STRUCTURE AND TECTONIC SIGNIFICANCE OF THE AILEU FORMATION EAST TIMOR, INDONESIA

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ABSTRACT

Structural analysis of the Aileu Formation of north Central Timor indicates a characteristic formation boundary and a polyphase history of ductile and brittle deformations. The Aileu Formation is composed of metamorphosed pelites, psammites, limestones and igneous bodies. Metamorphic grade generally increases from subgreenschist facies, in the south, to amphibolite facies along the north coast.

Ductile and brittle structures show the Aileu Formation has experienced at least three deformation phases. The first deformation phase (D1) is the most extensive and consists of a coaxial layer parallel foliation but no recognisable F1-folds. D1 is interpreted as extensional in origin and may be associated with Mesozoic rifting on the northwest margin of Australia. The occurrence of mafic and ultramafic intrusive bodies along the north coast may be associated in time and space with this rifting. D2 deformation is non-coaxial producing micro- to mesoscopic tight fold types (F2) and penetrative S2 cleavages. D2 deformation relates to structures produced by arc-continent collision, which juxtaposed the Aileu Formation with the other units. The progressively weaker post-D2 deformation phases form locally-developed folds and faults. Normal faults are commonly the youngest deformational features.

In relation to other units of the Banda orogen, the Aileu Formation displays both tectonic and stratigraphic contacts. Its most southern part is transitional with unmetamorphosed Permian-Mesozoic Maubisse Formation. East and west of this stratigraphic transition the Aileu Formation is in contact with undifferentiated Permian-Mesozoic sedimentary rocks along a N-dipping reverse fault. The transitional boundary with the Maubisse Formation indicates a depositional age the Aileu Formation of Permian-Mesozoic suggesting it was part of Gondwana.

Structural and lithological relations indicate that the depositional basin of the Aileu Formation was deformed and partially metamorphosed by Mesozoic rifting and Neogene arc-continent. The collision was associated with mostly top to the north shortening in the northern Aileu and top to the south shortening in the southern Aileu. This compressional stack is cut down to the north by normal faults along the north coast of Timor.

INTRODUCTION

1.1 Problem and Purpose

The occurrence of allochthonous rocks is associated with orogenic belts that lie along convergent boundaries. This association reflects the significant role of the allochthonous rock in the development of an orogenic belt. Allochthonous refers to rocks that are displaced and bounded by faults and commonly applied to sheets or nappes that have travelled great distances.

Some distinctive allochthonous rocks occur on Timor island, eastern Indonesia, in the convergence zone bet ween the NW Australian continental mar-gin and the Banda island arc. Audley-Charles (1968) recognized four separate formations that are

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completely allochthonous in East Timor : the Lolotoi Complex, Aileu Formation, Maubisse Formation, and Bobonaro scaly clay. Later Audley-Charles and Harris (1990) recognized another allochthonous nappe, the Occussi nappe, in West Timor (Figure 1).

Among those allochthons, the Aileu Formation is poorly understood in term of its structure and contact relationship with the other units. Al though there have been many geological investigations in Timor (Audley-Charles 1968; Barber et al 1976, 1977, and 1986; Berry et al 1981; Brunnschweiler 1978; Chamalaun et al 1978; Charlton et al 1991; Grady et al 1975, 1977; Harris et al 1989, 1990, 1991, 1993; Rosidi et al 1979; Sopaheluwakan 1990; and Tobing 1989) only a few have included studies of the metamorphic complexes, including the Aileu Formation.

No detailed studies have previously reported examining the Aileu Formation as an intrinsic part of Timor orogenic wedge. Only Berry and Grady (1981) provided detailed structural analyses of the NE part of the Aileu Formation. Berry and Grady (1977, 1981) inferred that the Aileu Formation was juxtaposed with the other units by dip slip, high-angle faulting. On the other hand, Audley-Charles (1968) mapped this contact as a low-angle thrust. More recent studies (Barber et al 1976; Carter et al 1977; Harris and Tobing 1990) interpreted the contact relationship between Aileu and Permian Maubisse Formations as a stratigraphic transition.

In addition to this controversy about the nature of the contacts, the internal structure of the Aileu Formation remains poorly described. Audley-Charles (1968) suggested the thrust pla-nes that carry the Aileu Formation dip north. Harris and Tobing (1990) noted the occurrence of two fault sets in the Aileu Formation. Near the north coast, fault planes dip primarily to the south with northward movement of the hanging wall. Northward vergence is also indicated by asymmetric folds with south dipping axial surface. Berry and Grady (1981) observed no evidence of internal thrusting, imbrication or extension in the Aileu Formation.

Of the many structural uncertainties of the Aileu Formation, this paper focus on the following :

(1) the contact relationship between the Aileu Formation and the other geologic units (what is the type of the contact? Structural or Stratigraphical contact?).
(2) brittle and ductile structural evolution of the Aileu Formation (What is the kinematic pattern and its tectonic significance?).

It is suggested that these questions have important implications for interpretation of the tectonic evolution of metamorphic rocks in the Banda and other orogens.

1.2 Methods

The approach of this study involves map-ping the boundary between Aileu Formation and the other units and a descriptive structural analyses within the Aileu Formation along several cross-strike traverses. Accessibility to many parts of the Aileu Formation was limited.

Laboratory analyses include petrographic and microstructural studies, and computer analysis of map and structural data. Geometric analyses was carried out using the Stereo™ Version 5.00 Stereographic plots which examined all structural data from various defor-mational domains of the study area.

Field investigations were conducted in three periods. The first period was from August to September 1990 in the area east of Laclo village and around the town of Aileu. The second field work was conducted in June 1993 in the area south and north of the Laclo river. And the third field party was performed in June 1994 in the area around Ermera, Maubara, and west of Dili. The 1990 field study was part of a regional investigation of mineral deposits in East Timor conducted by the UPNV (Universitas Pembangunan Nasio-nal Veteran) Yogyakarta and the provin- cial government of East Timor. The 1993 and 1994 field works were carried out as part of the Banda Orogen Research Group Project led by R.A. Harris (West Virginia University).

1.3 Location of Study Area

The study area is located in the NW part of East Timor (Figure 2). It extends from 11 km west of the town of Manatuto in the east to about 30 km west of Maubara village in the west. From the north coast the study area extends to the Laclo river in the SE, town of Aileu in the south, and Letefoho village in the SW (Figure 3).

The study area is accessible by air through the city of Dili. By land a recently asphalted road connects Dili with Kupang (250 km to the SW), the capital city of West Timor. The connecting roads in the study area are mostly asphalted or stone-hardened. Many foot-paths and braided streams provide off-road access.

2 REGIONAL TECTONIC SETTING

2.1 Banda Orogen

Compared to the Sunda orogen, which is the product of interaction between the SE Asian continental and Indian oceanic pla-tes, the Banda orogen has a more com-plex geologic feature. The complexity of the Banda orogen results from interaction between three plates: the relatively stable SE Asian continental plate, the NNE moving Australian continental plate and the Pacific plate that is moving WNW. Shear at the intersection of these three plates is distributed through a complex zone of convergence and sinistral shear between the Terera-Aiduna and Sorong fault sys-tems (Fig. 4). Combination of the west-ward and northward plate motions in this region has detached, rotated, and moved westward several continental fragments from the Australian plate (Hamilton 1979). There are three major tectonic elements that form the Banda orogen (Fig.4) :(1) The Banda sea, (2) the northern Australia -New Guinea continental margin, and (3) the Banda island arc.

The Banda sea is a complex marginal basin that occupies the interior (concavity) of the Banda arc (Harris 1991). Three models are proposed regarding the origin of the Banda sea re-gion: (1) trapping of pre-Tertiary Indian-Australian oceanic crust behind the Neo-gene Banda arc (Bowin et al 1980, Silver et al 1985), (2) back-arc spreading in the Paleogene behind the Palelo arc (Carter et al 1976), and (3) Neogene spreading associated with the Banda arc (Hamilton, 1979). Harris (1989) studied fragments of the Banda sea which have been incorporated in the Banda orogenic arc and exposed on Timor, and suggested that the fragments are part of an active intra-oceanic arc system.

The NW Australian passive conti-nental margin formed during Middle-Late Jurassic breakup of eastern Gondwana and Early Cretaceous sea floor spreading in the adjacent Wharton Basin (Falvey 1972, Larson 1975). Continental material that has been incorporated into the Ban-da orogen can be correlated directly with undeformed laterally equivalent sequen-ces of the present NW Australian margin (Audley-Charles 1986). This correlation helps in structural restorations of continental margin stratigraphy in the fold-thrust zone of the Banda orogen (Harris 1991).

The Banda island arc constitutes an orogenic zone between Banda sea and Australian continental margin. The arc consists of the inner, volcanic arc and an outer, contractional wedge. The volcanic arc is presently inactive north of Timor and south of Seram, but active in the group of small volcanic islands to the east of Wetar island. The Banda volcanic arc is connected to the west with the Java-Sumatra volcanic arc (Norvick 1979). The outer arc, with Sumba, Timor, and Seram as the main islands, is composed mostly of underthrusted Australian continental margin material that have been stacked up during Neogene collision of the continent-bearing Australian plate with the Banda sea.

2.2 Geology of Timor

2.2.1 Stratigraphy

The geology of Timor owes its complexity to the fact that the northern margin of the Australian continental shelf has collided with the subduction system of the Banda arc (Hamilton 1979, Von der Borch 1979, Bowin et al 1980)(Fig.4). Most geologists who have worked for any length of time on Timor agree, although the structure is complex, it is possible to recognize distinct tectonic and stratigraphic units over wide areas. This has been shown by the work of Audley-Charles (1968) and Rosidi et al (1979) for East and West Timor, respectively. They divide the stra-tigraphy of Timor into autochthonous, para-autochthonous, and allochthonous units (Fig. 5). The autochthonous units include all those deposits that accu-mulated in their current position after the Neogene collision; para-autochthonous units range in age from early Permian to early Pliocene and include all the rocks found below the flat-lying thrust sheets of the allochthon. They are strongly folded and faulted, and have clear Australian affinities. The allochthonous units are those rocks that form flat-lying thrust sheets/nappes and their associated roots (Audley-Charles 1968). Like the paraautochthon, the allochthon also range in age from early Permian to early Pliocene.

The collision between the Austra-lian continental margin and the Banda arc has resulted in juxtaposition of several different lithotectonic units that comprise the bulk of the Timor thrust wedge (Harris 1991, Sawyer et al 1993), as shown in Figure 6. These lithotectonic units are:

(1) Te Banda terrane,
(2) Gondwana sequence, which is composed of Kekneno sequence and Tethys margin nappe (Sawyer et al 1993),
(3) Kolbano sequence, and
(4) The Banda orogen sequence which consists of a synorogenic deposit (Viqueque sequence), and a melange unit or the Bobonaro complex (Harris et al 1994) (Fig. 6).

2.2.2 Structural Models of Timor

Previous studies have given rise to a number of conflicting theories and deba-tes on the geological origin of Timor. Models proposed for the structural evolution of Timor are of three main types :

(1) the imbricate,
(2) overthrust, and
(3) upthrust models.

The imbricate or tectonic mela-nge (Fitch and Hamilton 1974, Hamilton 1979) interprets Timor as a frontal accre-tion zone of imbricated material at the hanging wall of a subduction zone whose surface trace is the Timor trough.

Overthrust model (Carter et al 1976, Barber et al 1977, Audley-Charles 1968, 1981, Harris 1989, Audley-Charles and Harris 1990) regards Timor as a series of thrust sheets (allochthon empla- cement) including both oceanic and continental material which have been thrust onto the Australian continental margin. A clear distinction is made between litho-tectonic units derived from the Australia continent and those of non-Australian origin, including ocean floor sediments and metamorphic and sedimentary rocks which were incorporated into the Banda forearc prior to its collision with Australia.

The Upthrust model (Grady et al 1977, Chamalaun and Grady 1978) suggests that the Australia continental margin entered the Banda arc subduction zone at a trench located in the north of Timor in the vicinity of the Wetar strait. Subsequently the continental lithosphere separated from the oceanic lithosphere which had been subducted ahead of it, resulting in the uplift of Timor by isostatic rebound controlled by steep faults. In this model the existence of flat lying thrust sheets is challenged.

Harris (1991) reconciled the three rival models by appealing to the time-transgressive nature of the collision along orogenic strike. Using geophysical and geological data, as well as more recent field observations, he recons-tructed seismically controlled cross-sections from various parts of the Banda orogen (Sumba, Savu, West and

East Timor). These sections show three diffe-rent phases of deformation similar to the three previous models (Fig. 7): (1) a pre-collisional phase of frontal forearc accre-tion and active island arc volcanism(Fig.7 a), (2) the initiation of arc-continent collision by nappe emplacement above a thickening accretionary wedge (Fig. 7b), and (3) a culmination phase where internal deformation and uplift of the orogenic wedge occurs in response to its collision with the Australia continental slope (Fig.7c, d).

3 AILEU FORMATION

3.1 Stratigraphy

The Aileu Formation was named by Audley-Charles (1968). Previous works called it the North Coast Schist (van Bem-melen 1949, in Audley-Charles 1968). Gageonnet and Lemoine (1958, in Audley-Charles 1968) were the first who dis-tinguished the rocks and referred them as the lower part of their Maubisse series. The type-locality for the Aileu Formation is the hilly country around the town of Aileu, approximately 40 km south of Dili.

The Aileu Formation is one of two major metamorphic units exposed in Timor. The other is the Lolotoi/Mutis Complex. Barber and Audley-Charles (1976) described them on the basis of their metamorphic grades as Lustrous Slate Group for the Aileu Formation, and Greenschist-Amphibolite-Granulite Group for the Lolotoi/Mutis Complex. In addition to metamorphic grade, the time of peak metamorphism and the associated rock sequences of the Aileu Formation and the Lolotoi/Mutis Complex are different. Metamorphic cooling ages of the Aileu Formation cluster around 10.8 Ma (Berry and Grady 1981), which is younger than that of the Lolotoi/Mutis Complex which yields K-Ar ages of 34.2 Ma (Earle 1981). While the Aileu Formation is closely related to the Permian Maubisse Formation and other units of the Gondwana sequence, the Lolotoi/Mutis Complex has a cover sequence with no Australian plate correlatives (Harris 1989).

The depositional age of the Aileu Formation remains uncertain. It is interpreted to range from Permian to Juras-sic based on the Permian ammonites and upper Jurassic belemnite fossils reported found in phyllitic rocks of the Aileu Formation (Brunnschweiler 1978). This study supports a Permian age for the Aileu Formation as indicated by deformed crinoid fossils found in sheared marbles near Riafusso village, 5 km south of Aileu, where the contact between Aileu and Maubisse Formations is gradational.

The crinoid fossils are similar to those found in the Maubisse Formation that are Permian in age (Audley-Charles 1968).

3.2 Lithology

In general the Aileu Formation is compo-sed of two major rock types, metasedi-mentary and metaigneous rocks. Meta sedimentary rocks consisting of slates, phyllites, schists and marble make up the bulk of the Aileu Formation. Minor amounts of metabasalt, metagabbro, serpentinized ultramafic rocks, and amphibolite occur within the Aileu Formation.

The NE part of the Aileu Forma-tion was mapped in detail by Berry and Grady (1981). The lithological divisions they employed are of compositional but not necessarily stratigraphic significance. The present study applies this approach throughout the exposure of the Aileu For-mation in the study area and divides it into 8 mappable lithological units with boundaries between units often being gradational (Fig. 8). They are:

1) slates and pelitic phyllites unit,
2) pelitic phyllites and schists with minor quarzt schists unit,
3) quartzites, psammitic quartz phyllites and schists unit,
4) lenticular amphibolite unit,
5) amphibolite, pelitic, and calc schist unit,
6) marble unit,
7) serpentinized ultramafic unit, and
8) metaigneous unit.

3.3 Formation Boundary

The boundary of the Aileu Formation with other units has been investigated by the present study in four traverses, from east to west, they are: Laclo, Aileu-Maubisse, Letefoho, and Hatolia traverses (see Fig. 3 for their locations).

In Laclo traverse, the boundary between Aileu Formation and the Undifferentiated Permian-Mesozoic unit (Kekneno series) is characterized by a distinctive topographic break. Field observations indicate that this contact is a north-dipping reverse fault, which was called the Laclo fault by Berry and Grady (1981). Its W and SW continuation is inferred based on photogeology and Landsat image interpretations.

Field observations made in the Aileu-Maubisse traverse indicate a gra-dational stratigraphic contact relationship between the Aileu and Maubisse Formations. No clear stratigraphic or structural boundaries are found along this traverse. The occurrence of mylonitic marbles and strained crinoidal limestone are interpreted as the product of thrusting within this transition unit. Therefore, the boundary in this traverse is interpreted as a sheared or faulted depositional contact.

Like in the Aileu-Maubisse traverse, a distinct stratigraphic or structural boundary could not be located definitely in the Letefoho traverse, which is located 20 km west of the Aileu-Maubisse traverse. Here the contact between Aileu and Maubisse Formations is also interpreted as a faulted stratigraphical contact.

The formation contact feature in Hatolia traverse, which is located at the SW corner of the study area, is similar to those exposed in the Laclo traverse. This traverse crosses the contact between more resistant outcrops of the Aileu Formation to the north and softer sedimentary rock of the Kekneno series to the south. The presence of a number of north-dipping minor reverse fault in the zone of contact suggests it is more likely a north-dipping reverse fault contact.

4 STRUCTURE

The Aileu Formation has undergone multiple phases of deformation. Berry and Grady (1981) recognized five structural phases in the NE part of the Aileu Formation. Throughout the study area these five phases were not completely observed in this study.

The present structural study found two early ductile deformational phases and two later brittle deformational phases throughout most parts of the Aileu Formation. Ductile structure includes foli-ations or cleavages, and folds; while fractures, veins.and faults are included as brittle structures. Their characteristics are outline using notations: Dn (n=1, 2, 3 ..... in sequential order) for deformation phase, Fn for fold structures, and Sn for metamorphic foliation.

4.1 Ductile Structures

4.1.1 S1 Structure

S1 is the primary foliation the Aileu Formation. It is present in virtually every out-crop of the Aileu Formation. S1 is defined by segregation and preferred orientation of metamorphic minerals and is generally subparallel to large-scale compositional layering that may represent primary bedding (So) (Fig. 9). Although S1 foliation is well developed throughout the Aileu Formation, no fold structures (F1) associated with D1 deformation have been observed.

S1 orientation throughout Aileu Formation show a distribution that can be grouped into five domains, namely from east to west domains I, II, III, IV, and V (Fig. 10). Variation in S1 orientations is interpreted as a function of lithologic vari-ations and late-formed folds and faults.

Domain I is divided into domain Ia in the north and domain Ib in the south. The orientations of S1 in domain I show an east-plunging antiformal structu-res which is defined by SSE-dipping S1 in domain Ib and ENE-dipping S1 in domain Ia. The antiformal structure continues to the west as indicated by the orientations of S1 in domain IIa. In domains IIb and IIc, which lie south of domain IIa, S1 dip north and south, respectively. Further west, in domains III, IV, and V, S1 tend to have only one dominant orientation. In these domains the bedding-parallel S1 foliations generally dip SSE to SSW. The fact that the antiformal structure does not continue to the west indicate it was probably only locally developed and was associated with the formati-on of late structures. Alternatively, changes in dip may be fault related.

4.1.2 S2 Structures

D2 deformation folded and crenulated both lithological layering and S1 structu-res resulting in F2 and S2 structures. These structures are well-developed mainly in the northern part of the Aileu Formation where higher-grade rocks are widespread. F2 folds vary in style and range in scale from microscopic to meso-scopic (Fig. 11). The minerals defining S2 are chlorite and muscovite in the south and muscovite, biotite, and amphibole in the north. In the north S2 is subparallel to S1 and F2 folds plunge gently ESE with axial planes dipping NNE.

4.1.3 F3 Structures

The structures produced by D3 deformation are locally developed and can only be observed in the NE part of the Aileu Formation. They occur generally as mesoscopic folds (F3). F3 folded both S1 and S2, and can be easily distinguished from earlier fold (F2) if both are exposed in one outcrop. F3 folds are commonly open with wave lenghts 30 - 50 cm.Axial planes to F3 folds are generally steeply dipping with fold axes plunging SE.

4.1.4 F4 Structure

Mesoscopic folds related to D4 deforma-tion are locally developed and are most common in the NE part of the Aileu Formation. F4 folds have small, open, angular forms with wavelenghts of 0.5 - 2.0 m and deform S3 and earlier structures. Fold axes plunge gently to the NNE. Berry and Grady (1981) recognized a north-striking macroscopic D4 synform 2 km east of Dili.

4.1.5 F5 Structure

No direct overprinting evidence has been found during this study for a fifth stage of deformation. However, Berry and Grady (1981) recognized several macroscopic folds as D5 structures. The F5 folds have ESE to SE-trending axial surfaces.

There are some types of fold commonly found within 10-40 m of fault zones in the southern area of the Aileu Formation. The folds are open, angular, asymmetrical in style with wavelengths of 0.5-10 m and trend generally E-W. The close association of these folds with fault zones leads to an interpretation that the folds are probably contemporaneous with a deformation phase similar in orientation at least to D5, a phase which is dominated by faulting.

4.2 Brittle Structures

The principal brittle structures in the Aileu Formation are roughly E-W, ESE-WNW, and ENE-WSW trending thrust faults, NE and NW-trending normal faults (Fig.12), and SE and NE-trending strike-slip faults. Mode 1 fractures, some of which occur as veins, are also found throughout the Aileu Formation.

4.2.1 Thrust Fault

The most prominent thrust in the study area is the Laclo fault which forms the southern boundary of the Aileu Formati-on. This thrust is the only fault in the stu-dy area whose surface trace is recogni-zable on aerial photographs and Landsat imagery.

Smaller, north and south-dipping thrusts occur throughout the Aileu Formation. These thrusts generally have short traces, small displacements, and low-angle dips ranging from 30°-50°. The lateral traces of these faults are mostly inferred on the map. Most of the S-dipping thrusts are found in the north, while the N-dipping thrusts are mostly found in the southern part of the study area (Fig.13). Displacements along these faults are difficult to measure due to lack of adequate markers. Where markers, such as quartz veins. do occur (Fig.13) displacements are on the order of 1 m with top-to the north sense of slip.

4.2.2 Normal Fault

A number of normal faults were recog-nized in the north and NW part of the study area. They mostly occur in quartz-pelitic phyllites and schists, and meta-igneous rocks. In laminated phyllitic rocks, the normal sense of movement is indicated by the offset of quartz veins and drag folds, whilst in the metaigneous rock the normal slip movement is indicated by well-developed slickensides (Fig.14), and the faults trend NE to NW. Like the thrust faults, the traces of the normal faults from where they were found in outcrop are mostly inferred from aerial photos.

4.2.3 Strike-slip Fault

Strike-slip faults were found in units bounding the Aileu Formation. A small, SE-trending, left-lateral fault was observed in a shale unit of the Kekneno series just south of the Laclo fault, north of the Laclo village. Its orientation suggests that this fault cuts into the Aileu Forma-tion and postdates the Laclo fault. A large, NE-trending, left-lateral fault, named here the Noru fault, has been found in the Kekneno series in the SE part of the study area (Fig.15). This fault can be easily recognized on topographic map, aerial photos, and Landsat imagery as a distinct lineament.

4.2.4 Fractures

Veins filled with secondary minerals such as calcite and quartz, and joint sets with no mineral fillings are common throughout the Aileu Formation (Fig.16). Veins are most abundant in the north. There are two types of veins: those that are parallel to foliation and those that are perpendicular to foliation. Steep dipping vein and fracture orientations from the northern part of the Aileu Formation show a mostly NE-SW trend.

5 DISCUSSION

Each of the three different models propo-sed for the structural style and evolution of Timor, namely the imbricate, over-thrust, and upthrust models, differ in the parts of orogen where the observations were made. Harris (1991) suggested that each of these models depicts a different orogenic phase in the evolution of Timor. Harris' model (1991) (Fig. 7) consists of structural transects through different parts of the Banda arc, from W to E, namely the Sumba, Savu, West Timor, and East Timor transects. These transects show major phases of deformation in the Banda orogen involving frontal accretion, allochthon emplacement, and culmination development.

The East Timor transect provides a perspective of the Banda orogen structural style that is not found in any other part of the Banda arc, with the possible exception of Seram. The exposures of the internal parts of the orogenic wedge consist of underthrust pre-breakup sequences of the Australian margin. The occurrence of metamorphic rocks that have Australian passive margin deposit affinities in the northernmost part of East Timor led Harris (1991) to interpret that collision between the Banda arc and the NW Australian continental margin began in central Timor or NW East Timor, where the Aileu Formation is exposed, and mig-rated to the SW.

The results of field mapping and structural analysis of the Aileu Formation documented by the present study are consistent with the following history: Formation of the protolith in an epicontinental marine environment; early prograde, rift-related metamorphism with penetrative deformation and greenschist facies metamorphism (D1); collision, with ductile deformation and moderate P-T (greenschist-amphibolite) metamorphism (D2), followed by major nappe displacement; and uplift, accompanied by locally-developed folding, backthrusting, extensional faulting, lower-grade alteration, minor recrystallization, and cooling. A summary of these ideas is presented in the following table :

DEFOR-MATION	META-MORPHISM	TECTONIC SIGNIFICANCE
post-D2	low-grade alteration	locally-developed folding, backthrust (?) and extensional faulting, accompanying uplift.
D2	greenschist-amphibolite facies	collision-related ductile deformation (transposition of layering), thrusting.
D1	prograde metamorphism, greenschist facies	ductile deformation (layer parallel foliation), rifting (?).

The Aileu Formation consists of a sequence of predominant metapelite with interbedded metabasites and marbles. The sequence is transitional from metapelite, minor carbonate-rich metasediment and metavolcanic rocks in the south to clastic-rich, intensely-deformed, and metamorphosed psammites, pelites, calc-schists, and amphibolites in the NE. Relict textures such as bedding, a considerable portion of metapelite, and interbedded marbles indicate that the original sediments (protolith) of the Aileu Formation formed a monotonous thick sequence shales and limestone deposited in a quiet basinal marine environment (Audley-Charles 1968). Berry and Grady (1981) proposed that this sequence is similar to the sediment accumulated in graben structures in the NW

Australian shelf margin during the late Paleozoic and early Mesozoic.

The NW Australian passive conti-nental margin formed during Middle-Late Jurassic breakup and Early Cretaceous sea-floor spreading in the adjacent Whar-ton Basin (Larson 1975, Falvey 1972). If a graben, similar to those currently developed in the NW Australian shelf, had been filled with Aileu sediments, the Late Jurassic major rifting event would have caused extensive deformation associated with crustal extension. The high T - low P metamorphic event associated with rifting would be localized and effect only the most distal sections of the NW Australian slope, represented by the northern-most part of Aileu Formation. The close proximity to a rift is supported by the occurrence of numerous mafic and ultramafic intrusive bodies adjacent to the highest grade metamorphic belt as documented in the Aileu Formation by Berry and Grady (1981) and the present study. This first deformation phase (D1) appears to have been extensional in origin, producing a widespread layer parallel schistosity (S1) but no recognisable F1 folds.

In addition, intrusive relations documented in the present study emphasize the role of local magmatic activity along the NW coast of East Timor as the cause of higher-grade metamor-phism of the surrounding rocks. A rapid decrease of metamorphic grade away from the intrusive bodies is found along the north coast. The age of D1 remains uncertain but is inferred as syn-rifting from Late Jurassic to Early Cretaceous which is the oldest age of oceanic crust immediately adjacent to the NW Australian margin.

The D2 structures that record a collision event are intense shortening by transposition of layering (S2), isoclinally mesoscopic folding (F2), and later internal thrusts and movement along the Laclo fault. Regional dips on the S1 schistosity (parallel to subparallel to lithological layering) suggest an overall antiformal structure that probably developed during D2 shortening. The formation of this structure might have accompanied the emplacement of the Aileu Formation along a major thrust that forms its southern formation boundary. In the eastern part of Aileu Formation this thrust is represented by the Laclo fault. In the SW, the Aileu Formation grades transitionally into the Maubisse Formation as indicated by the results of boundary mapping conducted by the present study. This relationship implies the Aileu and Maubisse Formations both rode upon the same thrust that forms the Laclo fault in the east.

Collision-related nappe emplacement was accompanied by overthrusting of the Banda Terrane and the formation of internal smaller north and south-dipping thrusts that have been mapped for the first time by the present study. No cross-cutting relationships have been observed among these structures. Therefore it is difficult to postulate which one of these structures predates others. The following is an attempt to interpret the relationship between the major thrust that bounds the Aileu Formation (the Laclo fault) and the internal faults. The relationships could have significant role in interpreting the dynamics of the Aileu "massif" as an intrinsic part of the Timor convergent orogenic wedge.

Malavieille (1984) developed a multilayer model for the evolution of a thrust system affected by asymmetric shortening (Fig.17). The experiment predicts a structural sequence and style that -according to the present study - is similar to that found within the Aileu Formation and its immediate adjacent units (Fig. 18). This model is characte-rized by the formation of a set of forward thrusts (numbered in order of formation from 1 to 7 in Fig.17) that dip in the direction of subduction, and antithetic backthrusts (R1 and R2 in Fig.17). Figure 17 indicates that both types of thrust are younger away from apex of the orogenic wedge. To some extent, the orientations of foward thrust and back-thrust could be correlated with north and south-dipping thrusts of the Aileu Formation, respectively (Fig. 18). While the backthrusts (R1 and R2) of the Malavieille's model developed simultane-ously with the forward thrusts, the south-dipping thrusts, or "backthrusts", of the Aileu Formation possibly postdate the north-dipping thrusts. This interpretation is based on field relations in that some of the "backthrusts" on the north coast offset quartz veins, which may be the more recently-developed structures. Another possibility with regard to the south-dipping backthrusts in the Aileu Formation is that these faults are subsidiary faults associated with the main north-dipping thrusts (Fig. 18 and 19). If the latter is the case, both types of thrusts may still be proceeding indicating that the collision processes remain active.

Although there are many exten-sional faults developed in the Aileu Formation, the stress regime experienced by the Aileu Formation remains compressive ini nature. This is indicated by orientations of brittle structures such as vertical fractures and veins, and strike-slip faults.

As collision between NW Austra-lian continental margin and Banda arc continues, post-D2 structures are developed during an uplift event. This event, which is dominated by vertical movements, is well-documented by the occurrence of thick fluvial terraces which rest unconformably on the Aileu Formation in many places and by the occurrence of beach deposits along the north coast at elevations up to 750 m.

6 CONCLUSIONS

The Aileu Formation is a single large massif in NW East Timor that consists of pelites, psammites, and marble interbedded with metavolcanics and metabasites. Along the north coast it is intruded by mafic igneous rocks in several places. The grade of metamorphism of the Aileu Formation increases from SW to NE, from subgreenschist facies in its type area near the Aileu village to amphibolite facies in the NE. Detailed geologic mapping along four different traverses has revealed two types of contact relationship between Aileu Formation and the adjacent units. In the eastern and western parts, a thrust fault marks the contact between the Aileu Formation and the undifferentiated Permian-Mesozoic sedimen-tary unit (Kekneno series). Along the southern-most boundary the Aileu Formation passes transitionally into the unmetamor-phosed Triassic-Permian Maubisse Formation, suggesting at least a partial Permian age for the Aileu Formation protolith. This estimated age is consis-tent with interpretation that the original sedimentary rocks of the Aileu Formation were deposited in the late Paleozoic in-tracratonic graben. Subsequently this deposit experienced Mesozoic rifting-related metamorphism (D1 deformation), producing a widespread layer parallel schistosity (S1) but no recognisable folds.

D2 represents shortening in the Aileu Formation and marks the initiation of arc-continent collision. This second deformation caused widespread trans-position of So and S1 on all scales and produced tight to isoclinal folds with an axial surface generally dipping to the north. This event caused retrograde metamorphism. Post-D2 deformation events which may be related to faulting.

Several types and ages of faults occur within the Aileu Formation; poor exposure prevents unequivocal interpre-tation of all them. N and S-dipping thrusts are exposed in several localities. This orientation suggests a characteristic response of the Aileu Formation, as part of the Timor orogenic wedge, to Banda arc-Australia collision-related shortening. Other faults, normal and strike-slip faults, clearly cut the thrust faults and, therefore, postdate the latter. The late-formed normal faults documented the most recent movement related to the uplift of the Aileu Formation, which is also indicated by the occurrence of fluvial and beach terraces overlying the Aileu Formation.

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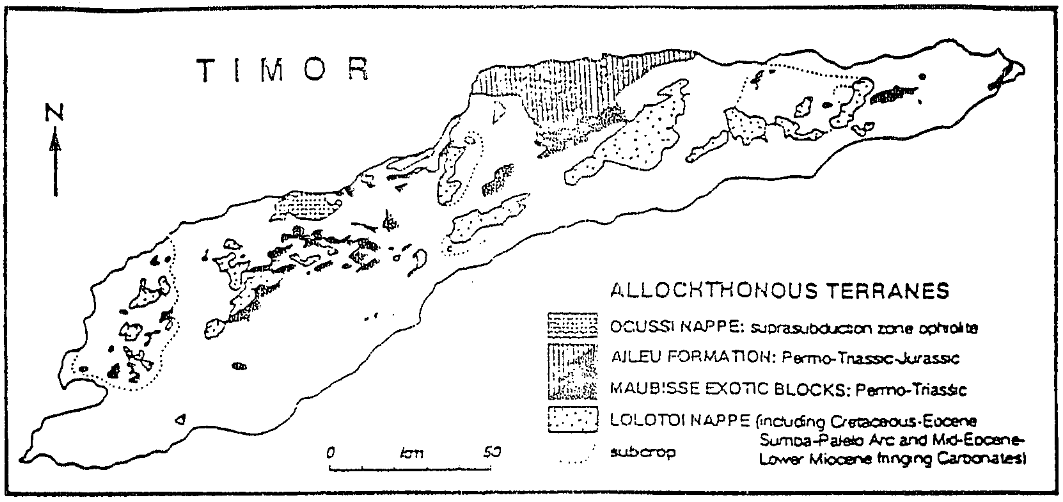


Figure 1 : Allochthonous terranes in Timor (Audley-Charles and Harris 1990).

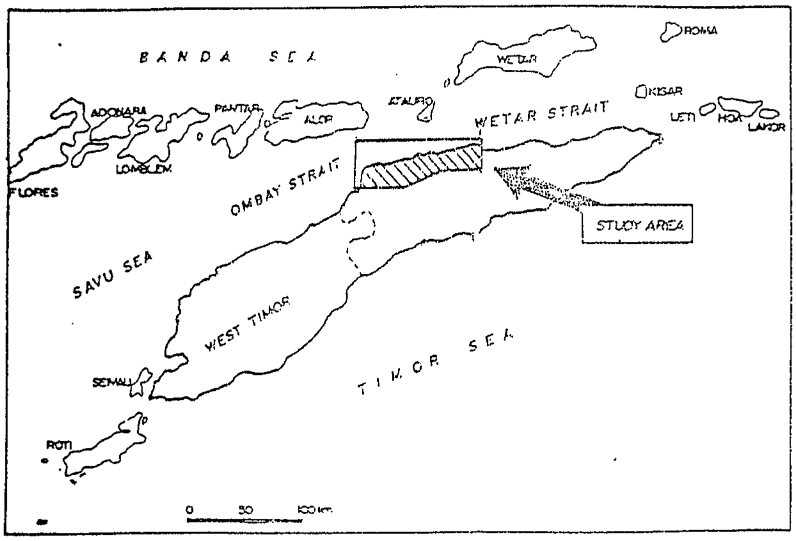


Figure 2 : Location of the study area

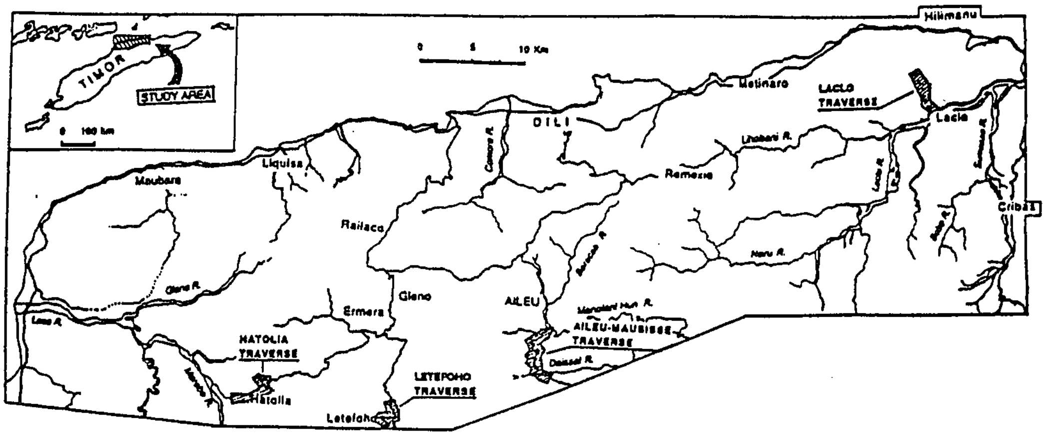


Figure 3 : Map of the study area showing the traverses of formation boundary mapping

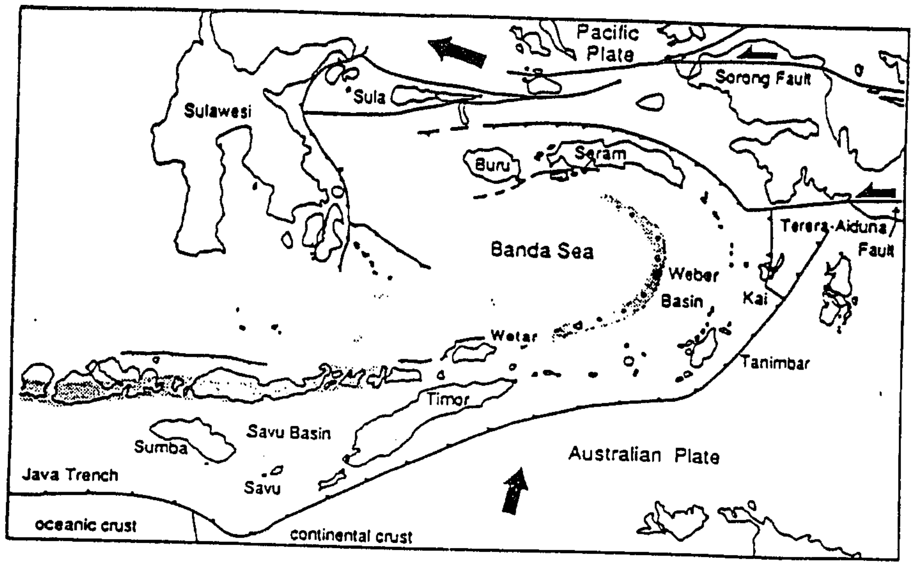


Figure 4 : Tectonic map of Banda arc. Zone of active volcanism and relative plate motion directions are indicated by shaded region and arrows, respectively (from Harris 1991).

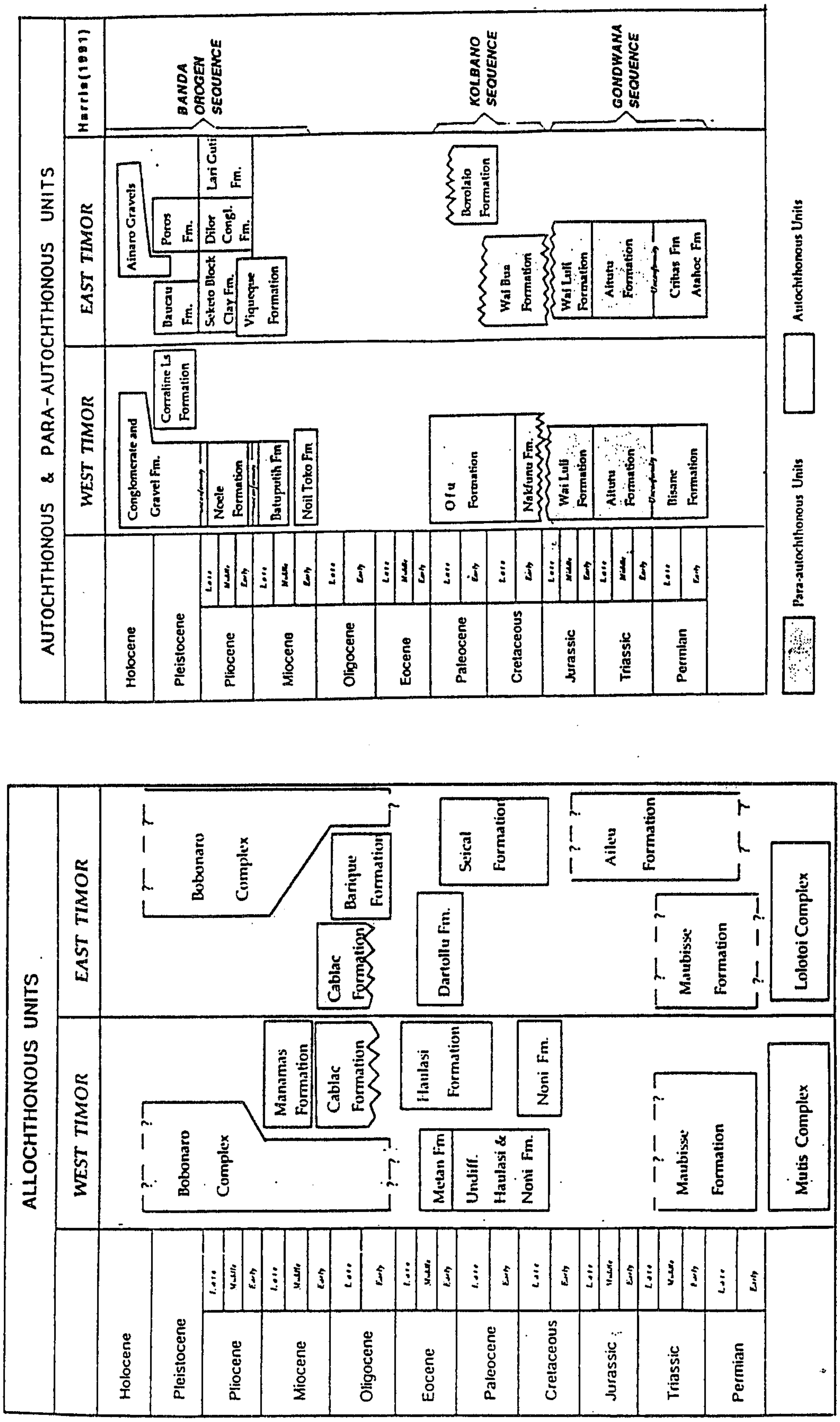


Figure 5 : Stratigraphy of Timor consisting para-autochthonous, autochthonous, and allochthonous units (simplified from Audley-Charles 1968; Rosidi et al 1979, and Harris 1991).

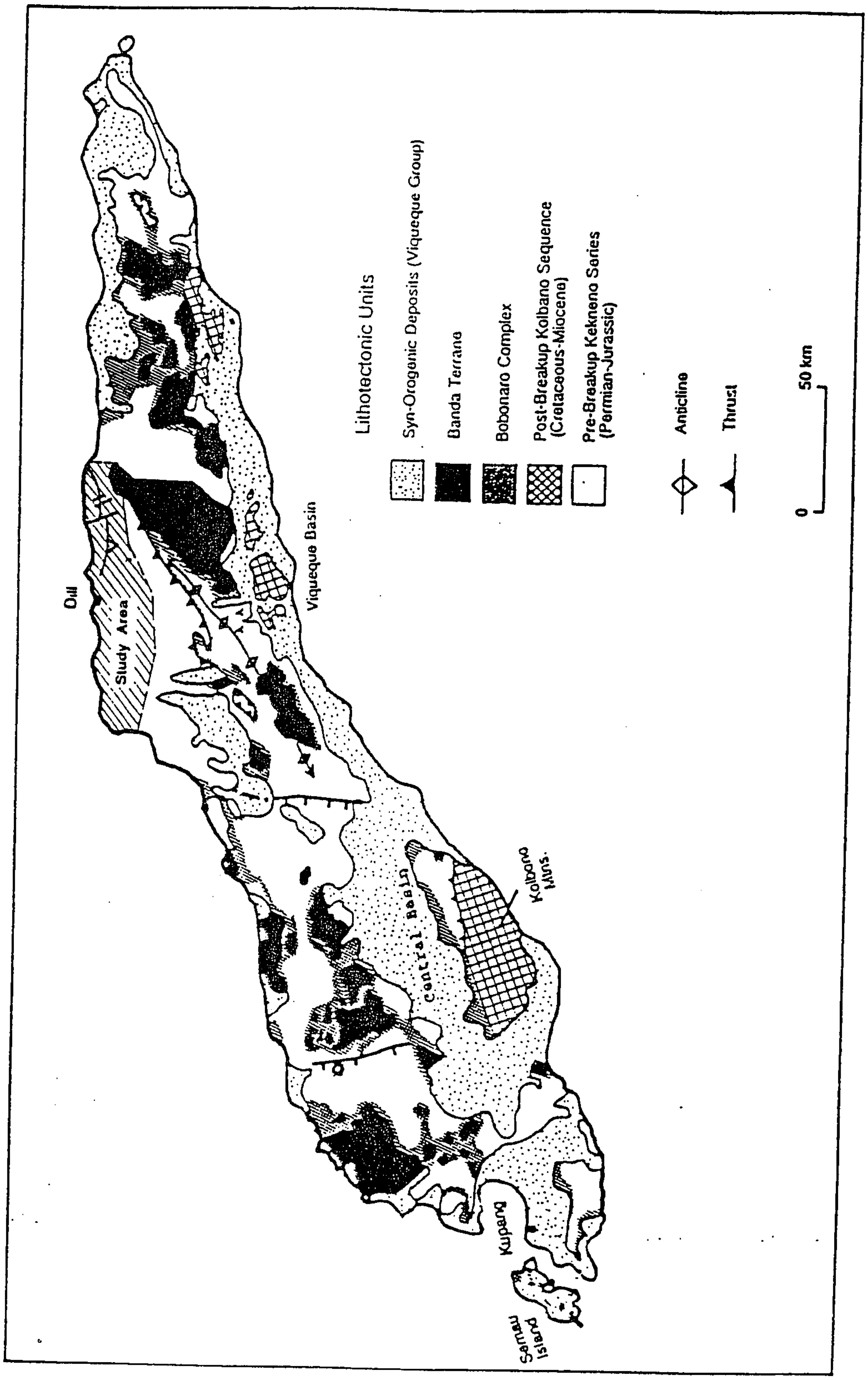


Figure 6 : Geological map of Timor (Harris et al in press).

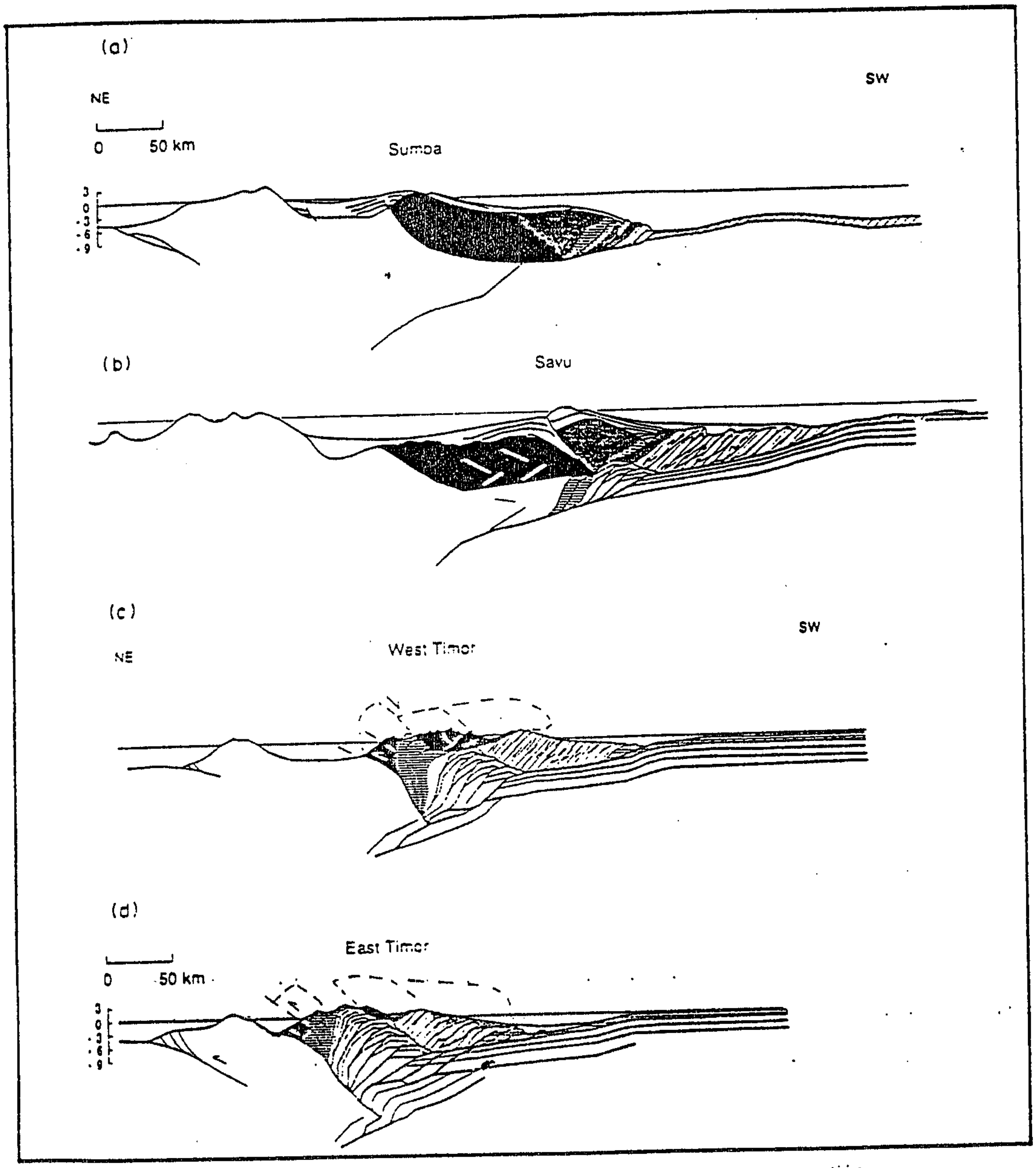


Figure 7 : Restored structural sections of various parts of the Banda arc. Lithotectonic units: **Black-** forearc basement upper plate (Banda allochthon). **Dark grey-** frontal accreti-onary wedge of Java trench and melange. **Horizontal stripes-** Permian to Triassic Aileu- Maubisse Formations (most distal raches of Australian continent). **Diagonal stripes-** Post-Breakup slope and rise deposits of Australian passive margin. **Brick pattern-** Shelf facies of Post-Breakup deposits. **Light-grey-** Permian to Jurassic Pre-Breakup sedimentary sequence. White unit underlying light-grey are Cambrian to Carbonifeous Pre-Breakup sediment or crystalline basement. White overlying orogenic wedge are synorogenic deposits (Harris 1991).

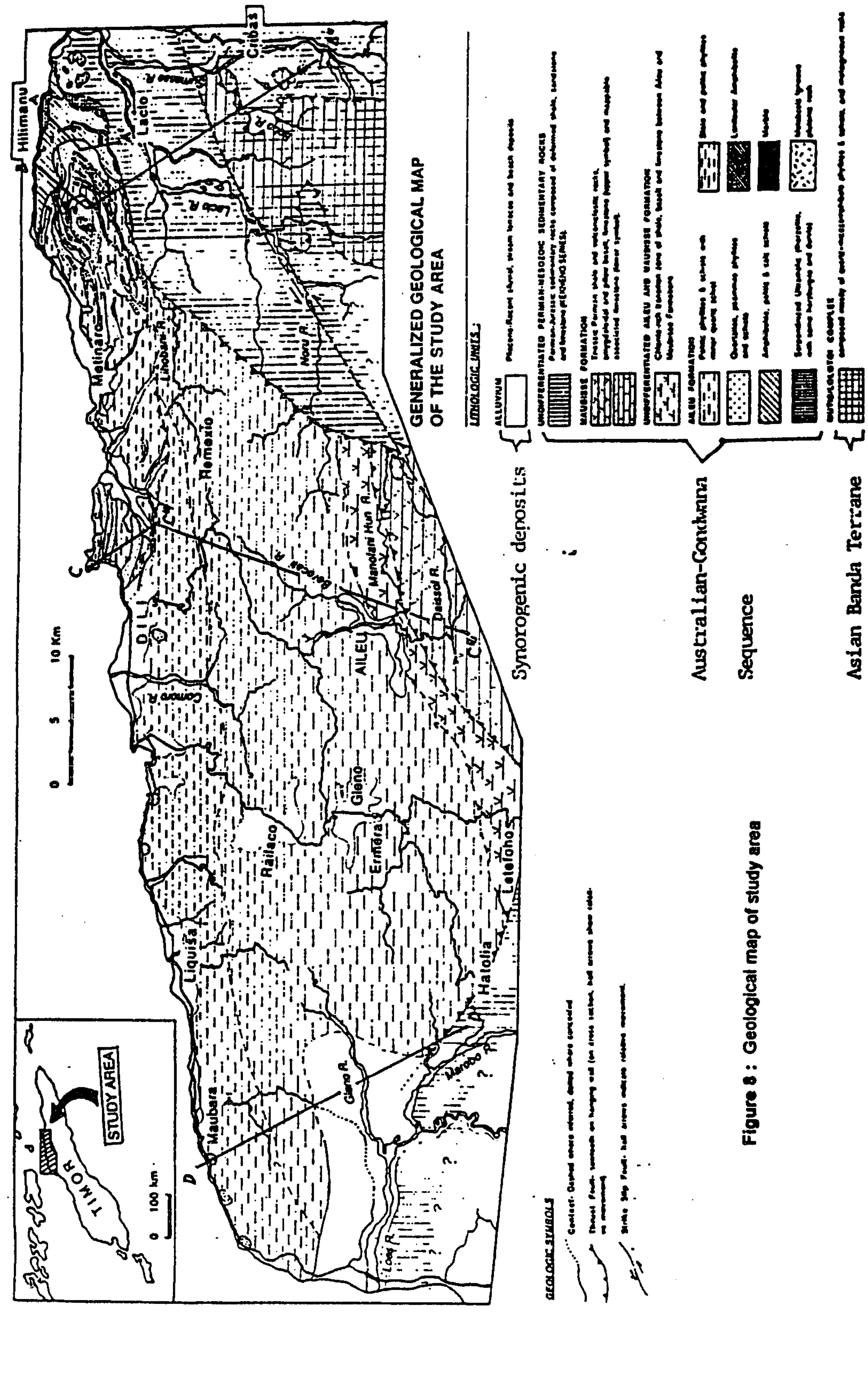


Figure 8 : Geological map of study area

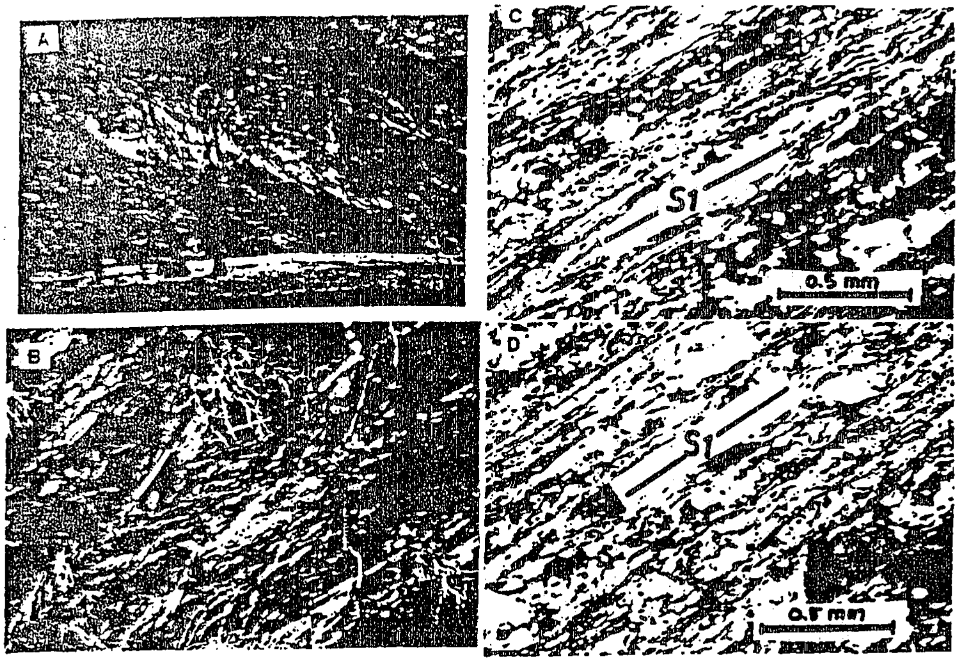


Figure 9 : S1 FOLIATION. (A) S1 foliation developed in interlayered quartz-pelitic phyllites and schists, and (B) in interbedded pelitic phyllites and calc schists. Note well-developed S1 foliation that parallel to compositional layering in both outcrops, (C) and (D) photomicrographs (in XPL=cross polarized light) of S1 foliation which defined by preferred orientation of mica and quartz.

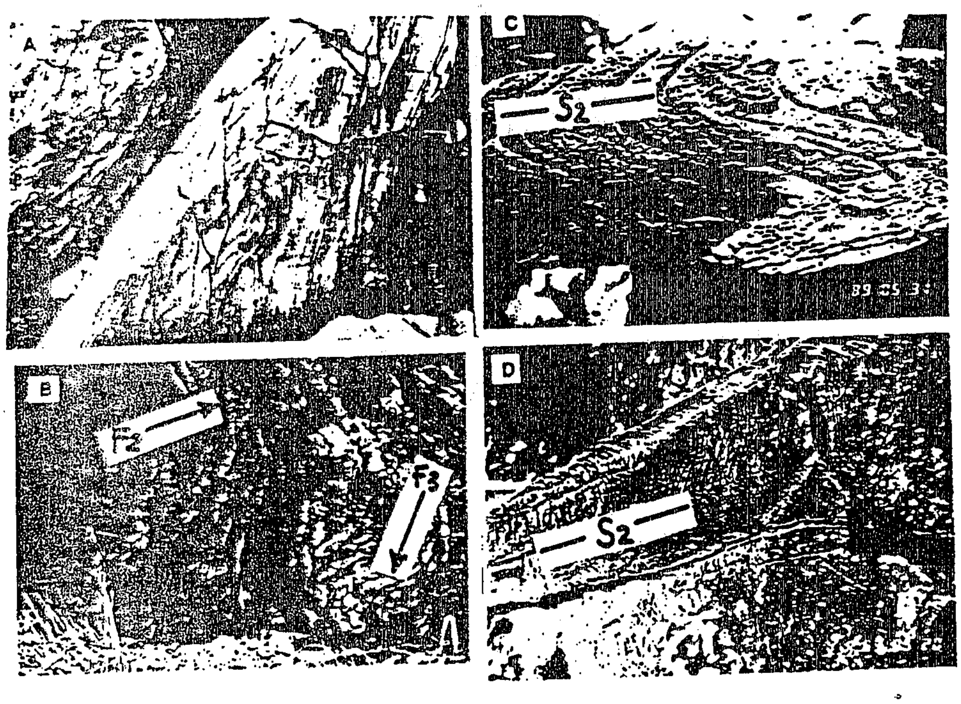


Figure 11: F2 AND S2 STRUCTURES. (A) An isoclinal F2 fold in the marble unit. Hammer is 33 cm long, (B) tigth F2 folds are refolded into open F3 folds in the quartz pyllite and schist unit. (C) and (D) S2 axial-planar cleavages in quartz, psammitic phyllite and schist (Photos C and D : RA Harris).

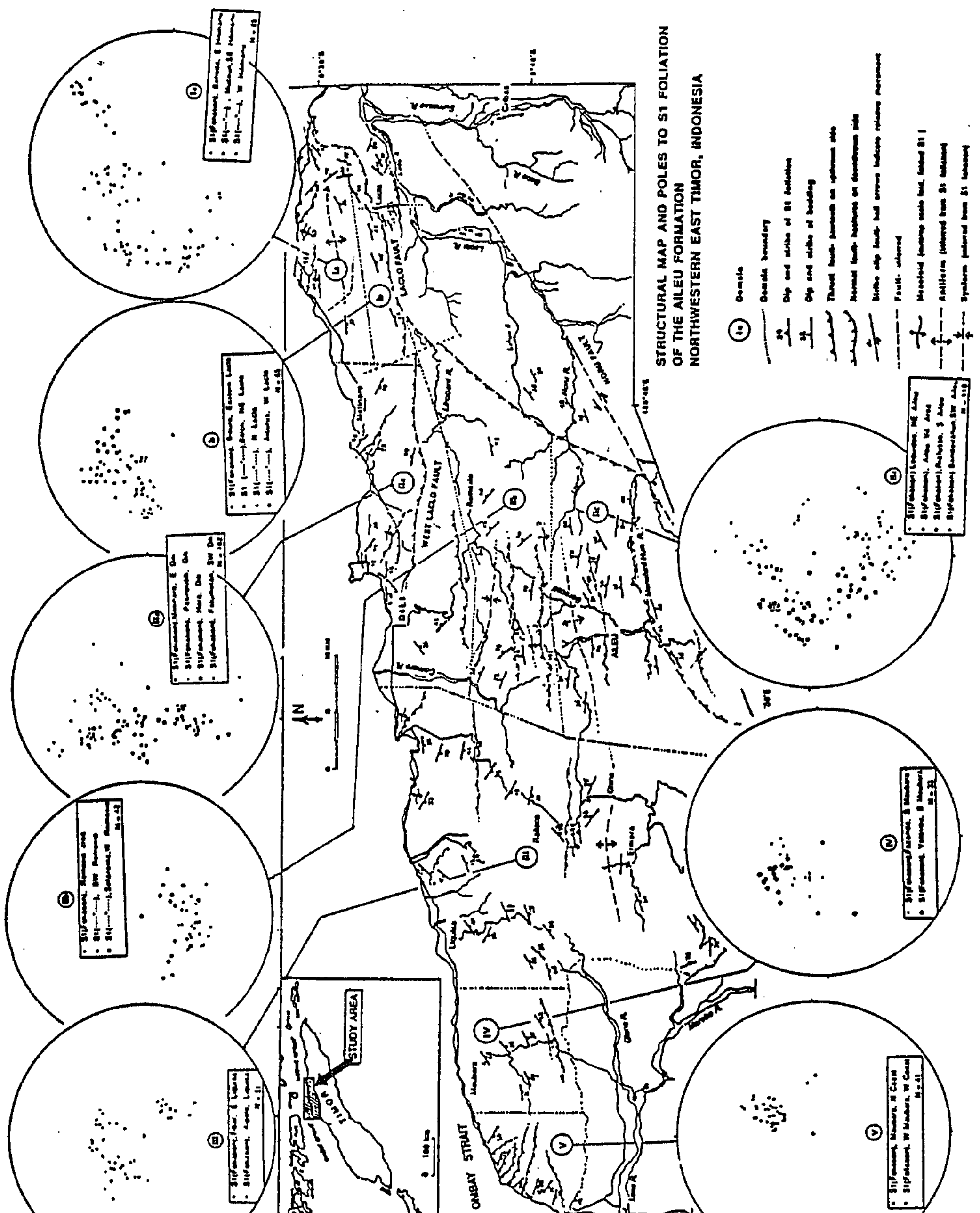


Figure 10. Structure and S1 foliation map

A

B

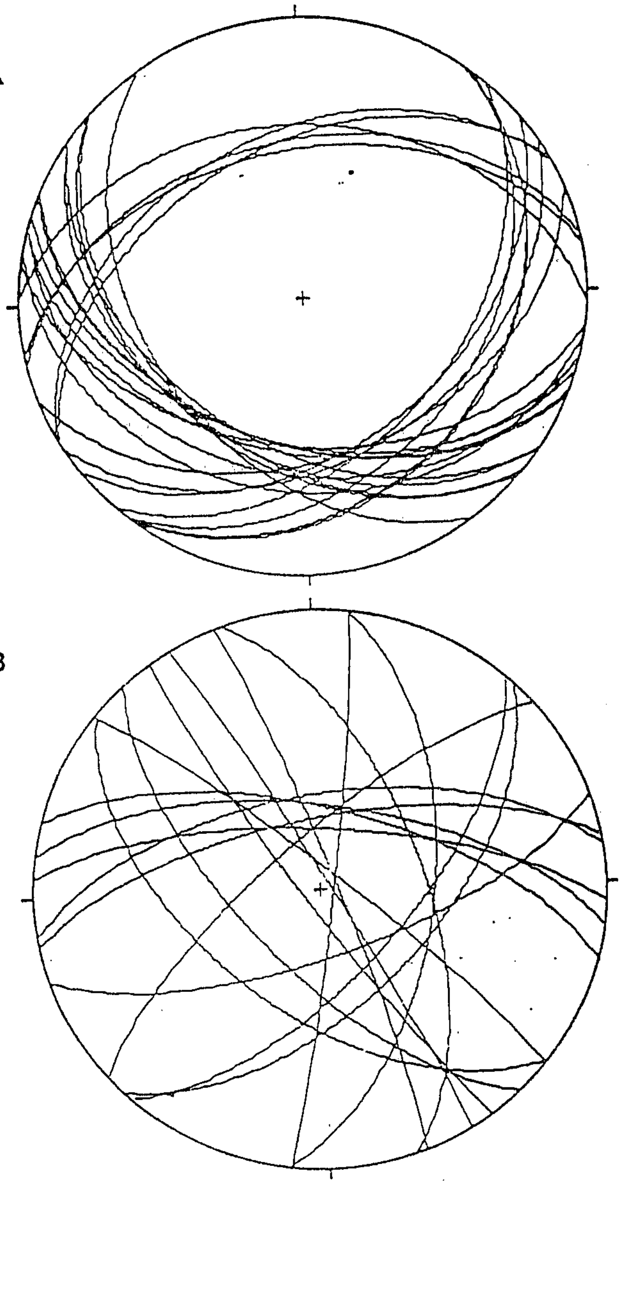


Figure 12 : FAULTS. Lower-hemisphere, equal-area stereograph of the great circles trace of : (A) low-angle faults, which are dominated by thrust faults, and (B) high-angle faults in which normal faults are most common.

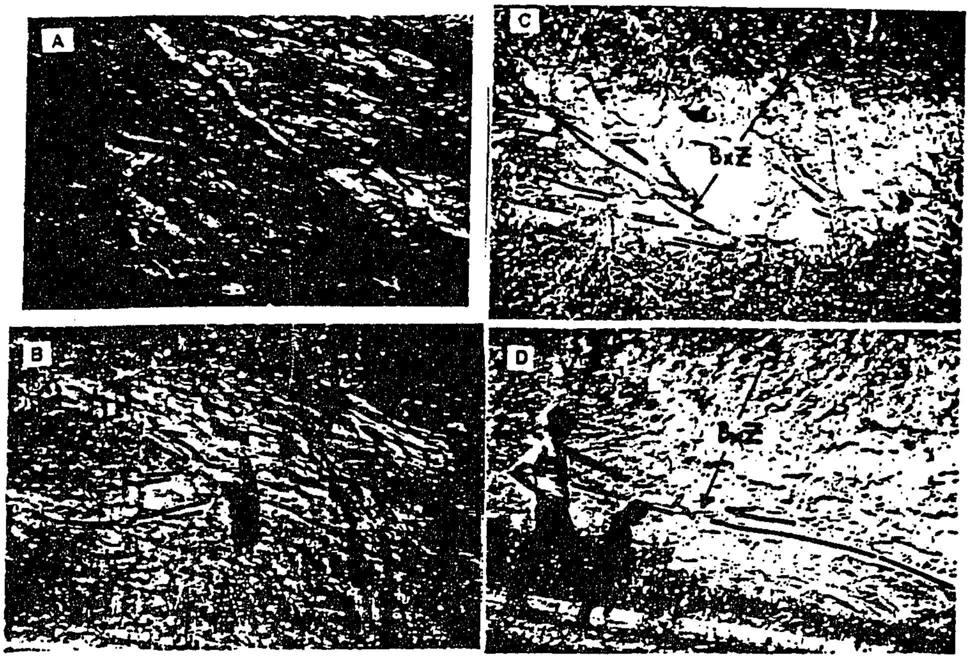


Figure 13 : THRUST FAULTS. South to southwestern-dipping thrusts found in : (A) quartz phyllite, (B) interlayered quartz-mica phyllite and schist, (C) and (D) chlorite-quartz phyllites. 1.2 m of offset quartz vein in (A) has "top-to-the north" sense of movement. Also note strongly developed brecciated zones (BxZ) in (C) and (D).

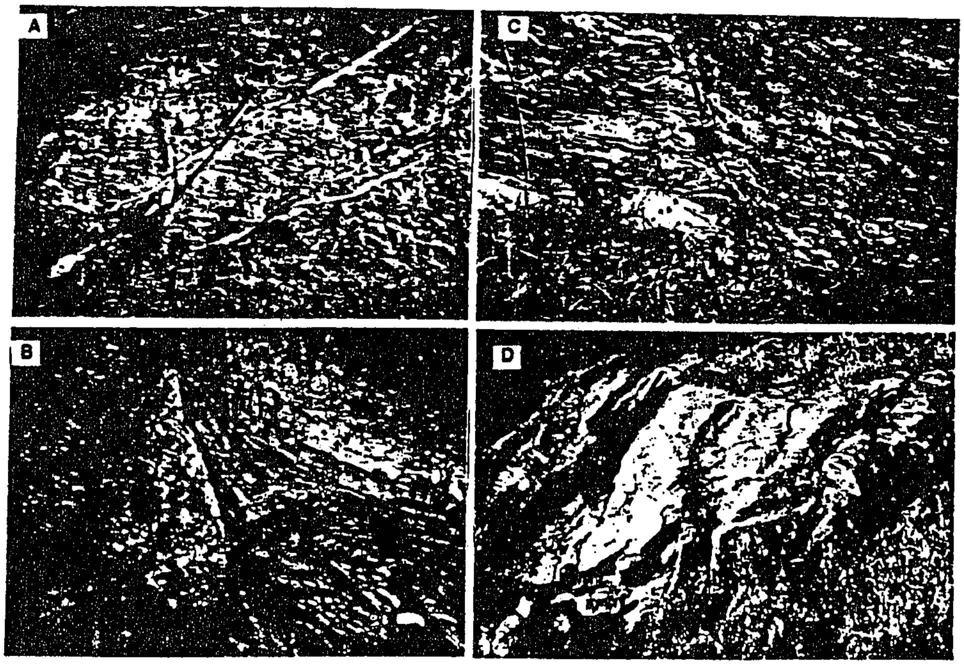


Figure 14 : NORMAL FAULTS. (A) A set of NE-dipping small normal faults in quartz-mica phyllite. (B) A NW-dipping normal fault-plane and the drag-fold in interlayered quartz-mica phyllites and schists. (C) The offset of quartz veins mark a NW-dipping normal fault in quart-mica phyllite. (D) A normal fault zone in metaigneous rock. Arrows indicate striations with normal sense of movement.

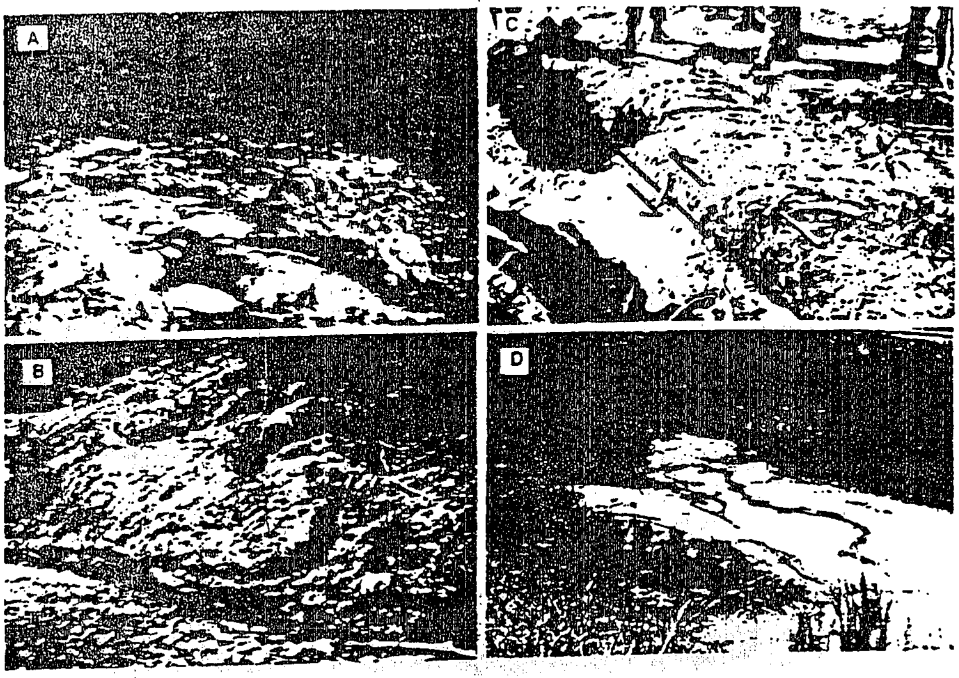


Figure 15 : NORU FAULT. A large, NE-trending, left-slip strike-slip fault found in the Noru river, SE part of the study area. The presence of this fault is evident by a zone of disruption (A) and (B), drag folds that have a left-lateral sense of movement (C), and hot-spring (D).

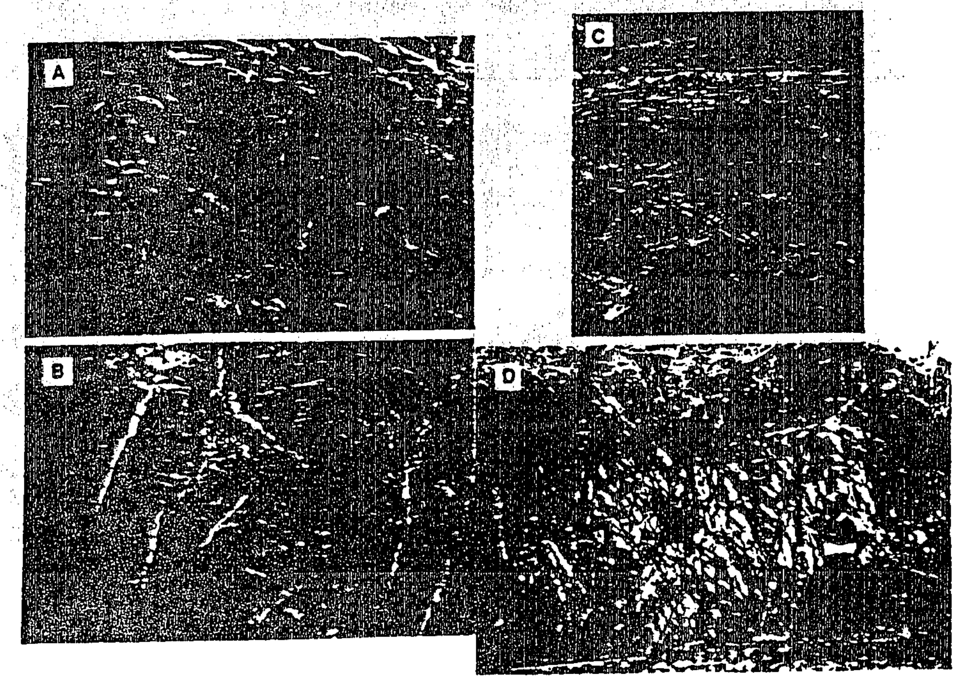


Figure 16 : FRACTURES. (A) and (B) quartz veins in quartz-mica phyllites and schists. (C) and (D) locally, well developed steeply-dipping joints and veins in quartzite and quartz-mica phyllites and schists.

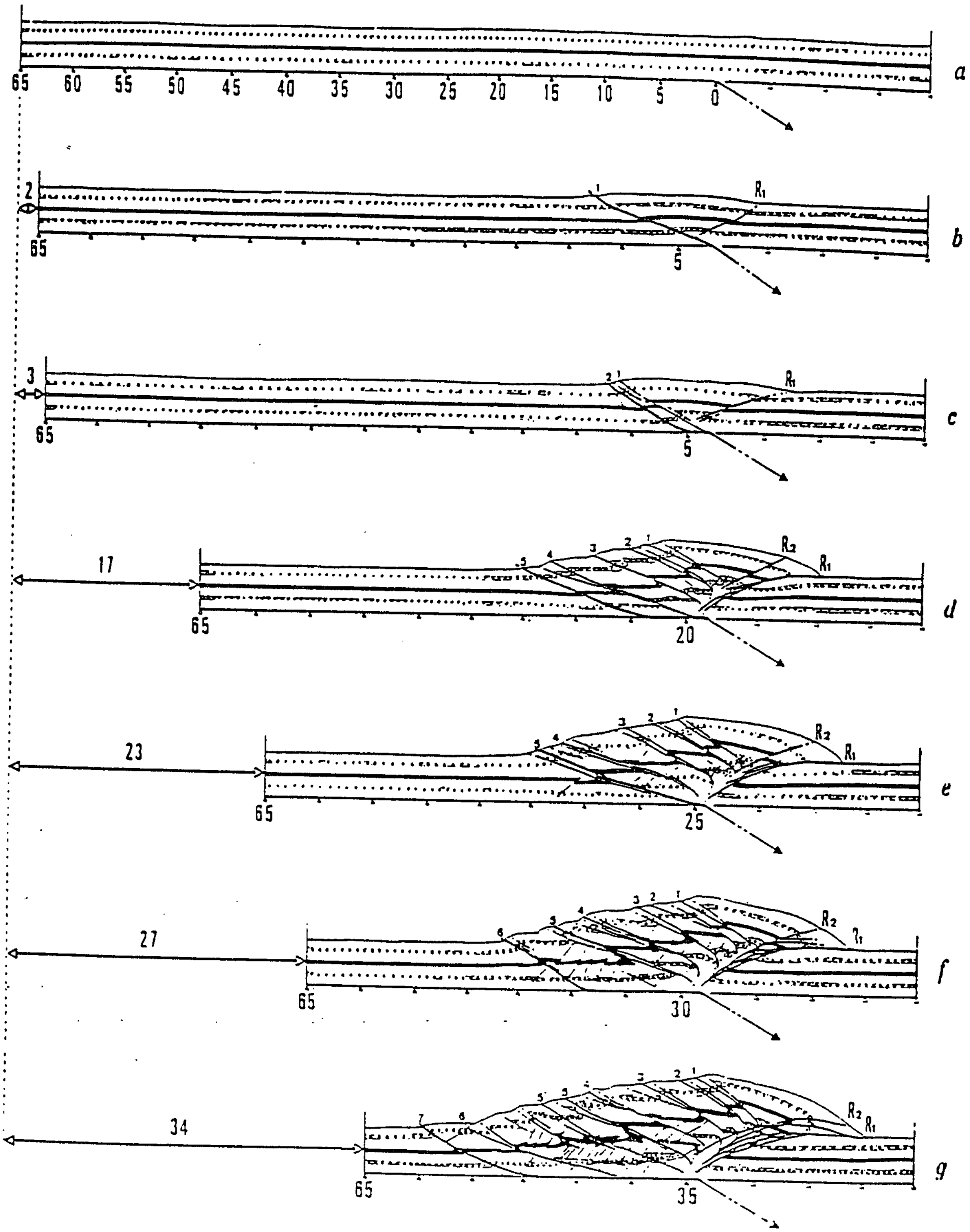
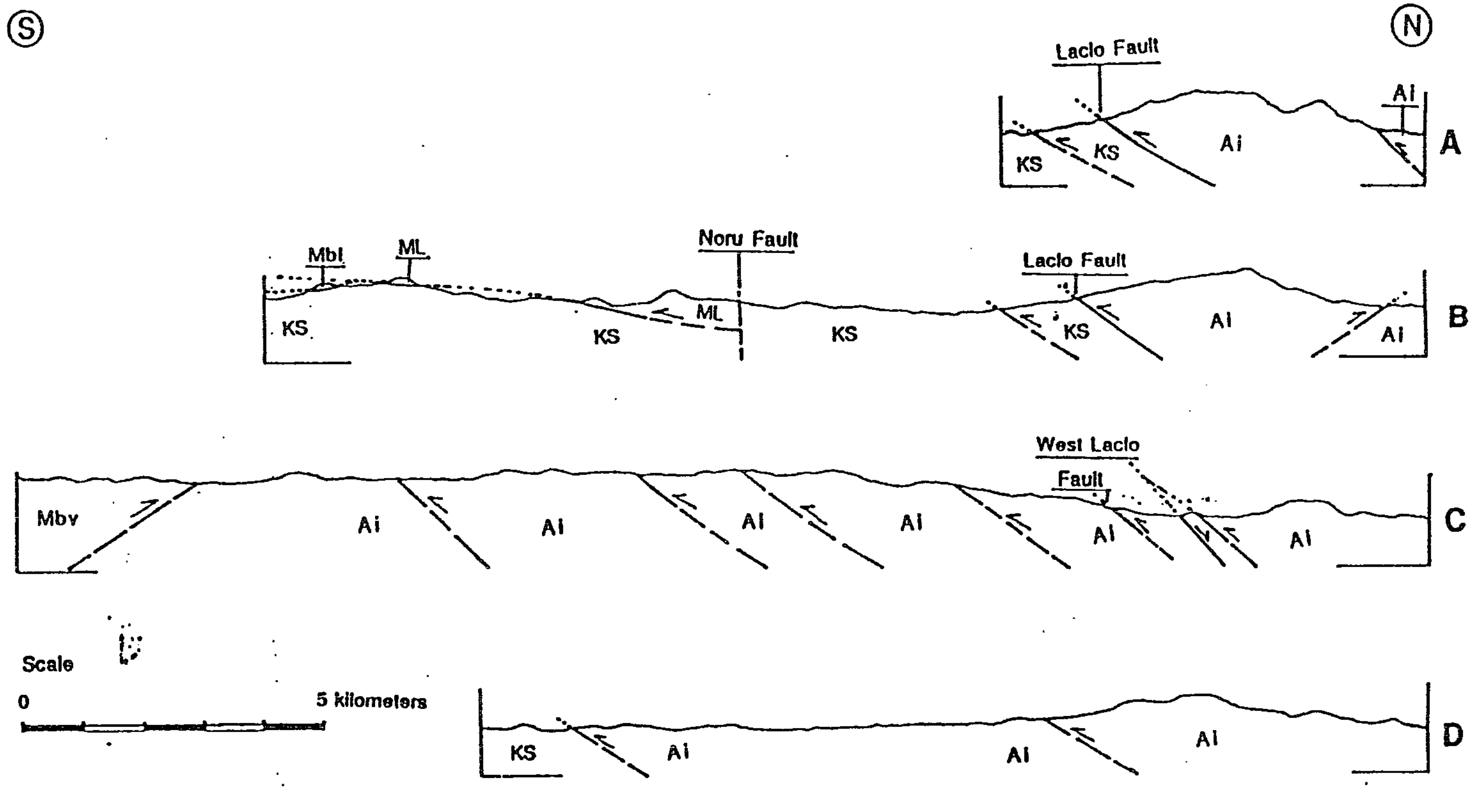


Figure 17 : Accretionary processes experiment (Malavieille 1984). Scale from 0 to 65 indicates progressive shortening. Fault numbers denote order of formation.



KS = Undiff. Permian-Mesozoic Sedimentary Rocks (KEKNENO SERIES)
Mbl = Maubisse Formation, mappable associated limestone
Mbv = Maubisse Formation; volcaniclastics, shale and limestone
Al = Alleu Formation
ML = Mutis/Lolotol Complex

Figure 18 : Generalized cross-section from the geological map of study area. (See the location of each section in the geological map, Fig. 8).

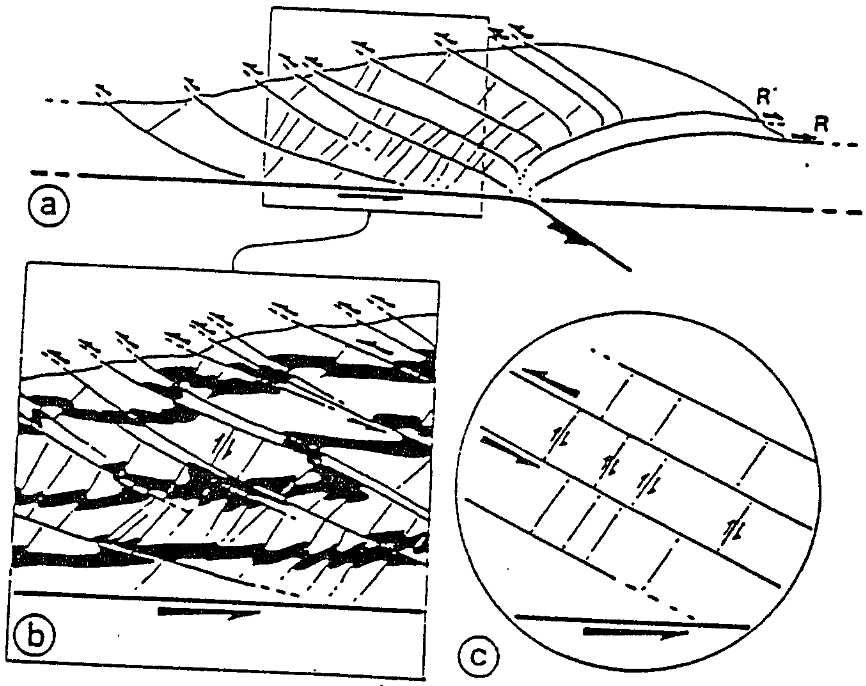


Figure 19: Formation of subsidiary faults associated with the main thrusts. (a) Thrust system in the shortened area, (b) details of (a), and (c) details of the kinematics (from Malavieille 1984).

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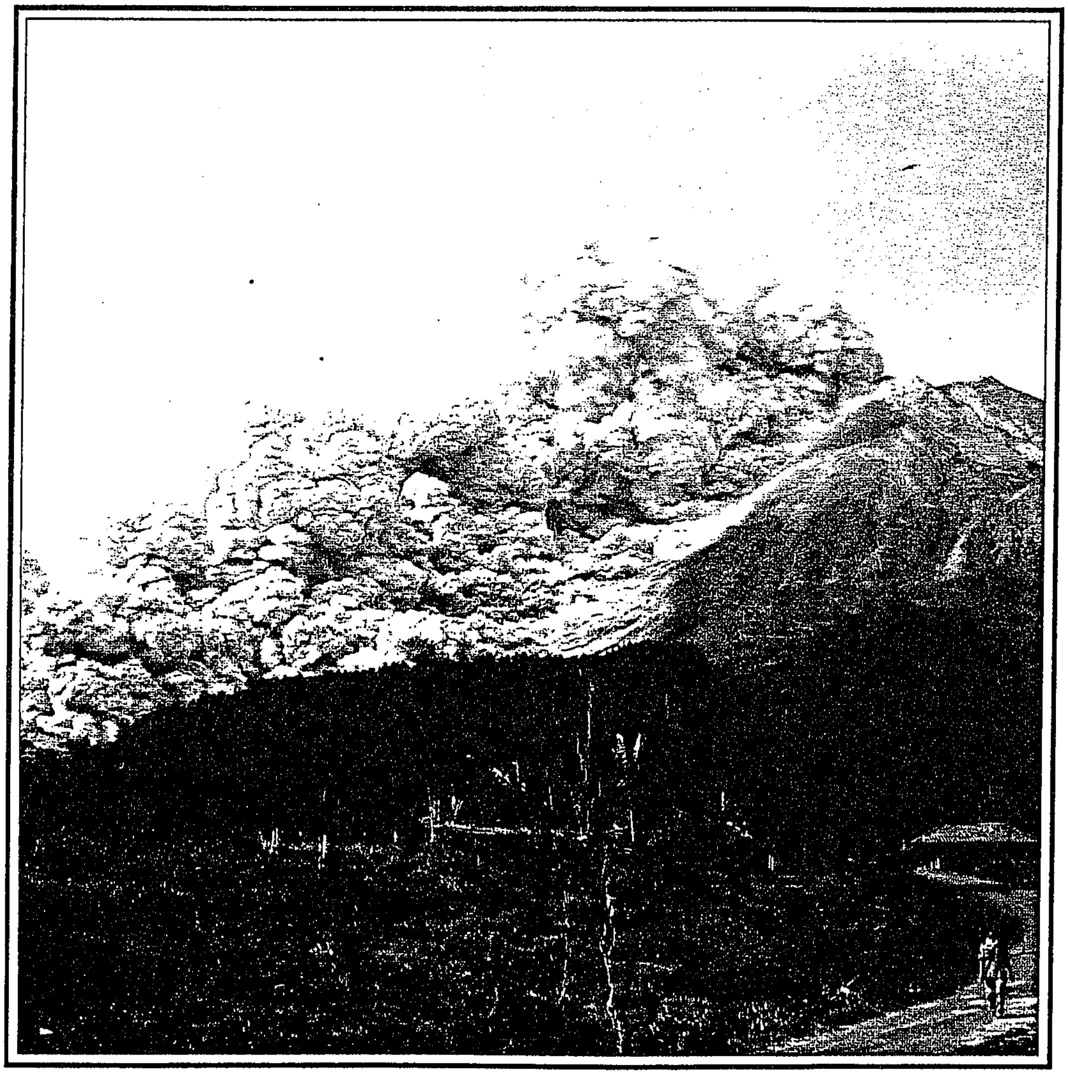

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