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THE BALI-FLORES BASIN:

GEOLOGICAL TRANSITION FROM EXTENSIONAL TO SUBSEQUENT COMPRESSIONAL DEFORMATION

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ABSTRACT

Analog and digital seismic reflection and gravity data from different sources, drill-holes, and SeaMARC II (seafloor mapping system) side-scan mosaic data from the Flores Basin, provide an excellent database with which to determine the geologic and

tectonic development of the Bali-Flores back arc fold-thrust zone.

Remarkable continuity of west-east structural orientation over 800 km along the Eastern Sunda back arc region suggests a uniformity in direction of convergence between the Indo-Australian and Eurasian plates.

Westward transition from a well-defined accretionary wedge to fold structural styles indicates a westward decrease in the total amount of shortening.

The phenomena of back arc thrusting north of Flores can be used as a good model of the initial stage of arc reversal polarity in which the oceanic crust of the Flores Basin is being subducted southward beneath the arc, opposite to the northward subduction of the Australian continental crust along the Timor Trough.

While the Bali Basin represents an excellent modern analog of the initial stage of a foreland fold-thrust belt formation, here the Sunda Shelf is down bowed to the south resulting in the compressional deformation along the southern margin of the Bali Basin. The back arc region of the Eastern Sunda arc is currently closing and will form a suture zone in a future stage of development.

The seismic and drill-hole data have supported several geologic and tectonic developments of the study area:

(1) most of the northern basin margin represents a Paleocene extensional (rifting) tectonic regime;

(2) this extensional tectonic environment was then inverted to form typical "Sunda Fold" structural styles;

(3) down bowing (flexural) of the southeast Sunda Shield margin (northern basin margin) occurs to the south beneath the volcanic ridge; and

(4) the back arc fold thrust zone formed since Neogene time was associated with both the Australian margin-Banda arc collision as well as subducting of the Roo Rise (oceanic plateau) in the Sunda Trench south of Bali:

INTRODUCTION

The Bali-Flores basin is situated on the southeastern part of the Sunda Shield margin. The basin is linear, and forms an east-west-oriented deep depression which tectonically occupies the eastern Sunda back arc region of Eastern Indonesia (Figure 1).

Overall, the back arc region consists of several prominent east-west elongated deep depressions, from the west to the east respectively including The Bali Basin, Lombok Trough, Flores Basin, and Banda Basin.

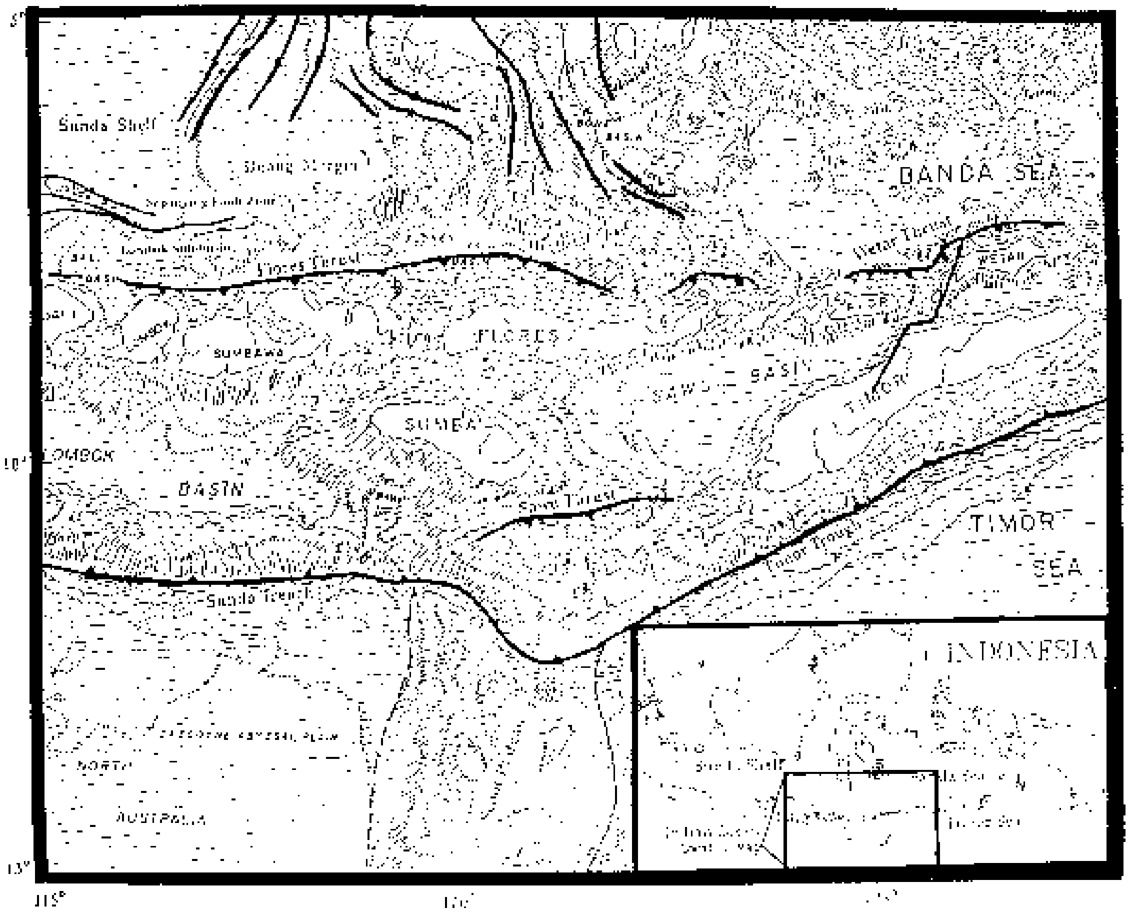

Figure 1

The Bali-Flores back-arc basin has been studied by numerous workers since the pioneer compilation of Hamilton (1979). Silver et al (1983a, 1986), Usna et al (1983), Prasetyo (1984), Prasetyo and Dwiyanto (1986), McCaffrey and Nabalek (1987) further define the characteristics and extend the thrust zone from study at the reflection profiles, side-scan mapping, seismicity, and other data.

The Bali-Flores Basin is similar to other Eastern Indonesia deep basins including the Makassar, Bone, South Banda, Sula (North Banda), Gorontalo, and Sulawesi Basins all of which origins are still controversial.

The most important question is how these unique basins are formed and later developed. The basins are located within the active collision zone between three major lithospheric plates the Eurasian, Indo-Australian, and Pacific Plates (Figure 2).

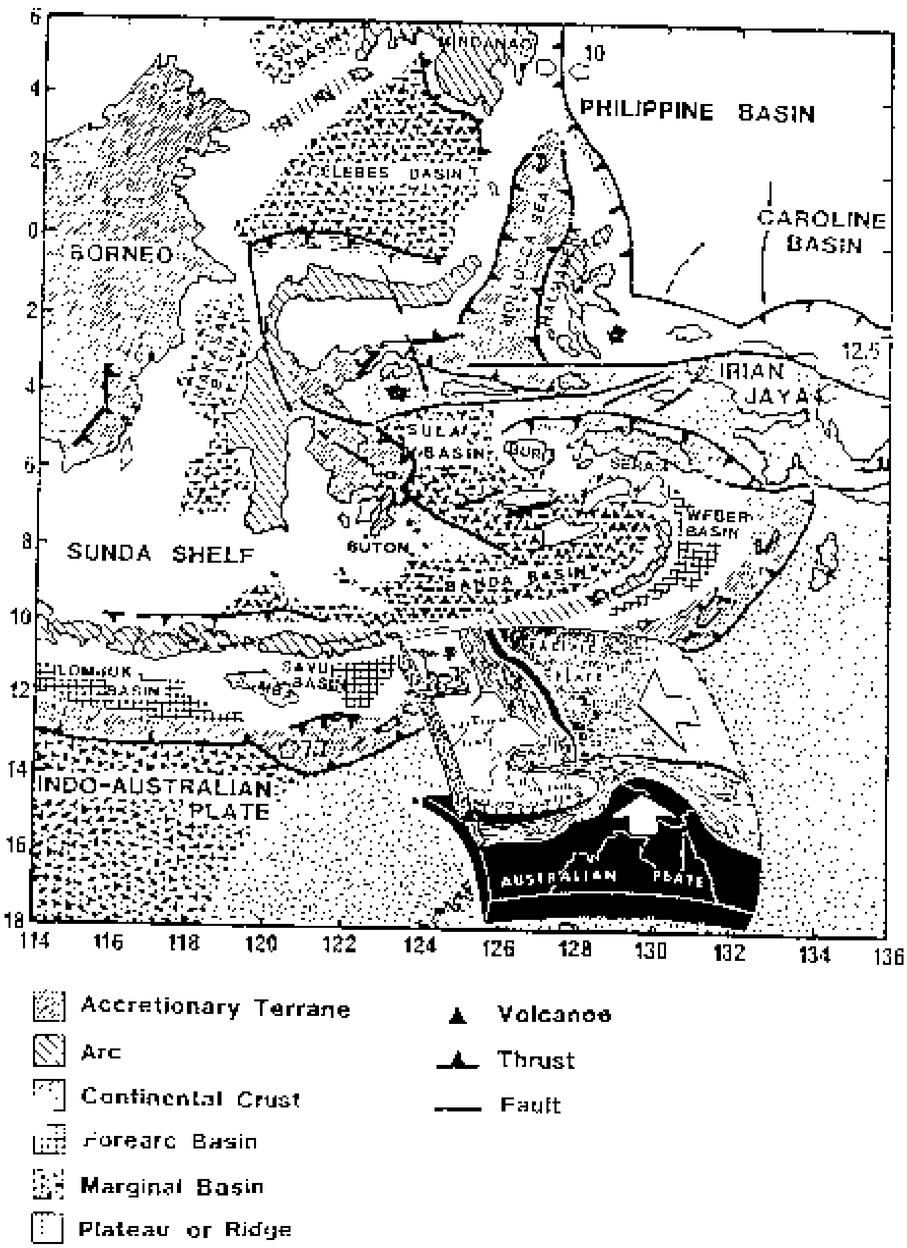

Figure 2.

Several workers (e.g. Taylor and Kasner, 1983; Silver et al., 1985; and Prasetyo, 1988) have specified some of the basins as marginal basins which are generally restricted to those underlain by oceanic crust basement.

Marginal basins can originate by at least five alternative mechanisms (Silver and Ranging, 1991, in press) including back arc spreading (e.g. Sulu Sea), extension of the global rift system into the edge of the continent, breakup of the continental margin by a collision process or extrusion tectonics, trapping of a part of a once larger ocean basin (e.g. Banda Sea), and transtensional basin formation by the movement of a major plate past a continental margin.

A detailed study of single and multichannel seismic profiles available from different sources north of the Bali, Lombok and West Sumbawa islands, clearly identifies acoustic basement blocks and rift structures. These features were originally thought to be tilted blocks or rifted crust of the continental origin in an extensional tectonic environment.

The Paleocene rift structures have also been identified in the deeper stratigraphic sequence of a fore-arc basin south of Bali Lombok (Weitze and Prasetyo, 1991A), in the Makassar Strait (Prasetyo and Kumala, 1990) as well as in the South Sulawesi (Gerrard et al., 1992).

Several workers (e.g. Hamilton, 1979; Silver et al., 1983 and

1986; Prasetyo and Dwiyanto, 1986; and McCaffrey and Nabalek, 1987) without further explanation have suggested that the Flores Basin is underlain by unknown origin oceanic crust.

Although variation in the nature of the basement occurs along the Bali-Flores Basin, presently tectonic activity in the region is dominated by a compressional tectonic system. This compressional related deformation has been accommodated by the Flores thrust zone on the east, the Lombok fold-thrust zone in the central part, and the Bali Fold to the north of central Bali on the west.

The Bali-Flores back-arc basin is relatively unexplored with several wells having been drilled mostly in the northwestern margin of the basin (adjacent of Kangean Island). These wells have contributed some understanding of the stratigraphic succession, but have been plugged and abandoned due to economic reasons.

This paper provides an overview of this offshore deep basin which can be used as general information for future exploration activity, particularly in the frontier region of eastern Indonesia.

The outlines-of a regional geologic and tectonic development of the Bali-Flores Basin, a morpho-tectonic transition zone from the western to eastern Indonesia region are discussed.

Special attention will be paid to the extensional (rifted) structural features of the SE Sunda Shield margin that was latter inverted, and which lies to the north of Lombok. This phenomena then will be used as an excellent example of an extensional tectonic environment that has been reshaped by a compressional tectonic regime.

Oil companies and academic institutions have become interested in the Bali-Flores Basin because of future hydrocarbon prospects in the deep sea area and its unique geological and tectonic nature.

This paper is also cited as a scientific proposal for conducting deep seismic profiling (DSP) across the fore-arc and back-arc region of Bali. A DSP survey crossing the Banda Sea to the Australian margin east of Timor, was successfully conducted for the first time February, 1992, (Prasetyo et al., 1992).

DATABASE AND STRATEGY FOR SPECIFIC APPLICATION

Six separate seismic surveys between 1980 and 1991 constitute the main information data based (Figure 3). Data quality vary from survey to survey, including:

- Single channel reflections of the Rama-12 Expedition (1981) covering the back-arc region from Bali to Banda Sea;
- Multichannel reflections of the Pacific Cruise (1982) north of Bali; Single channel reflections and side-scan images of SeaMARC II obtained by the Sinta Expedition (1983) north of Flores;

- Single channel reflections of the Toraja I expedition (1991) obtained using the R/V Baruna Jaya III of BPPT north of Bali and adjacent Kangean; and four regional multichannel reflections north of the Lombok and Sumbawa obtained recently by British Petroleum (1991).

- Gravity data of the Rama-12 expedition were previously compiled by Silver et al. (1983) covering west of the Banda Sea, and from McCaffrey and Nabalek (1987) particularly in the Bali Basin;

- Bathymetric data were compiled during the Toraja I Expedition, whereas a physiographic map was compiled in the cooperative program with the United States Geological Survey (USGS) in 1987.

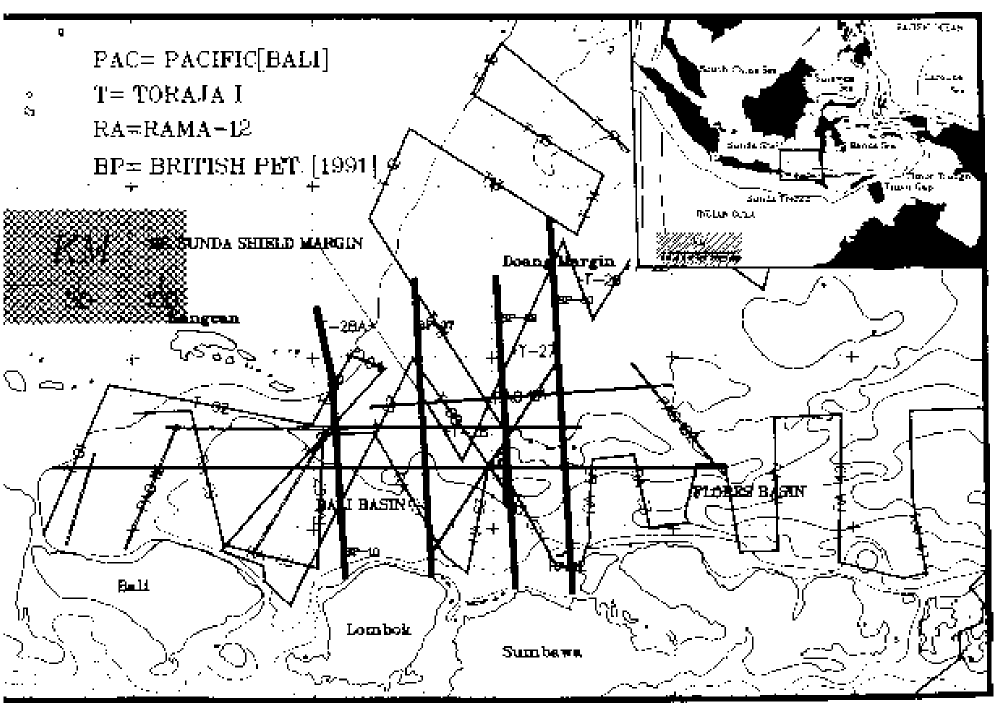

Figure 3.

The multichannel seismic profiles were used to delineate and define the deeper structural styles, particularly the nature of extensional (rift) related structures. Moreover, they are useful in tracing those features from the northern margin throughout and beneath the complex of compressional deformation features south of the Lombok Trough.

The integration of the multichannel, single channel reflections, bathymetry, SeaMARC II side-scan images with well exploration information provides information needed for constructing a 3-D view of the structural frameworks and predicting the time events of those structures.

REGIONAL TECTONIC SETTING

The Eastern Indonesia Collision Complex

Eastern Indonesia is characterized by a collection of landmasses or fragments and a number of deep sea basins of different origins that are trapped between converging Pacific, SE Asian (Eurasian), and Indo-Australian Plates (Figure 2).

These features display a variety of structural styles and settings, tectonic activity, sediment thickness, and proximity to the arcs or continental margins.

The arc-continent collision between the eastern Sunda Arc (called as the Banda Arc) and NW Australia forms the southern boundary of this mosaic of tectonic elements.

However, the mechanism by which the collision occurs remains a matter of controversy. This collision zone is in a young stage of evolution and is very similar in many aspects to normal arc-trench systems.

East of the island of Sumba, the oceanic crust of the Indian Ocean has been completely subducted and Australian crust is now underthrust over the Banda Arc.

To the west of the collision zone, the Sunda Arc extends onto the continental margin of SE Asia where it comprises one of the classic convergent systems, in which the old (>150 Ma) Indian-Australian oceanic crust is being subducted along the Sunda Trench.

It is known that the Indian Ocean-Australian plate is moving northward relative to the southeast Asian Plate at a rate of about 7.5 cm/yr (e.g. Curray 1989). The islands of Jawa, Bali, Lombok and Sumbawa are presumably formed by the construction of volcanic arcs on the previously passive southern margin of the Sunda Shelf.

Sumba is represented as uplifted fore-arc basement that has been trapped in the present fore-arc basin (Reed et al., 1986). Several types of evidence show that the geologic development of Sumba can be analogous to the Doang Borderland which is located at the leading edge of the Sunda Shield margin (Weitze et al., 1991A). The Lombok Fore-Arc Basin, which lies to the west of Sumba, is marked by rift structures at the deeper stratigraphic horizons (Weitze et al., 1991A).

The Sunda-Banda Arc transition zone records two well defined linear thrust zones, both in the fore-arc region. One is represented as a back thrust (e.g. Sawu Thrust) and the other in the back arc called the Flores back-arc thrust.

The two systems may be related (Silver and Reed., 1987). The back-arc region exhibits a laterally discontinuous zone of back-arc thrusting. These thrusts produce small, young accretionary wedges.

Morpho-Structural Style of the Bali-Flores Back-Arc and Adjacent Regions

The eastern Sunda Back-Arc and adjacent regions are composed of a complex mosaic consisting of nine different morpho-structural features (Figure 1).

The northern region included the SE Sunda Shelf and margin, Makassar extensional (rifted) Basin, Doang Borderland, SW Sulawesi Margin, Salayar Ridge, and the Bone (rifted) Basin.

The central region which is occupied by the back-arc basins consist of the Bali Basin, Lombok Trough, Flores Basin, and Wetar Subbasin. The southern region is formed by the Bali-Flores volcanic islands.

These morpho-structural features presumably represent differences in their origin, tectonic setting as well as geologic development.

Tectonic Framework of the Eastern Sunda Back-Arc Region

The back-arc region in eastern Indonesia is complex in terms of its origin as well as tectonic development.

The Bali Basin in the west is relatively wide and shallow. North of Lombok to central Sumbawa, the Lombok Trough is narrow and deep.

The Flores Basin to the east is narrow and deep with the seafloor at 5000 m depth. From Lombok to East Flores, the deepest part of the basin is along the south margin with a trough or trench like appearance both in bathymetric and seismic profile.

The above morphology represents a thrust system or deformation front which develops to the north of the eastern Sunda Arc slope. Toward the East, the Bali-Flores Basin is separated from the South Banda Basin by a series of NW-trending submarine ridges extending from Salayar to the Bonerate Islands.

The Banda Sea, which is a prominent feature in the back arc region, is situated behind the Banda Arc, and was deformed as a result of the collision between the Australian continental margin and the island arc (e.g. Prasetyo, 1985; McCaffrey, 1987).

The geology and structure of this region is complex. Compressional tectonics within the Banda Basin is due to the arc continent collision which is expressed along the margin. This position is supported by shallow earthquake focal mechanism data which shows that the Banda Sea is tectonically active.

This activity is due to the presence of both strike-slip faults and thrust faulting activities along the south margin of the Banda Sea (extending from the Flores thrust to Wetar the thrust). No extensional focal mechanism has been reported, suggesting that the Banda Sea is closing.

An additional interesting aspect of the Banda Sea is that the basin is a mixture of continental margin and oceanic crustal fragments derived either partially or entirely from the margin of the Australian continent (Silver et al., I985; Prasetyo, 1985 and 1988).

The age of the basin is unclear, however low heat flow, magnetic lineations, and measured water depth are consistent with an Early Tertiary or Late Cretaceous age (Prasetyo, 1988).

Most of the regions located north of the present backarc basins (e.g. East of Kangean) have several common features in their development. The regions evolved in the Paleocene-Eocene as rifted back-arc areas of an East-West and North-South (in the case of the Makassar Basin) trending volcanic arcs.

The Doang Borderland Iying on the northwestern margin of the Flores Basin consists of ridges and intervening troughs. This Borderland may play an important role in the origin of the Flores Basin.

GEOLOGY AND STRUCTURAL DEVELOPMENT OF THE NORTHERN MARGIN OF BACK-ARC BASIN

General

An understanding of the geology and structural framework of the regions located north of the Eastern Sunda Back-Arc region is critical due to three reasons:

(1) the dense coverage of multichannel reflections as well as a number of exploration wells;

(2) the availability of data and information provides a significant data base, particularly to study and understand the Paleogene Rift System which has resulted from regional extension and later modified by tectonic inversion; and

(3) the information as related to time control and the nature of the lower plate of the Bali-Flores thrust-fold system.

SE Sunda Shelf and Its Margin

The SE Sunda Shelf (Figure 4) has an average water depth of about 200 m and structurally consists of NESW oriented of Ridge (basement high) bounded faults and intervening Troughs (basement low).

The thickness of sediments ranges from 1 to 2km, and locally up to 3km which mostly occurs within the structural troughs. The age of basement rocks of the eastern Sunda Shelf ranges in age from 58 Ma to 140 Ma and consists of terrigenous and volcaniclastic metasediments, volcanic and granitic rocks. The oldest sedimentary sequence appears to be of Paleocene age.

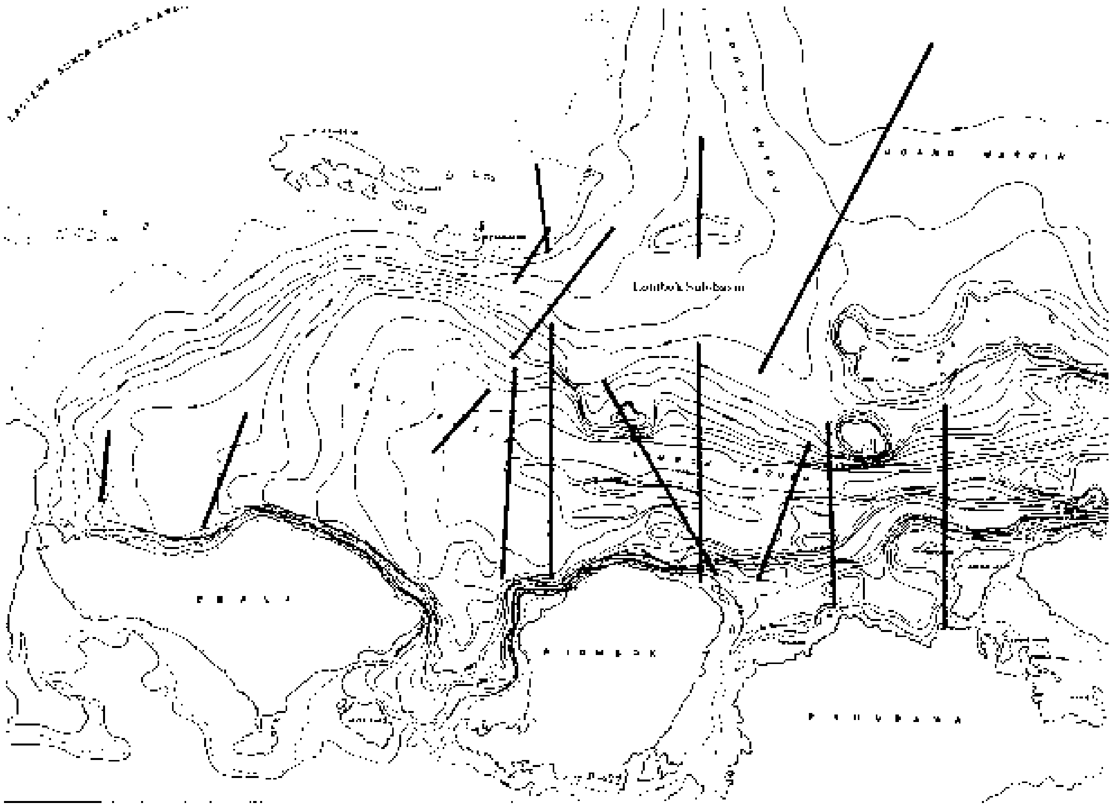

Figure 4.

The E-W-trending topographic ridges which exist at the southern margin of the Sunda Shelf include the prominent emerge at islands of Kangean, Sepanjang and Madura.

These structural ridges have been uplifted by compressional inversion and that uplift may be continuing at present (Figure-5). The area southeast of Sepanjang Island is occupied by a NE-trending depressional region called the Lombok Sub-Basin, which is bounded by the Sepanjang Ridge to the North and the

E-W basement high to the South (Figure 4).

The Lombok Sub-Basin, like most rift-related basins, can be characterized by a three phase tectonic and sedimentary evolutionary history (Harding, 1984).

In chronological succession they are a pre-rift phase, a rift phase, and a sag or post-rift phase. Each of these phases involves a separate distinct basin geometry, style of faulting, structural deformation and stratigraphic succession. Following the cessation of rift-related tectonics was a fourth wrenching phase. The rift-sag sequences can be identified from seismic reflections and confirmed by well data. This rifting was associated with half graben, graben, and tilted block structures which were latter followed by filling with synrift Paleocene sediments consisting of non-marine, deltaic and shallow marine sedimentary sequences.

Amplitude processed multichannel profiles (BP-series) have shown the existence of very high amplitude reflectors within the Rift sequence which seem to be from coal layers which can be traced along the whole profile (Newcome, 1991, oral communication).

The rifting during Paleogene appears to have been in response to a regional event affecting the entire Sunda Shield especially at the SE margin. The syn-rift sequences were then followed by the post-rift (sag basin) sedimentary sequences.

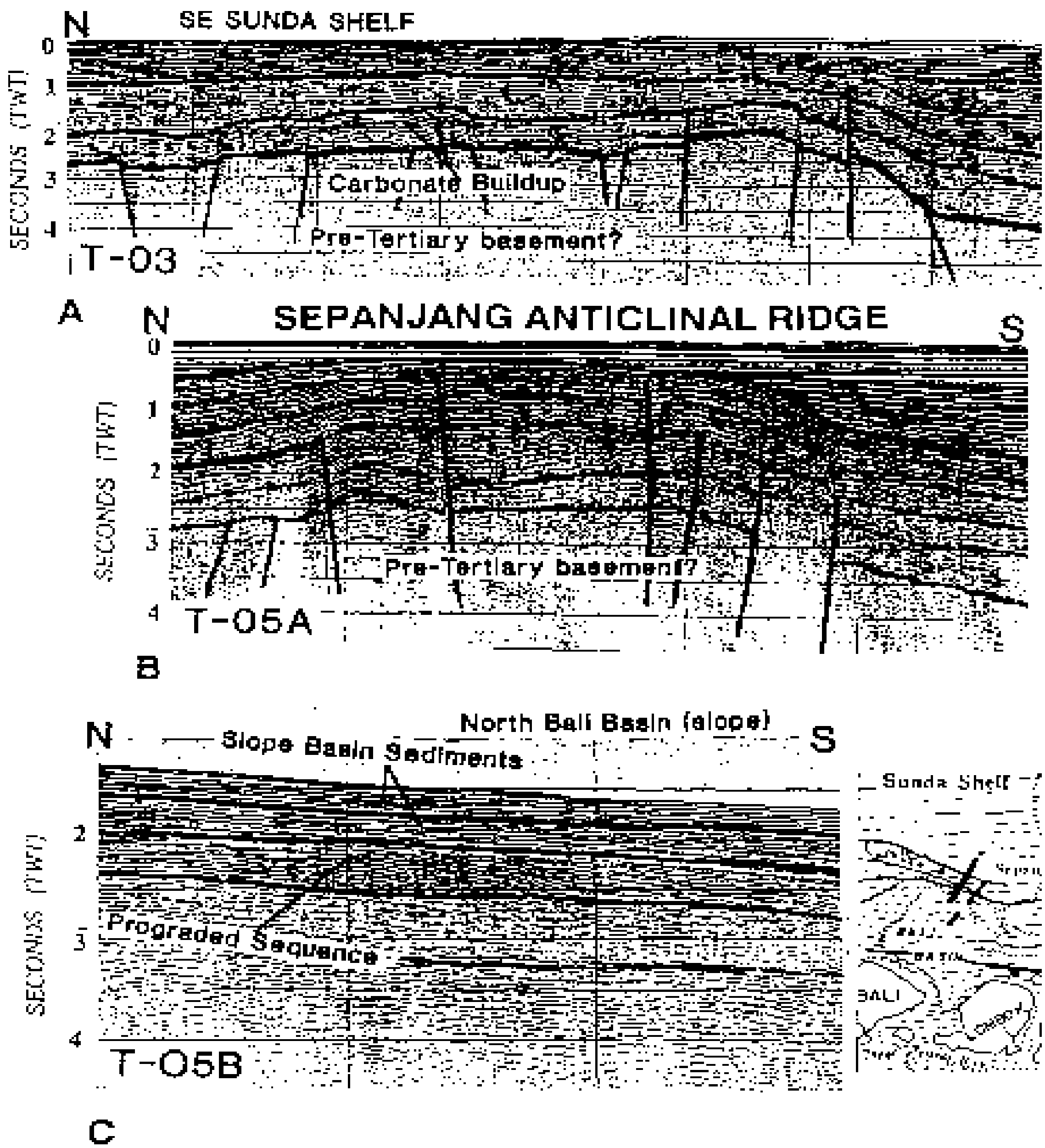

Figure 5.

The wrenching tectonic event in the Lombok Sub-Basin is characterized by tectonic inversion that started from Middle Miocene and is continuing up to Recent time. This inversion is resulting in E-W trending grabens, half grabens, thrusts and large scale fold structures (Figure 6) including the Kangean-Sepanjang anticlinal ridge which is representative of a "Sunda Fold" structural style.

The sag basin (post-rift) sequence was in some places interrupted by the inversion tectonic event. Consequently the post-inversion sequence is locally deposited on the topographic highs.

On the southern slope break, the sag-basin sequences are also influenced by the southward down bowed, or flexed SE Sunda Shield margin, which initially appeared in the Pliocene and is continuing until present.

This event will play an important role for foreland fold-thrust formation along the Bali-Lombok Basin.

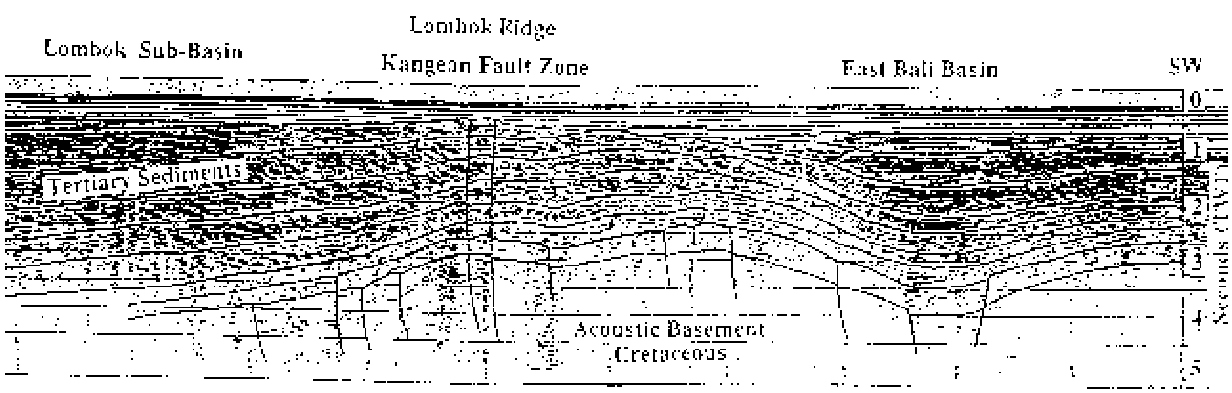

Figure 6.

Doang Borderland (DB)

The Doang Borderland is basically made up of a prominent NE-SW trending Doang Platform on the North (Figures 1 & 4) and a smaller Paternoster Platform on the Southwest. The borderland is surrounded by prominent depressions including the

South Makassar Basin to the north, the NW trending Spermonde Trough in the Northeast, to NW Flores Basin in the Southeast with its prominent escarpment, and the Lombok Trough in the Southwest.

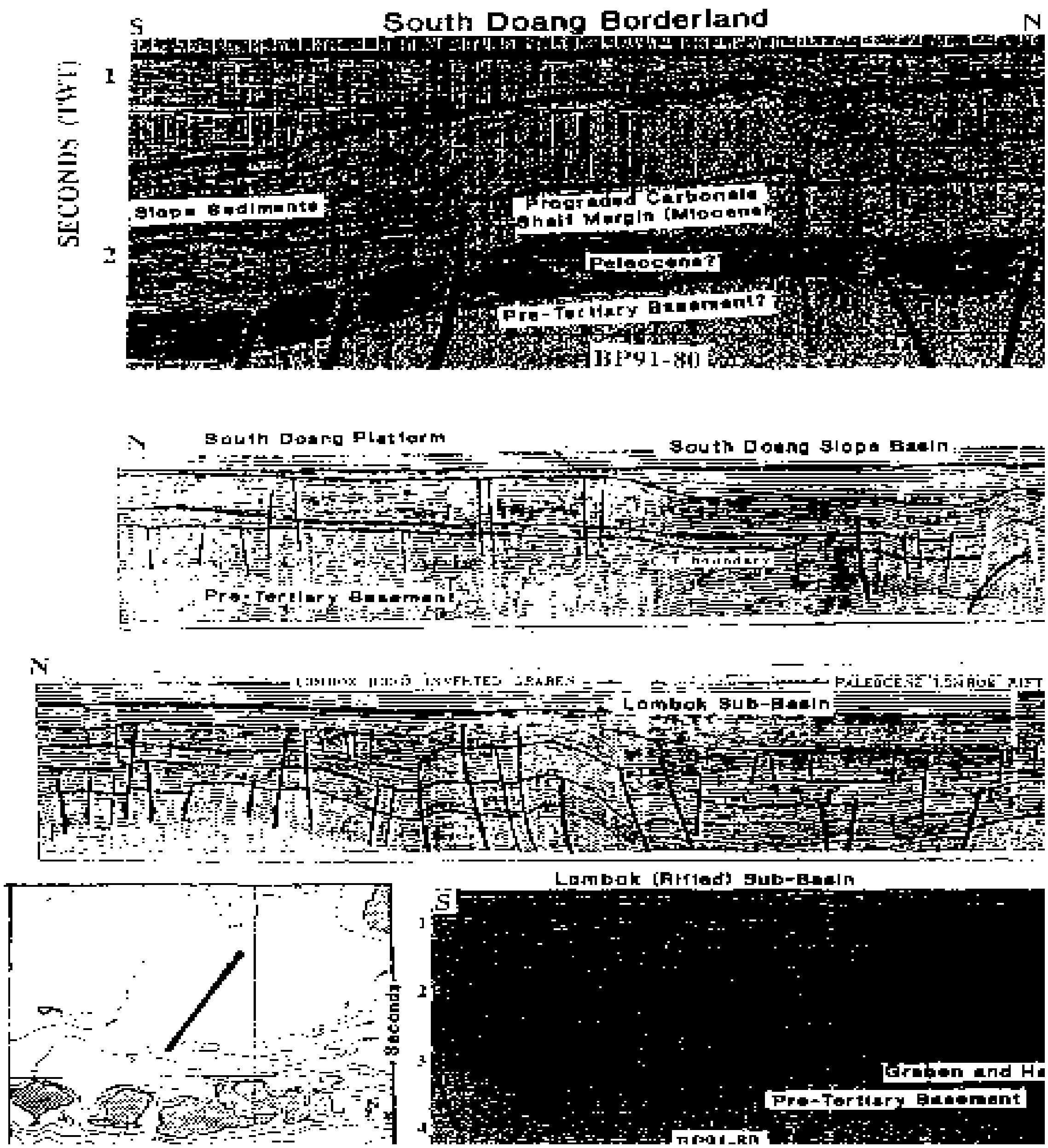

Figure 7.

The NE-SW trending Doang Trough separates the SE Sunda Shelf to the West from the Doang Borderland in the East. The Doang Margin (DM) is a depression which is represented by a prominent continental slope which separates the Doang Platform in the North from the Paternoster Platform in the South.

The Doang Margin has subsided since Upper Miocene. This subsidence is associated with southward progradation of the Miocene Carbonate Shelf (Figure 7).

The SeaMARC II side-scan mosaic and single channel profiles (Silver et al. 1986) delineated the structural framework of the southeast edge of the Doang Borderland which also represents the outer slope of the Flores Basin.

The NE-SW faults may represent the reactivation of older basement faults because they are parallel to buried faults mapped on the Sunda Shelf. Because the borderland in some part is analogous in stratigraphic and structural framework to the Lombok Sub-Basin, the reactivation may have involved Early Paleocene rift related structures.

The reactivation may have been a bending response to the development of the Flores Trench since Upper Neogene. Alternatively, these NE oriented faults may be caused by:

(1) the bending arc system in Miocene time, related to the development of the West dipping Sulawesi arc-trench system, in which the Southeast edge of the Doang Borderland is located within the junction (Trench-Strike

slip-Trench);

(2) the mechanism might be strike-slip faulting related to the collision because the trend of the faults is nearly 30° off the expected direction of convergence in the Flores Trench (Silver et al., 1986).

GEOLOGIC DEVELOPMENT AND STRUCTURAL STYLES OF THE BALI-FLORES BACK ARC BASIN

Bali Basin

cThe Bali Basin (Figure 4) is a narrow (100 x 200 km), half circle shape (looking from South) basin, with water depth gradually getting deeper to the East with the maximum depth of 1.5 km.

The basin is bounded on the North by the E-W trending Kangean-Madura Ridge which exists as the southern limit of the Sunda Shelf and forms a significant but gradual slope to the South.

In the East, the Bali Basin merges with the Lombok Trough, and towards the South the Bali volcanic island terminates the basin in a very steep slope. Toward the west of the Bali Basin is the eastern extension of the North Jawa sedimentary basin and the

Madura Strait depression region.

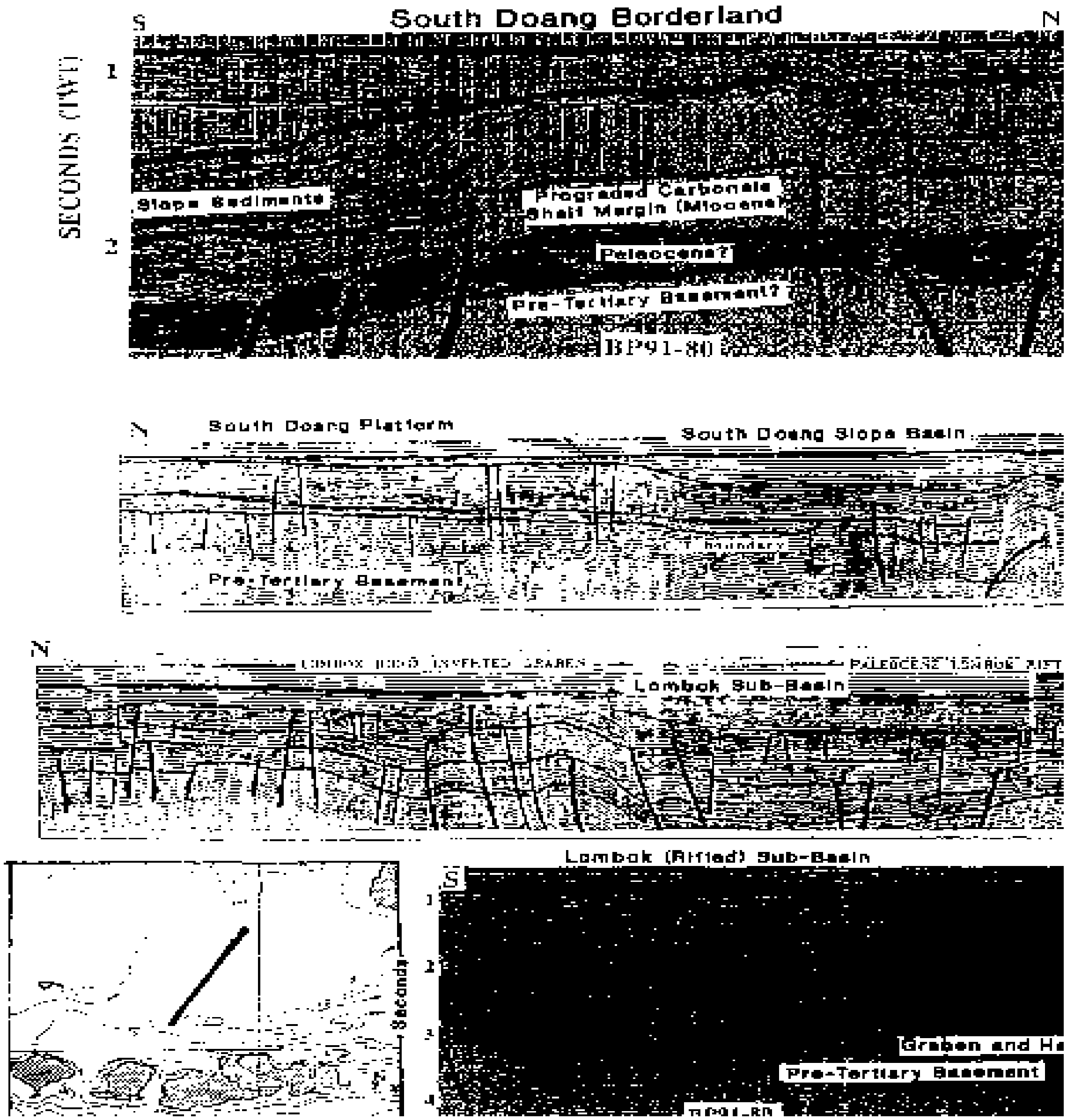

Figure 7.

The basin receives sediments transported from the north (Sunda Shelf), from the west (Madura Strait and Northeast Jawa), and principally from the South (Bali and Lombok volcanic islands). Figure 8 is a digital gravity map covering the Bali and Lombok-Trough areas as modified from McCaffrey and Nabalek

(1987).

In general, the Bali Basin is associated with a strong negative gravity anomaly over the deep parts of the basin and then an increase in gravity over the island. The low reaches below -60 mGal north of Lombok Strait and the strait between Lombok and Sumbawa.

West of the Bali Basin the area is characterized by a positive gravity anomaly with a closure of + 20 mGal. The Madura-Kangean Ridge is associated with a gravity high of 40 to 60 mGal which seems to be related to the proximity of higher density basement rocks on the seafloor (Ben-Avreham and Emery, 1973; McCaffrey and Nabalek, 1987).

The nature of the basement underlying the Bali Basin is still a matter of controversy The three alternative crustal types include a transitional crust (Curray et al., 1977; Hamilton, 1979) that has a thickness between oceanic and continental crust; Oceanic crust (Ben-Avreham and - Emery, 1973) mainly based on the position as a western extension of the Flores Basin; and Continental crust (McCaffrey and Nabalek, 1987) having the same thickness and origin as that beneath the Sunda Shelf.

Seismic reflection profiles West of the Bali Basin record a fold-thrust structural style that involves basement (Figure 9A). It is characterized by significant uplifted basement areas, some of which clearly show fold-thrust structures.

This is associated with a gravity closure of +20 mGal. The fold-thrust structure seems to be related to the North Jawa Tertiary sedimentary basin which is represented as a foreland fold thrust belt. The presumed Pre-Tertiary (Cretaceous) basement reflectors of the Sunda Shelf can be traced to the North basin margin beneath the Kangean-Sepanjang Ridge (Figure 9B).

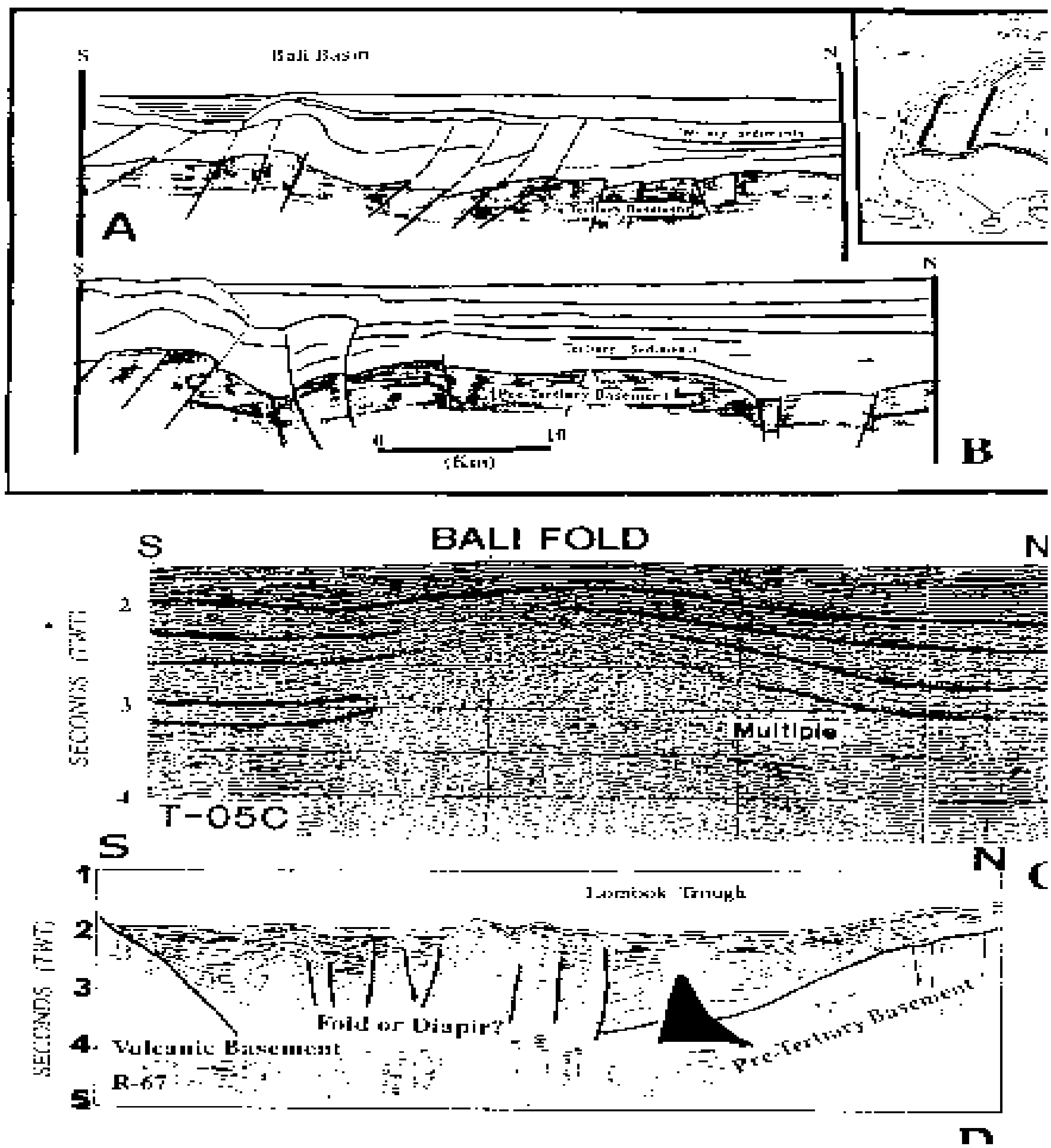

Figure 9.

The continuation of arching of the southeastern Sunda Shelf margin into the deepest part of the basin suggests that the bathymetric relief can best be explained by down bowing of the crust rather than down warping associated with thinning of the crust (as is the case for the Makassar Basin).

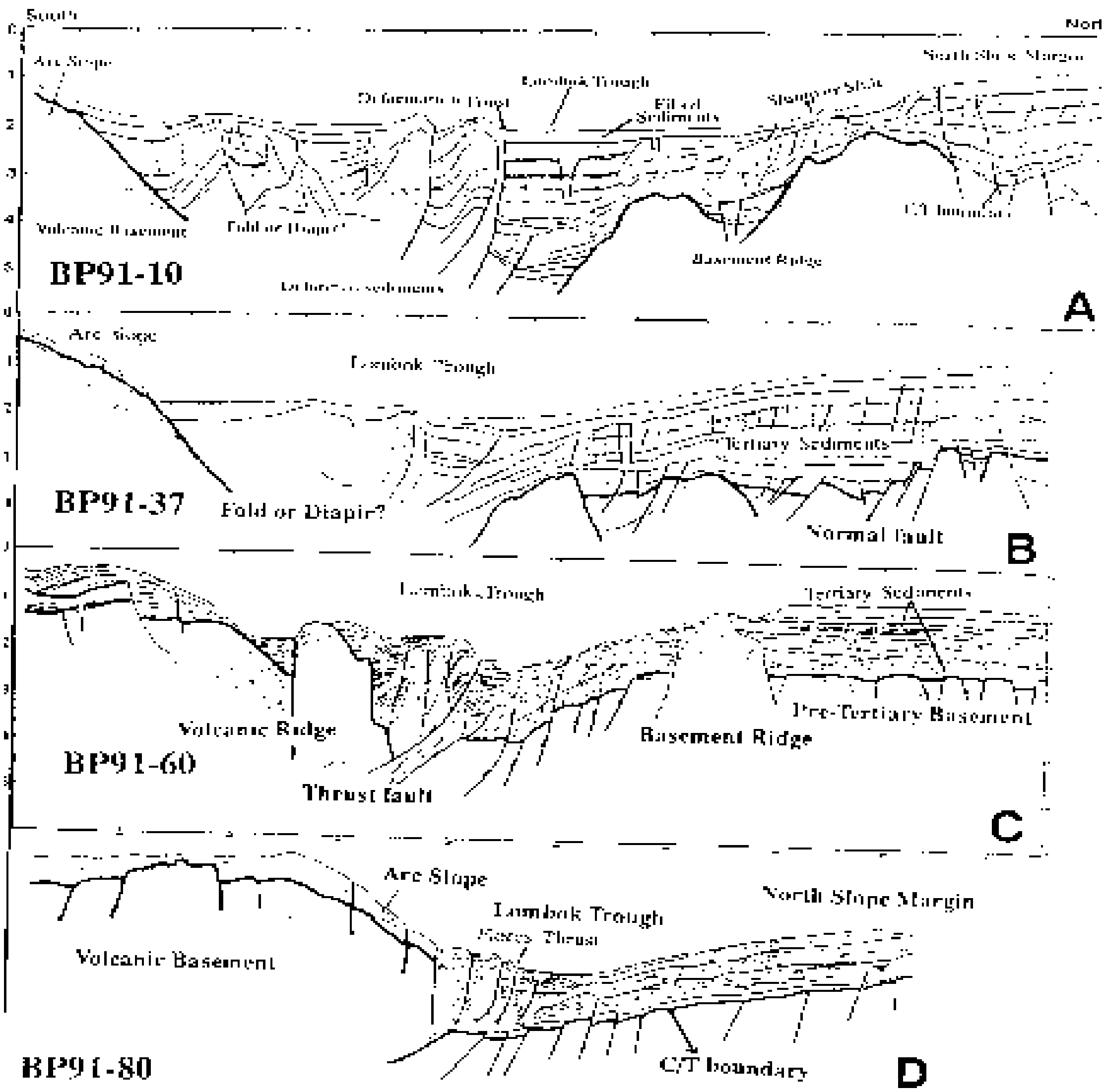

Figure 10.

Deformation concentrated along the southern margin of the Bali Basin was formed as compressional fold or diapir-like structures called the Bali Fold (Figures 9C and D). The fold is an embryo for diapirism.

Most of the folds in this region include the whole sedimentary section and are not truncated. These morpho-structural elements are more likely western propagations of the Flores Thrust Zone. The fold which is wider southward produces little morphological feature and represents little total convergence. To the West the Bali Fold loses surface expression.

The Lombok Strait lies Southeast of the Bali Basin and separates the East Bali and West Lombok islands. This strait is associated with NE-SW oriented depressions that may be related to the existence of cross-arc faulting.

Lombok Trough

The Lombok Trough (Figure 4) which extends from the North of Lombok to Central Sumbawa lies between the Bali Basin in the West and Flores Basin in the East. It is an East-West elongated, short (100 km long) and structurally narrow (50 km width) trough, with complex E-W ridge morphologies along the south margin.

The bathymetric trough lies at a water depth of 1.5 km, whereas the southern ridges are between 1000 to 1300 m deep. The cited characteristics of the Lombok Trough and Flores Basin have led some workers to conclude that the Lombok Trough is underlain by oceanic crust as a continuation of the Flores Basin.

Four new, regional, migrated, multichannel seismic profiles crossing from the northern slope break to the base of arc slope, clearly record the rift (extensional) and tilted block structures of the Lombok Sub-Basin which can be traced beneath the deformation front (thrust front) South of the structural trough (Figure 10). Several buried ridges or seamounts occur on the northern slope margin (Figures 11 A & B).

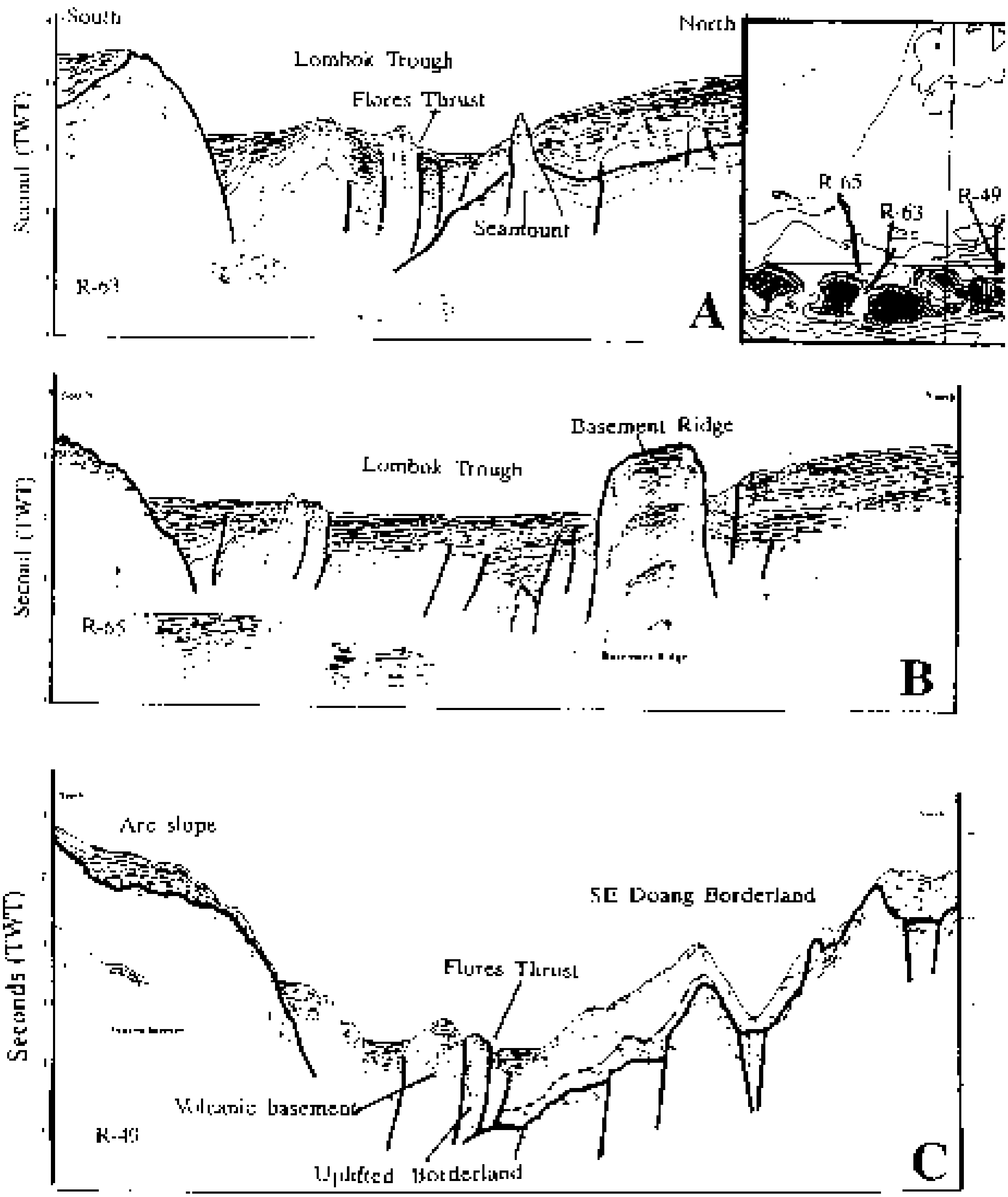

Figure 11.

The complex NE-SW (200 °E) oriented southern ridges are represented by a series of folds bounded by a south dipping thrust. Convergence as indicated by the series of folds increases in amplitude and breadth to the South. The north limbs of anticlines appear to be cut by south dipping thrust faults, but some of them do not extend to the surface.

The convergence between the north margin and the arc-slope to the South which occurs to the east of the Lombok Trough (Figure 11C), suggests that the trough is closing and a suture zone may be starting to form.

Flores Basin

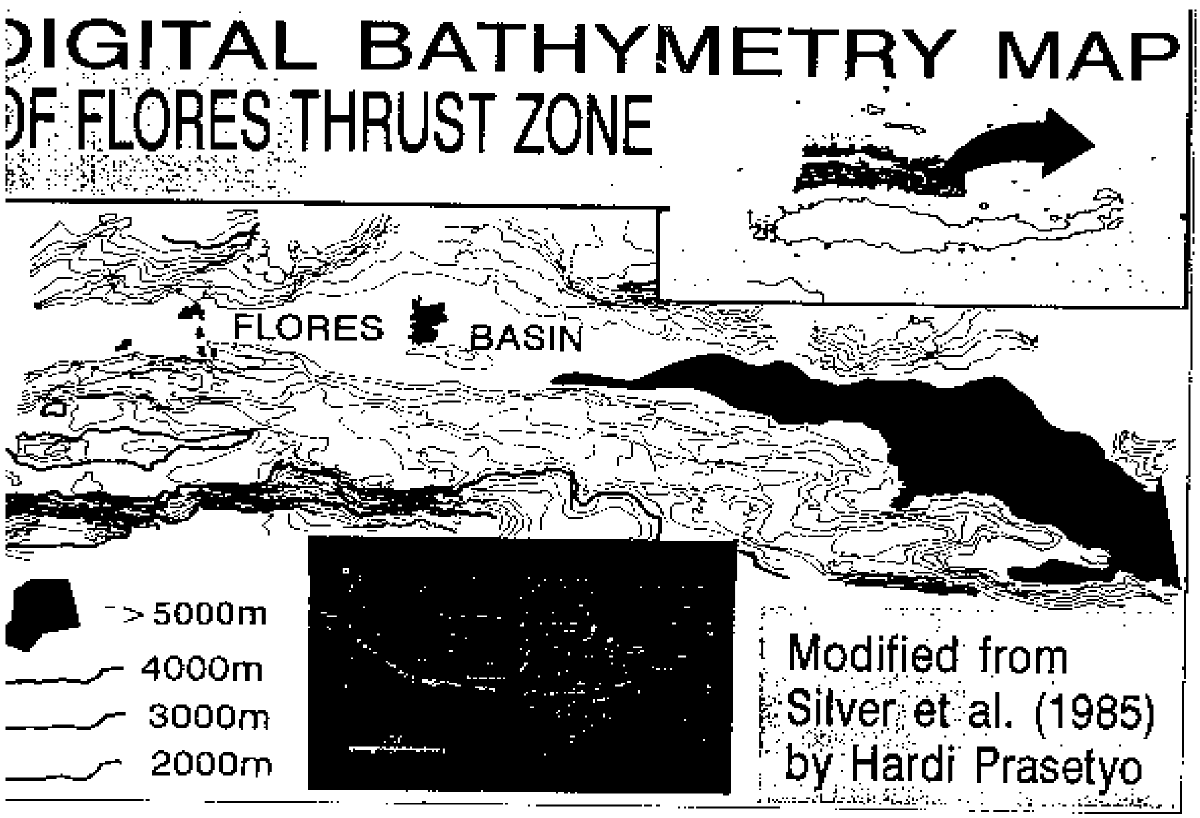

Figure 12.

The Flores Basin is an E-W turned to SE oriented deep depression having a seafloor depth in excess of 5 km (Figure 12). West of 120° 30' the Flores Basin is bounded by the NE trending slope of the southeastern flank of the Doang Borderland.

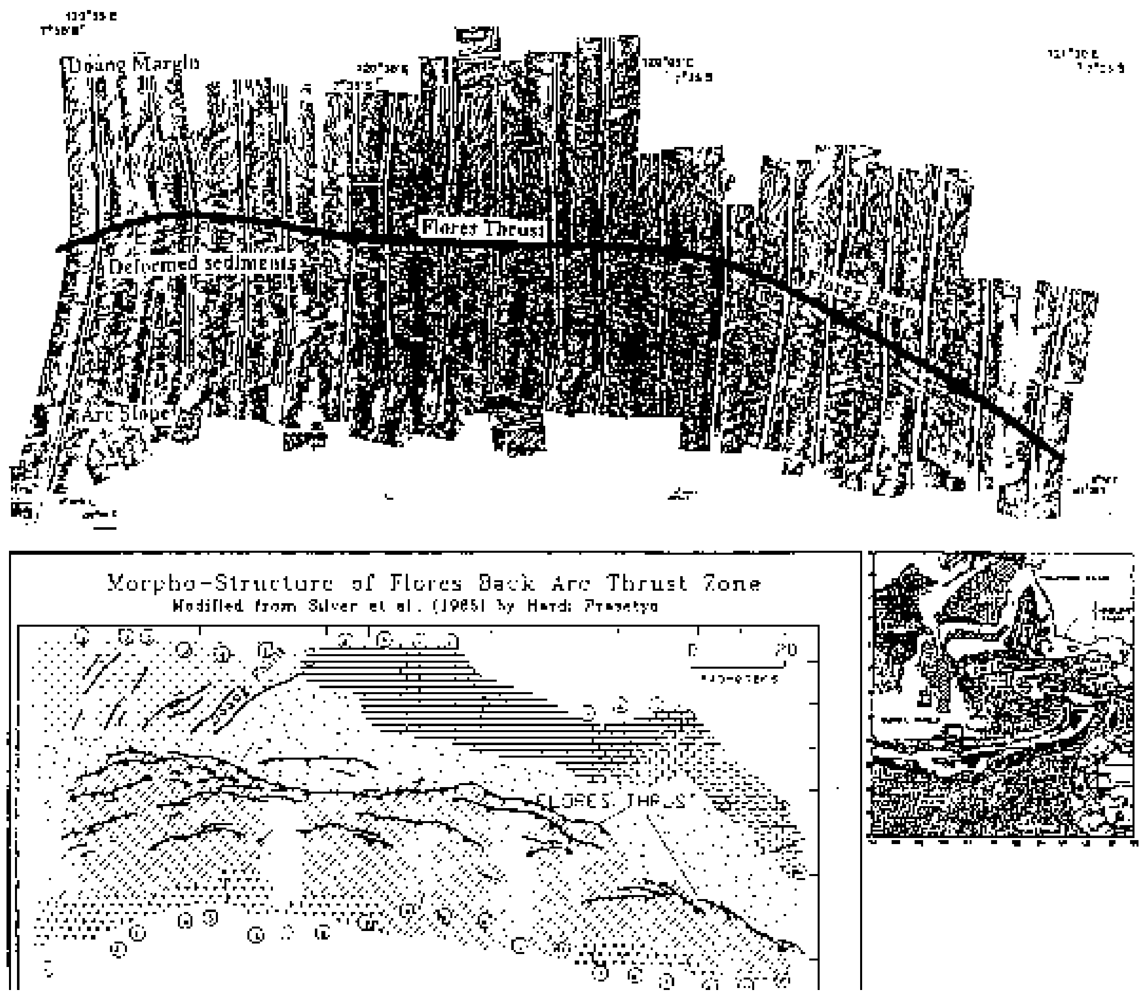

Figure 13.

Toward the east, the basin is bounded by the east Salayar Ridge extending onto South Sulawesi. In the western part of the ridge, the basin is composed of Neogene volcanic and sedimentary rock dipping to the West and Southwest. The NW-SE trend of coral atolls built on the Bonerote submarine ridge, marks a-topographic high on the eastern end of the Flores Basin and separates the Banda Marginal Basin to the East. The volcanic islands of Central Sumbawa to Flores form the southern margin. The Flores Basin merges with the Lombok Trough to the West, approximately North of Medano Island (Central Sumbawa). The Flores Basin has relatively dense coverage of single channel reflections as well as SeaMARC II side-scan mosaic (Figure 13). Those data were concentrated to delineate structural styles and particularly the origin of the Flores back arc thrust zone.

A seismic refraction station north of Flores (Curray et al., 1977) has shown that the oceanic layer was not detected. The mantle lies at only 14.3 km, a depth slightly greater than the oceanic average but significantly less than

under continental areas. It has been concluded that the crust of the Flores Basin is originally oceanic, as the crust in the enclosed Sulu and Sulawesi basins. At a station north of Sumbawa, however, oceanic crust was detected, and the mantle is suggested to be at considerable depth (more of 22 km), very similar to what was found in the arc-trench gap of south Java and Bali.

All later workers who have worked in Eastern Indonesia have concluded that the Flores Basin is underlain by unknown origin oceanic crust. They have based these conclusions on evidence from seismic profiles, bathymetry (water depth more than 5000 m), crustal models and the presence of a prominent back arc thrusting zone.

The Flores Thrust Zone (FTZ) is a prominent E-W oriented structural feature (Figures 12 & 13) extending from East of the Flores Basin to the Lombok Basin (Figures l & 2). The FTZ separates south dipping sedimentary sequences, including Paleocene Rift (extensional) and related sediments, from the complex deformed material to the south. A small trench in front of the accretionary wedge is filled with younger turbidites. This sediment has presumably been transported mostly from the South Sulawesi margin and Doang Borderland through prominent submarine canyons and then deposited local submarine fan systems (most prominent is North of 120° 30'E). Prominent accretionary wedges of 25 to 30 km width are well developed behind the arc-slope. Some of these accretionary wedges are associated with well defined imbricated thrust packets or sheets. These structural styles in some part seem to be analogous to those of the developed accretionary complex which results from convergence between the oceanic crust and the continental margin of the Sunda fore-arc (e.g. Prasetyo and Dwiyanto., 1986).

SUMMARY AND DISCUSSIONS

The main points raised by the analysis of the structural and tectonic framework of the back-arc basin can be discussed and summarized as follows:

Regional Model for Eastern Sunda Back-Arc Basin formation

The Bali-Flores Basin is an E-W trending depression which occupies the back-arc region of the eastern Sunda Arc.

The region represents a tectonic transition in which the convergent margin changes from subduction of old (>150 Ma) Indian ocean oceanic crust beneath the continental margin of the Eurasian plate to the West, to subduction of Australian continental margin beneath the Banda island arc which was previously built on oceanic crust.

The basins are bounded on the North by continental masses having water depth of 1000 m in the west and more than 5000 m in the east. It displays gravity anomalies and fold-thrust zone with a well-developed accretionary wedge.

The basin is now in a closing stage due to collision processes which may eventually lead to its disappearance. The evolution of the basin may lead therefore to a better understanding of geodynamic processes responsible for the formation and destruction of marginal basins in general, and of the evolution of each of these basins in particular.

Variation Along the Bali-Flores Back-Arc Region

Major variations occur along the length of this 800 km elongate-shaped, east-west-trending Bali-Flores Basin, including:

- the nature and development of the northern basin margin; the nature of basement beneath the basin;
- the amount of sediment and structural framework of the lower plate; and
- structural styles of the fold-thrust zone which also represents a degree of deformation within the fold-thrust zone.

The Nature and Development of the Northern Basin Margin

The northern margin of the back-arc basin is composed of different morpho-tectonic units.

In the north, the Bali Basin is bounded by the Madura-Kangean (inverted) Ridge which occurs at the SE margin of the Sunda Shelf.

The Lombok Trough is bounded by the Lombok Sub-Basin which represents the leading edge of the SE Sunda Shield margin.

Within this basin, the rifted back-arc passive margin processes (e.g. reviewed by Daly et al., 1991) including rift structural styles, rift-sag sedimentary sequences and inverted (post-rift) structural styles that have been accepted as a result of wrenched compressional tectonics are recorded.

In the northwest the Flores Basin is bounded by the Doang Borderland which is considered a continental mass that has experienced a long period of subsidence in association with the southern progradation of the Miocene carbonate shelf margin.

The Salayar ridge to the East was influenced by volcanic activity resulting from west dipping subduction.

The variations in origin and geologic development of the northern margin are very important in the development of the back-arc region (especially as it concerns structural styles).

Nature of Basement (crust)

There are variations in the origin of the basement (crust) underlying the Bali-Flores Basin.

The Bali Basin is underlain by crystalline basement which is analogous to the Sunda Shelf. The crustal profile from the Sunda Shelf to the Bali Basin shows the flexing of the lithospheric plate. Here, the gravity and bathymetric depocenters are due to down bowing of the crust of the Sunda Shelf.

The positive gravity values observed west of the Bali Basin are a result of the shallowing continental basement which is associated with the fold thrust at the deeper stratigraphic levels. Previous workers (e.g. Curray et al., 1977; Hamilton, 1979) have determined that the Lombok Trough is underlain by oceanic crust as the western continuation of basement of the Flores Basin.

However, interpretation of a new seismic reflection across the Lombok Trough clearly defined tilted blocks of the basement of the SE Sunda Shield margin. The basement can be traced beneath the deformed sediments.

Numerous buried basement blocks and seamounts on the northern slope margin may be associated with the intense rifting process. This evidence may suggest that rifted continental or transitional crust underlies the Lombok Trough.

Most workers have accepted that the Flores Basin is underlain by oceanic crust, however, the origin is still uncertain. Three possible mechanisms are:

(1) Trapped old (Middle Cretaceous) oceanic crust from the Indian Ocean as the Banda Basin was separated from the Flores Basin by the NW trending Bonerote submarine ridge;

(2) Back-arc spreading associated with the subduction of old (150 Ma) Indian Ocean Oceanic crust along the Eastern Sunda Trench;

(3) The creation of oceanic crust associated with rifting of the SE Doang Borderland which was previously located in a triple junction south of present day Sulawesi.

    Significantly, northeast-trending normal faults occur on the SE edge of the Doang Borderland, and the presence of Miocene subsidence which is observed on the SE Doang Borderland is supportive of this alternative mechanism.

Anatomy and Structural styles of the Bali-Flores Back-Arc Fold-trust Belt

Irregularities or variations in geometry and structural styles are observed along the Bali-Flores fold and thrust zone. The most important variable which caused those variations includes the nature of the lower plate (basement, morphology, sedimentary sequences), and the thickness of the turbidites filled trough.

For example, stratigraphic along the Bali-Flores Basin changing from west to east, will impact the change in the level of thrust decollement and then change the thickness of sediment accreted to the accretionary wedge.

Homogeneous layers of constant thickness would be expected to produce very regular fold/thrust packages. Silver et al., (1983, 1986), however, have demonstrated that the variations in structural styles also involve several parameters on the fore arc.

The deformation of the Bali-Flores back-arc basin is accommodated mostly along the southern margin of the basin north of the arc slope.

The degree of deformation increases eastward. West of Bali, the deeper stratigraphic levels are characterized by the presence of fold thrusts with basement involved.

However, from the central to east Bali Basin the deformation is characterized by a series of fold (Bali Fold) and diapir-like structures which involve all sedimentary sequences.

The lower plate is composed of SE Sunda Shelf crystalline basement and overlain by Tertiary sediments that down bowed or flexed to the South.

To the east, the deformation zone north of Lombok is characterized by a series of folds bounded by high angle south dipping thrust faults.

The folded sediments of the upper plate can be observed from the presence of prominent reflectors of the lower plate. The fold is wider to the south, and some clearly show as diapirs.

Turbidite sediments of the trough are thicker to the East. The lower plate consists of tilted basement blocks and rift related sedimentary sequences of SE Sunda Shield margin. Numerous basement ridges, buried ridges, and seamounts occur on the slope margin.

The Flores Thrust Zone is a dominant feature of the deformed sediments which involves the Flores Basin oceanic crust. Structural styles occurring in this thrust zone are analogous to accretionary wedge structures formed in the Sunda Fore-Arc, and are characterized by imbricated thrust sheets of deformed of north slope margin and turbidite filled trench sediments.

The lower plate of this thrust system is composed of slope margin sedimentary sequences of the SE margin of Doang Borderland in the west, and Miocene volcanic and sedimentary sequences of the Salayar Ridge in the east.

Driving Force Mechanism of the Bali-Flores Back-Arc Fold and Thrust Zone

The Bali-Flores back-arc fold-trust zone oriented 110-120 °E suggests a N:S to NE-SW direction of compression. This direction is relatively parallel to the convergence of the Indian Ocean and Eurasian Plates, and suggests that the plate motions are driving the back arc compressional related structures (Breen et al., 1986; McCaffrey and Nabalek, 1987).

Changes in structural styles from well-defined imbricated thrusts in the East (Flores Thrust), fold bounded thrusts in the central (Lombok Fold-Thrust), to a series of fold and diapir-like structures in the West (Bali Basin) suggests either the westward decreasing of compressional intensity or amount of shortening. The thrust deformation was propagated westward as well as an outgrowth associated with the closing of the back-arc basin.

In this framework, the Flores Thrust Zone is caused by the collision of the Australian continental margin and Banda arc. Moreover, this system is aided by interaction between the subducting Australian margin and a thick uplifted forearc basement (Sumba Island) within the forearc basin.

South of Bali and West Sumbawa is the prominent Lombok Fore-Arc Basin, however, the compressional folding is aided by collision with the Roo Rise, a morphologic feature that approaches the Jawa Trench between 110-115°E.

The Tectonic Evolution of the Bali-Flores Back-Arc Basin and Adjacent Areas

The Bali-Flores Basins were formed as part of larger processes in which larger lithospheric plates adjacent the basins move toward each other: the Indian-Australian, Pacific, and Philippine toward Eurasian.

The evolution of the basin overall, records transition from extensional to compressional tectonic environments which can be summarized in to four stages:

Stage 1, Rifted Back-Arc Passive Margin

The Southeast Sunda Shield margin is probably dissected by extensional (rifted) faults in the Paleocene. It is suggested here that the Paleocene extensional faulting occurred in linear belts across the platform. Paleocene rifting was affecting the southeast Sunda Shield margin (Lombok Sub-Basin).

This extensional tectonic environment also occurs in the Makassar Strait in the Eocene, which is associated with separation of Kalimantan and Sulawesi, but it has different orientation (N-S).

Within this tectonic regime the Doang Borderland is probably rifted (small scale) from the Sunda Shelf margin along the present Doang Trough, the strongest extension, particularly in the southeastern margin, may be associated with the creation of oceanic crust as well as numerous seamounts and volcanic ridge South of the Doang Borderland.

Another alternative is that the oceanic crust of the Flores Basin is trapped Indian Ocean crust similar to the Banda Sea. Since Miocene, the Southeast Doang margin has experienced subsidence associated with southward progradation of carbonate shelf margin beneath the Lombok Sub Basin.

This thermal subsidence may also be activated by the southward slab pull of the Flores oceanic crust.

Stage 2, Compressional (Inverted) Tectonic Environment

During this stage, several lines of evidence suggest the Neogene inversion (Miocene) of the Paleocene extensional faults occurred along the Sepanjang fault-fold zone.

Most topographic highs adjacent to the Kangean as well as the southwestern Doang Borderland were inverted in Miocene time.

Inversion also occurred in Southwest Sulawesi, and may be driven by collision of the Buton micro continent with the Sulawesi Arc.

Stage 3, Compressional (Collision) Tectonic Event

Collision of the Australian continental margin with the Banda Arc was initiated in Upper Miocene or Pliocene time.

This collision process is still continuing at present, and was influenced or driven to create the back arc thrusting north of

Flores, in which the oceanic crust of the Flores Basin has been subducted southward and was associated with the development of an accretionary wedge.

The Flores Thrust was propagated westward. On the West, the SE Sunda Shelf and margin down bowed or flexed southward and formed asymmetrical depression regions represented by the Bali Basin and Lombok Trough.

Continuing compression was also driven by the collision of the Roo Rise in the Sunda Trench south of Bali and has stimulated the formation of the "Bali Fold" west of Bali Basin and the "Lombok fold-thrust belt" north of Lombok.

Stage 4, Foreland Fold-Thrust Belt Formation

The Bali and Lombok Trough formed East of the Jawa Basin which is underlain by crystalline and transitional crusts, is now in the process of being closed by thrusting.

In the next stage, the shortening process will have implications for the development of a suture composed of continental fold-and-thrust belts and for the growth of continental arcs.

Implications: For The Future Hydrocarbon Prospects

One of the significant aspects of the back-arc region is that generally it has a high heat flow values which is an important parameter for maturation and migration of hydrocarbon. However, except for the Banda Sea heat flow studies are very limited.

The Bali-Flores Basin, like most other frontier basins, is known for the most part only through reconnaissance seismic investigations.

Compilation of a comprehensive basin framework within which to undertake further exploration is hampered by variable scale and quality of individual seismic surveys. This compilation in general provides excellent clues to view or understand the regional geologic and tectonic framework.

This information is important as basic knowledge for further review of future hydrocarbon prospects of this frontier region. Although the region is mostly covered by deep water, recent developments in advanced offshore drilling technology (Presently depth record is about 3000 m water deep, in the Gulf of Mexico) will make it possible to explore and drill deep water prospective areas in the near future.

Exploration wells drilled by several oil companies in both the SE Sunda Shelf and Doang Borderland show the occurrence of reservoir, seal, and trap potential, but unpredictability of an effective hydrocarbon charge system remains the primary risk critical to exploration success.

If the study area source rocks can be identified, and if traps were available to receive and retain charge from these source rocks, perhaps this area will yet become a further petroleum province.

Like most other rift related regions within the study area (e.g. South of Sepanjang, Lombok Sub-Basin, and Doang Borderland), all three possible potential sedimentary cycles (pre-rift, rift-fill, post-rift or sag) are present, and fall within the higher rank prospective play-types.

The detail lithologic nature of folded pre-rift (Cretaceous) rock which is overlain by an angular unconformity in the study area remains incomplete. The rift-fill sequence is faulted into a number of syndepositional grabens.

Several other prospective play types can be suggested as follows:

(1) carbonate buildup North of the Sepanjang Fault Zone;

(2) prograded shelf margin sequences (Miocene) of the south Doang Platform and SE Sepanjang Slope;

(3) structural traps formed during the formation of the Sepanjang wrench Fault system during Miocene, with folds (the Sunda Fold) and thrust faults;

(4) structural or stratigraphic traps associated with basement ridges and Paleogene seamounts along the northern margin of the Lombok-Trough and NW Sulawesi Basin; and

(5) the foreland thrust-fold structural styles in the West Bali Basin as well as the Bali Fold which is relatively less deformed.

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