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The Lubok Antu Melange, Lupar Valley, West Sarawak: a Lower Tertiary subduction complex

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Abstract: Detailed mapping in the Lupar Valley has resulted in the recognition of a Lower Tertiary melange here called the Lubok Antu Melange, and the of presence of low-grade regional metamorphic rocks of the prehnite-pumpellyite facies. The Lubok Antu Melange consists of blocks of Lower Cretaceous radiolarian chert, Upper Cretaceous graywacke and slate, ?Cretaceous and Eocene limestone, calcareous shale, mudstone and sandstone, hornfels, basalt, spilite and gabbro and their metamorphosed equivalents, and serpentinite in a pervasively sheared, dark gray pelitic matrix which, in places, yields fossils of early Tertiary age. It is bounded on the southwest by the Silantek Formation and on the northeast by the Lupar Formation. The metagraywacke, metaconglomerate, metavolcanic rocks and metagabbro, northeast of the Lupar Fault Zone, contain metamorphic mineral assemblages characteristic of the prehnite-pumpellyite facies, indicating low thermal gradient during alteration and, hence, a comparatively high-pressure, low-temperature metamorphism.

The postulated geotectonic setting for the origin of the melange involves late Cretaceous–early Tertiary southeast subduction of oceanic crust beneath a continental basement part of the West Borneo Basement.

INTRODUCTION

The Lupar Valley marks an important boundary in the geology of northwestern Borneo. Detailed geological mapping of the Valley has resulted in the recognition of a tectonic melange zone and a high-pressure low-temperature low-grade metamorphic belt. The area under discussion is located in northwest Borneo, in the State of Sarawak (Fig. 1).

The earliest geological work within the area was carried out by Dutch geologists before 1940 (e.g. Molengraaff, 1902; Zeylmans van Emmichoven, 1935, 1939; Zeylmans van Emmichoven & ter Bruggen, 1935; ter Bruggen, 1935; and Zeylmans van Emmichoven & Ubaghs, 1939). During the 1950's, more comprehensive studies of the geology of the Lupar Valley were carried out by geologists of the Sarawak Oilfields Limited and the Geological Survey (e.g. Milroy, 1953; Haile, 1957; Liechti, Roe & Haile, 1960).

Based on these earlier works and prior to the present study, various authors have attempted to explain the tectonic history of the Lupar Valley, and, that of Sarawak and Borneo in general, in terms of geosynclinal theory (Haile, 1968) and plate tectonics (Hamilton, 1973, 1974, 1977; Haile, 1973; Katili, 1973a, b, c, 1975a, b; Pupilli, 1973; Hutchison, 1973).

Starting in 1973, the Lupar Valley area has been remapped in more detail (Tan 1978, 1979).

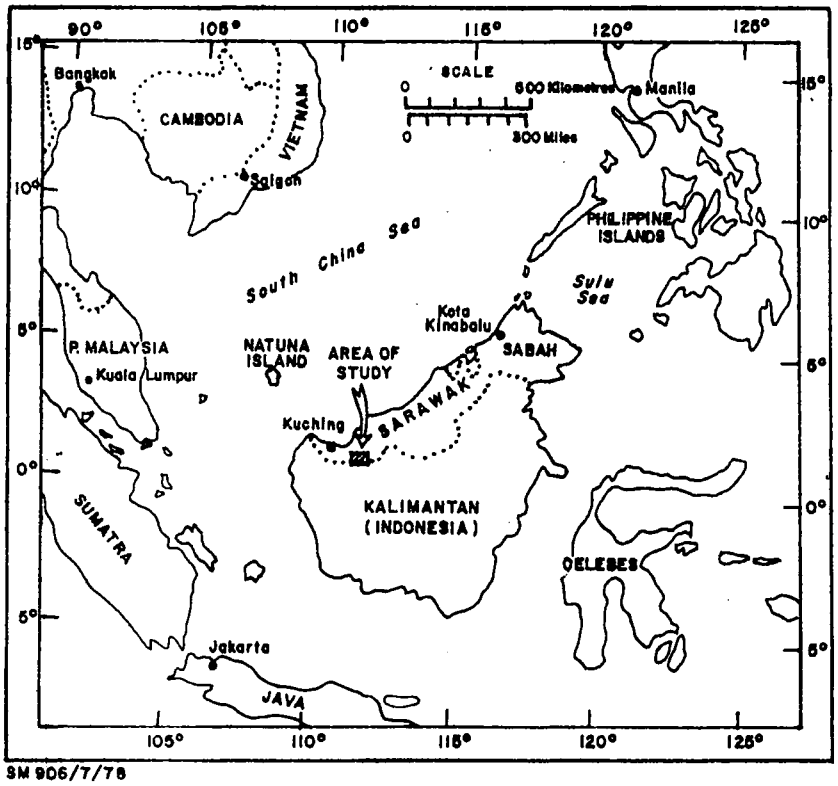

Fig. 1. Location map showing area of study.

This present study has resulted in some major changes in the interpretation of the stratigraphy and structure of the area. The important changes involved are the redefinition of the Lupar Formation of Liechti *et al.* (1960), the recognition of a tectonic melange belt, the abandoning of the name "Engkilili Formation", and the recognition of a high-pressure, low-temperature low-grade metamorphic belt of the prehnite-pumpellyite facies. Using these new data and interpretations the writer attempts to explain the geological evolution of the Lupar Valley in terms of plate tectonics.

GENERAL DESCRIPTION

The general geology of the Lupar Valley is shown in Figure 2. Northeast of the Lupar Fault Zone are exposed the Layar Member of the Belaga Formation, the Lupar Formation, the Pakong Mafic Complex and the Lubok Antu Melange. Southwest of the Fault Zone are the Silantek Formation, the Plateau Sandstone and the predominantly acid to intermediate hypabyssal igneous rocks which intruded the two formations.

The most prominent topographic feature is the Marup Ridge, extending in an almost straight line from near Simanggang southeast to Bukit Besai. It is underlain by steeply dipping to vertical beds of the Basal Sandstone Member of the Silantek Formation and marks the site of the southeast-trending Lupar Fault Zone. Southwest of the Ridge is exposed the Silantek Formation with its Temudok Member forming gently-dipping cuestas. The Plateau Sandstone forms prominent scarp ridges rising to 854 m, marking the international boundary between Sarawak and Indonesian Kalimantan.

Northeast of the Marup Ridge, the undulating lowlands exhibiting knocker topography, due to resistant blocks, are underlain by the Lubok Antu Melange. Adjoining the melange belt, the Lupar Formation forms a tract of undulating lowlands with low, southeast-striking ridges, broken by east-southeast-striking ridges, up to 425 m, formed by rocks of the Pakong Mafic Complex farther to the northeast. The Layar Member of the Belaga Formation forms deeply-dissected uplands with multi-directional ridges in the extreme northeast of the study area.

LITHOLOGY OF THE ROCK UNITS SOUTHWEST OF THE LUPAR FAULT ZONE

Silantek Formation

The Silantek Formation is a thick sequence of mainly silty, carbonaceous mudstone and shale, alternating with gray shale, siltstone, sandstone and coal seams. Conglomerate lenses occur near the base, and at the top is a sequence of red mudstone, shale, siltstone and sandstone. Lithological variations led to the establishment of three distinct members; namely (from bottom to top):

(a) **Basal Sandstone Member:** composed of steeply-dipping to vertical, yellow to white, porous, friable, polymict to quartzose sandstone beds, up to 15 m thick, interbedded with thin beds of silty shale, mudstone, and, occasionally, dark-gray calcareous shale and mudstone. No actual base to the formation has been seen in the Lupar Valley area, however, lenses of polymict conglomerate, up to 1 m thick, and pebbly sandstone occur towards the base;

(b) **Temudok Member:** a lenticular sandstone body comprising gently-dipping beds (3–150 cm) of yellowish-white to gray, fine to coarse sandstone alternating with thin beds of siltstone and sandy to silty mudstone and shale. Apparently no conglomerate or pebbly sandstone is present; and

(c) **Upper Silantek Redbed Member:** predominantly red micaceous shale and mudstone, red siltstone and red sandstone, alternating with thin beds of white to light-gray sandstone, dark-gray shale and mudstone, with dark, very hard ferruginous nodules.

Carbonaceous matter and poorly-preserved plant remains are common. Laminations of dark gray carbonaceous matter or whitish silt and very fine sand are common. Most are horizontal but some show ripple-laminations and cross-

laminations. Cross-bedding, and symmetrical, asymmetrical and interference ripple-marks are common in sandstone beds. Convolute laminae, collapsed ripple and flaser structures have been observed.

The Formation varies in thickness along its outcrop, being thickest in the east where its estimated thickness is about 5100 m. The base of the Formation is in sheared, faulted contact, along the Lupar Fault Zone, with the tectonic melange to the northeast. The top of the Formation changes conformably into the overlying Plateau Sandstone.

The Basal Sandstone Member is dated to be late Eocene (Tan, 1978, 1979) but the age of the rest of the Formation is uncertain.

The Silantek Formation is similar lithologically to the Melawi Group and Kantu Beds in central Kalimantan and is probably largely synchronous with them while the Upper Silantek Redbed Member is probably synchronous with the Lebang Mudstone.

The Silantek Formation, from study of its lithology, texture, biotic assemblage and sedimentary statistical parameters (Tan, 1978), may be considered to have been deposited in a near-shore to shallow marine environment (Basal Sandstone Member). gradually becoming estuarine and, in places, lacustrine (Temudok Member and major part of Formation), and finally terrestrial (Upper Silantek Redbed Member).

Plateau Sandstone

The Plateau Sandstone is a thick succession of thick-bedded to massive, cross-bedded polymict to quartzose sandstone, with minor intercalations of gray and red shale and mudstone, and lenses of conglomerate. It is folded into a broad synclinal basin with the northern rim exposed in Sarawak, the rest of the basin is in Kalimantan. About 152 m of of the lowermost portion of the Formation is exposed in Sarawak. The total thickness of the Formation in Kalimantan is estimated at 1830 m (Haile, 1957).

The Plateau Sandstone in the study-area is practically barren of fossils but is suspected to be Miocene, possibly late Miocene, in age.

Tertiary Intrusive Rocks

Mid-Tertiary, post-late Eocene, intrusive igneous rock intrude both the Silantek Formation and Plateau Sandstone, southwest of the Lupar Fault Zone. These igneous rocks, predominantly intermediate to acid in composition with minor basic varieties, occur as stocks, laccoliths intrusive sheets, dikes and sills. Generally, they are fine-grained and porphyritic with oscillatory zoning of the plagioclase indicating hypabyssal intrusion at relatively shallow depths.

Northeast of the Lupar Fault Zone,intermediate to basic igneous rocks of probable Tertiary age are emplaced into the melange at Bukit Semuyong, southwest of Lubok Antu, and at Bukit Kunang, east of Engkilili.

NORTHEAST OF THE LUPAR FAULT ZONE

Lupar Formation

The Lupar Formation, originally termed the Danau Formation (Molengraaff, 1902) was mapped as Cherty Facies Stage I of the Rajang Group by Haile (1957) and subsequently renamed the Lupar Formation by Liechti *et al.* (1960) who described it as comprising "a clastic succession of clay-shale, claystone, siltstone, sandstone, graywacke, conglomerate and rare limestone interbedded with thick, usually lenticular bodies of radiolarian chert, and volcanic breccias, spilitic extrusive rocks and associated tuffs: a typical radiolarite-ophiolite or chert-spilite association".

The present study, in particular examination of roadcuts not available during previous surveys, indicates that the Lupar Formation, as previously defined, can be remapped into three distinct units: a turbidite sequence, a chaotic assemblage of rocks forming a melange belt, and the ophiolitic rocks. The turbidite sequence retains the name Lupar Formation and is redefined as comprising rhythmically interbedded shale, mudstone, slaty shale, slate and graywacke, with lenses of granule to pebble conglomerate, and characterised by graded bedding, load and flute moulds, flame structures, sandstone balls and small-scale cross-bedding. This Formation underlies about 140 km^2 of the area, forming a 45 km-wide belt and extending into Kalimantan. Rocks showing strong lithological affinities to the Lupar Formation occur as blocks in the melange.

The Lupar Formation is folded, overturned, and, in places, intensely sheared and broken up into boudins and blocks giving the appearance of a "broken formation".

The presence of characteristic Upper Cretaceous foraminifers indicates that the Lupar Formation is Late Cretaceous in age, probably Santonian to Maastrichtian, and may possibly be as old as Turonian (Tan, 1979).

The Lupar Formation was deposited in a deep marine environment by turbidity currents and mass flows. Study of some 37 flute moulds over a limited area gives a palaeocurrent pattern dominated by diverging northeast directions, suggesting a source to the southwest, or at least a SW-NE oriented trough or trench.

Layar Member of Belaga Formation

The Belaga Formation underlies a major portion of central Sarawak and comprises four members, namely, Layar Member (Upper Cretaceous), Kapit Member (Palaeocene-Lower Eocene), Pelagus Member (Middle-Upper Eocene) and Metah Member (Upper Eocene). Only the Layar Member is exposed in the study area.

The Layar Member comprises mainly slate and phyllite rhythmically interbedded with laminae and beds of metagraywacke, up to 3 m thick, and, in places, minor hard, dark pyritic, sometimes calcareous nodules (1–15 cm across) and rare conglomerate lenses. The sequence appears to be distal turbidites (Tan, 1979).

The base of the Layar Member is, in places, in faulted contact with the Lupar Formation. This contact is marked by a 10–15 m wide shear zone in Sungai Kaong and

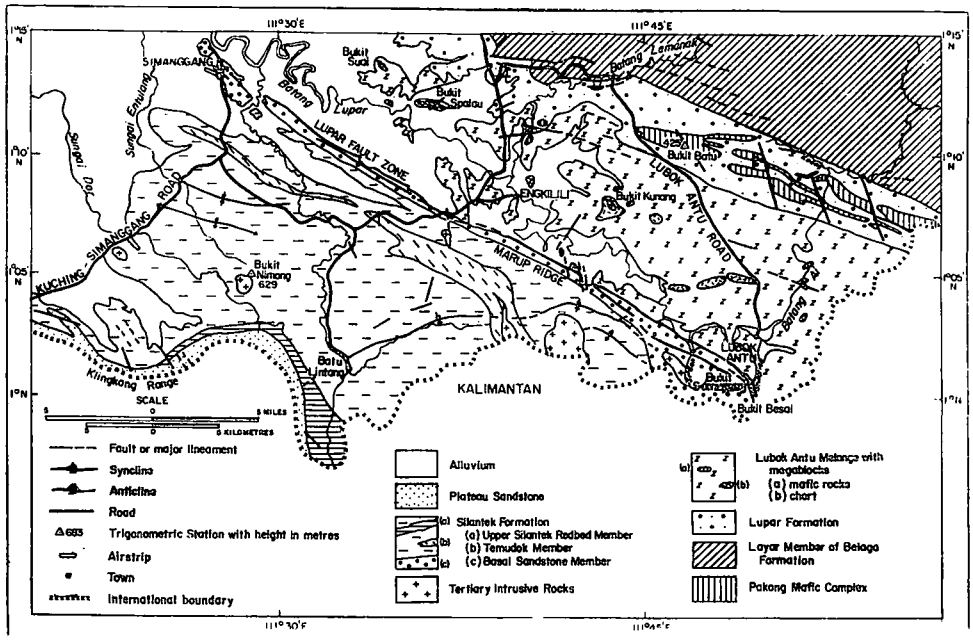

Fig. 2. Geological sketch map of the Lupar Valley, west Sarawak.

fault facets north of the Lubok Antu Road (see Fig. 2). The top of the Member grades into the Kapit Member.

The Layar Member was reported by W.E. Crews (*in* Milroy, 1953) and V.J. John (*in* Jordi & Bowen, 1956) to contain Upper Cretaceous foraminifers indicating a Cenomanian to Maastrichtian age.

The Layar Member was deposited by turbidity currents during the Late Cretaceous in a marine environment far from the source, as indicated by its lithology, sedimentary structures and fossils.

Pakong Mafic Complex

The Pakong Mafic Complex, a name introduced for a suite of spilite, basalt and gabbro in the study-area by Tan (1978, 1979), forms a discontinuous east-southeast striking belt, approximately 21 km long and underlying about 39 km^2 of the Lupar Valley. The complex consists of fine to coarse gabbro, diabase, basalt, and spilite, with their metamorphosed equivalents: the basalt and spilite are typically pillow lava, hyaloclastite, and, rarely, agglomerate. A Basalt Zone and a Gabbro Zone have been differentiated. The *Basalt Zone* (400 m–1 km thick) consists of massive basalt, spilitic and basaltic submarine lavas, commonly pillowed and grading into hyaloclastite and agglomerate. The pillow lavas are well-developed and are overturned, as indicated by their shape, dipping steeply at between 65° and 70° to the northeast. Fine-grained pelagic limestone occurs as infillings of interpillow spaces in an outcrop at Mile 10½,

Lubok Antu Road. The *Gabbro Zone* (1–1.5 km thick) consists mainly of granular, fine to coarse gabbro, probably layered, with an east to southeast strike. Probable cumulative pyroxenite was observed in one locality. The gabbro is usually sheared, with slickensided fractures and veins filled with quartz and, less commonly, prehnite and calcite.

Diabase dikes, up to 3–4 m wide, occur as swarms intruding both basalt and gabbro and are particularly common at the contact between the two zones.

Tan (1978) concluded that the rocks of the Complex resemble oceanic crust in rock types, sequential order and chemical characteristics. They probably form an incomplete ophiolite (Hutchison, 1975). However, subsequent observations made along Batang Ai by Dr D.S. Coombs and the writer indicate that, in parts at least, the Pakong Mafic Complex may be intrusive into, and in the case of the lavas, extrusive within the Lupar Formation.

Lubok Antu Melange Belt

The Lubok Antu Melange was first mapped and described by Tan (1978, 1979). This Melange is composed of fragments and blocks, ranging from a few centimetres to a few kilometres in maximum dimension, of mudstone, sandstone, shale, hornfels, chert, conglomerate, basalt and gabbro (and their metamorphosed equivalents), limestone and serpentinite in highly cleaved, chloritised, prevasively sheared dark-gray pelitic matrix. This chaotic assemblage is a tectonised unit and is a tectonic melange, in the sense of the term as used by Berkland *et al.* (1972). The Melange forms a belt, 10.5 km wide, underlying about 337 km^2 of the Lapur Valley and extends southeast into Kalimantan.

As a result of the recognition of the melange, it was found necessary to abandon the term 'Engkilili Formation' (Liechti *et al.*, 1960, p. 54–56). This 'formation' was defined as "an infolded or probably downfaulted occurrence of shale in which fossiliferous limestone is embedded" and considered to be "probably depositionally disturbed, but lithologically not different from shales of the underlying Lupar Formation, except that embedded in them at two outcrops are blocks of limestone up to 5 feet across on which the lithological distinction rests". Tan (1978) concluded that the 'Engkilili Formation' is actually part of the melange with the limestone occurring as exotic blocks.

Matrix of the Melange

The matrix of the Lubok Antu Melange is gray to dark-gray clays, pervasively sheared and chloritised with lustrous surfaces, giving it a 'scaly' appearance. Generally, the matrix is non-calcareous except for two locations, one near Engkilili and the other in Sungai Meriap, south-southwest of Lubok Antu.

The matrix has been dated as early Eocene based on the presence of Foraminifera and nannofossils. The assemblages of nannofossils in the matrix indicate a Tertiary age, probably Palaeocene to Miocene. One sample yields an assemblage characteristic of the *Discoaster lodoensis* zone which is Upper Lower Eocene (Tan, 1978, 1979).

Blocks

Blocks and fragments in the Melange range from a few centimetres to 5.5 km in length, though the average is 1–10 m. From detailed mapping, the following rock types making up the blocks have been identified: chert, hornfels, conglomerate, limestone, serpentinite, basalt and gabbro and their metamorphosed equivalents showing Pakong Mafic affinities, rhythmically interbedded graywacke and slaty shale showing Lupar Formation affinities, and calcareous sandstone, siltstone, shale and mudstone.

Chert: The chert occurs as exotic blocks and is widespread. The largest blocks form hills up to 5.5 km in length and 500 m high. The chert varies from whitish to greenish-gray to reddish-brown in colour with conchoidal to hackly fractures, depending on the degree of recrystallization. the reddish-brown chert is commonly interbedded with reddish-brown to maroon mudstone. Individual chert beds range from a few centimetres to a few tens of centimetres thick; a few are massive. The tectonised blocks of chert are thin coatings and veinlets of black lustrous manganese minerals, mainly lithiophorite and cryptomelane.

The chert has been dated by Radiolaria as Early Cretaceous, probably Valanginian to Barremian (Tan, 1978, 1979).

Limestone: Blocks up to 3 m across have been mapped near Engkilili and in Sungai San, west of Lubok Antu. Blocks of silicified limestone are found at Mile 1½, Engkilili Road. The limestone blocks near Engkilili are fossiliferous and have been assigned a late Palaeocene to Eocene age based on the presence of *Caulastrea* sp. cf. *Calamophyllia indica* Duncan, *Actinacis* sp., *Distichoplax biserialis* (Dietrich) Pia, *Halimeda* sp., *Discocyclina* cf. *ramaraoi* Samanta, *Globorotalia* sp. an *Nummulites* sp. The limestone blocks in Sungai San are of probable Cretaceous age as they contain *Globotruncana* sp., *?Pseudocyclammina* sp., *?Globigerina* sp., *Rotalia* sp., *Miliola* sp. and *?Stylina* sp.

Blocks of Lupar Formation affinities: Blocks of rhythmically interbedded, graded graywacke and slaty shale, some containing assemblages of Upper Cretaceous foraminifers similar to those of the Lupar Formation, are found throughout the melange. The largest of these blocks is about 1.5 km in length. Many of the smaller blocks and fragments of graywacke, metagraywacke, slate, slaty shale and mudstone show lithological similarities to the Lupar Formation and are thought to have probably been derived from it.

The presence of *Orbitolina*-bearing interbedded shale and sandstone in the southeast part of Batang Lupar was reported by Milroy (1953) and Haile (1975). During the present study, a 25 cm × 18 cm block of weathered, gray sandy siltstone packed with well-preserved *Orbitolina* spp., *Orbitolina* cf. *discoidea* Gras and *Orbitolina lenticularis* (Blumenbach) indicating a Late Cretaceous age probably Albian-Cenomanian, was found at Mile 18, Lubok Antu Road.

Conglomerate: Volcanic conglomerates, associated with mafic volcanic rocks and chert, are found at Bukit Suai and Bukit Spalau. The clasts are predominantly volcanic rocks, chert, vein quartz and recrystallised limestone with minor argillite,

sandstone and schistose rocks. Crews (*in* Milroy, 1953) found *Pseudocyclammina* sp. in a fragment of limestone in conglomerate from Bukit Suai and considered that a post-Late Jurassic or post-Early Cretaceous age for the volcanic conglomerates is likely.

Calcareous sandstone, shale and mudstone: Blocks of calcareous sandstone, shale and mudstone, lithologically and texturally different from similar rock types of either the Lupar Formation or the Layar Member, are also found in the melange. Most of these blocks are small, generally less than 1 m, the largest being about 20 m across consisting of light-gray calcareous shale interbedded with calcareous siltstone and sandstone and cut by numerous calcite veins.

The age of some of these blocks is indicated by nannofossils and Foraminifera to be early Tertiary, most probably early Eocene, similar to that of the matrix (Tan, 1978, 1979).

These blocks are considered to be native blocks, representing more brittle and resilient parts of the lower Tertiary sediments which have been tectonised to form the melange.

Pakong Mafic affinities: Blocks of mafic igneous rocks, up to 2 km across, comprising spilite, basalt, gabbro and their metamorphosed equivalents are ubiquitous. These rocks show mineralogical and textural similarities to those of the Pakong Mafic Complex and presumably have been derived from the Complex.

Blocks of spilitic tuff, lapilli tuff, spherulitic rhyolite and a single serpentinite block, 2 m across, have also been mapped in the melange.

Characteristics and Origin of the Melange

The characteristics and origin of the Melange are discussed below.

Characteristics of blocks

(a) The melange contains a chaotic, tectonically intermixed assemblage of angular, in places subrounded to rounded, irregularly shaped fragments and blocks of various rock types and ages set in a strongly sheared, dark gray pelitic matrix.

(b) The fragment and blocks are greatly variable in sizes from a few centimetres to 5.5 km. Blocks like the graywacke, slaty shale, slate, basalt, spilite, gabbro and their metamorphosed equivalents can be recognised as probably being derived from adjacent units: the Lupar Formation and Pakong Mafic Complex. The chert, volcanic conglomerate, ?Cretaceous limestone and serpentinite blocks cannot be correlated to any adjacent units and are probably derived from other, probably distant, hidden or eroded, sources. Some of these blocks give ages older than the melange matrix. Other blocks, however, like the Lower Eocene limestone, calcareous sandstone, shale and mudstone have ages similar to that of the matrix.

(c) No single rock type seems to dominate among the blocks but the chert blocks, due to their sizes and resistance to weathering appear to form a prominent lithologic component.

Characteristics of the Matrix

(a) The melange matrix is pervasively sheared, pelitic, and usually chloritised, with lustrous surfaces giving a 'scaly' appearance. In some places, the matrix is calcareous and fossiliferous and in others, it is cut by calcite veins. The colour of the matrix varies from gray to dark gray.

(b) The texture of the matrix suggests that it had been tectonically sheared and probably had undergone mild dynamic metamorphism.

(c) Foraminifera and nannofossils in the matrix indicate an early Tertiary age, probably early Eocene. Benthonic foraminiferal assemblages indicate that the original sediments were deposited in a deep marine environment.

Origin

The Lubok Antu Melange is interpreted to be derived by tectonic processes. The origin of melanges is still controversial (Hsü, 1968, 1974; Berkland *et al.*, 1972; Raymond, 1975) but it is generally accepted that tectonic melanges are commonly associated with subduction zones and probably mark the sites of fossil Benioff zones.

The Lubok Antu Melange is interpreted to have been derived by subduction, and its present distribution to mark the site of an old subduction zone. The presence of a former subduction zone in the Lupar Valley has been speculated on by various writers (Haile, 1973; Katili, 1973a, b, c, 1975a, b; Hamilton, 1973, 1974, 1977; Hutchison, 1975). This Melange probably marks the site of an old subduction zone created by a southwest-moving northeastern oceanic plate impinging onto and being subducted, during ?Late Cretaceous to mid-Tertiary, under the continental West Borneo Basement.

REGIONAL METAMORPHISM

The Layar Member, Lupar Formation, Pakong Mafic Complex and some blocks in the melange have, to a greater or lesser degree, been affected by regional metamorphism. The textural and mineralogical changes brought about by this metamorphism are particularly obvious in the metagraywacke, metaconglomerate, metavolcanic rocks and metagabbro.

Metagraywacke: The metagraywacke of both the Layar Member and Lupar Formation can be assigned to textural zones 1–2, and probably 2.5, following the criteria for textural zonation in the metagraywackes of the Franciscan (Blake, Irwin & Coleman, 1967; Ernst, 1971). It is obvious that a high degree of subjectivity is involved in determining the textural grade, which is based on the amount of reconstitution, both recrystallisation and cataclasis.

In the Lupar Valley, the metagraywacke of textural zone 1–1.5 appears unmetamorphosed, showing no evidence of cataclasis, either in outcrop or

handspecimen. In thin section, however, it would normally be termed "altered" or "sericitised" but its textural grade is the most obvious sign of metamorphism and it contains metamorphic minerals, regardless of the strength of reconstitution.

Metagraywacke of textural zone 2 in general, shows a more sheared appearance, with moderately well-developed platy cleavage in outcrop and is clearly cataclastic in handspecimen. The sheared nature of the rock is often enhanced by the presence of slickensided quartz veins up to 5 mm wide. This sheared nature is the result of moderately intense recrystallisation and incipient cataclasis.

Metagraywacke of probable textural zone 2.5 is not common and appears in outcrop and handspecimen as a cataclastic rock, strongly sheared, brecciated and cut by numerous criss-cross veins of quartz with minor prehnite, calcite and chlorite.

The metagraywacke, in general, appears to contain a rather undiagnostic suite of metamorphic minerals dominated by quartz, albite, chlorite and white micas (phengite). Sphene, calcite, stilpnomelane, pumpellyite, prehnite and epidote-clinozoisite occur in some of the metagraywackes. Detrital plagioclase has mostly been converted to albite. Pumpellyite occurs as bright-green pleochroic acicular crystals in the matrix near the edges of quartz clasts or in mafic volcanic clasts. Calcite occurs as fine patches in the matrix and in veins in some metagraywackes. Prehnite is present in veinlets and in the matrix of some metagraywackes.

Metaconglomerate: Metaconglomerate occurs as lenses in the Lupar Formation and as blocks in the melange. It consists predominantly of clasts of spilite, metabasalt, semi-schistose rocks, metaquartzite, metagraywacke and recrystallised limestone in a recrystallised groundmass with metamorphic minerals comprising quartz, albite, chlorite, phengite, prehnite, laumontite and pumpellyite, with or without stilpnomelame, calcite, epidote and sphene.

Metavolcanic rock: The metabasalt and spilite contain a characteristic metamorphic mineral assemblage comprising quartz, albite, chlorite, prehnite, epidote-clinozoisite, with or without stilpnomelane, pumpellyite, calcite, sphene and actinolite. These minerals occur in the groundmass, as replacement of original mineral grains, and in amygdules and veins. The common amygdule minerals are altered volcanic glass, chlorite, quartz, pumpellyite, prehnite, epidote-clinozoisite and calcite. In some cases, quartz rims a core of chlorite, prehnite rims a core of volcanic glass or quartz, and, in others, an intimate association of these metamorphic mineral exist. In most of the strongly sheared metabasalts and spilites, the mineral assemblages in the veins are similar to those filling the amygdules.

The pelagic limestone filling interpillow spaces of spilitic lava at Mile 10½, Lubok Antu Road has also undergone metamorphism, being partially recrystallised and cut by veins containing calcite,. chlorite, prehnite, epidote-clinozoisite and siderite.

Metagabbro: Some of the gabbros are partially to completely sheared and have undergone low-grade metamorphism with little of the original igneous texture and minerals preserved. These metagabbros developed a characteristic metamorphic

mineral suite comprising abundant prehnite, pumpellyite, epidote-clinozoisite and spherical sphene along with minor quartz, albite and chlorite.

Metamorphic Grade

The mineral assemblages of the metavolcanic rocks and metagabbros in the Lupar Valley resemble those in rocks of the prehnite-pumpellyite facies in New Zealand (Coombs, 1960; Bishop, 1972), Japan (Seki, 1961; Hashimoto, 1968; Herve, 1975) and British Columbia (Kuniyoshi & Liou, 1976). The mineral assemblages of the metagraywackes are not as diagnostic, but nevertheless show certain resemblances to those in New Zealand, Japan, California and Washington. This may be explained by the fact that the Lupar graywackes are generally more quartzose and less feldspathic than those of the Franciscan or Otago. The rock fragments are mostly cherty and argillitic sedimentary or metasedimentary types rather than volcanic or metavolcanic types. Thus, the mineral assemblage is less reactive overall and hence less capable of forming the Ca/Na-bearing minerals diagnostic of different low-grade facies. In this aspect, they are more similar to the Ouachita graywacke than the Franciscan or Otago graywackes (W.R. Dickinson, personal comm.).

The metamorphic mineral assemblages and textural grades of the rocks in the Lupar Valley indicate that they have undergone low-grade metamorphism of the prehnite-pumpellyite grade. The very wide distribution of prehnite-pumpellyite facies assemblages, with little apparent change in grade, is probable evidence of a low thermal gradient during alteration, indicating a comparatively high-pressure low-temperature metamorphism (D.S. Coombs, personal comm.).

In the Lupar Valley, greenschist facies rocks are not found, either because the deeper higher grade metamorphic rocks are not exposed or because the metamorphism has not reached that grade. Rocks of the zeolite facies have been found at only one locality, Bukit Spalau, where laumontite occurs as cement in a conglomerate. As it is partially replaced by prehnite; sieved with quartz, even this case may be transitional to prehnite-pumpellyite facies (D.S. Coombs, personal comm.). The absence of greenschist facies and possibly the zeolite facies rocks is not unique, as this has also been reported in the Karmutsen volcanic rocks in British Columbia (Kuniyoshi & Liou, 1976).

TECTONIC HISTORY

The Lupar Valley marks an important change in the post-Jurassic geology of northwestern Borneo. Traditional reconstructions of the geological history of the Valley involve the following succession of principal events:

(a) deposition of geosynclinal sediments north of the Lupar Fault Zone from Late Cretaceous to early Eocene with associated mafic magmatism and low-grade regional metamorphism associated with complex isoclinal folding in the late Eocene; and

(b) deposition of Upper Eocene to Miocene molasse deposits formed in 'back-deep' or 'intra-deep' south of the Lupar Fault Zone, followed by a period of major orogeny in Neogene time and a period of igenous activity subsequent to the orogeny (Haile, 1975, 1968).

In the light of the present knowledge of the geology of the Lupar Valley, attempts to deduce the tectonic history must account for and explain the following features: (a) the tectonically derived chaotic rock assemblage of the Lubok Antu Melange, (b) the high-pressure low-temperature prehnite-pumpellyite facies rocks northeast of the Lupar Fault Zone, (c) the high-angle Lupar Fault Zone, and (d) the spate of Mid-Tertiary magmatic activity southwest of the Fault Zone. These features can best be explained in terms of subduction of a northeast oceanic plate beneath a southwest continental plate. The write specifically proposes a subduction-related genesis for the Lubok Antu Melange.

On the basis of contemporary concepts of plate tectonics, various possible models may be erected to account for the geological evolution of the Lupar Valley. However, such models must remain, at best, speculative and fairly generalised and may prove inadequate in detail. Recognising this, the writer has attempted to set up a tectonic model of the area (figure 3) which would best explain the features noted above.

Early Cretaceous: The West Borneo Basement and pre-Cretaceous rock in west Sarawak form the continental basement under discussion. Events in the study area during Early Cretaceous are not well-documented. Northeast and adjacent to the continental basement lay a region of oceanic crust with Lower Cretaceous chert and associated pelagic red mud deposited on it.

Later Cretaceous: Pelagic sedimentation of chert and red mud appears to have given way to turbiditic deposition in Late Cretaceous. The Lupar Formation and Layar Member were deposited at about this time by turbidity currents from a source to the southwest.

Early Tertiary: Subduction of the northeast oceanic plate and its skin of Lupar Formation, Layar Member and pelagic sediments beneath the southwest continental basement took place probably from very late Cretaceous or Palaeocene to the end of Miocene time. Development of a wedge of deformed, tectonically derived assemblages of rocks–the melange–occurred at the subduction front, with incorporated blocks of chert and rocks of the Lupar Formation. The turbiditic sediments were compressed into a series of predominantly northwest trending folds.

During subduction, a high-pressure low-temperature regime was built up on the oceanic side of the melange belt, resulting in low-grade metamorphism of prehnite-pumpellyite grade. At the continental front, sedimentation continued, resulting in the accumulation of Eocene limestone and clastic sediments, which were later incorporated as blocks and matrix of the melange. At the same time, the Basal Sandstone Member of the Silantek Formation was deposited in a near shore to shallow marine environment, southwest of what was later to become the Lupar Fault Zone.

Late Tertiary: Subduction probably continued into Miocene time with the Lupar Formation and Layar Member becoming progressively more tightly folded and overturned. On the continental side, the basement was uplifted at its northern edge to form a closed basin within which deposition of the Silantek Formation and Plateau

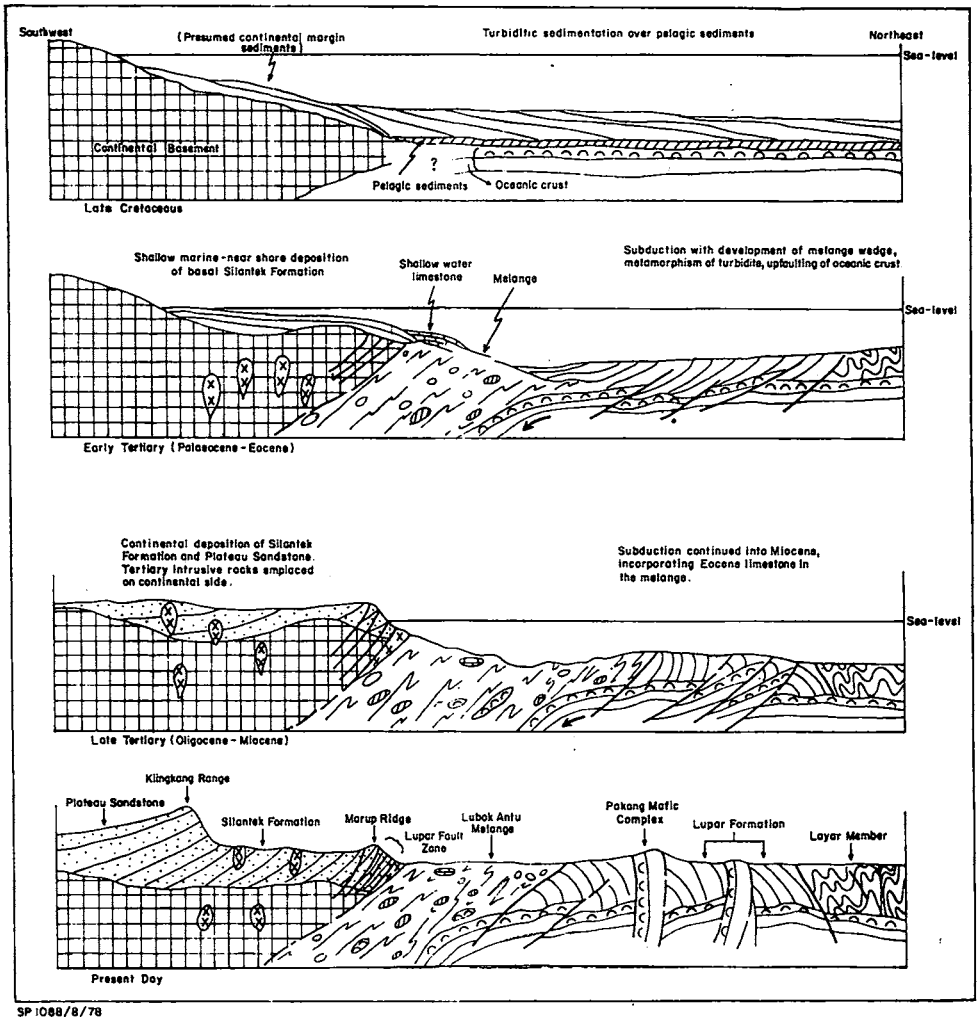

Fig. 3 Diagrammatic cross-sections to show the hypothetical evolution of the Lupar Valley.

Sandstone continued into the Miocene. The Basal Sandstone Member at the continental front was affected by high angle faults forming probably with some wrench component, the Lupar Fault Zone. Magma generated over the subduction zone intruded the Silantek Formation and Plateau Sandstone.

CONCLUSIONS

Detailed mapping in the Lupar Valley has resulted in the recognition of the tectonic Lubok Antu Melange and of the widespread distribution of low-grade metamorphic rocks of the prehnite-pumpellyite facies northeast of the Lupar Fault Zone.

The geotectonic setting is believed to have involved a period of very late Cretaceous to early Tertiary subduction of a northeast oceanic floor beneath the southwest West Borneo Basement, with the development of the melange, formation of the low-grade metamorphic rocks and the emplacement of fragments of oceanic crust into the Lupar Formation.

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