A FIRST GEOLOGICAL MAP OF MAKIRA, SOLOMON ISLANDS: STRATIGRAPHY, STRUCTURE AND TECTONIC IMPLICATIONS

M G Petterson[1], R Magu [2], A Mason[2], H Mahoa[2], D Tolia[2], C R Neal[3] and J J Mahoney[4]

[1]British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, UK

[2]Ministry of Energy Mines and Mineral Resources, PO Box G37, Honiara, Solomon Islands

[3]Department of Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, Indiana 46556, USA

[4]School of Ocean and Earth Science and Technology, University of Hawaii, 2525 Correa Road, Honolulu, Hawaii 96822, USA

ABSTRACT

This report presents the first ever comprehensive account of the geology of Makira (formerly San Cristobal). Makira is the last large island of the Solomon Islands archipelago to be systematically geologically mapped at a scale of 1: 50, 000.

Makira is readily sub divisible into the Makira Basement Complex (MBC) and the unconformably overlying Makira Cover Sequence (MCS). Currently available Ar - Ar whole rock radiometric age data indicates a Cretaceous - Oligocene (c. 98Ma - 34 Ma) for the Makira Basement Complex. The Harigha Sandstone Group, a unit within the Makira Cover Sequence has yielded Mid Miocene - Early Pliocene foraminiferal ages.

The Makira Basement Complex forms the great bulk of the volume of Makira (probably c. 90%) of which basaltic lithologies comprise >65%, and locally almost 100% of the sequence. The Makira Basement Complex comprises basalt and dolerite sheets and minor dykes with gabbroic and ultramafic sheets and intrusions (herein termed the Wairahiti Volcanic Group or WVG) with interbedded sedimentary limestones, cherts, sandstones, and basaltic breccias (herein termed the Waihaoru Sedimentary Group or WSG). The Wairahito Volcanic Group comprises a sequence of basalt, dolerite and gabbro sheets and dykes with local ultramafic sills and intrusions. A cumulate thickness is difficult to estimate as there are few regional stratigraphic units which can be used for correlation purposes; however geological cross sections suggest a minimum thickness of 2km. The Waihaoru Sedimentary Group rocks have a wedge or lens like morphology, with a local thickness maximum region which quickly pinches out along strike. Individual beds can attain considerable (tens to >100m) thickness locally. Monolithic basaltic breccias are particularly common within the WSG in the north of Makira. There are no diagnostic stratigraphical units within the basement which crop out on a regional basis, making cross-island correlation very difficult.

The Makira Cover Sequence comprises two main rock groups and an uppermost Quaternary - Recent sequence of alluvium, raised reef, beach, and mangrove swamp deposits. The Upper Miocene - Lower Pliocene Harigha Sandstone Group (HSG) comprises a varied sequence of weak - moderately cemented poorly - moderately sorted, soft, and sometimes chalk - like, calcareous sandstones and

siltstones with occasional interbedded basaltic sheets. The HSG is at least 100m thick. The Kahua Breccia Group (KBG) comprises monolithic basalt breccias and bi-lithic basalt - limestone breccias which locally grade into coarse, poorly sorted sandstones and interbedded basalt sheets. The KBG is at least 100 -200m thick.

Dacite dykes cut the basement at a number of localities. The dykes are several metres to ?tens of metres thick, fine - medium grained and leucocratic, with phenocrysts to microphenocrysts of hornblende, pyroxene, and feldspar (plagioclase and alkali feldspar) set in a fine grained felsic groundmass. Flow textures and accessory zircon crystals are common. The relationship of the dacite dykes to the cover sequence is uncertain. Many dykes strike NNE, parallel to the predominant extensional fault trend. The dacite dykes are evidence for a period of arc formation on Makira: corroboratory evidence is provided by Jeffrey et al, 1975, who document possible arc derived epiclastic sediments which crop out in the Arosi peninsular, in western Makira. The intermediate - acid volcanic and volcaniclastic rocks comprise the Makira Arc Group, which is post Oligocene (?Miocene - Pliocene) in age.

Compressive folding, extensional faulting, and unconformity structures are all present on Makira. The island is divisible into a number of fault blocks of varying size with NNE-SSW and east -west extensional fault structures separating discrete fault blocks. The density of faulting is greatest in the central, southern and eastern part of the island: western Makira appears to be the least affected by faulting, and contains the largest individual fault blocks by area. Faults are visible on all scales: from island wide structures to outcrop and smaller scales. Within an individual fault block there is a consistency to the structure: for example within western Makira it is possible to trace individual fold axes and lithological units for 10 - 15km along strike. Between many fault blocks, particularly in central Makira there is often an abrupt 90° change in strike trend from ESE to NNE indicating that there has been significant fault block rotation. Fold trends are predominantly east - west to ESE - WSW, with localised NNE-SSW trends, except within local fault blocks as described above. Fold geometry is essentially open and gentle: the degree of shortening is limited. The faulting and folding pattern of Makira can be most easily explained by the highly oblique collision between the Australian and Pacific plates (e.g. Petterson et al, 1997) which induces a predominant transpressive stress regime with resulting north - south compression and east - west sinistral shear. The interplay between the two dominant stresses (i.e. simple shear versus compression) appears to be highly complex with one dominating over the other at certain times and both acting simultaneously at other times. There have been at least two periods of transpression and uplift separated by a period of localised extension and localised basin formation dated at Mid Miocene - Early Pliocene.

The unconformity between the cover and basement sequences has some intriguing characteristics. Structural cross - sections suggest that the cover sequence has formed within small extensional ?pull - apart basins, with bounding listric, extensional, growth faults, and which received sediment from rivers draining the surrounding uplifted highlands of Makira. Basalt magma was extruded within these small basins. Despite apparent fault control on the basin margins the cover sequence exhibits a highly irregular surface contact relationship with the cover sequence suggesting that the youngest sediments overlapped the edge of the basin and were deposited irregularly on top of the basement. Some fold structures cut straight across the unconformity suggesting that at least some folding has occurred in the relatively recent past.

Makira appears to be most uplifted towards the south where the highest ridges are located. The major watershed of Makira (which trends east - west) is located only some 5 - 10 km north of the southern coast and separates relatively long north-flowing rivers from relatively short south-flowing rivers . The present drainage pattern reflects relatively recent uplift and tilting to the north in response to Makira's present forearc position. This uplift has stripped Makira of the bulk of its deep sea pelagic and arc rocks. The gross uplift and northwards - tilting of

Makira has a close analogue with Guadalcanal which exhibits a very similar structural style.

The geochronological age structure of the Makiran basement is uncertain as there is poor stratigraphical control across the island. Theoretically the oldest rocks should be exposed in the most uplifted southern part of the island (this is the case in Guadalcanal for example where there is better geological control). There is some support for this theoretical notion from unpublished preliminary Ar - Ar age dating results which have yielded plateau ages of c. 90Ma from basalt samples taken from the Matangarighi river (SE Makira); c. 55 - 67Ma from basalt samples taken from the upper Wairahito river (central - east Makira); 2); and c. 33 - 35Ma from basalt samples taken from northern Makira.

It is possible to subdivide Makiran basalt samples on the basis of varying Zr/Nb ratios and Nb concentrations. The bulk of Makiran basalt samples are compositionally most similar to Ontong Java plateau basalts, but a significant number of samples are more akin to ‘normal’ ocean floor basalts (e.g. Makira ‘MORB’) or alkaline ocean island basalts.

A geo-tectonic model of Makira is proposed which proposes that the Makiran basement represents the episodic accretion of oceanic basalts and sediments from the Cretaceous to the Oligocene from a range of oceanic environments. This composite basaltic terrain underwent compression and uplift during post - Oligocene / pre - Mid Miocene times culminating in the formation of an island block. The uplifted island underwent extension / gravitational collapse and erosion which produced a series of local submarine basins into which were deposited basaltic and limestone clastic sediments. An arc developed on Makira, probably after 8Ma. Since Late Pliocene times Makira has been subject to intense fore arc transpression.

INTRODUCTION AN SCOPE OF PAPER

This paper presents the first island wide comprehensive account of the geology of Makira (formerly known as San Cristobal). The systematic geological survey of Makira is still ongoing and will finish in either 1998 or 1999. This report is a preliminary summary of field investigations which took place between 1994 and 1997. The paper proposes a stratigraphic and structural framework for Makira and a preliminary geo - tectonic model.

This paper builds on the work of people who have made field investigations of makira in former times, most notably: Grover, 1958, Pudsey - Dawson et al, 1958, Thompson and Pudsey - Dawson, 1958, Coleman, 1965, and Jeffrey et al, 1975.

TECTONIC SETTING OF MAKIRA

The geographical and tectonic setting of Makira is presented in Figures 1 and 2. Makira is the most southeastern of the double chain of larger islands which form the bulk of the land mass of the Solomon Islands archipelago, SW Pacific. Solomon Islands is an upraised block bounded to the northeast by the Vitiaz (locally north Solomon) trench and to the southwest by the South Solomon (New Britain - San Cristobal) trench. The Solomon block is a composite terrain collage (Figure 2, Petterson et al, in press, a) comprising terrains dominated by thick ocean plateau crust (the Ontong Java Plateau (OJP) Terrain); terrains formed predominantly during Eocene - Lower Miocene stage 1 arc times (e.g. the Shortlands); and Upper Miocene - Present day stage 2 arc times (e.g. the New Georgia Group); and terrains which are themselves composite oceanic/arc terrains (e.g. Guadalcanal). Makira is a somewhat unique island even in Solomon Island terms as it is a composite of a number of oceanic units with a stage 1 arc. The Solomon arc is part of the Greater Melanesian arc which includes the active arcs of New Britain and Vanuatu (Figure 1)

The Solomon block is currently in collision with the Ontong Java Plateau (OJP) (Figure 1) and has been colliding with the OJP since around 20Ma (Petterson et al, in press, a). The Woodlark basin (Figure 1) is a young (< 5Ma) ocean basin which is being subducted at the South Solomon trench. The subduction of young, warm Woodlark basin

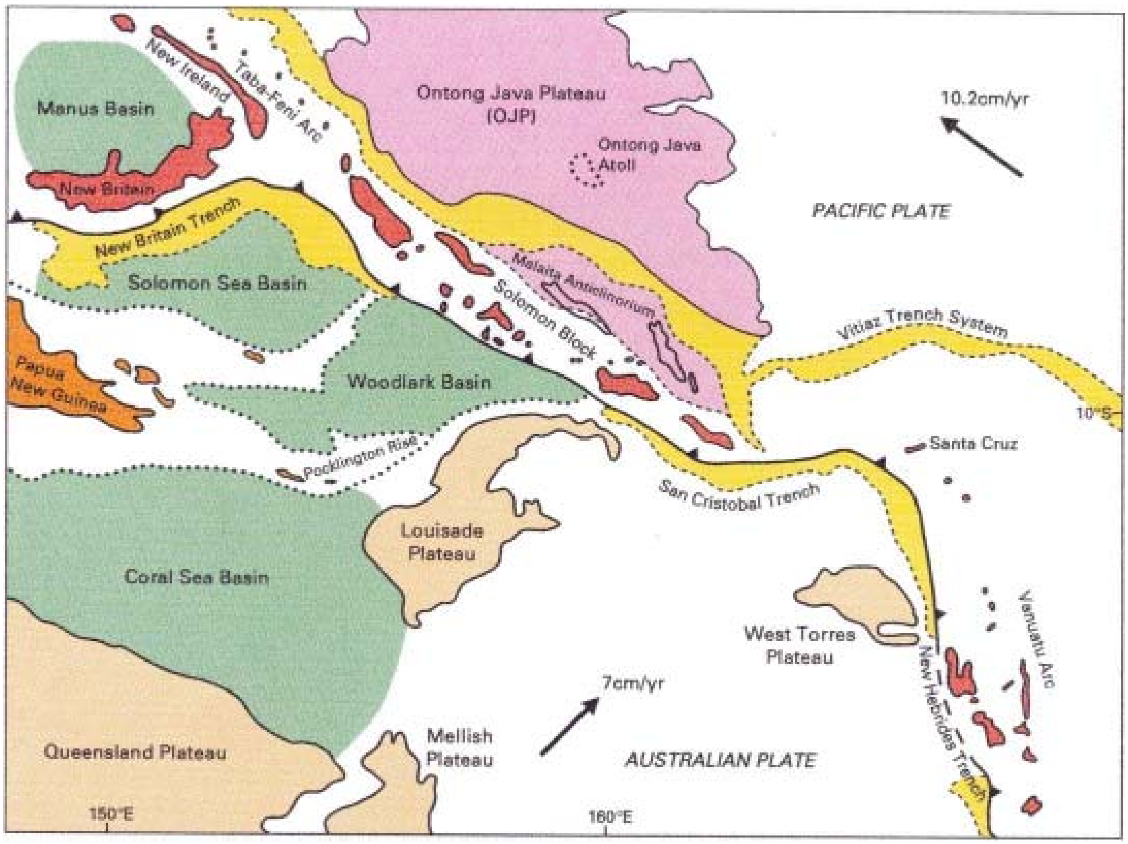

Figure 1. Tectonic Elements of the SW Pacific (reproduced by permission of Elsevier Publications). The Solomon block contains the Solomon Island archipelago, which is bounded to the north by the Vitiaz (north Solomon) trench and to the south by the New Britain - San Cristobal (South Solomon) trenches respectively. The Solomon arc is part of the much larger Greater Melanesian arc which includes the islands of New Britain, Santa Cruz, and Vanuatu. The Ontong Java Plateau (OJP) is in collision with the Solomon block, and the Malaita anticlinorium represents the obducted part of the OJP within the Solomon block. A number of ocean basins (some younger tha 5Ma) and plateaus are situated south of the Solomon block. Solomon Islands is situated at the highly oblique collisional boundary between the Pacific and Australian plates.

lithosphere has led to a range of tectonic phenomena including increased coupling between the Australian and Pacific plates, and the uplift of the Solomon forearc. The northern part of the Australian plate in the vicinity of Solomon Islands comprises a number of ocean basins and plateaus. The collision between the Australian and Pacific plates is a highly oblique one with the Australian plate moving northeastwards at c. 7cm/year and the Pacific plate moving WNW at >10cm/year.

STRATIGRAPHIC FRAMEWORK

A number of sections below describe the lithological characteristics of different units within the Makiran stratigraphy. It is useful to begin by outlining the larger scale geological framework (Table 1). The reader is referred to Figure 3 (geological map of Makira) while reading the following stratigraphic sections.

MAKIRA BASEMENT COMPLEX

Wairahito Volcanic Group

The Wairahito Volcanic Group is by far the most significant geological unit on Makira as it crops out over the bulk of the island (at least 65% of Makira is underlain by the Wairahito Volcanic Group). The WVG comprises a sequence of basalt, dolerite and gabbro sheets and dykes, with local ultramafic sills and intrusions. A cumulate thickness is difficult to estimate as there are few regional stratigraphic units which can be used for correlation purposes; however geological cross sections suggest a minimum thickness of 2 - 4 km.

Typically the Wairahito Volcanic Group (WVG) is characterised by a monotonous sequence of basalt sheets with little interbedded sediment. Observed sheet thicknesses vary between 1 and 25m and are typically of the order of 1 - 5m. Basalt sheets are pillowed, non pillowed, or 'bulbous',

Table 1. Stratigraphic Framework Model of Makira.

COVER SEQUENCE (Formal Name: Makira Cover Sequence)	
Recent & Quaternary Deposits	(Alluvial sands and gravels; raised beach and beach deposits; mangrove deposits; coralline reef deposits)
Makira Arc Group ? Late Miocene – Pliocene)	(Dacite dykes and reworked arc volcaniclastic (post-Oligocene, deposits)
Kahua Breccia Group (post – Oligocene,? Mid Miocene – Early Pliocene)	(Monolithic basalt and bi-lithic basalt/limestone breccias with sandstones and basalt lavas)
Harigha Sandstone Group (Mid Miocene – Early Pliocene)	(weak – moderately cemented calcareous sandstones & siltstones with occasional basalt lavas)
Unconformity	
BASEMENT SEQUENCE (Formal name: Makira Basement Complex)	
STRATIGRAPHIC UNITS	
Wairahito Volcanic Group (Cretaceous – Oligocene)	(pillowed and non pillowed basaltic to gabbroic sheets, and ultramafic rocks)
Waihaoru Sedimentary Group (Cretaceous – Oligocene)	(Limestones, basalt breccias, cherts, sandstones, mainly interbedded within the Wairahito Volcanic Group)

the latter field term designating basalts which display poorly developed pillow structures. Some pillow lavas exhibit black glassy carapaces to pillow structures; individual pillow diameters measure between 10 and 150cm and occasionally display 'mother and baby' pillow structures with larger (>1m diameter) pillows being interconnected with smaller pillows. Most basalt sheets are well jointed with joint systems oriented at least parallel and normal to sheet margins.

Basalt grain size varies between very fine grained and medium – coarse. The most featureless lavas are massive aphanitic and fine grained. Other sheets contain feldspar +/- pyroxene laths up to 1.5 - >3mm long, the latter displaying ophitic doleritic textures. Occasional examples of 'orbicular' basalt were observed with circular – ovate 'orbicles'/spherules of coarse dolerite – gabbro set in a fine grained basalt groundmass. The thickest sheets display the coarsest facies of basalt/dolerite. One locality within the Huni River (northeast Makira) contains an example of rhythmic layering with repeated coarser gabbroic layers up to 1cm thick set within a medium-fine grained groundmass.

Examples of interdigitating and wedging of individual basalt sheets were observed at several localities. Basalt-basalt contacts with little or no inter-sheet sediment are common indicating local rapid effusion of lavas/sills. Other areas contain thin to thick inter - sheet sediments indicating periods of quiescence with respect to basalt effusion. Rubbly bases and tops to basalt sheets are locally present.

The WVG basalts are invariably altered to some degree. At one extreme the basalts are affected by a high density of shear zones with an individual shear zone typically measuring c. 1m. Within shear zones the basalts display a greenschist epidote – chlorite mineralogy, and shear related fabrics. Chlorite +/– quartz +/– haematite +/– calcite veining is not uncommon within any part of the WVG, although the extent and density of veining is highly variable. Vein systems are best developed close to major shear or fault structures. Individual veins range up to 2cm wide.

In thin section the variation in basalt is predominantly related to grain size. The finest grained basalts are micro- to crypto- crystalline

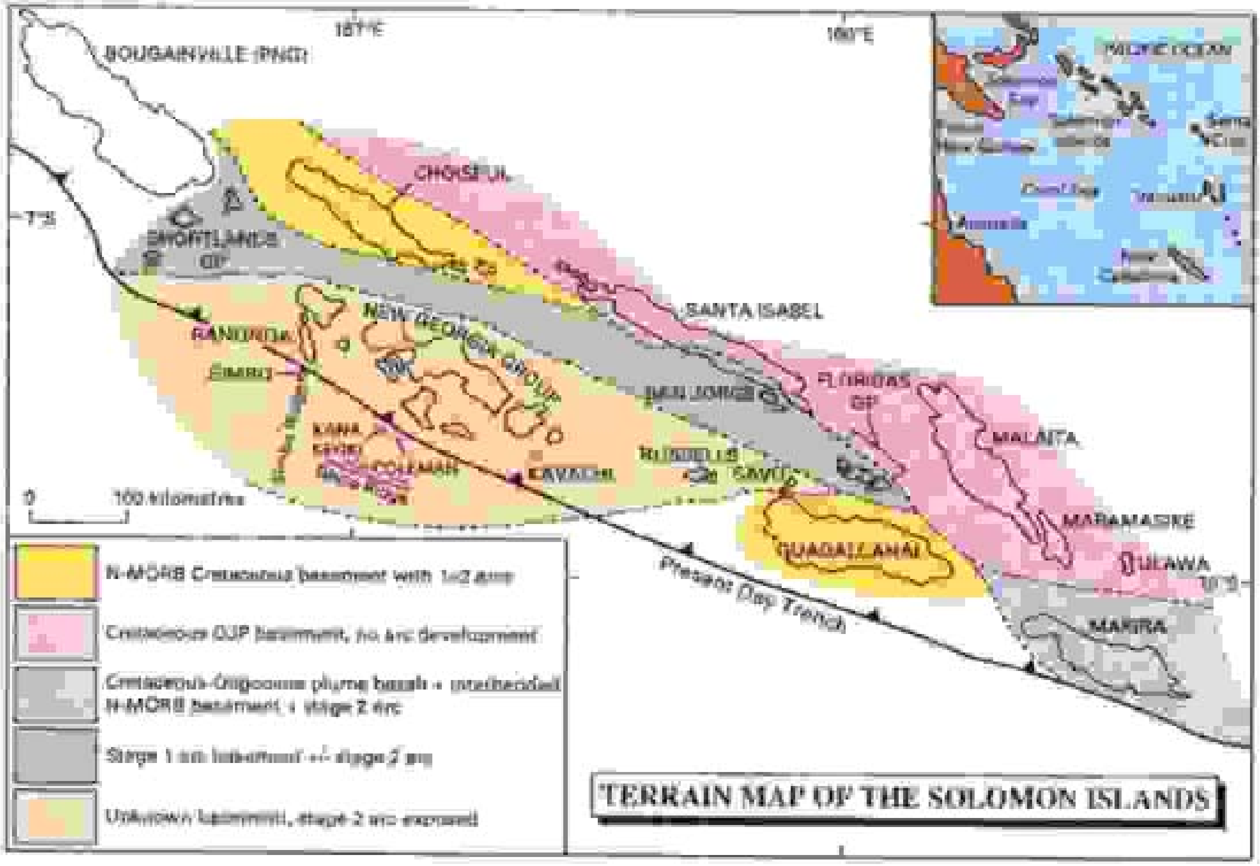

Figure 2. Terrain Map of the Solomon Islands (reproduced by permission of Elsevier Publications). Solomon Islands can be subdivided on the basis of age and geochemistry of the basement geology and the relative development, or lack of development, of two major stages of arc growth: stage 1 (Eocene - Lower Miocene); stage 2 (Upper Miocene to present day) respectively. Makira forms a unique terrain with a varied oceanic basement and some evidence of stage 2 arc growth.

and may contain the occasional micro phenocryst. Medium grained basalts tend to be subhedral- to euhedral- equigranular to inequigranular when glomerocrysts of larger gabbroic grade porphyritic pyroxenes and feldspars, set in a medium grained groundmass. The coarsest dolerites and gabbros tend to be euhedral- to subhedral- granular. All except the finest grade rocks are holocrystalline to slightly hypocrystalline: green to brown partly devitrified glass with occasional perlitic cracks is a common interstitial phase. The mineralogy is remarkably simple with plagioclase and clinopyroxene forming the great bulk of thin sections (usually > 85%) most usually in approximately equal proportions, with accompanying interstitial opaque minerals and brown - green glass. In the medium – coarser grained rocks the larger pyroxene phenocrysts tend to display an ophitic to sub ophitic texture. Occasionally olivine and orthopyroxene is present: in one section the modal abundance of olivine was 5 - 10%. The plagioclase crystals display random to variolitic and sub variolitic textures. In most medium and coarse grained sections the pyroxenes and plagioclase crystals display random, intricate, interlocking textures. Many thin sections display variable alteration, most notably within the mafic minerals which are altered to chlorite and/or actinolite. Chlorite, quartz, and calcite veins are common.

A number of ultramafic units crop out within the Makira Basement Complex, most notably in the hills south of Kahua Point in northeast Makira. Unfortunately no large outcrops of ultramafic material were observed in any river traverses, but examples of ultramafic units have been encountered as smaller scale sheets or sills and as float material. The Kahua Point Ultramafic body appears to be a sizeable body, measuring some 5 x 1.5km, has a distinctive expression on aerial photographs, and supports a depleted bush cover relative to typical Makiran rainforest. Serpentinite is the most common ultramafic rock encountered; most samples examined are serpentinised to some degree and have a greasy feel and smooth lustre. Rarer examples of fresher pyroxenite and peridotite were also encountered.

Only a small number of ultramafic thin sections were studied. Of these some are completely serpentinised. The few slides which contain relict

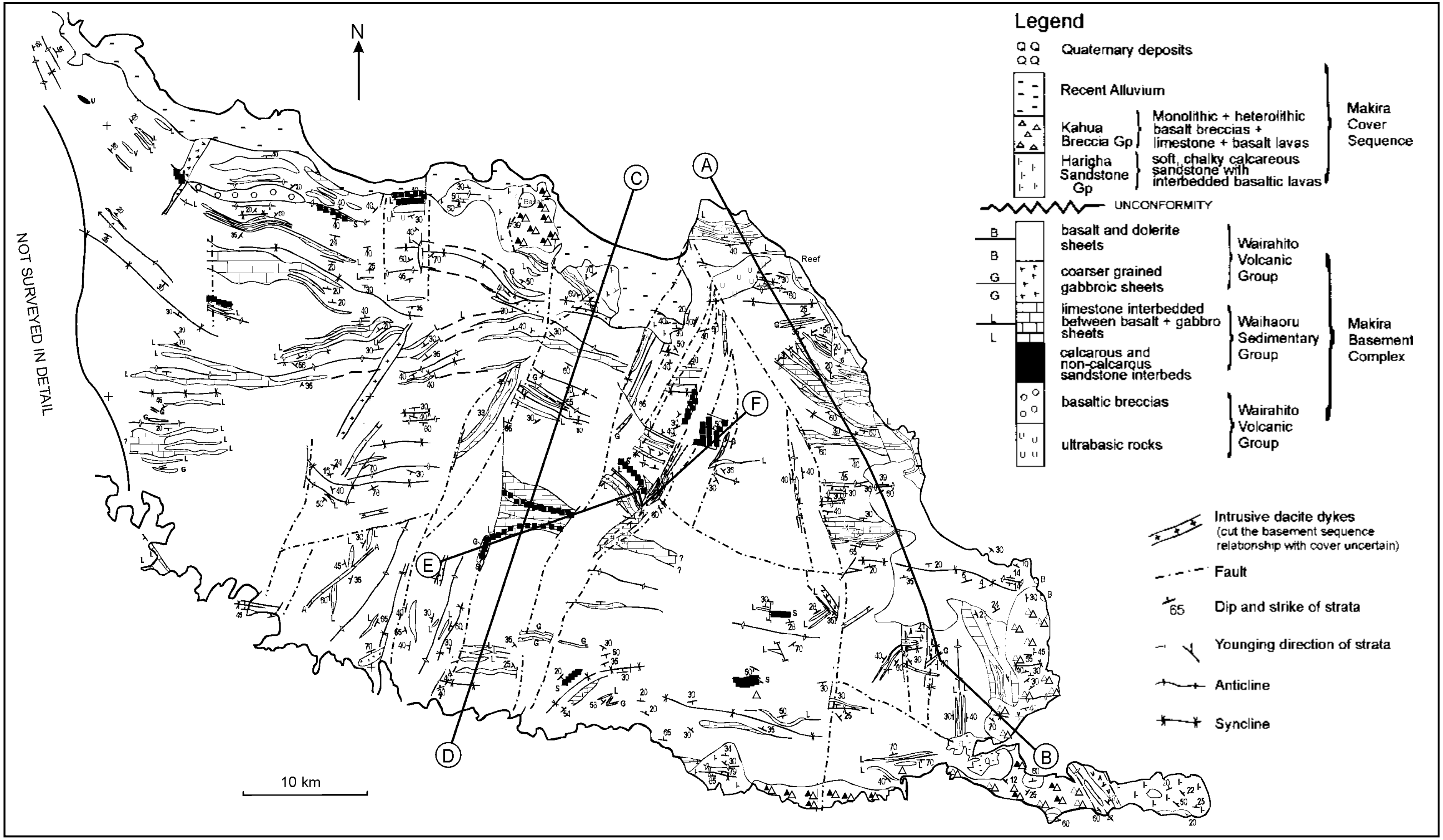

Figure 3. Geological Map of Makira. Over 90% of Makira is underlain by a Cretaceous - Oligocene oceanic basement comprising: 1) interbedded basalt, dolerite, gabbroic, and ultramafic sheets and a minor proportion of discordant intrusions (termed the Wairahito Volcanic Group); and an interleaved sedimentary assemblage of lithologies comprising pelagic limestones and cherts with basalt breccias and sandstones (the Waihaoru Sedimentary Group). The basement is unconformably overlain by the Mid Miocene - early Pliocene Harigha Sandstone, and Kahua Breccia Groups, and Quaternary to Recent alluvial and reef deposits. Intrusive dacite dykes of post - Oligocene (?Upper Miocene - Pliocene age) cut the basement. East - west trending folds and NNE and east -west faults dominate the structure of Makira. Locations of geological cross sections shown in Figure 5 are indicated. See text for details.

minerals and textures display coarse grained granular textures with interlocking euhedral - subhedral olivine, clinopyroxene and orthopyroxene crystals with interstitial opaques.

A number of basalt samples have been dated by Dr R Duncan using the whole rock Ar - Ar radiometric dating method. It is beyond the scope of this paper to discuss these results in detail, particularly as the results are, at present, preliminary results. However the analysed samples have yielded a broad spectrum of ages for basement basalts with three modal ages at circa 90Ma, 60Ma, and 30Ma respectively, indicating a Cretaceous - Oligocene age range for the Wairahito Volcanic Group, (see below for further details).

Waihaoru Sedimentary Group

The Waihaoru Sedimentary Group (WSG) comprises a relatively diverse sequence of sedimentary lithologies within the Makira basement Complex. The WSG most commonly occurs as interbeds within the basalt dominated Wairahito Volcanic Group, but individual units can attain local thicknesses of tens of metres upwards to >100m. There are three main facies of the WSG: cherts; limestones; and breccias. All WSG units have a wedge or lens like gross morphology / geometry, pinching out along strike from a thickness maximum location.

Cherts

Cherts are invariably interbedded within thicker limestones forming limestone – chert sequences, although occasionally limestones or cherts occur in isolation. Cherts usuallly occur as discrete beds or laminae or as nodules and concretions within thicker limestone units. Occasionally chert dominated Individual chert layers vary in thickness from a laminae/mm scale upwards to 40cm. Maximum total thicknesses of chert dominated deposits are in the order of several metres. The cherts are red or white, occasionally dark grey to black in colour, are fine to very fine grained and display a conchoidal fracture.

Only a small number of chert thin sections were examined. These sections are siltstones to mudstones with larger subrounded feldspar and pyroxene crystal – clasts set within a very fine grained dark to medium grey muddy matrix. Vague spherulitic ?radiolaria are locally present.

Limestones

Limestone dominated sediments are the most common lithology within the WSG. The limestones are white, red, pink, or grey, pelagic calcilutites and calcisilties and are interbedded within the basalt dominated WVG. Individual limestone units can attain local thicknesses of 40 – > 100 m but are more usually between 5 and 10m thick.

The limestones are usually hard and porcellainous, are parallel laminated to bedded and are invariably cut by an anastomosing network of calcite veins. The veins can occupy over 15% of the rock by volume with individual veins attaining thicknesses of 1-5 mm. In general the limestones are well jointed, can display karstic weathering features, and although are commonly reasonably pure calcareous lutites they can locally grade into darker coloured, more non-calcareous mudstone-rich sequences, and/ or contain thin laminae of dark mudstone material.

Parallel lamination/bedding predominates but locally sedimentary structures such as flame and load structures, slump folding and contorted and disrupted bedding are present, suggesting that wet sediment loading and deformation occurred locally within rather active tectonic depositional environments (?such as submarine active half grabens).

All colours and facies of limestones contain foraminifera, although modal foraminiferal percentage values vary between trace amounts and 40% with 15-30% being more typical. The foraminifera are set within a groundmass of very fine grained, generally light coloured, lime mud. The grey limestones are laminated, even on a microscopic scale, with the laminae being defined by alternating colours (e.g. dark grey and light grey) of mudstone.

In thin section the limestones display a variable purity in terms of their calcareous mud content, grading between a pure white – pale grey calcareous-rich facies, and a dark grey, non - calacreous, mudstone-rich facies. The matrix of the limestones is very fine grained and difficult to resolve, even under the microscope. Most sections contains reasonably preserved foraminiferal tests which have a modal abundance of circa 10-50%.

Breccias

Breccia units are of two main types: monolithic basalt breccias and bi - lithic basalt - limestone breccias. More rarely some lithologies include almost monolithic limestone breccias. Breccia units tend to have local rather than regional significance: they are particularly important in the Waihaoru area of NW Makira wher they form composite units with a total thickness of > 200m. More typically the breccias attain thicknesses of several metres to tens of metres.

The most common lithology is a poorly sorted monolithic basalt breccia with a high concentration of densely packed (occasionally clast supported), subangular to subrounded basaltic (+/- doleritic and gabbroic) clasts, with the larger clast sizes ranging between <1cm to > 2m (on average between 1 and 15cm), set within a dark mud to sand to gravel grade basaltic matrix. The breccias are usually interbedded with crystalline, non - brecciated basaltic lavas and sills, and occasionally grade into coarse sandstones. Bedding structures, where present, are usually weakly developed.

Bimodal basalt - limestone breccias display the same gross lithological characteristics as described for the basalt breccias. Basalt clasts are usually much more common than limestone clasts with 90% basalt to 10% limestone clast ratios predominating. More rarely limestone clasts may attain 50% of the total large clast population.

The breccias appear to be sedimentary in origin and suggest that submarine basalts and limestones were being eroded and redeposited together with available basaltic and calcareous detrital material within proximal environments. This suggests that submarine erosion and depositional processes were active, possibly adjacent to active ocean floor faults.

MAKIRA COVER SEQUENCE

Harigha Sandstone Group

The Harigha Sandstone Group (HSG) unconformably overlies the Makira Basement Complex, cropping out in north - central, southern, and east - southeast Makira. The thickness of the HSG is unknown but is at least > 100m thick.

The Harigha Sandstone Group is a sandstone dominated clastic unit which also contains finer grained siltsones and mudstones and coarse, poorly sorted conglomerates. The most common lithofacies is a grey to pinkish white to dark grey, weakly to moderately cemented, porous, and usually calcareous sandstone. The sandstone units within the HSG are variably sorted: some are well sorted whilst others are poorly sorted pebbly sandstones. The sandstones are most commonly massive to bedded (thinly-, well-bedded facies are not uncommon) and heterolithic (with basalt, limestone and sandsone lithic clasts) clast supported, with a calcareous matrix. Clast shape varies between sub rounded and well rounded. Fine grained calcisiltite to lutite chalk- like facies are also occasionally present within the HSG.

The coarser conglomerate facies can contain individual clasts which have long axes ranging up to 30cm, with a more usual 5 - 10cm maximum long axis size, and typical long axis dimensions of 5mm - 1cm. The conglomerates are heterolithic and contain basalt, limestone and sandstone clasts. The conglomerates are matrix supported with the subrounded larger clasts embedded within a siltstone - sandstone matrix. Bedding structures tend to be poorly developed although the conglomerates occasionally grade into coarse sandstone units, and one exposure exhibited coarse - tail normally graded bedding with the maximum clast size grading from 7cm at the base to 2cm at the top of a graded unit.

Sedimentary structures are common and include: parallel bedding; clast imbrication; flame and load structures; rip up clasts of mudstone within a laminated sand/siltstone; erosional surfaces/ bases to channels; and slump folding. These structures would indicate a certain amount of soft sediment deformation, gravity sliding, and loading, as well as the presence of current activity and channeling. Johanna Resig (pers. comm.) has analysed a number of HSG samples for their fossil content. Preliminary conclusions of Dr Resig include: 1) the HSG contains both pelagic and benthic foraminifera which yield Late Miocene to Early Pliocene (11 - 3Ma) ages; and 2) interpreted water depths of between 100 -300 and 1000 - 3000m for various foraminiferal genera and species. The presence of both pelagic, deep sea, and benthic, shallow marine foraminiferal fauna within the HSG can be explained by: 1) the existence of an HSG basin and shelf with pene-contemporaneous lateral facies variations; or, 2) rapid variations in depth with time indicating temporal subsidence and uplift.

Basalt lavas and breccias are interbedded with the sandstones.

Kahua Breccia Group

The Kahua Breccia Group (KBG) crops out in the central - north, east, and southeast of Makira and unconformably overlies the Makira Basement Complex. The relationship of the KBG with the Harigha Sandstone Group remains unproven and the two units could be penecontemporaneous. The thickness of the Kahua Breccia Group is unknown but is at least 150 - 200m.

The KBG is predominantly a sequence of heterolithic breccias and coarse lithic sandstones with occasional siltstones. Dominant clast lithologies include basalt and limestone with a basalt : limestone ratio of >1, and ranging up to 4. The breccias tend to be moderately bedded, with local graded bedding being occasionally present. Sorting is usually poor and the larger clasts are angular to sub angular in shape. The matrix material comprises mainly of sand and silt grade baslt and calcareous clasts. The KBG is generally weakly to moderately cemented.

Basalt lavas and breccias are present within the KBG.

Makira Arc Group

The Makira Arc Group (MAG) comprises a suite of andesitic to rhyodacitic rocks which occur either as dykes or larger scale plutons or reworked volcaniclastic material.

The most widely encountered lithology is andesitic to rhyodacitic dyke material. These acid dykes crop out in central, central-southern, and southeastern Makira. The most common lithology is a leucocratic, grey - white, hornblende +/- pyroxene- phyric dacite to rhyodacite. The hornblende phenocrysts are typically black and acicular to prismatic in shape, which range between 2 mm to 4 cm in length (usually 4-8 mm). Occasionally the crystals are aligned suggesting a degree of flow banding. The groundmass comprises a very fine grained, leucocratic, felsic, crypto-crystalline material. Some samples contain autoliths of mafic to ultramafic material, not unlike dacites described from Savo, (Petterson, 1995, in press, b). Mafic minerals comprise between 10% and 25% of the dacites and rhyodacites by volume.

Other crystalline lithologies described from various localities include: a hornblende-phyric, mesocratic micro-diorite; a diorite porphyry; and a medium grained diorite to granodiorite. The more basic lithotypes contain up to 30-40% mafic minerals by volume.

One of the frustrating things about piecing together the evidence for the full range of lithologies within the MAG is that the requisite lithologies have only occasionally been encountered at outcrop, and samples typically occur within the float material. It appears that the great bulk of the Makiran arc has been eroded and redeposited either within the present day South Solomon trench or within submarine basins to the north of Makira.

A small number of thin sections of the MAG were examined. Dykes from the Hao River are very fine grained. The groundmass occupies around 85-90% of the sections and comprises a leucocratic, felsic, microcrystalline to crypto-crystalline mass which is difficult to resolve. The remaining 10-15% of the sections comprise flow oriented laths of hornblende and pyroxene, the former occurring as acicular, lozenge, and rhombohedral shaped crystals. The Hao dyke rocks are probably dacitic to rhyodacitic in composition. One coarser grained rock from the Maghoha float is a medium grained hornblende -phyric acid andesite with relatively large patches of chlorite/actinolite possibly after pyroxene.

Jeffrey (1974) described a sequence of volcaniclastic sediments which crop out within a north-south trending graben situated in the Arosi peninsular of western Makira. This unit is termed the Waihada Volcanics which are a sequence of water laid tuffs, agglomerates, and assorted volcaniclastics, and have been assigned a Miocene age. The Waihada Volcanics include a varied sequence of lithologies such as: tuffs and volcanic breccias; hyaloclastite; pyroclastic deposits; tachylite; agglomerates; and cross laminated, reworked volcaniclastic sediments. Basalt dykes cut more acidic agglomeratic facies.

At the time of writing there are no available ages for any Makira Arc Group rocks. However the high silica, highly evolved nature of the rocks would suggest affinities with the second major stage of arc volcanism present within Solomon Islands which began during the Upper Miocene and continues to the present day (Petterson et al, in press, a). At the very least we can deduce that the MAG is post-Oligocene in age.

Recent – Quaternary Deposits

There are a number of areas where Quaternary – Recent deposits blanket the solid geology of Makira. Most notably these areas include a northern, coast-parallel strip of land some 1-4 km wide dominated by alluvial and beach sand, silt, and gravel deposits and a thin (< 1 km) eastern and southeastern coast-parallel strip of land dominated by coralline reef deposits. The southern coast is an upraised, erosional coastline. Some low lying areas of the interior contain moderately thick mangrove deposits.

STRUCTURE OF MAKIRA

Makira has not proven to be an easy island to map or understand from a geological viewpoint. This is because of two main factors:

- There is a lack of island-wide distinct stratigraphic marker units. This makes correlation, even on a local scale, very difficult.
- Makira is structurally complex. Makira is presently being stretched by left lateral simple shear (see sections below) which has produced a number of large scale extensional faults with resulting fault rotation, particularly in central Makira. This brittle fault tectonics has produced a rather piecemeal geological and structural scenario (Figures 3 and 4): there is a degree of geological and structural continuity within one fault block, but sudden changes occur across major fault structures.

Folding

Figure 4 illustrates the major fault axial trends and the local strike of distinctive stratigraphic units. The general regional fold axial and strike trend is east-west to ESE-WSW, and we take this trend as the local *orthogonal* trend to the maximum regional compressive stress direction. Figure 4 also illustrates that this regional picture is complicated by two main modifying tectonic controls: 1) Extensional brittle fault movements have involved significant to substantial rotational movements which have modified the regional strike. In some cases (for example in central-eastern and central-southern Makira; Figure 4) local fault rotations have changed the local strike from east-west to north-south; 2) sinistral (and local dextral) simple shear has produced a number of 'S' shaped fold axial trend morphologies indicating that the predominant north-south compression which resulted in the east-west regional strike had a left-lateral dominated shear component. In other words the predominant fold forming tectonic events were transpressional rather than pure orthogonal pure shear compression.

Faulting

Figures 3 and 4 highlight two main fault trends: NNE-SSW to north-south and east-west to WNW-ESE. Other minor fault trends include: NE-SW and NNW-SSE. The 'master' fault set appears to be the NNE - SSW trending structures which are large cross-island structures having strike-parallel dimensions of at least 30 km. As mentioned above these faults have a strong control on local outcrop patterns and structure and have a significant rotational component to their extensional movements. The east-west to ESE-WSW fault set are antithetic faults to the dominant NNE-SSW synthetic faults. The E-W antithetic faults also have a very significant rotational component to their movement tectonics and exert a strong control on local outcrop patterns and structure. The antithetic faults are much smaller structures with respect to the synthetic faults, extending over distances of 6-15 km.

The NNE-SSW and the east-west faults together produce a series of fault blocks. We have identified approximately 15 major fault blocks. The largest and least fragmented parts of Makira are in the west, whereas the smallest and most fragmented parts of Makira are in central-east Makira.

The density of faults and shears can be high on a local, outcrop scale. Most mapping traverses encountered locally deformed, sheared and highly faulted rocks. This relatively high density of faulting and shearing at a local scale probably reflects a combination of older, hydrothermal shear systems within the Cretaceous-Oligocene oceanic basement, and more recent brittle tectonics.

GEOLOGICAL CROSS SECTIONS

Figure 5 illustrates the general fold structure of Makira. Sections A-B and C-D respectively are simple north-south cross sections across the eastern and central parts of Makira. Section E-F is a NE-SW section which crosses a number of fault blocks in central Makira. All three sections bring out a number of features about the stratigraphy and structure: 1) the great bulk of the stratigraphy comprises basement basalts from the Makira Basement Complex; 2) ultramafic masses and younger andesitic dykes are intrusive bodies; 3) Limestone and coarse gabbro/dolerite sheets may attain significant local thicknesses but are not laterally continuous: they pinch out in all directions. The Makira

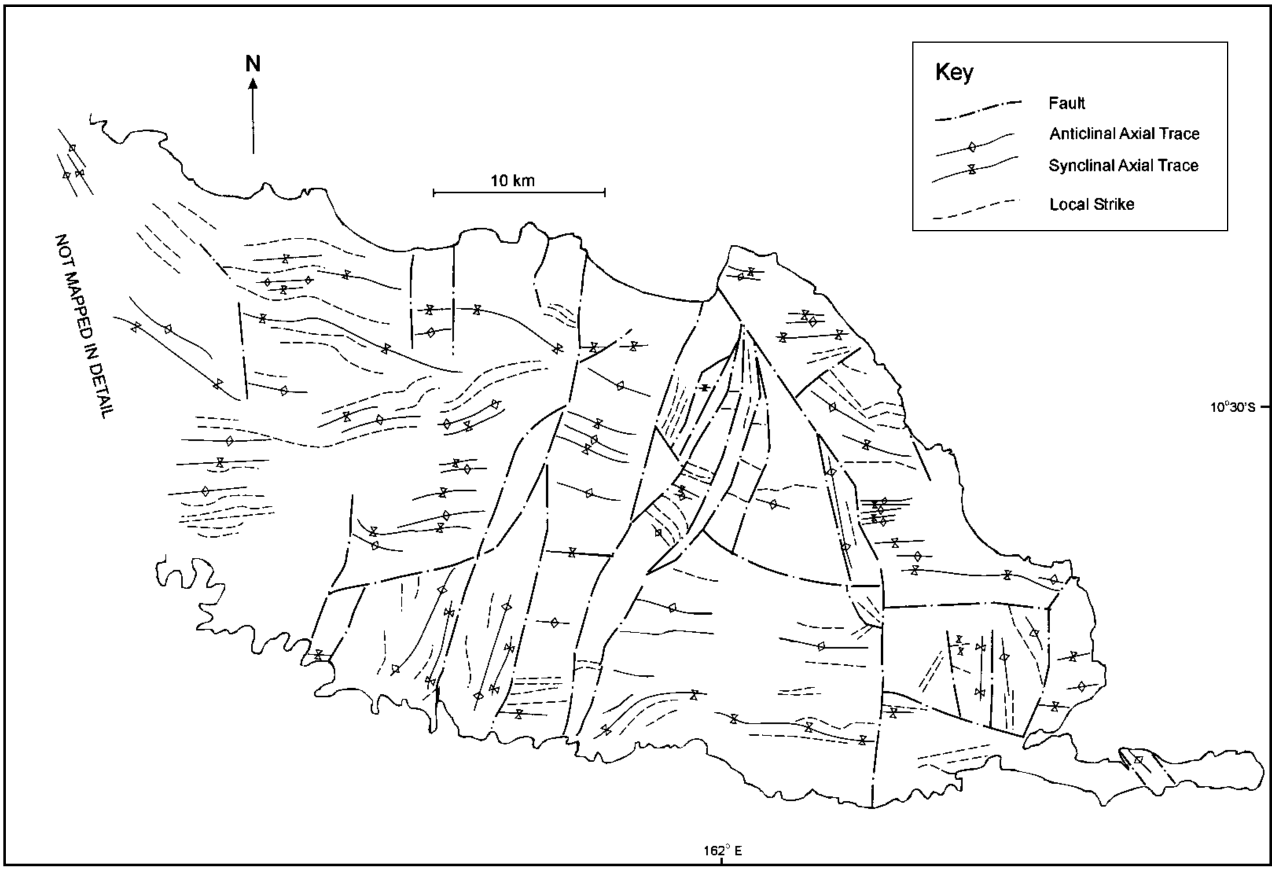

Figure 4. Structural Map of Makira. Predominant east-west trending fold axes are locally discordant due to: 1) fault rotations which can produce local north-south trending fold axial planes; and 2) sinistral dominated shear causing sigmoidal axial fold trends. The interplay of north-south compression and left lateral shear has strongly affected the structural development of Makira.

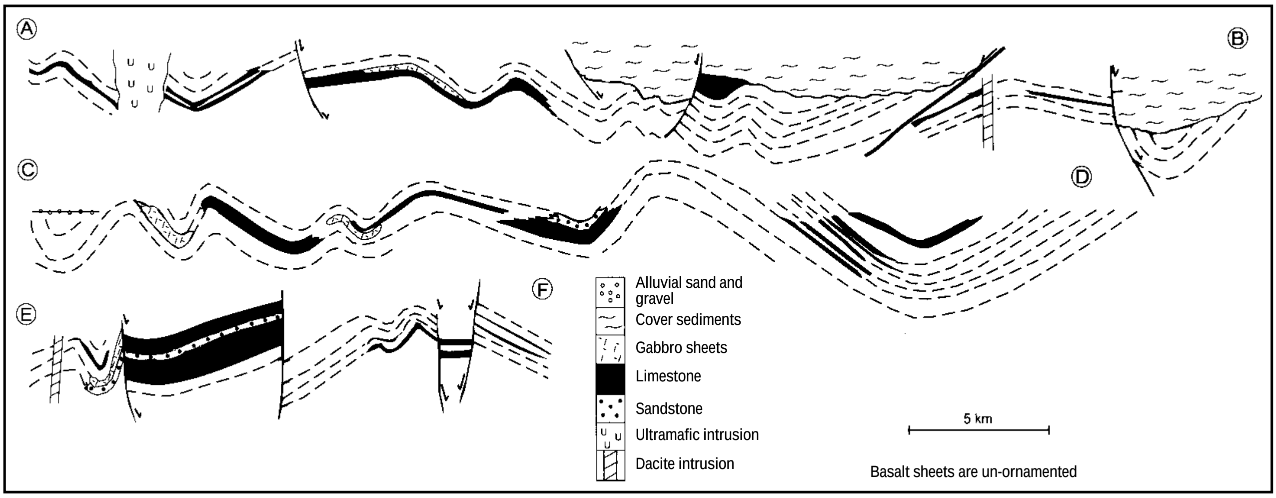

Figure 5. Geological Cross sections across Makira. Section C – D is the simplest section, which crosses central Makira and illustrates upright to slightly asymmetrical fold structures. Note the impersistence of limestone units which pinch out in both directions. Section A – B is drawn through eastern Makira and illustrates the Mid-Miocene to Early Pliocene basin fill cover sequences which unconformably overlie the basement. Note the listric bounding growth faults and the folding of the plane of unconformity. Section E – F is an oblique dip section which illustrates sudden changes in dip across key fault blocks.

Cover Sequence is unconformable on the Makira Basement Complex and its outcrop is controlled by listric, extensional growth faults. The unconfomity is not a simple one, as the plane of unconformity is itself folded and there is lateral continuity of some of the youngest fold structures between cover and basement. This suggests there has been at least two phases of folding separated by a period of extension, basin formation, and deposition.

Section C – D is the simplest section as it is drawn through one contiguous fault block. The folds have upright axial planes and are gentle to open folds, with a wavelength of 5-10 km. Most are symmetrical with a tendency to slight asymmetry indicating a possible northward fold vergence. The degree of shortening is relatively small: of the order of 10-18%.

Section A – B is a north-south section through easternmost Makira and crosses a number of fault blocks. The folds are symmetrical, and gentle to open with upright axial planes, with a wavelength of c. 5-8km. The amount of shortening within the basement is of the order of <10%. The cover sediments rest unconformably on the basement and are bounded by extensional listric faults which are modelled as variable in their angle of dip.

Section E – F subtends an angle of circa 45° to the regional strike and is used to illustrate the abrupt changes in dip across major faults and the rotational component of the brittle fault tectonics.

Basement - Cover Relationships

The geological map of Makira (Figure 3) demonstrates that the edge of the Makira Cover Sequence is locally highly oblique to the strike of the Makira Basement Complex, indicating an unconformable relationship. However, the unconformity is not a simple one. The continuity of the youngest fold axes between cover and basement, across the plane of unconformity indicates that both cover and basement have been folded by the most recent compressional events. Sensible geological cross sections through both basement and cover units can only be drawn if their mutual geometrical relationships are modelled using basin margin listric growth faults. The youngest sediments locally overlap the basin margin faults producing the unconformable outcrop pattern present in Figure 3. We model the cover sediments as localised basin fills. The basins formed during Mid Miocene – Early Pliocene times after a post-Oligocene period of uplift and compression . The uplift/compressional event produced an uplifted rigid block which gravitationally collapsed/extended in the southeast, and eroded to produce a considerable volume of basalt and limestone clastic material. This clastic material was quickly redeposited within proximal-medial shallow marine basins (100-300 m deep) which deepened off shore into very deep water (> 1000 m). Subsequent uplift during Upper Pliocene – Recent times has raised these shallow and deep water basins and their respective deposits to a subaerial setting..

Structure and Age Variation Across Makira

In terms of topography, Makira is characterised by a southern, coast -parallel backbone of ridges exceeding 1000 m above sea level which act as the major watershed. This major watershed is only 5-10 km north of the southern coastline and has influenced the development of relatively long, northward flowing rivers and short southward flowing rivers with steep long profiles. This is a similar situation to that of Guadalcanal and is due to the fact that both islands are within a frontal arc tectonic setting and have experienced signifcant uplift in Recent times, with the greatest uplift affecting areas closest to the South Solomon trench.

The uplift of the southern part of Makira could, in theory, bring older rocks to the surface: this is certainly the case in Guadalcanal where the oldest basement is exposed within the most uplifted southern regions (Hackman, 1980). It is unfortunate that the lack of stratigraphic control on Makira makes it difficult to make definitive statements concerning the age structure of Makira without the additional assistance of both isotopically and palaeontologically determined age data. It is for this reason that a number of samples have been sent to Drs Robert Duncan and Johanna Resig for isotopic/palaeontological age determination work respectively.

Figure 6 summarises recently determined Ar-Ar whole rock ages (R A Duncan, unpublished data). These data are provisional and should be treated with some caution. However, the limited data set do appear to suggest a geographical provincialism to the age of the Makira Basement Complex and a general younging to the north. The oldest ages of c. 98-92 Ma were determined from samples taken from southeastern Makira (the Matangarighi area); samples from central Makira (Wairahito) have yielded Ar-Ar ages of between 67 and 52 Ma, and the youngest basement ages of c. 34-35 Ma have been determined from samples from northern Makira.

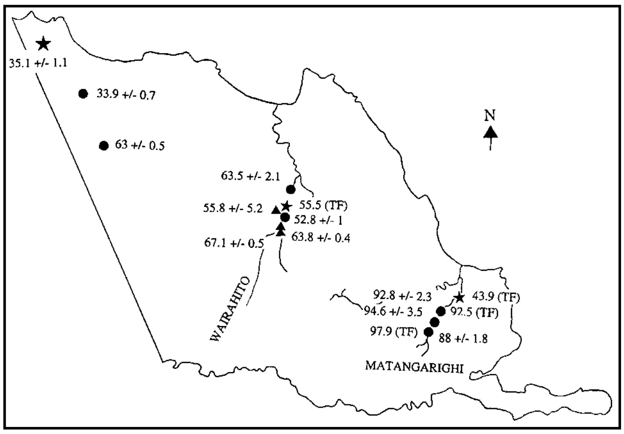

Figure 6. Map illustrating the currently available whole rock Ar-Ar radiometric data (R A Duncan, unpublished data). There is a clear age provincialism and younging-northwards trend. This figure also illustrates the stratigraphic interbedding of plateau lavas (circles); MORB lavas (stars) and alkaline basalts (triangles). Basalt classification is based on Zr/Nb ratios, see text for details.

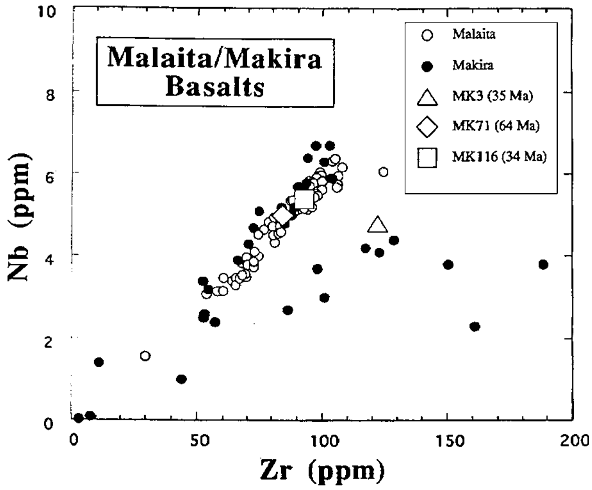

Figure 7. Nb-Zr scatter plot of Makiran basalts. Most Makiran basalts plot within the Ontong Java (OJP) field, here defined by basalts from Malaita. About a third of Makiran samples have higher Zr/Nb ratios more typical of N-MORB basalts.

This age pattern could be explained by: 1) a simple uplift model with the most uplifted southern regions exposing the oldest geology; or 2) a gradual northwards accretion of oceanic basement material with time, with major accretion events occurring periodically every 30 Ma or so.

Dr Johanna Resig has recently determined Mid Miocene - Early Pliocene (c. 11-3 Ma) ages from foraminiferal dominated faunal assemblages present within the Harigha Sandstone Group, which is a constituent unit of the Makira Cover Sequence (Table 1).

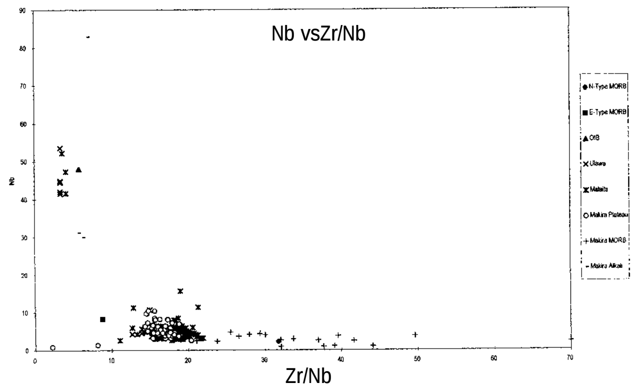

Figure 8. Nb-Zr/Nb scatter plot. Malaita (OJP) basalts and the bulk of Makiran basalts define a tightly constrained compositional field with Nb concentrations < 13 ppm and Zr/Nb ratios between c. 10 and 23. Makira MORB samples have Zr/Nb ratios >24, up to 50. Makiran (and Ulawa and Malaitan) alkali basalts have low Zr/Nb ratios (<8) and relatively high (30-85) Nb concentrations.

Basalt Geochemistry

Recently determined geochemical data on Makiran basalts is presented in Figures 6 – 9 inclusive. Figure 7 is a Nb-Zr plot, and Figure 8 a Nb-Zr/Nb plot of basalt samples from Malaita and Makira. Both illustrate the point that approximately two thirds of analysed samples from Makira plot within the Ontong Java Plateau (OJP) field, here represented by Malaitan basalts (which have identical compositions to the OJP, Petterson, 1995, Neal et al, 1997, Petterson et al, 1997) whilst approximately one third of Makiran samples have higher Zr/Nb ratios (>25), more typical of N-MORB basalts. A small number of Makiran samples have high Nb concentrations and low Zr/Nb ratios (< 10) which reflect a more alkaline (e.g. Ocean Island) basalt composition: some samples from Malaita and Ulawa have an even more alkaline composition than those from Makira.

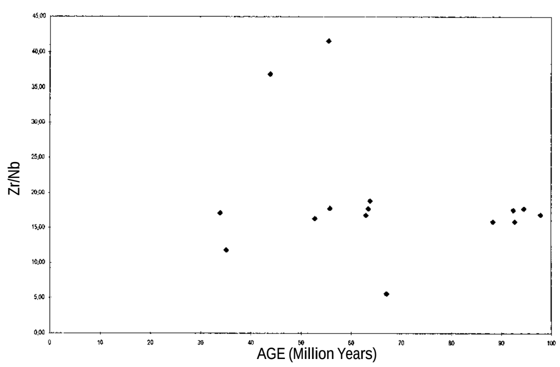

Figure 9. Scatter plot of Zr/Nb ratio with determined whole rock Ar-Ar age. Although the database is limited it shows that alkali, plateau, and MORB basalt magmas were available between c. 67 Ma and 48 Ma. The current database also suggests episodic accretion events at c. 88-98 Ma; 67-48 Ma; and 34/35 Ma respectively.

Figure 9 illustrates the point that the available (limited) combined geochronological and geochemical data show that basalts with Zr/Nb ratios of circa 5 (alkaline basalt); 15-20 (plateau basalt); and > 35 (MORB) were all simultaneously erupting between c. 70 and 45 Ma. Only plateau basalts have been dated at c. 90 and 34 Ma respectively. Figure 6 shows that within the Wairahiti area of Makira plateau, alkaline, and MORB basalts are all mutually interbedded, and all of an approximately penecontemporaneous age: this interbedded relationship is confirmed from undated samples taken from the Waihaoru river of northwest-central Makira (one dated sample here of 35.1 +/– 1.1 Ma, Figure 6).

The implications of the combined geochronological, geochemical, and mapping datasets are profound for the structure and stratigraphy of Makira. The data suggests that Makira was a depocentre for the eruption of basalts from distinct source regions. It is beyond the scope of this paper to hypothesise on the petrogenetic origins of the three basalt types suffice to say that the plateau and alkaline basalts are plume related and *may* be genetically linked to the OJP basalts (particularly the older c. 90 Ma basalts); whilst the MORB basalts were more likely erupted within an ocean ridge tectonic setting. Whatever the ultimate origin of the basalts, it is evident that Makira has accreted episodically through time, amalgamating basaltic units from a range of oceanic tectonic environments.

GEO-TECTONIC SYNTHESIS

Table 2 summarises the geological and tectonic evolution of Makira.

The Makira basement accreted somewhat episodically at c. 30 My intervals from around 100 Ma to 30 Ma. The relative volumes of these accretion events are difficult to assess at the present time. It appears that at least the c. 60 and c. 34/5 Ma events amalgamated basalts from plateau, ridge, and ocean island environments. The oldest event may only have amalgamated plateau basalts, although the database is limited. Most of the Makira basement records rapid effusion and accretion of basalt sheets, regardless of composition. However the basement also records localised periods of quiescence during which pelagic sediments were allowed to accumulate.

The basement was uplifted and folded between the Oligocene and the Mid Miocene. The tectonic cause of the uplift/compressional event is

Table 2. Geo-Tectonic Evolution of Makira.

AGE	GEO-TECTONIC EVENT
Cretaceous – Oligocene (c. 100 – 30Ma)	Accretion of basalt dominated oceanic sequences from plateau, ocean ridge, and ocean island environments. Main accretion events at c. 90-100 Ma, 55-67 Ma, and 34-35 Ma. Deep sea pelagic sedimentation throughout.
Post-Oligocene, pre-Mid – Miocene (c. 30 – 12Ma)	Compression and uplift. Formation of earliest east-west trending folds and uplifted island block.
Post-Oligocene (?Miocene – Recent? <8Ma)	Intrusion and extrusion of Arc material into and onto a basalt dominated basement.
Mid Miocene – Early Pliocene (11 – 3Ma)	Collapse /extension of uplifted island block in the SE. Erosion of uplifted basalt-limestone basement. Formation of localised shallow submarine basins. Deposition of locally derived basaltic and limestone clastic material within shallow marine basins. Deep sea pelagic sedimentation persisting in deeper sea offshore basins.
Late Pliocene – Present (3 – 0 Ma)	Transpressional tectonics within a forearc setting. Wedging of Makira between a northeast-ward moving Australian plate, a northwest-ward moving Pacific plate, and other transpressional vectors caused by impingement of Woodlark Basin, OJP, and Louisade Plateaus. Transpression causes east-west dominated folding, and left lateral, shear-induced normal faulting/fold axis kinking. Faulting most prevalent in central-east Makira. Makira is seismically very active at the present time, particularly in the west and south. Deposition of alluvial sediments and reef deposits.

unknown but it is tempting to link this with the initial docking of the OJP with the stage 1 Solomon arc (Neal et al, 1997, Petterson et al, 1997). The Oligocene – pre-Mid Miocene compressional event resulted in an uplifted island which subsequently extended during Mid Miocene – early Pliocene times to produce localised extensional basins. Basalt-limestone clastic sediments derived from the erosion of the uplifted island were transported by local fluvial systems into proximal-medial shallow marine basins with water depths of 100-300 m, and which deepened offshore into deep water pelagic sediment dominated basins with water depths of 1000-3000 m.

An arc developed on Makira. How extensive this arc was and what structures it formed is unknown. However the roots and reworked, redeposited sediments of the arc are locally preserved. The timing of the arc is problematical, but we suggest that it probably occurred during stage 2 arc , post-8 Ma times (Petterson et al, in press, a).

Since Late Pliocene times (c. 3 Ma) Makira has experienced a prolonged period of transpression and uplift. Figure 10 summarises some key plate movement and compressional vectors which have affected Makira during this period. The Australian plate is currently moving northeastwards and the Pacific plate is currently moving northwestwards giving a highly oblique plate collision. We know from structural studies on Malaita (Petterson et al, 1997) that the Malaita region experienced strong northeast-southwest compression between 4 and 2 Ma. Figure 1 shows the proximity of the Woodlark basin and OJP and Louisade plateaus with respect to the Solomon block. The interaction between the Woodlark basin/Louisade Plateau the Solomon block may have produced compressional to transpressional shear stress within the Makira region of the Pacific plate. Maps of recent seismic activity (e.g. Petterson, 1995) show Makira to be the most seismic large island within the Solomon archipelago, with the highest density of seismic events occurring in northwestern and southern Makira. Figure 10 models the large scale brittle fault pattern on Makira as resulting from a combination of north-south compression and WNW directed left lateral shear, resulting in a Riedel-shear type situation, forming NNE trending, predominant synthetic faults and ENE trending subsidiary antithetic faults.

This strong transpression has resulted in the piecemeal structural dissection of Makira, particularly in central-east Makira. Present day seismic activity may suggest that the maxima of

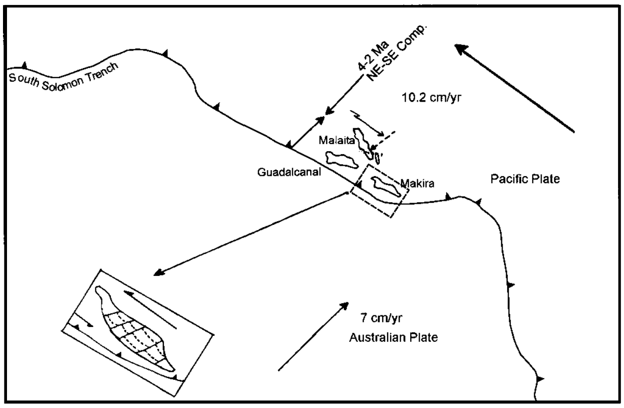

Figure 10. Makira is strongly affected by the highly discordant collision of the Australian and Pacific plates (solid vectors). Between c. 4 and 2 Ma the Malaitan area was affected by strong NE-SW directed compression caused by the collision and obduction of the Ontong Java Plateau. See text for discussion.

the present day transpression is located in western Makira.

Prolonged uplift of Makira since post-Oligocene times has resulted in relatively deep erosion of the island and the loss of the bulk of the pelagic cover and arc sequences. The dominant north - flowing rivers have formed an alluvial plain in the north of the island (similar to the Guadalcanal plains, Hackman, 1980). Reef deposits are present in eastern Makira.

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