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Papuan Ultramafic Belt: Gravity Anomalies and the Emplacement of Ophiolites

ABSTRACT

The Papuan Ultramafic Belt of eastern New Guinea is one of the largest known examples of the mafic-ultramafic complexes commonly termed ophiolitic. These complexes, widespread in orogenic areas, are characterized by a succession upward from a peridotite-pyroxenite basal layer through gabbro to dolerite, basalt (often pillowed), and deep-sea sediments. Large gravity anomalies associated with the Papuan ophiolites emphasize the similarities between eastern Papua and areas such as Cyprus, New Caledonia, and the Alpine Ivera zone; but the anomalies, considered together with the mapped geological relations, are difficult to reconcile with any of the commonly proposed modes of ophiolite emplacement. Although some problems remain unresolved, the most likely of the processes considered involves large-scale splitting of oceanic lithosphere as it approaches a subduction zone. This process may be characteristic of the destruction, not of normal oceanic crust, but of young basins formed at the rear of active volcanic arcs.

INTRODUCTION

It is now widely accepted (Dewey and Bird, 1971; Smith, 1971) that the layered masses of ultramafic and related rocks found in many orogenic areas are fragments of oceanic crust and uppermost mantle that have been incorporated in continental crust during orogeny. The term “ophiolite” is usefully applied to complexes having the entire sequence from peridotite, through gabbro and possibly a sheeted diabase layer, to basaltic lavas and associated deep-water sediments. Application of the term ophiolite in areas such as New Caledonia, in which felspathic rocks are rare or absent (Lillie and Brothers, 1970), can then be taken as implying the belief that the complete sequence was originally present but that the upper layers have been removed by faulting or erosion. Although it seems generally valid to conclude that the presence of ophiolites is evidence for the former existence of ocean between two now contiguous continental blocks, difficulties still arise in explaining the emplacement of some specific bodies. In particular, it has been noted (Dewey and Bird, 1971) that giant ophiolite nappes, such as those of Cyprus and Papua, pose a special problem. If intrusion in roughly the present locations, coupled with only minor subsequent faulting, is rejected as the origin, then three broad possibilities may be considered: (1) the nappes may be large gravity slides from former oceanic structural highs; (2) they may be fragments of normal ocean floor emplaced over continental material by thrusting in a zone of compression; or (3) they may be relict island-arc frontal zones. The landward walls of trenches are probably composed of nearly normal oceanic crust (Karig, 1971); therefore, the critical difference between these last two hypotheses is whether the plane of overthrusting can be regarded as a fossil Benioff zone. This paper is concerned mainly with information on the deep structure of the Papuan Ultramafic Belt provided by gravity observations, and with comparisons that can be made between Papua and areas such as Cyprus, Oman, New Caledonia, and the Ivera zone of the Alps, all of which have some similar characteristics. The resemblance between some models that are compatible with the geological and geophysical data available in Papua and models proposed for the Ivera zone on the basis of seismic refraction surveys suggests a similar origin for both structures.
and emphasizes the importance of such bodies in understanding the evolution of folded mountain belts.

PAPUAN ULTRAMAFIC BELT

The geology of the Papuan Ultramafic Belt (Fig. 1) has been described in some detail by Davies (1971) and that of the Papuan peninsula on which it lies by Davies and Smith (1971). The belt is a discontinuous arcuate ophiolitic mass with a strike length of some 400 km, bounded to the south and west for much of this distance by a major fault (Owen Stanley fault zone). In its western part, the belt appears to dip steeply toward the Solomon Sea, but dips flatten toward the east; at the eastern end, isolated, fault-bounded, flat-lying, mafic and ultramafic blocks are seen resting on nearly horizontal fault planes. The ophiolite sequence is most fully exposed in the Ajura Kujara Ranges and Bowutu Mountains (Dow and Davies, 1964) in the western part of the belt. In both areas, peridotite is overlain seaward by gabbro which is in turn overlain by tholeiitic basaltic lavas with some associated limestones and cherts. The basalts have been dated radiometrically and from microfossils in the associated sediments as Upper Cretaceous (Davies, 1971). Diabase dikes complex similar to those interposed between gabbro and basalt in Cyprus (Wilson, 1959) and Oman (Reinhardt, 1969) have not been found. Eocene tonalites intrude the mafic rocks in the vicinity of the basalt gabbro interface, and the belt is in places overlain by andesitic lavas also of Eocene age (Davies and Smith, 1971). As estimated by Davies (1971), the thicknesses of the ultramafic zone, the gabbro, and the basalts are 4 km to 8 km, 4 km, and 4 km to 6 km, respectively.

At the eastern end of the belt, the Papuan peninsula resembles New Caledonia both geologically and geophysically (Crenn, 1953; Avias, 1967), except where the extension of the Papuan coastline northward by Holocene volcanism has allowed the peak of the gravity anomaly associated with the ultramafic root zone to be defined by surveys on land. Upper Cretaceous basalts in this area are found directly underlying ultramafic-belt peridotites and are the youngest rocks so far identified in this structural position. The oldest deposits which definitely postdate the thrust movements are lower Miocene (Davies, 1971). Dewey and Bird (1971) stated that overthrusting took place during the Miocene Epoch but offered no supporting evidence. Miocene overthrusting appears unlikely, however, in view of the reported late Eocene or Oligocene commencement of strong uplift of the sialic core of the Papuan peninsula (Davies and Smith, 1971), necessitating thrusting of the belt up considerable and increasing gradients. An Eocene age for the overthrusting seems therefore most probable. The belt is at present sinking in relation not only to the possibly still rising central sialic core of the peninsula, but also to sea level, as evidenced by the drowned coastline east of the Bowutu Mountains.

Assuming that thrusting took place in early Tertiary time, it is difficult to see any genetic connection between the ultramafic overthrust and the Quaternary intermediate volcanism which, despite the absence of a Benioff zone, is a feature of the central and eastern part of the belt (Jakes and Smith, 1970). Hatherton (1971), however, has emphasized similar patterns of spatially associated, young, potassic volcanism and older ultramafic belts in New Zealand and California, and the association seen in Papua may record successive phases in a recurrent evolutionary pattern. It may be significant in this context that a zone of partial melting probably exists beneath the Ivrea body (Giese, 1968).

GRAVITY MODELS

The gravity anomaly associated with the Papuan Ultramafic Belt is, like the belt itself, arcuate and, at the highest field levels, discontinuous (Fig. 1). Three major peaks correspond to the three major areas of outcrop, and a fourth is partially defined where the anomaly passes out to sea east of Cape Nelson. In each case, the gravity peak lies seaward of the outcropping ultramafic rocks, which are assumed to represent the source of the high fields, and the degree of displacement increases from west to east. Zones of relatively lower gravity intersecting the belt in the east are associated with Quaternary volcanism, but the low gravity zone between the Bowutu Mountains and Ajura Kujara Ranges in the west is probably due to left-lateral movement along a major fault (Gira fault; Davies, 1971). Profiles across the three major gravity highs are shown in Figure 1, the westernmost (A-A, Bowutu) having been extended out to sea using marine measurements recently made by the Bureau of Mineral Resources (Director, Bur. Mineral Resources, 1972, written com-
mun.). The uncertainty in the land part of the Bouguer anomaly curve, which has been fully corrected for topographic effects, has been estimated at ± 5 mgal (Milson, 1973), while the marine part of the curve, being based on preliminary results only, may be somewhat less accurate.

It is notable that, although anomaly amplitude decreases eastward, the half width remains relatively constant. The centrally placed Ajura Kujara (B-B, Fig. 1) profile has been used in the model studies (Figs. 2, 3), since the Bowutu (A-A, Fig. 1) anomaly has been incompletely delineated by measurements on land and occupies an atypical position at the extreme western end of the belt. The single

Figure 1. Papuan Ultramafic Belt. Geology simplified from Davies (1971). Profiles and contours of Papuan Bouguer anomaly fully corrected for terrain effects. Geologic key: (1) peridotite, (2) gabbro, (3) basalt (of Papuan Ultramafic Belt only), (4) andesite, (5) tonalite, (6) granite. Profiles: (A) Bowutu, (B) Ajura Kujara, (C) Musa. Profile NC across New Caledonia, included for comparison, prepared from contour map by Crenn (1953).
Musa cross section shown (C-C, Fig. 1; Fig. 4) was obtained by modification of the Ajura Kujara overthrust model.

Choice of densities in the models presents a major problem, since the density of olivine-rich rocks depends critically on the degree of serpentinization and ranges from more than 3.3 gm per cc for fresh dunite to about 2.5 gm per cc for serpentine. Davies (1971) notes that outcropping ultramafic rocks in Papua average only 20 percent serpentinization, and he anticipates that this percentage, which corresponds to a bulk density of about 3.1 gm per cc, will decrease at depth where shears may be expected to be less common and water generally scarce. Wiebenga (1973) reports a density of 3.28 gm per cc for a specimen described (H. L. Davies, 1972, written commun.) as fresh harzburgite containing about 70 percent olivine. Densities in the region of 3.0 gm per cc are similarly reported for two samples from the gabbroic parts of the complex, and an average density of about 2.9 gm per cc for basalts and dolerites. Although these measurements do not in themselves constitute a statistically valid guide to the bulk densities of the various components of the belt, they do indicate that the values used by workers in Cyprus (Gass and Masson-Smith, 1963) and the Alps (Kaminski and Menzel, 1968) are probably appropriate to Papua also.

Computer programs based on the polygonal two-dimensional formulas of Talwani and others (1959) have been used in preparing the model cross sections. The validity of the two-dimensional approximation has been investigated using strike-limited models; but, in general, the effect of geologically reasonable strike limitation on the calculated Ajura Kujara and Musa profiles is not significant. Density contrasts refer to a standard crust 30 km thick underlain by mantle 0.4 gm per cc denser (Woollard, 1969). Fits between observed and calculated profiles have been tested at the points shown on the curves in Figures 2 and 4.

In terms of the geologic models suggested for the Papuan Ultramafic Belt, the most striking feature of the measured anomalies is their approximate symmetry and limited half widths; it is quite possible to obtain a symmetrical residual anomaly by removing a smooth regional "low" caused by an assumed variation in mantle depth. Although this cannot be taken as implying that the belt itself is a symmetrical feature, a conclusion that would be at variance with the outcrop pattern, it does severely restrict the allowable cross-strike extent of near-surface, high-density rocks.

In Figure 2, models are shown for the Ajura Kujara profile in which the Moho level is allowed to vary only slowly, producing a smooth regional field, and anomalous densities are otherwise restricted to a small number of foursided bodies. Although an exact fit to the observed field cannot be expected from such simple models, they are in some ways more useful than more complex models, because both their successes and failures tend to emphasize features which must be possessed by any mathematically acceptable model and which must therefore be features of the real geology.

The source of the main gravity anomaly is represented in Figure 2a by a vertical slab, which is asymmetric in that there is a "gabrialic" layer, with an excess density of 0.2 gm per cc, on the seaward side only. The crust mantle contrast of 0.4 gm per cc is also used for the ultramafic part of the slab, and the layer thicknesses are deduced from outcrop widths and the vertical-dip assumption. The model shown has approximately the correct

![Figure 2. Ajura Kujara Bouguer anomaly profiles and simple models. Key to outcrop geology shown on baseline as for Figure 1.](image-url)
total mass excess, but the width of the calculated anomaly is rather smaller than that actually observed. In view of the simplicity of the assumptions, the fit obtained can be considered quite reasonable. The most striking feature is the displacement of the slab from the area of actual ophiolitic outcrop. Movement of the uppermost part of the slab along a flat-lying fault plane could both widen the calculated anomaly and bring the model into accord with the mapped geology.

In the second model (Fig. 2b), the slab dips seaward, and the gravity peak is thus moved in this direction. Introduction of a dip angle renders the anomaly markedly asymmetric, unless, as shown, the slab is overlain by lighter sediments. This, in turn, requires either shallower mantle beneath the slab or a greater mass excess to be associated with the slab itself. The model is one of several which may be produced with different constant, but arbitrarily assigned, dips. As the dip flattens, the seaward displacement of the anomaly is increased, but the allowable decrease in dip is ultimately limited by the need to produce the observed steep seaward gravity gradients. Close agreement with both gravity field measurements and geologic data proves unobtainable unless the slab dip is allowed to steepen away from the outcrop area. Again, in the model shown, the slab “outcrop” lies some distance from the exposed ophiolites. The conclusion that at the outcrop the ultramafic rocks are relatively thin and flat lying and that dip increases with depth are supported by the aeromagnetic interpretation of this part of the belt (Compagnie Générale de Géophysique, 1969).

In contrast to the models of Figure 2, the gravity fields of those in Figure 3 fit the observed profile within the limits of observational error. Figure 3a shows a cross section of a type recently used by Woodward (1972) to account for the Fiordland anomaly in southern New Zealand, in which only the depth to the Moho varies. In view of Wiebenga’s (1973) contention that the islands and small ocean basins north of the Papuan peninsula have been formed by rifting accompanied by the intrusion of dense mantle material, it is interesting to see the extent to which fluctuations in the depth of a single interface, which is not allowed to overthrust, can give rise to the observed anomaly. As might be expected from consideration of the simple models of Figure 2, the highest points on the Moho lie well seaward (northeast) of the exposed ophiolites, and it is interesting to note that the gravity data do not require high-density material to outcrop. Although the mantle diapir explains the observed gravity field, some features of the model, particularly the greatly increased crustal thicknesses between −20 km and +10 km, do not really seem geologically feasible.

The model shown in Figure 3b is the most complex, and fits the observed field within the limits of error. The basis of the model is the assumption that the ophiolites represent a section of oceanic crust and uppermost mantle thrust over continental crust and overlain by light sediments. The sedimentary layer has
been assigned an average density contrast of 0.3 gm per cc down to a depth of 5 to 6 km (St. John, 1967). Continuity with the mantle, which is implicit in the overthrust hypothesis, is assumed for the peridotite mass; and for this and for the overlying felsiclastic rocks, a constant density contrast is assumed at all levels. Although unlikely to be true in detail, a constant density contrast probably represents a rough approximation of the real situation; at extreme depths, the normal crust-mantle relations should apply, while at shallower depths, the likely increase in fracturing and serpentinization probably reduces the densities of the bulk ophiolites to well below the calculated normative values.

The single model shown for the Musa profile (Fig. 4) was obtained by altering the final Ajura Kujura model to the smallest extent possible. At the southern end of the profile, bodies with excess densities of 0.2 gm per cc have been introduced corresponding to the ubiquitous basaltic rocks of this zone and the isolated and relatively heavily serpentinized, fault-bounded ophiolite blocks. A granitic intrusion slightly lighter than standard crust is assumed to occupy the center of the cross section; its presence is deduced from the existence of a still deeper gravity low and granitic outcrops east of the profile in the vicinity of Mount Suckling (Milsom, 1973). The area south of the main gravity high presents many problems, and a number of models seem equally satisfactory, but these questions are not directly relevant to emplacement of the ophiolites. In this latter respect, the model of the second Ajura Kujura by Byers and Menzel (1968) and the Gradoan zone, 1953) is most important. The fit between the model profile and the gravity field is improved if it is assumed that the low-density layer extends to a depth of about 1 km, although such an assumption adds to the difficulty of explaining the Mount Olympus negative anomaly. An improved fit can also be obtained by assigning a positive density contrast to the felsiclastic rocks which overlie the ultramafic rocks.

Two gravity profiles of the Ivrea zone have been analyzed by Byers and Menzel (1968). The existence of crustal cross sections based on the results of seismic refraction experiments (Giese, 1968) allowed unusually

Figure 6. Ivrea zone, western Alps. Bouguer anomaly profile and model cross section after Kaminski and Menzel (1968).

Detailed gravity interpretations to be prepared; although in the case shown (Fig. 7), the seismic model produced excessively large fields and had to be modified to some extent. All the refraction lines were directed roughly along strike of the Ivrea body (in other words, at right angles to the cross section shown), and the continuity with the mantle was inferred rather than proven.

A notable feature of the interpretation is the very low density and seismic velocity which characterize the rocks beneath the high-density slab and which Giese (1968) attributes to partial melting. He also regards the Ivrea zone, which is bounded to the north and west by a major fault (Insubric Line) and within which surface dips are close to vertical, as an area where a complete transition through the crust and crust-mantle transition zone is exposed at the surface, and he supports the suggestion by Michot (1968, written commun.) that this transition zone represents modified and metamorphosed oceanic crust.

The Ivrea and Troodos anomalies are similar to those in Papua in magnitude and half width, but the base levels are very different, reflecting the continental environment at Ivrea and the quasi-oceanic situation of Cyprus. Between these extremes lies the Papuan peninsula, flanked on both sides by oceanic crust but including a thick core of sialic rock.

ORIGIN OF ULTRAMAFIC BELTS

The Papuan Ultramafic Belt was originally described as a complex intrusive body (Smith and Green, 1961; Dow and Davies, 1964), although Thompson (quoted in Dow and Davies, 1964) had already suggested an origin as an oceanic overthrust. More detailed mapping which emphasized the asymmetric character of the belt, with gabbros and basalts on the seaward side only of the peridotites, and the recognition of nearly horizontal thrust planes at the base of the ultramafic blocks in the Musa area (Davies, 1971) have led to the virtual abandonment of the intrusion hypothesis.

Thrust emplacement of at least the exposed ophiolites in Papua is accepted as proven in the present discussion, but not all the arguments in favor of an oceanic overthrust origin for all ophiolites can be accepted as valid. The similarities may have been overemphasized; Moore and Vine (1971), for instance, found differences between Troodos pillow lavas and oceanic basalts, notably in the general lack of olivine phenocrysts in the former. In contrast, the Great Dyke of Rhodesia as described by Bichan (1970) resembles the Papuan Ultramafic Belt in chemistry, if not in detailed mineralogy, and this occurrence of high-magnesium ultramafic rocks in a major intracontinental dike demonstrates that such bodies cannot be automatically attributed to the influence of an oceanic environment.

In the following discussion, the problem of emplacement of the Papuan Ultramafic Belt is considered, but where it seems that valid comparisons may be made, evidence is drawn from other ophiolite occurrences.

Gravity Slide Hypothesis

The intimate association in ophiolites of plutonic, hypabyssal, and extrusive rocks led Aubouin (1965) to suggest that such complexes form as vast submarine outpourings of basic magma on the flanks of eugeosynclinal ridges (Fig. 7). The wide acceptance of plate-tectonic ideas has since brought the classical theory of geosynclines into question, and in particular this "plutovo-lcanic" hypothesis has been criticized on grounds summarized by Davies (1971) as follows: (1) The typical ophiolite is bottom heavy, with too much ultramafic differentiate for the volume of associated gabbro. (2) If the parent magma had been basaltic, there should be a fraction enriched in iron, nickel, and potassium to provide a chemical counterweight for the calcium-magnesium-rich ultramafic fraction. (3) Extrusion of a tongue of lava of such great volume at one time
Figure 7. Pluton-volcanic extrusion of ophiolites at geanticlinal ridges, after Aubouin (1965). Key as for Figure 1. Vertical lines denote diabase-dike complexes, and ultramafics are divided into a lower (peridotite) and an upper (pyroxenite) layer.

is unlikely. (4) Field evidence for a complete envelope of basalt and dolerite enclosing the plutonic rocks has not been established. (5) The gabro-peridotite contact, instead of being transitional, is commonly intrusive.

The first two objections are based on the experimental finding that, unless significant quantities of water are present, peridotite magmas can exist only at temperatures in excess of 1300°C (Clark and Fyfe, 1961). Since high-temperature metamorphism at ophiolite contacts has not been demonstrated, it is deduced that any "ophiolite" magma must have existed at a relatively low temperature and must therefore have been of overall basic rather than ultrabasic composition. It has been suggested, however, that peridotites may be emplaced as a semi-solid mush of olivine crystals (Thayer, 1969), and there seems little reason why such mushes should not "extrude" beneath an insulating basaltic caprace. Under these conditions, intrusive contacts of gabro, formed from the interstitial fluid, into peridotite would be expected in the solidified mass (see 5, above). Furthermore, since ophiolites are characteristically fault bounded, field evidence for complete envelopes or for contact effects is difficult to obtain; if, as Aubouin suggests, extrusion occurs on the flanks of submarine ridges, subsequent movement under gravity is almost inevitable, and shear planes may develop within, as well as at the edges of the ultramafic mass.

The remaining objection (3) cannot be regarded as conclusive for the majority of Mediterranean ophiolites, which are comparatively small bodies, and a modified form of the Aubouin hypothesis was accepted by Moores (1969) for the Vourinos ophiolite complex. In Papua, however, the size of the belt presents an insuperable obstacle to pure extrusion. The total indicated mass excess in the Ajura Kujara area is more than 10⁶ kg per strike kilometer, corresponding to a cross-sectional area for a purely ultramafic body of 300 sq km, or 400 sq km for a mass of mafic and peridotitic rock in 1:1 volume ratio. These figures are more in accord with Davies' (1971) estimate of a 12- to 18-km total thickness of the belt than with the shorter "stratigraphic columns" of Coleman (1971) and Dewey and Bird (1971), for which no supporting evidence has been presented. Not only does the extrusion of a body of this size seem subjectively implausible, but it would appear quite impossible for it to move as a surface mass under gravity. The necessary décollement plane at a depth of more than 10 km would lie well below the bottom of the deepest ocean trenches, whereas ophiolites are found emplaced above thick continental rocks.

Although gravity sliding of the entire Papuan Ultramafic Belt cannot be accepted, many of the smaller ophiolites may have reached their present positions in this manner. In particular, the Somal nappe of Oman (Fig. 8) has been interpreted as a gravity slide (Reinhardt, 1969). The thrust plane beneath the nappe is exposed in the Hansawa "window" across virtually its entire width, and the published cross section is unlikely to be significantly in error. The ophiolite lacks any sort of a root and will not give rise to gravity anomalies comparable with those shown in Figures 2, 5, and 6, but the outcrop pattern strikingly resembles that seen in Cyprus and in Papua, except for the absence of a sheeted diabase complex. Reinhardt's (1969) proposed emplacement by gravity sliding from an oceanic ridgeline model but does not stretch to be more than topographic...
However, the size of the belt presents a considerable obstacle to pure extrusion. The estimated mass excess in the Ajura Kujara or more than 10^9 kgm per strike kilometer, leading to a cross-sectional area for a ultramafic body of 300 sq km, or 400 sq km of mafic and peridotitic rock in the same ratio. These figures are more in line with Davies' (1971) estimate of a 12-to-total thickness of the belt than with later "stratigraphic columns" of Cale (1971) and Dewey and Bird (1971), for no supporting evidence has been presented. Not only does the extrusion of a body of this size seem subjectively implausible, but it also appears quite impossible for it to move this large a mass under gravity. The necessary thrust plane at a depth of more than 10 km would lie well below the bottom of the ocean trenches, whereas ophiolites are placed near the subcontinental rifts. Although gravity sliding of the entire Ultramafic Belt cannot be accepted, the smaller ophiolites may have their present positions in this manner. The Kurnell ophiolite of Oman (Fig. 1), for instance, has been interpreted as a gravity slide (Cale, 1969). The thrust plane beneath it is exposed in the Hawasina "win" virtually its entire width, and the cross section is unlikely to be erroneous. The ophiolite lacks any foot and will not give rise to gravity anomalies comparable with those shown in Figs. 5 and 6, but the outcrop patterns resemble that seen in Cyprus and in the absence in the latter of a subaerial complex. Reinhardt's (1969) hypothesis of emplacement by gravity sliding from an oceanic ridge resembles Aubouin's (1965) model but does not require the overthrust mantle to be abnormal in any respect other than topographic elevation.

A common feature of ophiolites, and one that is apparently shared by the Pauean Ultramafic Belt, is that a relatively short time appears to have elapsed between basaltic extrusion and thrust emplacement (Reinhardt, 1969; Moors and Vine, 1971; Smith, 1971). In Papua, the probable time interval between formation of the basalts and gabbros and overthrusting is of the order of 30 m.y. (Davies and Smith, 1971). If the belt did form as normal sea floor, it would still be roughly 1 km above its final "cold" equilibrium depth after this period of time (Schater and others, 1971). While this is very far from the time of extrusion that could be expected to produce gravity sliding over continental material, recurrence of a similar pattern elsewhere suggests that time relations in ophiolites are of great importance.

Oceanic Overthrust Hypothesis

If gravity sliding has to be rejected, thrust emplacement of the ophiolites must presumably have taken place in a compressive environment. Early schematic cross sections of the deep structure of the Pauean Ultramafic Belt (Davies, 1971) showed instantly appealing models in which the exposed mafic and ultramafic rocks were assumed to have formed part of the oceanic crust and mantle, with which they were still in contact. Such models would seem to imply normal sub-Moho densities for the ultramafics, perhaps slightly reduced by serpentinitization and by increases in pore and fracture volume made possible by the reduction in pressure (Long and Matthews, 1972). Calculations based on this assumption show, however, that the model itself must be drastically modified. Detailed comparisons of the calculated field caused by the simple overthrust (Fig. 9) with the Bowutu, Ajura Kujara, and Musa fields and models show that the excessive half width of the overthrust anomaly is due not to the thrust sheet itself, but to the shallow mantle postulated behind it. Satisfactory agreement with the observed field can be attained only by assuming a much deeper Moho, overlain by lighter rocks. A thick sedimentary column, seaward of the belt was proposed by Davies (1971), and this seems both more likely geologically and more in accord with the gravity data than large thicknesses of sialic igneous or metamorphic rock.

Little new evidence on the values of sedimentary rock densities appropriate to New Guinea has become available since St. John's (1967) discussion. He concluded that although densities of as much as 0.7 g/cm^3 below standard crust might be encountered, contrasts of 0.4 g/cm^3 or less would be more usual even for Miocene deposits, and at depths in excess of 6 km, little or no contrast would exist. If these estimates are acceptable, a Moho depth of at least 20 km is to be expected at the rear of the ultramafic belt in the Ajura Kujara area (Fig. 3).

The Musa cross section (Fig. 4) can also be regarded as an oceanic thrust model modified in accordance with the gravity data. The proposed thrust sheet is some 15 km thick and has a length of about 60 km from its junction with the mantle to its subcrop beneath the coastal plain. A further 30 km of ophiolites lie to the south of this area, so that it seems an oceanic thrust sheet at least 90 km long must have overridden this part of Papua.

Hubbert and Rubey (1959) have shown mathematically that thrusts which are long in relation to their thickness are possible if fluid pressures are high, and the equations may be extended to thrusts moving up slopes. For small dips (<5°) slab lengths are not significantly shorter than in the horizontal case; a thrust of the dimensions deduced in the Musa area would be possible at fluid pressures in excess of about 70 percent of the load pressure. Ringwood (1969) has concluded, however, that the small amount of water likely to be present in the upper mantle is held in amphiboles and that load pressures are likely to greatly exceed
the water partial pressures. Only if significant amounts of serpentine are present, and the physical properties of the Moho do not suggest that this is so, does there seem to be both a source for the necessary water and a means (Raleigh and Paterson, 1965) of reducing the cohesive force which Hsu (1969) argues must play an important part in limiting the length of overthrusts.

The formation of nappes in the Alps has been explained (Laubscher, 1971) by assuming that on collision with a subduction zone, continental crust may be wedged apart, a thin peel overriding the zone while the remainder of the plate is drawn down by the pull of dense, previously subducted lithosphere. This concept may be applied also to the Papuan Ultramafic Belt, seen as young and therefore buoyant oceanic crust, and the concept explains rather well the formation of a low-angle overthrust. Departure from the simple “two-dimensional” situation can result in larger allowable thrust lengths in restricted areas, because overthrusting at sea-floor-spread- ing rates of a few centimeters a year is implied and simultaneous erosion could have restricted the slab to mechanically plausible lengths at all times. Identification of the Papuan Ultramafic Belt as normal oceanic crust and uppermost mantle also poses some petrological problems, however. Davies (1971) has commented on the lack of metamorphic rocks in the supposed crustal component (basalts and gabbros) of grade higher than zeolite facies, yet Bonatti and others (1971) found no zeolites on the Mid-Atlantic Ridge, while amphibolites were common. In addition, the 8- to 10-km thickness of the feldspathic rocks estimated by Davies (1971) is considerably greater than most estimates of oceanic-crustal thickness, although recent studies suggest that a high-velocity basal layer may have been widely overlooked (Sutton and others, 1970). Perhaps the most striking compositional difference is the presence in Papua of intrusive and extrusive inter- mediate rocks (Davies and Smith, 1971).

![Diagram](image)

**Figure 9. Simple oceanic overthrust model, after Davies (1971), and calculated Bouguer anomaly profile.**
Reports on other ophiolites mention similar intermediate rocks, termed granophyres in Cyprus (Moore and Vine, 1971); and although diorites have been dredged from probable in situ locations on the Mid-Atlantic Ridge (Aumento, 1969), they do not seem to figure prominently in the deep oceans.

Island-Arc Frontal Zone Hypothesis

The theoretical obstacles to mechanical emplacement of a slab of normal oceanic crust and mantle of the required size on top of continental crust, the excessive estimated total thickness of the Papuan basalts and gabbros, and the presence in the Papuan Ultramafic Belt of significant quantities of intermediate and intrusive rocks, all suggest that some modification of the overthrust hypothesis is necessary. Implicit in modern theories of island-arc processes is the possibility that after a period of subduction of oceanic crust with accompanying inter-lateral volcanism, an arc may be underthrust by a continental margin. The proposal that the Papuan Ultramafic Belt is a relic of such an arc has been strongly supported by Davies and Smith (1971).

The common characteristics of gravity profiles across island arcs have been considered by Talwani (1970). The arcs themselves give rise to free-air anomaly maxima near the arc crests, and strong negative anomalies are associated with the trenches. This pattern is in the main a simple reflection of bathymetry, and the arc with its thickened crust is invariably an area of lower Bouguer anomaly than either the trench or the back-arc basin. The positive effect of the downgoing slab of oceanic crust is unlikely to be much in excess of 20 mgal (Oxburgh and Turcotte, 1970).

Displacement of the free-air minimum from the trench axis toward the arc appears to be characteristic of long-established subduction zones where the landward wall of the trench has been extended by sedimentation and by accretion of fragments of the upper parts of the downgoing slab. No material of this type is associated with the Papuan Ultramafic Belt; and the Tonga arc, which lacks sources of heavy sedimentation and from the trench of which ultramafic rocks have been dredged (Fisher and Engel, 1969), seems the most suitable analogue. Published cross sections for Tonga, based on the results of marine gravity and seismic refraction surveys (Talwani and others, 1961), can be modified by a hypothesized continental collision to produce gravity fields similar to those found in Papua. Very large uplift at the front of the overthrust is required, because, despite the peridotite exposures in the Tonga Trench, neither seismic nor gravity data suggest that sub-Moho material outcrops. Also, considerable subsidence must be supposed to have taken place at the rear of the arc to explain the seaward gravity gradient.

The model produced resembles that postulated by St. John (1967) with thick sialic crust seaward of the belt. Davies (1971) contended that continental rocks were unlikely in this situation in view of the regional geology, and his argument may be extended to the island-arc case. Extinct arcs have been identified only rarely in oceanic areas; the best documented example (Karig, 1970) is the Lau Ridge, Fiji, which, although inactive since the Miocene and probably only a rifted fragment, is still a strongly positive feature with numerous islands capping the crest of the rise. If Papua and New Caledonia were the sites of arc-continent collisions, crust at least as thick as that of the Lau would be expected to the rear of the ophiolite. The Loyalty Islands ridge would seem to satisfy this requirement in the case of New Caledonia; but in Papua, the rather similar Woodlark Rise converges on the peninsula and actually merges with it to the southeast of the Bowutus Mountains. To the east of these mountains, which form the largest ophiolite outcrop in Papua, with the largest associated gravity anomalies, there appears to be only oceanic crust deepening rapidly to the New Britain trench and overlain by very recent sediments. If the Bowutus do represent the frontal part of a former arc, then unless they have moved west along strike-slip faults to the north, as well as along the Gira fault to the south (Dow and Davies, 1964), the remainder of the arc must now form part of New Britain itself. The oldest rocks of this island arc are of approximately the same age as the acidic rocks of the belt (R. Ryburn, 1971, personal communication), and the present situation could have resulted from arc-associated rifting in the Solomon Sea (Karig, 1972). Such rifting appears to take place, however, while an arc is active (Karig, 1970); but the hypothesized separation of New Britain from Papua must have occurred either immediately prior to collision or at some later date. After
collision, subduction would presumably be impossible, and a compressional regime would be expected in the back-arc areas.

If the Papuan ophiolites are representative of island-arc crust, their composition should be related to the position of the former Benioff zone. The composition of the volcanic rocks generated in arcs appears to vary systematically from basalts (island-arc tholeiites; Jakes and White, 1969) near the trench to increasingly potassic andesites at distances of 100 to 200 km (Dickinson and Hacherton, 1967). Volcanism within 50 km of a trench axis is virtually unknown, even in cases such as New Britain and the Solomons where the Benioff zone dips almost vertically. The presence of Eocene intermediate rocks in the western part of the Papuan Ultramafic Belt is widely considered as evidence favoring the island-arc hypothesis (Davies and Smith, 1971; Karig, 1972). In some cases, these rocks occur within 30 km of the outer edge of the plane of overthrusting (the assumed fossil Benioff zone), implying that at least 20 km of the tip of the overthrust has been eroded away.

Comparable rocks are less common in the eastern part of the belt, which is in itself somewhat surprising, since the flattening of the plane of overthrusting has exposed a greater total width of ophiolites in this area. Unless there has been significant relative movement of fragments of the ultramafic belt, a cross-strike section of some 50 km is represented here. This approximately equals the width of exposed ultramafics in New Caledonia, and in neither area is the maximum development of ophiolites, as indicated by the gravity maximum, reached within the outer area.

Benioff zones commonly have near-surface dips in the region of 30°; remarkable consistency in this respect is shown in both Tonga (Mitroonovas and others, 1969) and the Marianas (Katsumata and Sykes, 1969). Significantly, lower dips seem to be confined to the margins of continents and large islands (Pfaffker, 1972) where the landward trench walls are probably later accretions. Thus, in both the western part of the belt, where at least 20 km of island-arc "tip" may be assumed to be missing, and in the east, where the plane of overthrusting is currently exposed at some points 30 km from the most advanced ultramafic outcrops, enormous volumes of sediment should have been produced by erosion of the main body of the arc. Although minor sedimentary basins north of the Papuan peninsula probably attain depths of 3 or 4 km (Milsom, 1973), there does not seem to be room for the deposition of an average of 200 cu km of sediment for each kilometer of strike of the ultramafic belt. Nor does there seem to be a sedimentary basin northeast of New Caledonia in which some 400 cu km of detrital material could have been deposited for each kilometer of strike length of the zone of overthrusting (Shor and others, 1971).

It must also be questioned whether the overall composition of the belt corresponds very closely to that which would be expected for island-arc crust in an area where andesitic lavas actually erupted, in other words, to the rear of the frontal rise. Although comparatively little is known of the transition from oceanic to continental crust in these areas, the strong supposition that Benioff zones develop only at continental margins, although they may later become detached by back-arc spreading, would seem to demand much less "oceanic" material than is actually found in ophiolite belts.

Objections to the island-arc hypothesis seem to have added force in Oman, as, unless the direction of movement has been completely misinterpreted, there seems to be no way in which the thrust plane at the base of the Senamau nappe (Fig. 8) can be equated with a fossil Benioff zone. The nappe is of almost uniform thickness throughout its width, and at the rear, the extrusive and hypabyssal components are in direct contact with the thrust.

Mediterranean Ridge Hypothesis

Recent surveys in the eastern Mediterranean (Wong and others, 1971; Woodside and Bowin, 1970; Rabinowitz and Ryan, 1970) have drawn attention to the aseismic Mediterranean Ridge, intermediate in thickness between oceanic and continental crust. Rabinowitz and Ryan (1970) deduce from profiler data and the gravity field that the ridge has been built up by southward-moving fault wedges of sediment. They extend this concept, which they term "orogenic thickening," to seamounts north of the ridge, where the fault planes are thought to have penetrated oceanic basement, and to the Troodos Massif, thought to be a fault wedge incorporating mantle material. Although these extrapolations may be valid, it must be remembered that, whereas the thickening of the ridge commenced only 6 to 8 m.y. ago, the Trogos Upper Cretaceous (Upper Cenomanian) was quite different in terms of the volcanic rocks. Thus, the continental margin may have been less than 100 km wide, and it is possible that the Benioff zone may have been thickened, forming the pre-oceanic part of the ridge. Applied hypothetically to the present-day Benioff zone, the general position of the back-arc fault might vary by several hundred kilometers, to explain the broad distribution of the volcanic rocks.

CONCLUSION

The Papuan Ultramafic Belt is a composite of several slabs of oceanic crust, now juxtaposed together, at least 100 km thick, to create an oceanic back-arc basin. The thickness of the allochthonous component of the belt, which is considered geologically older, is also unknown.

One may question, however, whether the eastern part of the belt is a continuation of the arc or, alternatively, a foreland basin. Although the eastern sector of the belt may be interpreted as the continuation of the core of an arc, such as the Papuan arc, the possibility that it may be a foreland basin cannot be discounted.

Further study of the Papuan Ultramafic Belt is needed to resolve these questions.
basins north of the Papuan peninsula attain depths of 3 or 4 km (Milsom, 1970); there does not seem to be room for the deposition of an average of 200 cu km of detrital material for each kilometer of strike of the ultramafic belt. Nor does there seem to be a similar basin northeast of New Caledonia (Knipe, 1970); some 400 cu km of detrital material have been deposited for each kilometer of length of the zone of overthrusting (Moore and others, 1971).

It must also be questioned whether the overthrust position of the belt corresponds very closely to that which would be expected for oceanic crust in an area where andesitic lavas have erupted, in other words, to the rear of a frontal rise. Although comparatively unknown of the transition from oceanic to continental crust in these areas, the proposition that Benioff zones develop continental margins, although they never become detached by back-arc spreading, would seem to demand much less material than is actually found in the belts.

Inconsistencies of the island-arc hypothesis in the Arabian peninsula have added force to an idea, unless it has been completely retrenched, that there seems to be a thrust plane at the base of the Mesozoic sequence (Fig. 8) can be equated with a Benioff zone. The nappe is of almost constant thickness throughout its width, and at least the extrusive and hypabyssal complexes are in direct contact with the thrust.

Granite Ridge Hypothesis

Surveys in the eastern Mediterranean by others, 1971; Woodside and others, 1970; Rabinowitz and Ryan, 1970) pay attention to the aseismic Mediterranean Ridge, intermediate in thickness between oceanic and continental crust. Rabinowitz and Ryan (1970) deduce from profiles of the gravity field that the ridge has not been formed by southerly moving fault slabs sediment. They extend this concept, using the term “orogenic thickening,” to the north of the ridge, where the fault thought to have penetrated oceanic crust to the Troodos Massif, thought to be a normal fault wedge incorporating mantle as well as an aseismic area north of the ridge. Although these extrapolations may not be remembered, whereas the thickening of the ridge commenced only a few million years ago (Rabinowitz and Ryan, 1970), the Troodos Massif was probably emplaced in Upper Cretaceous time (Moore and Vine, 1971), when tectonic conditions may have been quite different. Crustal thickening at the outer margin of a tecton in a modern ocean has been deposited for each kilometer of length of the zone of overthrusting (Moore and others, 1971).

CONCLUSIONS

The hypothesis that the Papuan Ultramafic Belt is composed of large oceanic nappes as slabs of oceanic and frontal crust overthrust, together with slices of underlying mantle, onto continental margins is compatible with the observed gravity fields provided that a number of restrictions are accepted. In some respects, the allowable structures are so limited that they become difficult to reconcile with the mapped geology and the mechanical conditions for overthrusting, but since the belt undoubtedly exists, an emplacement mechanism must exist also.

One characteristic of many ophiolites which may be re-emphasized here is that a comparatively short time seems to have elapsed between extrusion of the basaltic carapace and thrusting of the complex over continental crust. Although this does not exclude an origin at an oceanic rise, it does favor a history such as that outlined by Karig (1972) in which marginal basins formed to the rear of island arcs are subsequently consumed following reversal of arc polarity. This is especially relevant to Papua, seen by Karig (1972) as a type area for such reversals, and where later rifting may explain the absence of island-arc-type rocks immediately behind the ophiolites. If this is so, the ophiolites are actually marginal-basin crust, probably modified during a period as the hanging wall of a Benioff zone, and cannot be automatically considered typical of the deep ocean.

As discussed in preceding sections, descriptions of the geology of the Papuan Ultramafic Belt are in some respects difficult to reconcile with any form of the island-arc hypothesis, “orogenic thickening” of the Mediterranean type may provide the answer. A primary cause of this abnormal response to the approach of subduction could be the relative youth and concomitant elevation and low density of the crust and uppermost mantle involved. This mode of origin would seem to require the diversion of some intermediate magma up the Benioff zone and into the near surface imbricate mass, and the gravity excess associated with ophiolite belts must be due to the summed effect of a number of imbricate slices at various depths, and not of a single coherent body. Gravitational emplacement is then a possible consequence of detachment of a slice from the root zone, even the Semal nappe can be understood in this way, although not without some difficulty.

Older theories, involving combined intrusion and extrusion, with the main gravity anomaly derived from the intrusive stock, seem less likely than orogenic thickening in view of the seismically determined dipping form of the Ivrea body. The geological relations in the Ivrea zone and the similarities between the Mediterranean region and the ophiolites suggest that the currently rather fashionable view of the oceanic crust as basically oceanic (Wyllie, 1971, p. 152) may have to be reassessed.

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