Geol. Soc. Malaysia, Bulletin 35, July 1994; pp. 25-35

Kinematic analysis of striated fractures in Titiwangsa granitoid, Karak Highway — Selangor side

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Abstract: Reliable fault-sense indicators: bruised steps, pluck steps, accretionary steps, stoss spalls, trail ridges, fault roche moutonnee, prod depressions and prod ridges establish the nature of motion on slickensided fracture planes in Titiwangsa granitoid along the Karak Highway. In certain instances subsidiary structures: *en echelon* tension gashes and drag features, and fault separations provide additional information on the sense of fault motion.

Right lateral and left lateral fault motion took place most frequently along NNE-NE and along ENE-E trending, steeply inclined to vertical fractures, respectively. This movement pattern is consistent with maximum horizontal compression within the 33° to 48° sector, which deviates about 20° from the direction of regional compression that affected Peninsular Malaysia, but is compatible with the vergence of the Genting Thrust Belt. Therefore, contemporarily of thrusting and lateral fault motion on these particular fractures is indicated.

Among those studied, a comparatively small number of vertical fractures indicates lateral motion in response to compression that acted approximately perpendicular to that in the established sector. It appears that the NW-SE compression resulted from relaxation of the NE-SW maximum horizontal stress. Superimposed striations and other fault markings on a number of fracture planes represent isostatic adjustments through gravity faulting.

INTRODUCTION

Between Gombak and Bentong, the Karak Highway traverses mainly granitoids of the Titiwangsa mountain range (Fig. 1). Along a number of stretches, the highway exposes fresh granitoids, often below 30-metres or thicker soil. The igneous rock is fractured. Some fracture sets are roughly parallel to the topographic surface and their spacing typically increases downward into the fresh rock. These surface-parallel fractures represent exfoliation joints. The majority of fracture sets, however, are vertical – subvertical to steeply inclined. Wide outcrops of igneous rock contain such fracture sets, and those closely spaced represent genuine shear zones. Often horizontal to subhorizontal striations adorn these fracture planes.

This study analyses markings of movement sense on striated fracture planes. A number of these markings are definitive indicators of movement sense (see below). The movement pattern deduced from these fracture planes may indicate the generative stress system.

It has been widely accepted that so called slickensides of fractures planes may only indicate the latest fault movement since older fault markings are believed to have been obliterated. Field experience has taught me that this is not always the case. I saw up to three different sets of striations in a few occurrences. Two sets of crossing striations on a single fault plane are rather common. The older set is preserved in hollows or behind protrusions of the fault plane. However, where criss-crossing fault striae occur it may be difficult to determine without ambiguity their senses of motion. The small scale markings may exhibit effects of reshaping or remoulding which masks their identities.

FAULT-PLANE MARKINGS

Since Paterson (1958) demonstrated through laboratory experiments that the so called "smoothness criterion" for determining sense of fault motion is not always valid, several other researchers identified specific fault-plane markings as sense indicators. The state-of-the-art can be judged from papers in a special issue of the Journal of Structural Geology, Volume 9 (numbers 5–6) of 1987.

The markings to be described below are those from my own field experience over the past thirty years. The main markings are in Figure 2.

1. Bruised step, an elongate step riser perpendicular to and facing the direction of fault motion. The "bruise" consists of finely brecciated fault gouge. Carbonate gouge is commonly recrystallised; quartz gouge may or may not have recrystallised. Bruised steps may rise as high as a decimetre above the fault surface but are usually less than a centimetre high (Fig. 3A). Bruised steps obviously negates the classical "smoothness

Paper presented at GSM Annual Geological Conference '92.

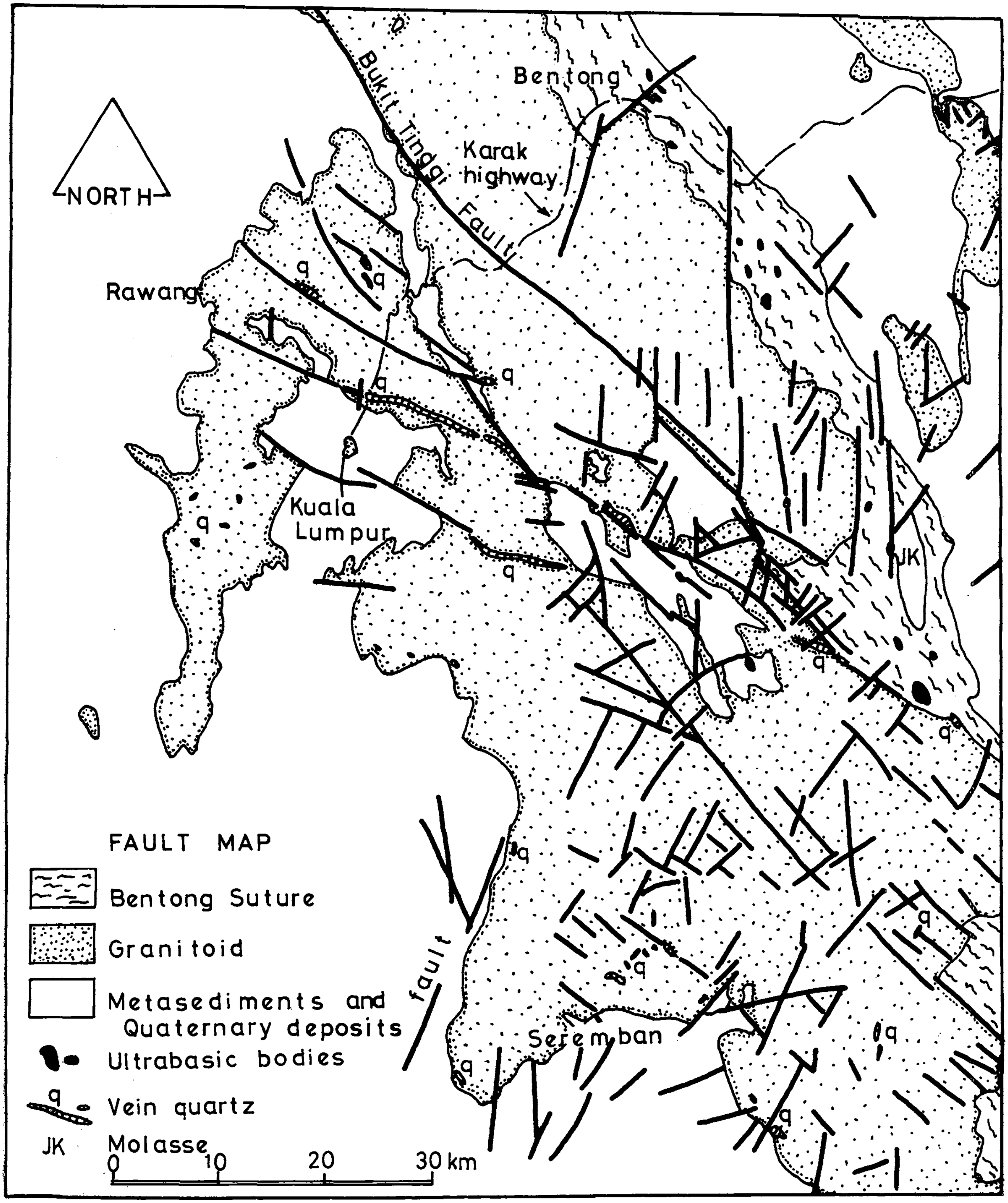

Figure 1. Map of faults and geology of the Seremban-Kuala Lumpur-Bentong region. Solid lines are faults. The map is based on the Geological Map of Peninsular Malaysia, 8th edition (Geological Survey of Malaysia, 1985).

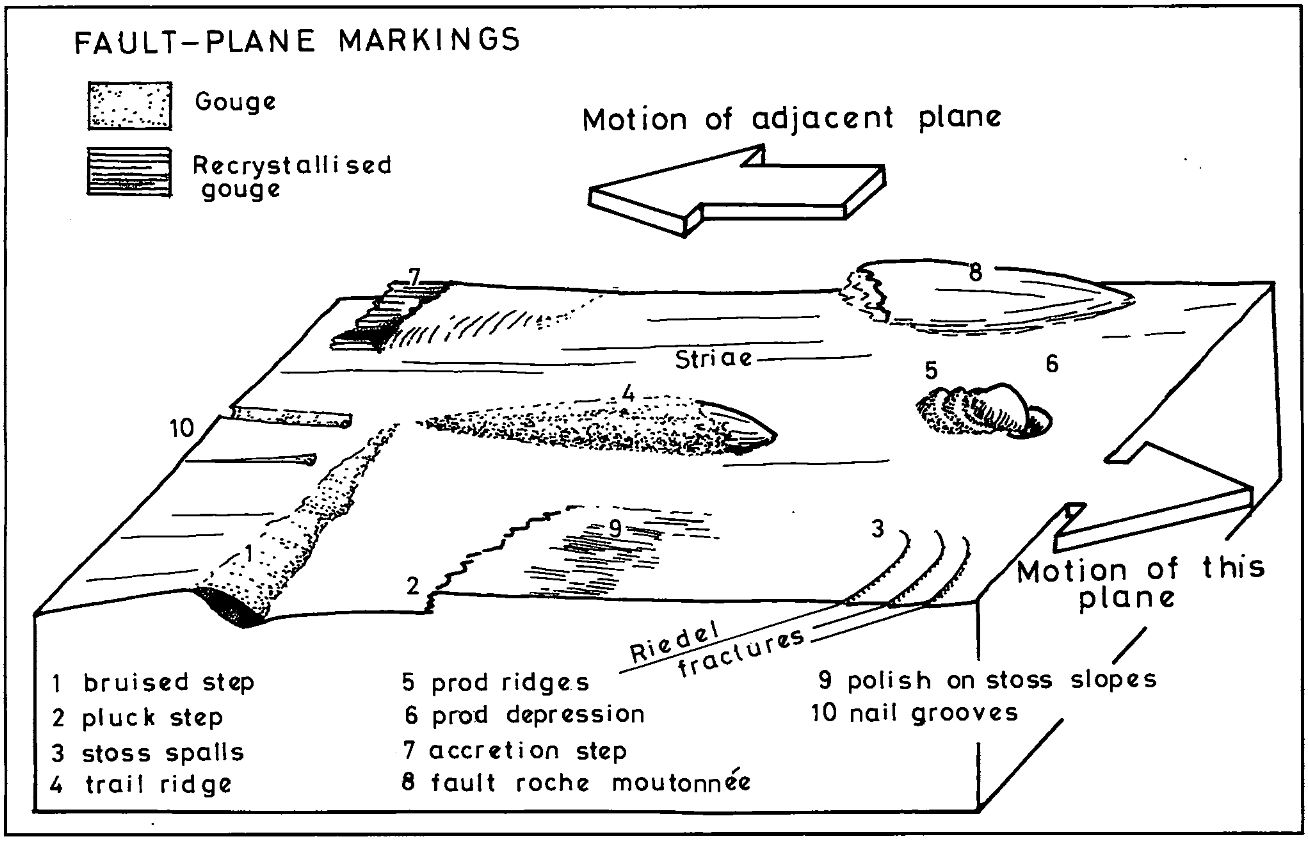

Figure 2. Block diagram of fault-plane markings that are reliable indicators for movement sense.

criterion" for determination of fault sense.

2. Pluck step and **7. accretion step** are also elongate risers positioned perpendicular to fault movement. The pluck step may be jagged. It may be accompanied by recrystallised gouge that form an accretion step (marking no. 7 in Fig. 2). The crystals in accretion steps are mostly arranged parallel to the fault motion and may be larger than those forming bruised steps. The difference in recrystallisation may be especially clear when both, bruised steps and accretion steps occur on the same fault surface.

3. Stoss spalls consist of flakes of gouge or of the rock mass that is faulted. Often stoss spalls are convex in plan facing into the direction of fault motion (Figs. 2 and 3B). In cross section, stoss spalls composed of the rock mass suggest them to represent Riedel fractures inclined in the direction of fault motion (Fig. 2). Stoss spalls in granitoid consist of both: flakes of gouge material (mainly derived from the feldspars) and flakes of the faulted rock mass (Fig. 3B).

4. Trail ridge is an elongated and streamlined accumulation of gouge trailing behind a protrusion of the fault plane (Fig. 2). In essence, the trail gouge became preserved from attrition by continuing fault motion through the protective presence of the protrusion. "Crag and tail" are similar features formed by glacier motion.

5. Prod ridges and **6. prod depression**. Prod ridges are small bulges of the faulted rock mass or of fault gouge that developed through pushing or prodding by a resistant clast into the fault surface (Fig. 2). Often the resistant clast, also known as prod tool, leaves on its stoss side a depression in the fault plane. The prod ridges may be short and in such cases their orientation with respect to fault motion may not be obvious. However, the combined alignment of prod ridges, prod tool and prod depression is distinct and is parallel to fault motion.

In a few field examples I saw prod depressions that exist as long grooves parallel to fault motion. The prod tools were clasts of resistant rock types or quartz grains that resided in the lee ends of the grooves.

8. Fault roche moutonnee, a streamlined portion of the faulted rock mass that protrudes above the fault surface. The ideal shape consists of an elongate ridge tapering and more gently inclined towards its stoss side with a jagged lee-side end (Fig. 2). The jagged appearance is due to plucking. These elongate ridges grade into broader forms without clear orientation to the fault motion; but smoother and gentler inclined stoss slopes are still characteristic. This type of fault marking resembles the roche moutonnee of bedrock material in glaciated terrain. Fault gouge that is streamlined by fault motion into ridges are called **fault drumlins**.

9. Polish on stoss slopes consists of a film of recrystallised gouge on the stoss sides of protuberances of the fault surface. The gloss of such films becomes clearer when viewed against a light source that grazes the fault surface.

A special case of polish is that of a "smeared-out" film of gouge. Such gouge film is seen to gradually thin out or fade towards the lee side resulting in the smeared-out appearance.

10. Nail grooves are elongate depressions that taper off to points towards the lee side (Fig. 2). Nail grooves are most probably formed as elongate prod depressions in which the size of prod tools decreases through attrition during continued fault motion.

ANALYSIS OF OUTCROPS

The index map (inset of Fig. 4) shows the approximate locations of outcrops studied. The localities along the Selangor side of the Karak Highway are indicated by the letters A, B, C, D. E, and F, in order of increasing distance from Kuala Lumpur. Other localities of Titiwangsa granitoids on the Pahang side of the Karak Highway are shown by the letters K and H. Locality I is also a Titiwangsa granitoid outcrop in Pahang a few kilometres from the Selangor boundary. Still other localities are indicated by the remaining letters and are included to show the pattern of maximum horizontal stress directions in this part of the country.

The fault striations and other structural elements recorded from each outcrop are plotted on

Figure 3A. Bruised step risers (1) on a granitoid fracture plane. Arrow is 7 cm long and indicates motion sense of the missing surface. Some of the fault gouge form accretion spalls (3).

Figure 3B. Flakes of stoss spalls (2) convexly facing the direction of motion (arrow). The light coloured stoss spalls to left of centre consist of feldspar phenocrysts in the fault surface of the granitoid.

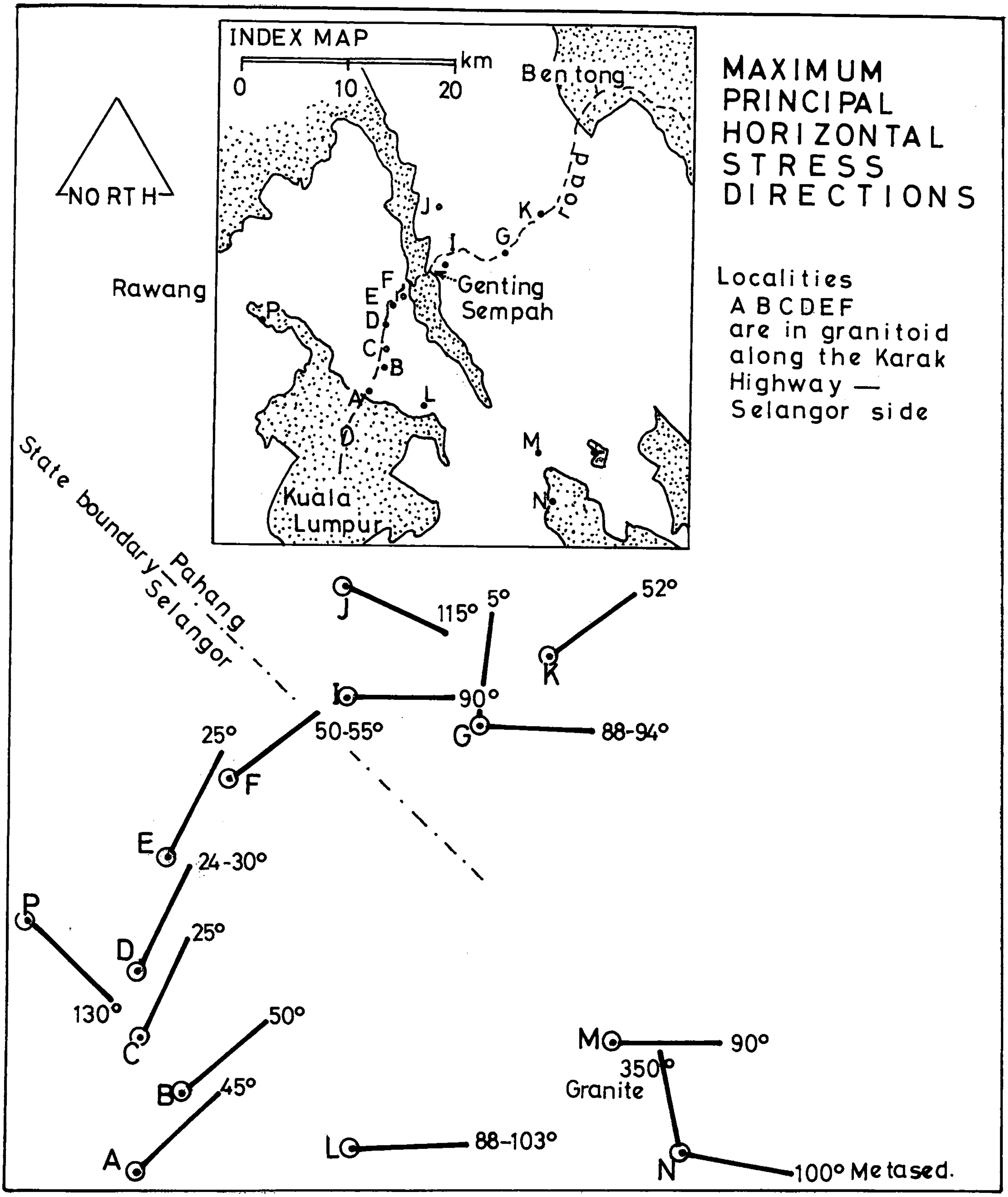

Figure 4. Plane of maximum horizontal stress directions in the study area. Inset shows the localities. The blank areas represent Titiwangsa granitoids. Maximum horizontal stress (MHS) directions are shown by bold lines. Each of localities G and N has two MHS directions that are mutually perpendicular.

the lower hemisphere equal-area projection. Sense of fault motion is indicated by half-tipped arrows; the arrow tips also indicate the pitch angle of the striations. At pitch angles less than 45°, strike-slip displacements are more important than their corresponding dip slip components. Component of lateral slip becomes increasingly more significant with decreasing pitch angles. When the plot consists of definite groupings of lateral fault slips, the generative maximum horizontal stress (MHS) direction or sector can be determined.

Locality A (Fig. 5), Genting Kelang Quartz Dyke that outcrops at the Gombak entrance of the Karak Highway. This belongs to the more than 20 km long WNW-trending quartz dyke marking the north side of Kuala Lumpur. On the equal-area plot, the NW-striking older quartz vein within the large quartz dyke is transected by other quartz veins, designated as younger quartz veins. The orientations of fracture sets are parallel to, normal to, or make angles of 35° and of 55° with the interpreted MHS direction in 45°. Respectively, the cited fracture sets may represent extension, tension, first-order shear and second-order shear fractures developed in a stress system where its MHS acted in 45° direction and its corresponding intermediate principal stress was vertical. This MHS direction also accounts for right lateral slippage along the shear zone.

Locality B (Fig. 6), granitoid exposed in long roadcuts on both sides of the Karak Highway. In 1986, the nearest road marker indicated 23 km to Kuala Lumpur and 237 km to Kuantan. Since then, however, road markers along the highway may have been changed due to continued improvements of its alignment.

A MHS direction of 50° explains almost all senses of fault motion at this locality. The quartz vein seems to fill a fracture approximately perpendicular (= tension fracture) to the interpreted MHS.

Locality C (Fig. 7), roadcut of granitoid transected by a 5 m wide quartz dyke and several smaller quartz dykes. The nearest road marker is 24 km to Kuala Lumpur. If all lateral slips were generated by the same stress system, its generative MHS direction was 25°. The quartz dykes fill tension fractures perpendicular to this MHS direction.

Locality D (Fig. 8), granitoid roadcut on the highway some 25 km to Kuala Lumpur. Wide aplite dykes, a quartz dyke and quartz veins transect this granitoid outcrop. It is also cut by an ENE-trending left lateral shear zone. Most lateral slip senses, the orientation of aplite and quartz dykes are accommodated by a MHS that acted in the 24°–30° sector.

Locality E (Fig. 9), granitoid outcropping on the NW side of the highway near the Orang Asli Settlement, about 27 km to Kuala Lumpur. The reverse fault vergence suggests MHS in 25° direction which also explains 65% of the lateral fault slips. The remaining 35% of lateral fault slips may be explained as representing response to another lateral compression directed normal to the MHS. This second lateral compression normal to MHS resulted from stored strain energy being released when the strength of the MHS decreased. In other words, slippage on those particular fractures (the 35% of the fracture population) may be described as rebounding phenomena.

Locality F (Fig. 10), granitoid roadcut on the Karak Highway, approximately 29 km to Kuala Lumpur. The majority of lateral fault slips are accommodated by a MHS acting in the sector 50°–55°. The fault slips incompatible with this MHS sector can be explained by an second maximum horizontal stress direction in about 142°, or about perpendicular to the earlier interpreted MHS sector. The occurrence of a second MHS direction may be attributed to rebound in the same fashion as described for Locality E.

Locality I (Fig. 11), granitoid on the old trunk road to Bentong, about 3 km from Genting Sempah. The pattern of fault slips is compatible with a MHS acting in the sector 80°–109°. A MHS = 90° best explains all fault slips and the orientation of quartz veins, which are interpreted to occupy extension fractures parallel to MHS.

Locality G (Fig. 12), gneissic granitoid on the Karak Highway, Pahang side near Bukit Tinggi village. Almost all lateral fault slips are explained by a MHS acting in the sector 88°–94°. The single reverse fault vergence towards north and other fault slips incompatible with the above interpreted MHS-sector probably resulted from a second maximum compression directed N-S. This second MHS may represent released strain energy after the E-W MHS decreased in strength; or in other words, the second MHS caused rebounding on existing or newly created fractures.

Locality K (Fig. 13), a Karak Highway roadcut of zonally flasered, porphyritic granitoid near Lentang, Pahang. The range of possible MHS to explain the fault slips is between 42° and 60°. A MHS = 52° best explains the fault slips and is perpendicular to the aplite dykes (occupying tension fractures?) and the strike of feldspar flasers in the granitoid.

Locality J (Fig. 14), comprises several roadcuts in non-granitoid rock along the access road from Genting Sempah to Genting Highlands. Roadcuts at 4, 6 and 11 km (from Genting Sempah) consist of rhyolite-ignimbrite, roadcut at km 9 is of bedded

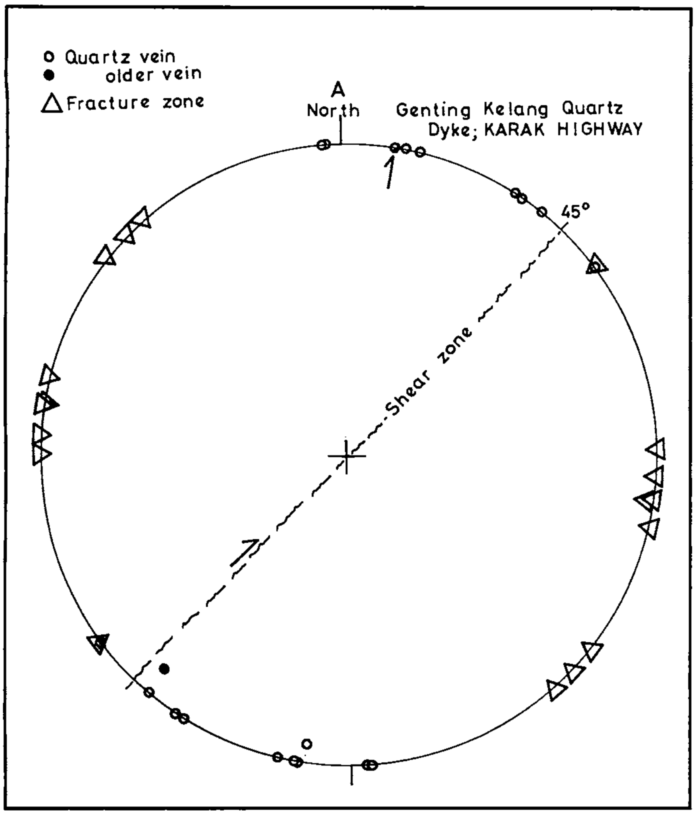

Figure 5. Equal-area projection, lower hemisphere of structural elements in Genting Kelang Quartz Dyke, Karak Highway at Gombak, Locality A. Half-tipped arrows indicate right slip sense.

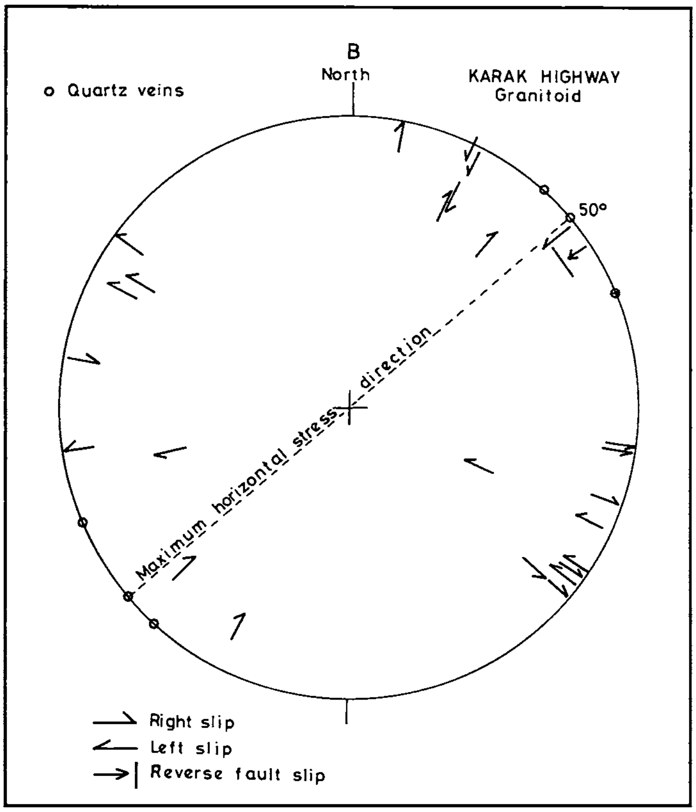

Figure 6. Equal-area projection, lower hemisphere of structural elements in Titiwangsa granitoid, Karak Highway 23 km to Kuala Lumpur, Locality B.

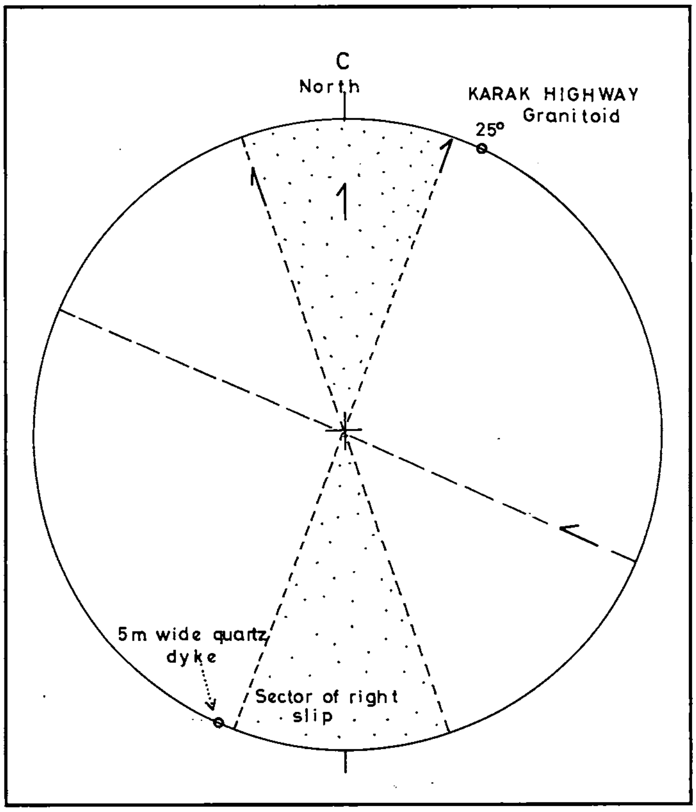

Figure 7. Equal-area projection, lower hemisphere of structural elements in Titiwangsa granitoid, Karak Highway 24 km to Kuala Lumpur, Locality C. Symbols are explained in Figure 6.

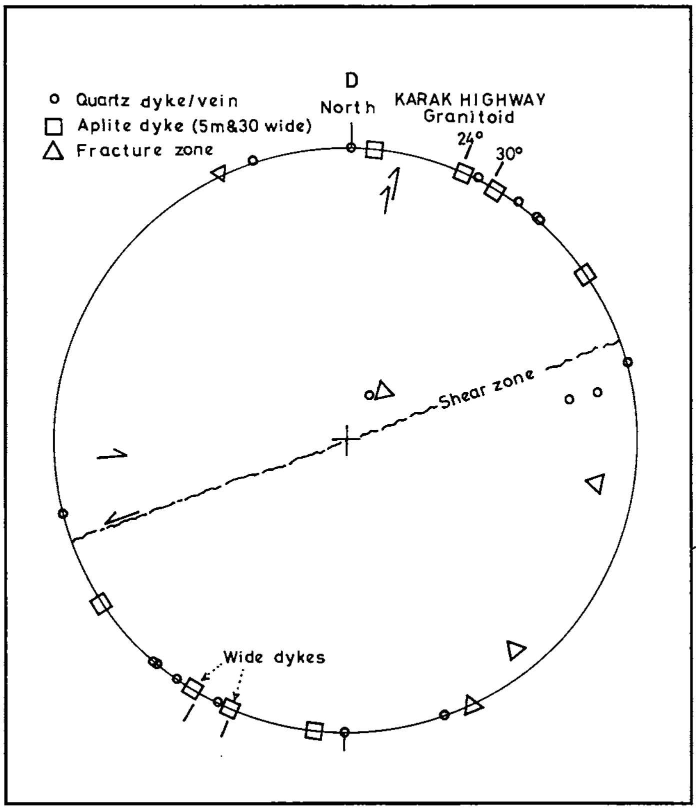

Figure 8. Equal-area projection, lower hemisphere of structural elements in Titiwangsa granitoid, Karak Highway 25 km to Kuala Lumpur, Locality D.

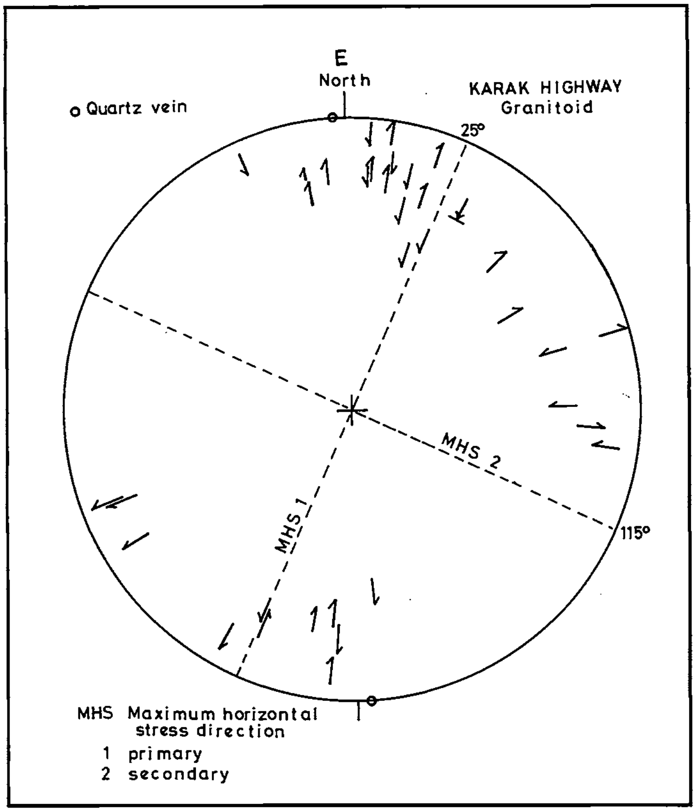

Figure 9. Equal-area projection, lower hemisphere of structural elements in Titiwangsa granitoid, Karak Highway 27 km to Kuala Lumpur, Locality E.

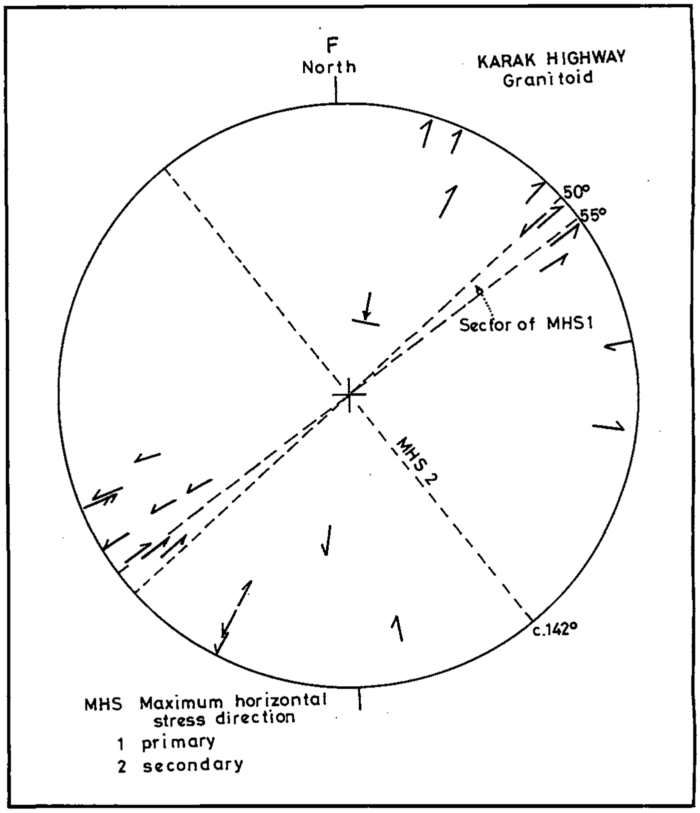

Figure 10. Equal-area projection, lower hemisphere of structural elements in Titiwangsa granitoid, Karak Highway 29 km to Kuala Lumpur, Locality F.

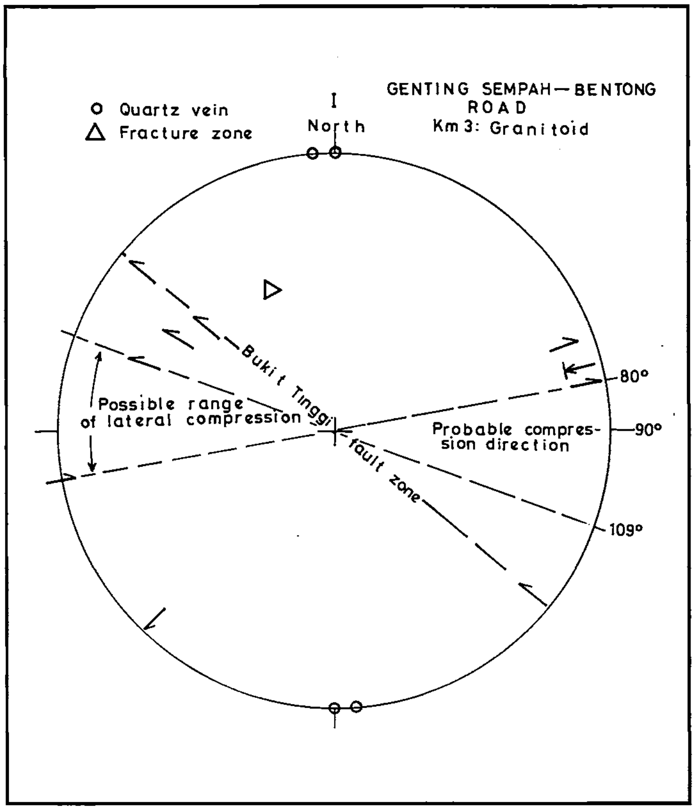

Figure 11. Equal-area projection, lower hemisphere of structural elements in granitoid, old Gombak-Bentong trunk road, Locality I.

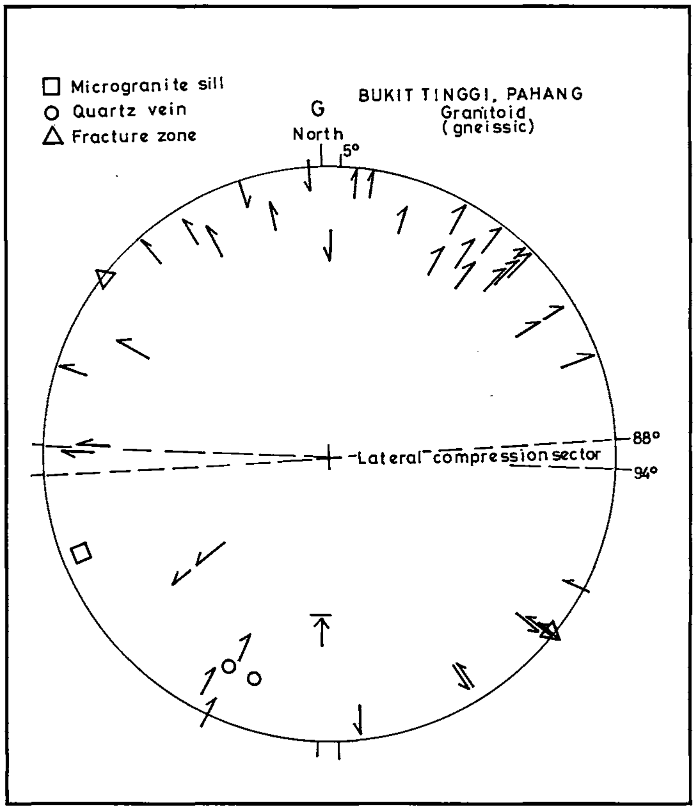

Figure 12. Equal-area projection, lower hemisphere of structural elements in gneissic granitoid, Karak Highway near Bukit Tinggi village, Pahang, Locality G.

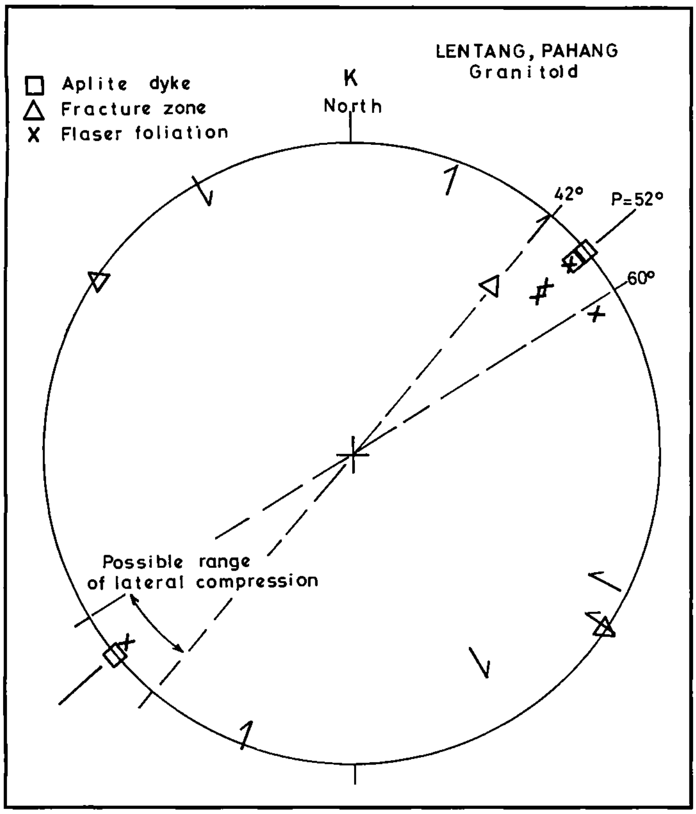

Figure 13. Equal-area projection, lower hemisphere of structural elements in porphyritic granitoid, Lentang, Pahang, Locality K.

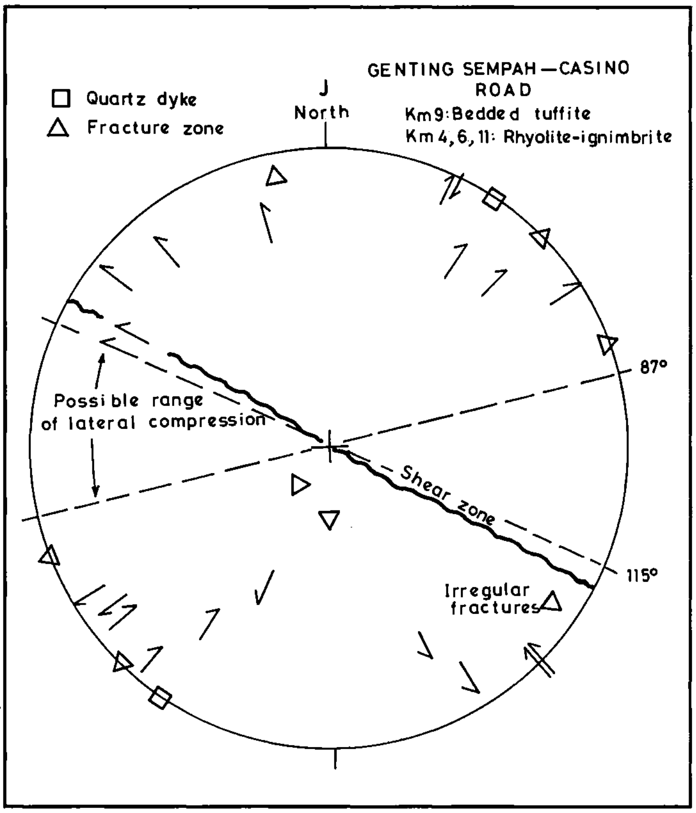

Figure 14. Equal-area projection, lower hemisphere of structural elements in rhyolite-ignimbrite and meta-tuffite, Genting Sempah-Genting Highlands (Casino) road, Locality J.

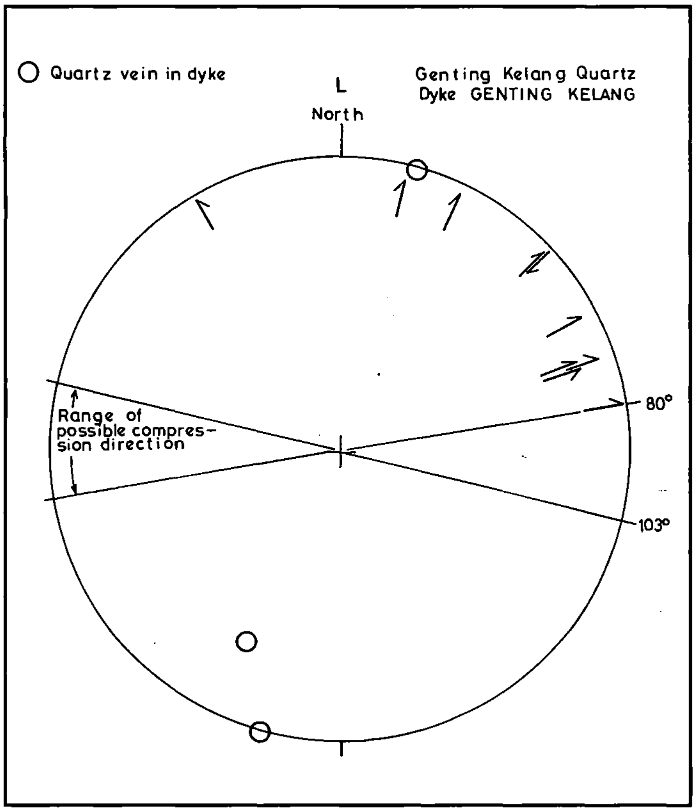

Figure 15. Equal-area projection, lower hemisphere of structural elements in Kelang Gates Quartz Dyke, Hulu Kelang, Locality L.

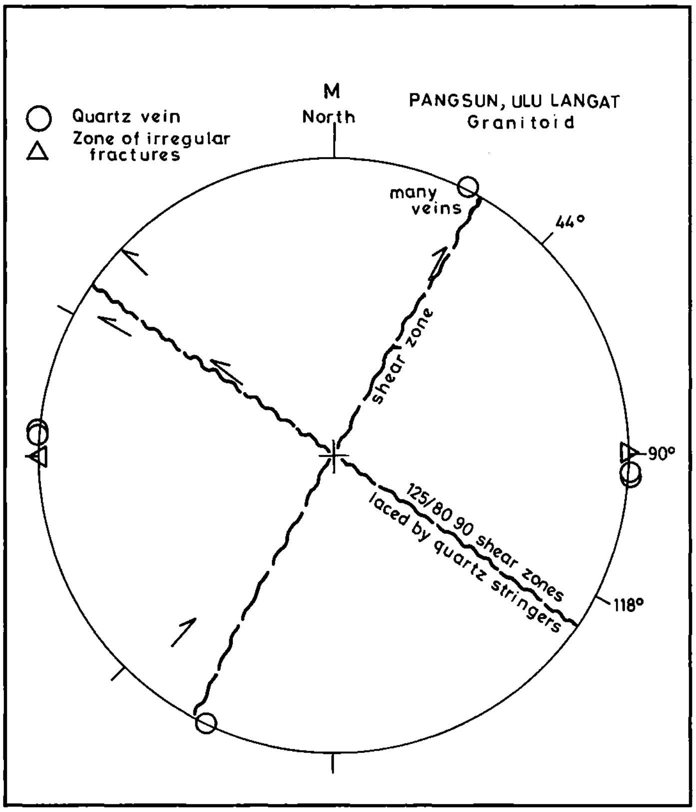

Figure 16. Equal-area projection, lower hemisphere of structural elements in Titiwangsa granitoid, Pangsun, Ulu Langat, Locality M.

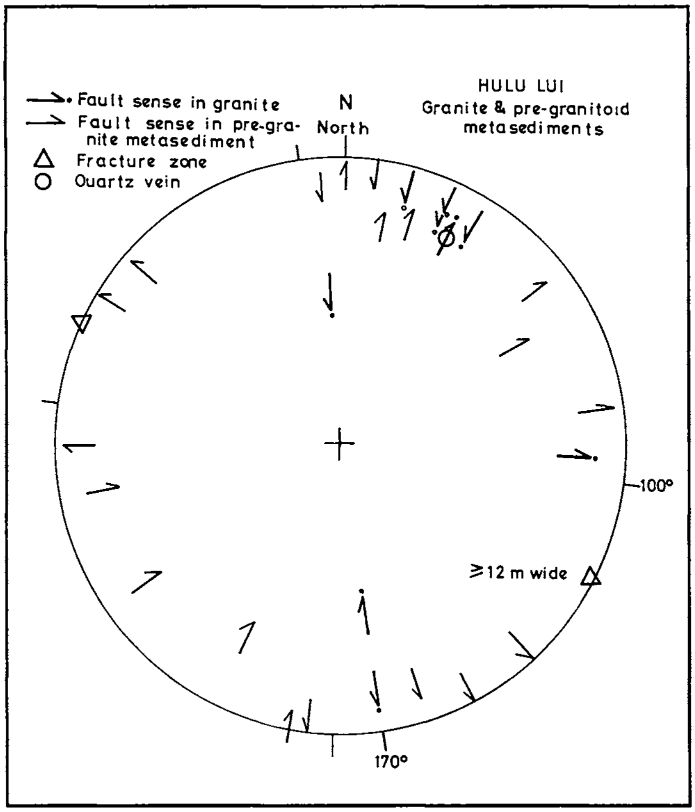

Figure 17. Equal-area projection, lower hemisphere of structural elements in granitoid and metasedimentary rock, main road Semenyih-Jelebu District, Hulu Lui, Locality N.

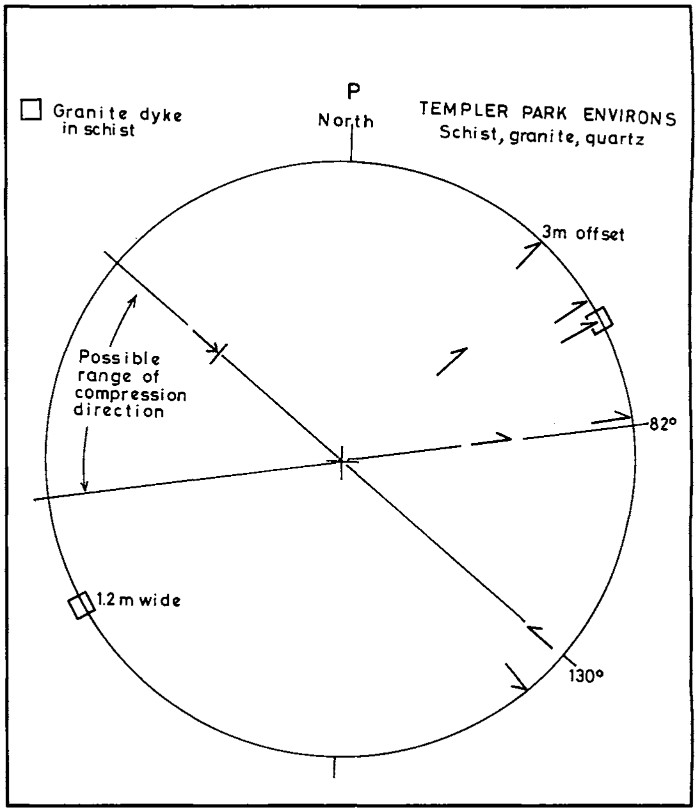

Figure 18. Equal-area projection, lower hemisphere of structural elements in Titiwangsa granitoid, crystalline schist and quartz intrusions, Kuala Lumpur-Rawang trunk road, Locality P.

meta-tuffite. The possible range of MHS is 87°–115° and MHS = 115° best explains the lateral fault slips and is also perpendicular to a quartz dyke. The dyke may have filled a tension fracture.

Locality L (Fig. 15), Genting Kelang Quartz Dyke at the reservoir outlet northeast of Kuala Lumpur. Steeply inclined to vertical quartz veins cut into the large quartz dyke. The possible MHS range is 80°–103°, which explains all except a single fault slip sense in Figure 15. The orientation of the younger quartz veins suggest them to occupy extension fractures parallel to MHS.

Locality M (Fig. 16), Titiwangsa granitoid at Pangsun, Ulu Langat. The few fault slip senses result in a wide range of possible MHS direction, that is, between 44° and 118°. An MHS of approximately east — which is normal to the zone of irregular fractures and to some of the quartz vein — best explains the structural movement pattern. The irregular fractures and the particular quartz veins probably occupy tension fractures.

Locality N (Fig. 17), comprises Titiwangsa granitoid and pre-granitoid metasediments exposed along the main road in Hulu Lui, between Semenyih and Jelebu District. The fault slips on fractures within the metasediments indicate a MHS = 100°. Almost all senses of fault slips on fractures in the granitoid seem to have responded to a second MHS direction in 350°, which is roughly perpendicular to the MHS for the metasediments. The 350°-MHS direction probably resulted from released strain energy in the granitoid. That strain energy accumulated in the granitoid when it was subjected to an earlier 100° directed MHS.

Locality P (Fig. 18), comprises Titiwangsa granitoid, pre-granitoid crystalline schist and post- or penecontemporaneous quartz intrusions, km 17, Kuala Lumpur-Rawang trunk road. A vertical granitoid dyke cuts across schist. The NNW-trend of this dyke is parallel to the regional tectonic compression of Peninsular Malaysia which acted in approximately 65° direction. The fault slips, however, indicate a MHS-range of 82° to 130°. The southeast verging reverse fault is consistent with MHS = 130°.

INTERPRETATION AND CONCLUSIONS

The radiometric dates for the Titiwangsa granitoids in the study area ranges between 198

Ma and 215 Ma (Geological Map of Peninsular Malaysia, 8th edition, Geological Survey of Malaysia 1985). These dates correspond with Late Triassic to Early Jurassic which is recognised as a period of large-scale granitoid emplacements in Peninsular Malaysia.

The interpreted MHS directions for the various localities in the study area are shown by bold lines on Figure 4. The inset shows their localities with respect to the geology. Three main MHS directions are apparent, that is,

NNE-NE	localities A, B, C, D, E, F and K
approximately East	localities G, I, L, M and N
ESE-SE	localities J and P

Two north-trending MHS at Localities G and N occur together with east-directed MHS. As explained above, the north-trending MHS represent a second stress system that developed when strain energy in the rock became free after the original east-directed MHS decreased in strength.

The common regional compression direction for Peninsular Malaysia is 65°–70° and in certain areas is 90° (see Tjia, 1972, 1978). Of the three groups of MHS-directions listed earlier, the roughly east-directed MHS most probably represented the areal tectonic compression that was active during the granitoid emplacement or in post-granitoid time. The ESE-SE MHS directions are of unknown origin; these MHS-directions may represent local stress systems or tectonic terrains that became rotated through continued strike-slip movements along the Kuala Lumpur and Bukit Tinggi fault zones.

The NNE-NE MHS directions in the general Genting Sempah region are parallel to the vergence of the Genting Thrust Belt, which was towards southwest (see Lim and Tjia, 1979).

The following conclusions are drawn from this study.

(1) The areal tectonic compression direction for the Titiwangsa granitoids exposed along the Selangor-side of the Karak Highway is in the sector NNE-NE. This is parallel to the vergence of the Genting Thrust Belt. Therefore, the granitoids were already solidified when thrusting took place. The emplacement age of the granitoids is Late Triassic to Early Jurassic.

(2) Outside the Selangor-side of the Karak Highway, the Titiwangsa granitoids were subjected to mainly east-west tectonic compression.

(3) The regional compression stored strain energy in the rock mass. This strain energy became released when the strength of the regional compression decreased. The ensuing secondary MHS direction was perpendicular to the original regional compression direction. It appears from the Hulu Lui analysis that only structurally isotropic rock masses, such as granitoid plutons, may store strain energy. In the largely anisotropic metasedimentary rock, strain imparted by the regional compression was probably dissipated along lithological boundaries and other weak zones.

ACKNOWLEDGEMENT

Mr. Mohd. Amin Abu Bakar of Universiti Kebangsaan Malaysia, Bangi, facilitated fieldwork by preparing a base plan of the highway.

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Manuscript received 14 November 1992