Cenozoic volcanism, tectonics and mineralisation of Woodlark Island (Muyuw), eastern Papua

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Abstract

Cenozoic geology of Woodlark Island was influenced by events prior to the onset of continental rifting at *ca* 8 Ma and the slightly later commencement of seafloor spreading in the eastern Woodlark Basin between *ca* 6–3.6 Ma. The embryonic Woodlark Island consisted of latest Paleocene(?)–Eocene shallow marine, deep-water shelf and turbidite deposits (Loluai Formation) and small submarine and emergent mafic volcanic centres (Utavai Basalt Member). Platform carbonates extended across the Woodlark Basin in the late Oligocene–middle Miocene (Nasai Limestone). Onset of middle Miocene eruptions in the north-northeast-trending Okiduse Volcanic Zone (OVZ) were localised in the similarly trending Kulumadau Horst and Graben Zone (KHGZ). Volcanic centres flanked major structures in the 12.5 km wide horst and graben zone, suggesting a link between volcanism and extensional tectonics. It was not an island arc settling and there are neither andesites nor an obvious subduction zone. Offshore the KHGZ is connected with the similarly trending Nubara Fault, the plate boundary between the Solomon Sea Plate and Woodlark Plate. Contrasting volcanic deposits were erupted from volcanoes of the OVZ, *viz.* Mt Kabat Eruptive Centre, Uvarakoi Caldera, Watou Mountain Eruptive Centre and Suloga Harbour Tuff Cone. The epithermal Busai and Kulumadau gold deposits are located in the KHGZ. They are hosted by porous and permeable crystal lithic lapilli tuff beds in the Monasiy Tuff (Uvarakoi Caldera). Emplacement of thick dolerite sills (Auyed Dolerite) occurred post-middle Miocene. Sill emplacement coincided with the *ca* 6–3.6 Ma commencement of seafloor spreading in the eastern Woodlark Basin. A major phase of extensional tectonics along the KHGZ commenced post-middle Miocene and has persisted to the Holocene. Uplift was accompanied by rapid erosion and the widespread deposition of poorly to chaotically sorted gravels (Na'ku'iel Conglomerate).

KEY POINTS

1. Middle Miocene volcanism occurred from four volcanic centres in the north-northeast-trending Okiduse Volcanic Zone.
2. Volcanism was confined to the similarly north-northeast-trending Kulumadau Horst and

   Graben Zone. Volcanism was not located in an island arc setting as there are neither andesites nor an obvious subduction zone.
3. A major phase of extensional tectonics along the horst and graben zone commenced post-middle Miocene and has persisted to the Holocene.
4. Both the epithermal Busai and Kulumadau gold deposits exhibit lithological controls (porosity and permeability) on ore deposition.

KEYWORDS: Eastern Papua; Kulumadau Horst and Graben Zone; Miocene volcanism; Okiduse Range; Okiduse Volcanic Zone; Suloga Peninsula; Woodlark Basin Spreading Centre; Woodlark Island; Murua (Woodlark) goldfield

Introduction

Woodlark Island in southeast Papua, traditionally known as Muyuw or Muyua (Damon, 1990; Lithgow & Lithgow, 1974), provides an exposure of Cenozoic geology close to the Woodlark Basin Spreading Centre (Lindley, 2016). Detailed 1:12 500 scale geological mapping of the pre-Pleistocene rocks of Woodlark Island commenced 28 years ago in 1992 in the Okiduse Range (Lindley, 1993, 1994). This mapping utilised modern advances in the facies analysis of pyroclastic deposits. The mapping of the middle Miocene Okiduse Volcanic Group, host to most of Woodlark Island's historical gold and silver production and recently defined mineral resources, resulted in a detailed subdivision of the volcaniclastic sequence, elevation to group status and the recognition of two major volcanic centres that erupted synchronously during the middle Miocene (Lindley, 2016). These centres were referred to as the Watou Mountain Eruptive Centre and the Uvarakoi Caldera (Lindley, 2016). This study describes the final phase of systematic 1:12 500 geological mapping, of the Suloga Peninsula and in the southeast Okiduse Range (Figure 1) during a seven-week period between August–October 2018. The completion of 1:12 500 geological mapping of the sequence predating the Kiriwina Formation has necessitated a review of the volcanism, tectonics and mineralisation of Woodlark Island.

Regional tectonic setting of Woodlark Island

Woodlark Island is located in a tectonically complex region, one of the few places on Earth where continental breakup is occurring ahead of seafloor spreading (Wallace *et al.*, 2014). The reader is referred to Wallace *et al.* (2014) and Lindley (2016) for a discussion of regional tectonic setting of Woodlark Island.

Cenozoic geology of Woodlark Island

A description of previous geological work on Woodlark Island is contained in online data files. Various interpretations of the Cenozoic geology of the island resulting from this work are presented in Figure 2. The present interpretation of the Cenozoic stratigraphy of Woodlark Island is summarised in Table 1 and described in detail in online data files. Most of the 850 km^2 Woodlark Island is covered by Pleistocene raised coralline limestone and blue-grey marine claystone (Kiriwina Formation). It is only in the central southern sections of the island in the Okiduse Range, Suloga Peninsula and the Kulumadau area that metamorphosed basement rocks (Loluai Formation), late Oligocene–middle

Miocene limestone (Nasai Limestone), volcanic rocks and associated sediments (Okiduse Volcanic Group), post-middle Miocene dolerite sills (Auyed Dolerite) and post-middle Miocene conglomerate (Na'ku'iel Conglomerate) are exposed (Figure 3).

Basement geology

Outcrop of metamorphosed basement rock is restricted to the Suloga Range and southeast Okiduse Range. The Loluai Formation (amended name) is dominated by fine and very fine-grained sandstone typical of deep-water shelf or turbidite fan facies (Figure 4). Organised conglomerates are common in the southeastern Suloga Range and rarely found in the southeast Okiduse Range and are interpreted as deposits of the slope-channel facies association of a turbidite fan (Figure 4). In the southeast Okiduse, where the formation is intercalated with subaerial volcanic deposits of the Utavai Basalt Member (new name), fine-grained sandstone, siltstone and lensoidal conglomerate sequences are interpreted to have been deposited in a shallow marine shelf environment. There is no internal evidence for the age of these rocks. An inferred latest Paleocene(?)–Eocene age has been derived using paleontological evidence from overlying formations (Joseph & Finlayson, 1991).

The Utavai Basalt Member is sporadically exposed at sea level on the western coast of the Suloga Range and on Suloga Point. It extends below sea level. It is also exposed in the southeast Okiduse Range in the U'sei'siy River and Bugitai River. The member on the Suloga Peninsula consists of basalt, commonly with well-developed pillow structure, and is submarine in origin (Figure 5). Ashley and Flood (1981) described these rocks as low-K tholeiitic volcanic rocks of midocean ridge basalt affinity. In the headlands east of Saula'goi Creek and near Utavai village (Utavai Gorge measured section, Figure S2) on the west coast of the Suloga Peninsula the member is intercalated with and overlain by deep-water sedimentary rocks of the Loluai Formation. Ballistic basalt blocks are found in the fine-grained sandstone and siltstone immediately near their contact with the Utavai Basalt Member (Figure 4c). Deformation of beds is associated with bomb emplacement. The deep-water shelf and turbidite deposits and the basalt member are contemporaneous. The low-K tholeiitic basalts are thought to have accumulated in seamounts, likely associated with incipient rifting and seafloor spreading in the proto-Woodlark Basin. The Franklin Seamount described by Binns *et al.* (1993) east of Normanby Island, and near the western propagating tip of the Woodlark Basin seafloor spreading axis, is a good modern-day analogue.

By contrast, the Utavai Basalt Member in the southeast Okiduse Range consists of metamorphosed subaerial block and ash deposits, fine-grained mafic rock (basalt/andesite), fall deposits and crystal lithic tuff associated with high-level monzodiorite/monzonite porphyry (Figure 6). The abundance of basaltic fall and pyroclastic deposits in the U'sei'siy River and Bugitai River suggests subaerial volcanism. The association of fall and pyroclastic deposits with high-level monzodiorite/monzonite intrusive rocks suggests they were probably part of the vent association. This part of the proto-Woodlark Island was clearly emergent.

Late Oligocene to middle Miocene platform carbonate deposition

Platform carbonate deposition occurred across much of the southwest Pacific during the late Oligocene to middle Miocene, extending from southeast Asia through New Guinea and the Solomon

Islands to Fiji (Lindley, 2006). The Nasai Limestone was part of this vast carbonate platform, formed during a period of tectonically stability with little influx of detritus (Figure 7). A thick sequence of thinly bedded limestone cropping out 1000 m inland from Wa'beu Point, southeast Suloga Peninsula, contains evidence of the onset of middle Miocene volcanism. An outcrop of poorly sorted forereef breccia contains a large mafic ballistic bomb (Figure 8a) and interbedded calcareous sandstones contain at least five thin (5–10 cm) beds of feldspar–biotite crystal lithic tuff (Figure 8d). These airfall tuff beds are thought to be part of the middle Miocene Monasiy Tuff of the Uvarakoi Caldera. Their presence has necessitated a revision of the age of the Nasai Limestone, extending it into the middle Miocene.

Onset of middle Miocene volcanism in the Okiduse Volcanic Zone (new name)

The 17 km long Okiduse Volcanic Zone (new name) comprises four middle Miocene volcanic centres with north-northeast-trending alignment (Figure 3). The 14–12 Ma old volcanic belt, from north to south, includes the Mt Kabat Eruptive Centre (new name), Uvarakoi Caldera, Watou Mountain Eruptive Centre and the Suloga Harbour Tuff Cone (new name). The zone is located within the similarly trending Kulumadau Horst and Graben Zone (new name). The Okiduse Volcanic Group underlies all of the isolated ridges and small hills to the northeast of the Sinkwarai Fault, almost the entire Okiduse Range and a large area north and northeast of the Suloga Range in the Wonai, Mweim and The Ben districts (Figure 3). The group is economically important and is host to most of the island's historical gold production of 5900 kg and the presently defined gold reserves and resources in the Kulumadau and Busai deposits.

Volcanic centres of the Okiduse Volcanic Zone

The Mt Kabat Eruptive Centre is a small structure, with a basal diameter estimated to be about 1.5 km and a height of at least 243 m. The breccia cone is dominated by block and ash deposits.

Uvarakoi Caldera is centred on the Busai–Bomagai area (Figure 3). It is a felsic volcanic system and appears to have erupted synchronously with the Watou Mountain Eruptive Centre. The caldera was formed during a series of violent explosive eruptions by rapid removal of magma from the underlying chamber, followed by collapse (Lindley, 2016). The intracaldera sequence includes the Busai Hill Ignimbrite, and the size of the collapsed caldera is indicated by the 7 km^2 areal extent of this ponded unit (Lindley, 2016). The widely dispersed and highly fragmented tuff deposits of the Monasiy Tuff have been mapped up to 15 km from the caldera on the Suloga Peninsula. These outflow facies tuffs were the result of magma–water mixing in the surface environment. The Uvarakoi Caldera appears to have been small compared with average dimensions of felsic systems. The caldera probably had a lifespan in the order of 10^5 to 10^6 years (Lindley, 2016).

The Watou Mountain Eruptive Centre was a typical moderate-sized composite volcano (or stratovolcano), centred on Boganuse Mountain in the Okiduse Range (Lindley, 2016). The rocks of the Watou Mountain volcano have been divided into lava with high-level intrusive (Boganuse Formation and Kuikébeim Microdiorite), breccia (Nikuben Formation) and epiclastic (Talpas Creek Formation) dominant facies typical of composite volcanoes (Lindley, 2016).These facies girdle Boganuse Mountain, and were interpreted by Lindley (2016) to represent vent, cone-forming and ring plain associations, respectively (Table 1). Lindley (2016) used the mapped extent of facies of the Watou Mountain volcano, slope measurements on modern composite volcanoes and Houghton's (1987) model for the distribution of facies in composite volcanoes, to determine a reconstructed volcano height of 1700 m and a basal diameter of 7 km. The volcano grew during frequent small eruptions of widely varying styles (Lindley, 2016). Eruptions of 10^4 to 10^7 m^3 of magma and frequencies of 10–10 000 years are common (Houghton, 1987). Pyroclastic deposits on the steep cone were rapidly reworked and were redeposited in a series of coalescing aprons (ring plain facies) surrounding the volcano. Ring plain sediments have been mapped as far as 7.5 km southwest of Watou Mountain volcano, in the Wonai district (Figure 3; Sheet 2, online data files).

The Suloga Harbour Tuff Cone is centred on Ukwa'muk'wam Mountain, located on the western shores of Suloga Harbour (Figure 3; Sheet 2, online data files). The small semi-circular tuff cone was built on the ring plain of the Watou Mountain Eruptive Centre during the waning stages of the middle Miocene Okiduse Volcanic Zone. It had a basal diameter of about 1.5 km and height of at least 230 m. The tuff cone, consisting of highly fragmented tuff deposits of the Suloga Harbour Tuff, was constructed during multiple small phreatomagmatic eruptions, the result of magma mixing with shallow surface water (Figure 9).

Discussion

The north-northeast-trending alignment of volcanic centres in the Okiduse Volcanic Zone is similar to that in east New Britain, where a series of volcanic centres known as the Gazelle Volcanic Zone extends for a 65 km length across the Gazelle Peninsula (Johnson *et al.*, 2010). The volcanic centres are localised in a broad extensional zone consisting of the Baining Mountain Horst and Graben Zone on the Gazelle Peninsula and extending offshore into St George's Channel Trough (Lindley, 1988, 2006). Volcanism in the Gazelle Volcanic Zone ranges from earliest Miocene in the south (Lindley, 1998) to Holocene in the north (Johnson *et al.*, 2010).

Volcanic centres of the Okiduse Volcanic Zone closely flank major structures in the Kulumadau Horst and Graben Zone, suggesting a link between volcanism and extensional tectonics. The volcanic zone is located entirely in the horst and graben zone. It is not an obvious island arc settling and there are neither andesites nor an obvious subduction zone. The Kulumadau Horst and Graben Zone is connected with the Nubara Fault, a similarly aligned seafloor structure with a 300 km strike extent. The Nubara Fault is considered to be the plate boundary between the Solomon Sea Plate and the Woodlark Plate (Fitz & Mann, 2013; Wallace *et al.*, 2014).

Commencement of spreading on the Woodlark Basin Spreading Centre and the emplacement of the Auyed Dolerite (new name)

Three large dolerite sills (each ~200 m thick) inland from Kwegai, Loluai, Utavai and Auyed, on the western coastline of the Suloga Peninsula, are concordant with the deep-water sediments of the Loluai Formation (Figure 10; Sheets 2 and 3, online data files). Numerous narrow sills (<1 m thick) are also present (Sheet 3, online data files). Dolerite sill rock crops out on Uskweilele Mountain on Suloga Point and on Mapas Island, in the entrance to Suloga Harbour. Dolerite also occurs as discordant sheets, narrow dykes and dyke-like protrusions from sills. The presence of a narrow dolerite dyke cross-cutting the late Oligocene–middle Miocene Nasai Limestone west of Suloga Point (Figure 10b) suggests dolerite emplacement was post-middle Miocene. This age for dolerite emplacement on Woodlark Island is in agreement with the Taylor *et al.* (1999) and Taylor & Huchon (2002) estimate of the onset of continental rifting in the region, at around 8 Ma, and the slightly later commencement of seafloor spreading in the eastern Woodlark Basin (east of 151.5°E), between *ca* 6–3.6 Ma.

The volume of emplaced dolerite preserved on Woodlark Island is estimated to be between 5–10 km^3. This is a relatively small volume by comparison with the large 15 000 km^3 of dolerite intruded into the flat-lying Permian–Triassic Parmeener Super Group, Tasmania (Hergt, 1987). Significant dolerite sill development is expected to be present in the submarine geology of the broad and relatively shallow Woodlark Rise surrounding Woodlark Island.

Horst and graben tectonics, basement uplift and deposition of the Na'ku'iel Conglomerate (new name)

Although they are a relatively minor component of the sedimentary record, coarse grained alluvial deposits have considerable importance because of their tectonic significance (Rust, 1983). The sedimentary record preserved in the extensive gravels of the Na'ku'iel Conglomerate provides an insight into the tectonic history of the Kulumadau Horst and Graben Zone (Figures 11 and 12). The predominantly clast supported unit is distinctive for its chaotic sorting and clast composition dominated by resistant hard lithologies. Megaclasts are in excess of 5–10 m size (Figure 12a). Clasts are angular to subangular and are overwhelmingly dominated by metamorphosed siltstone and sandstone of the Loluai Formation. Well-rounded, large and tough granite clasts are present in the southeast Okiduse Range near 'Camp Creek' (Figure 11b), beside the Guasopa Road east of the Sinkwarai River crossing (Figure 11c) and along the eastern shoreline of Suloga Harbour. Matrix supported gravel deposits (or debris flow deposits) have been noted in middle Bulbem Creek in the southeast Suloga Range (Sheet 2, online data files). Sharp-edged angular clasts of fine-grained indurated siltstone ('Suloga stone') are set in an unstratified muddy sand matrix (Figure 12c). The obvious source for the siltstone may be To'bu'kui Mountain, 1.5 km to the northwest and the quarry site of 'Suloga stone'.

Tectonic movements played a key role in the deposition of the Na'ku'iel Conglomerate. Sustained and rapid uplift along major normal faults of the Kulumadau Horst and Graben Zone resulted in the juxtaposition of metamorphosed basement rocks of the Loluai Formation against less-resistive middle Miocene volcanic rocks of the Watou Mountain Eruptive Centre (Figure 3). The axis of maximum uplift extended north-northeast through To'bu'kui Mountain and Kuikébeim Mountain towards the Sinkwarai River. The depositional environment in which the Na'ku'iel Conglomerate accumulated was particularly humid and mountainous with an abundant sediment supply. The proximal reaches were characterised by extremes of precipitation and streams with short fetches and steep gradients, providing little likelihood of any significant sorting. Stratification is typically absent. However, a rare exposure of stratified rocks of the Na'ku'iel Conglomerate located east of the Wa'beu Fault in the southeast Suloga Range (Figure 12b, Sheet 2, online data files) contains a fining upward sequence, interpreted as indicating pulsating cycles of uplift and erosion. Energetic uplift resulted in proximal deposits dominated by mass wasting and sediment gravity flows, including landslide deposits, debris flows and alluvial fan deposits. Lobes of multiple debris flows can be seen on the west coast of Suloga Peninsula extending south from Norac (Figure 12d). The preservation potential of coarse alluvial deposits in such a tectonically dynamic environment may be expected to be low. Therefore, it is of interest to note that the measured thickness of the Na'ku'iel Conglomerate ranges from 179 m to 237 m in the two unnamed streams, in the southeast Suloga Range, designated type locality.

The distal reaches of the Na'ku'iel Conglomerate are exemplified by auriferous conglomerate exposures along Taneigas Ridge at Great Northern and Waiakum. Matrix supported deposits are moderately sorted, with a maximum clast size about 20 cm, commonly with a clay matrix. Distinctive clasts of rocks of the Loluai Formation, with characteristic rind and fluted surfaces (Figure S10a online data file), represent about 40% of clast composition. Ignimbrite clasts, that can only have been sourced from the Busai Hill Ignimbrite, make up 25% of clasts. The presence of these clast lithologies suggests that the auriferous Na'ku'iel paleo-stream passed through the Busai–Bomagai area and had its headwaters in either or both the Okiduse Range and Suloga Range.

Duration of tectonic activity along the Kulumadau Horst and Graben Zone

The alignment of middle Miocene volcanic centres of the Okiduse Volcanic Zone, parallel with and flanking major structures of the Kulumadau Horst and Graben Zone, is the earliest evidence of the influence of this structural zone. The deposition of the Na'ku'iel Conglomerate indicates the horst and graben zone continued to be tectonically active post-middle Miocene. The horst and graben zone remains active, as evidenced by exposures of the Na'ku'iel Conglomerate overlying the upper Pleistocene Kiriwina Formation in the southeast Okiduse Range and significant Holocene uplift, or arching, of the Kiriwina Formation on Taneigas Ridge and adjacent the Taneigas Ridge Fault (new name).

Epithermal gold mineralisation

The epithermal Busai and Kulumadau gold deposits are located in the Kulumadau Horst and Graben Zone. The Busai deposit has recently been studied by Cameron (2017) and the Kulumadau deposit by Burkett *et al.* (2015) and Cameron (2017). Cameron's (2017) study of both deposits was thorough, based on lithological, alteration and structural logging of 4454 m of drill core, the compilation of detailed sections and plans and field traversing.

Cameron's (2017) work has confirmed the similarities between gold mineralisation at Busai and Kulumadau, with both deposits exhibiting lithological controls (porosity and permeability) on ore deposition, as described by Lindley (1993, 2016). In particular, mineralisation in both deposits is hosted in a reddened (hematite altered) feldspar-rich, crystal lithic lapilli tuff horizon in the upper part of the lower Monasiy Tuff of the Uvarakoi Caldera. Cameron (2017) noted that at Busai, the bedding parallel mineralisation is associated with incipient hydrothermal brecciation. This is due to the overlying Busai Hill Ignimbrite, which acted as a relatively impervious cap rock, pooling early fluids within more permeable units of the underlying Monasiy Tuff (Cameron, 2017; Lindley, 2016). The incipient brecciation of an over-pressured fluid reservoir preceded fault rupture and irreversible decompression of the fluid, leading to chemical changes that controlled gold deposition (Cameron, 2017). Cameron (2017) also noted that both deposits are traversed by northeast-trending structures, undoubtedly related to the Kulumadau Horst and Graben Zone.

The Kulumadau deposit contains remnants of an early breccia phase with clasts of diorite (with rare bornite and D-type veining suggestive of porphyry copper affinities), dolerite (with magnetite alteration) and wallrock thought to have been plucked from surrounding walls during the ascent of hydrothermal fluids (J. Kerr, pers. comm., 2020). An important difference between the Busai and Kulumadau deposits is the amount of overprinting by zones of clay ± carbonate rock and associated argillisation in the latter deposit (Cameron, 2017). Rare wood fragments have also been noted in these rocks (J. Kerr, pers. comm., 2020). These fragments were likely drawn down from the surface following a maar eruption and the collapse/consolidation of vent material. The deposit-wide cross-sections of Cameron (2017) indicate that the clay rocks form a network of anastomosing, steeply plunging zones with individual segments up to 40 m wide (*e.g.* drillhole BKLD002). The origin of these clay ± carbonate zones is controversial. Cameron (2017) considered them to be the result of cataclasis (*i.e.* brecciation and comminution). However, Burkett *et al.* (2015) interpreted them as phreatic or phreatomagmatic breccias (Table 1). Burkett *et al.* (2015) (Figure 3, Cross-section 8995875, Unit 5 and Unit 6) depicted two steeply dipping clay-altered pipe-like breccia bodies 75–100 m wide, each flanked by stringers of monolithologic breccias, with the >1 g/t Au zone confined to the breccia bodies. The Kulumadau deposit may be associated with a diatreme and the overprinting anastomosing network of clay zones and associated argillic alteration may be the result of late-stage gas streaming through the collapsed/consolidated structure.

The strong hematite alteration at Busai and Kulumadau is part of an early propylitic assemblage of chlorite–hematite–calcite (Cameron, 2017). At both Busai and Kulumadau the best gold grades (>2 g/t Au) are associated with increasing complexity of paragenesis. Early hematite–jasperoid ± silica ± pyrite veinlets and breccias usually carry low grades or are barren (Cameron, 2017). High grades of gold mineralisation are related to an overprinting of the early alteration event with later carbonate ± quartz–pyrite ± sphalerite and galena veinlets and veins (Cameron, 2017).

Cenozoic geological history of Woodlark Island

Cenozoic volcanism and tectonics on Woodlark Island were influenced by events prior to the onset of continental rifting in the region at around 8 Ma and the slightly later commencement of seafloor spreading in the eastern Woodlark Basin between *ca* 6–3.6 Ma. The embryonic Woodlark Island consisted of latest Paleocene(?)–Eocene shallow marine and deep-water shelf and turbidite deposits of the Loluai Formation and small submarine and emergent mafic volcanic centres of the Utavai Basalt Member.

Tropical to sub-tropical platform carbonates extended across the region during the late Oligocene. On Woodlark Island, the late Oligocene–middle Miocene Nasai Limestone is unconformable on the latest Paleocene(?)–Eocene units, and consists of pale and dark grey massive limestone, thinly bedded limestone, forereef breccia and calcareous sandstone. A thick sequence of thinly bedded limestone cropping out 1000 m inland from Wa'beu Point, southeast Suloga Peninsula, contains evidence of the beginning of middle Miocene volcanism. A poorly sorted forereef breccia outcrop contains a large mafic ballistic bomb and interbedded calcareous sandstones contain at least five thin (5–10 cm) beds of feldspar–biotite crystal lithic tuff. These airfall tuff beds are thought to be part of the middle Miocene Monasiy Tuff.

The middle Miocene (14–12 Ma) eruptions from the north-northeast-aligned Okiduse Volcanic Zone were localised in the similarly trending Kulumadau Horst and Graben Zone. Volcanic centres closely flank major structures in the 12.5 km wide extensional zone, suggesting a link between volcanism and extensional tectonics. It is not an obvious island arc settling and there are neither andesites nor an obvious subduction zone. Offshore, the Kulumadau Horst and Graben Zone is connected with the similarly trending Nubara Fault. This fault is the plate boundary between the Solomon Sea Plate and the Woodlark Plate. The contrasting volcanic deposits of the Okiduse Volcanic Group were erupted from a series of volcanic centres, including (from north to south) the Mt Kabat Eruptive Centre, Uvarakoi Caldera, Watou Mountain Eruptive Centre and Suloga Harbour Tuff Cone. The epithermal Busai and Kulumadau gold deposits are located in the Kulumadau Horst and Graben Zone. The deposits are hosted in lithologically favourable porous and permeable crystal lithic lapilli tuff beds in the Monasiy Tuff of the Uvarakoi Caldera.

During the middle Miocene, north–south-striking felsic dyke and minor mafic dyke swarms were intruded within the Kulumadau Horst and Graben Zone. Dyking was likely in response to renewed extensional activity in the horst and graben zone.

Emplacement of thick dolerite sills (each ~200 m thick) of the Auyed Dolerite occurred post-middle Miocene. Most of the dolerite sill rock is thought to be contained in the submarine geology of the broad and relatively shallow Woodlark Rise surrounding Woodlark Island. A mechanism of dolerite intrusion similar to the Tasmanian dolerites is likely to have occurred on Woodlark Island, with intrusion as a large cone sheet and magma rising through much of the crust confined to relatively narrow conduits. Lateral migration within the sedimentary rocks of the Loluai Formation occurred because of the density contrast between the magma and the relatively thin sedimentary sequence, and the greater work required in the dense magma plumbing its way to the surface. Regional dyking appears to have been in response to extension related to the onset of continental rifting (*ca* 8 Ma) and the emplacement of the dolerite sills of the Auyed Dolerite coincided with the slightly later (*ca* 6–3.6 Ma) commencement of seafloor spreading in the eastern Woodlark Basin.

A major phase of extensional tectonics along the Kulumadau Horst and Graben Zone commenced post-middle Miocene and has persisted to the Holocene. The sedimentary record preserved in the extensive gravels of the Na'ku'iel Conglomerate provides an insight into the tectonics of the horst and graben zone. Energetic post-middle Miocene tectonic activity resulted in the uplift of metamorphosed basement (Loluai Formation and Utavai Basalt Member) and juxtaposition with middle Miocene volcanic rocks of the Watou Mountain Eruptive Centre. Uplift accompanied rapid erosion and deposition of the poorly to chaotically sorted Na'ku'iel Conglomerate. Proximal deposits are dominated by mass wasting and sediment gravity flows, including landslide deposits, debris flow deposits and alluvial fan deposits. The presence of auriferous gravels of the Na'ku'iel Conglomerate on Taneigas Ridge at Great Northern and Waiakum, containing a high percentage of clasts sourced from the Loluai Formation and the Busai Hill Ignimbrite, suggests the Na'ku'iel paleo-stream passed through the

Busai–Bomagai area and transported coarse, auriferous gravels for distances up to 10 km from headwaters in either or both the Okiduse Range and Suloga Range.

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Disclosure statement

No potential conflict of interest was reported by the author.

Data availability statement

Detailed mapping (three 1:12 500 scale A1-format map sheets and legend) and a revision of stratigraphic and structural units that support the findings of this study are openly available in figshare at http://doi.org/10.6084/m9.figshare.12965156 .

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Figures

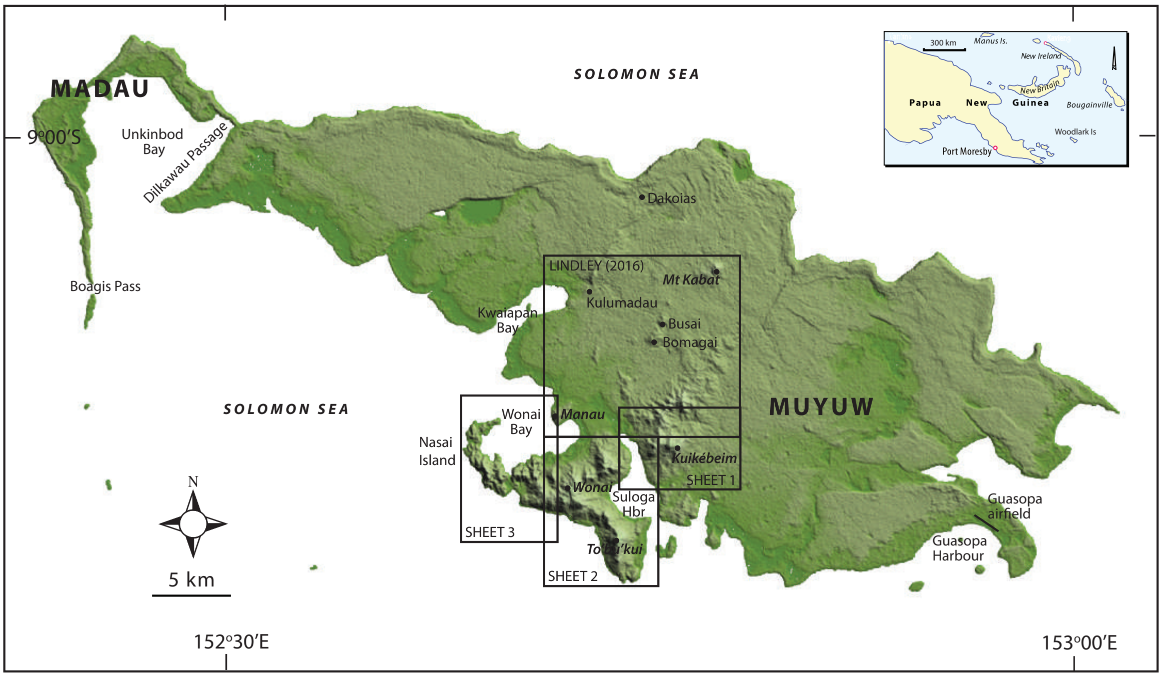

Figure 1. Woodlark Island 1:12 500 mapping project. The mapped area of Lindley (2016) is shown with the present mapping of the Suloga Peninsula and the southeast Okiduse Range (Sheets 1 to 3, online data files). Inset shows location of Woodlark Island in Papua New Guinea.

Stanley (1912)	Trail (1967)	Joseph & Finlayson (1991)	Lindley (2016) & this paper
Alluvial and Coral Limestone	Alluvium, limestone, coral limestone, marine clay, conglomerate	Kiriwina Formation	Kiriwina Formation / Na'ku'iel Conglomerate
Limestone (Tertiary)?			
Granite and Porphyry	Nasai Limestone (Early Miocene) Okiduse Volcanics Wonai Hill Formation Tabukui Beds Suloga Limestone (Early Miocene)	Okiduse Volcanics Wonai Hill beds Nasai Limestone	Okiduse Volcanic Group (Middle Miocene) Uvarakoi Caldera / Watou Mountain Eruptive Centre / Suloga Hbr Tuff Cone Nasai Limestone (Late Oligocene-Middle Miocene)
Sedimentary Metamorphic	Loluai Volcanics	Loluai Volcanics	Loluai Formation Utavai Basalt Member

Figure 2. Correlation of Cenozoic stratigraphy, Woodlark Island.

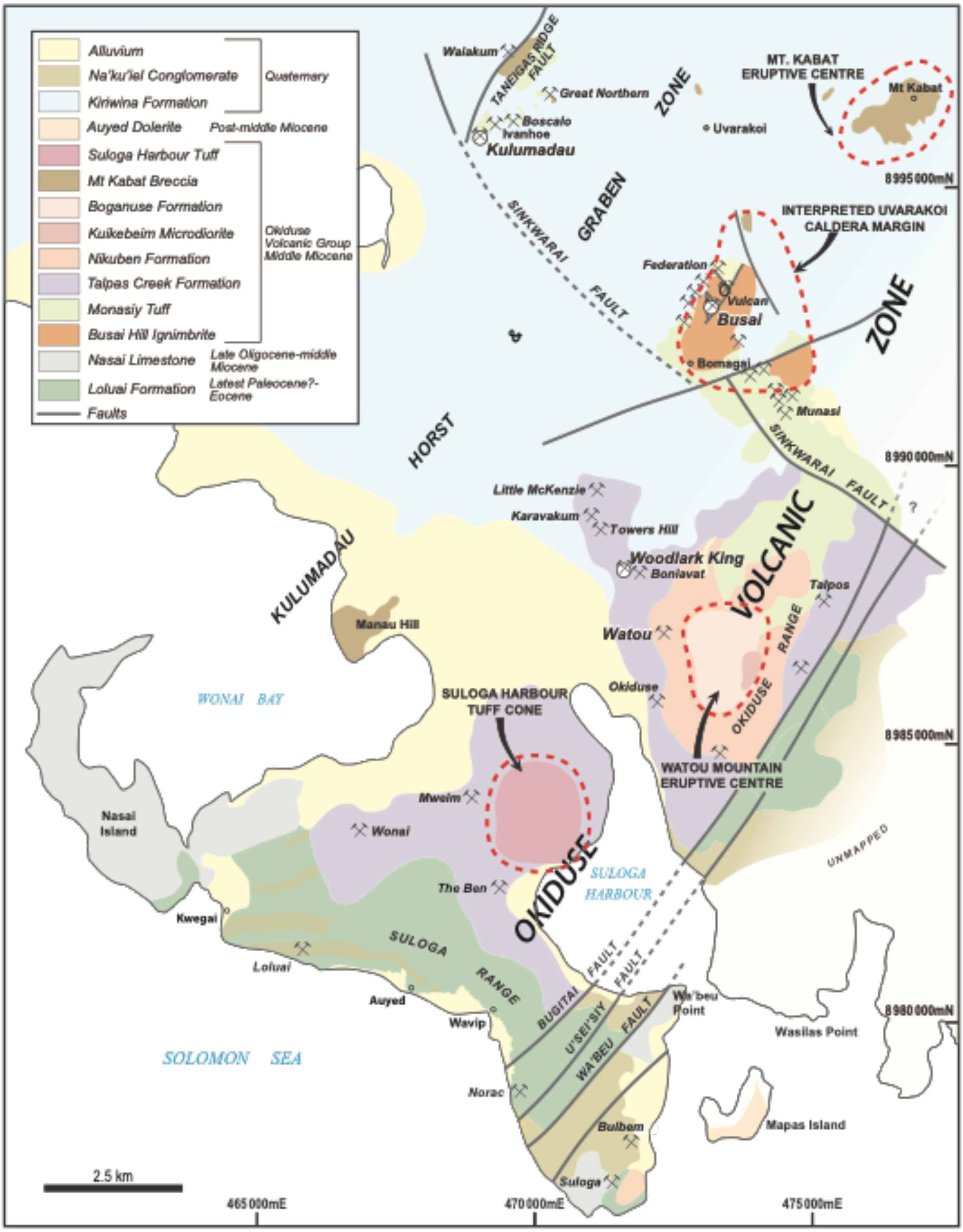

Figure 3. Summary geological map of the Suloga Peninsula, Okiduse Range and Kulumadau area. For simplicity, mafic dykes of the Okiduse Volcanic Group and the numerous meridionally trending Miocene felsic and mafic dykes have been omitted from the map. Detailed maps are included in the online data files.

Figure 4. Loluai Formation. Type section. (a, b) Cliff exposures of turbidite rocks on the coastline, west of Utavai. (c) Basalt ballistic bomb near the base of the Loluai Formation, emplaced at a low angle and associated with deformation of adjacent turbidite beds (right of view), west of Utavai. (d) Syndepositional slumping in sandstone beds near the base of the Loluai Formation, west of Utavai. (e) Laminated chert beds interbedded in the turbidite sequence in the Utavai Gorge. All photographs are located on the measured section (Figure S2 online data files).

Figure 5. Utavai Basalt Member on the Suloga Peninsula. (a, b) Pillows in coastline exposures of basalt near Saula'goi Creek, west of Utavai. (c) Typical outcrop of fractured massive basalt on the headland east of Saula'goi Creek.

Figure 6. Utavai Basalt Member in the southeast Okiduse Range. (a) Lava spatter (block and ash deposit) formed due to lava fountaining during Strombolian eruption. Metamorphosed float boulder in Bugitai River, 475 200 mE/8 984 911 mN. (b) Accretionary lapilli bed in a fall deposit. Rounded lapilli are not of juvenile origin and are thus thought to be accretionary lapilli. Note deformation of bounding ash beds by lapilli. Float, headwaters of Right Hand Branch of U'sei'siy River, 473 994 mE/8 984 168 mN. (c) Nonwelded poorly sorted mafic pyroclastic deposit, interpreted as a deposit of the vent facies of a composite volcano. Bugitai River, 475 074 mE/8 985 002 mN. (d) Nonwelded reversely graded pyroclastic beds. A deposit of the vent facies of a composite volcano. Strike 000°/dipping 30°W, outcrop in Bugitai River, 475 325 mE/8 984 891 mN.

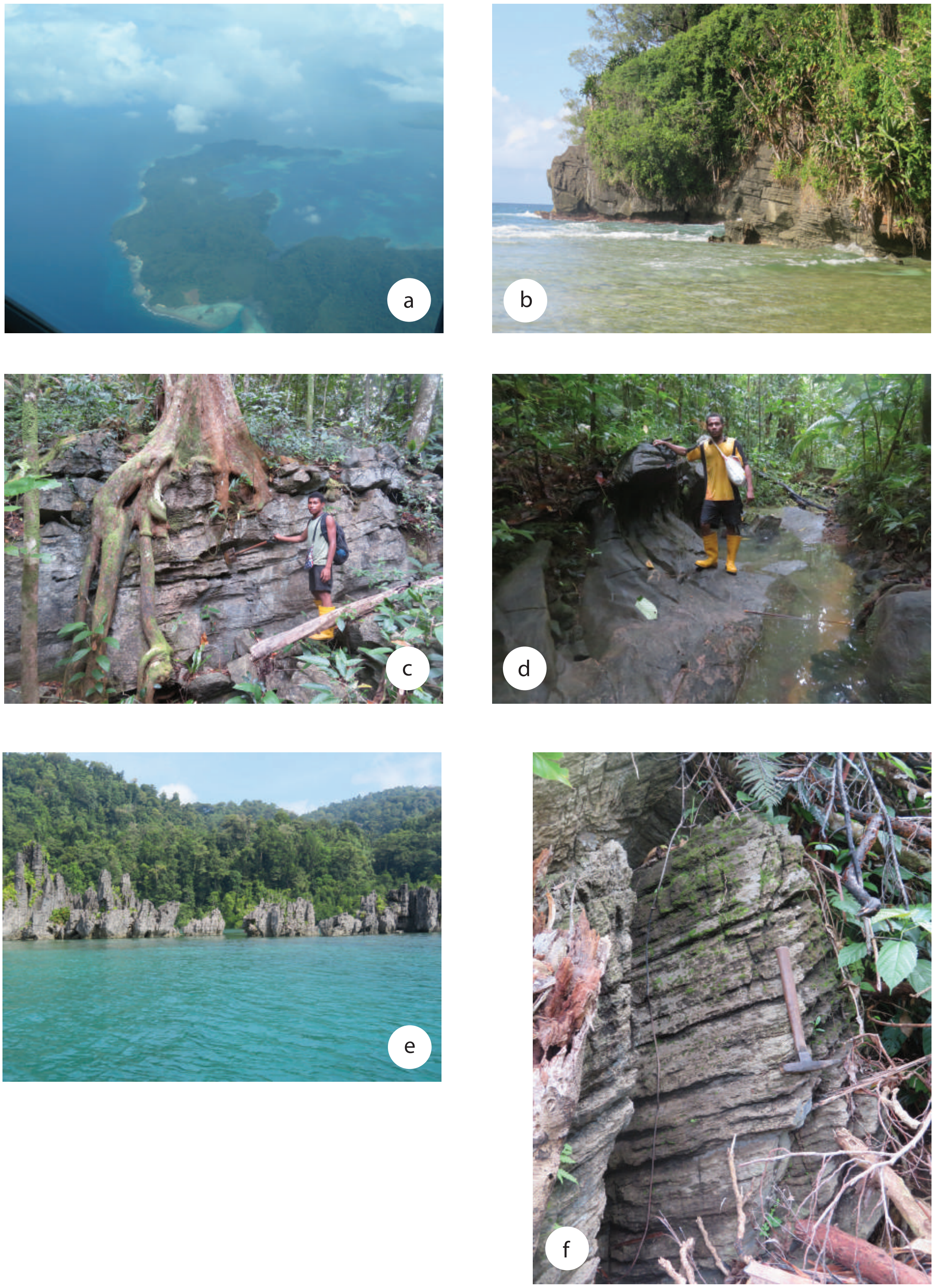

Figure 7. Nasai Limestone. (a) Nasai Island, southern Woodlark Island, is the designated representative section for the formation. The island is separated from the Suloga Peninsula by the north–south Kwegai Passage, located lower right of image. (b) Suloga Point coastal outcrop. (c) Thinly bedded exposure west of Suloga Point, 470 911 mE/8 976 988 mN. (d) Karst in dark grey to black massive limestone, Left Hand Branch of U'sei'siy River, southeast Okiduse Range, near 474 749 mE/8 983 750 mN. (e) Limestone karst developed on the southern shores of Wonai Bay. (f) Thinly bedded limestone near Wa'beu Point, 472 322 mE/8 979 991 mN.

Figure 8. Nasai Limestone talus breccia, southwest of Wa'beu Point. (a) Chaotic limestone talus breccia with a ballistic bomb. (b) Detail of talus breccia. (c) Talus breccia beds strike 330°/25°W. (d) The west-dipping limestone breccia is overlain by calcareous sandstone containing thin beds of feldspar–biotite crystal lithic tuff. Mapping shows these tuff beds are part of the Monasiy Tuff, indicating the Okiduse Volcanic Group conformably overlies the Nasai Limestone and that the formation ranges in age to the middle Miocene.

Figure 9. Suloga Harbour Tuff Cone. (a) Suloga Harbour Tuff Cone, a small 1.5 km diameter, 279 m high cone centred on Ukwa'muk'wam Mountain, on the western shore of Suloga Harbour. (b) Feldspar biotite crystal tuff, a deposit from the cone, headwaters of Lai'ava'kain Creek, 468 439 mE/8 982 223 mN. (c) Surge deposit in a creek 1.7 km SW of cone, 468 750 mE/8 982 668 mN. (d) Collapsed pumices in partially welded ashflow tuff, southwest flanks of cone, 469 325 mE/8 983 140 mN. (e) Monolithologic lahar deposit with clasts of felsic tuff, outcrop on north-northeast flanks of cone, unnamed creek, 470 596 mE/8 984 967 mN. (f) Plinian fall deposit, southwest flank of the cone, 469 325 mE/8 983 140 mN.

Figure 10. Auyed Dolerite. (a) Dolerite, apparently from the upper part of a 190 m thick sill in Ulma'loom Creek, west of Auyed, 467 434 mE/8 981 189 mN. (b) Dolerite dyke (Tme) intruding Nasai Limestone (Tmn), coastal exposure west of Suloga Point, 470 516 mE/8 976 942 mN. This important observation suggests intrusion of the dolerite post-middle Miocene (c) Polygonal cracks in columnar jointed dolerite sill west of Loluai. (d) Columnar jointing in dolerite sill west of Loluai. (e) Dolerite sill (Tme) concordant with deep-water turbidites of the Loluai Formation (Tel), west of Mus'e'wol Creek, 464 919 mE/8 981 322 mN. (f) Multiple concordant dolerite sills in deep-water turbidites of the Loluai Formation, west of Mus'e'wol Creek, 464 673 mE/8 981 350 mN.

Figure 11. Na'ku'iel Conglomerate in the southeast Okiduse Range. (a) Conglomerate (Qpn) overlying coralline limestone and blue-grey claystone of the Kiriwina Formation (Qpk) in 'Camp Creek', a southern tributary of Sinkwarai River, 476 040 mE/8 989 757 mN. (b, c) Accumulations of large granite boulders in 'Camp Creek', a southern tributary of Sinkwarai River, 475 923 mE/8 985 762 mN; and beside the Guasopa Road, several kilometres east of Talpas Bridge, where they rest on Kiriwina Formation. Both granite boulder accumulations are downslope from the only outcropping granite observed on Woodlark Island and their size and the distance moved to their present positions attests to energetic Pleistocene uplift and erosion. (d) Accumulation of boulders of the Loluai Formation overlying lava of the Boganuse Formation, headwaters of a Wayay Creek tributary on Okiduse Mountain, 473 066 mE/8 985 697 mN.

Figure 12. Na'ku'iel Conglomerate on the Suloga Peninsula. (a) A large 5 m boulder near the trace of U'sei'siy Fault, eastern slopes of To'bu'kui Mountain, 470 507 mE/8 981 134 mN. (b) Fining upwards sequence in the Na'ku'iel Conglomerate, located east of Wa'beu Fault and indicating pulsating cycles of uplift and erosion, 471 344 mE/8 977 839 mN. (c) A debris flow deposit in the Na'ku'iel Conglomerate, containing abundant angular and tough clasts of metamorphosed siltstone ('Suloga stone') in a matrix of muddy sand, middle Bulbem Creek, southeast Suloga Range, 471 351 mE/8 978 120 mN. (d) One of several distinctive lobes of gravel visible along the coast south from Norac, west coast of Suloga Peninsula, 470 293 mE/8 977 071 mN. (e) Large rounded clast in a consolidated chaotically sorted conglomerate, lower eastern slopes of Ma'ket Mountain, 470 111 mE/8 981 465 mN.

Table

Table 1. Cenozoic stratigraphy of Woodlark Island. Refer to Lindley (2016) and online data files for descriptions of units.

Age			Unit or Formation	Lithology	Estimated thickness	Remarks
PLEISTOCENE			Kiriwina Formation Qpk	Coralline limestone and blue-grey marine claystone	9–91.5 m (Joseph & Finlayson, 1991)	^{14}C dates range 31 500-39 500 years b.p. (Joseph & Finlayson, 1991)
POST-MID MIOCENE-HOLOCENE			Na'ku'iel Conglomerate (new name) Qpn	Massive, poorly to chaotically sorted gravels, cemented by a weakly to moderately lithified matrix of fine to coarse-grained lithic fragments	179–237 m in southeastern Suloga Peninsula. The unit since the late Pleistocene has been subjected to rapid erosion.	Southeast slopes of the Okiduse Range and southeastern slopes of southern Suloga Peninsula
POST MIDDLE MIOCENE			Auyed Dolerite (new name) Tme	Dark grey to blue coloured dolerite with columnar jointing	Three thick (each >200 m) sills and numerous narrow (<1 m) sills	Southern coast of Suloga Peninsula between Auyed and Kwegai. Also inland and east of Kwegai to Watson's Creek, Mapas Island, Uskweilele Mtn, southern Suloga Peninsula
MIDDLE MIOCENE			Felsic dykes Tmd	Porphyritic felsic dykes, with rare xenoliths of hornblendite	5–60 m width. Meridional strike	Regional dyke swarm in western Okiduse Range and Suloga Range
			Mafic dykes Tmm	Andesite and pyroxene-bearing porphyritic basalt with rare gabbro dykes	1–4 m width. Meridional strike	Regional dyke swarm restricted to south of Sinkwarai Fault and eastern Okiduse Range
MIDDLE MIOCENE	OKIDUSE VOLCANIC GROUP	MT KABAT ERUPTIVE CENTRE	Mt Kabat Breccia Tmok	Very poor to extremely poorly sorted monolithologic breccia. Clasts range from angular to well-rounded, with extreme grainsize variation and lacking well-defined stratification	123 m	Vent breccia underlying the slopes of the distinctively conical Mt Kabat. A volcanic edifice with a 1.5 km diameter and a height of 243 m
		SULOGA HBR TUFF CONE	Suloga Harbour Tuff (new name) Tmos	Felsic volcanic deposits, including feldspar crystal tuff, ashflow tuff, surge deposits, Plinian deposits and monolithologic lahar deposits	279 m	On and surrounding the slopes of the distinctively conical Ukwa'muk'wam Mtn, on west shores of Suloga Harbour. A cone with a basal diameter of about 1.5 km and a height of 229 m
		UVARAKOI CALDERA	Monasiy Tuff Tmou$_1$	Non-welded reddish-grey felsic tuff	+90 m	Outflow facies distributed widely throughout Okiduse Range and extending onto Suloga Peninsula, cropping out east of To'bu'kui Mtn and near Wa'beu Point. Intracaldera facies ponded in Uvarakoi Caldera. The collapsed caldera is 7 km^2 in size (Lindley, 2016)
			Busai Hill Ignimbrite Tmou$_2$	Densely welded even-grained ignimbrite with aligned crystals of feldspar, some broken, in ash matrix	+36 m	Ponded in Uvarakoi Caldera. Underlies prominent hills at Busai, Bomagai and Reilly's Creek and to north of Federation.
			Vulcan Lava Tmou$_3$	Light brown to grey lava, fine-grained with amygdales of quartz and calcite	2–7 m	Ponded in Uvarakoi Caldera. Known only from drillhole
			Federation Breccia Tmou$_4$	Heterolithologic breccia, matrix dominated and red-grey colour	29 m	Ponded in Uvarakoi Caldera. Known only from drillhole
			Manau Hill Tuff Tmou$_6$	Non-welded grey ashflow containing ~50 % crystals	40 m	Resistant capping on Manau Hill
		WATOU MTN ERUPTIVE CENTRE	Boganuse Formation Tmow$_0$	Basaltic flows with breccia and welded fall deposits, and minor medium-grained mafic rocks	160 m	Upper reaches of Talpas and Thompson's Creeks, draining Boganuse and Okiduse Mountains
			Kuikébeim Microdiorite Tmow$_1$	Dense grey andesite to fine-grained diorite	-	Upper Talpas Creek
			Nikuben Formation Tmow$_2$	Dark grey block and ash deposits with basaltic flows	+80 m	Talpas Creek headwaters; Wayay

		and associated red, oxidised autoclastic breccias. Minor poorly sorted heterolithologic lahar deposits		Creek on western slopes of Watou Mountain. Ok'a'kam Creek headwaters
	Talpas Creek Formation Tmow$_3$	Heterolithologic lahar deposits, volcanic conglomerate, volcanic sandstone and carbonaceous mudstone. Minor basalt flows and mafic airfall deposits. Ballistic bomb beds are common.	+114 m (from drillholes on Watou Mtn)	Eastern and western foothills of Okiduse Range at Boniavat, Okiduse and Karavakum; northern and northeastern Suloga Range at Mweim, Wonai and The Ben
	Mafic dykes Tmow$_4$	Fine-grained mafic and gabbroic dykes	2–4 m width. Variable strike	Dykes in Thompson's Creek, Wayay Creek and east of Elliott's Creek near Wonai
LATE OLIGOCENE-MIDDLE MIOCENE	Nasai Limestone Tmn	Pale to dark grey massive and thinly bedded limestone. Intercalated with ash layers of the middle Miocene Monasiy Tuff near Wa'beu Point, Suloga Peninsula	180 m	Nasai Island, western Suloga Ranges to Watson's Creek and southern shores of Wonai Bay, southeast Okiduse Range, southeastern Suloga Peninsula, inland from Wa'beu Point and west of Uskweilele Mtn, south Suloga Peninsula
POST EOCENE?	Granite Tg	Coarse equigranular granite	-	Restricted to a small creek in the southeastern Okiduse Range. Large well-rounded float of granite is locally common along the eastern shores of Suloga Harbour and in some creeks draining the southeast Okiduse Range
LATEST PALAEOCENE?-EOCENE	Loluai Formation (amended) Tel	Thinly interbedded siltstone and fine-grained sandstone with chert beds. In southeast Okiduse Range sandstone and siltstone interbedded with lensoidal conglomerate. Thermally metamorphosed	+300 m	Suloga Range and southeast Okiduse Range
	Utavai Basalt Member (new name) Telu	Dark grey to black, fine-grained, massive and pillowed basalt. In southeast Okiduse Range sub-aerial mafic volcanics and subvolcanic intrusive rocks	Unknown	Coastline between Loluai and Utavai, west coast of Suloga Peninsula. Also Suloga Point, Wasilas and U'sei'siy River and Bugitai River area in southeast Okiduse Range