2.

The Western and Central Fault zones have merged as part of the anastomosing Sumatran Fault System. They continue to the northwest as a single zone that extends offshore as a transform fault in the Andaman Sea floor spreading centre. The fault zone has a large component of thrust and reverse faulting, and it part of the Gumpang Line (Bennet et al., 1983). The Western Fault Zone may continue southward into the offshore forearc region where offsets of 100 km have been interpreted from seismic surveys (Karig et al., 1980).

The Geureudong volcanic centre (Plio-Pleistocene to Holocene) intrudes rocks of the Kluet Formation and forms one of the largest volcanic centres in North Sumatra. It forms part of an E-W belt along the north eastern coast of Sumatra and may be related to underthrusting of oceanic crust from the Andaman Sea, rather than subduction at the Sunda Arc (Rock et al., 1982; Aspden et al., 1982).

The western margins of the NSB are strongly deformed by the Eastern Fault Zone. The BGS/DMR geological map shows a wide covering of Recent alluvium over much of the basinal area (Keats et al., 1981), but published seismic sections from the Arun and Cunda gas fields show N-S trend subsur face faults (Fig. 10. Graves & Weegar, 1973, Burnaman et al., 1985). Fig. 11 shows basement faults that extend to depths of 3-5 km, using the model in this report, these faults are extrapolated to depths of 10 km where they shallow out to a major decollement horizon at an inferred brittle/ductile transition zone within the upper crust.

Folding and faulting within this part of the North Sumatra Basin is very gentle. Deformation may be an effect of ramps and flats in the basal decollement, and is also related to diapirism in the overpressured Baong formation mudstones (e.g. west of the Lhokseumawe Fault, fig. 10). Diapirism was activated by wrench faults, and may have been initiated during the Plio-Pleistocene as the Keutapang Formation sandstones were deposited on top of the over pressured Baong Mudstones producing a density inversion (Cameron et al., 1982).

Some seismic sections for the North Sumatra Basin show that the flower structures and listric faults die out up wards in the Baong Formation, as the overpressured mudstones accept the shear stresses but do not transit them. Similarly, faults in the Keutapang and younger sediments occur as listric faults that fail within the Baong Forma tion and have relatively shallow depths of detachment (approximately 3-4 km). Further seismic sections need to be studied throughout the basin to confirm and modify these interpretations.

Figure 12 shows a seismic section of the Arun Field. The northward dipping thrust fault that occurs to the south of the Arun Gas Field (Fig. 12a) may be related to wrench faulting and associated strike-slip displacement of structural blocks at the Eastern Fault Zone of the Sumatra Fault System.

V. CONCLUSIONS

The geological evolution of North Sumatra is considerd to have been controlled by strike-slip tectonics throughout most of the Tertiary. The area experienced extensional and transtensional regimes during the Paleogene; rift basins opened up between major wrench faults, and rates of subsidence and sedimentation were rapid.

Structures in North Sumatra were inverted by a phase of post-Mid Miocene compression and transpression, and the extensional faults were reactivated and modified.

Plio-Pleistocene strike-slip faulting caused major dextral wrench faulting in Sumatra, mainly along NW-SE and N-S fault trends.

A structural model for North Sumatra has been developed, with fault systems at major wrench faults linked to flower structures that control the horizontal displacement of structural blocks, due to the stresses from a largely dextral strike-slip system. These structural blocks root down to depths of about 10 km and are often bounded by listric faults that shallow out to a basal decollementat this depth. Deformation at the decollement horizon corresponds to a brittle/ductile transition in the Upper Crust, and it controls structures in the Sumatran Fault System, and within the forearc and back arc basins.

Data from geological maps, and a limited number of seismic sections, were used to interpret the geological structure of North Sumatra. The ideas need to be applied to a series of regional seismic sections that are available for the basinal area, in order to improve the model.

Structural models of this type, that consider the geometry of fault systems to greater depths within the crust (e.g. 10-15 km) would benefit enormously from deep seismic reflection surveys that measure two way time to 10-15 seconds, compared to 4-5 seconds for a conventional survey. Such deep seismic surveys would greatly improve structural interpretations and more refined interpretations of basin evolution could be developed. Deep seismic surveys do not cost much more than conventional surveys and provide geophysical data to depths of 15-20 km within the crust.

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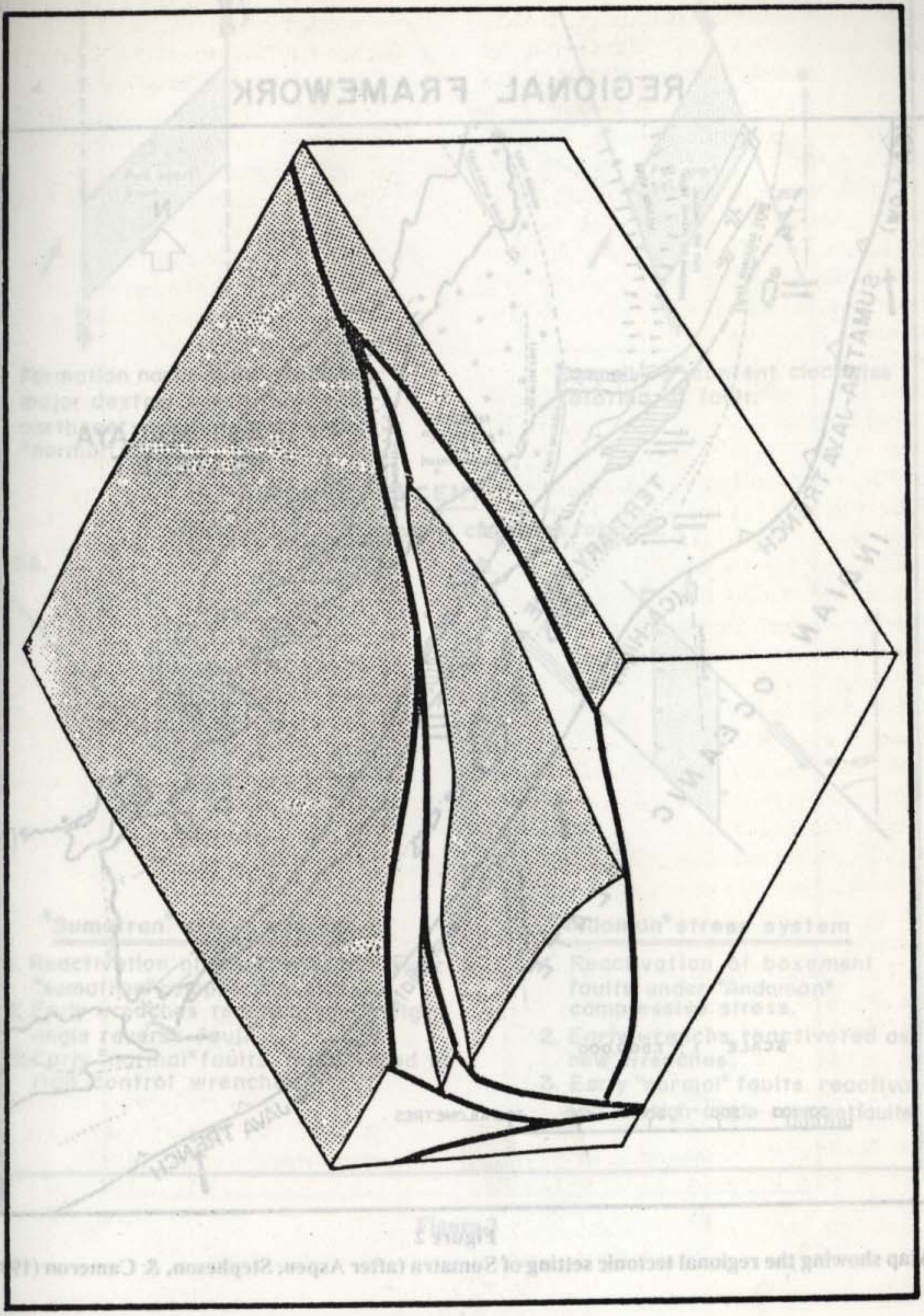


Figure 1. Steep and shallow dipping faults linked to a detachment, with oblique slip and strike-slip displacements (Gibbs, 1985)

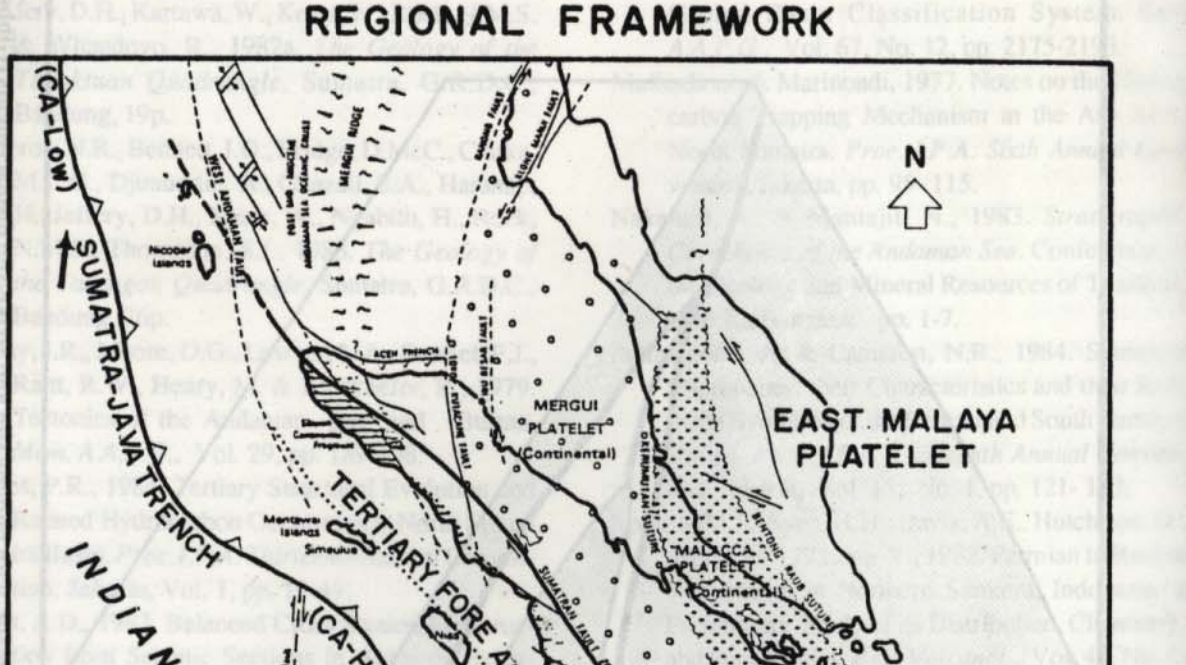
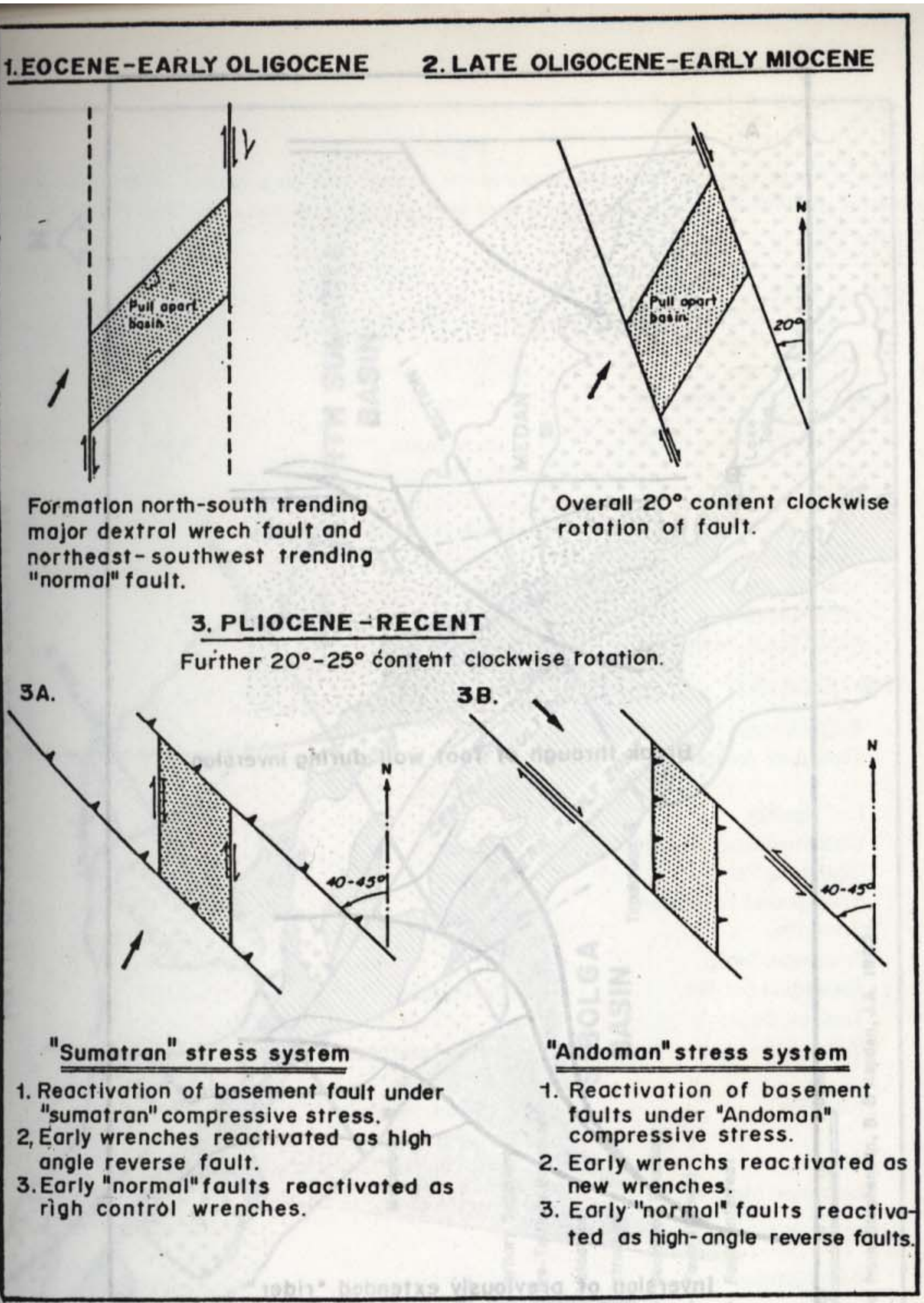


Figure 2

Map showing the regional tectonic setting of Sumatra (after Aspen, Stepheson, & Cameron (1982)



Formation north-south trending major dextral wrech fault and northeast-southwest trending "normal" fault.

Overall 20° content clockwise rotation of fault.

3. PLIOCENE-RECENT

Further 20°-25° content clockwise rotation.

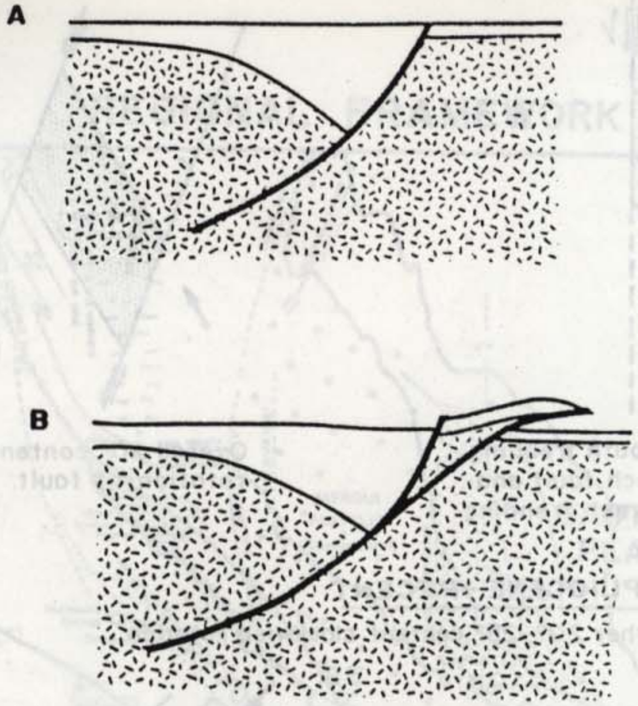
"Sumatran" stress system

1. Reactivation of basement fault under "sumatran" compressive stress.
2, Early wrenches reactivated as high angle reverse fault.
3. Early "normal" faults reactivated as righ control wrenches.

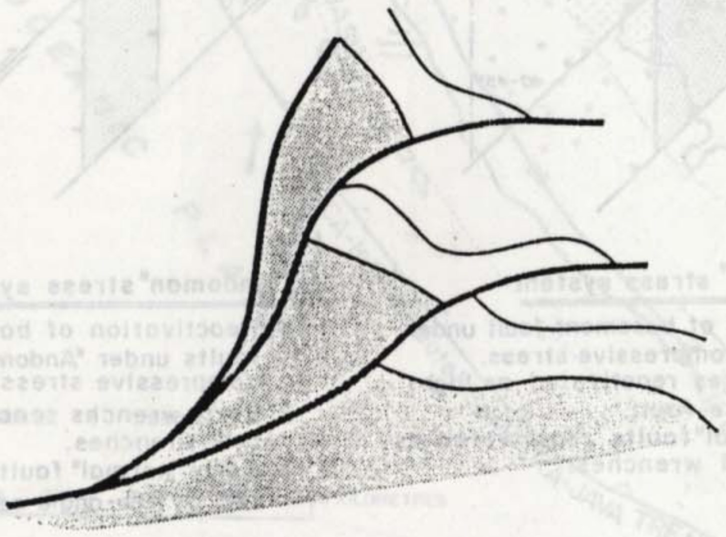
"Andoman" stress system

1. Reactivation of basement faults under "Andoman" compressive stress.
2. Early wrenchs reactivated as new wrenches.
3. Early "normal" faults reactivated as high-angle reverse faults.

Figure 3



Break through of foot wall during inversion



Inversion of previously extended "rider"

Figure 4
Models for structural inversion (after Gibbs, 1985)

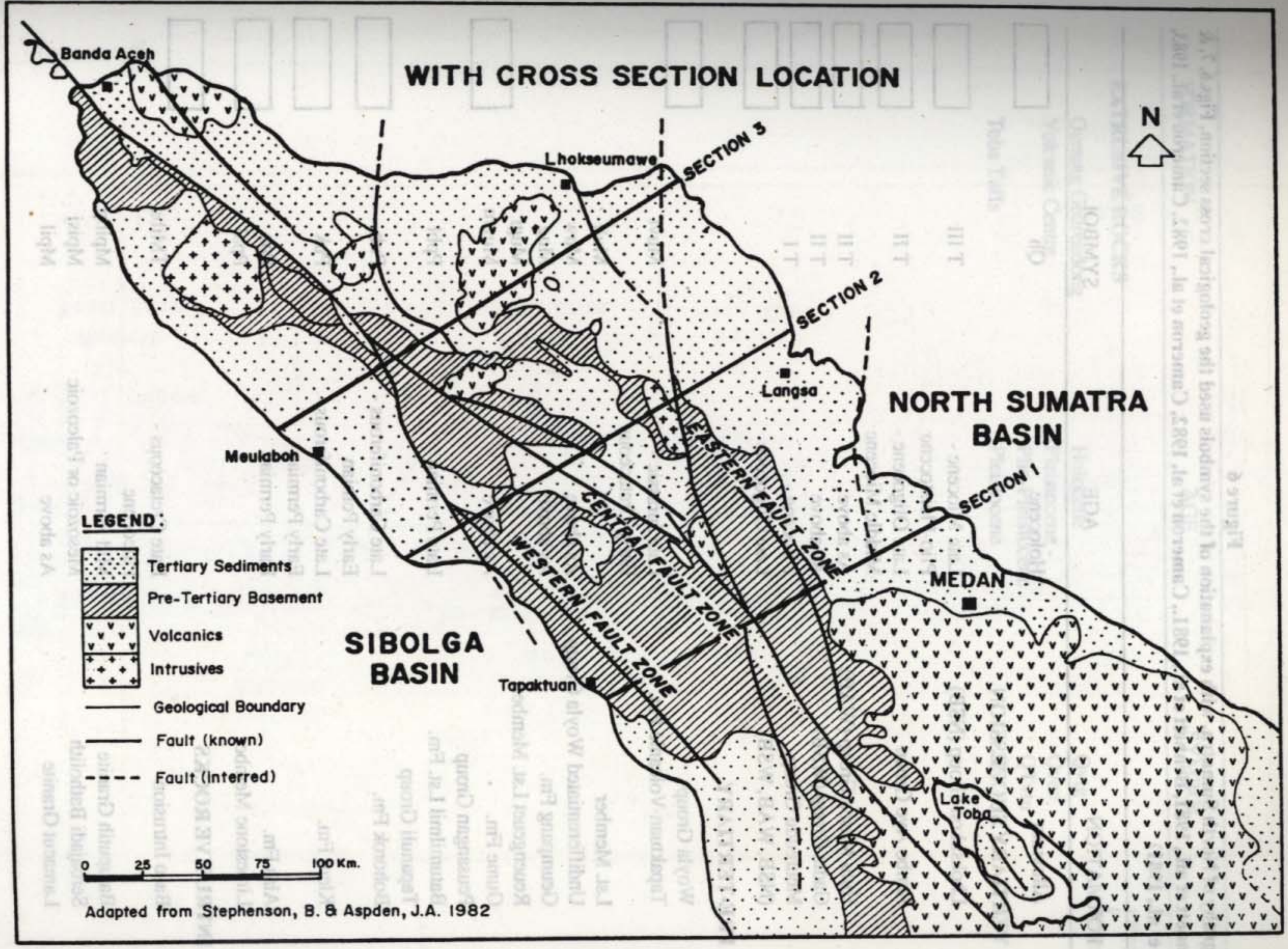


Figure 5. Simplified geological map of North Sumatra, with cross section location (from Stephenson, B and Aspden, JA, 1982)

Figure 6

Stratigrahy of North Sumatra, with explanation of the symbols used the geological cross section, Figs.6, 7, & 8. (Bennett et all., 1981, Bennett et al., 1981., Cameron et al, 1982, Cameron et al., 1982, Cameron et al., 1983, Keats et al., 1981)

FORMATION	AGE	SYMBOL	
Alluvium	Holocene	Qh	☐
TERTIARY SUCCESSION			
Lhoksukon Group (NSB)	Late Miocene - Plio-Pleistocene	T III	☐
Jambo Aye Group	Late Oligocene - Middle Miocene	T II	☐
Hulu Masen Group (WAB)	As above	T II	☐
Gadis Group (WSB)	As above	T II	☐
Meureudu Group (NSB, WAB, WSB)	? Eocene - Late Oligocene	T I	☐
PRE-TERTIARY			
Woyla Group			
Tapaktuan Volcanic Fm.	Late Jurassic - Early Cretaceous	Muvt	☐
Lst. Member		Mult	
Undifferentiated Woyla Group	As above	Muw	
Geumpang Fm.	As above	Mug	
Reuengeuet Lst. Member		Mugr	
Gume Fm.	As above	Mugm	☐
Peusangan Group			
Batumilmil Lst. Fm.	Late Permian	Ppbl	
Tapanuli Group			
Bohorok Fm.	Late Carboniferous - Early Pemian	Pub	☐
Kleut Fm.	Late Carboniferous - Early Permian	Puk	☐
Alas Fm.	Early Permian	Ppa	☐
Limestone Member		Ppal	
INTRUSIVE ROCKS			
Baso Intrusion	Late Cretaceous - Paleocene	TMibs	☐
Batuputih Granite	Mid Permian	Mpibp	
Serbajadi Batholith	Mesozoic or Paleozoic	Mpisj	
Lamacut Granite	As above	Mpil	

FORMATION	AGE	SYMBOL	
EXTRUSIVE ROCKS			☐
Gunung Geureudong Volcanic Centre	Holocene	Qvtg	
	Pleistocene -	Qvee	
	Plio-Pleistocene	QTvtu	
Toba Tuffs	Pleistocene	Qvt	

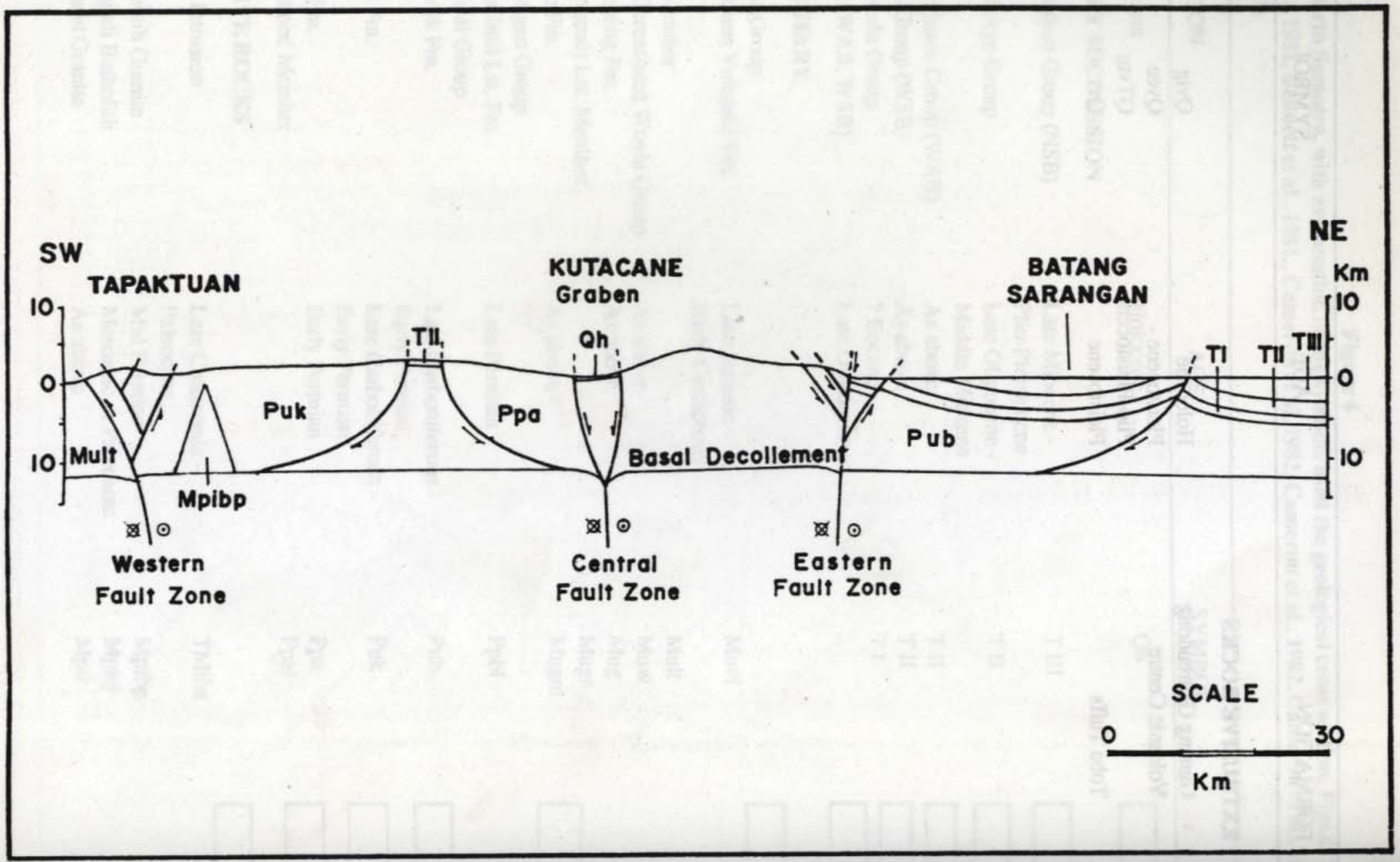


Figure 7. Section 1 : Tapaktuan-Kutacane-Batang Sarangan

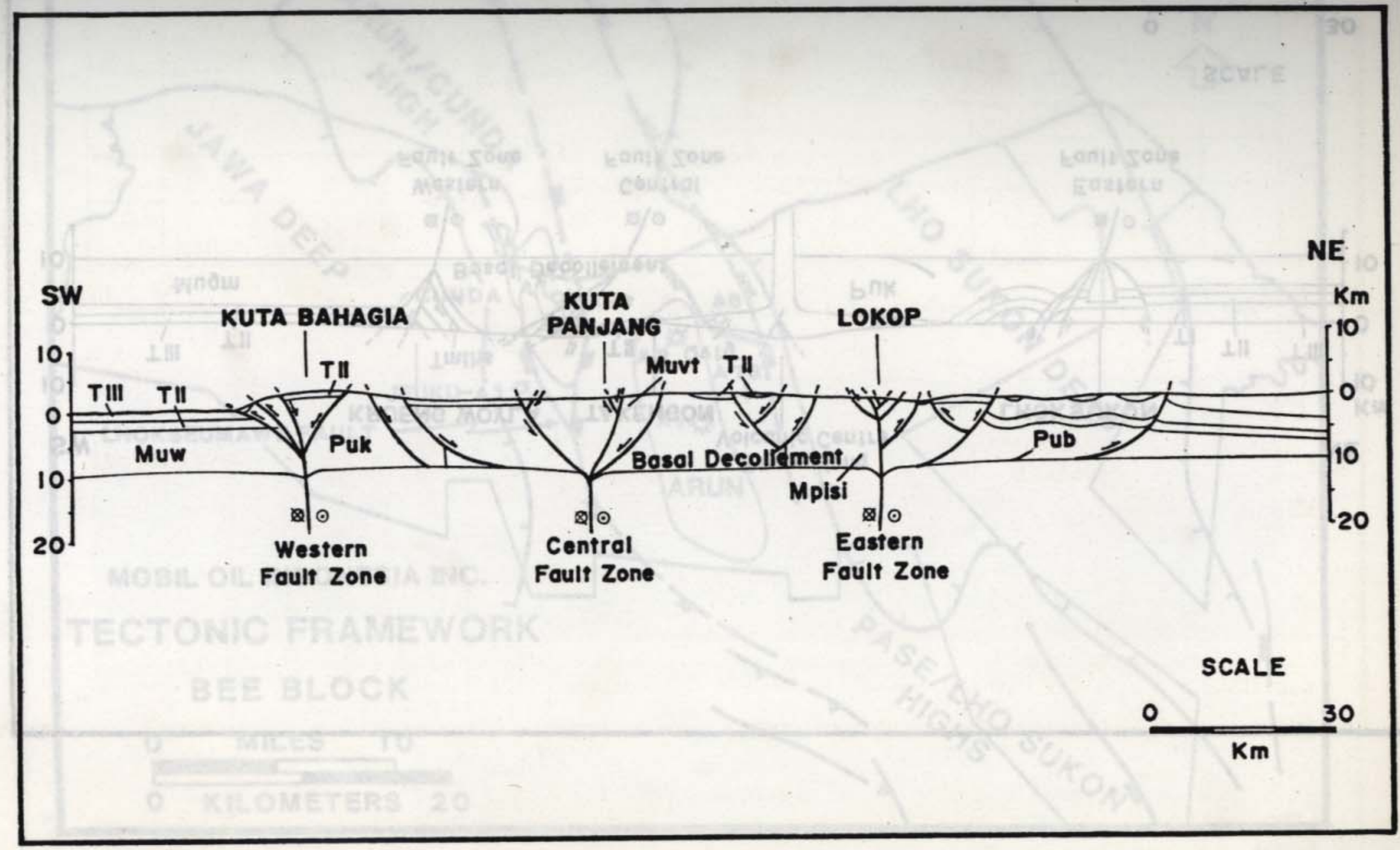


Figure 8. Section 2 : Kuta Bahagia-Kuta Panjang-Lokop

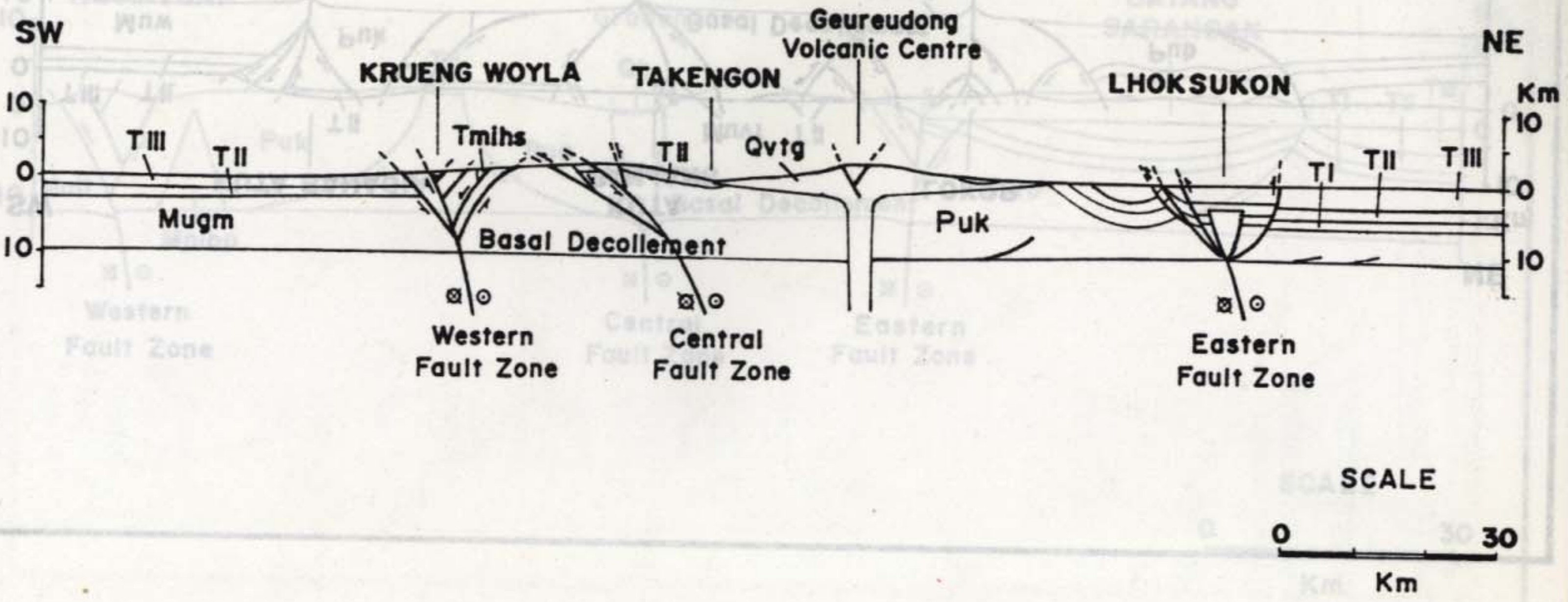


Figure 9. Section 3 : Krueng Woyla-Takengon-Lhoksukon

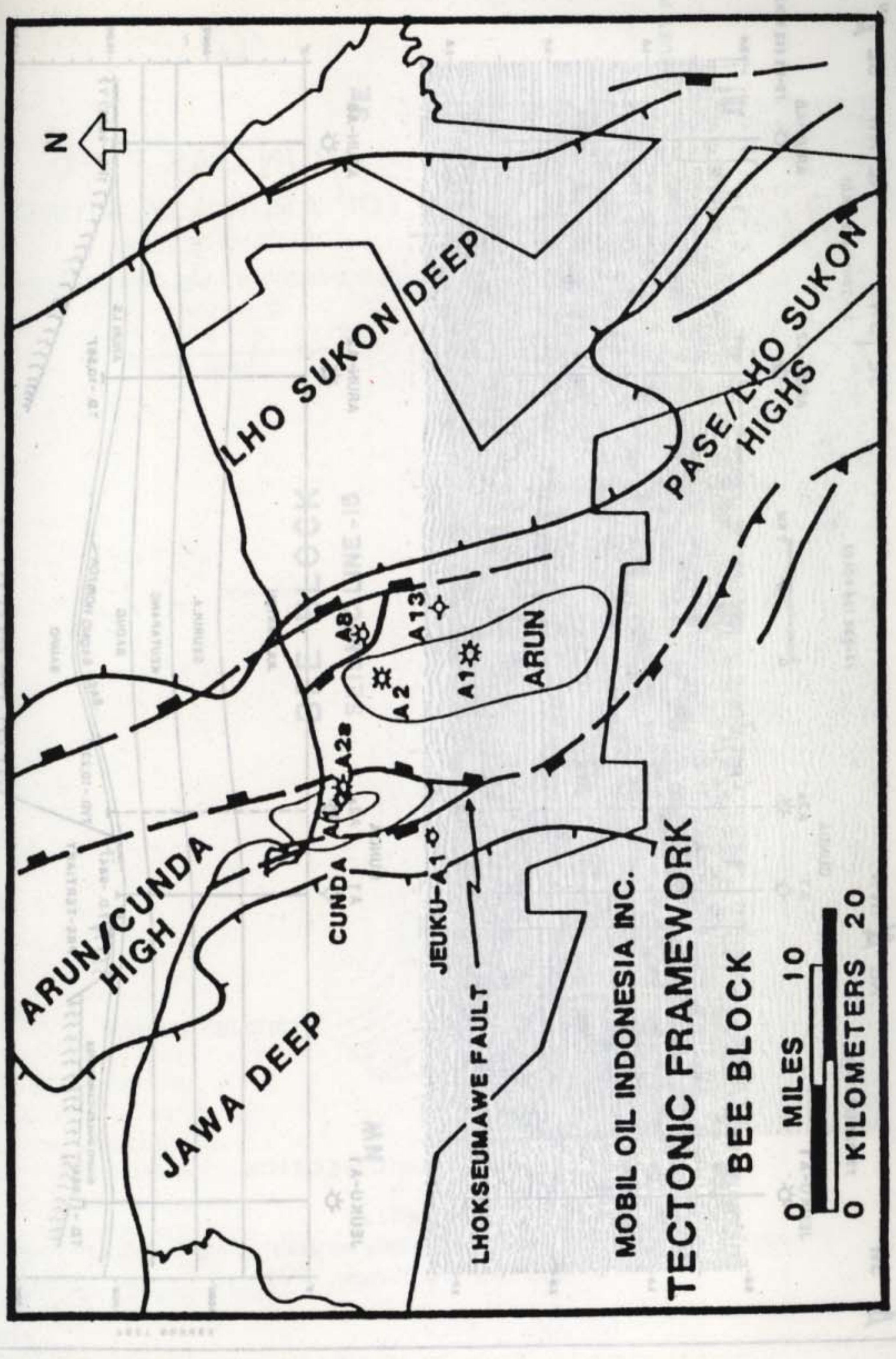


Figure 10. Tectonic framework of Arun/Cunda region, North Sumatra (after Burnaman et al., 1985)

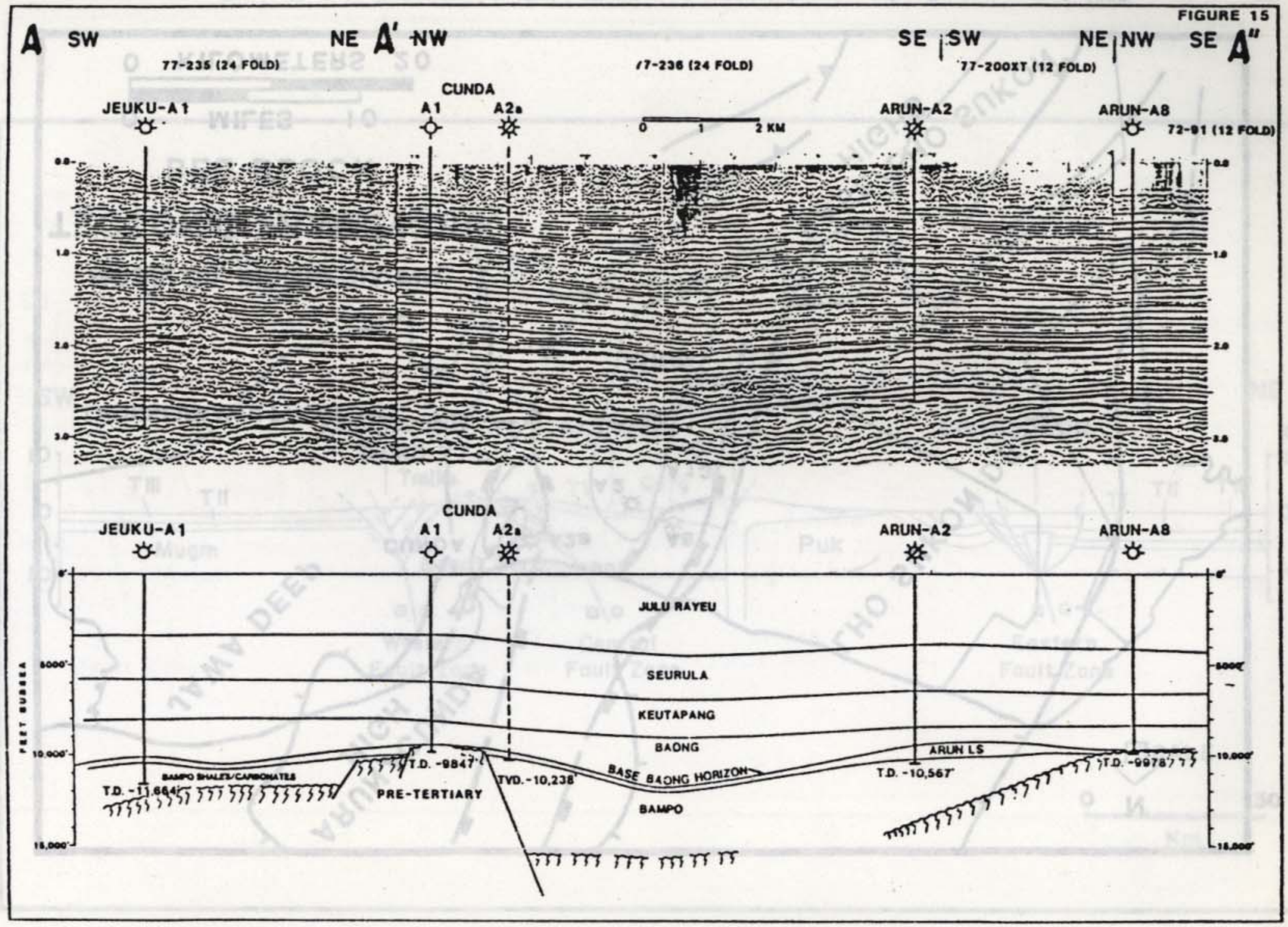


Figure 11. Seismic and geological interpretation of Cunda structure and Arun field (after Burnaman et al, 1985)

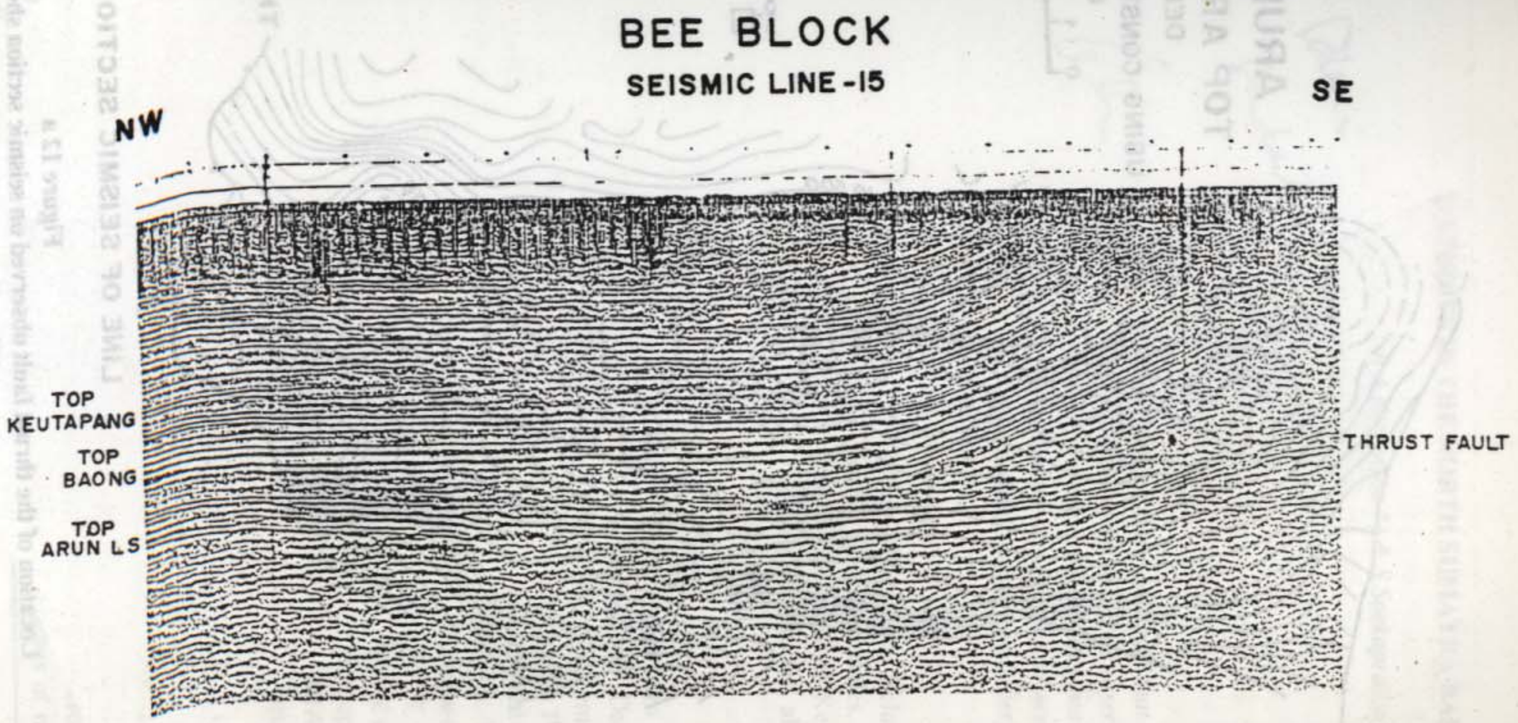


Figure 12 . Seismic section of the Arun field, showing a northerly dipping trust fault (after Graves & Weegar, 1973)

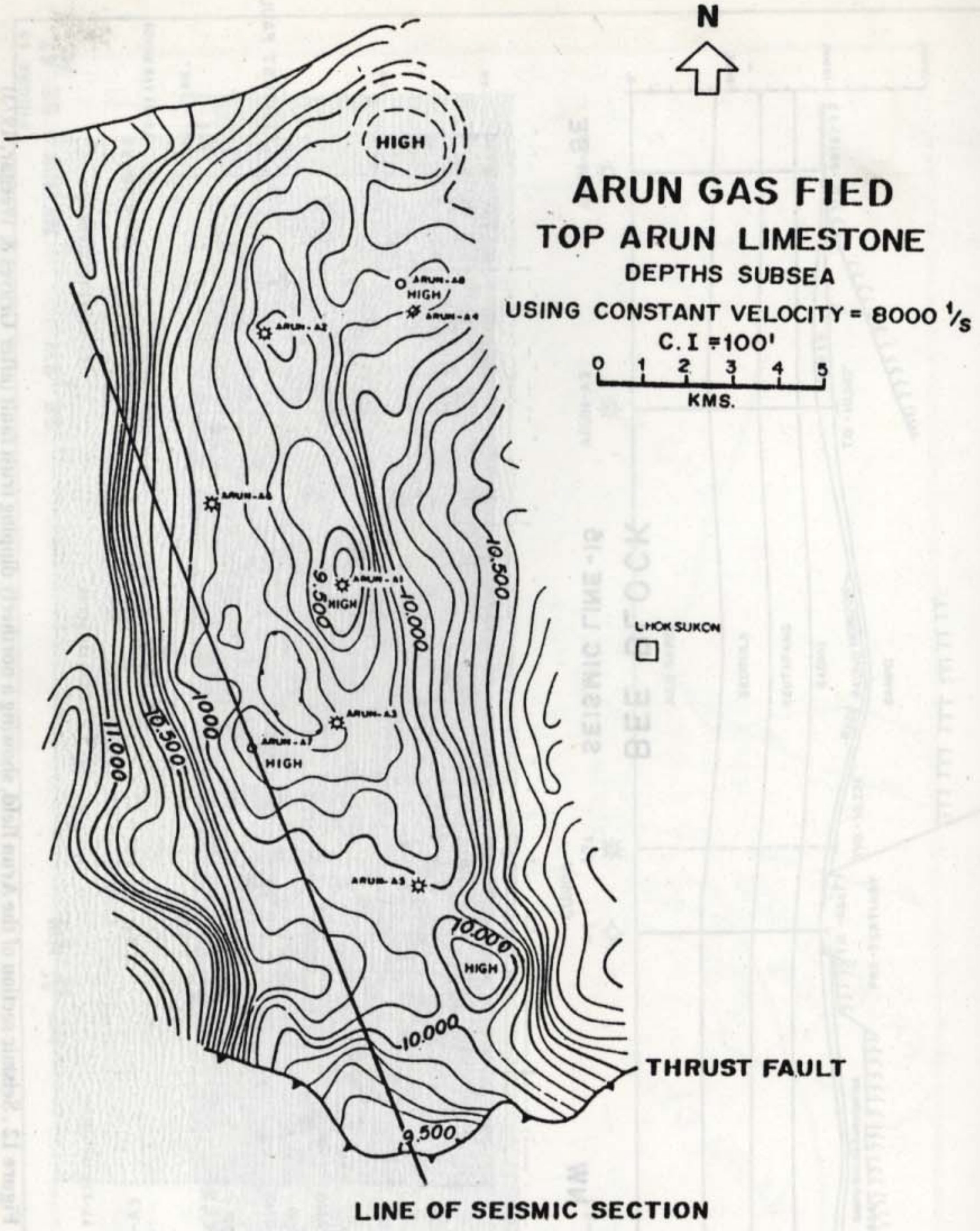


Figure 12 a
Location of the thrust fault observed on seismic section shown in Fig.12, Arun area (after Graves & Weegar, 1973)

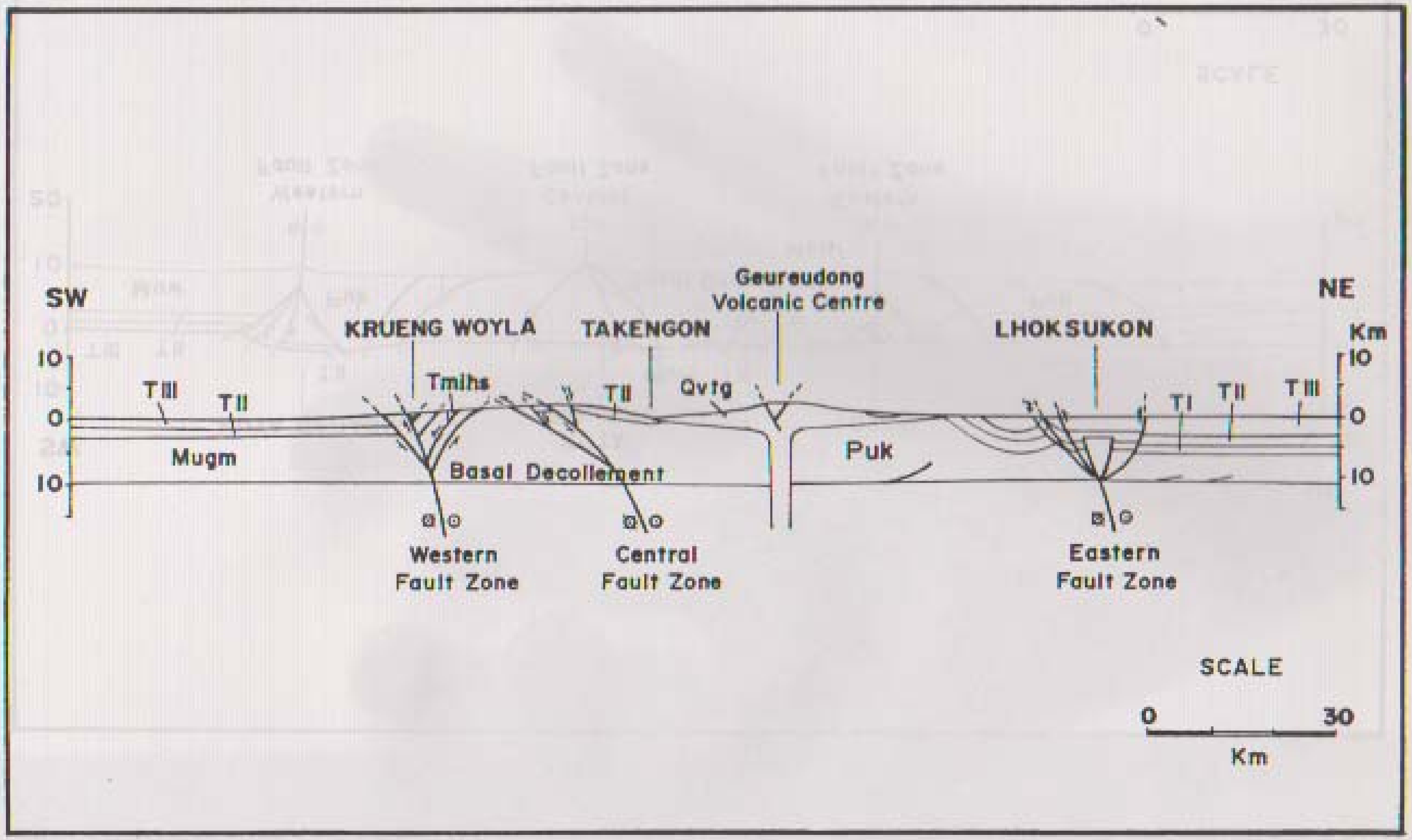


Figure 9. Section 3 : Krueng Woyla-Takengon-Lhoksukon

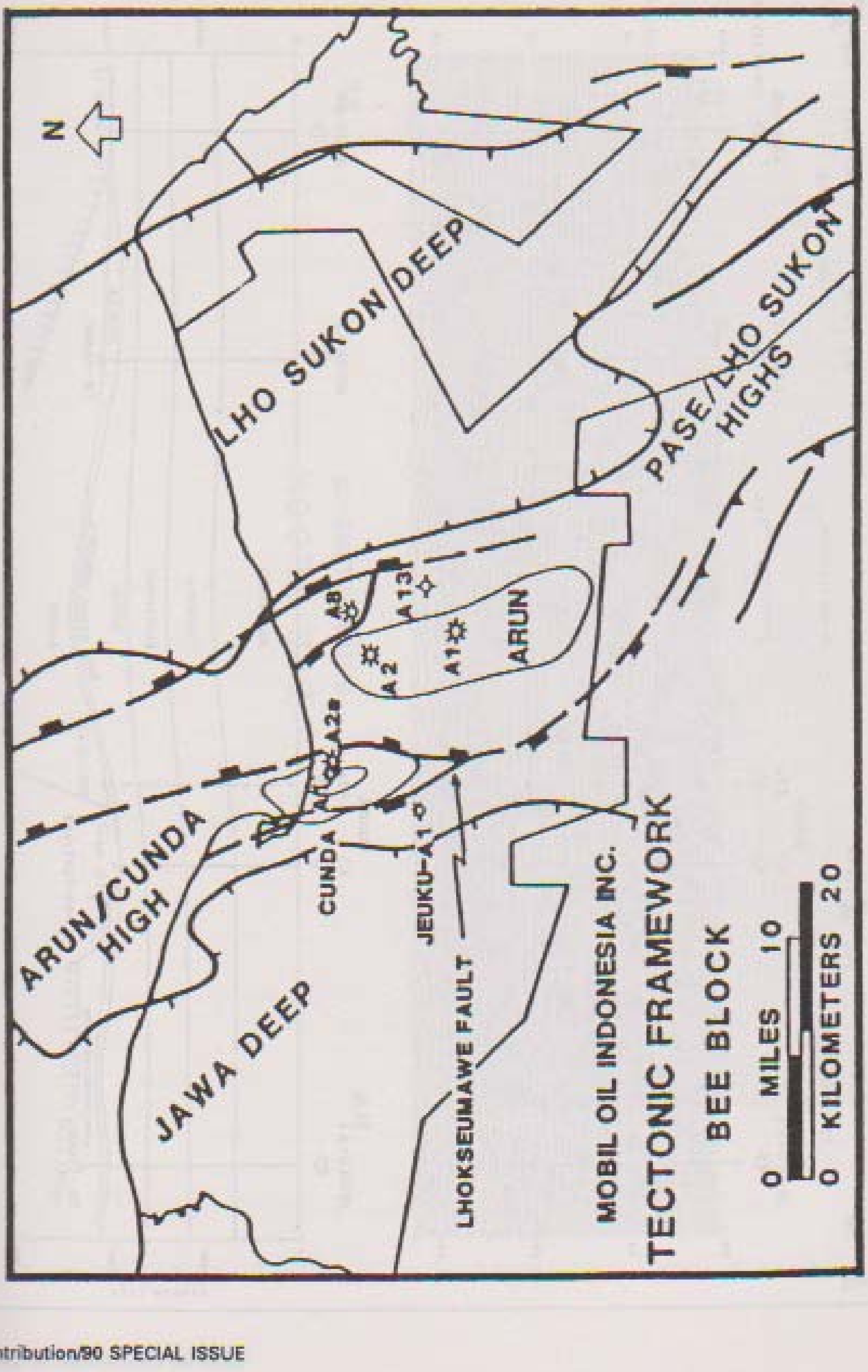


Figure 10. Tectonic framework of Arun/Cunda region, North Sumatra (after Burnaman et al., 1985)

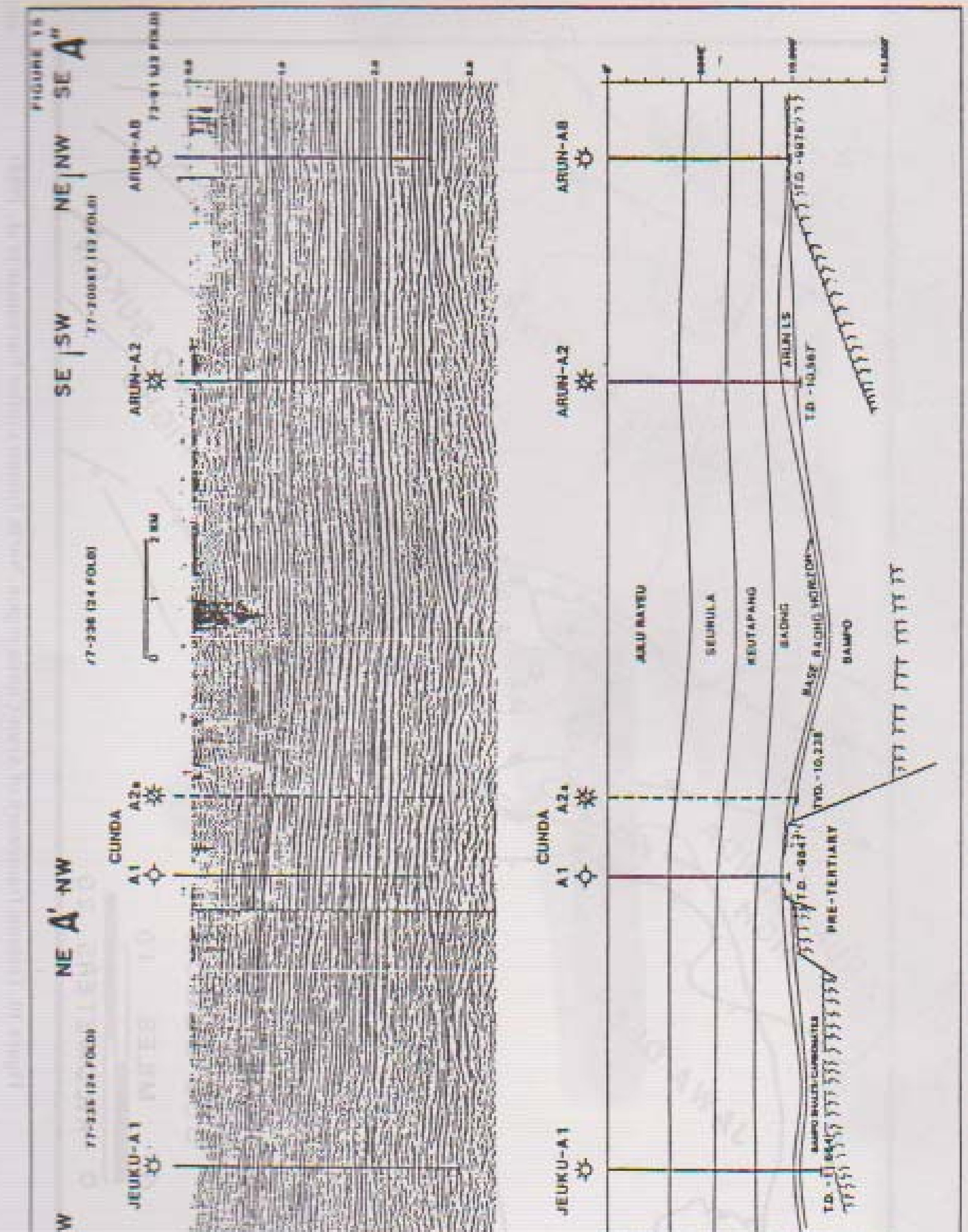


Figure 11. Seismic and geological interpretation of Cunda structure and Arun field (after Burnaman et al, 1985)

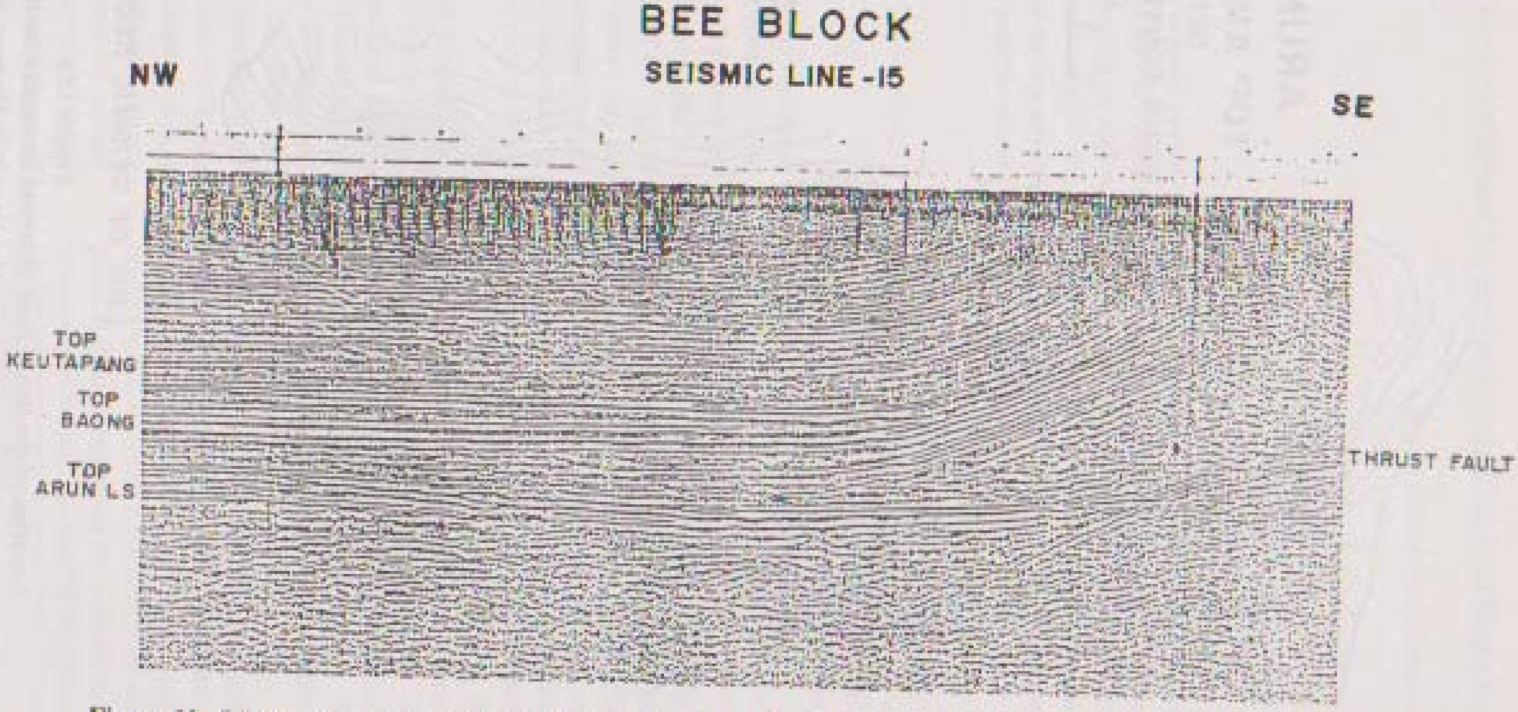


Figure 12 . Seismic section of the Arun field, showing a northerly dipping trust fault (after Graves & Weegar, 1973)

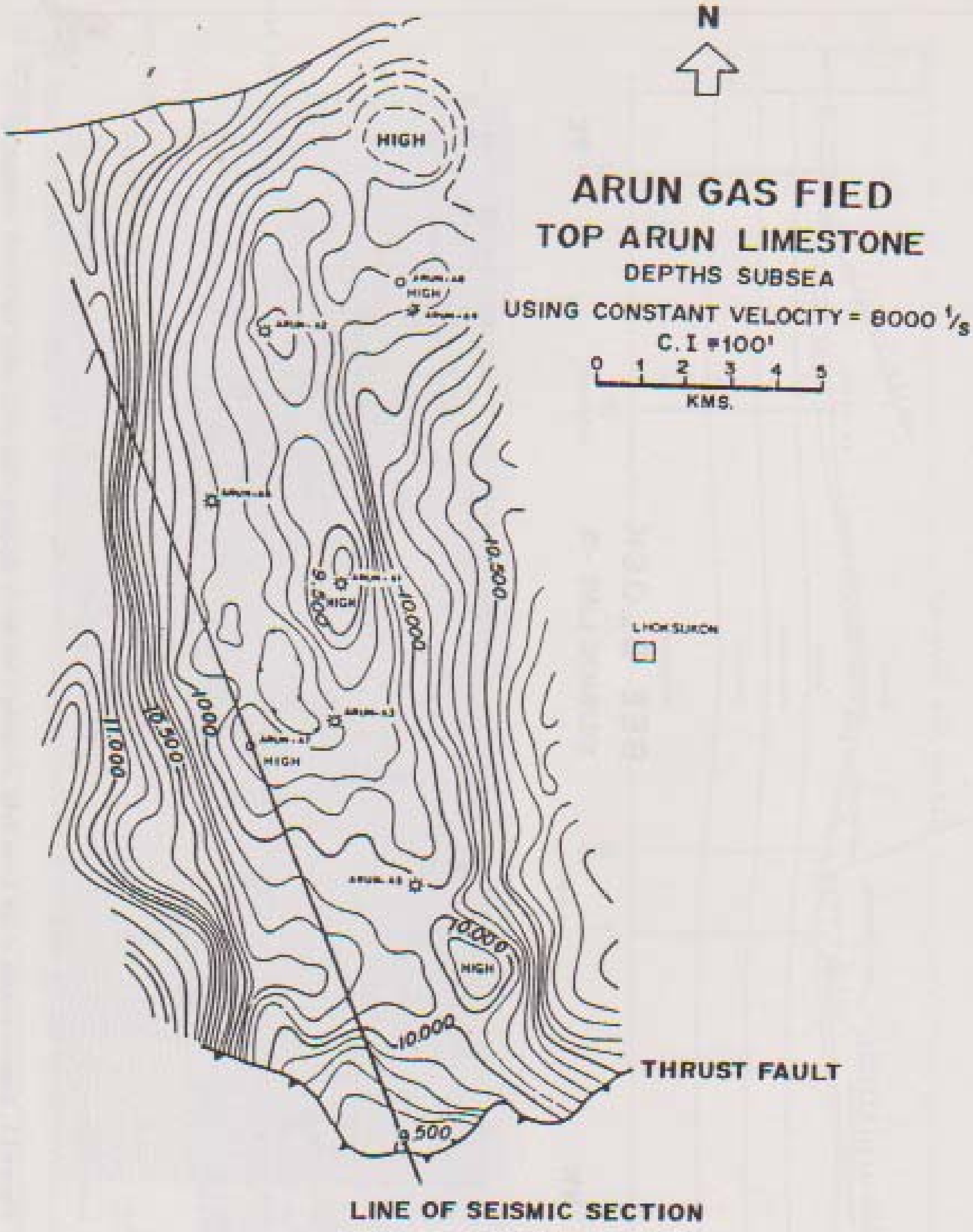


Figure 12 a
Location of the thrust fault observed on seismic section shown in Fig.12, Arun area
(after Graves & Weegar, 1973)