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Superimposed deformations and vergence of lower Tertiary sediments near Tatau, Sarawak

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Abstract: Good, and often extensive outcrops along the trunk road in the vicinity of Tatau, Central Sarawak, exhibit a variety of complex structures. The older rocks are typical turbidites of Late Eocene to Early Oligocene age that in the Arip area are also associated with products of explosive volcanism. These are unconformably separated from mid-Oligocene to mid-Miocene sediments of neritic, but mostly of littoral character. The younger rocks are much less deformed than the former.

The turbidites possess wide zones of slumping and upon these non;diastrophic structures were superimposed tectonic structures. Mainly two tectonic vergences were found, an earlier vergence northward that is represented by large-scale recumbent folds and a later west vergence that produced overturned folds of moderate dimensions.

We interpret the lithology, soft-sediment and tectonic deformations of the Early Tertiary sediments in the Tatau area to have taken place in a fore-arc basin on the ocean side of a magmatic arc. The superimposed west upon north vergence may have been formed by warping about the Tatau area of an initially east-west elongated fore-arc basin. The regional structural trends support this interpretation. As an extrapolation of the interpreted island-arc setting for the Tatau area, some 200 to 250 km north of the Arip area is probably the buried SW-extension of the Palawan subduction zone. Activity on this particular extension began in the Late Eocene, while the Palawan suture proper only started in mid-Oligocene time.

INTRODUCTION

Along the trunk road between Bintulu and Sibu, in the vicinity of Tatau, are exposed Palaeogene sediments that were deformed into complex structures. In the past two field seasons, detailed observations were carried out for roadcut outcrops that occur along a stretch approximately 6 km to the north and 8 km to the west of the bridge across Batang Tatau (Fig. 1). In addition, two of us carried out several off-the-road traverses to complete mapping for the final year undergraduate reports required by the Department of Geology, Universiti Kebangsaan Malaysia. Borhan Sidi (1985) and Teoh Chuen Lye (in preparation) mapped areas east and west of the Batang Tatau, respectively.

Wolfenden (1960) wrote Memoir 11 of the Geological Survey of Malaysia (at the time of publication known as the Geological Survey Department, British Territories in Borneo). This memoir includes the Tatau area. On the latest regional map of Sarawak (Tan, compiler, 1982) the geology of the Tatau area is shown identical to those produced by Wolfenden. However, the newer map indicates some changes in regional stratigraphy.

GEOLOGIC SETTING

The stratigraphy of Tatau and environments to be described below has been compiled from published information by Liechti (1960), Wolfenden (1960), the new regional map of Sarawak, and our field observations.

The oldest rocks are sediments that belong to the Bawang Member of the Belaga

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Formation and is of Tb age. The Bawang Member consists of argillite, phyllite and rare arenite, intensely folded and with low-grade metamorphism. However, along the road west of Tatau bridge, where it entirely runs in the Bawang Member according to published maps, we saw that arenite of graywacke and subgraywacke types were not rare. The sediments show all characteristics of typical turbidites. Interbeds of dm-dm to cm-dm arenite and argillite (which are often tuffaceous) with sole markings including small flute, groove, and prod casts, graded bedding, metres-wide slump horizons, occasional intraformational conglomerate and rare ripple marks are typical. Barely, a few scores of metres thick packets of red mudstone or shale among the sequence probably represent deep-sea red clay deposits. Locally black and also tuffaceous argillite beds have been sheared by flexuring parallel to bedding and have become phyllitic. These phyllitic mylonite zones may contain subangular to streamlined arenaceous clasts and nests of medium-sized quartz crystals. Bed-parallel shearing of argillite beds is especially common in outcrops occurring within a stretch of 3 km to the west of Tatau bridge. According to Liechti (1960, p. 676, etc.) the Bawang Member was deposited in a bathyal environment.

Published information on the next rock unit, the upper Ta to lower Oligocene Tatau Formation, mentions that it can be distinguished by its more arenaceous character and its moderate deformation. The different deformation styles between the Tatau and Bawang units and some stratigraphic considerations (see below) led previous authors to interpret an unconformity between the rock units. Where the road is supposed to run within the Tatau Formation, northeast of Tatau bridge, argilllites are indeed of less importance and arenaceous beds tend to be thicker and sometimes massive. Nevertheless, the main lithologic character is that of turbidites consisting of arenaceous-argillaceous interbeds, slump horizons, sole markings, and graded beds. In our study we were unable to improve on Wolfenden's map and a detailed stratigraphic investigation is required to map the boundary of these rock units. Ten kilometres southwest of Tatau hamlet, the Tatau Formation also includes rhyolitic and andesitic lava and ignimbrite. According to Liechti (1960, p. 47 etc.) the Tatau rocks in the particular study area belong to the upper part of the formation. Marl and small lenses of limestone have also been mapped. Upward the formation passes into the Buan Formation. The lava flows were formed subaerially, but the sediments were deposited in a neritic environment. However, the regular turbidites and slump horizons associated with neritic sediments are best explained as having developed at the foot of a continental slope where the turbidites were *in situ* and the neritic sediments slid down from the shelf area. The modern designation of olistostrome for the Tatau Formation seems appropriate.

The Tatau Formation is conformably overlain by the Buan Formation (mid-Tcd) that consists of arenite, lutite, and arenaceous argillite. The unit is moderately folded. The Buan rocks were probably deposited as littoral sediments; occasionally true neritic conditions prevailed.

The Nyalau Formation (upper Tcd to Te_{1-4}) intercalates with the Buan Formation and is locally unconformable upon the Tatau as well as upon the Belaga Formation (to which the Bawang Member belongs). The Nyalau Formation consists of thick arenaceous beds with subordinate lutite and argillite, locally conglomerate and lignite beds. South of the Kelawit fault, the formation consists of carbonaceous shale with sandstone interbeds. These beds strike 70° and are near-vertically dipping near the fault. Approximately 6 km from Tatau junction towards Bintulu, the base of the Nyalau Formation is represented by polymict conglomerate containing arenaceous lenses. The phenoclasts are arenite, quartzite, and flat/elongated argillite fragments set in an argillaceous matrix. Farther eastward along the road, the Nyalau rocks are characterised by moderate to gentle deformation forming wide open folds with kilometres-long wave lengths in stark contrast to the tight structures exhibited by the Tatau and Bawang lithologic units. The competent arenite beds of the Nyalau Formation form ridges and cliffs near Tatau.

Outside the immediate vicinity of Tatau, the next younger unit is represented by the Tf Balingian Formation of arenite, argillite and lignite. Beds incline gently at 10 degrees or less on Wolfenden's map. No rock of Te_5 -age has been proved and the base of the Balingian Formation is not known. The abundance of lignite, occurrence of brackish-water foraminifera with lenticular beds of fine grained to very coarse grained clastics define a deltaic environment of deposition. Upward the formation is unconformably overlain by the Begrih Formation; its lower boundary has not been observed. Its fossils posses no stratigraphic value and investigators assigned a Tf age to the formation, while part of it may be older (Wolfenden, 1960, p. 74).

The succession further comprises the Pliocene Begrih Formation (older), the Pliocene Liang Formation (younger), and unconsolidated sediments plus terrace deposits that have been assigned a Quaternary age. The Begrih Formation begins with a basal conglomerate resting upon an unconformity. Upward it is succeeded by other clastics and is separated by another unconformity from overlying beds. Fauna indicates a mixed marine and brackish-water depositional environment and some of the fossils represent Tg age. Tuffaceous admixtures in some of the Liang beds are believed to have originated in the Usun Apau region, some 130 km to the east of Tatau. The Liang Formation began with a marine transgressive sequence and ended as lagoonal or deltaic sediments. Geophysical studies indicate that the Liang Formation underlies much of the present coastal plain. The formation mainly consists of arenaceous clay and bluish clay containing fossil casts, abundant lignite and ends with conglomeratic sand. Its foraminiferal content is considered to indicate Late Pliocene age. Its depositional environment was probably mixed deltaic/lagoonal and shallow marine. Each of these three units is separated by unconformities from the older units. The Quaternary deposits are undeformed, the Pliocene units only mildly so.

In terms of petroleum geology, the Tatau area forms part of the southern boundary of the Balingian Province (see e.g. Ho, 1978). South of Tatau hamlet a 60° striking fracture, the Kelawit fault separates the Upper Eocene Bawang Member in the north from the Te_{1-4} Nyalau Formation to its south. Downthrow towards south is of the order of a few hundred metres. Towards Bintulu, a similarly striking fault, the Batu Kapal fault (Kho, 1965) is arranged *en echelon* with respect to the former. This fault downthrows towards the north for several hundred metres. The original investigators believed these faults to possess normal character. Their rectilinearity, *en echelon* arrangement and downthrows in opposite directions are features usually associated with strike-slip faults. The Bawang sediments strike ENE while the Nyalau beds south of Tatau trend easterly; both trends suggesting left lateral slip along the Kelawit fault. This fault and the Batu Kapal fault may represent an important strike-slip fault zone in central Sarawak.

Figure 2 shows schematically the geological history of the northern part of Borneo. The

Tatau area under discussion is included in central Sarawak. Pre-Tertiary rocks are only known from the core of Borneo that includes that part of Sarawak west of an including the Lupar valley. In central Sarawak, three deformation phases have been interpreted (Liechti, 1960). An upper Eocene phase occurred within the geoclinal depositional sequence, or between the rocks of the Bawang Member and those of the Tatau Formation. Two upper Neogene phases of deformation bracket the Liang Formation. Details were given by Wolfenden (1960, p. 92-105). From the tectonic and regional maps (Liechti, 1960; Tan, 1982) we see that Tatau forms a pivot in Sarawak; structural strikes are ENE and WNW to the east and west of Tatau, respectively.

FIELD OBSERVATIONS

The following descriptions of relevant outcrops begin at the northeast end of the road stretch under study where the base of the Nyalau Formation is exposed and proceed southerly towards Tatau and westward beyond Tatau bridge. Localities are shown on figure 1.

Locality 1.- At this locality is exposed the base of the Nyalau Formation and consists of polymict conglomerate at least 10 metres thick that stratigraphically upward is succeeded by thick-bedded arenite and argillite beds. The arenite is cross-bedded. The dip is 32 degrees and on Wolfenden's map this locality is part of a northeast plunging anticline. The beds are transected by a vertical fault striking 340° which parallels bedding strike. On the fault plane striations are 160/10 and a fault-prod groove indicates left slip. This motion was succeeded by normal faulting that caused downthrow to the east.

Locality 2.- Two long, opposing roadcuts exhibit a large recumbent fold consisting of 50 cm thick arenite beds intercalated with 20 cm argillite beds. Stratigraphic facing is indicated by graded bedding and suggests the large structure to be a recumbent anticline with its fold axis = 150/0 and its vergence towards east-northeast (fig. 3). A reverse fault, 130/40 also indicates tectonic transport towards northeast. The turbidite at this outcrop belongs to the Tatau formation.

Thinner intercalations of arenite and argillite in the vicinity of locality 2, and, therefore, presumably also belonging to the Tatau Formation, were deformed more tightly and sometimes may consist of contorted folds (fig. 4a). The deformed fold axes may exhibit general parallelism to nearby large fold axes or appear to be of only local importance being associated with steep to near-vertical axes. The second category of axes is classified as tectonically deformed slump fold axes.

Locality 3.- At locality 3, approximately 4.5 km from the Tatau junction towards Bintulu, the eastern roadcut exhibits a slump horizon some 7 m wide (fig. 4b). The diamictite consists of warped arenaceous clasts reaching lengths of 0.8 m, enclosed by deformed and sheared argillite. The bent arenaceous clasts and drag in adjacent sediments suggest that transport (slumping with or without tectonic motion) was towards north. Rocks of this outcrop probably belong to the Tatau Formation.

Locality 4.- At this locality some 2 km towards Sibu from Tatau bridge are exposed arenite (not more than 40 cm thick) interbedded with argillite (25 cm or less thick) to form turbidites. Occasionally there are single or a couple of up to 75-cm thick arenite beds. The argillite is light coloured and is tuffaceous. These beds are usually sheared through bed-

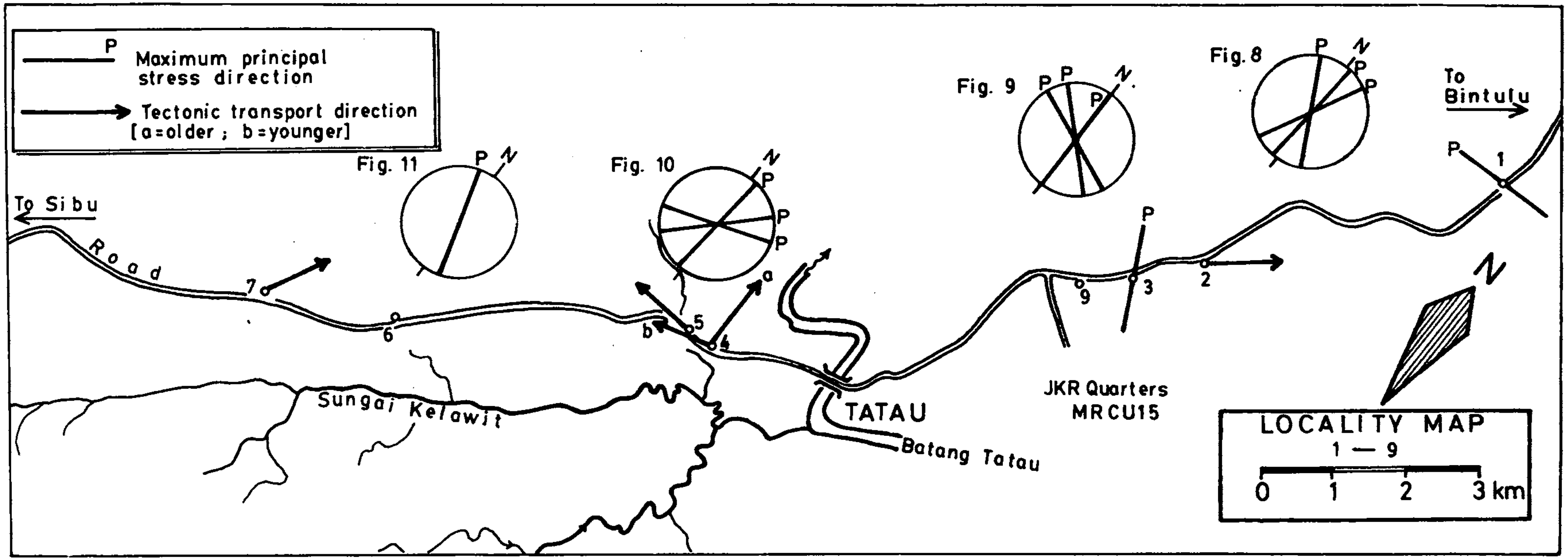

Fig. 1 a. Locality map of the road stretch near Tatau and discussed in this article. Localities are numbered.

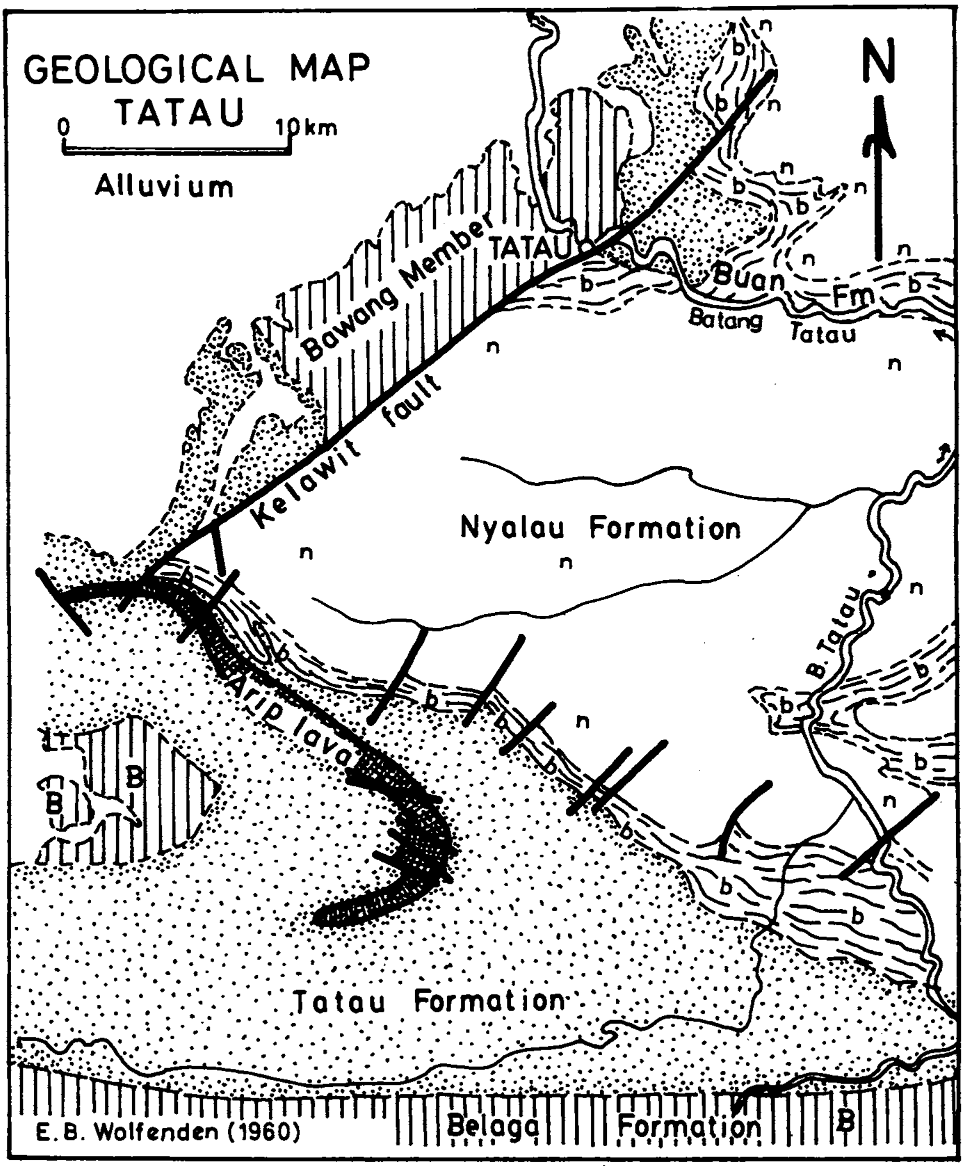

Fig. 1 b. Geological map of Tatau and environments copied from part of E.B. Wolfenden's (1960) map.

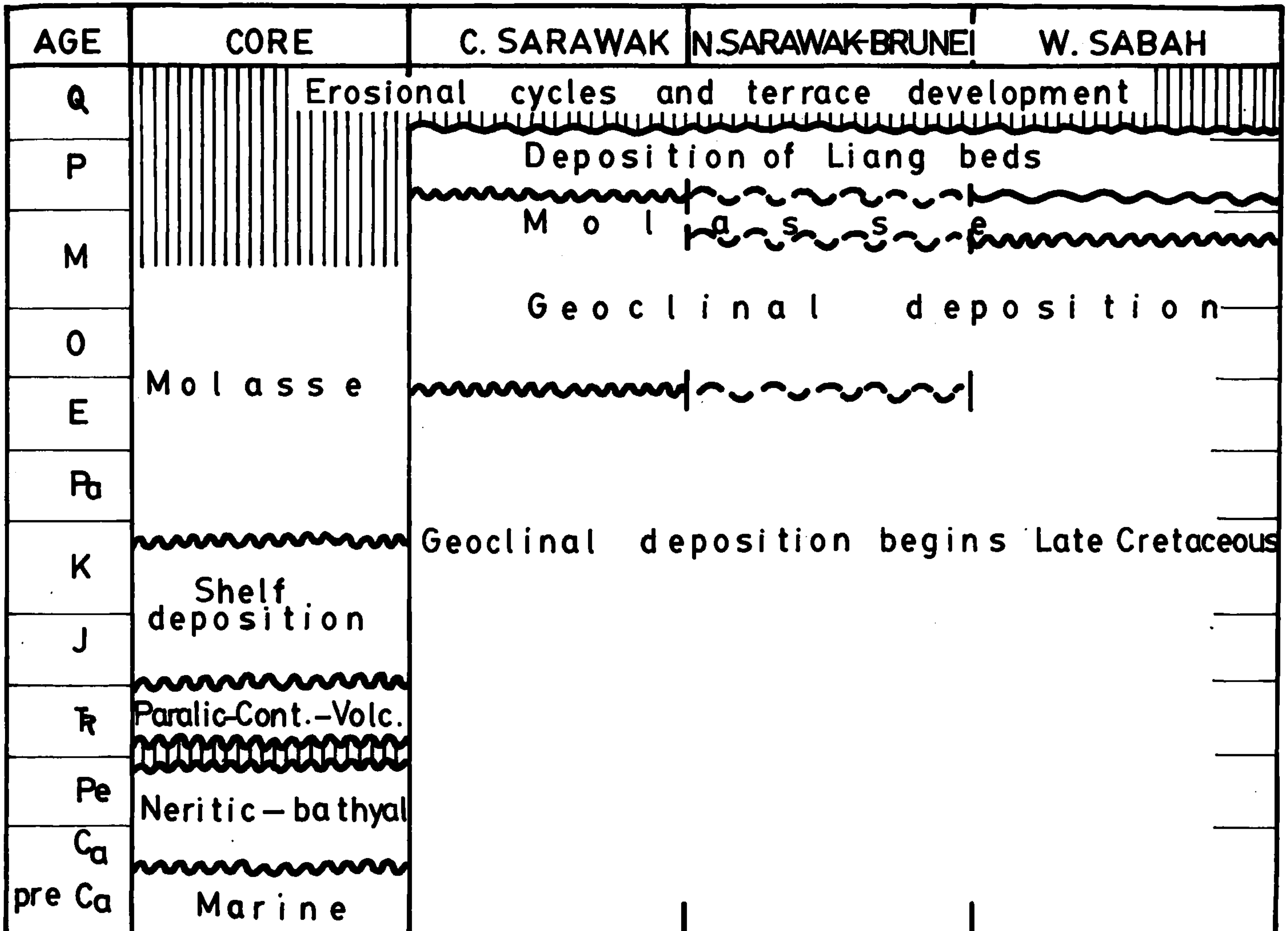

Fig. 2. The geological history of the core and northern region of Kalimantan-Borneo. Geoclinal deposition = thick accumulation of sediments in elongated basins through ordinary sedimentary processes, slumping, and accretion resulting from subduction. Data are from various sources mentioned in the reference list.

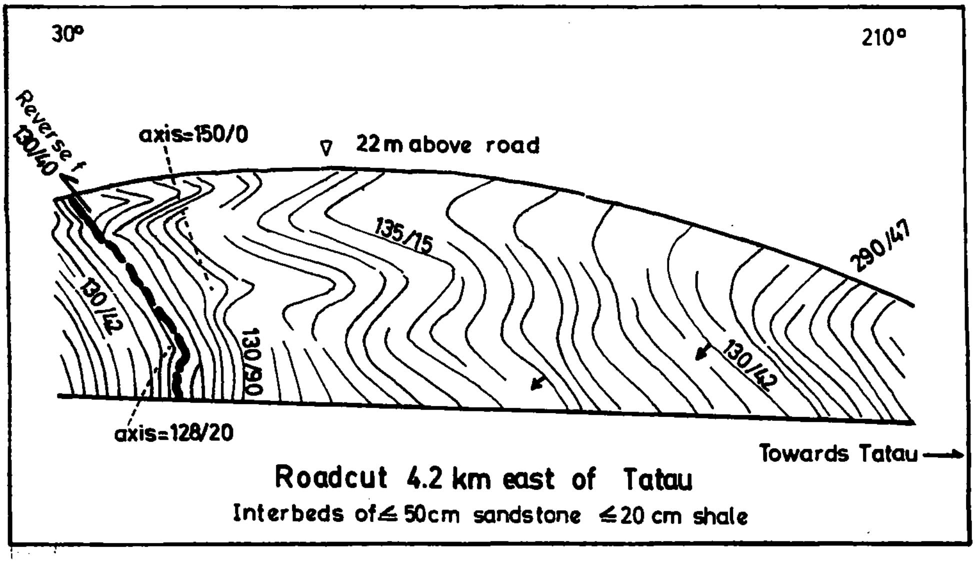

Fig. 3. A long road cut exhibiting part of large recumbent anticline with northeast vergence in turbidites of the Tatau Formation. Locality 2 (see fig. 1 a).

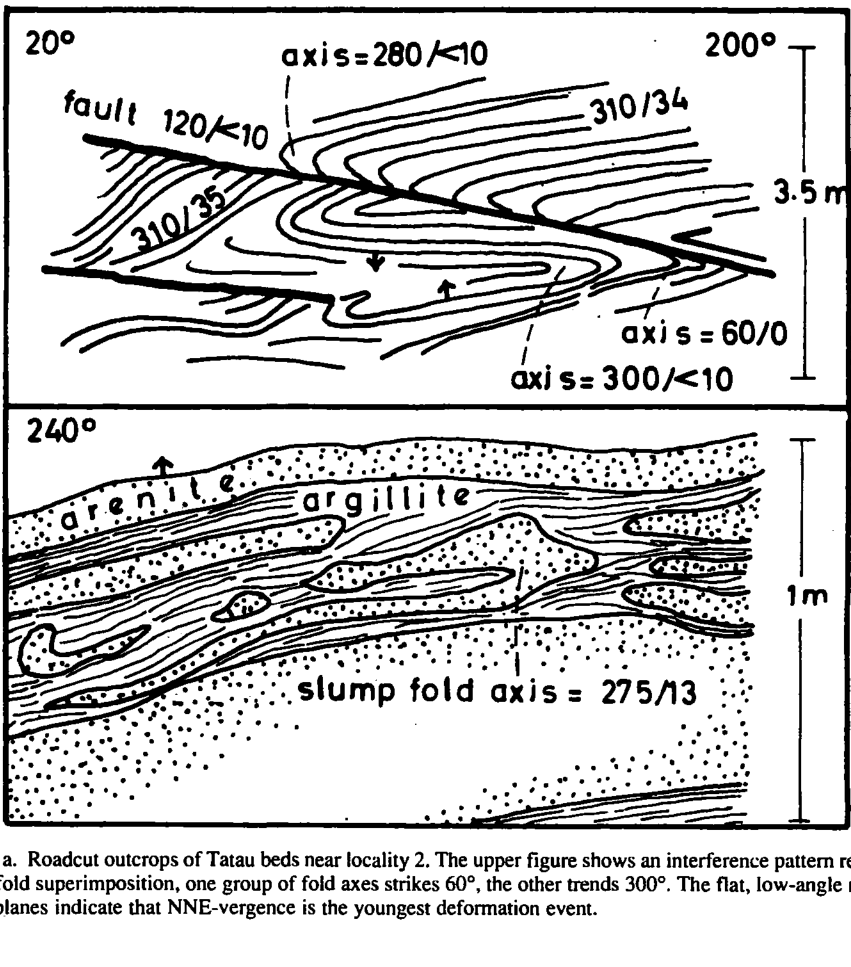

Fig. 4 a. Roadcut outcrops of Tatau beds near locality 2. The upper figure shows an interference pattern resulting from fold superimposition, one group of fold axes strikes 60°, the other trends 300°. The flat, low-angle reverse fault planes indicate that NNE-vergence is the youngest deformation event.

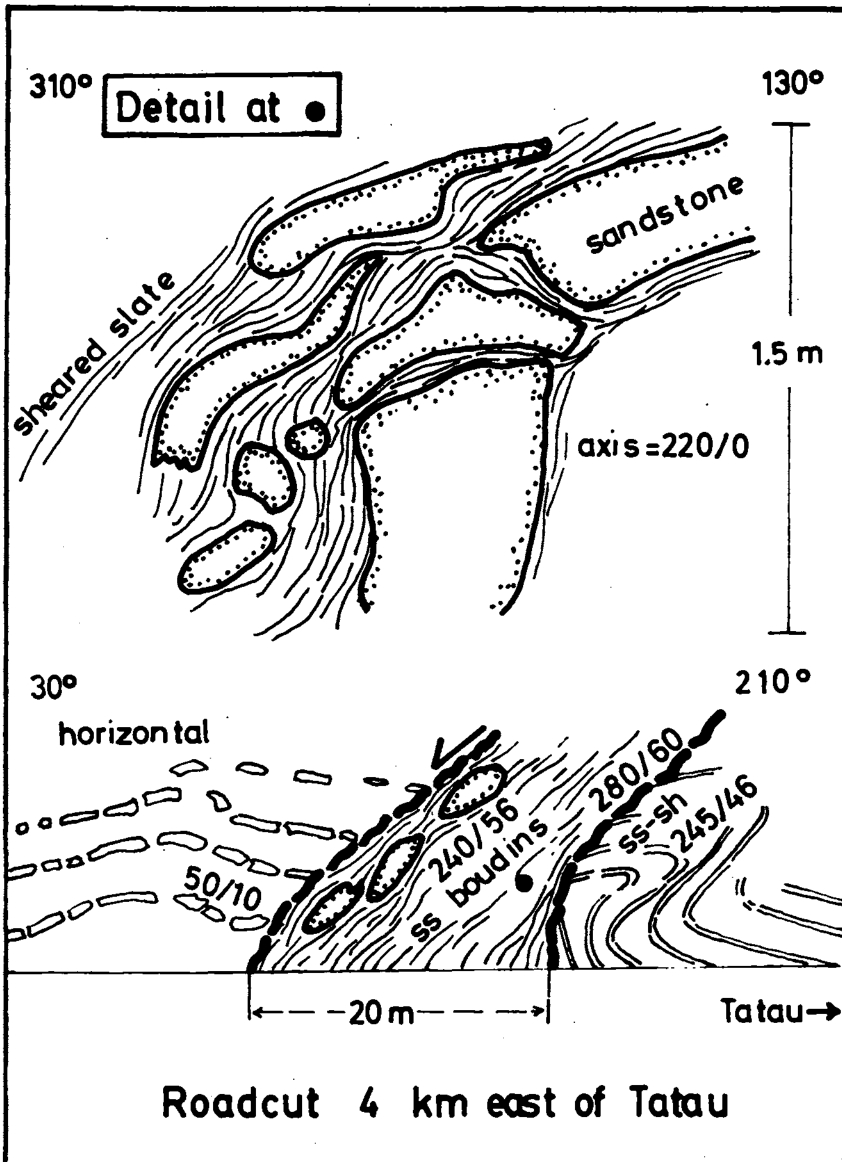

Fig. 4b. A 7-metre wide (its outcrop is approx. 20 m wide because of the oblique intersection of outcrop face with the strike of the slump zone) slump zone consisting of large, sometimes bent arenaceous clasts in argillaceous matrix (see detail in the upper part) separates two different deformation styles of Tatau beds to the SW and the NE of the zone, respectively. Locality 3 (see fig. 1a).

parallel flexuring. On Wolfenden's maps the locality is within the Bawang Member. The lithology, however, resembles that of the Tatau Formation.

Grading is common in the arenite beds and stratigraphic facing can be confidently established (see fig. 5). The general style is that of medium size overturned folds with N-S trending limbs and cut by strike-parallel reverse faults. Fold axes may dip steeply and non-coaxially superimposed folding is apparent in the eastern side of the outcrop. Stratigraphic

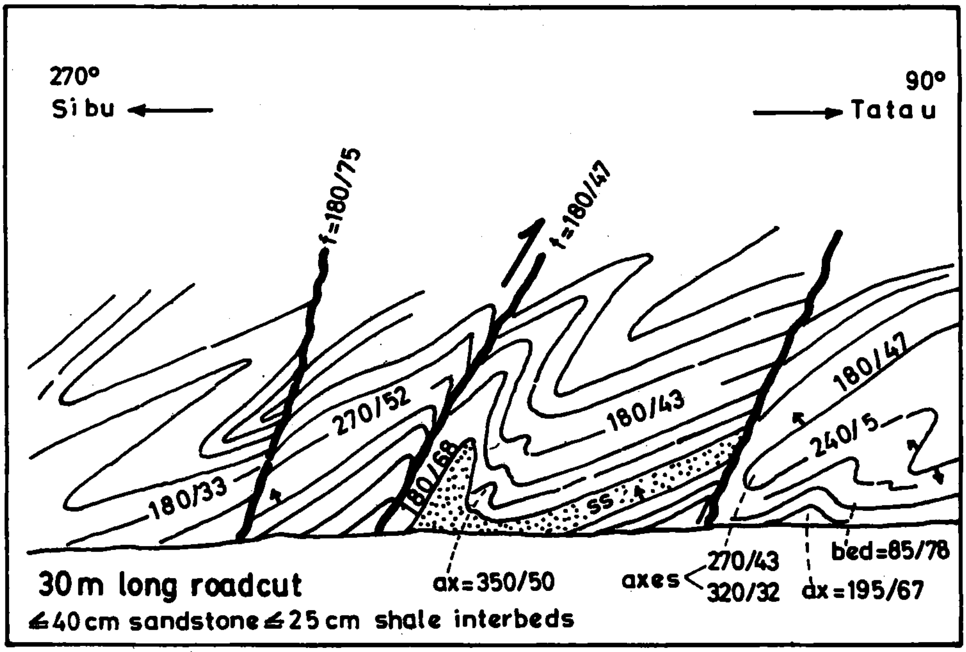

Fig. 5. Turbidites (as reference one of the arenite beds in shown by fine dots) deformed into overturned folds striking N that locally (e.g. on the east side) consist of folded folds striking oblique or normal to that of the overturned folds. Stratigraphic facing is shown mainly by graded bedding. Locality 4, road Tatau towards Sibu.

facing and difference in complexity of deformation there suggest that tectonic transport towards west was superimposed upon east-striking recumbent folds with north vergence. Another vergence that is indicated by the reverse faults may be interpreted as backward (towards east) transport as a byproduct of westward transport which encountered some resistance in the foreland. The flatness of those reverse faults is consistent with our interpretation that west vergence was younger than north vergence.

Locality 5.- This locality is 400 m more towards Sibu from the previous locality. The rocks are similar to those exposed at locality 4. Sole markings (flute, groove and other casts) and graded beds indicate facing and the turbidite character. Deformations produced folded folds with steeply dipping axes. The antiform east of centre on figure 6 represents and overturned syncline that now plunges at 50 degrees towards 186°. At the plunge many sole marks adorn the now-upward facing bottoms of arenaceous beds. General strike is approximately north-south with west vergence. The overturned syncline among other folds,

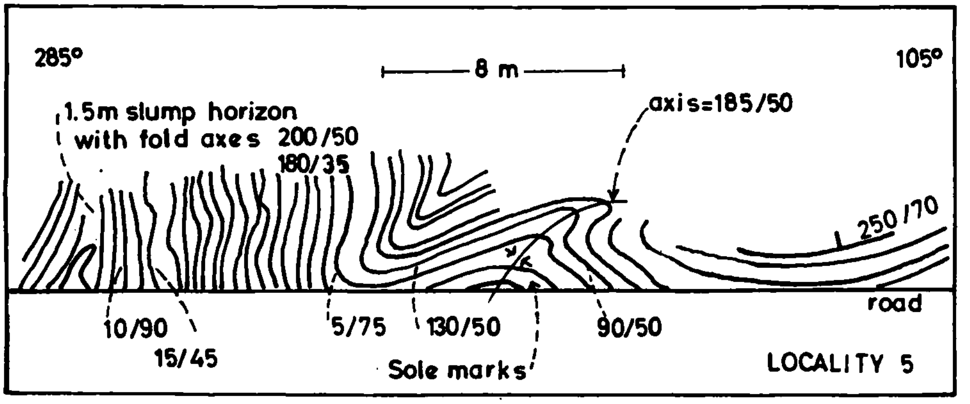

Fig. 6. Turbidites deformed into superimposed folds. Facing is indicated by sole markings and graded bedding. Discussion in the text. Locality 5.

however, indicates that it was formed about an east-west axis and attained its present position through north vergence. From this outcrop we are not able to conclusively determine the deformation sequence. Both vergences at locality 5 have representatives at locality 4, where evidence indicates north vergence occurred prior to transport westward.

Localities 6 through 7.- Localities 6 through 7 are the extremities of a 2-km road stretch at the Sibu-end of the road that we investigated for this report. The rocks are turbidites possessing sole markings and metres-wide sedimentary slump zones here and there. Bedding strikes are east to ENE and beds dip steeply as a rule and are often in overturned position (indicated by many sole marks and graded bedding). At one high outcrop (fig. 7) is exhibited a large overturned limb of an anticline that strikes approximately west. Transport was towards north.

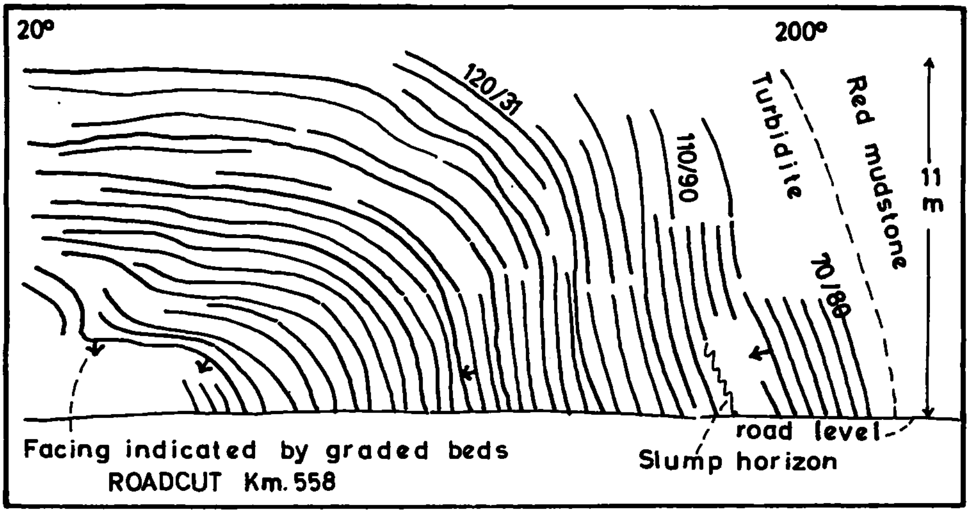

Fig. 7. Part of a large overturned anticline with north vergence in turbidites between localities 6 and 7 on fig. 1A.

EQUAL-AREA PLOTS

The frequent variations of bedding attitude along the surveyed stretch of road made it necessary to plot various structural elements on equal-area projections. These plots should indicate if there are preferred orientations. The outcrops at localities 4 and 5 already showed that at least two, mutually perpendicular strikes, that is, north and east, have been superimposed.

Figure 8.- This lower hemisphere, equal-area plot, includes readings from outcrops at and between localities 1 and 2. The rocks belong to the Buan and Tatau formations according to Wolfenden's map.

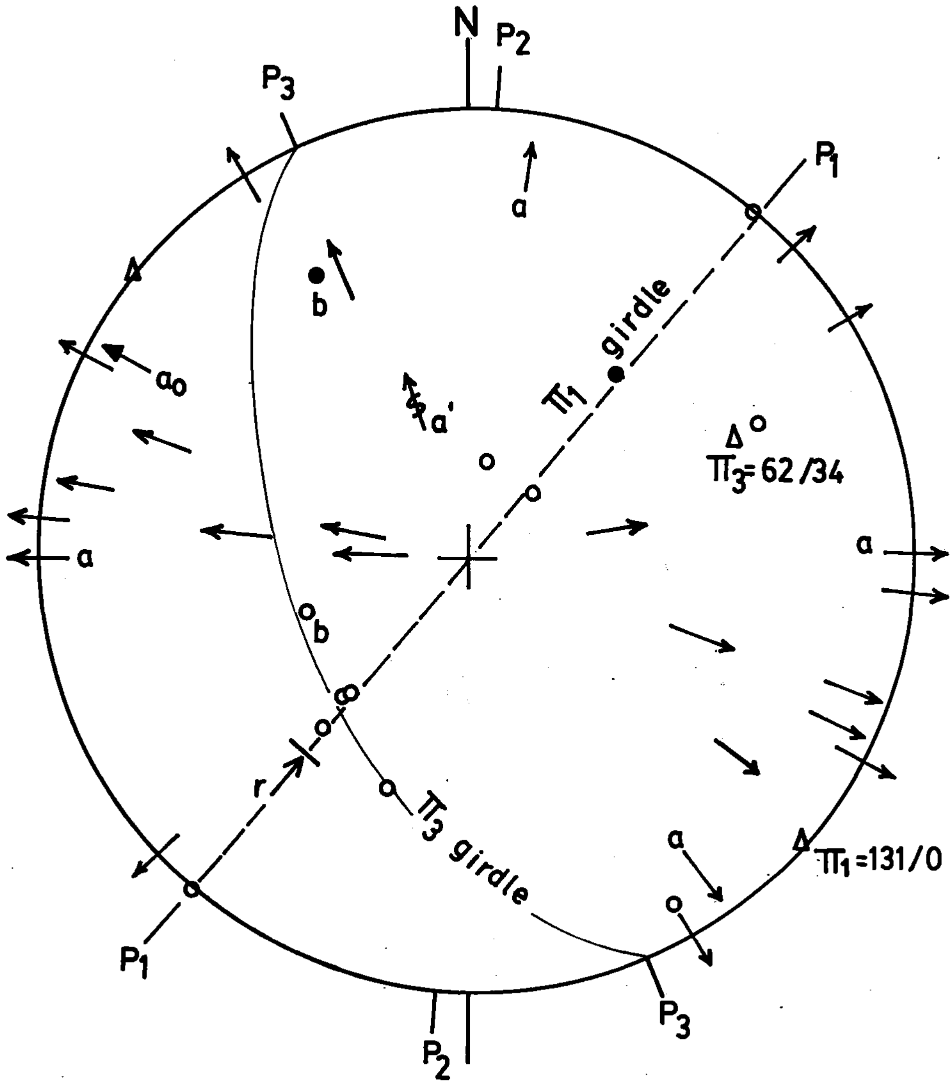

Fig. 8. Equal-area projection, lower hemisphere, of structures occurring in a stretch of road between approx. locality 1 and 3 on fig. 1A. Key for this figure and the following equal-area plots: a = axis of large fold; a = medium to small fold axis; a' = axis of drag fold; b = beds (open circle = right-side up, closed circle = overturned); constructed Pi-poles and girdles represent three lateral compressions P_1, P_2 and P_3. Rocks are mostly Tatau turbidites with some Buan beds near locality 1.

Two Pi-girdles can be constructed with poles Pi_1 = 131/0 and Pi_3 = 62/34. Their corresponding lateral, maximum principal stress directions are P_1 = 41-221° and P_3 = 332–152°. The presence of easterly striking fold axes suggests another lateral, maximum principal stress direction P_2 = 005-185°. The steeply plunging fold axes very probably represent slump folds rather than tectonic folds. The Pi_1 -axis is horizontal, therefore, the corresponding P_1 may belong to the youngest deformation phase. The relative age of the older P_2 and P_3 stresses cannot be determined from this plot.

Figure 9.- This equal-area plot contains observations from outcrops at locality 9 near the junction of the main road with the side road leading towards the Jabatan Kerja Raya camp MRCU15 (see fig. 1). The rocks consist of dm-bedded argillite and arenite with rather contorted appearance that according to Wolfenden's map belong to the Bawang Member. Twenty eight bedding attitudes appear to define three Pi-girdles with poles Pi_1 = 45/0, Pi_2 = 270/40, and Pi_3 = 26/0. Stratigraphic facing is indicated by, occasionally excellent, grading of arenaceous beds. Most fold axes are near-horizontal and are related to lateral compression in directions approximately paraallel to P_1 and P_3. Two of the subvertical axes belong to asymmetrical folds that suggest right lateral slip along WSM-ENE direction.

We interpret the lateral maximum principal stresses P_1 and P_3 to represent an older stress system and their small range of directions as result of interference by the younger stress system P_2.

Figure 10.- This equal-area projection display structural elements that were recorded along a 3-km stretch of road from the Tatau bridge towards west. On Wolfenden's map the rocks belong to the Bawang Member. However, we found at the first roadcut a few hundred metres west of the bridge, thick-bedded, gray arenite interbedded with thin, black phyllitic argillite. The beds strike 250° and dip 80 degrees northward. These are overturned as indicated by graded beds. The lithology resembles that of the Tatau or Buan formations. On the north side of the road are exposed cm-thick lutite to fine-grained arenite alternating with dm-thick black shale. These rocks resemble the lithology of the Bawang Member. Their strikes are parallel to those in the cut across the road but beds dip 85 degrees towards south and are right side up.

The projection on figure 10 indicates that bedding generally dips steeply and overturned positions are common. Four groups of fold axces correspond with compression directions in 319°, 340°, 005°, and 045°. The steeply, southward plunging fold axes are interpreted to represent slump folds, although some may also be early tectonic folds that were reoriented by later deformations.

Figure 11.- This equal-area projection contains structural elements recorded in roadcuts along a stretch 3 to 6 km west of Tatau bridge. The rocks are turbidites and on Wolfenden's map are designated as Bawang Member. Beds generally dip steeply and overturned positions are common. By construction the following Pi-poles were found. Pi_1 = 80/21 and Pi_2 = 253/40 correspond with lateral compression that acted in approx. 343 to 350 direction. One fold axis that plunges at moderate angle towards NW may be the result of lateral compression approximately perpendicular to it in NE-SW direction. The structural style displayed in figure 7, that is, large recumbent folding, probably characterises the entire road stretch.

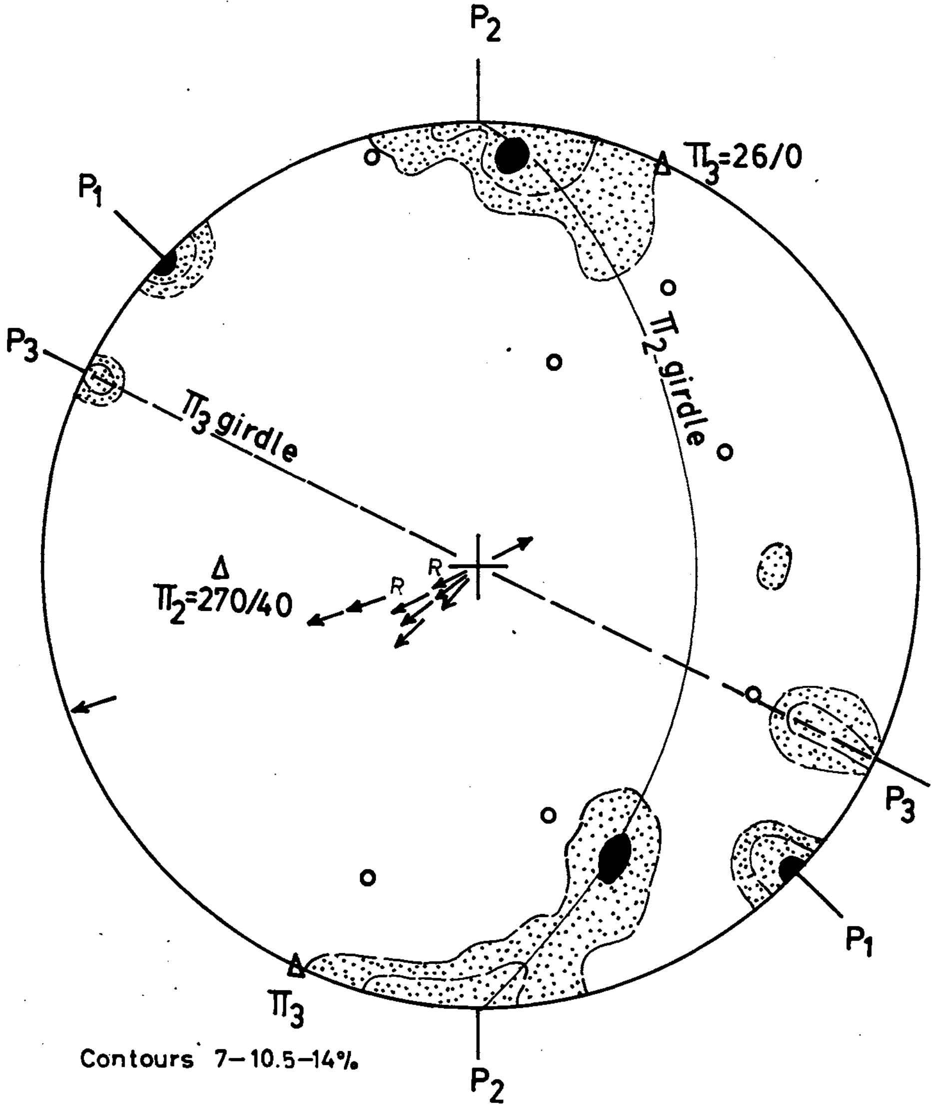

Fig. 9. Equal-area projection, lower-hemisphere, of structures in a roadcut at locality 9. Readings consist of 11 fold axes and 20 beds (only bedding-poles located outside the contoured areas are individually shown by open circles); small triangles are Pi-poles; P = lateral compression. Most fold axes plunge steeply; R indicates that these two fold axes may have been formed by right-lateral flexuring along bedding in approx. WSW direction, probably as result of P_1 and/or P_3, but definitely not of P_2.

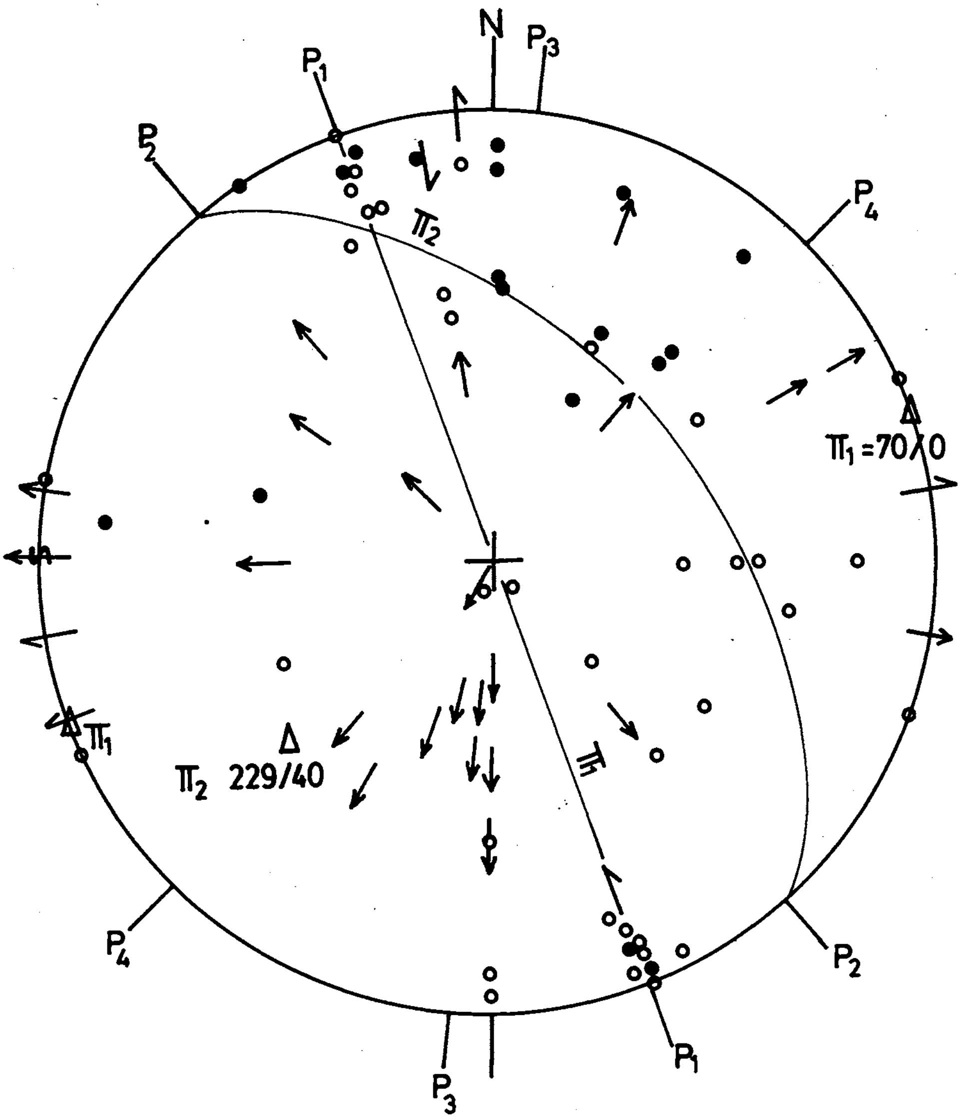

Fig. 10. Equal-area projection, lower hemisphere, of structures outcropping between Tatau bridge and locality 5. Note that the beds generally dip steeply and that fold axes also plunge steeply. Four lateral compressions (P) are interpreted to have caused the four groupings of fold axes. The steeply, south-plunging axes probably represent slump folds or tectonically deformed slump folds. Further discussion is in the text.

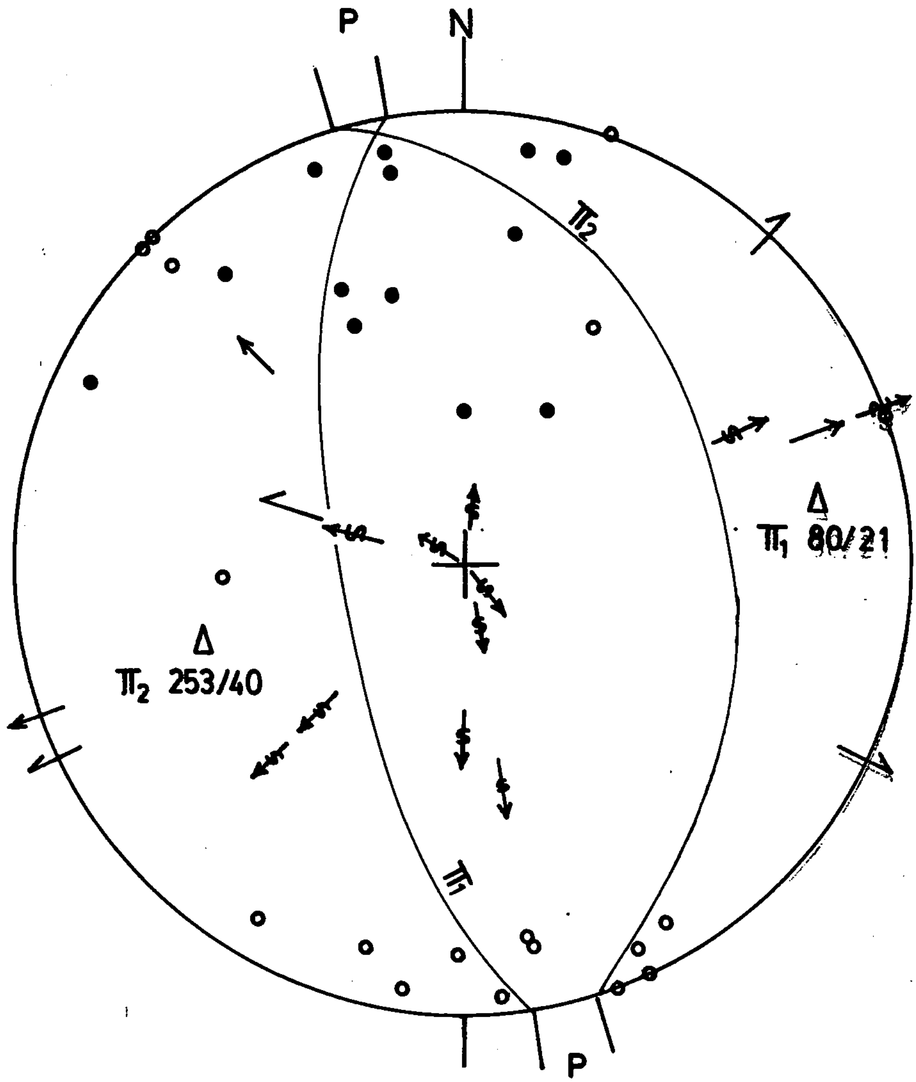

Fig. 11. Equal-area projection, lower hemisphere, of structures observed along the Tatau-Sibu road stretch approx. 3 to 6 km west of the Tatau bridge. The steeply dipping and partially overturned beds suggest two Pi-girdles corresponding with folds striking similarly but plunging in opposite directions (80° and 253°). The variety of fold axial directions (of slump as well as tectonic folds) suggest that more than one lateral compression direction was responsible for the structural style. From this plot, however, the above assumption cannot be established with some measure of confidence.

DEFORMATION HISTORY

Table 1 compiles the compression directions interpreted from the equal-area plots shown as figures 8 through 11. Five groups of compression directions can be easily distinguished:

Northerly, 4 times
041-045°, 4 times
332-340°, 2 times
315-319°, 2 times
295°, once

TABLE 1

LATERAL COMPRESSION DIRECTIONS INTERPRETED FROM FIGS. 8 THROUGH 11.
(Note: the subscripts are used to distinguish various directions on individual figures, but do not indicate relative age)

Figure 8; Buan & Tatau formations	P_1 = 041 – 221° P_2 = 005 – 185° P_3 = 332 – 152°
Figure 9; Bawang Member	P_1 = 315 –135° P_2 = 000 – 180° P_3 = 295 – 115°
Figure 10; Bawang Member	P_1 = 340 – 160° P_2 = 319 – 139° P_3 = 005 – 185° P_4 = 045 – 225°
Figure 11; Bawang Member	P = (343–350) – (163–170)°

We already interpreted that lateral compression in the 295° direction is but a reorientation of that in the 315° direction or vice versa (Fig. 10). All four equal-area plots exhibit the northerly compression direction. This means that north-south compressions have been strong and have affected Eocene up to Miocene (Buan Formation) sediments. This may also mean that north-south compression was the youngest event, or, more probably, that north-south compression persisted since the Late Eocene and that the northeast and northwest compression directions represent but local deviations of a continuing north-south stress-influenced deformation process. During this long deformation process there were probably pulses of stronger deformations, e.g. through faster spreading of lithospheric plates (see below). Also during the deformation process, an originally east-west orientated sedimentary basin, the so called Northwest Borneo Geosyncline, became warped around the general Tatau area, producing ENE and WNW strikes to the strikes to the east and west of Tatau, respectively. The bend in regional strikes as described above is shown on the tectonic map of Liechti's (1960) and on the regional map by Tan (1982).

In recapitulation we would like to state our conclusion that the rocks in the Tatau area were partially deformed as soft sediments through slumping, upon which were superimposed tectonic deformations that had essentially northerly vergence. This continuing deformation process took place from the Late Eocene to Miocene time. Evidence of tectonic deformation accompanied by west vergence, such as at locality 4, is interpreted as a result of warping around the Tatau area as pivot of an initially east-west orientated, elongated sedimentary basin, the so called Northwest Borneo Geosyncline. This warping occurred as byproduct of the general north vergence during the entire deformation process.

REGIONAL TECTONICS

The Tatau area is located within the so called Northwest Borneo Geosyncline that developed throughout the Cenozoic on the northern side of Borneo's continental core. Tan (1982) established that during the Early Eocene, a subduction zone existed along the Lupar valley region. This zone is represented by the Lubuk (or Lubok) Antu mélange (Fig. 12).

Recent regional mapping in West Kalimantan resulted in the discovery of an early Late Cretaceous subduction zone to the south of the Lupar suture. The associated tectono-sedimentary unit has been named the Boyan mélange (Williams, *et al.*, 1986) and it occupies what in the older literature has been known as the Semitau ridge (see fig. 12).

Taylor and Hayes (1980) interpreted approximately east-west magnetic lineations in the South China Sea Basin as result of sea floor spreading that was active from the mid-Oligocene to the Early Miocene (32-17 m.y. B.P). The spreading zone seems to coincide with east-west aligned seamounts close to latitude 15° N. Less defined is the magnetic pattern in the western third of the basin, but Taylor and Hayes speculate that the data indicate a major change in spreading style that was associated with a northeast trending relict spreading zone in the southwest of the basin. These authors also report on indications that an older basin probably existed southeast of Reed Bank. The northeast trending Palawan suture (fig. 12) marks the subduction zone on the southern edge of the above mentioned spreading sea plate. This suture is now inactive (see Hamilton, 1979). We surmise that towards southwest the Palawan subduction continued but now lies buried under Neogene sediments of the North Borneo Geosyncline. If we relate the Arip volcanic outcrops with this subduction, the latter's position may be 200-500 km north of the Arip area, which is in the neighbourhood of the northern border of the Balingian petroleum province. The magmatic arc - trench (= subduction zone) distance at active island arcs, such as the Sunda arc, is approximately 200 to 250 km. Our supposition also requires that the proposed southwest end of the Palawan subduction was already active in Late Eocene time and that the Palawan suture proper developed later, that is, in mid-Oligocene time. Non-synchroneity in activity along subduction zones is probably not rare.

The three subduction zones discussed above indicate that on the north side, Borneo's core has accreted tectonic and sedimentary rock units in a progressive fashion since early Late Cretaceous time (see fig. 12).

Based on our present knowledge, we constructed the schematic cross section showing the geologic setting of the Tatau area in the Late Eocene (fig. 13). From SSE to NNW we can distinguish the following structural elements.

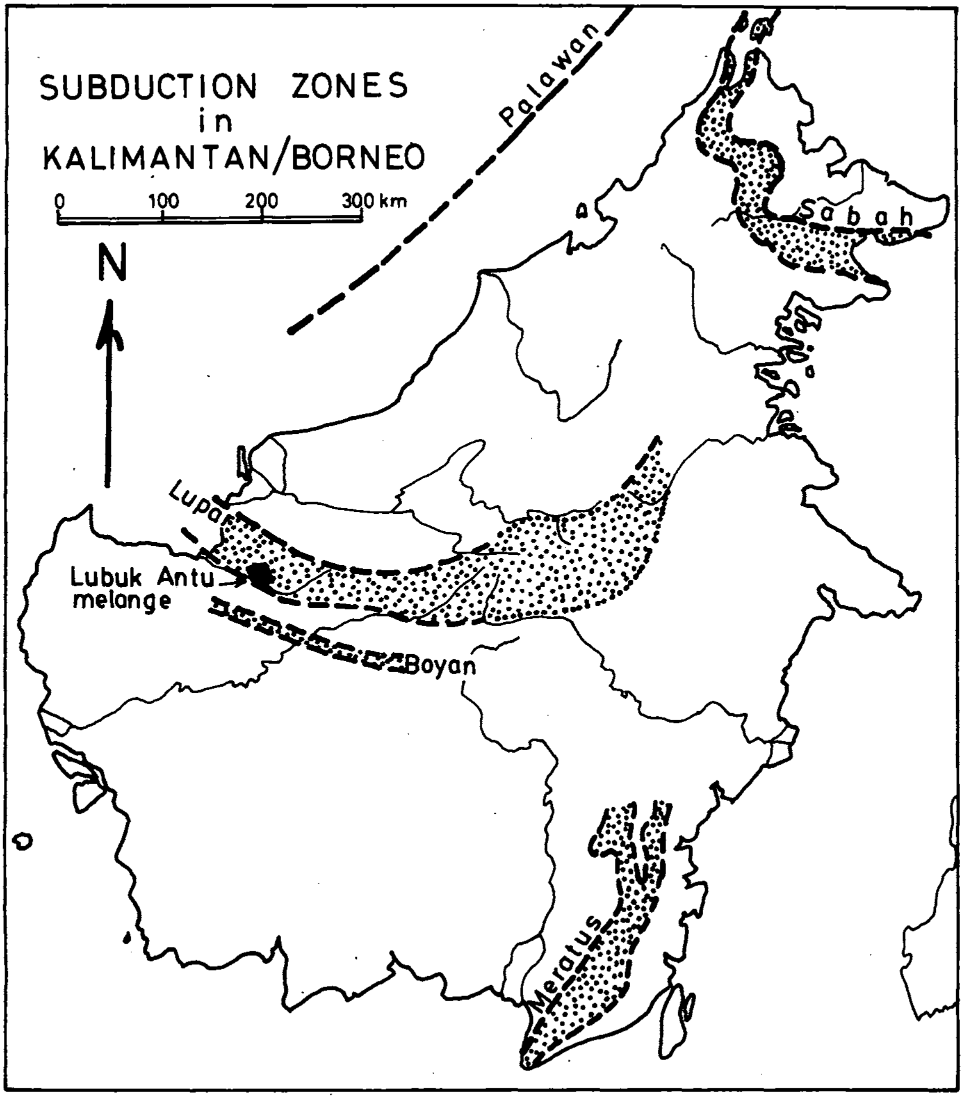

Fig. 12. The known subduction zones of Borneo. The Meratus and Sabah mélanges suggest Cretaceous-Early Tertiary age. Better information defines the ages of the Boyan (early Late Cretaceous) and Lubuk Antu (early Eocene) mélanges. The present paper proposes that in the Late Eocene a subduction zone existed north of Tatau and was the SW-extension of the Palawan subduction zone. Further discussion is in the text.

(a) A shallow back-arc basin, partially filled by Belaga beds and subsiding in order to receive younger sediments;

(b) a volcanic island arc that is now represented by outcrops of Arip volcanics and by tuffaceous admixtures in the Bawang and Tatau beds;

(c) a submarine slope of the volcanic arc, where gravity sliding took place off and on, forming slump folds and associated structures, and that led into

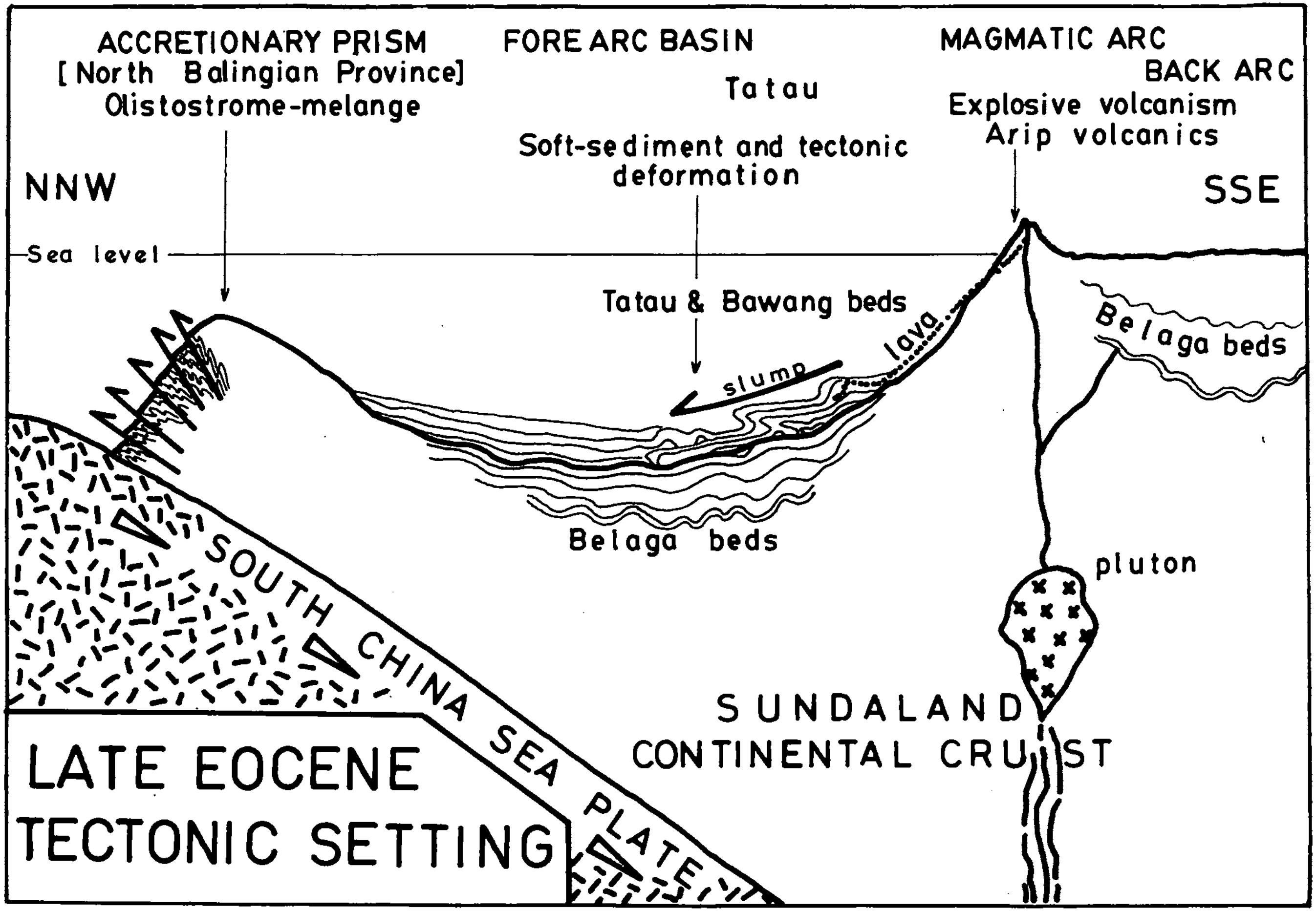

Fig. 13. A schematic cross section across the Tatau area shows our interpretation of its Late Eocene tectonic setting. From SSE towards NNW are four tectonic elements of an island arc configuration similar to that associated with active arcs. The Belaga, Bawang and Tatau beds are shown as being deformed by both gravity and tectonic processes. Note that deformation is shown stronger for the older layers in order to imply that the process was continuous, most probably resulting from convergence between the subducting South China Sea plate and the Continental Sundaland plate.

(d) a deep fore arc basin where partially slumped Bawang and Tatau strata were being deposited and at the same time were tectonically deformed as the basin constricted as result of north-south converging plate motions;

(e) a, probably submarine, tectonic arc (= accretionary prism) that developed by accretion of deep-sea sediments onto the leading edge of the Sundaland lithospheric plate. Accretion took place by subduction of the South China Sea plate beneath Borneo. These accreted sediments became mixed, through continuing convergent plate motions, with Belaga and Tatau equivalents of the northern Balingian Province into a tectonic melange. This particular subduction zone is the southwest extension of the Palawan suture and the former was already active in Late Eocene time.

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