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DEFORMATION OF AN ALPINE ULTRAMAFIC ASSOCIATION IN DARVEL BAY, EAST SABAH, MALAYSIA

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"I regard the ultramafic and gabbroic parts of ophiolite complexes as being identical with, and part of, the alpine igneous rock suite. – Thayer (1967, p. 222)

SUMMARY

The island-arc system of the Philippines, which includes the well-known Zambales alpine complex, continues westwards along Palawan island and along the Sulu achipelago into North Borneo. Within this arc, there is a characteristic association of ultramafic rocks, banded amphibolites of gabbroic composition, and a younger flysch sequence characterised by abundant spilites. In the Darvel Bay area of east Sabah (North Borneo), the ultramafic rocks are shown to be concordantly interfoliated with the banded amphibolites. The folding, which is predominantly along an east-west axial direction, has been accompanied by dynamothermal metamorphism characteristically to almandine-amphibolite facies. An increase in metamorphism to hornblende-granulite facies occurs in a "thermal aureole" of the syntectonic ultramafic body in central Darvel Bay.

The island-arc system has been subjected to several periods of deformation, the youngest of which was accompanied by greenschist facies metamorphism, which has affected not only the ultramafic-metabasite association, but also the overlying flysch sequence and has converted many of the spilites to amphibolites. Structural data indicate that ultramafic intrusions accompanied both the older and the younger periods of deformation.

Subsequent intense faulting has further obscured the earlier tectonic history of the ultramafic association.

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INTRODUCTION

a. *Nomenclature*

In descriptions of alpine ultramafic associations (Wyllie, 1967), the adjective "contact" is frequently used without due regard to the principles of metamorphic facies.

Most alpine ultramafic bodies are emplaced syntectonically into mesozonal or catazonal rock assemblages and are often enclosed by, and folded together with, crystalline schists of almandine-amphibolite facies (Sørensen, 1967). The high tectonic pressure (up to 9kb) would clearly prevent the formation of the hornfels facies series; the increase of temperature around an intrusion may result, however, in a higher grade of dynamothermal metamorphism.

This localised increase of dynamothermal metamorphism cannot be accommodated within the commonly accepted definition of contact metamorphism, in which the magma is presumed to intrude "relatively shallow and cold regions of the crust" (Winkler, 1967). Of deeper-seated conditions, Miyashiro (1961) observes "the metamorphic facies series developed in the contact aureole of synkinematic granites is practically identical to that developed through regional metamorphism of the same region". In other words, synkinematic mesozonal and catazonal intrusions may cause an increase in the grade of dynamothermal metamorphism depending upon the temperature difference existing between the ambient regional tectonic temperature and the magma temperature.

In addition, localised high temperature zones may

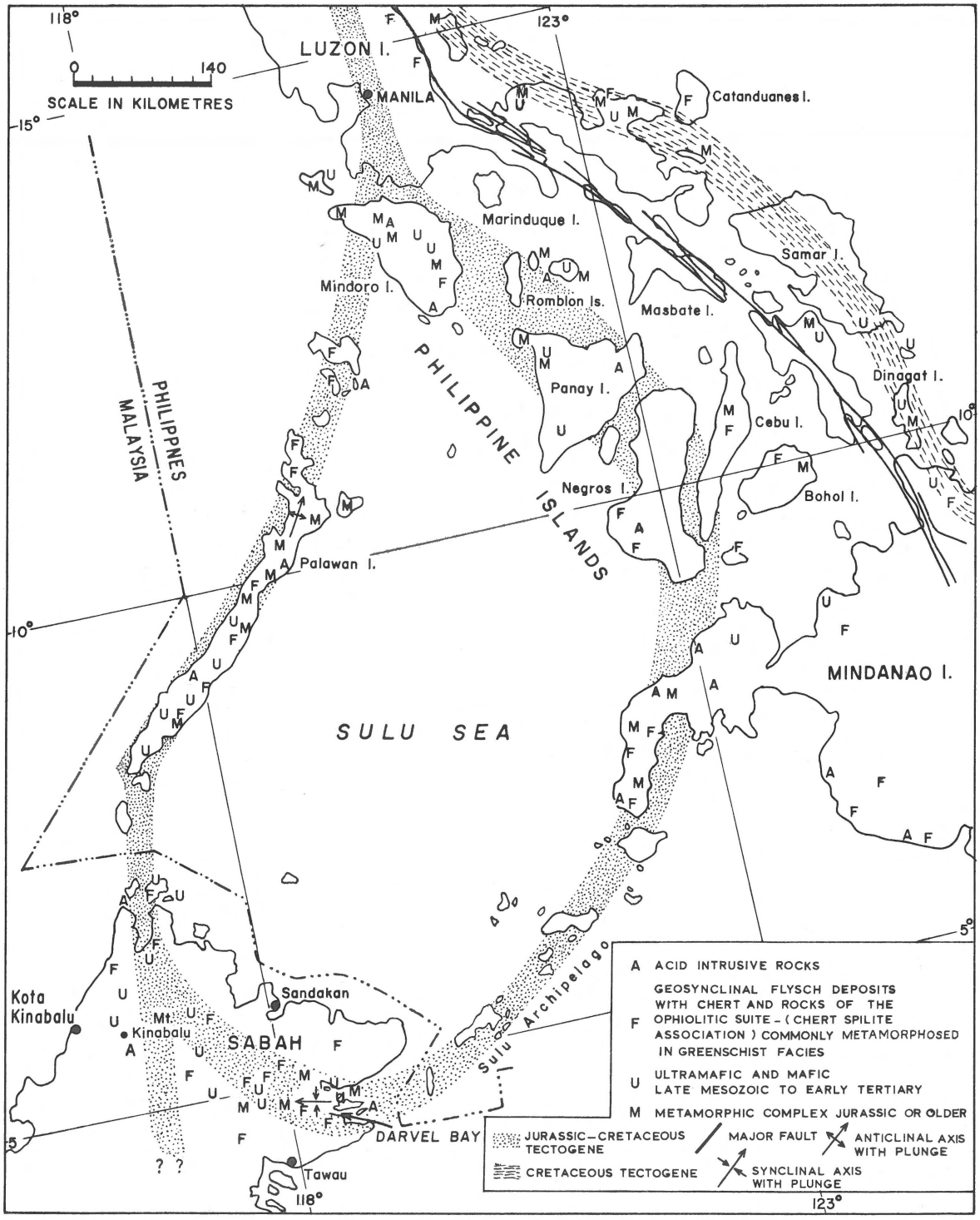


Fig. 1
The island-arcs of Sabah and the Philippines. Darvel Bay lies to the south of the Sulu Sea, where the Sulu Archipelago runs into mainland Borneo.

be due to higher geothermal gradients unrelated to igneous bodies. These have been referred to as "thermal domes" (W e n k, 1962).

The terminology confusion results from the almost universal association in the literature of "contact metamorphism" and "hornfels", and the latter is all too frequently taken as the only criterion for the former (G r e e n, 1967). In the hope of obviating such confusion, we propose the following usage:

Contact metamorphism and *contact aureoles* should be reserved for high-level epizonal phenomena characterised by the hornfels facies series.

Thermal domes and *thermal aureoles* should be reserved for deeper-seated mesozonal and catazonal phenomena of localised increase of the dynamothermal facies series.

Since all alpine ultramafic aureoles are of a dynamothermal character, we feel that many ultramafic bodies, which have heretofore been described in the literature as exhibiting no "contact metamorphism" may indeed, upon re-examination, be shown to have caused a localised increase of dynamothermal grade in a *thermal aureole,* as in the case to be described in the following pages.

b. *regional setting*

The rocks of the Darvel Bay area, east Sabah, Malaysia (Fig. 1), have been described petrographically by H u t c h i s o n and D h o n a u (1969, in press). They are divided into the following groups (Fig. 3):

1. (youngest) : Late Quaternary fissure eruptions of olivine basalt in the Mostyn Wharf area (K i r k, 1968).
2. Post orogenic (Pliocene to Quaternary) acid to intermediate intrusive rocks of tonalite prophyry, quartz porphyry, and microgranite on Timbun Mata (Kirk, 1968).
3. Sedimentary formations of Oligocene-Miocene age, including the Segama Group north of Lahad Datu and the Kalumpang Formation of Timbun Mata. These formations are of thick, folded, marine-shelf sedimentary rocks of varied lithology: sandstone, shales with volcanic detritus, tuff and volcanic conglomerate (W i l s o n, 1966).
4. Sedimentary formations of Eocene age – the Kulapis Formation, consisting mainly of red massive sandstone and chert with some shale and a basal conglomerate (F i t c h, 1955).
5. The Chert-Spilite Formation: This assemblage of rocks outcrops in south-east Sabah and in north Sabah; it was formed in a geosynclinal flysch environment during the late Cretaceous and Eocene, and consists of a variety of sedimentary rocks, including cherts, and spilites. We consider that in the Darvel Bay area, certain low-grade amphibolites are early-formed representatives of spilites of this formation. It must, however, be clearly stated that we have no proof of the age of these rocks in the Darvel Bay area and we have simply followed F i t c h (1955) in ascribing them to the Chert-Spilite Formation. The Chert-Spilite Formation of Sabah has been correlated by B r o n d i j k (1964) with the Danau Formation of Central Borneo (M o l e n g r a a f f 1902), but this correlation is disputable since there is no continuity of outcrop, neither is it certain that north Borneo and West Sarawak belong to the same geosyncline.
6. Ultramafic rocks: these are peridotites, pyroxenites, and dunites that have been syntectonically intruded either mesozonally or catazonally into rocks of the Silumpat Gneiss. Their age is apparently late Mesozoic.
7. The Silumpat Gneiss: these are the oldest rocks in Sabah, a series mainly of banded amphibolites of metamorphic grade ranging from the top of the greenschist facies to the hornblende granulite facies. They were originally igneous of the gabbro clan. We suggested giving these rocks the status of a formation (H u t c h i s o n and D h o n a u, 1969, in press), defining it at a point on the east coast of Silumpat island (Fig. 2D). The rocks of the Silumpat Gneiss were metamorphosed to their present state probably in the late Jurassic.

The present study is concerned entirely with the pre-Tertiary rocks of the Darvel Bay area, that is of the above groups 5, 6 and 7.

Previous workers in the Darvel Bay area have interpreted the geology there in various ways. R e i n h a r d and W e n k (1951, p.99) called the older matamorphic rocks *Crystalline Schists,* and considered that they represented a basement older than the Danau Formation. They also suggested that the *Crystalline Schists* might possibly be the metamorphic equivalent of the rocks of the Danau Formation, but although this was acceptable on petrological grounds, they felt that it was the less

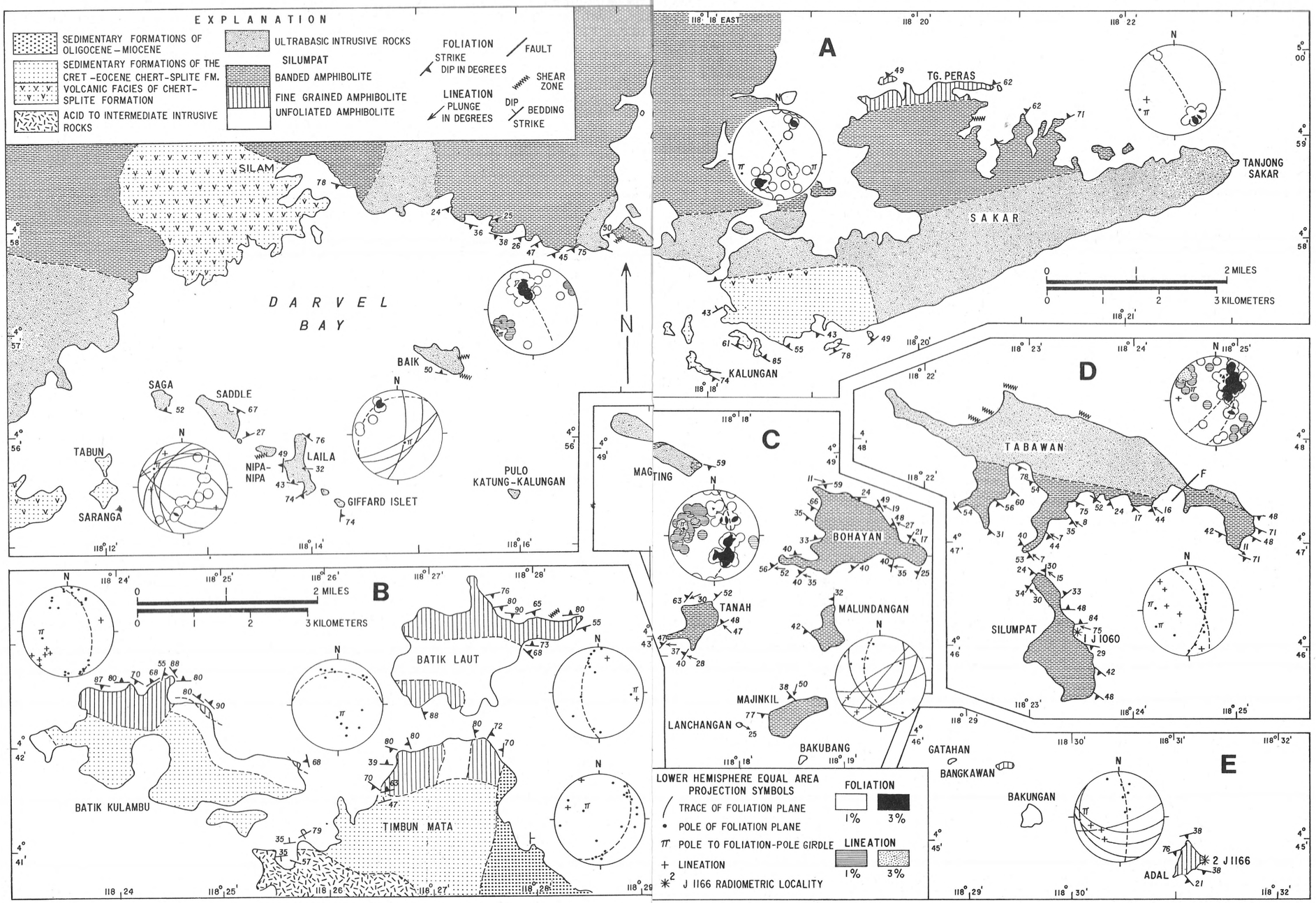


Fig. 2
Structural map of the islands and coastline of Darvel Bay.
The complete data are included in the lower-hemisphere equal-area stereograms, but only a few selected foliation and lineation readings have been included to prevent overcrowding. Areas A, C, D and E are based on the work of the present authors; B is after Koopmans (1968). The correct relative positions of the islands are shown in figure 3.

probable interpretation.

Fitch (1955) considered that all the rocks in the Darvel Bay area, except the sediments of the Chert-Spilite Formation, are igneous, comprising ultrabasic rocks that are unbanded or slightly banded, and mainly dioritic rocks that are strongly banded. The fact that these dioritic rocks are composed essentially of hornblende and untwinned intermediate plagioclase, with segregation into hornblende-rich and plagioclase-rich bands, did not suggest to him that these rocks might be better considered of metamorphic origin, as it did to the earlier workers (Reinhard and Wenk, 1951), and to the present authors (Hutchison and Dhonau, 1969, in press; Dhonau and Hutchison, 1966; Hutchison, 1968). Fitch (1955, p.55) wrote – "Few metamorphic rocks occur in the Segama and Darvel Bay area, despite the many intrusions there".

Kirk (1962) also considered these rocks to be intrusive, describing them as pre-orogenic, basic and ultrabasic, associated with metamorphic amphibolites (p. 110 and 118).

Most recently of all, Wilson (1965, p.84-85, after Kirk, 1965 and 1968) refers to the metamorphic rocks as the *Crystalline Basement,* composed of pre-Jurassic rocks that underlie the rocks of the Chert-Spilite Formation and consist of "amphibolitised banded gabbros, diorite and granite" with Tertiary intrusions "predominantly ultrabasic and basic".

c. *Silumpat Gneiss*

We have used the term *gneiss* in the name of this formation with no mineralogical connotation, simply as a textural term to indicate a group of rocks with a gneissic fabric.

The rocks of the Silumpat Gneiss are Reinhard and Wenk's *Crystalline Schists,* Fitch's *banded diorites,* and the *Crystalline Basement* of Kirk and Wilson. There is very little doubt of their ultimate igneous origin, though they have been intensely and repeatedly metamorphosed. The commonest rock type is amphibolite, a coarse-grained, well-foliated and well-lineated, green and white rock which is often well-banded; there are also pyroxene amphibolites, more massive than the banded amphibolites; and fine-grained dark-green amphibole schists and amphibolites. The grade of metamorphism ranges from the quartz-albite-epidote-biotite subfacies of the greenschist facies (the B 1.2 subfacies of Winkler (1967)), through the almandine-amphibolite facies (Turner and Verhoogen, 1960) to the hornblende-orthopyroxene-plagioclase granulite subfacies (de Waard, 1965 and 1967; Winkler, 1967). Most of the amphibolites belong to the almandine-amphibolite facies; a few, on Sakar island (Figs. 2 and 3) belong to the quartz-albite-epidote-almandine subfacies of the greenschist facies (B 1.3 of Winkler (1967)). It is the pyroxene amphibolites that fall into the granulite facies – they contain hypersthene with plagioclase and hornblende, and some look remarkably like charnockites (Hutchison and Dhonau, 1969, in press).

d. *Ultramafic rocks*

These include peridotites, pyroxenites, and dunites, commonly serpentinised. They are coarse-grained massive rocks, except in a few localities near their contact with the Silumpat Gneiss, where there is a rude folation that makes it appear in the field as though there is a transition between the massive ultramafic rocks and the Silumpat Gneiss (Hutchison and Dhonau, 1969, in press).

There is a continuous range of variation from dunite through peridotite to pyroxenite. The rocks are not porphyritic but are even-grained, lacking any regular alignment of the minerals, except near the contact with the Silumput Gneiss where a mineral segregation into bands is discernable. In some rocks, interstices between coarse grains are filled with finer-grained material, indicating perhaps that the intrusion took the form of a crystal mush with not much magma, rather than of a wholly liquid magma of very high temperature.

Many of the rocks have been serpentinised, by weathering, or by hydrothermal action, or by dynamothermal metamorphism (Miyashiro, 1966); relict minerals are commonly still to be seen in thin-sections. Secondary formation of tremolite has also taken place, and there are a few outcrops of pure tremolite rocks. Many of the most intensely altered ultramafic rocks have also been sheared and dislocated by faulting.

Folding and boudinage of chromite bands in the ultramafic rocks indicate that the intrusions were probably synorogenic.

e. *The Chert-Spilite Formation*

In the Darvel Bay area, we have attributed certain metamorphosed rocks to this formation, together with the spilites, cherts and other unfossiliferous sedimentary rocks (Hutchison, and Dhonau, 1969, in press). There are low-grade metasediments in south-west Sakar and in the nearby islands (Fig. 2A): there can be little doubt that these are representatives of what Fitch (1955) mapped as the Chert–Spilite Formation. There are also fine-grained amphibolites and amphibole schists outcropping on south-west Sakar, and the nearby islands (Fig. 2A), which we consider most likely to be metamorphosed equivalents of early-formed spilites of the Chert-Spilite Formation.

A more problematical group of low-grade fine-grained amphibolites and meta-spilites with relict ophitic tectures, occurs on the Adal group of islands (Fig. 2E) and on Lanchangan (Fig. 2C), and in addition Koopmans (1968) has reported amphibolites on the islands near Timbun Mata (Fig. 2B). We have shown these on the maps (Figs. 2 and 3) as belonging to the Silumpat Gneiss, on the basis that they share similar structures with the Silumpat Gneiss, but the fact that they have been metamorphosed to no more than greenschist facies might indicate that they would better be correlated with the meta-spilites of S.W.Sakar (Fig. 2A) which we have ascribed to the Chert-Spilite Formation. These rocks might be regarded as either a later phase of the Silumpat Gneiss or an earlier phase of the Chert-Spilite Formation.

The highest grade of metamorphism shown by all these fine-grained amphibolites, metasediments, and meta-spilites is the quartz-albite-epidote-biotite subfacies of the greenschist facies (Turner and Verhoogen, 1960; Fyfe, Turner and Verhoogen, 1958); in many of these amphibolites relict ophitic textures and clouded plagioclase phenocrysts are to be seen. In the past, these amphibolites have on occasion been called hornfelses (Kirk, 1962); this is not correct; hornfelses are products of contact metamorphism whereas these amphibolites have resulted from dynamothermal metamorphism, but often posses only a rude foliation.

Amphibolite and hornblendite sheets have been intruded in places into the Silumpat Gneiss; these sheets may either be correlated with the early-formed amphibolites that we attributed to the Chert-Spilite Formation, or to a possible late phase (post almandine-amphibolite metamorphism) of the Silumpat Gneiss, since they consistently show greenschist metamorphism whereas their host rocks still retain their former almandine-amphibolite metamorphism (Hutchison and Dhonau, 1969, in press).

STRUCTURE

The structural data collected are shown in figures 29, 30, 31, 32 and 33 of Dhonau and Hutchison (1966). That publication is simply a progress report and contains the data as collected without any attempt at interpretation. A summary of the data (only selected foliation and lineation readings are shown) is given in figure 2.

The relative distribution of the areas A,B,C,D and E of figure 2 can be seen on figure 3. The data of figure 2 consist mainly of dip and strike readings for foliation planes and the trend and plunge readings for lineations in metamorphic rocks (the lineation measured is that formed by the alignment of hornblende crystals or aggregates of crystals). Fewer readings were made of dip and strike of bedding planes of unmetamorphosed or weakly metamorphosed rocks and of the plunge and trend of fold axes. A few representative readings are presented as they were plotted on the field maps. The complete data are also presented for areas of similar fold style in the form of lower-hemisphere equal-area stereograms constructed by the methods advocated by Fairbairn (1949) and Turner and Weiss (1963). The main conclusions to be drawn from the stereograms are that the rude great circles of foliation poles indicate that the foliation has been folded, and that the orientation and scatter of the universal lineations show that they were formed during folding, but were later deformed by a later period of folding. Equally, the foliations must have pre-existed to have been folded. In some areas more than one fold trend can be detected.

The only major structure that has already been described in the area (Kirk, 1962, p.128) is a synform on Bohayan and Tanah islands (Fig. 2C). The Foliation poles for this area fit well on a girdle and from this the axis of the fold can be deduced to plunge at 20° westwards. The plotted lineations of the hornblende crystals, however, do not concentrate well around the pole of the foliation girdle, indicating that the hornblende crystallisation is not entirely

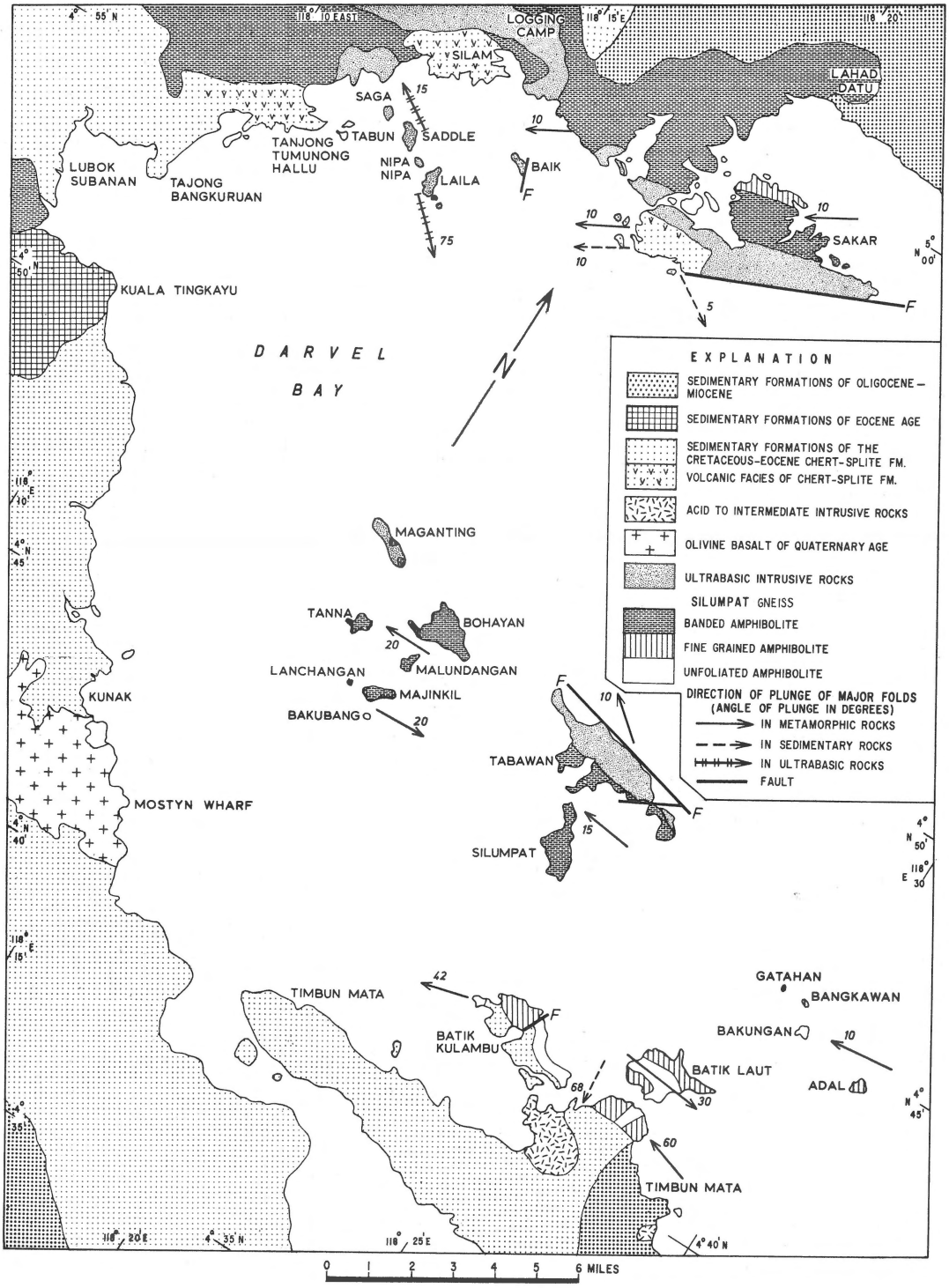


Fig. 3
Structural map of the islands and coastline of Darvel Bay showing only the principal fold axes as have been deduced from the data of figure 2. Major fault and dislocation directions are also shown.

related to this westerly-plunging fold. The lineations range in direction from westerly to north-westerly, all with a plunge of about 20° to the horizontal. The Silumpat Gneiss on Tabawan and Silumpat (Fig. 2D) forms a continuation of the north limb of the Bohayan synform. On Tabawan, the lineations concentrate well around the foliation pole in a north-westward direction at a plunge of about 10°, whereas on Silumpat the axial plunge is maintained to the west.

The general east-west structural trend is very obvious on all the outer islands of Darvel Bay (Fig. 2 C,D,E) and has been noted also by K o o p m a n s (1968) (Fig 2B) for the metamorphic rocks of south Darvel Bay.

Along the coastline of mainland Borneo (Fig. 2A) and on the north of Sakar island, the folding is predominantly also in an east-west direction, but here the folds plunge at only 10° in a westerly direction. Outcrops on the south-west corner of Saker of unmetamorphosed shales and of other sedimentary rocks of the Chert-Spilite Formation are folded, and the structural data from these rocks (Fig. 2A) show that the folding pattern in part conforms to that of the underlying Silumpat Gneiss, that is with a fold axis plunging at 10° in a south-westerly direction. However, a superimposed folding pattern with a fold axis plunging at 5° towards the sout-east can also be discerned in the sedimentary and metamorphic rocks of Sakar. The Chert-Spilite sedimentary rocks and spilites here are slightly metamorphosed, and it is thought that this southeasterly fold direction is associated with the final deformation and low-grade metamorphism which has affected the Chert-Spilite Formation rocks and also caused retrogressive metamorphism in the Silumpat Gneiss: in north Sakar, the Silumpat Gneiss shows no higher than greenschist facies metamorphism.

If the main fold axes are extracted from the data presented in figure 2 and shown on a map in which the islands are in their correct relative positions (Fig. 3), it now becomes possible to attempt an overall synthesis. The following are considered the most important points which emerge from the regional pattern:

1. The predominant fold direction of the Silumpat Gneiss is approximately east-west. The folds occasionally plunge gently eastwards; more commonly gently westwards. It is thought that this fold direction is associated with the earlier period of deformation accompanied by dynamothermal metamorphism to almandine-amphibolite facies.

2. A second, and apparently younger fold axis direction trends southeastwards. This is developed in the Chert-Spilite Formation rocks of S.W.Sakar and in the ultrabasic rocks of the Saddle group of islands (Fig. 2A). The mineral lineation on Tabawan island (Fig. 2D) appears more related to this youger fold direction than to the older east-west folding. K o o p m a n s (1968) found a fold system which plunges southwards at 68° in the Chert-Spilite Formation rocks on Timbun Mata (Fig. 2B).

3. The ultrabasic rocks of Tabawan island are concordantly folded with the Silumpat Gneiss with an east-west axis, whereas the ultrabasic rocks of the Saddle group of islands are folded along the apparently younger N.W.-S.E. direction and are certainly discordant to the Silumpat Gneiss nearby on the mainland. This may suggest that ultrabasic intrusions of the Darvel Bay area are not all of the same age, a view held by Dr. R. A. M. W i l s o n (personal communication). It appears, therefore, that ultrabasic intrusions occur syntectonically with the earlier east-west deformation, and again with the later N.W.-S.E. deformation.

Most of the foliations were recorded from metamorphic rocks. There is, however, a zone of transition between the Silumpat Gneiss and the ultrabasic rocks which is well shown on Tabawan (H u t c h i s o n and D h o n a u, 1969, in press). Near the contact between the ultrabasic rocks and the Silumpat Gneiss, the ultrabasic body is poorly foliated, in marked contrast to its more common structurelessness. This foliation in the ultrabasic rocks is parallel to that of the adjacent amphibolites.

There has been strong faulting in the area, and zones of dislocation and brecciation are common. The amphibolites of the small islands of Gatahan, Bakungan and Bangkawan (Fig. 2E) show signs of mylonitisation and brecciation. Mylonitic amphibolite is exposed in several places (J 1031, J 1044) and cataclasites are to be found all over these islands (J 1024, J 1035). There is a strong tendency for the shape of the islands in the Darvel Bay region to be controlled by the strike of the zones of dislocation: for example, the north coast of Tabawan (Figs. 2 and 3) and the south coast of Sakar are so controlled by dislocation zones which trend 110° and 70° respectively. The positions of the zones and direction of movement, where known, have been recorded on

figures 2 and 3.

The dislocations and shearing have undoubtedly been connected with intense serpentinisation of the ultramafic rocks. Many of the serpentinites are shattered and have slickensided surfaces. There is probably still movement on some of these dislocations: the Darvel Bay area is susceptible to earth tremors, which have frequently been noticed by people living in the nearby town of Lahad Datu.

RADIOMETRIC DETERMINATIONS

Five specimens were sent to the Age Determination Unit of Overseas Geological Surveys for radiometric determination by the potassium-argon method. The specimens were J 1060, J 1166, J 1216 and J 1298; details of them are given in Hutchison and Dhonau (1969, in press).

Only two of the specimens could be dated: the potassium content of the others was too low, both in the whole rock and in the pyroxene and amphibole concentrates.

Details of the dated rocks are as follows:

1. OGS.65.120 *Hornblende from banded-amphibolite* J 1060 (Fig. 2D) N.E. Silumpat island, Darvel Bay, Sabah; 4°46.5′ N. 118°23.4′ E. %K = 0.15 Rg.^{40}Ar = 0.0011 ppm. Age = 101 ± 15 my.
2. OGS.65.126 *Total rock, fine-grained lineated amphibolite* J 1166 (Fig. 2E) E. Adal island, Darvel Bay, Sabah; 4°48.8′ N. 118°31.3′ E. %K = 0.30 Rg.^{40}Ar = 0.0031 ppm. Age = 140 ± 20 my. (N.J. Snelling, written communication, 1965; Anonymous, 1966)

The age of 101±15 my. for the specimen of Silumpat Gneiss (J 1060) lies within the Cretaceaus; the age of 140±20 my. for the specimen of amphibolite (J 1166) lies within the Upper Jurassic and the Lower Cretaceous.

RELATIONSHIP BETWEEN THE METABASITES AND THE ULTRAMAFIC MASSES

On Tabawan (Fig. 2D), the ultramafic rocks are interfoliated with the metabasites. Hornblende-orthopyroxene-plagioclase-granulite subfacies is particularly frequent of occurrence near the peridotite body, and occurs nowhere else in the Darvel Bay area (Hutchison and Dhonau, 1969, in press).

De Waard (1967b) suggested a temperature of 800°C and a load of 10 kb, with a tectonic depth equivalent of 35km for the hornblende-orthopyroxene-plagioclase granulite subfacies terrane of the Adirondacks. If the same conditions pertain to Tabawan island, then the mineral facies of the ultramafic rock to be expected under such pressure-temperature conditions is the spinel-lherzolite facies (forsterite + diopside + enstatite + spinel) (O'Hara, 1967). However, a calcic plagioclase commonly occurs in the peridotites (Hutchison and Dhonau, 1969, in press), putting the ultramafic rock into O'Hara's orthopyroxene-plagioclase-lherzolite facies which is stable at similar temperatures but at pressures less than 6kb. Temperatures of about 800°C would put the Tabawan peridotite into Wyllie's (1967, p.411) middle-temperature ultramafics.

The metamorphism in the Darvel Bay area is entirely dynamothermal in character, and a pressure-temperature combination of 10kb and about 700°C is normally to be expected in an oceanic area such as the Darvel Bay area (see Fig. 1.1, O'Hara, 1967), Most of the Silumpat Gneiss rocks in central Darvel Bay are of almandine amphibolite facies; one can therefore assume that the ambient regional orogenic temperature was between 600 and 700°C.

The frequency with which granulite facies rocks occur closer to the ultramafic mass on Tabawan island strongly suggests that the intrusion raised the temperature locally to something of the order of 800°C.

Our general conclusion, therefore, is that the metamorphism of the Silumpat Gneiss is entirely dynamothermal in character, and in central Darvel Bay has occurred under pressures approaching 10kb, and a temperature of 600 to 700°C. The syntectonic intrusion of peridotite raised the temperature of the country rocks very locally to cause a thermal aureole in which temperatures were raised to 800°C, thereby making it possible for hornblende-orthopyroxene-plagioclase granulite subfacies to develop in the Silumpat Gneiss. Both the metamorphism, and the intrusion of the peridotite in central Darvel Bay must be considered as catazonal.

However, not all the ultramafic bodies of the Darvel Bay area were finally emplaced catazonally; the bodies in the Saddle group of islands and on Sakar (Fig. 2A) are related to younger folding associated with greenschist facies metamorphism and

are therefore mesozonal. It is of interest that these are more serpentinised than the catazonal ultramafics of Tabawan, and fit into O'Hara's (1967) serpentinite facies, which is stable at temperatures less than 450°C.

TECTONIC HISTORY OF THE DARVEL BAY AREA

The first event of which any record remains is plainly the intrusion or extrusion of the proto-Silumpat Gneiss. These rocks were almost certainly gabbro or basalt (Hutchison and Dhonau, 1969, in press). There are no rocks that could be interpreted as the original country rocks into which a gabbro might be intruded: this favours the interpretation that the proto-Silumpat Gneiss was a series of basaltic lava flows, perhaps representing oceanic basalts of the lower crust.

The proto-Silumpat Gneiss then underwent catazonal dynamothermal metamorphism whose intensity varied from place to place. Such patchy metamorphism has been noted and described in similar type rocks by Daniels, Skiba and Sutton (1965) and by Sutton (1965). The metamorphic facies ranged from greenschist to almandine-amphibolite. During this orogenic, period, the foliation and lineation associated with the east-west fold system developed. Metamorphic segregation led to the separation of hornblendic and feldspathic layers. A little migmatisation probably also occurred at this time by partial fusion of albitic feldspar. A syntectonic intrusion of middle-temperature peridotite from the mantle, into the region of Tabawan island, locally resulted in a thermal aureole of granulite facies in the Silumpat Gneiss. Even within this aureole, the metamorphism is patchily distributed between almandine-amphibolite and granulite facies, although the latter predominates.

The peridotite tends to have rather rounded crystals in a finer-grained matrix; it was probably intruded as a crystal differentiate in a minimum of liquid at a rather low temperature of about 800 to 850°C. This mode of intrusion is not inconsistent with interpretations of ultramafic intrusions by other authors (Green, 1964; Noble and Taylor, 1960). Certain outcrops on Tabawan island (J 1081, J 1109) suggest that the peridotite intrusion incorporated blocks of the amphibolite. Near its contact with the Silumpat Gneiss, there is a distinct foliation in the peridotite on Tabawan island. This foliation is almost certainly an extension of the east-west fold system in the Silumpat Gneiss, formed by simultaneous deformation of the ultramafic rock and the amphibolites; a proof of the syntectonic nature of the intrusion.

Next came renewed igneous activity, and dolerite sheets were emplaced both in the Silumpat Gneiss and in the ultramafic rocks. Perhaps the rocks that are now the amphibolites of the Adal group of islands(Fig. 2E) and of the islands off the west point of Sakar (Fig.2A) were also formed at this time. These were rocks of the gabbro and alkali-gabbro clans – probably basalts, dolerites and spilites, which might well represent an early part of the Chert-Spilite Formation.

Renewed orogenesis was accompanied by low-grade dynamothermal metamorphism to no higher than the middle of the greenschist facies, transforming the rocks into amphibolites and metamorphosing the sediments on west Sakar and the nearby islands. Very likely the ultramafic rocks on Tabawan were slightly serpentinised at this time. This period of deformation resulted in folding about a N.W.-S.E. axial fold system, and caused a certain amount of retrogressive metamorphism of the high-grade Silumpat Gneiss, causing, in part, a recrystallisation of the hornblende crystals into a new N.W.-S.E. lineation.

The ultramafic intrusions on the Saddle group of islands and on mainland Borneo (Fig. 2A) were syntectonically intruded into this mesozonal tectonic enviroment. The Saddle group ultramafic mass may have been re-intruded at this time from a deeper tectonic level; it appears to have little, if any, thermal aureole and may have been emplaced largely as serpentinite at a low temperature. Mackenzie (1960) concluded that most peridodite bodies appear to have been re-intruded.

Subsequent deposition of Tertiary rocks occurred on the edges of, and mainly outside the map area of figure 3. Post-orogenic porphyry intrusions and basaltic flows occur on the edges of the area but these have not been studied by the present authors.

Faulting is assumed (Wilson, 1965, p.85) to be later than the events already described. This faulting, with accompanying intense shearing, has controlled the shapes of the islands and has caused the mylonitisation and cataclasis to be seen in the outer islands. Hydrothermal action along the fault planes has

serpentinised the ultramafic rocks and produced tremolite rocks in many places.

The age determinations (see above) conflict with our interpretation of the geological history. According to the two determinations, the specimen of Silumpat Gneiss is Lower or Upper Cretaceous and the specimen of amphibolite from Adal island (which may be considered as later Silumpat Gneiss or early Chert-Spilite Formation) is Upper Jurassic or Lower Cretaceous, whereas we maintain from the geological evidence that the Silumpat Gneiss is the older formation. What the age determinations measure is when the last event occurred for each formation that could have caused argon to be lost. Such events are deformation or metamorphism (Miller and Fitch, 1964, p.109-115); the metamorphism need not have been so severe as to cause any marked recrystallisation. Both the fine-grained amphibolite of Adal island and the coarse-grained banded amphibolite of Silumpat island have been deformed and dislocated, and both very likely have undergone weak retrogressive metamorphism. As yet there are not enough age determinations of rocks from Darvel Bay nor is the geological history of the area known in enough detail for actual events to be correlated with age determinations. Indeed, these ages may not be directly related to an actual event; dislocation or weak metamorphism could have caused the loss of part only of the radiogenic argon already formed; if so, the determined age would then be an apparent age, not the actual age of an event. Further, the determination for the fine-grained amphibolite was made on the whole rock, so including feldspar; as feldspar easily loses radiogenic argon, this determination could well be too low.

Notwithstanding the apparent conflict between the age determinations and the geological history, it is fair to say that the age determination for the fine-grained amphibolite from Adal island – Upper Jurassic or Lower Creraceaus – is consistent with the beginning of deposition of the Chert-Spilite Formation. It is also fair to say that the age determination for the Silumpat Gneiss shows that this formation is no younger than the Cretaceous; but the geology suggests that it is older than this, and perhaps much older.

REGIONAL SETTING

A similar rock association, with two discernible orogenic periods, as is found in the Darvel Bay area, is characteristic of two island arcs, one extending from the main Philippine island of Luzon along Palawan into north Borneo, the other extending from Mindanao across the Sulu archipelago into Darvel Bay (Hutchison, 1969). These two arcs appear to coalesce somewhere in central Sabah (Fig. 1), although in this region rocks of the Darvel Bay association are largely covered by younger formations.

In as far as is known, the fold axes in the metabasites of these arcs lie parallel to the arcs themselves. In the Darvel Bay area, the fold directions fit well into the postulated landward extension of the island arc (Fig. 1).

Hutchison (1968) has given a detailed correlation of the pre-Tertiary geology of Sabah and the Philippines in which the island arcs (Fig. 1) are postulated to represent tectogene, or root zones, beneath the main Chert-Spilite Formation geosyncline. The structural evidence presented in this paper lends further support to this hypothesis.

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