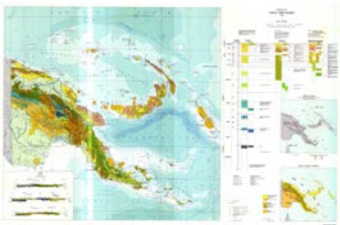
Mineral Resources Authority

Geological framework and mineralization of Papua New Guinea – an update



Port Moresby 2012

Geological framework and mineralization of Papua New Guinea — an update

by

S Sheppard and L Cranfield

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Contents

Figures

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Abstract

The Geology and Mineral Potential of Papua New Guinea (PNG) was outlined in a volume published in 2005 (Williamson and Hancock, 2005). This technical note revises and updates chapters 4–6 from that volume, and also adds new information from references published since. The detailed knowledge of the evolution of PNG is very speculative as recent in-depth studies over large parts of the country using modern research methods are absent. Much of the Tertiary and recent history of PNG is linked to multiple terrane collisions as the Australian Plate moved northwards. These terranes may be autochthonous or allochthonous; in many instances this is not obvious. What is clear is that PNG is a very prospective region to explore for a number of mineralization styles, including epithermal and porphyry-related high- and low-sulfidation systems, skarns, volcanic massive sulfides, exhalative manganese deposits, lateritic nickel–chromite–cobalt and sea floor massive sulfides.

KEYWORDS: arc magmatism, accretion, ophiolite, tectonostratigraphic terranes, epithermal mineralization, porphyry-style mineralization, Permian, Mesozoic, Cenozoic, Papua New Guinea, Australian Plate, Pacific Plate, Woodlark Plate, South Bismarck Plate, Woodlark Basin, New Britain Trench, Manus–Kilinailau Trench, New Guinea Orogen, Melanesian Arc, Papuan Fold Belt, New Guinea Thrust Belt, Bewani–Torricelli Terrane, Finisterre Terrane, Aure Fold Belt, East Papuan Composite Terrane, Owen Stanley Metamorphics, Fly Platform, Maramuni Arc, Wau Basin, Papuan Ultramafic Belt.

Introduction

Papua New Guinea's rugged mountains, complex geology and its substantial mineral resources all result from its location along the collision zone between continental crust of the Australian Plate to the south and oceanic crust of the Pacific Plate to the north (Fig. 1). Presently, oblique convergence of up to 11 cm/year between northward motion of the Australian Plate and west-

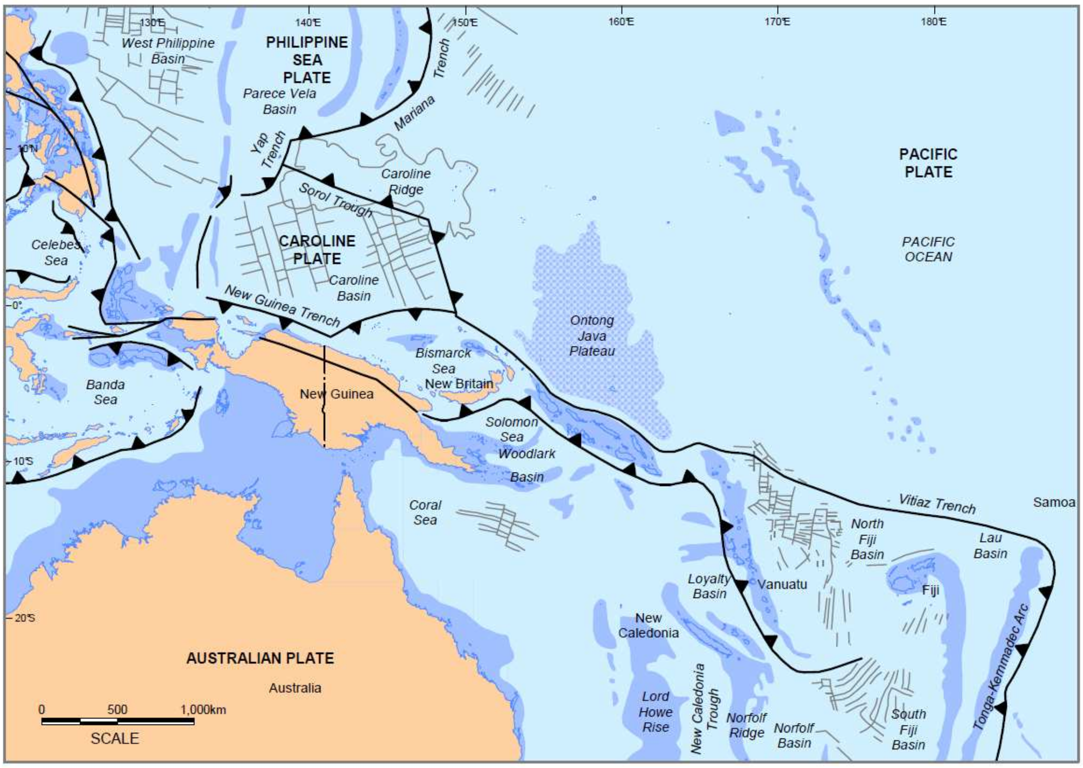


Figure 1. Main geographical features of the southwest Pacific region discussed in the text. The light shaded areas are regions of submerged continental crust drawn at the 200 m bathymetric contour (modified from Hall, 2002).

north-westward motion of the Pacific Plate (Tregoning et al., 1998; Wallace et al., 2004) is absorbed by deformation distributed over a very wide zone that incorporates several microplates (Hall, 2002). Nevertheless, it is likely that the present relative plate motions can only be applied to the last 5 million years or so and that these motions are of little help in reconstructing the long-term tectonic history of Papua New Guinea (Hall, 2002). The tectonic history of Papua New Guinea before 5 Ma is much more complicated than it having simply acted as the bow wave of the Australian Plate as it moves northwards.

Many aspects of the geology and tectonic evolution of Papua New Guinea remain poorly understood, and this is partly a function of the extensive rainforest cover, rugged terrain and lack of infrastructure. However, it is also related to the paucity of publically available whole-rock geochemical, geochronological and isotopic data, and to the scarcity of well-constrained paleomagnetic data, for many rock units. In addition, there is great uncertainty about the age and kinematics of many of the major structures, and it is commonly not clear as to which deformation and regional metamorphic events are of regional significance rather than of local extent only. Therefore, any description of the geology and tectonic evolution of Papua New Guinea must necessarily be somewhat speculative.

There are very few publications that summarize the geology of Papua New Guinea, despite the presence of several very large or giant deposits, and the tremendous prospectivity of the country. Most publications consist of journal papers that deal with specific aspects of the geology or very small areas. Hill and Hall (2003) and Hall (2002) produced a tectonic history of Papua New Guinea as part of a wider computer-based tectonic reconstruction of the southwest Pacific that included animations, and Quarles van Ufford and Cloos (2005) and Cloos et al. (2005) produced summaries of the Cenozoic tectonic evolution of the whole island of New Guinea. Despite the former two publications being up to a decade old, there are no more recent overviews to supplant them, and there is probably not a great deal of new information in the public domain that invalidates their interpretations. Baldwin et al. (2012) have recently produced a colourfully illustrated review of New Guinea, in which they summarize current work on the tectonic elements, plate motions, and seismicity of the region, and their possible links to mantle dynamics.

A major consensus in these publications is that most of the deformation and uplift in New Guinea began in the latest Miocene or the Pliocene (<8 Ma), as indicated by apatite fission track analysis (Hill and Gleadow, 1989); the present-day very rugged topography is, therefore, a very young feature of the plate margin (although there is evidence for an ?Eocene orogenic event along the Papuan Peninsula). This is consistent with the burial of Eocene to early Pliocene carbonate platforms south of the orogen in the late Pliocene by abundant siliciclastic sediments shed from the rising mountain range (e.g. Tcherepanov et al., 2008).

Williamson and Hancock (2005) produced a profusely illustrated, major summary of the mineralization styles, and the mineral projects and mines, of Papua New Guinea, along with a brief summary of the geology and tectonic evolution of the country. The current mineral projects and major prospects in PNG are shown in Figure 2. In this publication we provide an update of the three chapters in Williamson and Hancock (2005) that deal with the *Geological Framework of PNG* (Chapter 4), *Geological Terranes and Mineralisation* (Chapter 5), and *Tectonics and Mineralisation* (Chapter 6).

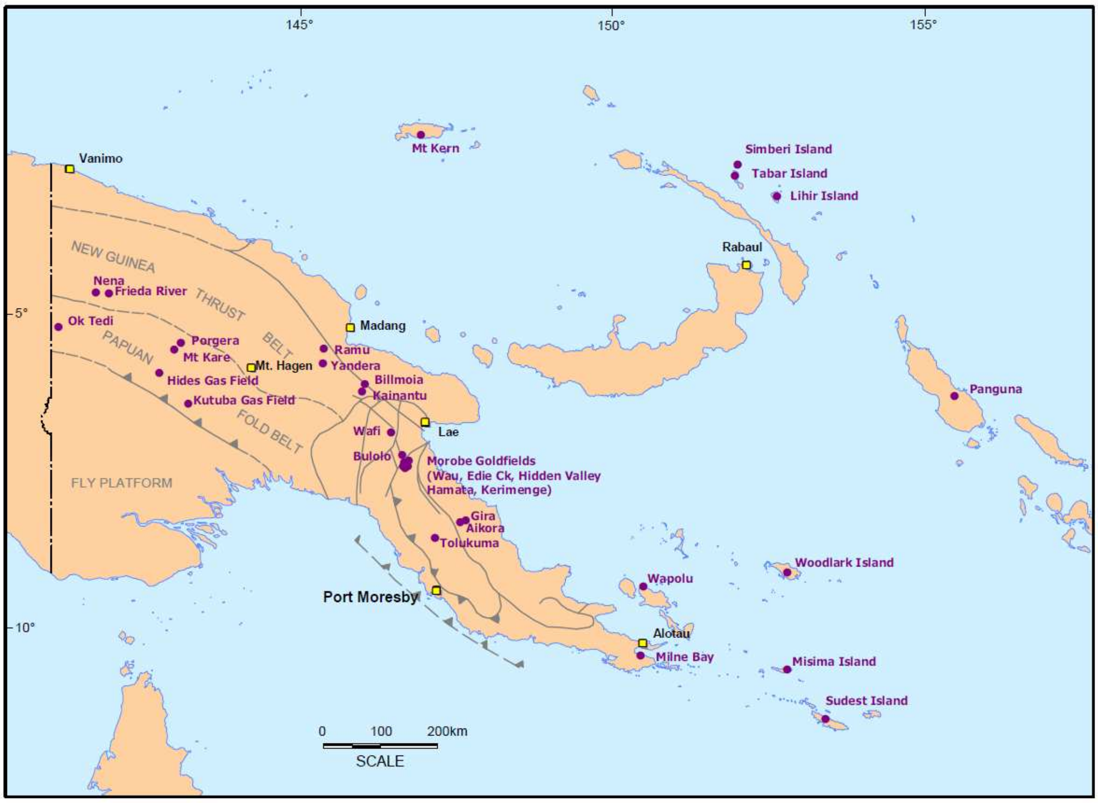


Figure 2. Mines, prospects and other localities referred to in the text. Also shown are the boundaries of the Fly Platform, Papuan Fold Belt and New Guinea Thrust Belt.

Present-day plate configuration

The boundary between the Australian and Pacific plates is a complex arrangement of active subduction zones and associated island arcs and spreading centres extending east and south through the Solomon Islands, Vanuatu and Fiji to New Zealand, and west into Indonesia and Malaysia (Fig. 1). The tectonics of Papua New Guinea and surrounds is related to the complex interaction of several subduction zones (with their attendant volcanic activity), transform and strike-slip faults and spreading ridges (Fig. 3).

The southern part of the island of New Guinea comprises Mesozoic–Cenozoic shelf sedimentary rocks overlying Paleozoic crystalline basement of the Australian continent, whereas the northern part encompasses late Cretaceous–Paleogene intra-oceanic island arc complexes of the Pacific (Pigram and Davies, 1987). Oblique convergence between the northward-moving Australian Plate and the west-northwestward-moving Pacific Plate in the Tertiary induced tectonism,

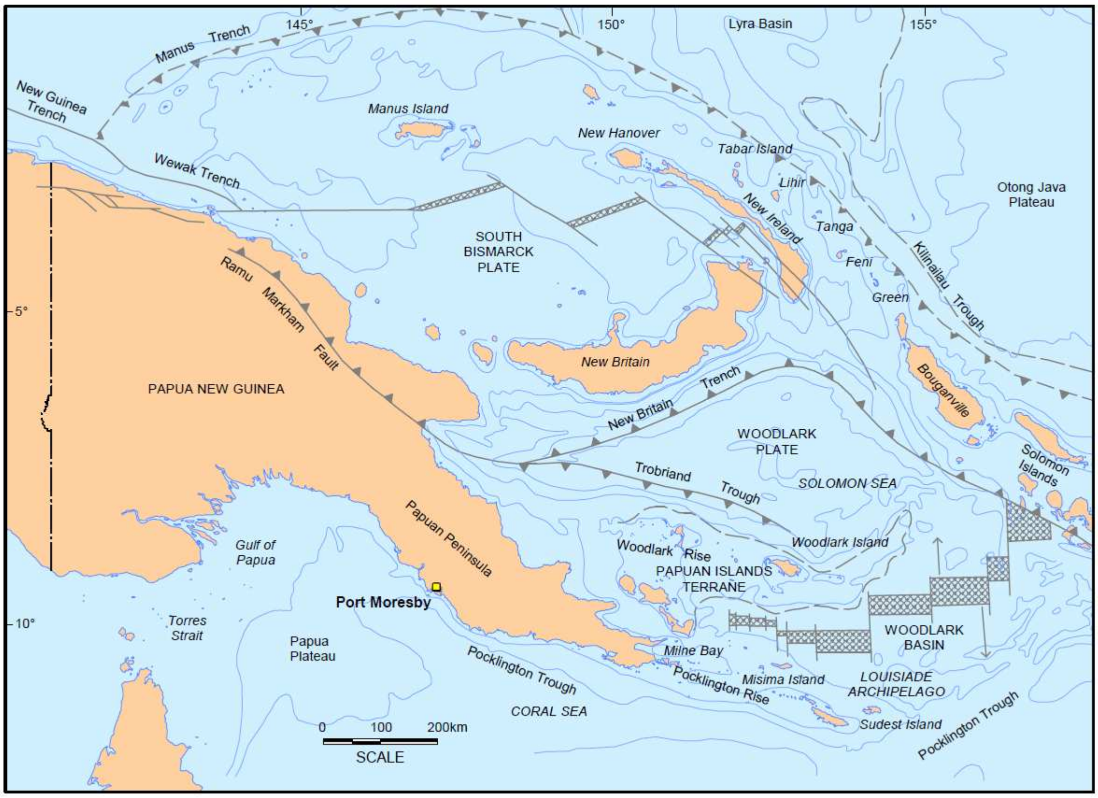


Figure 3. Main geographical features of the Bismarck Sea and Woodlark Basin and surrounding regions, with bathymetric contours at 200 m, 2000 m, 4000 m and 6000 m. Modified from Hall (2002).

metamorphism, magmatism, ophiolite obduction and uplift, and accretion of tectonostratigraphic terranes along the northern margin of the Australian Plate (Dow, 1977; Hall, 2002; Klootwijk et al., 2003; Quarles van Ufford and Cloos, 2005; Davies, 2009). The thickness and strength of the Australian basement, along with the presence of large extensional structures formed during rifting of the margin, probably exerted an important control on deformation during accretion and collision (Davies, 1991; Buchanan and Warburton, 1996; Hill et al., 1996; Hill and Hall, 2003) and perhaps also on later epithermal and porphyry-style mineralization (Corbett, 1994).

Oblique convergence between the Australian and Pacific Plates is presently about 11 cm per year and is responsible for the broadly sinistral transpressional setting of New Guinea (Tregoning et al., 1998; Wallace et al., 2004). A number of microplates have developed between the Australian Plate and the Pacific Plate (Fig. 3; Tregoning and McQueen, 2001; Bird, 2003; Wallace et al., 2004; Davies, 2009). Boundaries of these microplates offshore are marked by spreading ridges, deep-sea trenches and transform faults while those onshore are indicated by thrust, extensional, and strike-slip faults (Davies, 2009). At present, northward-directed subduction along the New Britain Trench (Fig. 3) is being driven by clockwise rotation of the South Bismarck Plate, whereas farther to the west, the continuation of the plate boundary onshore — the Ramu–Markham Fault — is largely locked (Tregoning and McQueen, 2001; Wallace et al., 2004). The Ramu–Markham Fault records thrusting of the Finisterre Terrane onto the New Guinea margin (Abbott et al., 1994). Farther to the southeast, the Papuan Peninsula is undergoing rapid extension related to the Woodlark Basin spreading centre (Baldwin et al., 2004).

Seismicity of the PNG region

The oblique collision zone between the Australian and Pacific plates is marked by the presence of several minor plates. The Woodlark Plate lies in the south-eastern part of the region, whereas the South Bismarck and Caroline Plates occupy the north-eastern and northern part of the region.

The main concentration of active seismicity is at the northern and north-eastern margins of the Solomon Sea (Fig. 4) where the Woodlark Plate is being subducted northwards beneath the Bismarck and Pacific Plates along the New Britain Trench. Seismicity in this area has been described as the most intense in the world (Ripper and McCue, 1983; Cooper and Taylor, 1989). From this area the seismicity continues towards the southeast through the Solomon Islands, and towards the northwest under the northern part of the New Guinea Island. The other main belts of seismicity in the Papua New Guinea region are along the Woodlark Spreading Centre (Woodlark Basin; Fig. 3) at the southern margin of the Solomon Sea, along the Manus Spreading Centre in the Bismarck Sea, and along an arc north of Manus Island and New Ireland where the Pacific and Caroline plates are being subducted beneath the South and North Bismarck Plates at the Manus–Kilinailau Trench. Most of the seismicity is at shallow depths (less than 40 km; Fig. 4) but there is substantial deeper seismicity, with focal depths up to 600 km.

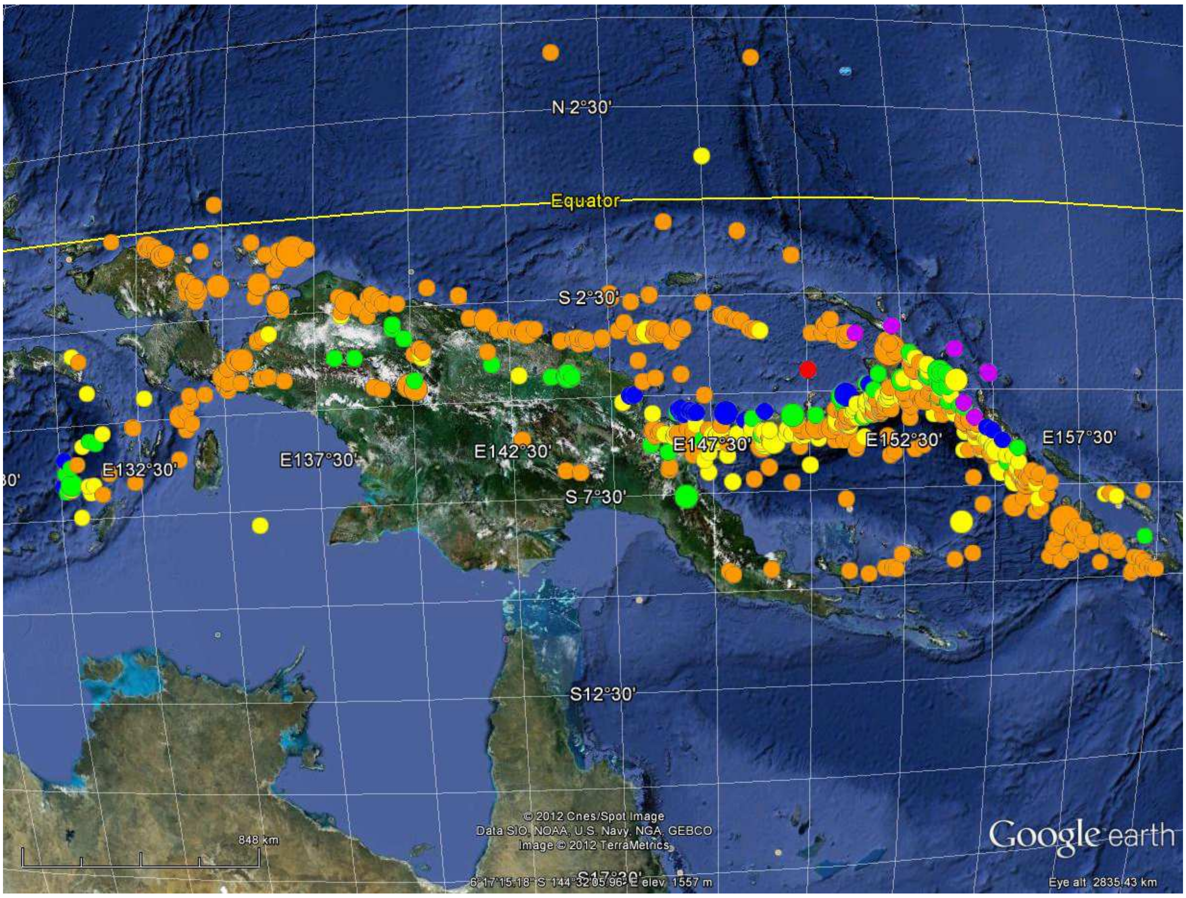


Figure 4. Earthquakes of magnitude 6 or greater in the Papua New Guinea region between 1973 and 2012. Depths: orange = 0–35 km, yellow = 35–70 km, green = 70–150 km, blue = 150–300 km, pink = 300–500 km, and red = 500–800 km. From the USGS/NEIdatabase, accessed at http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_rect.php>.

Geological elements

Papua New Guinea comprises a series of tectonic provinces (Figure 5) mainly bounded by major faults or shear zones. Although most of these provinces are widely recognized, a precise definition of each province is commonly lacking, including the precise nature of the boundaries. The terminology used to describe individual provinces, and their constituent terranes (fault-bounded regions with a discrete geological history) is an amalgam of work from the past 35 years or so (see Pigram and Davies, 1987; Struckmeyer et al., 1993; Davies et al., 1996; Hill and Hall, 2003; Klootwijk et al., 2003; Quarles van Ufford and Cloos, 2005; Davies, 2009). The broad nature of these provinces, and their development over time, is the subject of this section. Each tectonic province has a distinctive metallogenic signature, the result of its unique geological history.

At its broadest definition, three main components define the geological framework of Papua New Guinea:

1. the Australian Craton, which underlies much of the western part of Papua New Guinea, as well as Torres Strait to the south,

2. the New Guinea Orogen, the mountainous spine of Papua New Guinea, which comprises sedimentary and volcanic rocks that have undergone fold-and-thrust belt deformation and metamorphism, granitic and gabbroic rocks, and obducted oceanic crust, and

3. the Melanesian Arc, consisting of a series of island arcs and ranges to the north of the New Guinea Orogen.

The Australian Craton floors the Fly Platform, and probably extends northwards beneath much of the New Guinea Orogen. The orogen in western Papua New Guinea comprises the Papuan Fold Belt and New Guinea Thrust Belt, and the oceanic Torricelli and Finisterre terranes. In the eastern part of the country, from west to east, the orogen includes the Aure Fold Belt, East Papuan Composite Terrane, and the Wau Basin. To the north and northeast of the orogen are the Torricelli and Finisterre terranes and the New Guinea islands. The New Guinea Thrust Belt and East Papuan Composite Terrane each contain numerous terranes (see Pigram and Davies, 1987; Davies et al., 1996; Struckmeyer et al., 1993; Davies, 2009) that will not be discussed individually here, except for the Owen Stanley Metamorphics (or Terrane) and the Papuan Ultramafic Belt (Bowutu Terrane of Pigram and Davies, 1987). The Papuan Islands in the southern Solomon Sea east of the Papuan Peninsula, probably represent a continuation of the Owen Stanley Metamorphics (Pigram and Davies, 1987).

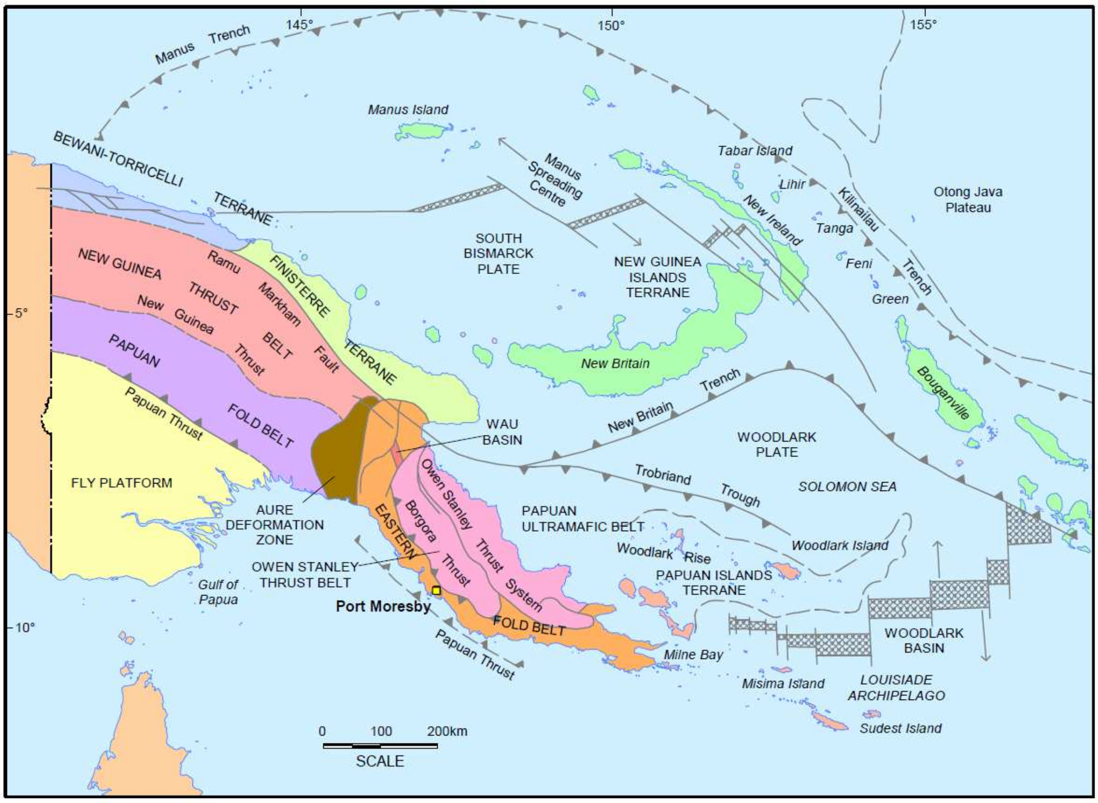


Figure 5. The main geological elements of Papua New Guinea, modified from Williamson and Hancock (2005).

Fly Platform

Geology

The Fly Platform is a broad, low-lying, plain south of the central mountain range in south-western Papua New Guinea underlain by continental crust of the Australian Craton. The boundary between the Fly Platform and the Papuan Fold Belt to the north is marked by the Papuan Thrust. This structure comprises a series of north-dipping thrust faults (including the Cecelia and Hegigio Thrusts) along the edge of the foothills of the Southern Highlands. It is interpreted as the basal thrust separating deformed sedimentary rocks of the Papuan Fold Belt from the underlying, essentially undeformed sedimentary rocks of the Fly Platform (Rogerson et al., 1987a). The thrust is inferred to continue south-eastwards offshore, south of, and parallel with, the coastline of mainland Papua New Guinea. In eastern Papua New Guinea the thrust is interpreted to separate Paleozoic crystalline basement from the overlying Aure Fold Belt (Rogerson et al., 1987a).

The basement to the Fly Platform comprises Permian metasedimentary rocks intruded by granites of Early to Middle Triassic age (Rogerson et al., 1987a; Van Wyck and Williams, 2002; Crowhurst et al., 2004). These rocks were exposed and eroded, before rifting began in the Late Triassic and subsidence and sedimentation continued until the Cretaceous (Dow, 1977; Home et al., 1990). Latest Cretaceous to Paleocene uplift across southern Papua New Guinea, including the Fly Platform, may have been associated with opening of the Coral Sea. Deposition of an extensive carbonate platform began in the Eocene and continued until the late Miocene (Pigram et al., 1989; Tcherepanov et al., 2008). During the Pliocene to Holocene, the carbonate rocks were buried beneath prograding siliciclastic sediments derived from the rising mountain chain to the north. The total thickness of sediment is estimated to be about 2–4 km onshore and 3–10 km offshore (Pigram and Symonds, 1993).

Slight uplift in the north of the Fly Platform, with consequent southwards tilting of the platform, has produced shallow incision of present-day streams north of the Fly River. Laterite development of probable Miocene age is common in many areas. The central northern section of the platform is blanketed by Quaternary pyroclastic flows and lahars and reworked outwash fans derived from the extinct Mt Murray, Mt Sisa and Mt Bosavi stratovolcanoes and associated parasitic cones (MacKenzie, 1976).

Mineralization

Alluvial gold (probably locally derived) is worked in the Ningerum area south of Ok Tedi, and also occurs farther east in streams draining southwards onto the Fly Platform from the Bolivip and Idawe Stocks. Alluvial gold has also been reported from the south-western slopes of Mt Bosavi. Volcanic rocks in this region may have potential for near-surface epithermal gold mineralization.

The lateritized soils of the Fly Platform including coastal Daru island were tested for bauxite by a Lands Department geologist Mr G Brouschon (Sydney Morning Herald, 1963), but the profile was found to be too immature for economic concentrations (Williamson and Hancock, 2005). Beach sands have been tested along the coastline from the Fly River delta and further east into the Papuan Gulf between Daru and Kerema (Klammer, 1965; Manser, 1971). Exploration carried out in the 1970s (Lowenstein, 1974) indicated sub-economic titanomagnetite concentrations, but further work may be warranted.

Papuan Fold Belt

Geology

The Papuan Fold Belt is a southeast-trending province separated from the Fly Platform to the south by the Papuan Thrust, and juxtaposed against the Aure Fold Belt to the southeast by a major thrust fault. In the Papuan Fold Belt, Miocene limestone and younger sandstone and shale of the Fly Platform are deformed by northeast-dipping thrusts and associated folds in a foreland fold-and-thrust belt (Dow, 1977; Mason, 1996; Buchanan and Warburton, 1996; Hill et al., 2008; Craig and Warvakai, 2009).

The thickness and strength of the Australian basement, along with the presence of large extensional structures formed during rifting of the margin, probably exerted an important control on deformation during accretion and collision (Davies, 1991; Buchanan and Warburton, 1996; Hill et al., 1996; Mason, 1997; Hill and Hall, 2003; Fig. 6). A major geographical feature of the fold belt is the Darai Plateau, which is an extensive belt of inhospitable karst limestone country developed on thrust sheets of late Eocene to late Miocene Darai Limestone.

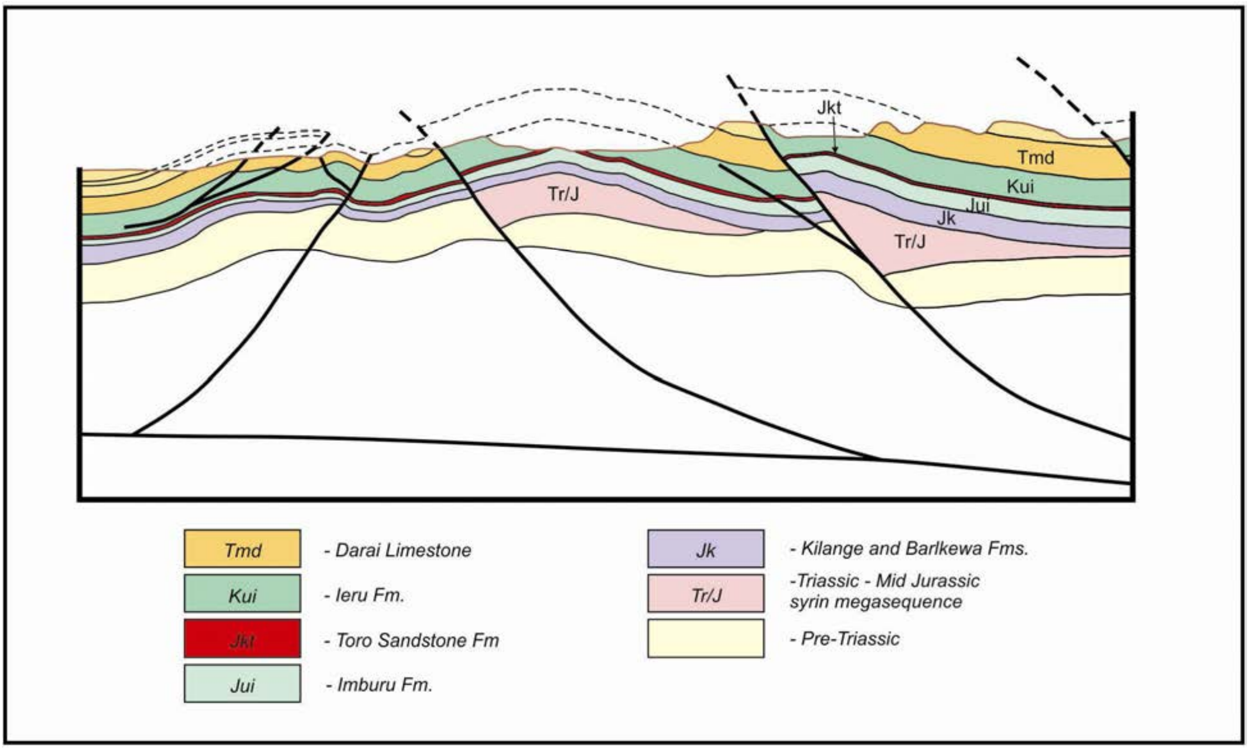


Figure 6. Cross-section showing the presence of broad anticlines with basement involvement in the northwestern part of the Papuan Fold Belt. These structures were interpreted by Buchanan and Warburton (1996) to be typical of inversion of original extensional structures. Modified from Buchanan and Warburton (1996).

Basement to the Papuan Fold Belt, as with the Fly Platform, consists of Permian metasedimentary rocks intruded by Early to Middle Triassic granites (Rogerson et al., 1987a; Van Wyck and Williams, 2002; Crowhurst et al., 2004; Fig. 7). In West Papua, by contrast, the Permian sedimentary rocks are not deformed and there is a well-preserved Neoproterozoic to Devonian section (Fig. 7). The Papuan Fold Belt is dominated by a thick succession of deformed marine sedimentary rocks of Late Triassic to Pliocene age (Dow, 1977; Home et al., 1990; Davies, 1992; Pigram et al., 1989; Tcherepanov et al., 2008) that occupy the southern fall of the central mountain range in the western mainland. The

Mesozoic clastic succession ranges from about 2–5 km thick (Hill et al., 1996), and this is overlain by up to 1 km of Miocene to Quaternary

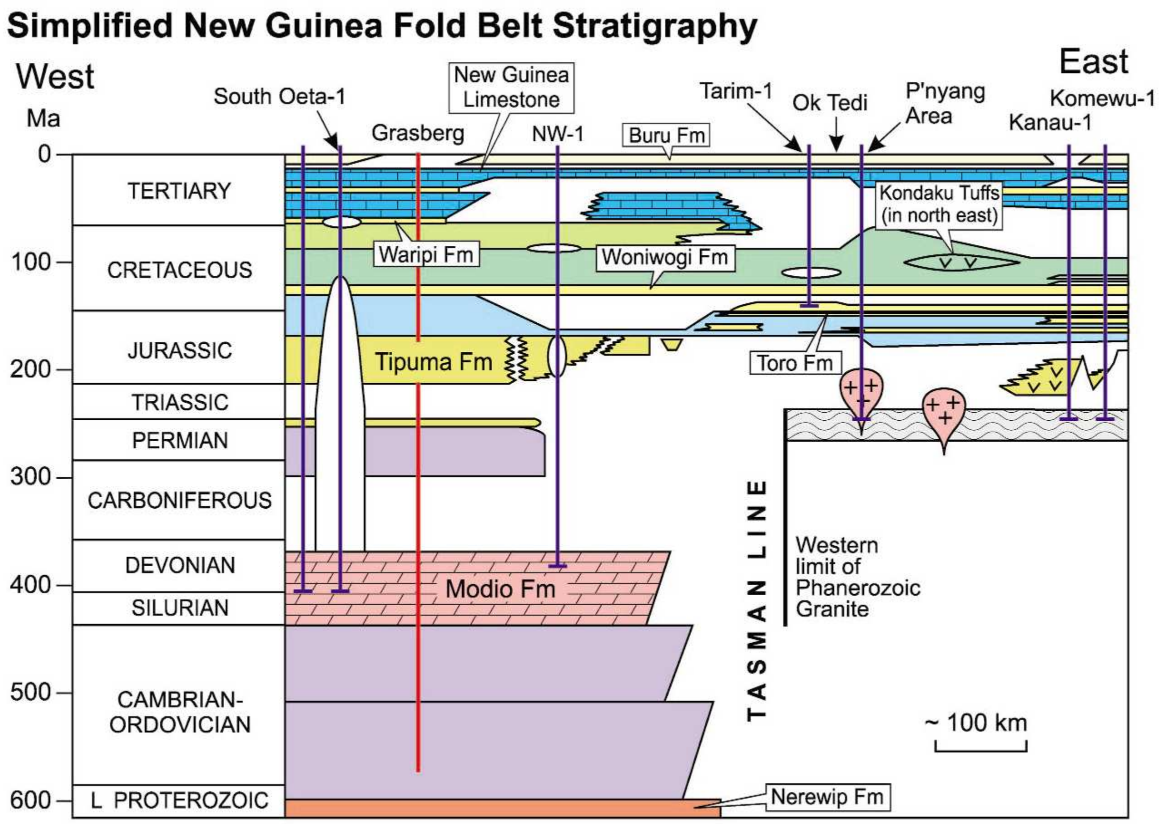


Figure 7. A diagrammatic chronostratigraphic column for the Papuan Fold Belt. The Tasman Line marks the eastern limit of old Australian continental crust. (After Hill and Hall (2003)).

limestone, sandstone and shale (Davies, 1992). These rocks are intruded by granites of late Miocene to Pleistocene age (including those at the Ok Tedi and Porgera mines and the Mt Kare prospect) in the western section of the belt. Deeper erosion at the northern extremity of the fold belt exposes underlying Mesozoic sandstone, siltstone and shale, as well as local intrusions, below the Miocene limestone.

Quaternary shoshonitic stratovolcanoes at Mt Bosavi and Mt Murray, which rise 1500–2000m above the surrounding countryside, are surrounded by thick, lahar outwash deposits. Volcanic activity has ceased, but local oral history, and the presence of fumaroles hot springs, suggests a major eruption occurred in the Doma Peaks area several hundred years ago. Some craters are deeply eroded, but many volcanic centres, including Holocene cones, are still well preserved and can be identified on aerial photographs. Other centres extend southeast from the Mt Bosavi volcano to the margin of the Fly Platform.

The Papuan Fold Belt is separated from the New Guinea Thrust Belt to the north by the New Guinea Thrust, which comprises a corridor of arc-parallel structures. In the western part of the thrust, the most prominent structure is the Lagaip Fault, but it also includes the Trangiso, Stolle and Figi Faults (Davies, 1982). To the east, the thrust probably encompasses the Ambum and Kubor Faults (Davies, 1983), but it is not easily traced east of Quaternary basalt cover in the Mt Hagen area (Dow, 1977; Rogerson et al., 1987b; Smith, 1990).

Mineralization

The Papuan Fold Belt hosts large resources of minerals, oil and gas (Fig. 2). The Porgera Au mine (Fleming et al., 1986; Richards and McDougall, 1990; Richards and Kerrich, 1993; Ronacher et al., 2002; Williamson and Hancock, 2005) and the Ok Tedi Cu–Au mine (Arnold and Griffin, 1978; Rush and Seegers, 1990; Hill et al., 2002; van Dongen et al., 2010) are large-scale, open pit operations. Mineralization at Porgera is associated with an intrusive complex dated at c. 6 Ma, whereas mineralization at Ok Tedi is related to a porphyry complex with igneous crystallization ages of c. 2.4–1.1 Ma. Exploration has been undertaken on the Mt Kare epithermal Au (Richards and Ledlie, 1993; Laudrum, 1997) and the Bolivip porphyry Cu–Au projects. The distribution of this mineralization, and the associated mantle-derived magmas, may have been controlled by north-northeast-trending lineaments (Davies, 1991) or arc-normal transfer faults (Corbett, 1994). Many other mineralized intrusive stocks throughout the belt have been prospected, and good potential still remains for identifying precious metal mineralization on the margins of intrusive rocks within the belt.

The Papuan Fold Belt also contains the Kutubu Oilfield, which originally contained recoverable reserves of more than 350 million barrels of oil (Bradey et al., 2008) and the giant Hides gas field (more than 5 trillion cubic feet of reserves), which will form the core of the PNG LNG project (Johnstone and Emmett, 2000; Hill et al., 2008; Fig. 2). The same arc-normal transfer faults that may have been important in concentrating mantle-derived magmas and precious metal mineralization may also have been central in the distribution of hydrocarbons in the fold belt (Hill et al., 2008).

New Guinea Thrust Belt

Geology

The New Guinea Thrust Belt is a major foreland thrust belt (Rogerson et al., 1987b) bounded by the Papuan Fold Belt to the south, the Torricelli and Finisterre terranes to the north, and the Aure Fold Belt to the east (Rogerson et al., 1987a,b). It roughly corresponds with the Western Mobile Belt of Dow (1977). Many of the major structures (Lagaip, Fiak–Leonard Schultz and Bundi Faults) represent crustal-scale thrust faults and host fragments of obducted oceanic crust. The belt is characterised by late Miocene, sub-horizontal to shallowly north-dipping, stacked thrust sheets of regionally metamorphosed and strongly cleaved Triassic to Eocene fine-grained sedimentary rocks and minor volcanic rocks. Following a middle Oligocene hiatus, siliciclastic sediments, carbonates and volcanic rocks were deposited until thrusting began in the middle Miocene (Rogerson et al., 1987a; Dobmeier and Poke, 2012; Dobmeier et al., 2012). The Australian Craton extends as basement north into the New Guinea Thrust Belt, in areas such as the Bena Bena, Jimi and Kubor terranes (Page, 1976; Rogerson et al., 1987a; Van Wyck and Williams, 2002; Crowhurst et al., 2004).

The New Guinea Thrust Belt is divisible into two zones:

(i) a southern zone of predominantly low-grade metasedimentary rocks that occupies the northern flank of the central mountain range, and which hosts the extensive Maramuni Arc magmatism, and

(ii) a northern zone of medium-grade metamorphic rocks probably related to the Tasman Orogen, which form the low mountain ranges surrounded by the Sepik Plain. This zone hosts Sepik Arc magmatism.

The two zones are separated along the foot of the main mountain range by an anastomosing system of easterly trending, low-angle faults of the Fiak–Leonard Schultze Thrust system, which extends eastward into the Ramu–Markham Fault Zone.

Igneous activity within the New Guinea Thrust Belt comprises subaqueous and sub-aerial volcanism, and associated intrusions, that vary from batholiths to stocks and dykes. Findlay et al. (1997a; as cited in Findlay, 2003) used earlier classifications (Dow, 1977; Davies et al., 1996) to separate the existing Maramuni Igneous Association of Rogerson et al. (1987b) into a 30–22 Ma (latest Oligocene to earliest Miocene) Sepik Event and a more extensive 17–10 Ma (latest early Miocene to earliest late Miocene) Maramuni Event (Dow, 1977). Findlay (2003) suggested that the Maramuni Event extended into the late Pliocene (c. 3 Ma) since the magmatism is essentially continuous from 17 Ma onwards.

The New Guinea Thrust Belt includes three extensive ophiolite complexes: the Landslip Range Ophiolite Complex in the west, the April Ophiolite Complex in the centre (Jaques, 1981; Rogerson et al., 1987b; Hoeflaken van and Dobmeier, 2012; Spieler and Hoeflaken van, 2012), and the Marum Ophiolite Complex (Pigram, 1978; Dobmeier and Poke, 2012), which hosts the Ramu Ni–Co deposit, in the east. These complexes were emplaced along the northern front of the central mountain range by late Miocene thrust faults (Rogerson et al., 1987b; Fig. 8).

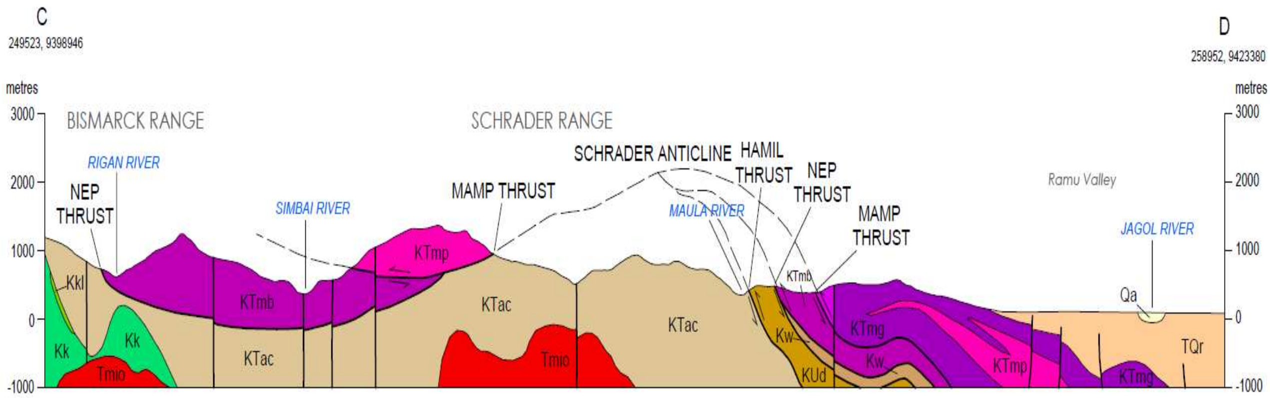


Figure 8. Diagrammatic cross-section from the Aiome 1:100 000 map sheet showing the interpreted structural style of the thrust belt and emplacement of the Marum Ophiolite Complex. From Dobmeier and Poke (2012).

The northern boundary of the New Guinea Thrust Belt is taken as the Ramu–Markham Fault Zone. This fault zone is widely regarded as a terrane boundary between the New Guinea Orogen and the Finisterre Terrane, which is inferred to be allochthonous (e.g. Jaques and Robinson, 1977; Abbott and Silver, 1991; Abbott et al., 1994 — although see Findlay, 1997b, 2003 for a different interpretation). Modern-day GPS measurements support convergence across the Ramu–Markham Fault Zone, although the north-western end appears to be locked (Wallace et al., 2004; Fig. 9), consistent with the presence of thick Pliocene sediments covering the projected northwestern extension of the fault. A combination of this locking (resistance to underthrusting) and rapid extension in the Manus Basin is producing rotation of the South Bismarck Plate (Wallace et al., 2004). The Bewani–Torricelli Fault System (Dow, 1977) locally separates part of the Bewani–Torricelli Terrane from the New Guinea Thrust Belt in the vicinity of the Sepik Basin.

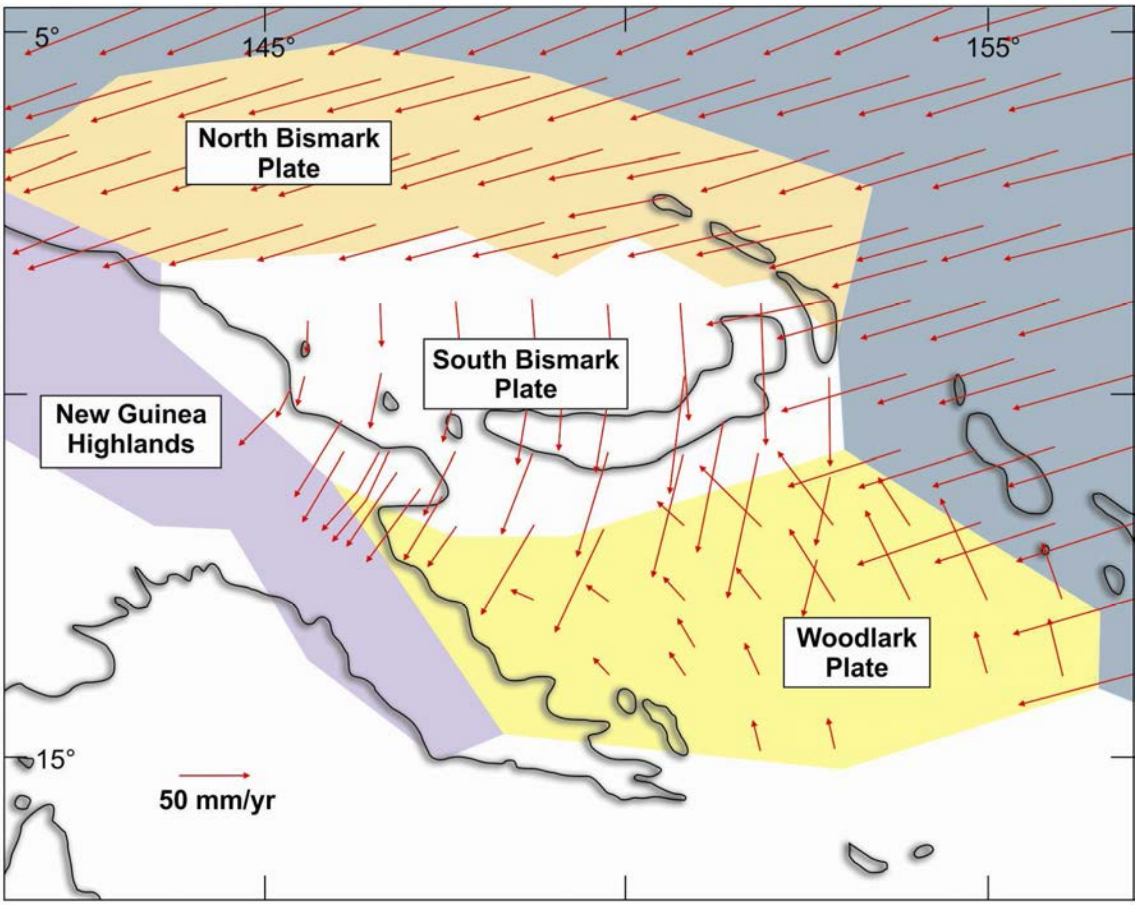


Figure 9. Rotational part of the velocity field as predicted by the Euler vectors of the best fit, six-block model to the GPS velocities in Papua New Guinea (relative to Australia) from Wallace et al. (2004). Also shown are selected poles of rotation, which are labelled according to their corresponding plate: AUS/SBS and NGH/SBS are the poles of rotation for the South Bismarck Plate relative to Australia and to the New Guinea Highlands. Modified from Wallace et al. (2004).

Mineralization

The New Guinea Thrust Belt hosts intrusion-related gold and copper mineralization, the Ramu Ni–Co deposit, alluvial gold, and sub-economic volcanic-hosted massive sulfide (VHMS) mineralization.

Intrusion-related gold and copper mineralization developed in two periods: during the older Sepik Event (30–22 Ma), and during the younger Maramuni Event (<17 Ma). Mineralization related to the Sepik Event is mostly small to medium in size, although some high-grade gold occurrences are present. The prospects remain under-explored, with only limited drilling of targets. Gold, and some copper, mineralization is associated with intrusions of the Sepik Event in:

- the Right May River area near the West Papua border;
- the Waskuk, Yerakai and Garamambu areas near Ambunti;
- the Hunstein Ranges;

- the Salumei and Cone Mountain prospects between the lower Salumei and Korosomeri Rivers;
- the lower Maramuni River to Yuat Gorge; and
- the lower Lai River area at the eastern extremity of the arc.

The Maramuni Event represents the main period of magmatism and related mineralization on mainland Papua New Guinea. It forms a 40–60 km-wide belt of intrusions stretching for 750 km from the Indonesian–PNG border to the Wau district south of the Huon Gulf, and sporadically into the offshore Papuan Islands (e.g. Woodlark Island). Mineralization related to intrusions of intermediate composition of the Maramuni Event occurs along the whole length of the belt. Notable prospects in the New Guinea Thrust Belt associated with the Maramuni Event include Frieda, Horse Ivaal, Trukai, North Debom (porphyry Cu–Au), Yandera (porphyry Cu–Mo–Au), Nena (high-sulfidation epithermal Cu–Au) and Kainantu (low-sulfidation epithermal Au) (Page and McDougall, 1972; Titley et al., 1978; Watmuff, 1978; Britten, 1981; Whalen et al., 1982; Rogerson and Williamson, 1986; Hawkins, 2001; Hawkins and Akiro, 2001; Espi et al., 2002).

Numerous other prospects have been drilled for Au or Cu–Au in the Sepik region in the May, Walio, April, Korosameri, Karawari, Maramuni (Tarua), Yuat and Lai River areas. The Malaumanda Cu–Au prospect on the Korosameri River has been drill tested. Farther east, Au or Cu–Au prospects related to intrusions of the Maramuni Event have been drilled in the Simbai and Jimi Valley regions. East from Simbai, major uplift of the mountain range south of the Ramu River has exposed batholiths of the Maramuni Event, namely the Bismarck Intrusive Complex and Akuna Intrusive Complex. Much of the Cu–Au mineralization throughout these regions (Yandera, Kathnell, Kainantu, Bilimoia and Mt Victor) may be associated with Pliocene intrusions that overprint mineralized Miocene intrusions (Rogerson and Williamson, 1986).

A large area of upper mantle-derived ultramafic rocks (the Marum Ophiolite Complex), is exposed along the front of the Bismarck Range south of the Ramu River, in which deep tropical weathering of dunite has produced the Ramu (Kurumbakari) Ni–Co laterite deposit (Queen et al., 2001). Exploration for lateritic nickel was also undertaken in the late 1960s and 1970s in the South Sepik region, principally in the Hunstein Range and April River areas, mainly by the testing of soils developed on partly serpentinized, upper mantle-derived dunite and peridotite. Results of those initial surveys did not yield any economic occurrences and no significant further work has been completed to 2011.

Alluvial gold has been worked throughout the New Guinea Thrust Belt, most notably in the Jimi Valley and Simbai areas, westwards along the foothills of the central cordillera, and across the South Sepik region. Volcanic-hosted massive sulfide deposits located in the Jimi Valley have been prospected, but an economically viable occurrence is yet to be located.

The Bewani–Torricelli Terrane

Geology

The Bewani–Torricelli or Torricelli Terrane (Pigram and Davies, 1987) extends along the north-western coast of Papua New Guinea from the Irian Jaya border through the Bewani and Torricelli Mountain ranges to southeast of Wewak. We use here an expanded definition of the terrane, which includes the Mount Turu and Prince Alexander terranes of Pigram and Davies (1987). In the west, the southern limit of the terrane is defined by Pliocene sedimentary rocks of the Aitape Trough. In the North Sepik region, widespread outcrop of Mesozoic metamorphic rocks and intrusions interpreted from gravity data, suggests that a continuous crystalline basement extends at depth from the coastline across the Sepik Basin south to the central mountain range (Milsom et al., 2001).

The Bewani–Torricelli Terrane is dominated by probable Late Cretaceous to Eocene sea-floor volcanic rocks and late Oligocene island arc volcanic rocks, with widespread, largely co-magmatic intrusions with K–Ar radiometric ages in the range of 73.2–17.3 Ma (Late Cretaceous to early Miocene; Hutchison and Norvick, 1980; Pigram and Davies, 1987). In the Prince Alexander Mountains high-grade metamorphic rocks are Early Cretaceous in age, but parts of the complex may be as old as Middle Jurassic (Pigram and Davies, 1987). In this region, and around Mount Turu southwest of Wewak, metamorphic rocks are intruded by undeformed granitic rocks of late Oligocene to early Miocene age (Hutchison and Norvick, 1980).

Mineralization

Gold is being reworked into present-day streams from widespread uplifted auriferous paleogravels (including early to late Miocene conglomerate). This includes the flanks of the Jurassic core of the Prince Alexander Mountains, the intrusive core of the Torricelli Mountains and, to a lesser extent, the Bewani Mountains. Alluvial gold is accompanied by traces of platinum in the Kilifas area of the Bewani Mountains and was discovered by Babbington in 1968 (Papuan Precious Metals Ltd, 2011). In the Maprik area of the Prince Alexander Mountains, the mining of high fineness alluvial gold provides a good cash flow for the local people. Minor primary gold and base metal mineralization is associated with hydrothermally altered basic intrusions, particularly in the western Bewani Mountains (Papuan Precious Metals Ltd, 2008).

Finisterre Terrane

Geology

The Finisterre Terrane forms a mountain belt extending for more than 550 km along the northern coast of the New Guinea mainland from the Sepik River mouth eastwards through the Adelbert, Finisterre and Sarawaget Mountains. The Sarawaget Mountains in the Huon Peninsula is where the terrane is widest (about 100 km wide). The Finisterre Terrane is separated from the New Guinea Thrust Belt by the Ramu–Markham Fault Zone, which would appear to be the westward extension of the New Britain Trench (e.g. Milsom, 1981; Abers and Roecker, 1991; Abers and McCaffrey, 1994). Interpretations of gravity and seismic data suggest that strike-slip movement on the Ramu–Markham Fault Zone is of Recent origin, and that the Finisterre–Sarawaget Mountains (with their spectacular 4,000 m-high summits and Pleistocene reef terraces up to 700 m above sea level at the north-eastern corner of the Huon Peninsula) are a nappe on a shallow north-dipping thrust plane that is an extension of the new Britain Trench (Milsom, 1981; Milsom et al., 2001; Fig. 10).

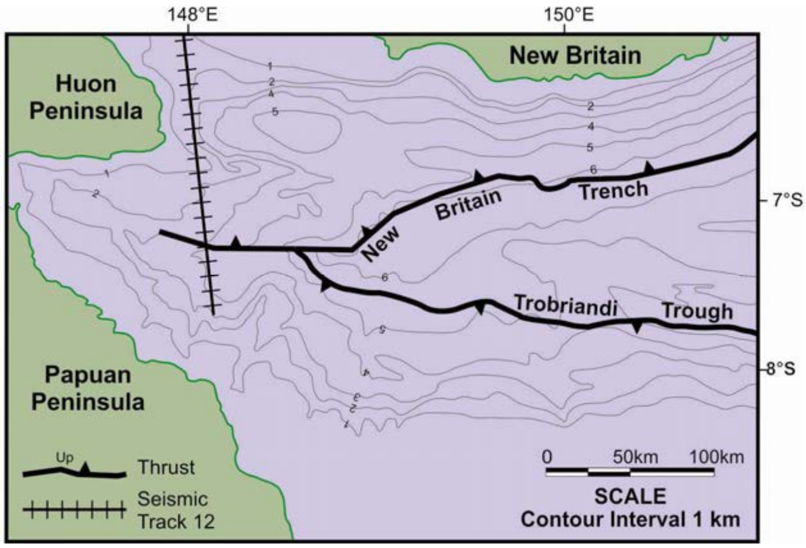
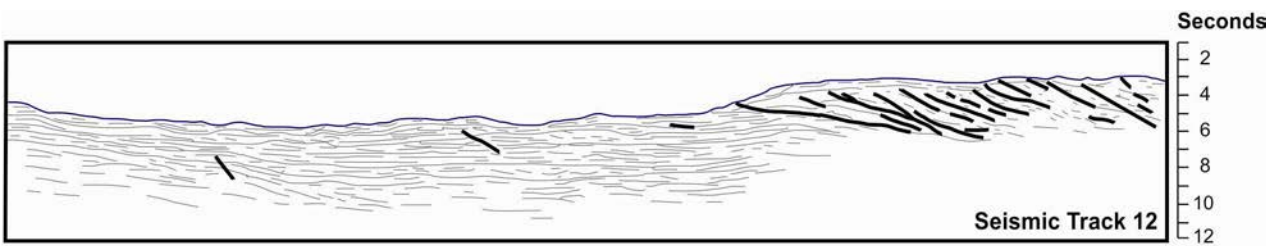


Figure 10. a) Location of seismic track 12 from the University of California, Santa Cruz cruise with line drawing interpretation (×1.4 vertical exaggeration). Hatched part of the line represents the area portrayed in the interpretation.



b) The vertical scale shows two-way travel time in seconds. Modified from Silver et al. (1991).

The Finisterre Terrane comprises a thick sequence of chert, argillite and volcaniclastic rocks deposited in the middle to late Eocene, overlain by early Oligocene to early Miocene basalt and andesite deposited in an island arc or back-arc setting. These are in turn overlain by a thick package of middle Eocene to Pliocene shallow water limestone (Pigram and Davies, 1987).

The Finisterre Terrane is a classic example of an accreted island arc terrane (e.g. Dewey and Bird, 1970; Pigram and Davies, 1987; Silver et al., 1991; Abbott, 1995; Davies et al., 1996), and one that is still active (Abers and McCaffrey, 1994; Wallace et al., 2004). Collision probably began in the Pliocene (Abbott et al., 1994). Present-day collision between the Finisterre Terrane and the New Guinea Thrust Belt may be the cause of rapid clockwise rotation of the South Bismarck Plate about a vertical axis in the New Guinea Highlands to the northwest (Wallace et al., 2004). In contrast, Findlay (1997b; 2003) suggested that the Finisterre Terrane is not allochthonous; however, this suggestion is based only on lithostratigraphic correlations with units south of the Ramu–Markham Fault Zone.

Mineralization

Gold mineralization is not recorded in the Finisterre Terrane, in which there are very few granitic intrusions. Disseminated chalcopyrite is associated with andesitic volcanic horizons in the Finisterre Volcanics (Chrome Corporation Ltd, 2009). Several leases are being explored for massive sulfides and porphyry- and epithermal-style mineralization by Pristine Pacific Ltd as part of their Markham Valley Project (Pristine Pacific Ltd, 2011).

The Aure Fold Belt

Geology

The Aure Fold Belt (see Davies, 2009) incorporates the Aure Deformation Zone and Eastern Fold Belt of Williamson and Hancock (2005), and the Port Moresby, Kutu and Menyamya terranes of Pigram and Davies (1987). The Aure Fold Belt is separated from the Papuan Fold Belt and the New Guinea Thrust Belt to the west by a major thrust fault. The northern limit of the Aure Fold Belt is marked by the Ramu–Markham Fault Zone, and to the east the fold belt is juxtaposed against the East Papuan Composite Terrane along the Bogoro Thrust. The following description of the Aure Fold Belt is taken largely from Davies (2009) and Pigram and Davies (1987).

The Aure Fold Belt is composed of a thick sequence of mainly clastic sedimentary rocks that were deposited from the late Oligocene to the Pliocene. These rocks were folded and faulted possibly in response to westward movement of the East Papuan Composite Terrane (Davies, 2009). East of about Port Moresby these folded sedimentary rocks give way to thrust-bounded, strike ridges of Paleocene to Eocene fine-grained siliciclastic sedimentary rocks with minor coarser grained Oligocene sedimentary rocks, all of which were intruded by Oligocene gabbro of the Sadowa Gabbro during the early Eocene to middle Oligocene. The sequence is interpreted to have formed as an accretionary prism above a northeast-dipping subduction zone, before being thrust-stacked sometime between the middle Miocene and early Pliocene (Rogerson et al., 1981) or during the mid Pliocene (Francis et al., 1982; Worthing et al., 1992). These rocks are overlain unconformably east of Port Moresby on the Sogeri Plateau by Pliocene basalt and andesitic volcanic and volcaniclastic deposits (Yates and de Ferranti, 1967; Pieters, 1978; Abiari et al., 2001).

Farther to the east, the remainder of the peninsula mainly consists of tholeiitic basalt with minor pelagic limestone of Late Cretaceous and middle Eocene age. These rocks are intruded by scattered stocks of syenite and related alkaline rocks.

Mineralization

The Aure Fold Belt contains only minor mineralization. The Laloki massive sulfide deposits (Shedden, 1989) comprise conformable lenses of massive sulfide with an unusual Cu–Fe mineralogy (Kulange et al., 2012). The ore is associated with a laminar, grey lutite marker unit within the upper portion of a late Paleocene sequence of siliceous to calcareous and carbonaceous mudstone and minor chert. The gold occurrences in the massive sulfide are described by Noku et al. (2012), who have shown gold mineralization as blebs in the early stage massive pyrite–marcasite–chalcopyrite formed by reduction of hydrothermal fluids with organic rich sediments. These rocks are overlain by Eocene biomicrite and chert (Davies, 1961; Williamson, 1983; Rogerson et al., 1981; Banda, 2001). The Eocene hemipelagic Port Moresby Beds are host to manganese occurrences of both stratiform and concretionary type. These occurrences contain evidence for substantial planktonic test dissolution, organic combustion and metal movement during diagenesis (Finlayson and Cussen, 1985).

East Papuan Composite Terrane

Geology

The East Papuan Composite Terrane comprises several terranes, but it is dominated by ophiolite of the Papuan Ultramafic Belt on the northeast side and metamorphic rocks of the Owen Stanley Metamorphics to the southwest. The two are separated by a major fault, the Owen Stanley Fault.

Owen Stanley Metamorphics

The Owen Stanley Metamorphics forms the mountainous spine of the Papuan Peninsula, with elevations up to 4000 m. The metamorphic complex is nearly 400 km long and 80 km wide, trending in a south-easterly direction from near Lae. The complex comprises two belts: a western belt of very low-grade rocks and an eastern belt of higher grade rocks with evidence of high-pressure metamorphism. The western belt consists of argillite, shale, lithic and feldspathic sandstone, greywacke with minor limestone, conglomerate and spilitic volcanic rocks, whereas the eastern belt is composed of phyllite, slate, pelitic and psammitic schist, and lesser metavolcanic rock, with blueschist and granulite close to the Owen Stanley Fault System and the overthrust Papuan Ultramafic Belt (Pieters, 1978; Rogerson and Francis, 1983; Pigram and Davies, 1987; Worthing, 1988). Protoliths to the Owen Stanley Metamorphics were fine-grained marine sediments deposited as a thick pile on the rifted margin of northern Australia during the Cretaceous. Medium- to high-pressure regional metamorphism is associated with obduction of the Papuan Ultramafic Belt. Metamorphic amphiboles from the sole thrust of the Owen Stanley Fault System were dated by Lus et al. (2004) at 58.3 ± 0.4 Ma using $^{40}Ar/^{39}Ar$ geochronology; they interpreted this age to reflect cooling after obduction of the ophiolite.

Metamorphic rocks of the Owen Stanley Metamorphics are intruded by Oligocene gabbro and by Miocene granites, including the mid-Miocene Morobe Granodiorite (Fisher, 1944) of the Maramuni Event, and overlain by late Oligocene and younger volcanic and sedimentary rocks. The Morobe Granodiorite yielded K–Ar biotite and hornblende dates and Rb–Sr biotite dates between c. 15 Ma and 11 Ma (Page, 1976; Cussen et al., 1986), and comprises about 3,500 km^2 of medium-grained granodiorite, locally with monzogranite and monzonite (Fisher, 1944; Mackay, 1955; Carswell, 1990).

The Papuan Ultramafic Belt

The Papuan Ultramafic Belt is an ophiolite complex about 400 km long and 25–40 km wide, located along the north coast of the Papuan Peninsula (Davies, 1971). The belt extends onto the Papuan Islands as peridotite bodies mapped on Normanby and Fergusson Islands. The Papuan Ultramafic Belt comprises the hanging wall to the Owen Stanley Fault. The belt comprises 4–8 km of variably tectonized ultramafic rock, overlain by about 4 km of granular and high-level gabbro, which is in turn overlain by up to 4 km of basaltic volcanic rock (Davies, 1971; 1977; Pieters, 1978). The ophiolite complex is probably Cretaceous in age (Davies, 1977).

The Papuan Ultramafic Belt is intruded by Eocene tonalite, and is unconformably overlain by middle Eocene andesitic volcanic rocks (Pigram and Davies, 1987).

Papuan Islands

The Papuan Islands represent the eastward extension of the Papuan Peninsula and include the islands of the D'Entrecasteaux Island Group (Goodenough, Ferguson and Normanby Islands), the Louisiade Archipelago (Misima, Sudest (Tagula) and Rossel (Yela)), Woodlark Island, and many other smaller islands. The islands lie on two east-southeast trending oceanic highs within the Solomon Sea — namely the Woodlark Rise to the north and the Pocklington Rise to the south — that are separated by the Woodlark oceanic spreading centre which commenced opening about 5 Ma ago (Benes et al., 1994). Most of these islands probably represent an eastward continuation of the Owen Stanley Metamorphics (Pigram and Davies, 1987).

On Misima Island, Paleogene basement consists of ophiolitic meta-igneous rocks of the Awaibi Association in the west, and metasedimentary rocks of the Sisa Association in the east. The two associations are separated by a thrust fault with later extensional reactivation (Williamson and Rogerson, 1983; Adshead and Appleby, 1996; Adshead, 1997). The Sisa Association is intruded by many small stocks of the 8.1 ± 0.4 Ma Boiou Granodiorite. All these rocks are overlain by a Pliocene volcanic and sedimentary sequence, which is in turn overlain by alkali basalt (Williamson and Rogerson, 1983). Sudest and Rossel Islands are dominated by monotonous slate and phyllite that are probably part of the Owen Stanley Metamorphics. Tertiary-age mafic intrusions with a porphyritic texture are scattered throughout the islands. Islands of the D'Entrecasteaux Group comprise metamorphic core complexes: that is, a lower plate of gneissic domes (gneiss, schist, mylonite and amphibolite) structurally overlain by an upper plate of largely undeformed and unmetamorphosed mafic and ultramafic rocks cut by shear zones and detachment faults (Baldwin et al., 2004). Crustal extension, doming and unroofing of these core complexes is associated with the westward-propagation of the Woodlark Rift spreading centre (Fig. 11). Seismic studies of the Papuan Islands have shown rates of extension in the region of between 30 and 70 mm per annum, and decreasing westward to zero at about 147°E on the peninsula (Abers et al., 1997).The metamorphic core complexes contain the youngest known eclogite exposed at the Earth's surface; high-pressure and ultrahigh-pressure (≥90 km) eclogite facies metamorphism has been dated at between 7.9 ± 1.9 Ma and 2.09 ± 0.49 Ma (Baldwin et al., 2004; Little et al., 2007; Monteleone et al., 2007; Baldwin et al., 2008; Zirakparvar et al., 2011). Exhumation, which began about 4 m.y. ago, was accompanied by granodiorite intrusion, and uplift continues to the present day (Baldwin et al., 1993; Baldwin and Ireland, 1995; Miller et al., 2012).

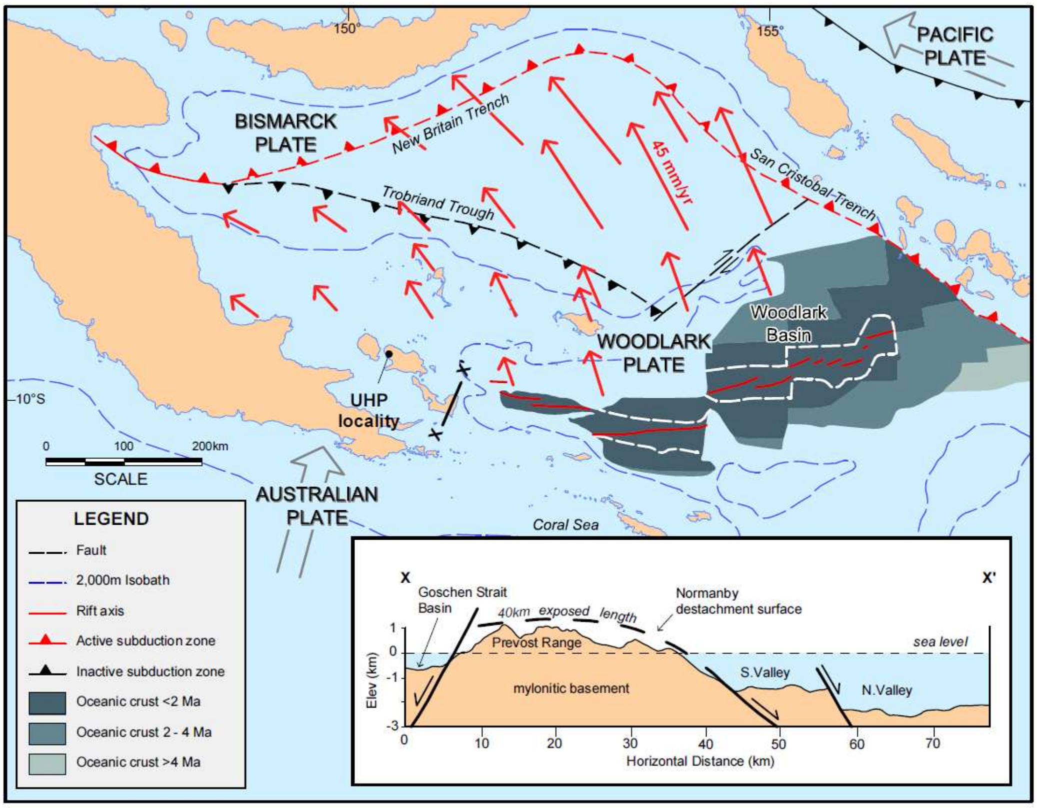


Figure 11. Simplified tectonic map of the Woodlark Basin and surrounds. Note location of the diagrammatic cross-section shown in the inset. Modified from Little et al. (2007) and Baldwin et al. (2008).

Most of Woodlark Island is covered by Pleistocene limestone which surrounds a 12 km-wide ‘basement’ horst block. The block consists of Eocene ocean-floor, low-K basaltic rocks of the Loluai Volcanics, overlain by Miocene Wonai Hill beds (16.5–13 Ma; Smith and Milsom, 1984), high-K volcanic rocks and co-magmatic porphyritic intrusions (Joseph and Finlayson, 1991). The Trobriand Islands and a number of smaller groups are composed of Pleistocene to Recent coral atolls.

Wau Basin

The Wau Basin developed on Cretaceous metasedimentary rock of the Owen Stanley Metamorphics and Miocene granodiorite (Morobe Granodiorite). The basin is about 40 km long and 20 km wide, and may have formed during the Pliocene by oblique extensional rotation of north-northwest trending structures formed during earlier accretionary events, such as the Wandumi and Upper Watut Faults (Corbett, 1994; Neale and Corbett, 1997; Corbett and Leach, 1998). The basin is bounded to the north by the northeast-trending Sunshine Fault and to the south by the Lakekamu Fault, both of which are interpreted as transfer structures, although this interpretation is disputed by Findlay et al. (2002).

Felsic volcanic rock of the Bulolo Volcanics is exposed in the Wau Basin and overlies rocks of the Owen Stanley Metamorphics and the Miocene Morobe Granodiorite. These volcanic rocks are extensively intruded by domes, dykes and sills of dacitic porphyry (e.g. Edie Porphyry: Fisher, 1945), which are interpreted as co-magmatic with the volcanic rocks. Several K–Ar determinations by Page and McDougall (1972) on biotite and plagioclase from volcanic rocks in the Bulolo Volcanics yielded an age of about 3.5 Ma, consistent with a hornblende K–Ar date of 4.5 ± 0.4 Ma determined by Cussen et al. (1986). The Namie Breccia, which encompasses a variety of hydrothermal breccias composed of Edie Porphyry and fragments of milled basement material, is associated with several dome complexes, including diatremes (Sillitoe et al., 1984). Other breccias occur along faults and at the contacts of Edie Porphyry intrusions. The Bulolo Volcanics are overlain by the mid-Pliocene Otibanda Formation, a 700 m-thick sequence of poorly sorted conglomerate, sandstone, siltstone and reworked tuff (Plane, 1967; Cussen et al., 1986) in the northern part of the Wau Basin.

Mineralization

At its simplest, porphyry- and epithermal-style mineralization in the Owen Stanley Metamorphics appears to be associated with Pliocene intermediate to acid porphyry intrusions and volcanic rocks. Mineralization includes the giant Wafi–Golpu group of deposits, the Morobe Goldfield (Wau, Hidden Valley, Edie Creek, Hamata, Kerimenge, Ribroaster and Bulolo deposits), and the Tolukuma mine.

The Wafi–Golpu deposits comprise porphyry Cu–Au and high- and low-sulfidation epithermal mineralization (Erceg et al., 1991; Corbett and Leach, 1998). As of early 2012, the deposits contained an estimated mineral resource of 26.6 Moz of Au and 9 Mt of Cu according to the Morobe Mining Joint Venture website < http://www.morobejv.com/about/wgjv/index.htm>. Mineralization is associated with a series of porphyry intrusions and a diatreme breccia pipe that cut low-grade metasedimentary rocks of the Owen Stanley Metamorphics. Potassium–argon (K–Ar) dating of biotite in the potassic alteration yielded an age of c. 14 Ma and dating of alunite in the advanced argillic alteration yielded an age of c. 13 Ma (Tau-Loi and Andrew, 1998).

The Morobe Goldfield is associated with Pliocene magmatism in the Wau Basin, which developed on Cretaceous rocks of the Owen Stanley Metamorphics and the Miocene Morobe Granodiorite. Active hot springs along the Wandumi Fault, and other northwest-trending structures within the basin, have deposited silica sinter and travertine. Mineralization at Hidden Valley is hosted in fractures formed in the hanging wall of northwest-trending listric faults, which are interpreted to be related to formation of the Wau Basin (Hoppe and Korowa, 2001). Dating of adularia associated with Au mineralization at

4.15 Ma at Hidden Valley is consistent with the idea that mineralization is related to the Edie Porphyry (Nelson et al., 1990) and extensional structures associated with its emplacement. The northeast-trending Au lodes at Hamata (Denwer and Mowat, 1997) may be related to a splay off the same northwest-trending fault (Upper Watut Fault) that is associated with the Hidden Valley deposit (Corbett and Leach, 1998). Gold mineralization at Wau is also hosted by the northwest-trending Escarpment Fault, which outcrops as a spectacular 10 km-long normal fault (Sillitoe et al., 1984), and the parallel Edie structural corridor (Lowenstein, 1982; Neale and Corbett, 1997). South of Wau, Au mineralization at Kerimenge is associated with north-trending faults (e.g. Corbett and Leach, 1998). It is estimated that 3.2 Moz of alluvial gold was won from the Morobe Goldfields up until 1977 (Lowenstein et al., 1982), the majority of which came from the Bulolo dredging operations. Although large-scale alluvial mining operations have long ceased, the area continues to be the scene of a vibrant small-scale mining industry and a forest plantation industry (Neale, 2001). Further testing of the Bulolo gravels is currently underway under granted exploration permits and it is proposed to re-mine these gravels as they still contain a resource of >1 million oz that could be profitably extracted (Pacific Niugini Minerals (PNG) Ltd, 2010).

About 150 km south-southeast of Wau, gold mineralization at the Tolukuma mine lies on the faulted western margin of the Mt Davidson Volcanics. Potassium–argon dating indicates the volcanism is about 4.8 Ma (Langmead and McLeod, 1991; Dekba, 1993; Davies and Williamson, 1998). The volcanic rocks extend 25 km further south to a major volcanic centre at Mount Cameron, and comprise andesitic and dacitic lahars often with a shoshonitic affinity, and tuffs with intercalated sedimentary units. The volcanic rocks unconformably overlie rocks of the Owen Stanley Metamorphics.

Williamson and Hancock (2005) reported that in the northern section of the Papuan Ultramafic Belt, narrow vein-style gold mineralization is associated with Eocene tonalite (50–40 Ma). Significant amounts of alluvial Au and minor Pt have been worked in many parts of the Papuan Peninsula for more than a hundred years. A number of alluvial Au areas are still being mined by local people employing small-scale mining methods. The alluvial Au and Pt are probably derived from potassic intrusions, many of which were emplaced along the Owen Stanley Fault eastwards to Milne Bay. The Lokanu Volcanics hosts chalcopyrite within amygdales, and also chalcopyrite, sphalerite, galena and silver within shear zones.

Epithermal Au mineralization is associated with dormant Quaternary stratovolcanoes in the central north-eastern part of the peninsula. Nickel sulfide mineralization is locally remobilised into shear zones, possibly associated with Miocene to Pliocene porphyry intrusions (Davies and Smith, 1974). Disseminations and veinlets of primary platinum and chromite, and lateritic nickel, are primary exploration targets in this region.

The lateritic nickel occurrence at Wowo Gap is less well defined than that at Ramu, but is estimated to have an indicated and inferred resource of about 125 Mt averaging 1.06% Ni and 0.07% Co (Resource Mining Corporation Limited, 2012). It is also similar in metallurgical characteristics to the Ramu ore, but is still at the exploration stage (Williamson and Hancock, 2005) with drilling currently being undertaken. The Mumbare Plateau, Kokoda, also has the potential to host a significant nickel-cobalt lateritic deposit. Other laterites in the area include the Ibau Plateau and the Keman and Awariobo Ranges, south of Wowo Gap.

In the Papuan Islands, alluvial gold was discovered on Sudest Island in 1888 and subsequently on the adjacent islands. Most of the 10,000 oz of alluvial and eluvial gold won from Sudest has since been traced to its hard-rock sources; these sources are either saccharoidal and epithermal quartz noted in the Mt Adelaide and Cornucopia Mine workings (Corbett et al., 1991) or metamorphic rocks (Williamson, 1984). On Misima Island there were auriferous epithermal quartz veins at the Umuna open pit mine (now closed), and lodes on Woodlark Island were mined before World War II. A feasibility study is currently being undertaken on Woodlark Island prior to application for a mining lease. Skarn mineralization is associated with the Boiou intrusions that are cut by later extensional faults hosting 4–3.2 Ma (Adshead, 1997) epithermal gold mineralization (Umuna Lode).

At the Wapolu Prospect on Fergusson Island, gold mining was undertaken on a modest scale in 1996, but the operation ceased soon afterwards due to low gold grades. The epithermal gold mineralization is interpreted as very low-temperature, low-sulfidation quartz vein–breccia localised within detachment fault zones (Chapple and Ibil, 1997).

New Guinea Islands

Geology

The New Guinea Islands may be considered to comprise two main arcs: the Melanesian Arc (Manus, New Britain, New Hanover, New Ireland, Bougainville and the Solomon Islands) and the Tabar–Lihir–Tanga–Feni island chain to the northeast of New Ireland (Fig. 5).

The Melanesian Arc formed in the Eocene behind the New Guinea–Vitiaz Trench, where the Pacific Plate was subducted beneath the Australian Plate (Hall, 2002). Magmatism ceased as the subduction zone became choked by the arrival of the Ontong–Java Plateau during the Miocene (Kroenke et al., 2004; Petterson, 2004), which was followed by widespread deposition of limestone on the volcanic edifices. Following limestone deposition the area has been overprinted by younger magmatism on New Britain and Bougainville owing to north- and northeast-directed subduction of the Woodlark Plate at the New Britain–San Cristobal Trench from the late Miocene to the present day (Petterson, 2004).

Manus Island in the far north of Papua New Guinea, at 100 km long, is the largest of the Admiralty Islands Group. Basement of probable oceanic origin is overlain by Eocene to Mid-Miocene (47–20 Ma) island-arc andesite, basaltic agglomerate, tuff and breccia up to 2000 m thick over most of the island (Jaques, 1980). These rocks are in turn overlain by early to middle Miocene limestone and calcareous sedimentary rocks. The volcanic and sedimentary rocks were intruded by the multiphase Yirri Intrusive Complex at c. 17–10 Ma (Jaques and Webb, 1975 cited in Jaques, 1980).

New Britain is typical of the other Melanesian Islands (Blake and Miezitis, 1967; Hilyard and Rogerson, 1989; Rogerson et al., 1989), comprising a thick basal sequence of late Eocene basaltic to andesitic lava, breccia and associated sedimentary rocks that are overlain by Oligocene island-arc volcanic rocks and intruded by their plutonic equivalents (30–22 Ma; Ryburn, 1975, 1976). The hiatus in volcanism in the Miocene is represented by extensive, locally thick, shelf limestone with karst topography, which is in turn overlain by Pliocene volcaniclastic sedimentary rocks. Renewed magmatism in the Pliocene resulted in development of volcanic edifices as two separate chains and also overprinted existing island arcs. One arc extends for 1000 km from close to the north coast of Papua New Guinea, eastward as the Schouten Islands Group (Manam, Karkar, Bagabag, Long and Umboi or Rooke Islands), and then along the north coast of New Britain through to Rabaul in East New Britain, and then southwards through Bougainville.

The Tabar–Lihir–Tanga–Feni island chain to the northeast of New Ireland is about 250 km long and trends northwest. The arc is inferred to be related to subduction of the Woodlark Plate into the New Britain Trench, under New Britain and New Ireland, which began the late Miocene (Lindley, 1988; Hall, 2002; Petterson, 2004). Volcanic activity began at c. 6.3 Ma on Simberi Island (Tabar island group) in the New Ireland fore-arc region (Rytuba et al. 1993). Many of the volcanic rocks appear to be associated with extension of the arc and have an alkaline character, but with chemical compositions strongly influenced by previous subduction events (Stracke and Hegner, 1994).

Mineralization

On Manus Island, Arie and other nearby prospects were explored from 1968 though the 1970s for porphyry Cu-style mineralization The mineralization identified mainly forms stockwork veins and disseminated sulfide within the middle to late Miocene Yirri Intrusive Complex (Jaques, 1980) and adjacent volcanic rocks. In the area near Mt Kren, mineralized intrusions are overlain by an extensive blanket of cliff-forming silica–alunite–pyrite alteration typical of the shoulders of barren advanced argillic alteration that commonly forms in the vicinity of porphyry Cu–Au deposits at depth (Corbett and Leach, 1998). Epithermal gold mineralization (Metawarei) has been identified in epiclastic rocks of the Middle Miocene Tasikim Volcanics about 12 km east of the porphyry Cu–Au mineralization.

The Schouten Islands–New Britain–Bougainville arc contains a number of Au and Cu–Au deposits, the largest of which is the Panguna porphyry Cu–Au deposit on Bougainville. Panguna is developed at the margin of the multiphase early Pliocene (5–4 Ma) Kawerong Quartz Diorite at the contact with the Panguna Andesite (Page and McDougall, 1972b; Baumer and Fraser, 1975; Baldwin et al., 1978; Clarke, 1990). Potassium–argon dating of biotite and K-feldspar from the alteration assemblage yielded an age of c. 3.4 Ma (Page and McDougall, 1972b).

In central New Britain, several occurrences of porphyry Cu mineralization related to 30–22 Ma granitic intrusions (Plesyumi, Kuku, Wala River, Torlu River, Ala River and Esis-Sai) were prospected during the 1970s and 1980s (Hine and Mason, 1978; Hine et al., 1978). In East New Britain epithermal Au related to a 23–22 Ma-old intrusion, variably named Wild Dog (Lindley, 1987), Nengmukta or Sinivit (Lindley, 1998) can be traced for several kilometres (Corbett and Leach, 1998). East New Britain also hosts a small high-sulfidation gold occurrence at Maragorik that has developed at a very high crustal level and demonstrates both lithological and structural controls on mineralization (Corbett and Hayward, 1994; Corbett and Leach, 1998). Simuku is an important tenement in the centre of New Britain that shows a resource of 200 Mt @ 0.47% copper equivalent (Coppermoly Ltd, 2012a). Current drilling intersections show the potential for a resource upgrade (Coppermoly Ltd, 2012b).

In the Bismarck Sea between New Ireland and New Britain a sea floor massive sulfide containing a high-grade copper–gold resource was initially drilled by Nautilus minerals in 2007 who compiled a 43-101 (TSX) indicated resource of 1.03 Mt of 7.2% Cu, 5 g/t Au, 23 g/t, and 0.4% Zn and an inferred resource of 1.54 Mt @ 8.1% Cu, 6.4 g/t Au, 34 g/t Ag and 0.9% Zn (Nautilus Minerals, 2011). Environmental permits and a Mining Lease have been granted for this project which will be a world first in mining at water depths greater than 1500 m. Nautilus has a raft of other projects along the margin of sea floor from Papua New Guinea to New Zealand that are dependent on the success of Solwara 1.

The Tabar–Lihir–Tanga–Feni arc hosts several epithermal Au deposits. Lihir Island hosts the giant Ladolam gold deposit (Moyle et al., 1990; Muller et al., 2002; Corbett et al., 2001), which developed at the transition from a porphyry-style to an epithermal setting, during a Mount St Helens-style sideways collapse of the volcanic edifice. The Luise Caldera which hosts Ladolam is the youngest of several volcanoes on the island, with alteration and mineralization dated between c. 0.9 Ma and c. 0.1 Ma (Wallace et al., 1983; Moyle et al., 1990; Davies and Ballantyne, 1987). Many workers have discussed the relationship between shoshonitic magmatism and gold mineralization on the Tabar–Lihir–Tanga–Feni island chain (Heming, 1979; Wallace et al., 1983; Muller et al., 2001).

On Simberi, epithermal Au mineralization is associated with early K-feldspar flooding followed by pyrite grading to arsenean pyrite and arsenopyrite, in which gold is encapsulated within sulfides. Later high-grade gold is associated with sphalerite, pyrite and carbonate. Alteration and mineralization at Simberi are typical of the intrusion-related low sulfidation-style formed peripheral to an alkaline magmatic source at depth (Corbett and Leach, 1998).

On a seamount 10 km south of Lihir Island, sampling in 1,050 m water depth has yielded gold values up to 230 ppm in association with stockwork pyrite veins and sphalerite, galena, chalcopyrite and marcasite with anomalous Sb, As, Ag and Hg. Not surprisingly, Petersen et al. (2002) interpret the mineralization to have formed as magmatic sea-floor deposits.

On Ambitle Island in the Feni Island Group, a summit caldera contains young (0.68 ± 0.1 Ma and 0.49 ± 0.1 Ma) domes, a phreatomagmatic eruption (dated at 2300 ± 100 yBP) and many active hot springs. Silica sinter deposits located adjacent to the springs assayed up to 33g/t Au (Licence et al., 1987).

Alluvial gold was worked on Simberi and Tatau Islands, the latter being traced to a hard-rock source at Tugi. Four eroded volcanoes were explored extensively in the 1980s, leading to the drill testing of many prospects.

In the Manus Basin, volcanic-hosted massive sulfides (Cu–Pb–Zn–Ag–Au) are currently being deposited by black smoker-style vents within ridge spreading centres, dacite lavas and caldera collapse settings (Binns and Scott, 1993; Parr et al., 1995; Gena et al., 2001; Hrischeva et al., 2007).

The relationship between mineralization and tectonics

Introduction

The relationship between mineralization and tectonic setting is not always clear, owing to considerable uncertainty about the tectonic evolution of Papua New Guinea and a lack of age information on many mineralizing and tectonic events. Therefore, it is commonly unclear as to how the two processes are related in detail. In the absence of country-wide datasets in the public domain, it is not possible to determine, for example, if porphyry-style and epithermal mineralization is related in any way to crustal thickness, or to the chemical or isotopic compositions of the associated magmas. Some porphyry-style and epithermal mineralization has been related to transfer structures, but it is still not clear why some of these structures are associated with giant deposits and others not. Sillitoe (1997) proposed that very large porphyry-style and epithermal deposits are more likely to be related to partial melting of stalled slabs and their associated metasomatized mantle wedge following accretion of terranes or collision (delayed partial melting).

There is certainly no consensus amongst geologists on the tectonic evolution of Papua New Guinea; for example, there is disagreement about the locations of terrane boundaries, the extent of allochthonous terranes (for example, the nature of the Finesterre Terrane), the timing of collision(s), and the number of subduction zones and their orientation (Hall, 2002, p. 391–393). This is not surprising given the rugged terrain, the extensive rainforest cover, the lack of coherent geological datasets across the country (particularly geochronological and paleomagnetic data), and the sheer structural complexity of this convergent margin. It is, however, possible to make some generalisations about the tectonic evolution of Papua New Guinea, even if many workers will argue about the details. The tectonic evolution, and its relationship to mineralization, is considered here in a series of time slices, because the tectonic setting for any given area will change with time. The geological history outlined below borrows heavily from Hall (2002), which is probably the only internally consistent account, which also considers individual plates and their boundaries.

Papua New Guinea has long been cited as a classic setting for porphyry Cu–Au and epithermal Au–Ag mineralization within a subduction-related magmatic arc (Page and McDougall, 1972; Titley, 1975; Titley and Heidrick, 1978; Corbett, 2003, 2009, Sillitoe, 2010). Nevertheless, the presence of giant gas fields in the Papuan Fold Belt, the large Ramu Ni laterite deposit, active oil fields, and recent interest in the coal, coal-seam gas, rare earth element and offshore base metals potential of the region, demonstrates that Papua New Guinea is more than just a porphyry Cu–Au province. Although Papua New Guinea has a geological history extending back into the Permian (or possibly the Archean; Baldwin and Ireland, 1995), most of the mineral deposits (in particular, porphyry and epithermal style) and the oil and gas fields are very young, having formed during the late Miocene to Pleistocene (Sillitoe, 1997; Hill et al., 2008). The Ramu deposit is developed in ultramafic rocks of ?Cretaceous age, but it was only tropical weathering in Recent times that upgraded the Ni to an economic grade.

Geological History

Mesozoic

There appears to be a fundamental difference in the nature of the basement underlying the island of New Guinea across roughly the position of the international border between Papua New Guinea and West Papua. West of the border, undeformed Paleozoic sedimentary rocks overlie Precambrian basement, whereas to the east, the basement comprises Paleozoic metasedimentary rocks and Triassic granites (Struckmeyer et al., 1993). In Papua New Guinea, inliers of basement in the Papuan Fold Belt and New Guinea Thrust Belt include the Kubor Intrusive Complex, the Amanab Block and the Bena Bena Metamorphics. These inliers have a similar geological history to the New England Fold Belt in eastern Australia (Van Wyck and Williams, 2002; Crowhurst et al., 2004) indicating that they are not exotic terranes, but are part of the Australian Craton, perhaps comprising a series of paraautochthonous terranes that represent ribbons of rifted continental crust. The Australian Craton appears to floor Papua New Guinea northwards to at least the Markham Valley in the eastern Highlands region (Rogerson et al., 1987b; Van Wyck and Williams, 2002).

Metasedimentary rocks of probable Permian age were intruded by granites in the Early to Middle Triassic, probably in a convergent continental margin setting (Van Wyck and Williams, 2002; Crowhurst et al., 2004). These rocks were exposed and eroded, before rifting began in the Late Triassic to Early Jurassic (Pigram and Panggabean, 1984; Home et al., 1990; Struckmeyer et al., 1993; Cole et al., 2000), with subsidence and sedimentation continuing until the Cretaceous (Dow, 1977; Home et al., 1990). These structures, along with those formed during subsequent Paleocene rifting, probably exerted an important control on the thickness and strength of the Australian basement and, in turn, on the degree and style of deformation during Miocene accretion and collision (Davies, 1991; Buchanan and Warburton, 1996; Hill et al., 1996; Mason, 1997; Hill and Hall, 2003). Therefore, a large part of Papua New Guinea is composed of material formed at a Late Paleozoic to Mesozoic passive continental margin.

Davies et al. (1997) suggested that a north- to northeast-dipping subduction zone was located off the north and north-eastern parts of the passive margin, above which the Irian Arc and the East Papua Arc, respectively, were developed. These arcs were accreted onto the Australian Craton, together with ophiolite assemblages, in the Late Cretaceous (Irian Arc) and Paleocene (East Papua Arc).

Paleocene (65–56 Ma)

During the Paleocene, the northern margin of the Australian Craton underwent extensive rifting associated with the opening of the Coral Sea, which detached the Papuan Peninsula from the Queensland Plateau (Weissel & Watts, 1979; Pigram and Symonds, 1993; Davies et al., 1997). Differential uplift and erosion associated with opening of the Coral Sea removed Late Cretaceous sedimentary rocks over much of the Papuan Basin in the Papuan Fold Belt and Fly Platform (Home et al., 1990; Struckmeyer, 1990). In the eastern part of the basin, latest Jurassic to Late Cretaceous sedimentary rocks were stripped (Struckmeyer, 1990). Deposition in the basin did not recommence until the Oligocene (Home et al., 1990). Rifting at this time, and during the Late Paleozoic and Mesozoic, was associated with the development of numerous transform faults roughly perpendicular to the strike of the orogen (Dekker et al., 1990; Hill, 1990; Corbett, 1994; Hill et al., 2008). These structures project from the basement and are now imposed on the overlying accretionary wedge, and may have contributed to localising much younger mineralization such as Porgera and Ok Tedi (Dekker et al., 1990; Corbett, 1994).

To the north, the Papuan Ultramafic Belt was sutured to the Owen Stanley Metamorphics at the end of the Paleocene, based on dates of 58.3 ± 0.4 Ma, the cooling age of hornblende porphyroblasts from granulite facies metamorphic rocks in the sole thrust to the Owen Stanley Fault (Lus et al., 2004). Hall (2002) suggested that this event was part of a larger, somewhat diachronous, accretion event in the southwest Pacific that extended into the earliest middle Eocene, during which the fore-arcs of two or more small plates were obducted onto the passive margin from New Caledonia across to West Papua.

The Laloki volcanic-hosted massive sulfide mineralization may have developed at this time in a small ocean basin termed Uyaknji by Davies et al. (1997).

Eocene (56–34 Ma)

The tectonic setting of the southwest Pacific changed dramatically in the Eocene (at about 45 Ma; compare Figs 12a and 12b) as the Australian Plate started to move rapidly northward, following an increase in the rate of separation between Australia and Antarctica, and with the possible loss of two spreading ridges in the Pacific (Hall, 2002). These changes, along with others, may have produced plate boundary forces that caused a change in direction of the Pacific Plate. As a result, opening of the Coral Sea was terminated, and the Melanesian Arc (including New Britain, New Ireland and the Solomon Islands) formed above a southwest-dipping subduction zone (Kilinailau Trench; Fig. 12b). It has been suggested that the Melanesian Arc was comprised of fragments rifted from the eastern margin of Australia in the middle Eocene (Crook and Belbin, 1978), which is consistent with paleomagnetic data published during the 1980s and 1990s (Hall, 2002). Hall (2002) proposed that the intra-oceanic Sepik Arc was accreted to the northern margin of Australia by 45 Ma (Fig. 12b), but Davies et al. (1997) suggested instead that the arc developed above a north-dipping subduction zone to the north of the emergent land mass in the Eocene and was stitched by the late Oligocene (see: Oligocene (34–23 Ma) below).

There is a paucity of Eocene clastic sedimentation in eastern Papua New Guinea compared with farther west (Hill and Hall, 2003) and south along the northern part of the craton, which was the site of thick limestone deposition.

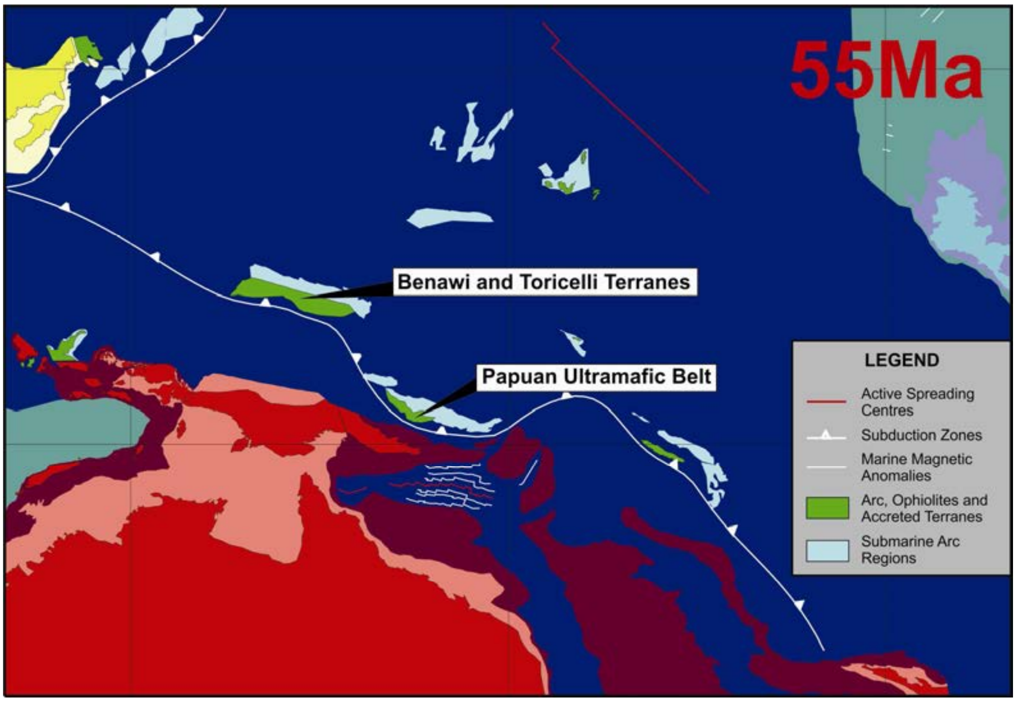


Figure 12. Snapshots showing the plate tectonic reconstructions of Hall (2002) for the New Guinea region. Modified from Hall (2000). (12 A- 55 Ma)

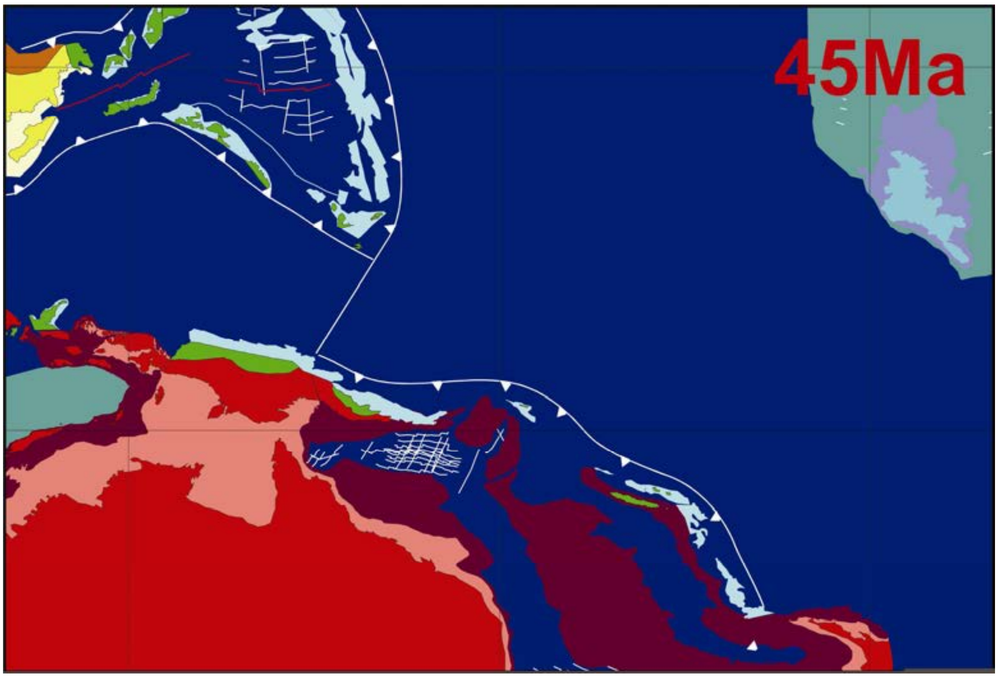


Figure 12. Snapshots showing the plate tectonic reconstructions of Hall (2002) for the New Guinea region. Modified from Hall (2000).(12b - 45Ma)

Oligocene (34–23 Ma)

During the Oligocene, the Solomon Sea, which opened between mainland New Guinea and the Melanesian Arc, continued to widen (Fig. 12c). At its western end, the Solomon Sea spreading centre was being subducted beneath the South Caroline Arc, which along with the Melanesian Arc to the east, continued to rotate clockwise (Hall, 2002). The New Guinea Islands now formed emerging submarine volcanic edifices and co-magmatic intrusions above a southwest-dipping subduction zone (Kilinailau Trench) that was initiated in the Late Eocene, well to the north of the Australian Craton.

The Sepik Arc is interpreted to have accreted to the Australian Craton in the late Eocene to middle to late Oligocene (Davies et al., 1997) or in the earliest middle Miocene (Hall, 2002). Collision is thought to have continued through the Oligocene as indicated by fault-bounded slivers of ultramafic rocks present within thrust sheets in the western part of the orogen. In each case, medium- to high-pressure metamorphism of the accretionary wedge has accompanied ophiolite emplacement and grades away from the basal thrust into the underlying older metamorphic rocks (Rogerson et al., 1987b; Pieters, 1978).

On the mainland, accretion of the Sepik Arc resulted in substantial uplift and metamorphism of the Cretaceous marine sedimentary pile, and contributed to the termination of volcanism; the cooling age of the Alife Blueschist at 23 Ma (Rogerson et al., 1987a) in the Sepik region corresponds well with the cessation of magmatism associated with the Sepik Event at about 22 Ma (Findlay et al., 1997b). The accreted Sepik Arc now forms a 600 km-long zone straddling the Sepik River in which medium-grade metamorphic rocks contain Oligocene to Early Miocene intrusions. Volcaniclastic sedimentary rocks, such as the Wogamush Formation, were deposited on the north side of the range in the Sepik headwaters. A south-dipping subduction zone developed at the northern edge of the craton (Fig. 12d) resulting in accretion of terranes in the latest Oligocene (Rogerson et al., 1987b) and the formation of a continental volcanic arc from Miocene times (Maramuni Arc; Dow, 1977).

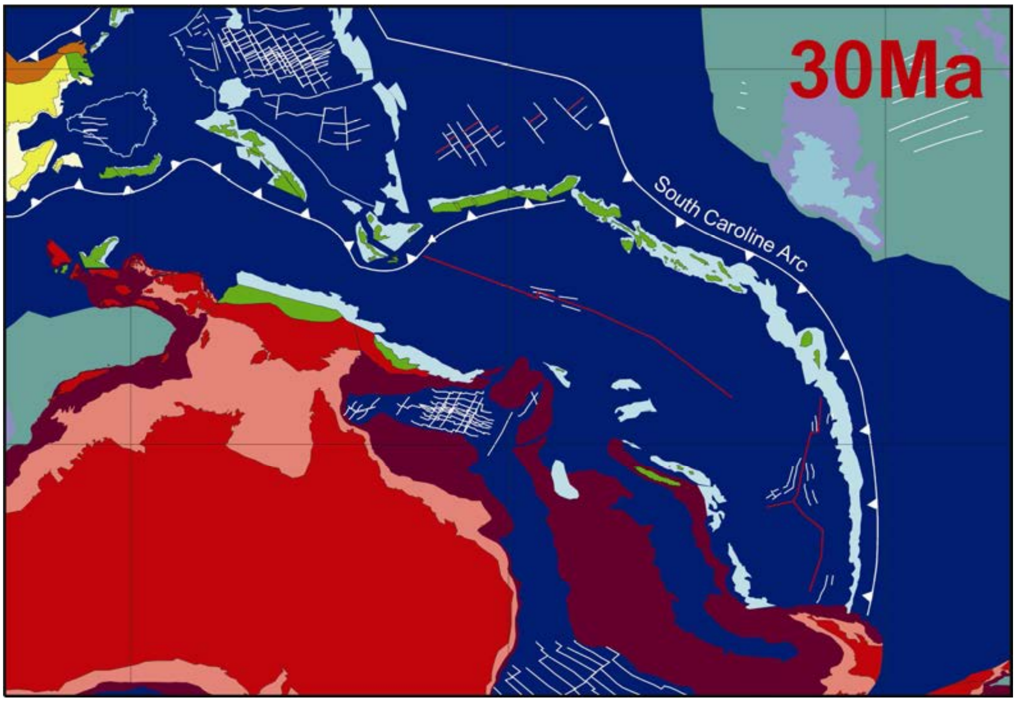


Figure 12. Snapshots showing the plate tectonic reconstructions of Hall (2002) for the New Guinea region. Modified from Hall (2000). (12 c- 30 Ma)

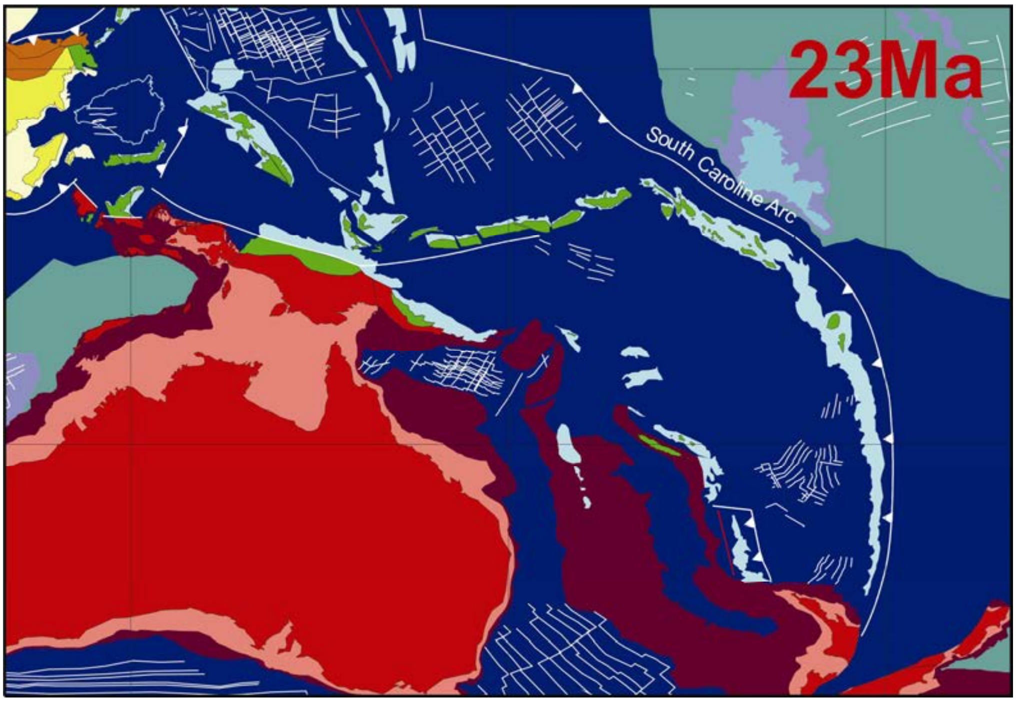


Figure 12. Snapshots showing the plate tectonic reconstructions of Hall (2002) for the New Guinea region. Modified from Hall (2000). (12 D- 23 Ma)

In the Papuan Basin there is a major hiatus in the Oligocene as the basin changed from a passive margin setting to a foreland basin setting (Struckmeyer, 1990). In the proximal foredeep, siliciclastic sediments were deposited from an emerging land mass to the north related to incipient arc–continent collision. In the shallower parts of the basin, there was widespread deposition of shallow marine limestone (Darai Limestone; Home et al., 1990; Struckmeyer, 1990; Pigram and Symonds, 1991).

Miocene (23–5.3 Ma)

At about the Oligocene–Miocene boundary, plate margins in the southwest Pacific underwent a major reorganization with (1) the Melanesian Arc (amongst others) becoming coupled to the Pacific Plate, and (2) a major sinistral strike-slip boundary through northern New Guinea being established, which marked the end of northward-directed subduction (Hall, 2002). The cause of this reorganization is unclear, but it could be, in part, related to arrival of the thick, rigid volcanic pile of the Ontong–Java Plateau at the Melanesian Arc and its continued movement to the southwest (Figs 12e–g).

The New Guinea Islands region underwent significant tectonism in the late Oligocene to middle Miocene. From about 22–20 Ma the Ontong Java Plateau jammed the Kilinailau subduction zone northeast of Bougainville (Bruns et al., 1989; Kroenke et al., 2004; Petterson, 2004). The subduction zone progressively locked from the southeast to the northwest over a protracted period, but by about 15 Ma was coupled to the Melanesian Arc (Hall, 2002). As a result the Eocene–Oligocene submarine andesitic volcanism, which accounted for development of the New Guinea Islands archipelago, ceased in the late Miocene, and for much of the Miocene and Pliocene the emerging volcanic edifices became capped by shallow marine limestone and sediments. Deep erosion has exposed porphyry Cu–Au mineralization associated with some granite intrusions (Plesyumi and Esis in Central New Britain). At higher crustal levels, structurally controlled, intrusion-related, low-sulfidation epithermal gold mineralization is locally preserved (Wild Dog, East New Britain). High-sulfidation mineralization in the same district may not be of the same age (Maragorik). Most of the intrusive complexes on New Britain were dated at 30–22 Ma using K–Ar mineral and whole-rock geochronology (Page and Ryburn, 1973).

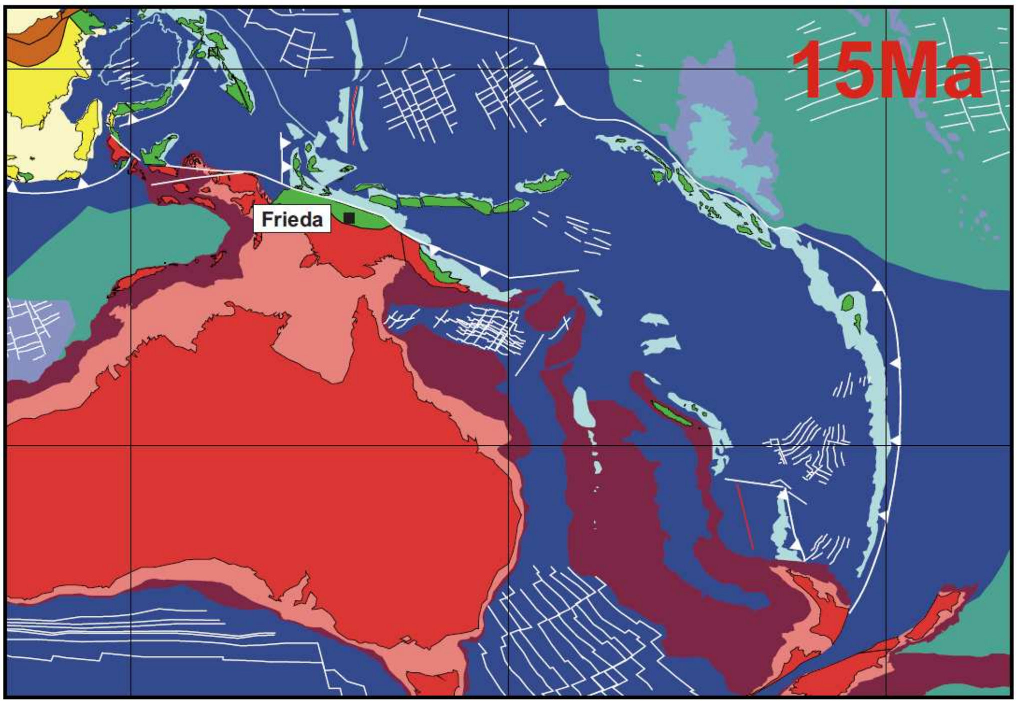


Figure 12. Snapshots showing the plate tectonic reconstructions of Hall (2002) for the New Guinea region. Modified from Hall (2000). (12 E- 15 Ma)

Jamming of the Kilinailau Trench at 22–20 Ma initiated a southwest-dipping subduction zone at the Trobriand Trough (Maramuni Trench of Hall, 2002) at the south-western boundary of the Woodlark Plate. Subduction along this trench system was responsible for Maramuni Arc magmatism (Rogerson et al., 1987b).

The Maramuni Event (of the Maramuni Arc; Dow, 1977) is primarily Miocene in age, with a peak in magmatic activity between about 17 Ma and 10 Ma (Findlay et al., 1997b), although Findlay (2003) argued that magmatism continued uninterrupted into the Pliocene. The event represents the main period of magmatism and related mineralization on mainland Papua New Guinea. It forms a belt of intrusions 750 km long and 40–60 km wide from the Indonesian–PNG border, to the Wau district south of the Huon Gulf, and sporadically into the offshore Papuan Islands (e.g. Woodlark Island). In the central part of the New Guinea Orogen uplift and erosion has exposed granite batholiths of the Maramuni Event: for example, the Morobe Granodiorite (Wau–Bulolo), the Bismarck Intrusive Complex (Yandera), and the Akuna Intrusive Complex (Kainantu area), each of which host younger intrusions with associated Cu–Au mineralization. The Nena–Frieda and Wafi porphyry–epithermal Cu–Au hydrothermal systems represent some of the main events related to the Maramuni Event (Figs 12e,f).

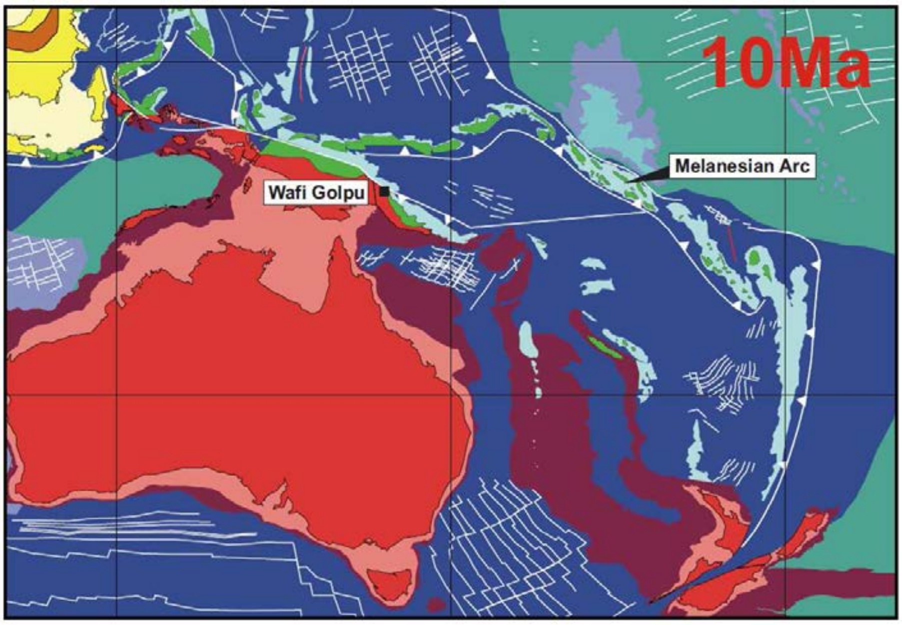


Figure 12. Snapshots showing the plate tectonic reconstructions of Hall (2002) for the New Guinea region. Modified from Hall (2000). (12 F- 10 Ma)

At Wafi, porphyry Cu–Au mineralization is capped by high-sulfidation gold mineralization and surrounded by low-sulfidation gold mineralization. The mineralization is localised by prominent north-northeast-trending structures, possibly originally developed as Mesozoic rift-related faults. While some workers place similar trending structures in the vicinity of the Frieda porphyry Cu–Au and adjacent Nena Cu–Au deposits, the location of the mineralization may have been controlled by dextral strike-slip movement on arc-parallel structures (Corbett, 1994; Corbett and Leach, 1998). The porphyry intrusions may have been localised on a splay off the Fiak–Leonard Schultze Fault. Intrusions began to be emplaced in the Frieda area at about 17 Ma, but much of the mineralization is interpreted to have developed in the waning stages of magmatism at about 11.9 Ma (Hall et al., 1990). At Yandera, mineralization is thought to be related to small porphyry bodies dated at c. 6.5 Ma (Grant and Nielsen, 1975) that intrude the main mass of the Bismarck Intrusive Complex which was emplaced at 14–12 Ma (Page, 1976).

Farther south at Porgera, high-level porphyry intrusions that are related to Au–Ag mineralization, were emplaced at about 5.9 Ma (Ronacher et al., 2002; Fig. 12g). This intrusive complex includes alkali basalts and gabbro with intra-plate chemical affinities (Richards et al., 1990). Hill and Hall (2003) suggested that the New Guinea Orogen was in compression at the time, and that only small volumes of magma could be emplaced into local dilational sites, such as at the intersection of old extensional faults and northeast-trending transfer structures. Although arguments are commonly advanced for the favourable structural setting of many deposits in retrospect, it seems that no specific structural setting is responsible for the location of very large porphyry-style and epithermal deposits (Sillitoe, 1997).

At about 10 Ma, northward-directed subduction was initiated along the contiguous New Britain and San Cristobal Trenches on the northern and eastern sides of the Solomon Sea (see Fig. 12f). In conjunction with subduction along the Trobriand Trench, the Woodlark Plate began to shrink rapidly. At about the same time, or slightly later, spreading began along an east-trending transform fault representing the eastern extension of the Trobriand Trench, thus forming the Woodlark Basin (Hall, 2002). The opening of the Woodlark Basin divided the Papuan Islands by rifting at an estimated rate of 150 mm/y over the past 3.5 m.y. (Benes et al., 1994; Taylor et al., 1999). By about 5 Ma the Trobriand Trench was inactive, with subduction mainly directed northwards underneath the New Britain Arc, which was then rapidly converging on the Papuan Peninsula (Hall, 2002).

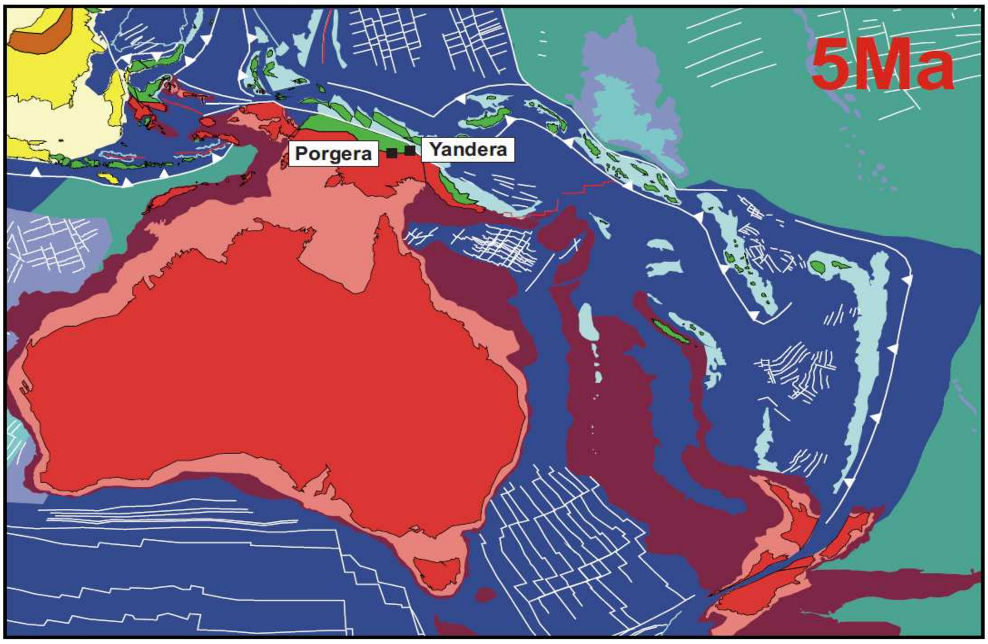


Figure 12. Snapshots showing the plate tectonic reconstructions of Hall (2002) for the New Guinea region. Modified from Hall (2000). (12 G- 10 Ma)

One of the greatest manifestations of collision-related shortening on mainland Papua New Guinea was the development of a foreland fold-and-thrust belt, particularly in the western part of the orogen, where sedimentary rocks of the Papuan Basin were extensively deformed and thrust southwards from the late Miocene to the present (Rogerson et al., 1987a). Substantial uplift (>4 km) began at about 8–5 Ma ago across central and northern New Guinea following collision with, and obduction of, the Melanesian Arc (Finisterre Terrane) (Abers and McCaffrey, 1994; Crowhurst et al., 1996; Hill and Raza, 1999; Milsom et al., 2001). Cloos et al. (2005) suggested that mantle upwelling and uplift of New Guinea was caused by delamination of the Australian Plate. This uplift is reflected in the Papuan Basin by the late Pliocene and Pleistocene influx of siliciclastic sediment from the rising mountain chain, which has buried the late Oligocene to early Miocene carbonate platform (Struckmeyer, 1990). This siliciclastic sediment load into the foreland basin has continued to the present day. It was at about 8–5 Ma ago that the present-day sinistral transpressional setting along this plate margin was established (Fig. 12g).

Pliocene (5.3–2.6 Ma)

The Miocene–Pliocene boundary roughly coincides with another major change in plate motions in the southwest Pacific, most of which can be traced until the present; for example, subduction had ceased along the southern margin of the Solomon Sea leaving the Trobriand Trough as a relict trench (Fig. 12g), and rapid westward migration of the Woodlark Basin spreading centre started "…ripping open the Papuan Peninsula and forming core complexes in advance of the propagating tip" (Hall, 2002; Baldwin et al., 2004) in response to slab-pull forces at the New Britain Trench (Hill and Hall, 2003). Subduction continued along the northward-dipping New Britain Trench and the contiguous north-eastward-dipping San Cristobal Trench under the Solomon Islands. Subduction was responsible for substantial volumes of Pliocene magmatism, although individual volcanic centres may have been active since the late Miocene. Since 3.5 Ma, the Manus Basin to the north of New Britain has opened by seafloor spreading in the eastern part of the basin and by sinistral strike-slip displacement on associated transform faults (Taylor, 1979). The very fast rate of sea floor spreading in the basin has been linked to the arrival of a plume (Hall, 2002).

On mainland Papua New Guinea, the Finisterre Terrane, which represents the western part of the Maramuni Arc, docked with the mainland in the late Miocene (e.g. Jaques and Robinson, 1977; Davies et al., 1996) or Pliocene (Abbott et al., 1994; Abbott, 1995; Weiler and Coe, 2000). The Finisterre Terrane appears to be rotating clockwise as a rigid body with convergence along a sinistral strike-slip margin (Ramu–Markham Fault) that has evolved to one with nearly orthogonal convergence (Weiler and Coe, 2000). The Ramu–Markham Fault represents the onshore extension of the New Britain Trench to the east. At the New Guinea Trench along the southern margin of the Papuan Peninsula, Hall (2002) suggested that "…limited and poorly-defined subduction…" at this trench began only at about 5 Ma.

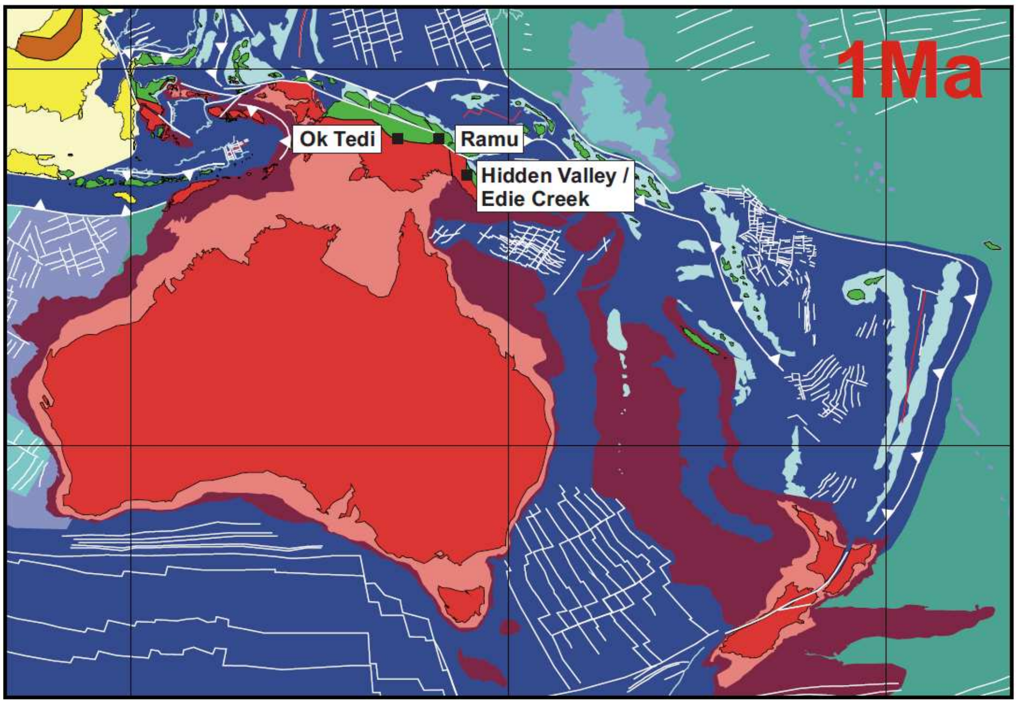


Figure 12. Snapshots showing the plate tectonic reconstructions of Hall (2002) for the New Guinea region. Modified from Hall (2000). (12 H- 1 Ma)

Latest Miocene magmatism due to rapid unroofing of the Maramuni Arc continued into the early Pliocene. In the eastern part of the orogen, porphyry Cu–Au mineralization developed at Mt Bini. Adularia–sericite-style, low-sulfidation gold veins at Tolukuma developed in the possible rifted margin of a major volcano-plutonic complex. The Morobe Goldfield at Wau–Bulolo is developed within the Pliocene Wau Basin. Northwest-trending ?extensional structures localise the Edie Porphyry intrusions dated at between 4 Ma and 3 Ma by K–Ar dating on biotite (Page and McDougall, 1972), along with phreatomagmatic breccias, and associated mineralization.

Pleistocene and Holocene (2.6 Ma–present)

Magmatic activity along the Tabar–Lihir–Feni–Tanga island chain is thought to be unrelated to subduction at the New Britain Trench (Rogerson et al., 1989), but it may have been localised by an earlier structural grain derived from the Kilinailau Trench. Individual volcanic centres (Lihir, Tabar Island; Fig. 12h) are aligned along fanned north-trending structures possibly formed as tension fractures as the downward moving Woodlark Plate was progressively deformed. Gold-rich, high-K to shoshonitic magmatism along this island chain started at about 3.7 Ma, coincident with opening of the

Manus Basin to the west, and continued until at least the Holocene (Johnson et al., 1976; Wallace et al., 1983). Magmatism is interpreted to have been derived from melting of refertilized lithospheric mantle during extension and splitting of a stalled subduction zone (Wallace et al., 1983; Johnson, 1987; McInnes and Cameron, 1994). This magmatism is associated with epithermal-style mineralization, including the giant Ladolam deposit on Lihir.

Pliocene to Quaternary volcanism also developed in another arc stretching for 1000 km from close to the north coast of Papua New Guinea in the Sepik region, eastward through the Schouten Islands, Manam, Karkar, Bagabag, Long and Umboi, and then along the north coast of New Britain as the Mt Andewa and Mt Schrader stratovolcanoes, to the Willaumez Peninsula, Hoskins and East New Britain, again mimicking an earlier structural grain. In the western part of the orogen, the Ok Tedi intrusions were emplaced at about 1.4–1.1 Ma (van Dongen et al., 2010) into north-northeast-trending structures, which possibly formed during Mesozoic rifting of the continental margin.

Massive high-grade sulfide mineralization currently being deposited from black smokers in the Manus Basin forms the target of major offshore exploration and likely development.

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