DISPLACEMENT PATTERNS OF STRIKE-SLIP FAULTS IN MALAYSIA – INDONESIA – PHILIPPINES

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ABSTRACT

Detailed field studies on seven important strike-slip faults in East and West Malaysia, West Sumatra, Java, and Central Sulawesi, used reliable, minor fault-plane markings (bruised step riser, spall, crescentic gouge, lunate fracture, chatter mark, pluck mark, slickenside prod mark) to determine the sense of displacement. The sense of movement on about ten other major transcurrent faults in the region was derived from the literature.

A common direction of horizontal compression for each of three tectonic domains that subdivide the region between the Asian and Australian continents is indicated by consistent displacements along the wrench faults. For two of the currently active tectonic domains the directions of regional compression are 10°-190° (for Sumatra and Java) and approximately east-west (for the Philippines and the Indonesian islands east of Strait Makassar). These directions of regional compressions are parallel to compressive stress directions computed from sea-floor spreading rates by Le Pichon (1968) and to earthquake-slip vectors interpreted by Isacks et al. (1968) for the margins of the region under discussion.

INTRODUCTION

Structural studies of the Indonesian Archipelago *sensu lato*, Malaysia, and the Philippines have brought to light that many large faults moved horizontally during at least part of their diastrophic histories (fig. 1). Recognizable horizontal displacements along these faults amount to scores of kilometers; the faults should therefore be classified as strike-slip faults. Fault lenghts range from about 25 kilometers to more than 1500 kilometers.

The recognition of large-scale wrench faulting in the region has made slow progress which may be explained by the difficulty of tracing comparatively very narrow shear zones over long distances through densely vegetated areas and on account of the tropical soil cover that understandably appears to be thickest within fault zones. In addition, detailed geologic mapping has covered much less than ten percent of the land area so that displacements of geologic boundaries by faulting have only been verified along a few of the fracture zones.

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With the help of good aerial photographs and detailed fault-plane studies at isolated outcrops of various fault zones, the author has been able to determine in the field the senses of movement of a number of the faults in Sarawak, West Malaysia, Central Sumatra, Java, and Central Sulawesi. Shear planes of these fracture zones commonly possess horizontal to subhorizontal striations. Fault-plane features like bruised step-risers, crescentic gouges, lunate fractures, pluck markings, irregular spalls, chatter marks, grooves occupied at one of the ends by the furrowing "tools" are excellent indicators of sense. The use of minor fault-plane markings in kinematic studies has been comprehensively described by Dzulynski and Kotlarczyk (1965) and by the author (1964, 1967, 1968, and in press). Confirmation has come among others from laboratory experiments by Riecker (1965), Currie (1968), and Gay (1970).

Moreover, drag, en echelon arrangement of tension gashes, and minor offsets along smaller strike-slip faults within and parallel to the fault zones may also indicate the sense of movement along the major faults. The senses of movement have been considered to represent the actual motions of the respective faults if the displacement-sense for each fault zone has been recorded from more than two outcrops along the shear belt. In practice, the sense of movement at an outcrop has been determined from seven to more than fifty shear planes. Sometimes more steeply pitching striations are superimposed upon representatives of lateral displacement. Such vertical movements generally prove to represent normal faulting and have been considered as manifestations of attempts towards a new state of isostatic equilibrium after it became disturbed by strike-slip faulting.

The evidence for horizontal dislocation along some of the faults is still rudimentary; the faults themselves have been recognized as such, however. In spite of this fact, these faults have been included in the present discussion for two reasons. In the first place it is foreseeable that in the next ten years or even longer, lack of personnel and research funds will add only little new, detailed information on these large faults. The present objective of geologic mapping in the region is primarily economic and investigations for the sake of geologic knowledge alone are exceptional. Secondly, this paper hopes to stimulate field parties working in the vicinity of the faults into paying special aatention to the structures.

The Malaysia-Indonesia-Philippines region is composed of two large geologic provinces, one of which is a semicraton that became stable by the Early Tertiary and that includes the Malay Peninsula, the Sunda Shelf as far south as Bangka and Billiton islands, western Kalimantan and Sarawak (fig. 1). Collectively the semi-craton is also known as the Sunda Land in geologic literature. The second province consists of the tectonically active island arcs of Indonesia and the Philippines which rims the Sunda Land on all sides but the north.

AREAL DESCRIPTIONS

Sunda Land Province

West Malaysia. – Scores of radiometric age determinations of granitic rocks indicate that West Malaysia experienced three major orogenic periods in Late Carboniferous, Lower Triassic and Upper Triassic (Anonymous, 1969). Others indicate the latest and main orogeny to have occured in Late Triassic to Early Jurassic (see e.g. Burton and Bignell, 1969). Granites with late Cretaceous to early Tertiary ages have been considered to be mere metamorphic manifestations by these authors.

Six major strike-slip fault zones have so far been recognized, ranging in lengths between 70 kilometers to over 300 kilometers (fig. 2, table I). One of the wrench faults strikes approximately north-south and displays right offset in the order of 5 to 10 kilometers (Tjia, 1972). The remaining strike-slip faults show left offset. Two of them strike west-northwest and three trend between northwest and north-northwest. Interpreted left offsets amount to a maximum distance of 55 kilometers, which was determined by Burton (1965) for the Bok Bak fault in northwestern Malaya. If these faults moved as consequence of a single stress system, the direction of horizontal compression should have been oriented 80°-260°. Many shear planes of lesser dimensions have fault markings that are compatible with the interpreted regional compression direction. The granites have been sheared by the large faults; the evidence suggests that wrench faulting may have lasted up to early Tertiary time. Striations and other markings on the fault-planes imply that the latest movements on the faults were predominantly vertical and were superimposed upon more lateral motions (Tjia, 1972).

Sarawak, East Malaysia. – In western Sarawak a left-slip fault that trends 340° demarcates east-northeast trending structures to the west of the fault from west-northwest to northwest striking structures to the east. At one locality the fault zone is 80 meters wide and comprises cataclastic mudstone, limestone and chert beds. Drag, horizontal motion on smaller faults that are within and parallel to the main fault zone, and interpreted fold directions to the west and to the east of the fault zone, all suggest left motion (Tjia, 1970a). Geological discontinuities on existing maps and topographic lineaments imply that this Sarawak-kiri fault zone, as it has been named,

TABLE 1
Strike-slip faults in Sunda land province

Fault and location	Fault length Fault width Orientation	Sense and amount of displacement	Duration of active faulting Reference
1. Bok Bak fault Northwest Malaya	Length = 115 km Width = 1-10 km Strike = 325°	Left 55 km	Probably up to Cretaceous and vertical movement in Early Tertiary. Burton, 1965.
2. Kelau-Karak fault Central Malaya	Length = 180 km Strike = 355-360	Right 5-10 km	Probably Jurassic to Cretaceous. Tjia, 1972.
3. Lebir fault East coast states of West Malaysia	Length = 320 km Width = 5 km Strike = 340°	Left 20-40 km	Probably up to Cretaceous with vertical movements during Jurassic and Cretaceous. Tjia, 1972.
4. Bukit Tinggi fault West-central Malaya	Length = 70 km Strike = 320-325	Left 6 km	Probably up to Cretaceous. Shu, 1969.
5. Kuala Lumpur fault West-central Malaya	Length = 80 km Width = 15 km Strike = 280-300	Left 20 km	Up to Early Tertiary with vertical movements during later part of its active history; discussed by Tjia, 1972.
6. Mersing fault East-central Malaya	Length = 100 km Width = 30 km Strike = 290°	Left 20-40 km	Probably up to Cretaceous time. Chong et al., 1970.
7. Sarawak-kiri fault Sarawak	Length > 10 km Strike = 340°	Left 3.5 km	Probably up to Cretaceous and vertical movement during Early Tertiary. Tjia, 1970.

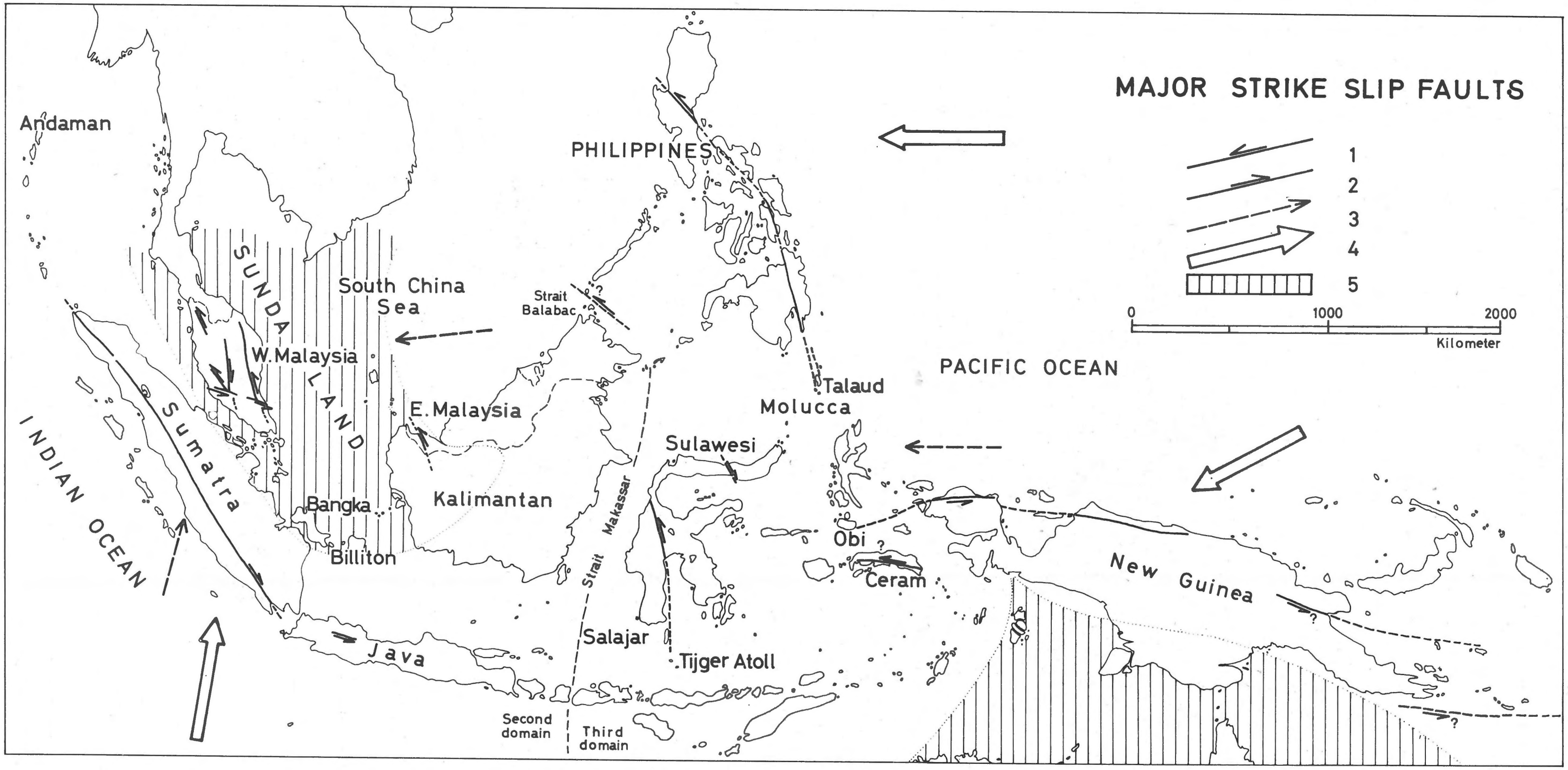
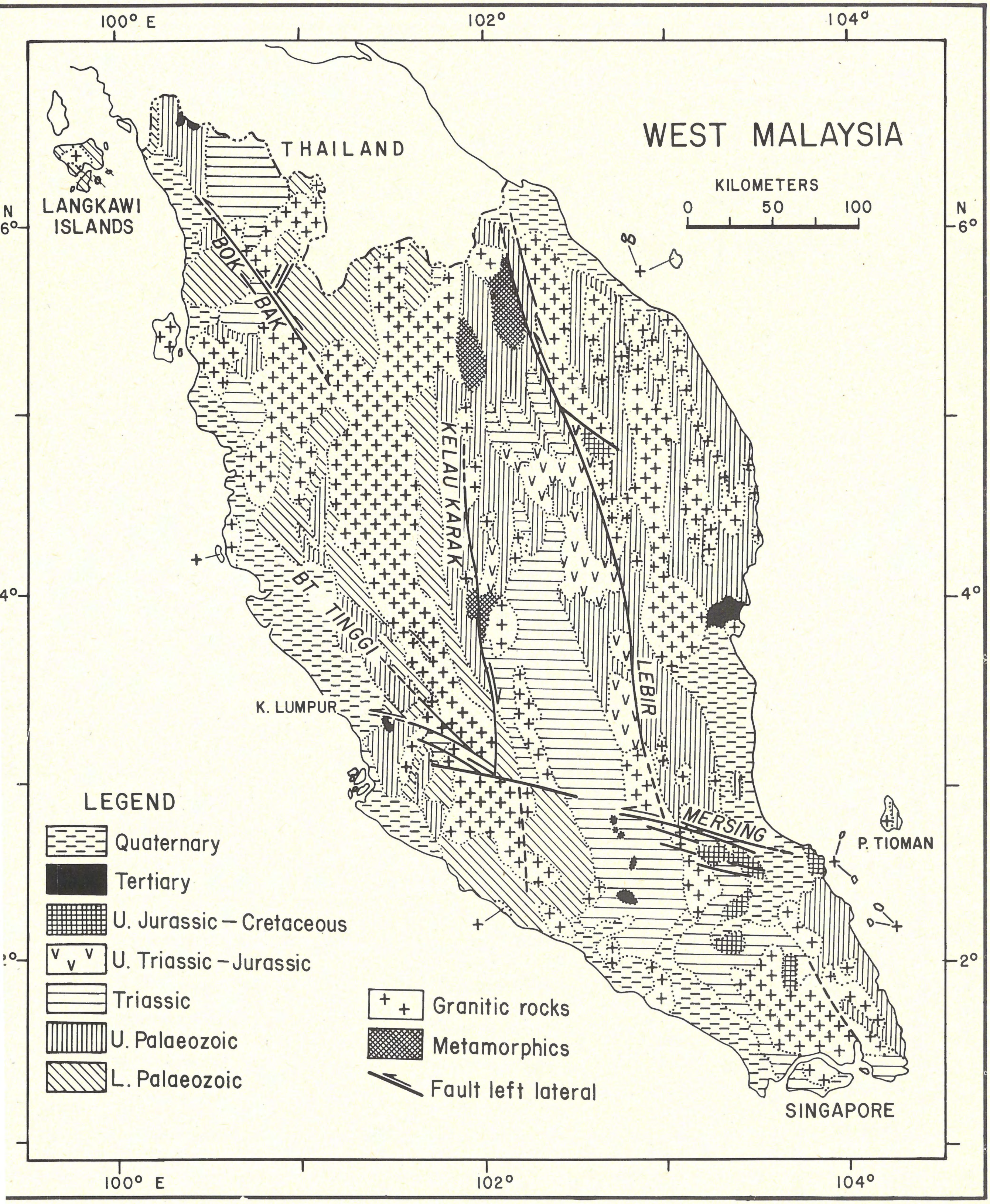


Fig. 1
1: Left strike-slip fault. 2: Right strike-slip fault. 3: Direction of regional compression interpreted from fault-plane studies. 4: Direction of com-ession at contacts between oceanic and Asian lithospheric plates on account of sea-floor spreading (after Le Pichon, 1968, and Isacks et al., 1968). 5: Semi-cratonic areas.



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tablished strike-slip faults in West Malaysia.

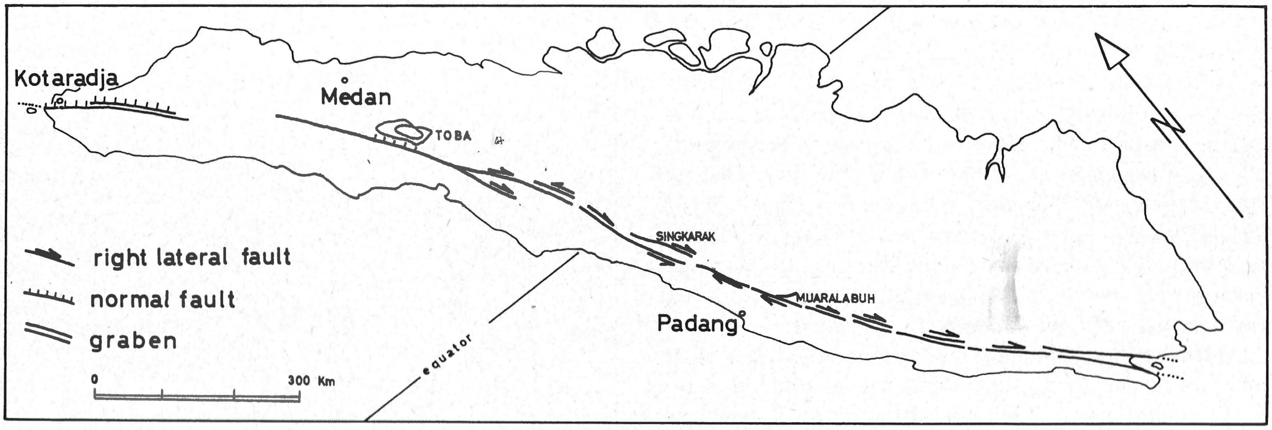

Fig 3
The Sumatra fault zone. The fault trace is mainly after van Bemmelen (1949) and Westerveld (1952) with the writer's additions based on fieldwork and interpretation of topographic maps.

may be a large and important fracture that starts in Indonesian West Kalimantan (Borneo) and extends northward along the edge of the continental shelf below the South China Sea. The fault cuts through upper Paleozoic and Mesozoic sediments. The structural history of western Sarawak suggests that faulting may have persisted into Paleogene time, after which the area has become stable as did the other parts of Sunda Land. Vertical movements seem to have controlled the latest phase of diastrophic activity; this is implied by the basinal character of all Paleogene deposits (T j i a, 1970a).

Tectonically Active Province

Sumatra, Indonesia. – Roughly parallel to the longitudinal axis of Sumatra is a discontinuous chain of straight river valleys and wider, elongated intermontane depressions with widths up to 17 kilometers. These lineaments form the Semangko or Sumatra fault zone (fig. 3) which is traceable along a distance of 1500 kilometers, that is almost the entire length of the island. D u r h a m (1940) has observed for the first time stream offsets along a 500-kilometer long stretch of the fault zone between the latitudes of Medan and Padang. V a n B e m m e l e n (1949) and W e s t e r v e l d (1952) among other investigators have interpreted the fault zone to represent a huge graben structure. The existence of stream offsets has been ascribed to hinge faulting by V a n B e m m e l e n (1949). On existing maps K a t i l i and H e h u w a t (1967) have demonstrated that right offsets along parts of the fault are predominant. According to these authors traceable right offsets range up to about 25 kilometers. West of Lake Toba, the Sumatra fault zone appears to have displaced the Toba ignimbrite over a distance of 20 kilometers; the radiometric age of the ignimbrite has been determined as less than 300,000 years (reported by K a t i l i, 1969). In that case the gross annual rate of dislocation appears to be about 70 millimeters.

Independently the present writer has found on 1:40,000 and 1:100,000 topographic maps of Sumatra that locally vertical and left displacements predominate over the general right wrenching of faults. (T j i a, 1970b). One of the areas where complex fault movements were suspected, consists of the Singkarak and Solok depressions of West Sumatra. A field check in February 1971 confirmed that these intercon-

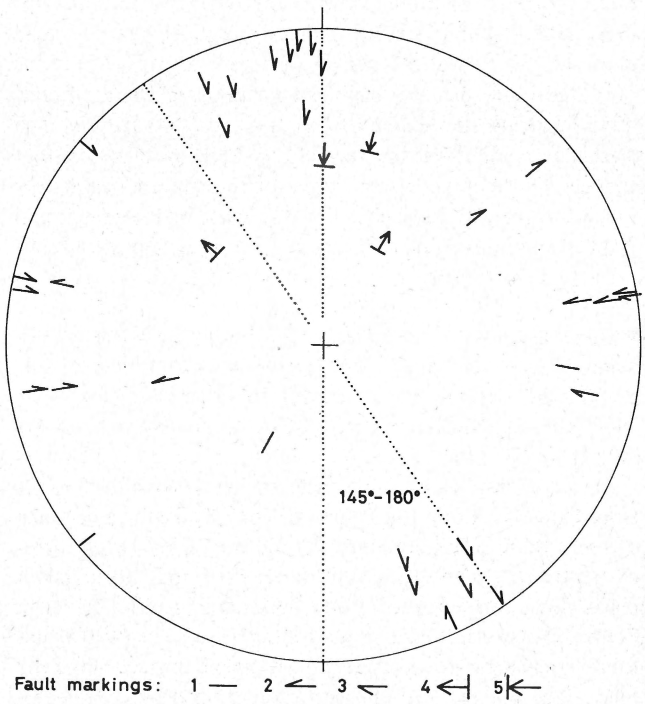

Fig. 4
Synoptic equal-area projection, lower hemisphere, of senses of fault displacement at 22 localities along a 50-kilometer section of the Sumatra fault zone south of Alahanpandjang (100°45′E/1°06′S). Sense has been determined using fault markings; 1: sense not known, 2: left, and 3: right displacement, 4: normal faulting, 5: reverse faulting.

nected depressions are bounded by oblique-slip faults that moved along the west and east walls with left and right components of offsets, respectively. It appears as if the depressions were downfaulted as a unit with a horizontal component towards the northwest with respect to their margins. In the narrower sections of the fault zone, however, fault-plane markings and subhorizontal striations on shear plane suggest predominantly right motion (fig. 4; T j i a, 1971). Between Lake Singkarak and Muaralabuh, that is approximately 120 kilometers along the Sumatra fault, right stream offsets amount to an average of 200 meters, while left displacements are about 150 meters.

Evidence of contemporary dislocations along parts of the fault zone favours right movement. Accurate geodetic measurements indicate that the 1892-earthquake of Tapanuli resulted in 1250 millimeters right movement along 50 kilometers of the Sumatra fault belt. (M u l l e r, 1895). Bent steel rails by the 1926 Padangpandjang earthquake also imply right displacement (see photograph published by V i s s e r and A k k e r s d i j k, 1927; interpreted by John A. Katili, personal communication). K a t i l i (1969) has cited other earthquake evidence from various parts along the Sumatra fault zone which appears to indicate right movements.

Java, Indonesia. – From this island only one medium-sized strike-slip fault is known with certainty. This is the Lembang fault north of Bandung which outcrops as a 22-kilometer long, 100°-striking left slip fault through Holocene volcanic deposits. No historical disturbances are known from this fault. Morphologically it has the appearance of a normal fault downthrowing the area north to it 50 to 400 meters. The west half of the fault has several consistent river offsets that average 140 meters. These lateral offsets are approximately twice the vertical displacements. The sense of movement and displacement ratio are also shown on a slickensided fault-plane (T j i a, 1968b).

Sulawesi (Celebes). Indonesia. – Early investigators in Sulawesi have recognized the existence of a number of important fault zones. Summaries of these surveys have been published by B r o u w e r (1947), V a n B e m m e l e n (1949), and K a t i l i (1969).

A large, important fault zone strikes 165° and extends from Palu Bay along the Palu and Koro rivers for a distance of more than 200 kilometers. B r o u w e r (1947) has already suspected that strike-slip movements may have taken place along this so-called Fossa Sarasina and other faults in Central Sulawesi. From a map study K a t i l i (1969) has found consistent river offsets indicating left motion along the Fossa. The present author has measured on Brouwer's geological sketch map of Central Sulawesi probable left river offsets that range between 2 and 5 kilometers; an example is a 4-kilometer left deflection of a tributary to the upper Kulawi river (see also fig. 6). In April 1971, Thomas Zakaria and the writer have surveyed a 100-kilometer section of the (re-named) Palu-Koro fault zone between Donggala and Kulawi (fig. 5). We found evidence of general left movement (horizontal striations and minor features of shear planes) and also of vertical movement that occured in the Palu Bay and Palu valley. Gently folded alluvial deposits along the Tawaeli river suggest left drag (fig. 6). Compared to the horizontal displacements (at least a few kilometers) the vertical throws are of distinctly lower order (a few hundreds of meters) and the fault zone should be considered as a wrench fault. A photogeological study is under way to determine the maximum amount of displacement along the fault. Current activity of the Palu-Koro fault is indicated by frequent earthquakes and a fault-terminated alluvial fan a few kilometers southeast of Palu town. Towards the south the Palu-Koro fault appears to continue along the fairly straight west edge of the Bone Basin as far south as Taka Garlarang or Tijger atoll-group. K u e n e n (1935) has interpreted this submarine lineament as a normal fault on account of its linearity, quite steep slope, flat bottom of the Gulf of Bone, and the general westward tilt of Salajar islands which lies to the west of this lineament. If this is true, the Palu-Koro fault zone comprises a length of about 750 kilometers.

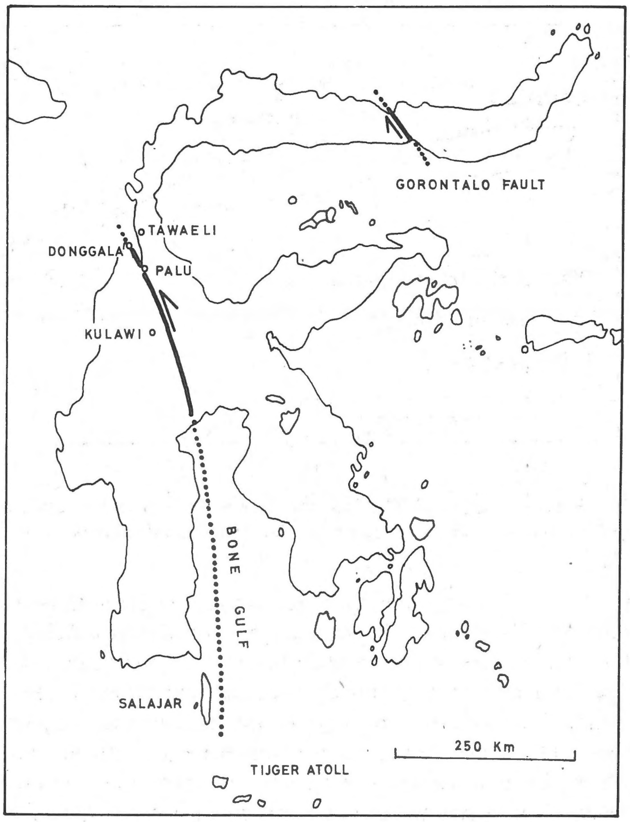

Fig. 5
Strike-slip faults of Sulawesi and index map.

From maps and geologic considerations K a t i l i (1969) has assigned 35 kilometers of right movement to a 335° trending lineament across the north arm of Sulawesi near Gorontalo (fig. 6).

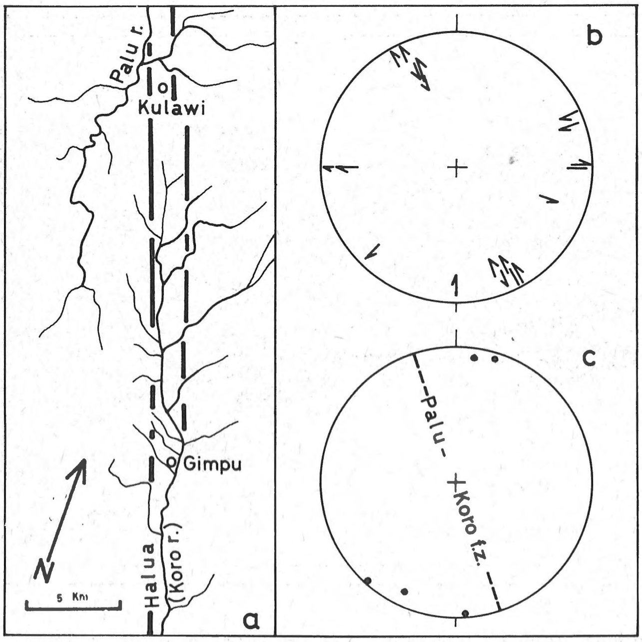

Fig. 6
(a) Left stream offsets along a segment of the Palu-Koro fault zone, Sulawesi. Fault trace by former investigators and field observations north of Kulawi. Drainage from a 1: 200,000 planimetric map of the Indonesian Topographical Survey.
(b) Synoptic equal-area projection, lower hemisphere, of senses of displacement at three localities along the Palu-Koro fault zone, i.e. 1) a few kilometers south of Donggala, 2) near the confluence of the Gumbasa river with the Palu river (119°57′E/1°12′S), and 3) a few kilometers north of Kulawi.
(c) Equal-area projection, lower hemisphere, of fold axes in alluvial deposits now 20 meters above the Tawaeli river; fold wave lengths are about 100 meters. The folds are most probably drag phenomena by left displacement along the Palu-Koro fault zone, about 4 kilometers to the west of this locality (119°55′E/0°40′S).

Strait Balabac fault. – F i t c h (1961) has proposed a northwest trending fault beneath Strait Balabac between Banggi and Palawan islands off the northern tip of Borneo (fig. 1). Indications consist of a sudden magnetic anomaly change that suggests a drop of the basement from 900 meters to 3000 meters, the transection of Tertiary structure to the west of the strait, and a probable 50-kilometer, left displacement of two geologically similar islands, namely Palawan with respect to Banggi.

Ceram island, Indonesia. – The existence of a 300-kilometer, west-northwest trending graben that includes the Tala, Ruatan, Bobot, and Masiwang valleys in Ceram has been well established (V a n B e m m e l e n, 1949, p. 451). The vertical movements that have resulted in the graben are believed to have predominated in the Middle Quaternary. Fig. 7 indicates that north of the longitudinal Ceram fault, crystalline schists outcrop as far east as the longitude of Wahai. South of the structural line, crystalline schists outcrop 60 kilometers farther to the east in the vicinity of the Bobot valley. Furthermore, V a l k' s (1945) geologic map of western Ceram shows consistent left offsets of a few hundreds of meters along various tributaries to the Tala river.

On these grounds it appears that the Ceram fault may represent left movement during at least part of its existence. The latest movements on the fault seem to have been predominantly vertical, but throws are probably of a lower order compared to horizontal displacements. For instance, Plio-Pleistocene deposits imply by their locations an uplift of about 900 meters in Ceram in the last few million years.

West Irian (Indonesia) and Eastern New Guinea (Australia). – Oil explorations carried out after World War II in West New Guinea resulted in the discovery of a large, approximately east-west trending series of fault zones that extend onshore for a distance of 1300 kilometers between Sorong and Wewak (fig. 8). Various names have been given to the interrupted parts of the lineament by V i s s e r and H e r m e s (1962), but for brevity sake the entire fault zone will be referred to as the Sorong fault zone in this article. At its west end, the Sorong fault zone *sensu stricto* comprises cataclastic and mylonitic bands that may attain combined widths of 4 to 8 kilometers. The tectonic breccia consists of small to gigantic blocks, most of which indicate derivation from formations adjacent to the fault zone. In the northeastern part of the Bird's Head (Vogelkop) elongated igneous bodies appear to have been emplaced in the Sorong fault zone and their sheared nature implies continued movements after consolidation. On stratigraphic grounds V i s s e r and H e r m e s (1962, p. 159) have interpreted the Sorong fault zone as a strike-slip fault with about 350 kilometers left displacement since Middle or Late Miocene. This distance is suggested by a northern provenance of the middle to late Miocene Klasafet beds that outcrop to the south of the shear zone in the Bird's head, while the Klasafet detritus is similar to certain Jurassic rocks that outcrop on Obi island (fig. 1). The stratigraphy also suggests that the fault movements persisted at least into the Pleistocene. Since the deposition of the Klasafet beds the gross annual rate of horizontal movement along the fault averages 30 millimeters.

Other large faults in New Guinea strike more or less parallel to the Sorong fault zone or in northwesterly direction (fig. 8). The linearity of these faults and the orientation of folds nearby suggest strike-slip movements. For instance, left displacement along the north-northwest-striking Jakati-Jamur fault zone is implied by the more northerly trend of fold-axes immediately east of the fault zone (see V i s s e r and H e r m e s, 1962, fig. III-II, p. 147). However, the majority of previous investigators has thought of these shear zones as normal faults. It seems quite possible that, for reasons given at the beginning of this paper, these geologists have not yet been able to detect horizontal dislocations and may have been impressed by the results of vertical components of movement.

An exception is K r a u s e (1965, 1967) who has assumed left movement on at least two submarine fault zones, that is

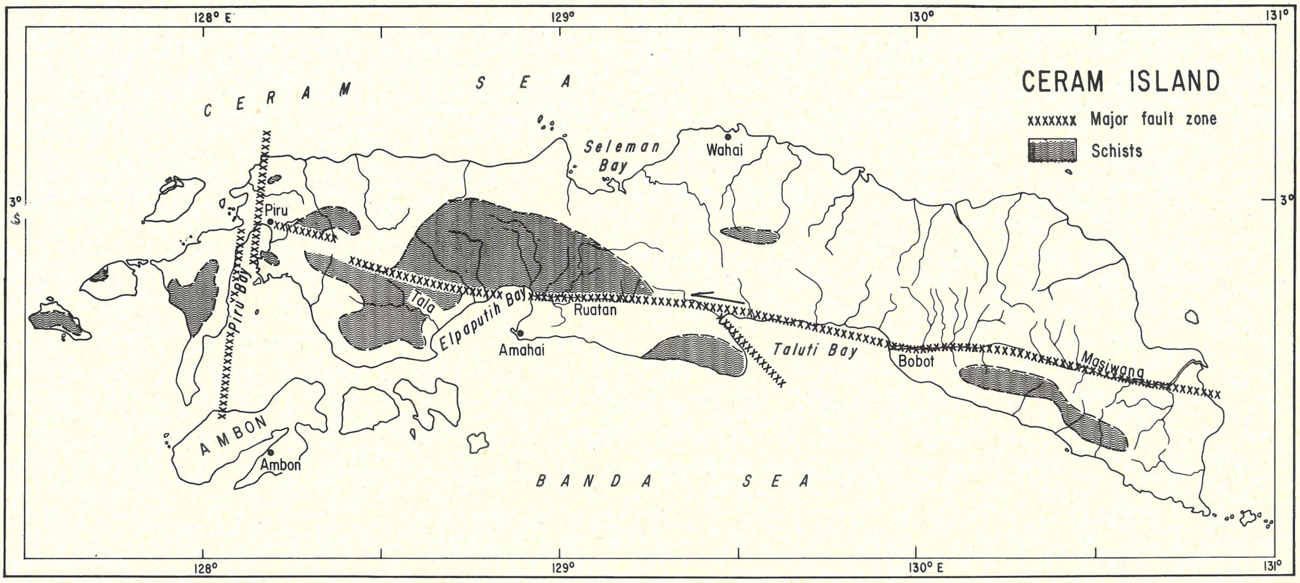

Fig. 7
The Tala-Ruatan-Bobot-Masiwang structural belt interpreted as a graben by previous investigators. The distribution of schists shown on Rutten's geologic sketchmap (1927, fig. 227) suggests left dislocation.

the west-northwest striking, 700 kilometer long Papua-Solomon fault zone (probably 180 kilometer offset) and the east-west trending, 1100 kilometer long Pocklington fault zone. Krause has advanced as supporting evidence for the strike-slip character of these faults their great lengths, linearities, and parallelism to the Sorong fault zone.

Philippines and northern Moluccas.– Geological correlation of various islands of the northern Moluccas, Indonesia, and new bathymetric information have led K r a u s e (1966) to extend the Philippine fault zone for another 450 kilometers farther towards the south into northern Molucca. This left slip fault is known to be 1200 kilometers long within the Phillipine archipelago (A l l e n, 1962). K r a u s e (1966, p. 828 etc.) has contended that the Talaud islands may have been counterparts of the Nanusa islands before the two groups became separated by 110 kilometer left displacement along the fault zone. The relief that has been caused by young vertical movements amount to a few thousand fathoms which seem to be a small fraction of the horizontal dislocation.

CONCLUSIONS

It has been shown in the foregoing sections that various large fault zones in the Indonesia-Malaysia-Philippine region have important horizontal displacements some of which amount to scores of kilometers, The size of these faults and the consistent sense of movement along each of the shear zones must reflect the influence of regional stress systems. Three tectonic domains, each with a characteristic stress system, can be distinguished. One domain coincides with the Sunda Land Province where strike-slip faulting appears to have been controlled by a regional compression acting in 80°-260° direction. The compression resulted in right displacement along the north-south trending Kelau-Karak fault zone and imparted left dislocations on six other fault zones (two striking west-northwest and four striking within the northwest to north-northwest sector (table 1, T j i a, 1972). In West Malaysia medium-sized wrench faults (a few hundred meters long) also display senses of motion that are compatible with a similar compression direction. For instance, in the Sungei Lembing tin mine (103°E, 40°50'N) the 60°-striking Kabang fault caused 600 meters right offset. In turn a possible north-northwest trending fault offsets the Kabang fault left by 300 meters (F i t c h, 1952).

The geology of the Sunda Land suggests that horizontal compression may have persisted up to the end of the Mesozoic or even into Early Tertiary. At several fault zones, more vertically pitching fault striations are considered as superposition upon indications of horizontal motion. Normal faulting most probably indicates attempt toward restoration of the isostatic equilibrium that became disturbed by the strike-slip movements.

The second tectonic domain comprises Sumatra and Java. The predominantly right movement along the Sumatra fault zone suggest a horizontal compression acting along the south-east to southwest trends. In west central Sumatra, field data from a 120-kilometer long section of the fault zone indicate a compression between south and south-southwest (T j i a, 1971; to be published). Active right dislocations are indicated by several recent earthquakes. The left displacement on the 100°-striking Lembang fault in Java is compatible with a

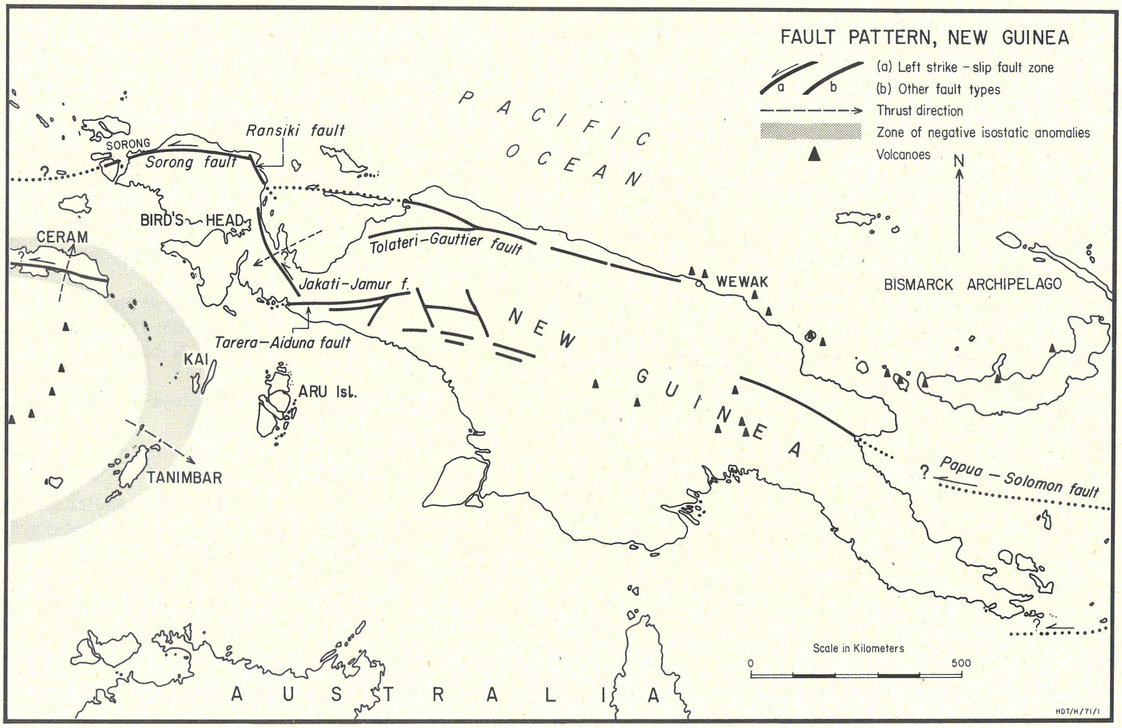

Fig. 8
Left slip on Sorong fault zone and other major fault belts in West Irian and Eastern New Guinea.

general southwest-northeast compression.

In the third tectonic domain that includes Indonesia east of Strait Makassar, eastern New Guinea, and the Philippines, the senses of large-scale strike-slip faulting may be explained by one regional compression acting approximately east-west. One exception is the right Gorontalo fault that does not seem to have moved as direct consequence of that compression.

Three rather recent papers have expanded upon the hypothesis by Vening Meinesz (1954) that the southeast Asian region is pushing southeastward against Australia. Allen (1962) has proposed that such movement of the Southeast Asian block has caused right and left wrench faulting along its western (Sumatra fault) and eastern (Philippine) margins. Rodolfo (1969, fig. 15, p. 1226 etc.) has suggested that the "rhombochasms" of the Andaman basin and the South China Sea basin may have expanded in a NNW-SSE direction which caused net movement of the Southeast Asian block to the south-southeast and shearing along its margins. Katili (1969) agrees with Allen (1962) and observed that the Palu-Koro fault (his Fossa Sarasina) and Gorontalo fault appear to fit into the shear grid pattern of Vening Meinesz (1954). Katili further related movements along the Bok Bak fault (his "Malayan fault"), Lembang and Sorong faults with eastward drift of Australia relative to the westward motion of the western Pacific floor.

The present paper has shown that the geologic development on the Sunda Land has reached stages different from the presently active regions. Some of the aforementioned authors have overlooked this fact and have tried to relate the Bok Bak fault movement, presumably the only strike-slip fault that was known from the Sunda Land at the time of their writings, with fault movements of still active shears in Sulawesi and Irian.

The compression directions for the active western part of Indonesia and for the other areas east of Strait Makassar as concluded in this paper are in rather close agreement with Le Pichon's (1968) stress directions for this region. The stresses that occur at contacts between the six major lithospheric plates of the earth have been computed by Le Pichon from rates of ocean floor spreading and from orientations of transform faults near the spreading centers (mid-oceanic ridges). Isacks et al. (1968, p. 5861) have largely corroborated le Pichon's findings with earthquake mechanism studies. Both papers show that the direction of compression between the Indian Ocean plate and the Asian plate is approximately 10°-190° near Sumatra and Java (fig. 1). At the latitude of the Philippines the compression is east-west and off the north coast of New Guinea it is 60°-240° between the Asian Plate and the East Pacific plate (fig. 1). Provided that the right-slip nature of the Gorontalo fault has been correctly deduced, its seemingly aberrant motion with respect to the regional compression direction may probably be attributed to a faster rate of northward movement of the area west compared to that east of the fault.

Similarly, the 80°-260° compression direction that seems to have influenced horizontal motions on large strike-slip faults of the Sunda Land may have been generated by a? late Mesozoic spreading movement of one of the adjoining ocean floors relative to the Asian lithospheric plate.

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