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A gravity high in Darvel Bay

PATRICK J.C. RYALL[1] AND DWAYNE BEATTIE[2]

[1]Department of Geology
Dalhousie University
Halifax, Nova Scotia
Canada B3H 3J5

[2]Geoterrex Ltd.
2060 Walkley Road
Ottawa, Ontario
Canada K1G 3P5

Abstract: A gravity survey was carried out along the coastlines of Darvel Bay and many of the islands (e.g. Sakar, Tabauwan, Silumpat) in the Bay. In addition stations were located along the road from Kunak to Lahad Datu. The resulting Bouguer anomaly map shows a broad gravity high of at least 60 mgal which strikes west northwest with its maximum on the southern coast of Pulau Sakar. The anomaly narrows and decreases where it comes ashore and may continue along the Silam-Beeston Complex.

This large positive anomaly suggests that there is an extensive ultramafic body beneath Darvel Bay. The gravity anomaly can best be modelled as a 3 to 5 km thick slab of ultramafic rock under the Bay with amphibolites on its northern and southern edges dipping away from the Bay. This model is consistent with a folded structure which brings upper mantle rocks to the surface. It is unlikely that there is a significant thickness of Chert-Spilite Formation beneath Darvel Bay, although the gravity data would permit a thickness of up to a few hundred metres.

INTRODUCTION

Borneo

The island of Borneo is located in a complex tectonic region. According to Hamilton (1979) the basement terrain of western and interior Borneo consists of Paleozoic and Mesozoic, and possibly Paleogene sedimentary, metamorphic, granitic and volcanic rocks. This region behaved as a craton in middle and late Cenozoic time. Bounding this old terrain on the east, northwest and north are younger additions to the continental crust: regions whose basement consists of subduction complexes of Late Cretaceous, Eocene and Middle Tertiary ages respectively.

Haile *et al.* (1977) have determined that the Cretaceous terrain has undergone a net rotation of about 45 degrees counterclockwise in the last 80 Ma but has had no net change in latitude.

The northeastern half of Sabah consists mostly of mélange and broken formations in a broadly arcuate belt that swings from west-southwestward strikes in the east, where the Sulu Arc comes ashore, to northwestward in the northwest. In the northwest it then swings abruptly to become the subduction terrain of the Northwest Borneo system (Hamilton, 1979).

Hutchison (1968, 1975) considers the ophiolitic rocks of Darvel Bay as part of a strongly arcuate line which runs from the Sulu Archipelago in the northeast, through Darvel Bay and northwestern Sabah and along Palawan (Fig. 1a). He considered the northeastern corner of Sabah and the adjoining Sulu Sea to be a large flake, as defined by Oxburgh (1972), of oceanic lithosphere that had been thrust over the older continental rocks of Borneo. Hutchison (1975) concluded that the parallel andesitic volcanic arc to the south of Darvel Bay on the Semporna Peninsula (Kirk, 1968) of Pliocene age and the submarine structure of the Sulu Sea (Murauchi *et al.*, 1973) indicated that the Sulu Archipelago and Darvel Bay part of the ophiolite resulted from the southward subduction of the Sulu Sea oceanic or marginal basin crust.

Leong (1978) has identified a blueschist belt stretching northwest from the Dent Peninsula (Fig. 1b) which he has suggested is related to the presently inactive southward dipping subduction of the Sulu Basin. Tjia (1988) has defined the Kinabalu Suture Zone, an 80 km wide belt containing most of the Crystalline Basement, mafic and ultramafic rocks, Chert-Spilite ophiolite and mélange which extends in an arc from Darvel Bay to the northwestern tip of Sabah (Fig. 1b).

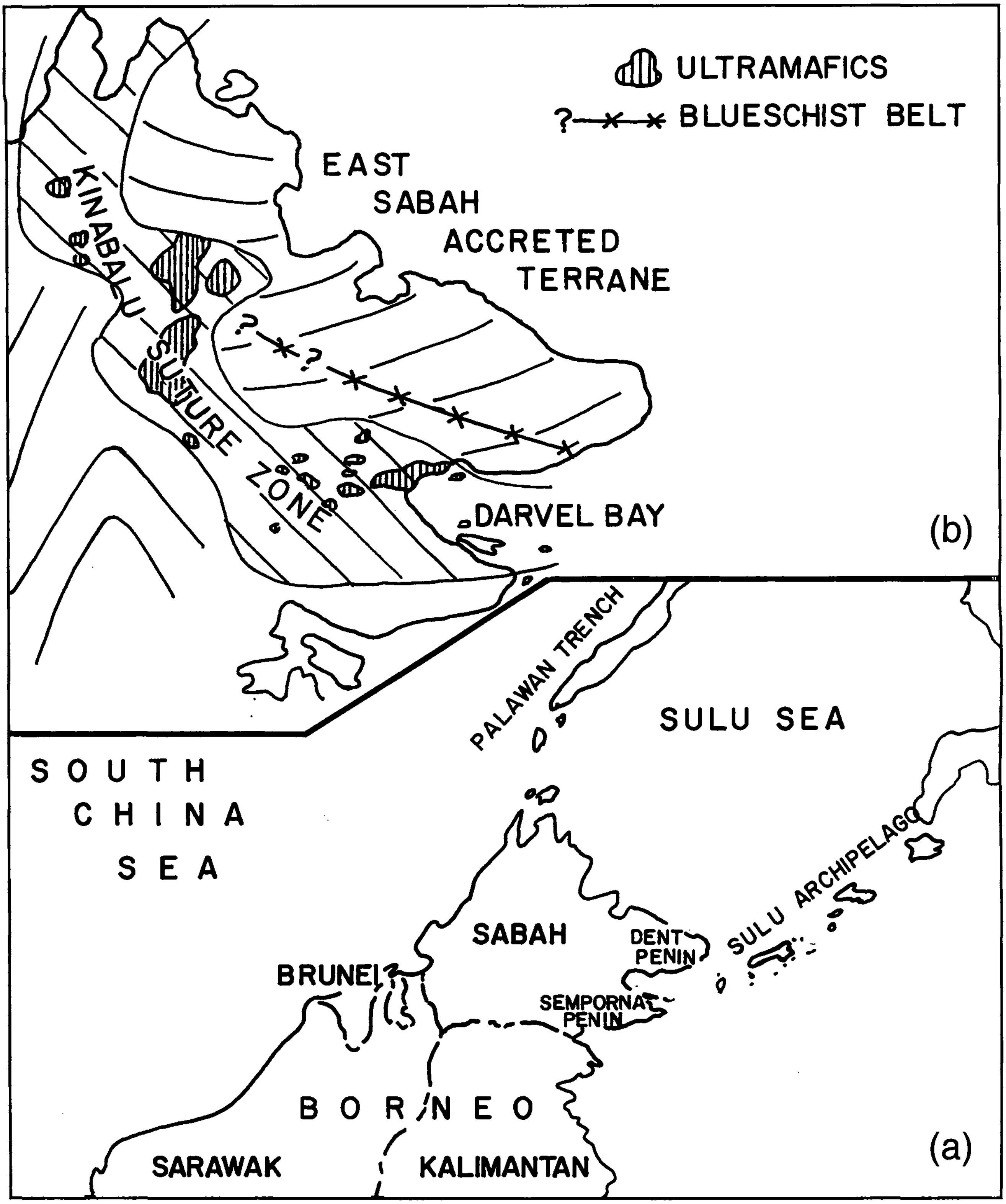

Figure 1. (a) Northern Borneo and surrounding regions. (b) East Sabah accreted terrane and Kinabalu Suture Zone (adapted from Tjia, 1988).

Darvel Bay Area

The pre-Tertiary rocks of the Darvel Bay area, Figure 2, consist of (Hutchison and Dhonau, 1969) the Chert-Spilite Formation and the ultramafic rocks:

The Chert-Spilite Formation

This assemblage of rocks outcrops in the Darvel Bay area and throughout the Kinabalu Suture Zone. This formation was considered to be late Cretaceous to Eocene (Fitch, 1955; Kirk, 1968 and Leong, 1974) on the basis of foraminiferal calcareous beds from the Upper Segama area. However, examination of radiolarian chert from the same area has yielded ages as early as Early Cretaceous (Valangian to Barremian) (Leong, 1975, 1977). Radiolarian cherts from Kudat near the northern tip of Sabah also give Early Cretaceous (Berriasian to Albian) ages (Jasin *et al.*, 1985).

Volcanic rocks are abundant and they comprise volcanic breccia, agglomerate, pillow lava, basalt, spilite, including hydrothermally altered volcanic rocks and associated dolerite. The sequences of volcanic-sedimentary beds are tightly folded, overturned and dipping steeply. Strong faulting and shearing has affected most parts of the formation which is probably several thousands of feet thick (Leong, 1974).

Hutchison (1975) considers this formation to form the basaltic layer of the ocean crust together with associated oceanic sedimentary deposits and has correlated this formation (Hutchison, 1968) with a similar chert and spilite association in Palawan and northwest Mindanao in the Philippines. The bedded character of the chert (Leong, 1974) indicates deposition in a tectonically created basin within the influence of a continental margin (e.g. a trench-island arc setting, a marginal sea or back arc basin) (Hein and Karl, 1983).

Ultramafic rocks

Ultramafic rocks in the map area can be grouped into two groups (i) those of the Darvel Bay area and (ii) those of the Silam-Beeston peridotite-gabbro complex.

Darvel Bay. The ultramafic rocks include peridotite, pyroxenite and dunite (Dhonau and Hutchison, 1966). Many of the ultramafic rocks have been more or less serpentinized. The ultramafics found along the coastal areas near Kampung Lamak and in the Saddle Island Group are characterized by the presence of disseminated chromite and chromite bands in serpentinized dunite (Leong, 1974). Dunite is more abundant in the Saddle Island Group than anywhere else in the map area. Serpentinite and serpentinized peridotite occur along the coastal areas near Kampung Lamak and Silam and on Pulau Sakar.

Samples collected by Kirk (1968) from Pulau Manganting were found to consist of dunite, harzburgite, olivine-gabbro, werhlite and other ultramafic rocks. Rocks from Pulau Tabauwan include serpentinized peridotite and serpentinite on the northern coastal areas and peridotite and olivine-gabbro south of the western headland.

The nature of the rocks of the southern part of Pulau Tabauwan is a matter of some dispute. Kirk (1968) considered the whole of Pulau Tabauwan as built up of ultrabasic and associated basic rocks. Dhonau and Hutchison (1966) mapped the banded hypersthene-bearing rocks and other hornblende-bearing rocks on the southern half of the island as the "Silumpat Gneiss Formation" which also included rocks exposed on Pulau Silumpat, on the northern part of Pulau Sakar, on the Bohayan group of islands and on the coastline between Tanjung Silam and the Silam timber camp. Although the rocks are mineralogically amphibolites, Dhonau and Hutchison (1966) called them amphibolite gneiss in view of their well-marked gneissic texture. They considered that the Silumpat Gneiss originated from the metamorphism of gabbros, possibly including some more ultrabasic rocks. Hutchison (1975) considered the Silumpat Gneiss Formation to be the equivalent of the gabbroic layer of ocean crust because (i) its thickness ranges from 1–2 km, (ii) at its lower contact with the mantle(?) harzburgite it consists of hornblende granulite and at its upper contact with the spilitic metabasalt it is of greenschist facies, and (iii) it is folded with overlying metabasalt and spilite and the underlying conformable harzburgite into broad open folds.

Leong (1974) considered the hypersthene to be a relict primary mineral in the parental gabbroic rocks which had been patchily metamorphosed in the amphibolite facies. While Dhonau and Hutchison (1966) mapped the islands and a small stretch of coastline of Darvel Bay, Leong's (1974) revision of Fitch's (1955) memoir covered a much greater area. Leong therefore mapped the Silumpat Gneiss Formation as part of the Crystalline Basement which occurs extensively on land (e.g. north of the Silam-Beeston complex) and considered the ultramafics of Pulau Tabauwan and Pulau Manganting etc. as a possible ultramafic complex of the Crystalline Basement.

The Mesozoic "Crystalline Basement" rocks of Sabah consist mainly of basic to intermediate igneous and metamorphic rocks and a few occurrences of granite.

Silam-Beeston Complex. The Silam-Beeston Complex is an east-west elongated body about 30 km long and up to 6 km wide. It forms a mountain range consisting of a series of high ridges between Gunung Silam and Gunung Beeston, each about

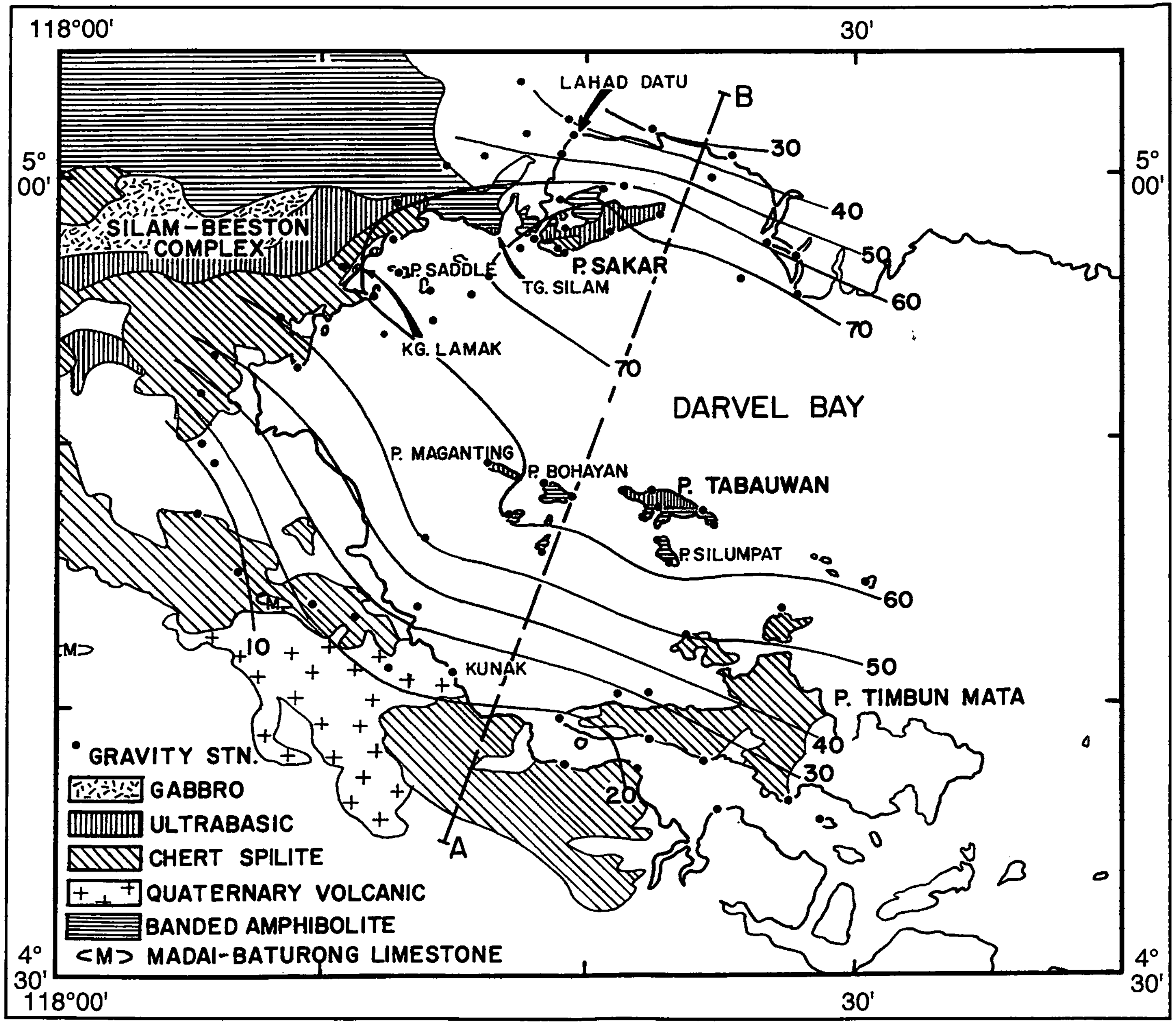

Figure 2. Bouguer Gravity (contours in mgal) and simplified geology of the Darvel Bay region (after Hutchison and Dhonau, 1969, 1971; Leong, 1974). Line AB is the location of the profile shown in Figure 3a. Dashed lines indicate the locations of Hutchison's (1972, 1975) cross sections.

1,000 m high. The complex contains almost equal proportions of gabbroic and ultramafic rocks with the former to the north and the latter to the south (Leong, 1974). Peridotite, mainly harzburgite, is the main ultramafic rock type, relatively fresh in the core of the intrusion and serpentinized near the margins. Contacts with the gabbro are normally sharp and generally faulted. Along with other ultramafic bodies, the Silam-Beeston Complex is believed to have been emplaced in Late Cretaceous time, contemporaneous with the early stage of deposition of the Chert-Spilite Formation and may be correlated with similar complexes of the Philippine Islands e.g. the Zambales Complex (Leong, 1974).

The essentially northwest-southeast structural pattern of the predominantly ultramafic rocks of the Saddle Group. Pulau Manganting, Pulau Tabauwan and Pulau Sakar described by Dhonau and Hutchison (1966) suggest a single ultramafic-mafic complex now disconnected and mainly submerged (Leong, 1974). Hutchison (1975) however, postulated the presence of a downfaulted block of Chert Spilite between Pulau Sakar and Pulau Tabauwan. The complex in Darvel Bay is discordant to the east-northeast trend of the Silam-Beeston Complex (Kirk, 1968) and is considered by Leong (1974) to be older than the Silam-Beeston Complex or the other ultramafic rocks thought to emplaced contemporaneously with the earliest stage of deposition of the Chert-Spilite Formation. Conversely, because of a diversity of fold axes of apparently different ages, Hutchison and Dhonau (1969) thought it possible that the ultramafic rocks of the Darvel Bay area may not be all of the same age.

GRAVITY SURVEY

Procedures

The proposal of Hutchison (1975) that the Darvel Bay ultramafics were part of an ophiolite belt could be tested by a gravity survey to put limits on their extent and provide a clue to their means of emplacement. The relative ease of access by boat around the perimeter of the bay and islands made such a survey feasible whereas a survey on land would be much more difficult. There was the added advantage that sea-level was readily accessible as a reference height. Most of the gravity stations were located on the shoreline within a few metres of the water. Station height above sea-level and time were recorded so that by using tide tables, height above datum was obtained. A few stations were located on coral reefs as much as half a metre below sea-level. A series of stations were situated along the road from Lahad Datu to Kunak. Elevations for these stations were obtained by altimeter and are probably accurate to about +/– 3 m compared to an accuracy of +/– 0.3 m for the other stations.

Results

The Bouguer gravity map is given in Figure 2 which also gives a simplified version of relevant geology based on Hutchison and Dhonau (1969) and Leong (1974). A gravity profile across Darvel Bay, line AB in Figure 2, is given in Figure 3a along with surface geological control adapted from Hutchison (1975). Consideration of Figures 2 and 3 yields the following results:

i. There is a large (> 60 mgal) gravity high trending west northwest cross Darvel Bay.
ii. The anomaly pattern is consistent with an approximately linear feature, possibly plunging to the west.
iii. The width of the anomaly and the slopes indicate a deep (several kilometre) dense (ultramafic?) body underlying Darvel Bay, possibly thinning or plunging to the northwest. This anomaly cannot be reconciled to Hutchison's (1975) suggestion of a graben-like structure of chert-spilite between Pulau Sakar and Pulau Tabauwan.
iv. The survey needs to be extended north and south away from Darvel Bay to define the flanks of the anomaly and inland (i.e. west from Kunak and Lahad Datu to confirm or deny the linear extension of the anomaly inland.

INTERPRETATION

Hutchison (1975, Fig. 3) has postulated that the Chert-Spilite Formation underlies Darvel Bay bounded by shear zones on the southern coast of Pulau Sakar and the northern coast of Pulau Tabauwan. In view of the gravity maximum over the Bay, it is highly unlikely that more than a thin veneer of Chert-Spilite is present under the Bay, or along the coast in the vicinity of Silam. The gravity contours strongly suggest that the ultramafics exposed at Sakar, Tabauwan and the Saddle Islands are a continuation of the Silam-Beeston Peridotite-Gabbro Complex.

Detailed interpretation using two and three dimensional models requires reliable estimates of the densities of the different rock types. The assignment of densities is fraught with uncertainties. Table 1 gives density average calculated from Christensen's (1982) tables and densities used in other gravity surveys over ophiolites as well as limited measurements made for this survey. The fact that most of the mapped

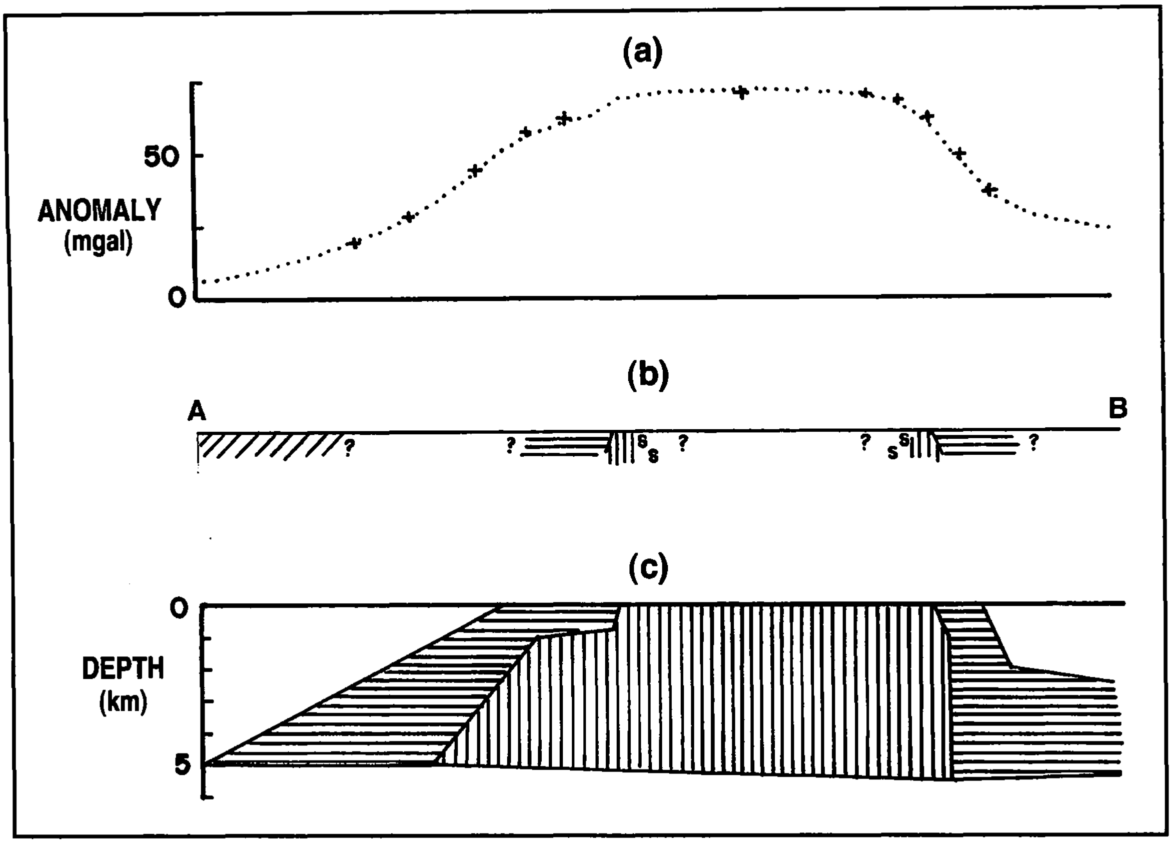

Figure 3. (a) Gravity profile along line AB (Fig. 2). Crosses indicate gravity values every 10 mgal from Figure 2. Dotted line shows gravity calculated from model at bottom of the figure. (b) Extent of surface geologic control. Vertical lines indicate ultrabasic rocks, horizontal lines indicate banded amphibolite and diagonal lines indicate Chert-Spilite Formation. Small s's indicate serpentinization. Question marks show where boundaries are unknown. (c) Simple model used to calculate gravity. Symbols as in 3b.

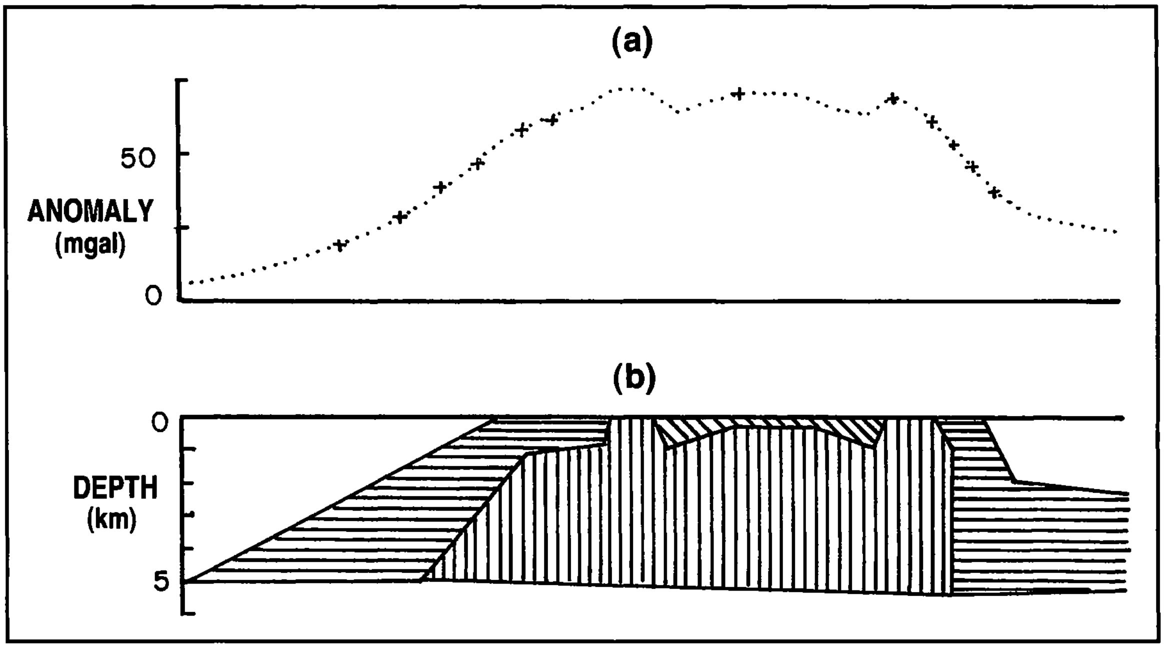

Figure 4. (a) Same as for Figure 3a. (b) Model used to calculate gravity. Symbols as in Figure 3b. This model has a few hundred meters of Chert-Spilite underlying Darvel Bay.

Table 1. Rock densities.

ROCK TYPE	REFERENCE				
	I $\rho \pm \sigma(n)$	II ρ	III ρ	IV $\rho \pm \sigma(n)$	V $\rho \pm \sigma(n)$
Serpentine and Serpentinized Peridotite	274 ± 0.19(39)		2.55	2.5	2.73 ± 0.08(2)
Peridotite	3.28 ± 0.16(15)	surface 2.90	3.3	2.52 ± 0.02(20)	
Dunite	3.26 ± 0.08(30)	3.30 depth			
Harzburgite	3.23 ± 0.06(7)			2.64 ± 0.02(20)	
Amphibolite	3.00 ± 0.05(6)				2.87 ± 0.10(7)
Gneiss	2.76 ± 0.13(12)				
Metabasalt	2.64 ± 0.08(8)				
Metagabbro	2.87 ± 0.11(44)				
Spilite	2.71 ± 0.02(4)				
Quartz Schist	2.73 ± 0.03(15)				
Other Schist	2.95 ± 0.11(50)				
Granulite	2.93 ± 0.16(23)				
Gabbro				2.92 ± 0.04(15)	
Pillow Lavas		2.65		2.91 ± 0.01(5)	

References: I. Christensen, 1982; II. Gass and Mason-Smith, 1963; III. Milsom, 1973; IV. Farah and Zaigham, 1979; V. Beattie, 1986.
Symbols: ρ = density (g/cm³), σ = standard deviation, n = number of samples

Table 2. Rock densities used in modelling.

	ρ	$\Delta\rho$
Chert-Spilite Formation	2.70 g/cm³	0.00
Crystalline Basement/Silumpat Gneiss	2.87 g/cm³	0.17
Ultramafics	3.00 g/cm³	0.35

geologic units consist of a range of rock types in unknown or ill-defined proportion further complicates the process. For modelling purposes, the densities given in Table 2 are used. In the models the density of the Chert-Spilite is used as a reference so that the model densities are the differences from the Chert-Spilite. A major uncertainty is the extent of serpentinization which will control the density. The resulting density can range from about 2.55 g/cm^3 for highly serpentinized peridotite to almost 3.30 g/cm^3 for totally unserpentinized rock. Clearly a highly serpentinized rock should produce a negative gravity anomaly while a fresh one will give rise to a large positive anomaly.

Figure 3c shows a simple model with an ultramafic body of intermediate density underlying Darvel Bay flanked by prisms of Crystalline Basement/Silumpat Gneiss (CB/SG). Agreement on the flanks of the anomaly, i.e. where observational control is best, is excellent. However, the breadth of the calculated anomaly also shows clearly the need to extend the survey north and south of Darvel Bay to properly constrain the model of the outer boundaries of the CB/SG. Figure 4 shows an attempt at modelling a thin (1 km–0.3 km) layer of Chert-Spilite under Darvel Bay. While this model does produce some short wavelength perturbations over the opposing coasts of Tabauwan and Sakar, it does fit the observations. However, a significantly greater thickness of Chert-Spilite would not do so because the perturbations would be larger and be seen in the observations.

DISCUSSION

The gravity survey is consistent with the hypothesis that Darvel Bay is underlain by a large block of ultramafic rocks. What is the structural relationship of this body with Gunung Silam, which is less than 20 km away, more or less in line and is made up partly of similar rocks?

Ophiolite bodies and suture zones are associated with compressional regimes. Nonetheless some amount of strike-slip motion is not unlikely to accompany he collision. If the fault trace is curved

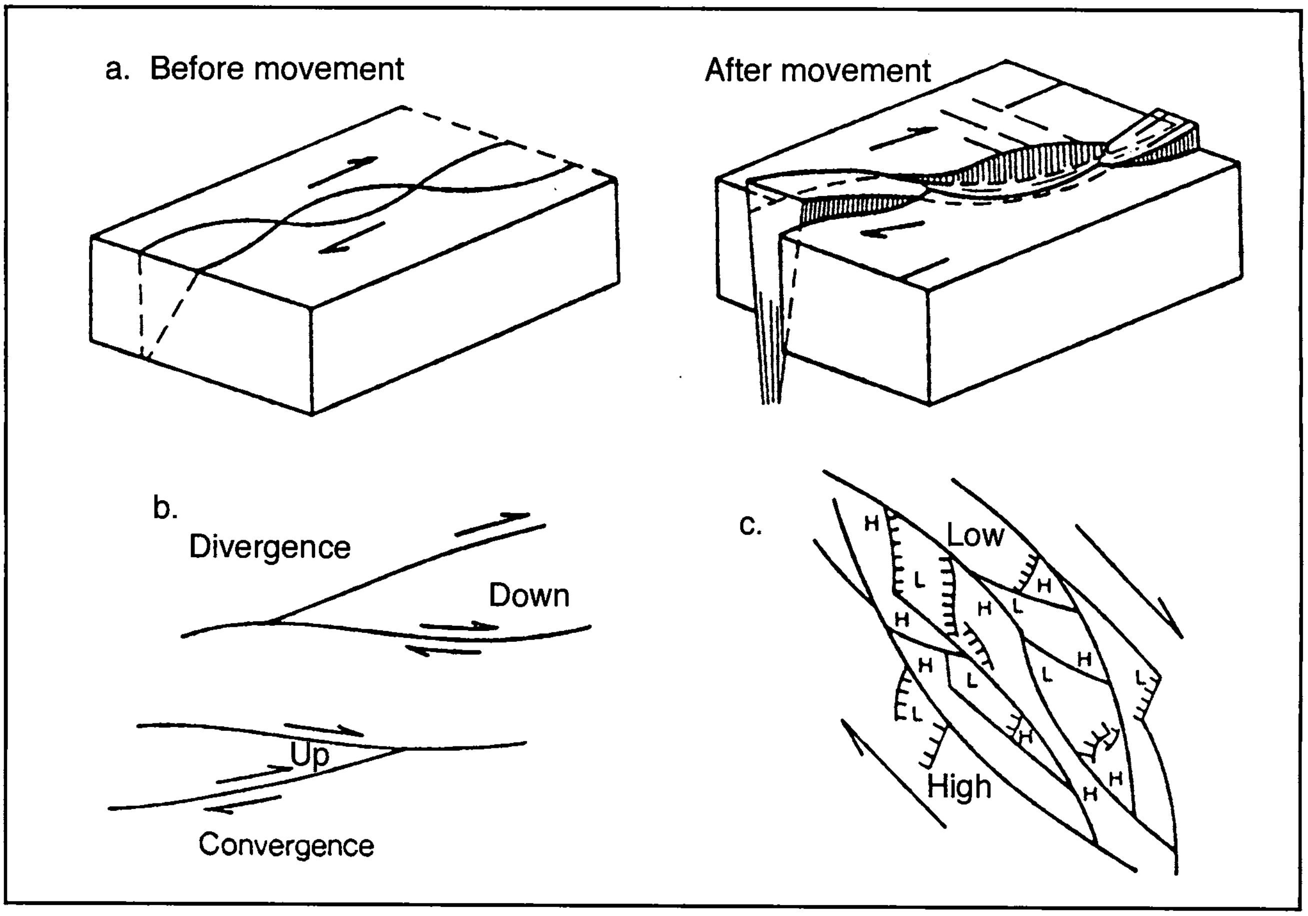

Figure 5. (a) Diagrams showing how strike-slip motion would produce vertical motion with alternately elevated and subsided blocks (from Reading, 1980). (b) and (c) Diagrams showing a more complicated pattern of uplift and subsidence due to anastomising faults (from Reading, 1980).

and braided — and certainly the suture zone is curved — then a small amount of strike-slip motion would produce predominantly vertical motion with alternating elevated and subsided blocks (Reading, Fig 3a, 1980) as shown in Figure 5a. The Silam-Beeston Complex might be an example of an elevated block, while the region underlying Darvel Bay would be a subsided block. A more complicated model which may apply to the Upper Segama Valley and Darvel Bay area is one of the convergent and divergent faults or anastomosing faults, Figure 5b (after Reading, 1980).

There are two competing models for the emplacement of ultramafic rocks in the Darvel Bay region, one a tectonic model which envisages the forceful emplacement of lower "oceanic" crust/upper mantle; the other (Leong, 1974) which views the ultramafics primarily as low temperature diapiric intrusions ("protrusions") of serpentine into pre-existing (?) Crystalline Basement and Chert-Spilite Formation. Strike-slip motion brings with it the potential for transtensional regimes and hence the emplacement of serpentine up fissures as proposed by Robertson and Woodcock (1980) for the Antalaya Complex in Turkey. Serpentines which are emplaced as protrusions must be less dense than the surrounding rock and will therefore cause negative gravity anomalies as is the case for the Joaquin Ridge serpentine body in California (Byerly, 1966). The ultramafic bodies on P. Sakar and P. Tabauwan are almost certainly not emplaced in such a fashion because of their strong positive gravity anomaly.

A subdued positive anomaly also seems to extend over the serpentine(?) bodies mapped by Leong (1974) in the Mostyn Estates area. A detailed follow up survey in this area should be feasible because of its cultivated nature and the relatively dense road network. The results of such a survey should help determine whether the outcrops are all separated bodies or are merely separate exposures of a single serpentine body buried beneath the Quaternary volcanics.

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