Isotopic mapping reveals the location of crustal fragments along a long-lived convergent plate boundary

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Abstract
New Guinea has acted as the boundary between the Australian and Pacific plates for hundreds of millions of years. Strike-slip movement and arc–continent collisions along this boundary during the Cenozoic have shuffled rocks of different age and composition in a series of terranes along the plate boundary making mapping them a considerable challenge. Here we report results of SrNd isotopic data obtained from rock samples from western New Guinea that are representative of the different terranes. These isotopic data reveal the crustal affinity of the terranes and we have used these data to map their spatial distribution. The isotopic data show three distinct crustal domains underlying western New Guinea; Palaeozoic–Mesozoic Australian continental crust \((87\text{Sr}/86\text{Sr} = 0.719594 \text{ to } 0.710921; \varepsilon\text{Nd} = -13.85 \text{ to } 1.373)\); thinned transitional crust intruded by Miocene–Pleistocene magmatic rocks \((87\text{Sr}/86\text{Sr} = 0.706524 \text{ to } 0.704019; \varepsilon\text{Nd} = 6.67 \text{ to } 2.13)\); and accreted island arc crust \((87\text{Sr}/86\text{Sr} = 0.704053 \text{ to } 0.703759; \varepsilon\text{Nd} = 6.63 \text{ to } 4.97)\). These data, together with crustal contamination models, indicate that the northern-most extent of Australian continental crust exists beneath the northern-most section of western New Guinea. We also combined our isotopic data with existing data across New Guinea and used these to develop an isotopic map that shows the position of the ancient Australian–Pacific Plate boundary, producing results that are also consistent with broad-scale seismic tomography imagery. Our findings provide a framework for mapping other plate boundaries, particularly ancient systems where only fragmentary data exist.

Keywords
boundary, isotopic, reveals, mapping, location, crustal, fragments, along, long-lived, convergent, plate

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Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
All data used in the production of this manuscript have been uploaded as separate supplementary data files.
Isotopic mapping reveals the location of crustal fragments along a long-lived convergent plate boundary

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Dear Dr Xian-Hua Li,

Lloyd White, Christina Manning, Benjamin Jost, Herwin Tiranda and myself wish to submit a manuscript titled: "Isotopic mapping reveals the location of crustal fragments along a long-lived convergent plate boundary" for publication as a research paper in the journal Lithos.

In this paper we present Sr–Nd whole rock isotopic data for Palaeozoic to Cenozoic oceanic and continental rocks collected from remote and difficult to access parts of NW New Guinea. These data are used alongside recently published field, geochemical, and U–Pb zircon geochronology data that record multiple periods of subduction and arc–continent collision in NW New Guinea, to determine the isotopic signature of these different tectono-magmatic events. We then use inverse distance weighted interpolation mapping to further define the location of crustal fragments with different isotopic signatures within NW New Guinea. The results presented here are used in conjunction with other isotopic studies from across New Guinea to further map the location and extent of crustal fragments along this convergent margin. Not only does this study greatly improve our understanding of the crustal structure of New Guinea and the northern-most margin of Australian continental crust, it also presents isotopic mapping as an effective tool for locating different crustal fragments on a regional scale in otherwise difficult to access or poorly exposed areas.

We greatly look forward to your response and do hope that this contribution will be considered for publication in Lithos.

Yours sincerely,

Max Webb
Ms. Ref. No.: LITHOS8860

**Title:** Isotopic mapping reveals the location of crustal fragments along a long-lived convergent plate boundary.

Dear Dr Xian-Hua Li,

We would like to submit a revised version of the manuscript “Isotopic mapping reveals the location of crustal fragments along a long-lived convergent plate boundary.” (LITHOS8860) for publication in Lithos.

Two reviewers gave positive reviews on the manuscript and the manuscript has benefitted from their obvious knowledge of New Guinea and convergent plate boundaries. We greatly appreciate these reviews.

The comments from Reviewer 1 centred around making the abstract and introduction more concise and readable, they also included several key works that should be cited along with good insights into the regional geology of New Guinea. At the request of the reviewer additional explanation has been given to the final IDW isotopic map that covers a large and under sampled region. Reviewer 2 had very minor comments that centred around re-phrasing sections of the text and improving the readability of the manuscript. Both sets of reviews have been helpful in improving this manuscript.

We provide detailed responses to each of the reviewers’ comments below and have modified the manuscript accordingly.

Yours sincerely,

Max Webb, Lloyd White, Christina Manning, Benjamin Jost, Herwin Tiranda
Detailed response to reviewer

Editor:

Delete Table 1, as it is identical with Supplementary Data File 1.

Response:

This is correct and Table 1 has now been removed.
Reviewer #1:

This paper is interesting and propose an attempt to present isotopic mapping in this region. I could check the geological data and interpretations of the paper which are solid; but I cannot evaluate with confidence the geochemical aspect. The paper is well written and concise. The references are correct and some can be added. The history of NG is clearly presented. The data are detailed in supplementary material and do not make the reading heavy. The interpretation of the different “zoning” of crust is consistent with other geological data (P wave Velocities and tectonic indicators of thick basement beneath the Fold-and-Thrust Belt). I have a bit of concern with the relevance of the IDW interpolation with very few control points with reference to the large area covered by the last map.

Response

We thank the reviewer for their helpful comments here, the concern for the control points presented in the IDW interpolation is addressed in detail in response to a relevant comment below.

Abstract:

The first third of the abstract is more like a general introduction to accretion tectonics and should be shortened a lot. This part could actually fit very well at the beginning of the introduction. the rest of the abstract could stick better to the discussion.

Response

This is a helpful comment and the abstract has been shortened with the additional information on accretion tectonics now included in the Introduction.

Comments in the text:

L.98-100: I know some large projects such as (IGCP662 from IUGS/Uneco) produced similar maps of large areas in central Asia (authors may check Wang Tao and his team; they may have published some material).

Response

We thank the reviewer for this helpful suggestion, relevant citations have now been included.

L127-130: The Neogene history of NG actually began in the Mid-Oligocene and is marked by the continental deposits at the front of the central Range (Pigram & Panggeanbean, and other authors); The Late Miocene is a more recent accretion event.

Response

This is correct and has been changed with updated references.

L133 and later. The BH is actually a separated block. Many contradicting models exist for the movement of the block relative to fix Australia; but the considerable amount of seismic in the area shows that it was rifted from the Triassic (extension starting in Permian times, (this comment also for line 315)) and remained probably close to Australia during the Jurassic formation of the NW shelf. The junction between the continental part of Australian continent and BH is the Lengguru FTB where continental crust goes far beneath the FTB. You may refer to Bailly et al. also in LITHOS (Deformation zone 'jumps' in a young convergent setting; the Lengguru fold-and-thrust belt, New

Response

This is correct and has been addressed in section 2.2, the ‘BH block’ in this instance relates solely to pre-Triassic rocks of the Kemum Block and while these may now be on a separated block they were formed prior to separation and still represent Proterozoic to Palaeozoic Australian continental crust. The question of rifting in the Triassic is also addressed here and at line 337.

L145 Cite Pigram & Davis 1987 for "terranes".

Response

This citation has been included.

L226. 8 samples are mentioned where I can see less even if we take those at the boundary.

Response

Whilst only 5 samples of granitic continental basement were collected from within the ‘Kemum Block’ 3 additional samples were collected from areas of continental crust that are equivalent in age and isotopic ratio to the Kemum Block (e.g., Figure 1b). Some of these samples (e.g., MW14-11 from the Netoni Fragment) may well have been part of the Kemum Block before displacement along the Sorong Fault Zone. All samples of granitic crust are representative of the underlying Australian continental crust; this has been clarified in the text.

L260. Need to cross check the age of the Moon volcanics and precise them. For info, I had Middle Miocene with old isotopic data and biostrat data just at the base with Lepidocyclina (N) sp., cf L. (N) howchini, Flosculinella bontangensis also of Middle Miocene age in database (maybe outdated). Actually correspond to what is written at line 167. L269 Age for other units studied could be indicated; for Mandi (Early Oligocene to Miocene), Lembai (15.8 +/- 0.5). I do not have Berangan ages.

Response

It is correct that the Moon Volcanics is middle Miocene in age, the large age range reported in the initial manuscript (Eocene to Pleistocene) was in relation to all Cenozoic volcanic rocks studied here, this has now been changed to clarify the ages of each formation studied.

Line 403 to 406 and fig5. Only 2 Ma separating the 2 clusters, it would be good to precise the error bars.

Response

Errors for these samples have now been included in the text.

L488. Check the age of initiation of Sorong fault which was estimated by the Mid Miocene previously (Dow and Sukamto). 300Km is excessive for Plio-Pleistocene according to GPS data (Stevens et al.).

Response

Dow and Sukamto estimate the initiation of the Sorong Fault as late Miocene (this has now been included), the ~300km of movement since the Plio-Pleistocene is consistent with plate motions of 10cm/yr since 3 Ma (proposed by Sapiie et al., 1999 and Sapiie & Cloos, 2004) and the 370km of
movement since the late Miocene proposed by Dow and Sukamto (1984). The plate motions and relative movement of the Sorong Fault are discussed in detail in (and cited in the text):


I do not understand very well the Fig 9a and the way the IDW map should be read (but I am not in this field). The P wave velocity map reflects pretty much what is inferred to be continental affinity material at depth, but the IDW map is not clear. The gridding is very loose and interpretation is to be taken with caution. We see on the map the decreasing IDW pattern toward the west but we also see an aureole around the data points in the region of Central Irian Jaya which do not match the background colour. If the data is good, the interpolation and the interpretation needs some clarification. This is important because the end of the discussion part relies on it.

Response

This is a good point and we have now addressed this comment in lines 619-624. The interpolation and interpretation techniques are the same as described in section 5.3 (including the values used to define continental, oceanic, and transitional crust). However, there is a problem with data saturation in the central region, few studies have reported isotopic data for the central and northern parts of New Guinea compared with this study in the west and previous studies in the east. This, along with extremely negative isotopic values recorded from thick and ancient continental crust in the region (e.g., Housh & McMahon, 2000) means that the presence of oceanic arc crust in central New Guinea is restricted to a series of aureole on the final IDW map.

Reviewer #2:

This is a very interesting manuscript that use Sr and Nd isotopic data from different terranes of western Guinea to locate the boundary between the Australian and Pacific plates in New Guinea. Analyzed samples are from volcanic, plutonic, metamorphic and sedimentary rocks. The authors discuss the isotopic data of the different rocks and blocks that make up New Guinea in the studied area, and provided a binary Nd and Sr isotopes modelling to calculate mixing curves, and AFC modelling to estimate crustal contamination in rocks from an intermediate block between continental (Australian plate) and oceanic (Pacific plate) zones. The Sr and Nd isotopic data were also used to produce an IDW interpolation map that delineate the approximate location of the different blocks in the studied area, and extended it to the New Guinea, using available data from the literature. The result is a very convincing map that shows the isotopic signatures of different crustal domains and the probable extension of the Australian continental crust beneath the northernmost section of New Guinea.

Response

We thank the reviewer for their helpful comments, all revisions cited below have now been made.

Although the manuscript is fairly well written and organized, I would suggest a reorganization of the order of description of some topics. In particular, in the results section, the analyzed rocks in the subitens should be grouped by block in which they occur. The Tamrau Formation, Aja limetone, Moon volcanic roks and Berangan andesite are all part of the Tamray block basement and should be subitem of the same item, as well as the Mandi volcanic rocks (Tosem block), and the Arfak volcanic rocks (Arfak block), which is described in the same subitem as the Lembai diorite (Ransiki fault zone).

Response
Thank you for this suggestion, the order for when these formations are introduced has now been changed in the results and discussion sections to better reflect their categorisation into specific blocks (Kemum Block, Tamrau Block, Tosem Block, Arfak Block) and the continental, transition, and oceanic zones.

As I am not an English native speaker I am not the appropriate person to correct the writing of a native one. However, I dare to suggest a few things as follows. The same order should be followed in all sections.

Response

All changes mentioned have now been made.

Line 77: has mean is has been... delete "is"

Response

The word ‘is’ has been changed to ‘it’ here to improve the grammar of the sentence.

Line 155: ... zone), this is an... replace for: which represents an...

Response

This change has been made.

Line 234: the reported initial 87Sr/86Sr ratios are actually back-calculated ratios, right?

Response

That is correct, the reported initial ratios have been back-calculated/age corrected to the age of their formation (based on U-Pb zircon ages), the way ‘initial 87Sr/86Sr’ values are reported in this line has been changed to ‘87Sr/86Sr(i)’ for clarity and consistency with the rest of the manuscript.

Line 364: ... as well as inheritance in its U-Pb zircon inheritance... do you mean zircon ages?

Response

Yes, this should read as ‘zircon ages’ and has now been changed.

Line 382: Both field and petrographic OBSERVATIONS indicate the presence of granitic XENOLITHS and quartz...

Response

This is correct and has been changed.

Line 391: INITIAL (?) 87Sr/86Sr values.

Response

The initial values were not used in this context or on the Figure that this text is referring to (Figure 5) as the samples are so young (less than 15 Ma) that back-calculating the initial ratios to account for radiogenic in-growth would show little effect on a Figure with such a broad scale (e.g., Figure 5).

Line 404: ... those with HIGHER (instead of increased 87Sr/86Sr (i) values...)

Response
This is correct and has been changed.

Line 405:... and THEREFORE crustal contamination may reflect...

Response

This is correct and has been changed.

General comment: It is better to avoid using adjectives alone without using a noun. This way, is more appropriate to say volcanic rocks than volcanics, and sedimentary rocks than metasediments or sediments (which are not rocks yet!).

Response

This is correct and has been changed throughout.
Abstract

New Guinea has acted as the boundary between the Australian and Pacific plates for hundreds of millions of years. Strike-slip movement and arc–continent collisions along this boundary during the Cenozoic have shuffled rocks of different age and composition in a series of terranes along the plate boundary making mapping them a considerable challenge. Here we report results of Sr–Nd isotopic data obtained from rock samples from western New Guinea that are representative of the different terranes. These isotopic data reveal the crustal affinity of the terranes and we have used these data to map their spatial distribution. The isotopic data show three distinct crustal domains underlying western New Guinea; Palaeozoic–Mesozoic Australian continental crust ($^{87}\text{Sr}/^{86}\text{Sr} = 0.719594$ to $0.710921$; $\varepsilon_{\text{Nd}} = -13.85$ to $1.373$); thinned transitional crust intruded by Miocene–Pleistocene magmatic rocks ($^{87}\text{Sr}/^{86}\text{Sr} = 0.706524$ to $0.704019$; $\varepsilon_{\text{Nd}} = 6.67$ to $2.13$); and accreted island arc crust ($^{87}\text{Sr}/^{86}\text{Sr} = 0.704053$ to $0.703759$; $\varepsilon_{\text{Nd}} = 6.63$ to $4.97$). These data, together with crustal contamination models, indicate that the northern-most extent of Australian continental crust exists beneath the northern-most section of western New Guinea. We also combined our isotopic data with existing data across New Guinea and used these to develop an isotopic map that shows the position of the ancient Australian–Pacific Plate boundary, producing results that are also consistent with broad-scale seismic tomography imagery. Our findings provide a framework for mapping other plate boundaries, particularly ancient systems where only fragmentary data exist.
Research highlights:

- We present new Sr–Nd isotopic data for magmatic rocks from NW New Guinea.
- Three different isotopic signatures can be linked to distinct crustal fragments.
- Isotopic mapping reveals the extent of these fragments across a poorly exposed region.
- We determine the northern-most extent of Australian continental crust.
- These data will better inform new tectonic reconstructions of this convergent margin.
Isotopic mapping reveals the location of crustal fragments along a long-lived convergent plate boundary

Max Webb\textsuperscript{1,2*}, Lloyd T. White\textsuperscript{2}, Christina J. Manning\textsuperscript{1}, Benjamin M. Jost\textsuperscript{1}, Herwin Tiranda\textsuperscript{3}

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Abstract

New Guinea has acted as the boundary between the Australian and Pacific plates for hundreds of millions of years. Strike-slip movement and arc–continent collisions along this boundary during the Cenozoic have shuffled rocks of different age and composition in a series of terranes along the plate boundary making mapping them a considerable challenge. Here we report results of Sr–Nd isotopic data obtained from rock samples from western New Guinea that are representative of the different terranes. These isotopic data reveal the crustal affinity of the terranes and we have used these data to map their spatial distribution. The isotopic data show three distinct crustal domains underlying western New Guinea; Palaeozoic–Mesozoic Australian continental crust ($^{87}\text{Sr}/^{86}\text{Sr} = 0.719594$ to $0.710921$; $\varepsilon_{\text{Nd}} = -$13.85 to 1.373); thinned transitional crust intruded by Miocene–Pleistocene magmatic rocks ($^{87}\text{Sr}/^{86}\text{Sr} = 0.706524$ to $0.704019$; $\varepsilon_{\text{Nd}} = 6.67$ to 2.13); and accreted island arc crust ($^{87}\text{Sr}/^{86}\text{Sr} = 0.704053$ to $0.703759$; $\varepsilon_{\text{Nd}} = 6.63$ to 4.97). These data, together with crustal contamination models, indicate that the northern-most extent of Australian continental crust exists beneath the northern-most section of western New Guinea. We also combined our isotopic data with existing data across New Guinea and used these to develop an isotopic map that shows the position of the ancient Australian–Pacific Plate boundary, producing results that are also consistent with broad-scale seismic tomography imagery. Our findings provide a framework for mapping other plate boundaries, particularly ancient systems where only fragmentary data exist.
Keywords:
Sr–Nd isotopes; New Guinea; Continental crust; Crustal contamination; Australian Plate
1. Introduction

Convergent plate boundaries are complicated zones where slices of the Earth’s crust of different age and composition (‘terranes’) are often juxtaposed. Unravelling the history of these zones is key to understanding what the Earth looked like in the past. New Guinea is recognised as one of the world’s youngest arc–continent collisional orogens (Ali & Hall, 1995; Hall, 2002; Hill & Hall, 2003; Baldwin et al., 2012; Davies, 2012; Holm et al., 2016), but has acted as a plate boundary to the northern margin of the Australian Plate since the Triassic (Hill & Hall, 2003; Jost et al., 2018). If we can understand the tectonic evolution of New Guinea in its current setting, then we can use this knowledge to better understand other much older plate boundary systems.

The island of New Guinea marks the meeting point of the Australian, Philippine Sea, and Caroline tectonic plates (Milsom et al., 1992; Bird, 2003; Hall & Spakman, 2003; Tregoning & Gorbatov, 2004). The interaction of these plates during the Cenozoic saw the production of subduction-related volcanism, the collision and accretion of island arc volcanoes, as well as extensive strike-slip faulting. All of this tectonic activity has resulted in the island’s current geological configuration, that is a complicated region of juxtaposed sections of oceanic and continental crust. The complicated tectonic history, together with large areas of difficult to access terrain (e.g., mountains, dense tropical rainforest, vegetated wetlands) has meant it has been difficult to identify the location of ancient plate boundaries.

Australian continental crust was initially proposed to extend no further north than the New Guinea Fold and Thrust belt in eastern New Guinea (Abers & McCaffrey, 1988). Recent studies from eastern New Guinea, however, show that underthrust Australian continental
crust may continue north beneath the New Guinea Mobile Belt and be in contact with
oceanic or island arc crust of the Marum Ophiolite and Adelbert–Finisterre–Huon Block
along the Ramu–Markham Fault (Crowhurst et al., 1996). Isotopic studies from central New
Guinea indicate that ancient Archaean or Proterozoic Australian continental crust extends
north beneath the Central Range to at least the 4th parallel South (based on the location of
crustally contaminated Pliocene–Pleistocene igneous rocks) (Housh & McMahon, 2000).

In addition, limited geophysical data exist in this region of the world. This means it is difficult
to map the variation of crustal thicknesses across New Guinea. Those data that do exist
(e.g., seismic tomography) have typically been applied to only eastern New Guinea (Abers &
McCaffrey, 1988; Abers, 1991; Abers & Roecker, 1991) or used to image subducted slabs
deeper in the mantle (Hall & Spakman, 2003), while other work has focussed on looking at
upper crustal structures that may control the location of ore deposits (White et al., 2013) –
however, all of this work has relied on predominately coarse resolution data. It therefore
presents a significant challenge as to how one could map the crustal structure of New
Guinea.

Recent Nd isotopic studies of the Australian continent have been used to isotopically map
different geological domains, from Archaean–Proterozoic cratons to Palaeozoic arc and
orogenic terranes (Champion, 2013; Mole et al., 2015; Champion & Huston, 2016). Such
work has also been applied in the Himalaya (Ahmad et al., 2000; Richards et al., 2005), the
western United States (Bennett & DePaolo, 1987), the Central Asian Orogenic Belt (Wang et
al., 2009; Wang et al., 2015), and Antarctica (Borg & DePaolo, 1994), providing insight into
the age and isotopic signature of juxtaposed terranes and the underlying crust. Here we
take a similar approach using $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ whole-rock isotopic data from a
series of Devonian–Carboniferous and Permian–Triassic basement rock granitoids, metamorphosed Mesozoic passive margin sedimentary rocks, Oligocene oceanic island arcs, and Miocene–Pleistocene magmatic rocks from NW New Guinea. Using these isotopic data, we define isotopic signatures for and map different crustal domains across the region. We then compared our data with existing isotopic data available from other parts of New Guinea to map the northern-most extent of Australian continental crust and other crustal fragments.

2. Regional Background

2.1. The crustal domains and tectonics of New Guinea

The island of New Guinea was largely formed by a long history of continental growth along an Andean-type subduction system during the Palaeozoic and Mesozoic, and the accumulation of multiple terranes along its northern margin throughout the Cenozoic (Figure 1a). The number of terranes and their crustal affinities vary depending on individual studies. For instance, one article indicates that New Guinea consists of up to thirty-two separate terranes (Pigram & Davies, 1987). However, more recent work shows that many of those thirty-two terranes are equivalent to one another, and after reflecting on these similarities, there are essentially four distinct belts that strike broadly east–west, along the length of the island (Figure 1a) (Baldwin et al., 2012; Davies, 2012). These include: a stable platform in the south composed of both Proterozoic (western New Guinea) and Palaeozoic (eastern New Guinea) continental crust overlain by thick carbonate sequences (Hill & Hall, 2003); the New Guinea Fold and Thrust Belt, consisting of Jurassic–Neogene sedimentary rocks, which have been deformed and uplifted since the Oligocene in response to at least
two arc–continent collisions (Pigram & Panggabean, 1984; van Ufford & Cloos, 2005; Cloos, 2005; Mahoney et al., 2019; Webb et al., 2020); the New Guinea Mobile Belt, a highly active region composed of terranes of both continental and oceanic crust (Hill & Hall, 2003), including Late Cretaceous to early Paleocene ophiolites (Davies & Jaques, 1984; Weiland, 1999); and a series of oceanic island arcs (Figure 1). These arcs formed during the Eocene–early Miocene in the Philippine Sea and Pacific plates above the northwards subducting Australian Plate (Hill & Hall, 2003; Webb et al., 2020) and collided with the northern margin of New Guinea during the Miocene (Hill & Hall, 2003; Cloos, 2005; Webb et al., 2019).

The Bird’s Head Peninsula of westernmost New Guinea is composed of three crustal zones containing rocks of similar affinities and deformation styles to those four regional tectonic belts (Pieters et al., 1983; Dow & Sukamto, 1984). These zones are: the continental zone consisting of Australian continental crust; the transition zone, made up of rocks derived from both continental and oceanic crust; and the oceanic zone, which includes obducted and accreted oceanic and island arc crust (Figure 1b). Understanding how these zones in the Bird’s Head and the rocks therein correlate with the major tectonic belts of the rest of New Guinea and how they relate to the underlying crust will improve our understanding of the tectonic evolution of NW New Guinea and the northern margin of the Australian Plate.

2.2. The geology of NW New Guinea

Previous mapping campaigns by Indonesian and Australian government geologists subdivided the rocks of the region into a series of tectonostratigraphic blocks belonging to different crustal zones (Figure 1b) (Pieters et al., 1983; Dow & Sukamto, 1984; Pigram & Davies, 1987). The Kemum Block (continental zone) in the south represents Australian continental crust and is composed of Siluro–Ordovician metaturbidites, intruded by
Devonian–Triassic granitoids, and overlain by Jurassic–Cretaceous passive margin sedimentary rocks (Dow & Sukamto, 1984; Gunawan et al., 2012; Jost et al., 2018). It should be noted that while some seismic and modern-day GPS plate motion studies indicate that the Kemum Block forms part of a separate microcontinental block (termed the Bird’s Head Block) that separated from the Australian continent during Late Triassic rifting (Pigram & Panggabean, 1984; Dow et al., 1988; Stevens et al., 2002; Bailly et al., 2009), studies of the Palaeozoic granitic rocks of the Kemum Block indicate that they formed as part of the Australian Plate during subduction beneath eastern Gondwana (Crowhurst et al., 2004; Webb & White, 2016; Jost et al., 2018). Immediately north and east of the Kemum Block are the Sorong and Ransiki fault zones, respectively, these are large strike-slip fault zones up to ~15 km across (Figure 1b). These fault zones contain fault bounded fragments of both continental and oceanic affinity and may have transported these fragments from up to ~300 km westwards (Pieters et al., 1983; Dow & Sukamto, 1984; Webb & White, 2016; Jost et al., 2018; Webb et al., 2019). North of the Sorong Fault Zone is the Tamrau Block (transition zone), which represents an allochthonous block that has been transported along the fault zone (Figure 1b). The block has a deformed metasedimentary basement (Jurassic–Cretaceous protolith), overlain by Palaeogene metacarbonate, both of which have been intruded by middle Miocene arc volcanic rocks, and unconformably overlain by Miocene–Pleistocene sedimentary rocks (Pieters et al., 1983; Webb et al., 2019). Along the northern and eastern coasts lie the Tosem and Arfak blocks (oceanic zone), these are composed of Eocene–Miocene oceanic island arc volcanic rocks, which collided with the northern margin of the Australian Plate throughout the Miocene (Pieters et al., 1983; Dow & Sukamto, 1984; Black & McCulloch, 1990; Webb et al., 2019).
The rocks analysed in this study include Devonian–Triassic granitoids of the Kemum Block (Mariam Granodiorite, Wasiani Granite, Wariki Granodiorite, and Anggi Intrusive Complex), Sorong Fault Zone (Sorong Granite and Netoni Intrusive Complex) and Bird’s Neck regions (Maransbadi and Kwatisore granites), Jurassic–Palaeogene metasedimentary rocks and Miocene–Pleistocene volcanics of the Tamrau Block (Tamrau Formation, Ajai Limestone, Moon Volcanics, and Berangan Andesite), middle Miocene diorites in the Ransiki Fault Zone (Lembali Diorite), and oceanic island arc rocks from the Tosem and Arfak blocks (Mandi and Arfak Volcanics, respectively).

3. Methods

3.1. Whole-rock Sr–Nd isotopic analysis

Twenty-two samples were analysed for their whole-rock Sr–Nd isotopic compositions and LREE concentrations. For both Sr and Nd analyses, 0.1 g of bulk rock powder was dissolved using HF–HNO₃ in Teflon beakers for 24 hrs at 180°C, they were then evaporated and converted to nitrate by digestion in HNO₃ before undergoing total dissolution in 10% HNO₃. Twenty-five percent of the resulting solution was then removed for analysis of the light rare earth elements (LREEs). Strontium isotopes were determined on an Isotopx Phoenix thermal ionisation mass spectrometer (TIMS) at Royal Holloway University using the multidynamic method of Thirlwall (1991b). During the period of analysis, SRM987 gave $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.71023 ± 9 and 0.710234 ± 8 (2SD). Neodymium isotopes were determined on a Thermo Scientific Triton TIMS at the University of Leeds; during these analyses the La Jolla standard gave $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.511860 ± 16 and 0.511876 ± 11 (2SD), both within published ranges for La Jolla 0.511858 ± 20 (Lugmair et al., 1978; 1983). The LREE samples were prepared and analysed using the same isotope dilution (ID) methods and multi-element spike as in
Thirlwall 1982, and were analysed on the RHUL IsoProbe MC-ICP-MS. Major and trace element data for the samples in this study were used to further support isotopic modelling and interpretation. These data were collected on fusion disks and pressed pellets, respectively. These were analysed using a 2010 PANalytical Axios sequential X-ray fluorescence spectrometer at RHUL. These data and a full account of the analytical methods used during data collection are presented in full in previous related studies (Jost et al., 2018; Webb et al., 2020).

All additional calculations made to the measured Sr–Nd isotopic data (e.g., age corrections and model ages) were made using the geochemical data modelling software GCDkit (Janoušek et al., 2006). Epsilon Nd data was calculated from the $^{143}\text{Nd}/^{144}\text{Nd}$ data using the present-day CHUR value - 0.512638 (chondritic uniform reservoir) (DePaolo & Wasserburg, 1976; Jacobsen & Wasserburg, 1980; DePaolo, 1988). Age corrections have been performed on all samples to correct for radiogenic ingrowth over time and yield $^{87}\text{Sr}/^{86}\text{Sr}(i)$ and $\varepsilon_{\text{Nd}}(i)$ values based on U–Pb zircon geochronology and apparent stratigraphic ages reported in recent studies of the region (Webb & White, 2016; Jost et al., 2018; Webb et al., 2019; Webb et al., 2020). Either single-stage or two-stage $T_{DM}$ Nd model ages were calculated for the samples in GCDkit (Janoušek et al., 2006) to model when the melts that formed these rocks separated from the depleted mantle model reservoir (DePaolo, 1988). The use of single-stage or two-stage $T_{DM}$ Nd model ages was dependent on if the sample was suspected of being partially or completely crustally contaminated (based on field observations, geochemistry, and U–Pb zircon geochronology) (Webb et al., 2020) or if the single-stage model age did not make geological sense (e.g., when they generate minus values or ages over 4.5 Ga). Calculation of two-stage $T_{DM}$ Nd model ages in GCDkit requires the input of a measured $^{147}\text{Sm}/^{144}\text{Nd}$ ratio (obtained during this study) and a crystallisation age (U–Pb...
zircon ages for all samples are reported in Webb et al., 2019; 2020) for each sample, an
assumed crustal evolution curve (\(^{147}\text{Sm}/^{144}\text{Nd}\) ratio of 0.12 - Liew & Hofmann, 1988) is then
used to determine when the sample separated from the depleted mantle (e.g., the two-
stage \(T_{\text{DM}}\) Nd model age). The two-stage \(T_{\text{DM}}\) Nd model age is used to correct for a range of
crustal processes (including crustal contamination) (Liew & McCulloch, 1985).

4. Results

4.1. Whole-rock \(\text{Sr–Nd}\) isotopic analysis

Twenty-one samples of volcanic, plutonic, metamorphic, and sedimentary rocks from the
Bird’s Head where analysed for whole-rock \(^{87}\text{Sr}/^{86}\text{Sr}\) isotopic data, twenty of these samples
were also analysed for whole-rock \(^{147}\text{Sm}/^{144}\text{Nd}\) and \(^{143}\text{Nd}/^{144}\text{Nd}\) data (Supplementary Data
File 1). The remaining sample (MW15-024) did not contain enough Nd for \(^{147}\text{Sm}/^{144}\text{Nd}\) and
\(^{143}\text{Nd}/^{144}\text{Nd}\) analyses. The results were sub-divided into six groups based on their isotopic
values and their geographic location. These groups are summarised in Supplementary Data
File 1 and Figure 1b.

4.1.1. The Kemum Block and continental basement (continental zone)

Eight granitoids analysed from the Kemum Block and surrounding areas of continental crust
in West Papua (e.g., the Netoni Fragment and Lengguru Fold and Thrust Belt; Figure 1b)
display relatively enriched isotopic values consistent with their formation within Australian
continental crust (\(^{87}\text{Sr}/^{86}\text{Sr}\) = 0.719594 to 0.710921; \(^{143}\text{Nd}/^{144}\text{Nd}\) = 0.512208 to 0.511928; \(\varepsilon_{\text{Nd}}\)
= −13.85 to −8.39; Supplementary Data File 1). Age corrections yield a significant change in
\(^{87}\text{Sr}/^{86}\text{Sr}(i)\) values (0.713538 to 0.703029), resulting from ingrowth of radiogenic Sr, while
\( \varepsilon_{\text{Nd}}(i) \) values remain relatively unchanged (−11.32 to −7.15). The two samples with the most significant change in values and lowest \( ^{87}\text{Sr}/^{86}\text{Sr}(i) \) (MW14-11 = 0.703029; MW15-024 = 0.703444) also have the highest \( ^{87}\text{Rb}/^{86}\text{Sr} \) values and have been extensively deformed and partially recrystallised (Webb & White, 2016; Jost et al., 2018). These processes may have altered the \( ^{87}\text{Sr}/^{86}\text{Sr}(i) \) values of these samples. Single-stage T\(_{\text{DM}}\) model ages for the Kemum Basement rocks are dominantly Archaean–Proterozoic (2.91–1.205 Ga) along with an anomalous and unrealistic age of 6.206 Ga (BJ-121). Given this anomalous age and earlier evidence for crustal contamination in these rocks (Jost et al., 2018), we consider that the two-stage T\(_{\text{DM}}\) Palaeoproterozoic model ages are more reliable (1.988–1.564 Ga), these ages also correlate well with inherited Proterozoic zircons within these granitoids (Jost et al., 2018).

### 4.1.2. The Tamrau Block (transition zone)

#### 4.1.2.1. Basement Rocks

The metapelite (Tamrau Formation; BJ-028) and metacalc-silicate (Ajai Limestone; MW16-034) basement rocks of the Tamrau Block yield moderately enriched isotopic values (\( ^{87}\text{Sr}/^{86}\text{Sr} = 0.713279 \) to 0.707256; \( ^{143}\text{Nd}/^{144}\text{Nd} = 0.512866 \) to 0.512252; \( \varepsilon_{\text{Nd}} = -7.53 \) to 4.45; Supplementary Data File 1). As they represent metasedimentary rocks derived from multiple age sources, age corrections on rocks from the Tamrau Block basement are not necessarily representative of the initial \( ^{87}\text{Sr}/^{86}\text{Sr} \) and \( \varepsilon_{\text{Nd}} \) values for the entire sample and as such should be treated with caution (\( ^{87}\text{Sr}/^{86}\text{Sr}(i) = 0.707247 \) to 0.707104; \( \varepsilon_{\text{Nd}(i)} = -5.95 \) to 4.72; Supplementary Data File 1). The ages obtained from these samples are derived from a youngest detrital zircon age from the Tamrau Formation (150.3 ± 7.4 Ma; 2\( \sigma \)) and a stratigraphy-based age for the Ajai Limestone (~40 Ma) (Webb et al., 2019). Model ages for
the two samples from the Tamrau Block differ significantly. Sample BJ-028 of the Tamrau
Formation yields older Mesoproterozoic single-stage (1.304 Ga) and two-stage (1.373 Ga)
T_{DM} ages, while sample MW16-034 of the Ajai Limestone has younger Cambrian to
Neoproterozoic ages (single-stage: 0.580 Ga; two-stage: 0.449 Ga).

4.1.2.2. Moon Volcanics

Intermediate–felsic intrusive and extrusive rocks of the middle Miocene Moon Volcanics
display variable isotope ratios (^{87}Sr/^{86}Sr = 0.706524 to 0.704019; ^{143}Nd/^{144}Nd = 0.512980 to
0.512806; \varepsilon_{Nd} = 3.28 to 6.67; Supplementary Data File 1). Given the relatively young ages for
all Cenozoic volcanic rocks presented here (Eocene to Miocene for the Mandi and Arfak
volcanics, middle Miocene for the Lembai Diorite and Moon Volcanics, and Plio-Pleistocene
for the Berangan Andesite, Pieters et al., 1983; Webb et al., 2020), age corrections for these
rocks have little effect (Supplementary Data File 1) and as such, we have used their
measured values to better understand the present-day isotopic signature of crustal blocks in
the Bird’s Head Peninsula. Single-stage T_{DM} model ages for the Moon Volcanics are
Mesoproterozoic to Mesozoic (1.036 to 0.236 Ga, including another unrealistic age of 9.12
Ga; MW15-078). Given this anomalous age, as well as the potential crustal contamination
within the Moon Volcanics (Webb et al., 2020) we consider the Palaeozoic two-stage model
ages (0.543 to 0.262 Ga) as being the most reliable for the Moon Volcanics.

4.1.2.3. Berangan Andesite

The Plio-Pleistocene Berangan Andesite yields moderately depleted isotopic data (^{87}Sr/^{86}Sr =
0.704951; ^{143}Nd/^{144}Nd = 0.512842; \varepsilon_{Nd} = 3.98; Supplementary Data File 1), which are
consistent with it being a crustally-contaminated mantle-derived melt (Webb et al., 2020).
The single-stage and two-stage $T_{DM}$ model ages from sample MW15-054 of the Berangan Andesite give Ordovician ages of 0.476 to 0.458 Ga, respectively.

4.1.3. Island arc and oceanic crust (oceanic zone)

4.1.3.1. Mandi Volcanics

Mafic–intermediate intrusive and extrusive rocks of the Oligocene Mandi Volcanics have depleted isotopic values indicative of their formation within an island arc ($^{87}\text{Sr}/^{86}\text{Sr} =$ 0.704053 to 0.703759; $^{143}\text{Nd}/^{144}\text{Nd} = 0.512964$ to 0.512893; $\varepsilon_{\text{Nd}} = 4.97$ to 6.36; Supplementary Data File 1). Single-stage model ages for the Mandi Volcanics again yield an anomalous age of −0.525 Ga (MW15-034). We therefore consider the Devonian–Carboniferous two-stage $T_{DM}$ model ages (0.392 to 0.330 Ga) as being the most reliable results for the Mandi Volcanics.

4.1.3.2. Lembai Diorite and Arfak Volcanics

Coeval middle Miocene quartz diorites from the Lembai Diorite (MW15-050, MW15-051) and the Arfak Volcanics (MW15-058) yield relatively depleted isotopic values ($^{87}\text{Sr}/^{86}\text{Sr} =$ 0.704575 to 0.704304; $^{143}\text{Nd}/^{144}\text{Nd} = 0.512892$ to 0.512747; $\varepsilon_{\text{Nd}} = 2.13$ to 4.95; Supplementary Data File 1). Single-stage model ages for the Lembai Diorite samples yield an anomalous age of −0.224 Ga (MW15-050). We have therefore used the two-stage $T_{DM}$ model ages (Devonian ages of 0.466 to 0.438 Ga). The single-stage $T_{DM}$ age for the quartz diorite within the Arfak Volcanics (0.351 Ga; MW15-058) is comparable to the Devonian–Carboniferous two-stage ages obtained from the coeval Mandi Volcanics, while its two-stage $T_{DM}$ model age is Neoproterozoic (0.612 Ga).

5. Discussion
5.1. The isotopic signature and tectonic evolution of NW New Guinea

Determining the Sr–Nd isotopic composition of the rocks of NW New Guinea and what they indicate for their source has implications for understanding the nature of the crust beneath NW New Guinea and determining the northern-most extent of Australian continental crust. It also provides a distinct isotopic signature for each of the terranes studied, allowing for the correlation of isotopic signatures and allochthonous terranes across New Guinea. This can in turn be coupled with tectonic reconstructions to better understand the tectono-stratigraphic evolution of New Guinea.

The Devonian–Triassic granitoids of the Kemum Block formed during two periods of continental arc magmatism; intruding into the Palaeozoic basement of the Kemum Block at middle to upper crustal levels (Jost et al., 2018). These granitoids display high $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.719594 to 0.710921) and low negative $\varepsilon_{\text{Nd}}$ values (−13.85 to −8.39) consistent with rocks derived from ancient continental crust, this is supported by a Proterozoic inheritance in the U–Pb zircon age spectra of these granitoids (Jost et al., 2018). Figure 2a-b shows that these granitoids lie close to the field of isotopic compositions obtained from Palaeozoic–Proterozoic crustal rocks in NE Australia (Black & McCulloch, 1990; Knutson et al., 1996; Blewett et al., 1998), which are likely comparable in age and isotopic composition to the underlying basement of the Kemum Block. This is supported by the Palaeoproterozoic two-stage T$_{DM}$ model ages of the Devonian–Carboniferous granitoids (Figure 3a) and suggests that Palaeozoic and Proterozoic Australian continental crust underlies the Kemum Block at middle to upper crustal levels.

The Tamrau Formation forms the Mesozoic basement of the Tamrau Block and formed during a period of extensive rifting and passive margin development that occurred along the
northern margin of New Guinea and eastern Australia in the Late Triassic to Cretaceous (Pigram & Panggabean, 1984; Hill & Hall, 2003). This led to the thinning of continental and transitional crust along this margin that now underlies the Tamrau Block. Radiogenic $^{87}$Sr/$^{86}$Sr (0.713279) and $\epsilon_{Nd}$ (−7.53) values and the Proterozoic two-stage $T_{DM}$ model age (Figure 3a) from the Tamrau Block basement (Tamrau Formation – BJ-028) are consistent with its derivation from both Proterozoic–Palaeozoic Australian continental crust (comparable to crustal rocks exposed in NE Australia; Figure 2) and Palaeozoic–Mesozoic granitoids of the Kemum Block ($^{87}$Sr/$^{86}$Sr: 0.719594 to 0.710921; $\epsilon_{Nd}$: −13.85 to −8.39). This is supported by its U–Pb detrital zircon spectra (Webb et al., 2019), which contains Triassic, Devonian, and Neo- to Mesoproterozoic ages, indicating potential sourcing from the Kemum Block basement (Decker et al., 2017; Jost et al., 2018) or NE Australia (Holm et al., 2020).

The Ajai Limestone of the Tamrau Block (MW16-034) is a calc-silicate rock containing both carbonate and siliciclastic material. It shows relatively high $^{87}$Sr/$^{86}$Sr (0.70756) compared to more depleted $\epsilon_{Nd}$ (4.72) values and does not reflect the more radiogenic, older crustal signature of the underlying Tamrau Formation and Tamrau Block basement. This is likely the result of the introduction of seawater Sr during precipitation of its carbonate component, the $^{87}$Sr/$^{86}$Sr isotopic composition of seawater during deposition of the Ajai Limestone (~40 Ma; Webb et al., 2019) was ~0.70760 (Koepnick et al., 1985), comparable to the $^{87}$Sr/$^{86}$Sr composition of sample MW16-034.

The Moon Volcanics represent a suite of intrusive and extrusive rocks that formed within a continental arc along the northern margin of New Guinea in the middle Miocene and intruded through the Mesozoic basement of the Tamrau Block (Webb et al., 2020). These rocks display variable and moderately radiogenic $^{87}$Sr/$^{86}$Sr (0.704019 to 0.706524) and $\epsilon_{Nd}$ values (3.28 to 6.67). These data lie outside the mantle array and the field representing
present-day oceanic basalts and island arc volcanics (Hawkesworth et al., 1991; Hofmann, 1997), trending to more radiogenic values (Figure 2a, b). These moderately radiogenic values indicate the addition of a continental crust component to an originally mantle-derived melt but are significantly less radiogenic than other examples of magmatism through thickened ancient Australian continental crust in New Guinea (Housh & McMahon, 2000). This is because the Moon Volcanics have instead intruded through the thinned continental or transitional Mesozoic crust underlying the Tamrau Block (the Tamrau Formation). Other isotopic studies of arc volcanism through thinned continental crust yield comparable isotopic data to the Moon Volcanics (Kurile Basin, Russia; $^{87}\text{Sr}/^{86}\text{Sr}$: 0.70652–0.70287) (Tararin et al., 2003) as do Pleistocene volcanics from the Sorong Fault Zone west of the Bird’s Head Peninsula, which have erupted through both oceanic crust and faulted slices of fragmented continental crust ($^{87}\text{Sr}/^{86}\text{Sr}$: 0.7087–0.7058) (Morris et al., 1983). Two-stage $T_{DM}$ model ages in the Moon Volcanics increase from N–S (MW16-021; 0.262 to MW15-078; 0.543; Figure 1b) indicating a change in crustal age from younger Triassic crust in the north to older and potentially thicker Cambrian crust in the south.

The Berangan Andesite erupted through the Sorong Fault Zone (which separates the Kemum and Tamrau blocks) during the Plio-Pleistocene following a period of crustal thickening and terminal arc–continent collision (Webb et al., 2020). Field and petrographic evidence, as well as inheritance in its U–Pb zircon ages indicate that the Berangan Andesite underwent crustal contamination during its formation. This is supported by $^{87}\text{Sr}/^{86}\text{Sr}$ (0.704951) and $\varepsilon_{\text{Nd}}$ (3.98) values that plot outside both the mantle array and present-day oceanic basalt and arcs field (Figure 2a, b), this along with its early Ordovician two-stage $T_{DM}$ model age (0.476 Ga; Figure 3b) indicate the incorporation of a Palaeozoic crustal component into the original melt.
Eocene to Miocene volcanic and intrusive rocks from the Mandi and Arfak volcanics and Lembai Diorite display low $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.704575 to 0.703505) and positive $\varepsilon_{\text{Nd}}$ values (2.13 to 6.36) consistent with mantle-derived rocks in volcanic arcs. They plot within, or close to the mantle array and the field denoting most present-day oceanic basalts and island arc volcanic rocks (Figure 2a, b) (Hawkesworth et al., 1991; Hofmann, 1997), consistent with their formation within or intrusion into the Eocene–Oligocene oceanic island arcs of the Philippine Sea Plate (Webb et al., 2020).

### 5.2. Evidence for crustal contamination

Previous field, petrographic, and U–Pb zircon geochronology studies of the Moon Volcanics and Berangan Andesite (Webb et al., 2020) indicate that they have undergone some degree of crustal contamination. The Moon Volcanics formed within a continental arc resulting from subduction of the Philippine Sea Plate beneath the Australian Plate in the middle Miocene (Webb et al., 2020). Field evidence shows granitoids associated with these volcanics in intrusive contact with metasedimentary rocks of the Tamrau Formation, pockets of granitic melt can be observed in the surrounding country rock and indicate ongoing partial melting and possible contamination during the intrusion of these peraluminous granitoids (Figure 4; Webb et al., 2020). The Berangan Andesite formed during continued crustal thickening, uplift, and strike-slip faulting during the Pliocene to Pleistocene following late Miocene to Pliocene island arc–continent collision in NW New Guinea (Webb et al., 2020). Both field and petrographic observations indicate the presence of granitic xenoliths and quartz aggregate xenocrysts in the Berangan Andesite, these xenocrysts are deformed (showing evidence for grain-boundary migration) and are likely derived from granitic basement rocks in the underlying Kemum Block (Figure 4; Webb et al., 2020). In addition, U–
Pb zircon geochronology from the Berangan Andesite shows the presence of Triassic, Devonian–Carboniferous, and Neoproterozoic inherited zircons, these ages correspond to those found in the underlying Tamrau and Kemum Blocks and further support crustal contamination (Webb et al., 2020).

To assess the degree of crustal contamination in these rocks we plotted their SiO$_2$ wt. % vs. $^{87}$Sr/$^{86}$Sr values. Figure 5 shows that samples from the Mandi Volcanics, Arfak Volcanics, and Lembai Diorite have relatively stable $^{87}$Sr/$^{86}$Sr values below ~0.7405 with increasing SiO$_2$ wt. %, indicating fractional crystallisation from a mantle-derived source (Downes, 1984). The same is true for three samples from the Moon Volcanics (MW16-021; MW16-022; MW15-074), they show uniform $^{87}$Sr/$^{86}$Sr values below ~0.7405 (reflecting a mantle source) with increasing SiO$_2$ indicating fractional crystallisation. However, two samples from the Moon Volcanics (MW15-031; MW15-078) are offset from the trend with both increased $^{87}$Sr/$^{86}$Sr with SiO$_2$ values of ~0.7064 and ~69 wt. %, respectively.

This indicates that these samples have likely undergone some degree of crustal contamination, increasing their $^{87}$Sr/$^{86}$Sr values and plotting them closer to those of the Tamrau Formation (Figure 5), into which the Moon Volcanics intrude (Webb et al., 2020). This crustal contamination appears to be temporally controlled, samples with low $^{87}$Sr/$^{86}$Sr values formed at ~14 Ma at the onset of subduction beneath the Moon Volcanics (MW16-021 – 14.5 ± 2.5 Ma) (Webb et al., 2020) while those with higher $^{87}$Sr/$^{86}$Sr values formed at ~12 Ma (MW15-078 – 12.4 ± 0.4 Ma, MW15-031 – 12.8 ± 1 Ma) (Webb et al., 2020) and therefore crustal contamination may reflect increasing crustal thickness during formation of the arc. Sample MW15-054 of the Berangan Andesite is also offset from the horizontal
fractional crystallisation trend (Figure 5), again indicating some degree of crustal contamination.

Binary isotope models ($^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$) were used to further test the degree of crustal contamination in the Moon Volcanics and Berangan Andesite and to identify potential sources of contamination (Figure 6a, b; Supplementary Data File 2). The $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios for the samples and contaminants were recalculated to initial values at 12 Ma to better reflect their isotopic signatures during magmatism in the Moon Volcanics. Two starting compositions were used for modelling, the first was the most depleted and oldest sample analysed from the Moon Volcanics (MW16-021; andesite; Figure 6a), to determine to what degree assimilation of crustal materials has affected the isotopic composition of the Moon Volcanics through time. A MORB starting composition (Figure 6b) (Sun & McDonough, 1989) was also used to model crustal contamination in the Berangan Andesite (which is likely mantle-derived much like other Plio–Pleistocene magmatic rocks in New Guinea) (Housh & McMahon, 2000) and as a secondary starting composition for modelling the Moon Volcanics to mitigate against potential crustal contamination in even the most depleted sample (MW16-021). The potential contaminants used include the Devonian–Triassic granitoids of the Kemum Block basement (which represent the middle to upper crust of the Kemum Block) (Jost et al., 2018) and the Jurassic–Cretaceous Tamrau Formation (BJ-028) of the Tamrau Block. Isotopic and geochemical data for all mixing components as well as parameters for the mixing models can be found in Supplementary Data File 1.

Figure 6a shows that mixing curves can be modelled for samples BJ-02 and 12JD332A of the Kemum Block basement (both Triassic granitoids). The more depleted samples of the Moon...
Volcanics (MW16-022 & MW15-074) lie along this curve indicating that they may well have
been partially contaminated with ~10% to 15% partial melt from the granitoids, however,
the most contaminated samples (MW15-031 & MW15-078) show no relationship with this
line. The Berangan Andesite also lies along this line, indicating potentially ~20% contribution
from the Triassic granitoid contaminants (this is supported by the presence of Triassic age
zircons and quartz aggregate xenocrysts in the Berangan Andesite; Figure 4a, b) (Webb et
al., 2020).

Figure 6b shows a model of mixing between the MORB starting composition and potential
contaminants. A mixing curve can be modelled between MORB and sample BJ-028 of the
Tamrau Formation in the Tamrau Block basement (Figure 6b). All samples of the Moon
Volcanics lie broadly along this curve, indicating that even the most depleted samples of the
Moon Volcanics have undergone some degree of crustal contamination. This mixing curve
indicates up to ~25% contribution in the most contaminated samples (MW15-078 & MW15-
031) and ~5% to 15% contribution in the least contaminated (MW16-021; MW16-022;
MW15-074; Figure 6b). This model is supported by field relationships, particularly the
intrusion of granitic rocks of the Moon Volcanics into the Tamrau Formation (Figure 4c, d) as
well as pockets of partial melt in the Tamrau Formation (Figure 4e, f). The Berangan
Andesite also lies close to this mixing line and may have been contaminated by the Tamrau
Formation (BJ-028) by ~15% to 20% (Figure 6b). A mixing curve can also be modelled to
potential contaminant BJ-138. Sample MW15-078 of the Moon Volcanics lies along this
curve indicating that it may have received ~10% to 15% contamination contribution from BJ-
138 (Figure 6b).
Finally, AFC modelling (based on the model provided in Ersoy & Helvacı, 2010) was used to determine which of these potential contaminants were most likely. AFC models were produced using the two starting compositions (MW16-021 & MORB) and all proposed contaminants (12JD332A, BJ-02, BJ-138, and BJ-028), a target composition was set at $^{143}\text{Nd}/^{144}\text{Nd} = 0.512806$ and $^{87}\text{Sr}/^{86}\text{Sr} = 0.706524$ based on the most enriched sample from the Moon Volcanics (MW15-078) (Supplementary Data File 2). Modelling between MW16-021 and BJ-02 (Figure 6a) produced the target composition at ~35% assimilation ($r = 0.4$). Whilst modelling between MORB and BJ-028 (Figure 6b) produced the target composition at ~30% assimilation ($r = 0.3$).

These models show that for the Moon Volcanics most of the crustal contamination (~25% to 30%) could be derived from partial melting of the Tamrau Formation into which they intrude (Figures 6b & 4c–f). There is also evidence for contamination of ~35% from Triassic granitoids in the middle to upper crust of the Kemum Block indicating that it continues north of the Sorong Fault Zone beneath the Tamrau Block (Figure 6a, b). The Berangan Andesite shows evidence for contamination of up to 20% from the Tamrau Formation or ~20% from the Triassic granitoids (Figure 6a, b), which is reflected in its U–Pb zircon spectra and the presence of deformed quartz aggregates (Webb et al., 2020; Figure 4a, b).

Contamination of the Moon Volcanics and Berangan Andesite of the Tamrau Block by Triassic granitoids of the Kemum Block basement indicates that Australian continental crust (represented by the basement rocks of the Kemum Block) may extend further north than previously thought, underlying at least some of the Tamrau Block (Figure 7).

5.3. The northern limit of Australian continental crust in New Guinea
The isotopic data presented herein show that Proterozoic to Mesozoic Australian continental crust does occur beneath New Guinea, however, the exact location of this underlying crust has often been disputed. Previous field studies have proposed that Australian continental crust does not occur north of the E–W striking Sorong Fault Zone (Pieters et al., 1983; Dow & Sukamto, 1984). They proposed that the region north of the Sorong Fault Zone (the Tamrau Block) is a so-called transitional zone of rocks derived from both the continental crust to the south and oceanic crust to the north. In contrast, the results from this study, including $^{87}$Sr/$^{86}$Sr and $\varepsilon_{Nd}$ isotopic data, Nd model ages, and previously published inherited zircon ages (e.g., Webb et al., 2020), indicate that the Tamrau Formation, Moon Volcanics, and Berangan Andesite of the Tamrau Block do indeed overlie Australian continental crust (Figure 7). However, it should be noted that any inference on this northern limit of Australian crust is based on the current location of an allochthonous fault bounded block (the Tamrau Block). While the Tamrau Block is underlain by the same Proterozoic–Palaeozoic continental crust as the rest of western New Guinea, it was moved into its current position by ~300 km of westwards strike-slip movement in the Plio-Pleistocene (Dow & Sukamto, 1984; Gold et al., 2014; Webb et al., 2019; 2020), following the onset of displacement along the Sorong Fault Zone in the late Miocene (Dow & Sukamto, 1984).

Inverse distance weighted (IDW) interpolation maps were produced for the $^{87}$Sr/$^{86}$Sr and $\varepsilon_{Nd}$ isotopic data and $^2T_{DM}$ Nd model ages for both the samples analysed in this study (Figure 7). These IDW maps delineate the approximate location of the different crustal blocks of the Bird’s Head Peninsula as well as the overall crustal signature of each block. The blue to green colours shown in Figure 7 define the highly radiogenic isotope signature and Proterozoic $^2T_{DM}$ model ages of the continental crust (i.e., the Kemum Block, as well as
sections of the Tamrau Block and Lengguru Fold and Thrust Belt). A more simplified image is shown in Figure 8. The pale orange and yellow colours shown in Figure 7 define transitional Miocene to Pleistocene magmatic rocks (Moon Volcanics, Lembai Diorite, and Berangan Andesite) which have intruded through both oceanic and continental crust and display moderately radiogenic isotopic data and Cambrian–Triassic $^{2}T_{DM}$ model ages. These transitional magmatic rocks differ from the ‘Transition Zone’ (Pieters et al., 1983; Dow & Sukamto, 1984) as they exclude the Tamrau Formation (derived entirely from continental clastic sources) and mark the change from continental crust to transitional or oceanic crust of the Australian Plate beneath the Tamrau Block (shown by the N–S change in the Moon Volcanics from mantle-derived material to crustal contamination and partial melting of the Tamrau Formation). Finally, the red areas in Figure 7 indicate the depleted and mantle-derived isotopic data and Devonian–Carboniferous $^{2}T_{DM}$ model ages of the accreted oceanic island arcs (Dore, Mandi, and Arfak Volcanics).

The $^{2}T_{DM}$ model age and $\varepsilon_{Nd}$ IDW maps (Figures 7d & f) provide a better visual representation of the isotopic composition of the crust than the $^{87}$Sr/$^{86}$Sr map (Figure 7b). These maps clearly define the structural boundaries between the Kemum and Arfak blocks (the Ransiki Fault), the Kemum and Dore Volcanics (the Sorong Fault), the Tamrau and Tosem blocks (the Koor Fault), the Netoni Fragment, and the south to north transition from continental to oceanic/transitional crust in the Tamrau Block (Figures 7 & 8). The transition from crustally contaminated magmatic rocks to mantle-derived volcanic rocks in the Moon Volcanics occurs at roughly the midpoint of the mapped extent of this unit and the northern boundary of the Tamrau Formation. This can be correlated with the outcrop locations of crustally contaminated granitoids in the south (samples MW15-031 & MW15-078; Figure 2b) and mantle-derived volcanic rocks in the north (samples MW16-021; Figure 2b). These
data indicate that Australian continental crust exists beneath the Bird’s Head Peninsula and extends northwards to at least latitude 0°30’ S at the present-day (Figure 7).

5.4. Correlating isotopic data across New Guinea

We compared our isotopic data with other data from across New Guinea with the aim of mapping the position of different isotopic domains (Figure 9). The Devonian–Triassic granitoids that intrude the Kemum Block represent the Palaeozoic–Mesozoic basement of the Bird’s Head at middle to upper crustal levels (Jost et al., 2018). Their isotopic data correlate well with Proterozoic–Palaeozoic continental crust in NE Australia (Figure 2c), which likely extends beneath the Arafura Sea and into western New Guinea (Hill & Hall, 2003) and represents a source of contamination in these granitoids. The Devonian–Carboniferous samples (BJ-121 & BJ-93) represent the oldest samples analysed for isotopic data from across New Guinea and magmatic rocks of that age are only found in the Bird’s Head. Samples of Triassic meta-diorite from the Amanab Block in eastern New Guinea have been analysed for their Sr–Nd isotopic signature, however, these have much less radiogenic isotopic signatures then our Triassic samples and have been interpreted to have formed during a period of post-subduction rifting in the Triassic (Crowhurst et al., 2004). Samples MW14-11, BJ-138, and BJ-93, have Sr–Nd isotopic values comparable to Pliocene intrusive rocks in the Central Range (Figure 2c), this is indicative of their shared contamination from an underlying Proterozoic continental crust source (Housh & McMahon, 2000).

No other Sr–Nd isotopic studies have been conducted on Palaeogene calc-silicate or carbonate rocks within New Guinea, so there are no data to directly compare with that obtained from sample MW16-034. However, early Palaeogene phyllites from the Frieda Province in eastern New Guinea have relatively depleted Sr–Nd isotopic compositions
(0.70585–0.70689 $^{87}\text{Sr}/^{86}\text{Sr}$; 5.29–6.59 $\varepsilon_{\text{Nd}}$) reflecting their derivation from arc-related volcanics (Crowhurst et al., 2004). The clastic component in MW16-034 may be in part derived from arc-related volcanics shedding onto the northern New Guinea margin in the Palaeogene, reflecting its depleted isotopic composition despite the introduction of seawater Sr. The more radiogenic Sr–Nd composition of sample of BJ-028 of the Jurassic–Cretaceous Tamrau Formation reflects its derivation from a Proterozoic–Palaeozoic continental crust source (similar to that observed in NE Australia; Figure 2). These data are comparable to other Jurassic–Cretaceous passive margin sedimentary rocks of the Om Formation from eastern New Guinea (Richards et al., 1990) indicating that continent-derived Jurassic–Cretaceous passive margin sedimentary rocks can be traced along the length of New Guinea (including the Kembelangan Formation of the Bird’s Neck and Central Range) (van Ufford & Cloos, 2005; Warren & Cloos, 2007; Decker et al., 2017).

Samples from the middle Miocene Moon Volcanics show the same trend towards more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ values as late Miocene to Pliocene intrusive rocks and hydrothermal fluids from the Porgera Intrusive Complex in Papua New Guinea (Richards et al., 1990; 1991). The Porgera samples with a more radiogenic isotopic composition were considered to be derived from mixing between depleted mantle melts and Jurassic Australian passive margin sedimentary rocks in a back-arc setting above a southward dipping subduction zone following arc–continent collision (Richards et al., 1990; 1991). The tectonic setting and isotopic data obtained from the Porgera samples are comparable to those of the Moon Volcanics with the mixing between mantle-derived melts and the Jurassic–Cretaceous Tamrau Formation above a southward dipping subduction zone (Webb et al., 2020). Hafnium on zircon isotopic studies from the Miocene–Pliocene Maramuni Arc in eastern New Guinea also show the continued crustal contamination of mantle-derived melts by
Mesozoic sedimentary rocks in the upper crust (Holm et al., 2015). However, these magmatic rocks are proposed to have formed following a period of continent–continent collision in the middle to late Miocene (Holm et al., 2015).

The low $^{87}\text{Sr}/^{86}\text{Sr}$ and moderate $\varepsilon_{\text{Nd}}$ values obtained from the Oligocene Mandi Volcanics in this study are comparable with isotopic data from early Miocene mafic intrusive rocks in the Bewani–Torricelli Mountains that also reflect an accreted island arc (Crowhurst et al., 2004).

The intrusive rocks of the Arfak Volcanics (MW15-058) and Lembai Diorite (MW15-050 & 051) have $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$ values comparable to Miocene intrusive rocks of the Bugalaga Traverse in the Central Range (Weiland, 1999). The rocks of the Bugalaga Traverse intruded through both the Irian Ophiolite and accreted mafic arc volcanic rocks, their field observations and isotopic data are consistent with the middle Miocene intrusives of the Arfak Volcanics (Figure 2c; Webb et al., 2020), indicating that they too may have intruded through previously accreted arc volcanic rocks and ophiolites (e.g., Webb et al., 2020).

Isotopic studies of Plio-Pleistocene magmatism across New Guinea reveal two distinct groups of data. Those in the east yield relatively depleted isotopic values, only slightly more radiogenic than MORB, and are proposed to have been formed by the crustal contamination of mantle-derived melts during either subduction or continental collision (Hamilton et al., 1983; Richards et al., 1990; Hegner & Smith, 1992; van Dongen et al., 2010; Holm et al., 2015). These data differ from the highly radiogenic isotopic values obtained from rocks in the Central Range of western New Guinea. These highly radiogenic data are thought to be the result of mixing of an ancient enriched mantle reservoir and Archaean or Proterozoic Australian continental crust (Housh & McMahon, 2000).
The youngest volcanic analysed in this study was from the Plio-Pleistocene Berangan Andesite. The isotopic data obtained for these rocks are comparable to data obtained from Pleistocene volcanoes of the Fly-Highlands in eastern New Guinea (Figure 2c) (Hamilton et al., 1983). These Pleistocene volcanoes are interpreted to have formed from the crustal contamination of mantle-derived magmas during Pliocene uplift following arc–continent collision (Hamilton et al., 1983). This mechanism is consistent with the crustal contamination of the Berangan Andesite by middle–upper crustal Palaeozoic–Mesozoic granitoids following late Miocene–Pliocene arc–continent collision in the Bird’s Head Peninsula (Webb et al., 2019).

We created a broader scale IDW interpolation of the $\varepsilon_{\text{Nd}}$ isotopic data from this study and those from earlier studies to capture the variation of isotopic values across New Guinea and map the extent of crustal fragments with different affinities (Figure 9a). Australian continental crust across New Guinea yields $\varepsilon_{\text{Nd}}$ values of $-20$ to $0$; transitional magmatic rocks yield $\varepsilon_{\text{Nd}}$ values of $0$ to $5$; and oceanic/island arc crust yields $\varepsilon_{\text{Nd}}$ values of $5$ to $10$ (Figure 9a). These values are comparable to the isotopic ranges derived from crustal fragments in the Bird’s Head Peninsula (Figure 8) indicating that $\varepsilon_{\text{Nd}}$ isotopic data can be used to track the nature of the underlying crust across New Guinea. There is a systematic change in the $\varepsilon_{\text{Nd}}$ values from west to east in New Guinea (Figure 9a). The west is dominated by negative $\varepsilon_{\text{Nd}}$ values indicative of contamination by the underlying Proterozoic Australian continental crust (Housh & McMahon, 2000). Isolated regions of positive values in the centre of the island correspond to the location of island arc material along the northern and central ranges (Figures 1a and 9a). However, the comparative lack of isotopic data obtained from central New Guinea (in particular the northern ranges) and the extremely negative continental crust values taken from samples in the New Guinea Fold and Thrust Belt (Housh...
means that the distinction between continental, oceanic, and transitional crust is less obvious here. In the east, the IDW map is dominated by positive $\varepsilon_{Nd}$ values (indicative of partially contaminated transitional material, primary mantle, or island arc material; e.g., Figure 8) with isolated negative values corresponding to Triassic granitoids and Jurassic–Cretaceous passive margin sedimentary rocks (Richards et al., 1990; Crowhurst et al., 2004). This isotopic variation is likely the result of both different degrees of crustal contamination in magmatic rocks across the island and the age and nature of the underlying continental crust (e.g., Proterozoic in the west vs. Palaeozoic in the east).

The level of contamination in New Guinea is governed by two factors: the thickness of Australian continental crust beneath New Guinea (with thicker crust corresponding to greater crustal contamination); and the age of the crust beneath New Guinea (with regions of particularly old continental crust giving more negative $\varepsilon_{Nd}$ values than regions of younger crust, irrespective of crustal thickness) (Housh & McMahon, 2000). To further test the isotopic mapping of continental vs. oceanic/island arc crust, we compared the interpolated $\varepsilon_{Nd}$ value map with P-wave velocity data generated for a depth of ~23 km (Figure 9b) (Li et al., 2008). The tomographic imagery highlights a band of faster velocities (shown in blue and green colours; Figure 9b) that strike east to west across the island. This region of higher velocities likely corresponds to dense, cold, continental lithosphere beneath New Guinea and shows little variation from east to west, indicating that the density and composition of continental crust remains relatively constant from east to west across the centre of the island. Regions of slower velocities are also present across New Guinea. These typically correspond to the locations of accreted island arc material and high positive $\varepsilon_{Nd}$ values (indicative of oceanic/island arc crust) along the northern margin of New Guinea (Figures 1a & 9a). We propose that these zones of slower velocity define zones of oceanic/island arc
crust thrust onto the leading edge of the Australian Plate (i.e., relatively thinner Australian continental crust than is found further to the south). Given that there is no apparent change in crustal density from east to west across New Guinea (Figure 9b), it is likely that the age of the underlying crust is the primary cause of variations in the \( \varepsilon_{\text{Nd}} \) data. The presence of Archaean or Proterozoic Australian continental crust beneath central New Guinea has been previously proposed (Housh & McMahon, 2000), and the results from this study indicate that Devonian–Triassic granitoids in the Bird’s Head have intruded through Proterozoic continental crust. The positive \( \varepsilon_{\text{Nd}} \) data in eastern New Guinea may represent the presence of younger Palaeozoic continental or transitional crust underlying this part of the island (Crowhurst et al., 2004). This can be compared to the transition from Archaean–Proterozoic stable cratons to Proterozoic–Mesozoic rifted and arc-related crust observed in eastern Australia (Aitchison et al., 1992; Simons et al., 1999; Debayle et al., 2000; Hill & Hall, 2003).

We determined the isotopic ranges for different crustal domains based on the data generated in this study and their correlation with similar rocks across New Guinea. Continental crust is defined by \( ^{87}\text{Sr}/^{86}\text{Sr} \): 0.719594–0.710921; \( \varepsilon_{\text{Nd}} \): −13.85 to −7.53; \( ^{2}T_{\text{DM}} \): 1.988–1.373, transitional Miocene–Pleistocene magmatic rocks are defined by \( ^{87}\text{Sr}/^{86}\text{Sr} \): 0.706524–0.704019; \( \varepsilon_{\text{Nd}} \): 6.67 to 2.13; \( ^{2}T_{\text{DM}} \): 0.612–0.262, and oceanic island arc crust is defined by \( ^{87}\text{Sr}/^{86}\text{Sr} \): 0.704053–0.703759; \( \varepsilon_{\text{Nd}} \): 6.63 to 4.97; \( ^{2}T_{\text{DM}} \): 0.392–0.330. Our aim here was to provide a framework for future workers to use when interpreting the extent of crustal domains using isotopic data, particularly in difficult to access regions.

6. Conclusions
Sr–Nd isotopic data from rocks in the Bird’s Head can be correlated with the isotopic compositions of coeval and cogenetic rocks across New Guinea and indicate the shared tectonic history of eastern and western New Guinea since at least the Triassic.

Binary isotope mixing models combined with field and petrographic studies show that the middle Miocene Moon Volcanics erupted through thinned continental crust and have been contaminated by up to ~25% partial melt of the underlying Tamrau Formation and ~10–15% partial melt from the middle–upper Australian continental crust. The Berangan Andesite also shows evidence for crustal contamination by both the Tamrau Formation (~20%) and the middle–upper crust of the Kemum Block (~20%).

Sr–Nd isotope and $^2T_{DM}$ model age signatures have been determined for Proterozoic–Palaeozoic middle–upper continental crust ($^{87}\text{Sr}/^{86}\text{Sr}$: 0.719594–0.710921; $\varepsilon_{Nd}$: −13.85 to −7.53; $^2T_{DM}$: 1.988–1.373), Eocene–Miocene oceanic island arc crust ($^{87}\text{Sr}/^{86}\text{Sr}$: 0.704053–0.703759; $\varepsilon_{Nd}$: 6.63 to 4.97; $^2T_{DM}$: 0.392–0.330), and transitional Miocene–Pleistocene magmatic rocks ($^{87}\text{Sr}/^{86}\text{Sr}$: 0.706525–0.704019; $\varepsilon_{Nd}$: 6.67 to 2.13; $^2T_{DM}$: 0.612–0.212), which intrude through both continental and oceanic rocks in the Bird’s Head. These isotopic crustal signatures can be used to map the extent of Australian continental crust and accreted oceanic island arc crust across New Guinea.

The northern-most extent of Australian continental crust has been determined to continue further than its previously proposed termination along the Sorong Fault Zone. Continental crust in the Bird’s Head extends beneath the Tamrau Block to at least latitude 0°30’ S.
The age of underlying Australian continental crust beneath New Guinea varies from Archean–Proterozoic in the west to Palaeozoic in the east.

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**Figure Captions**

**Figure 1**

Overview maps of the geology, terranes, and crustal domains of New Guinea and the Bird’s Head. a) Overview map of the geology and terranes that can be correlated along the length of New Guinea (the location of the different terranes has been adapted from Baldwin et al., 2012 & Davies, 2012). Included in the map are the locations of previous isotopic studies in New Guinea used for comparison with data from this study. b) Map of the Bird’s Head displaying the different crustal domains present (continental zone, transition zone, and oceanic zone), along with sample locations, terranes, and structures. The locations of crustal domains are based on Pieters et al. (1983).

**Figure 2**
Plots showing $\epsilon_{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic data for all samples from this study. a) Plot of measured $\epsilon_{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic data for all samples, with fields representing most present-day oceanic basalts and arcs (Hawkesworth et al., 1991; Hofmann, 1997) and NE Australia Palaeozoic and Proterozoic continental crust (Black & McCulloch, 1990; Knutson et al., 1996; Blewett et al., 1998) and the mantle array. b) Plot of age corrected initial $\epsilon_{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic data for all samples, fields are the same as those from Figure 2a. c) Plot showing measured $\epsilon_{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic data for all samples in this study with fields showing Sr-Nd isotopic from across New Guinea for comparison. Errors for all samples are too small to plot (e.g., smaller than the symbols used).

Figure 3

Two-stage $T_{DM}$ Nd model ages for all samples from this study. a) Two-stage $T_{DM}$ Nd model ages for all Cenozoic magmatic rocks and sample MW16-034 of the Tamravu Block basement. b) Two-stage $T_{DM}$ Nd model ages for granitoids from the Kemum Block basement and sample BJ-028 of the Tamravu Block basement. Errors for all samples are too small to plot (e.g., smaller than the symbols used).

Figure 4

Field photos and photomicrographs from the Moon Volcanics, Tamravu Formation, and Berangan Andesite showing evidence for crustal contamination and partial melting of country rocks. a) Hand specimen of the Berangan Andesite (MW15-054) showing the presence of aggregates of quartz xenocrysts reflecting crustal contamination. b) Photomicrograph of the Berangan Andesite (MW15-054) with deformed aggregates of quartz xenocrysts showing bulging and sub-grain rotation recrystallisation within and andesitic groundmass. c) Intrusive relationship between a microtonalite (MW15-078) of the
Moon Volcanics and a schist of the Tamrau Formation. d) Intrusive relationship between a granite (MW15-031) of the Moon Volcanics and a mylonitic schist of the Tamrau Formation (BJ-028), discordant ptygmatic veins of partial melt radiate from the contact. e) Contact between MW15-031 (Moon Volcanics granite) and BJ-028 (Tamrau Formation mylonitic schist), the schist contains pockets of quartzose partial melt concordant to the dominant fabric. f) Photomicrograph of sample BJ-028 showing pockets of quartzose partial melt crystallised in veins concordant to the main mylonitic fabric.

Figure 5

$^{87}\text{Sr}/^{86}\text{Sr}$ vs. SiO$_2$ wt. % plot for the Cenozoic magmatic rocks and the Tamrau Block basement. The plot shows the effects of crustal contamination on increasing $^{87}\text{Sr}/^{86}\text{Sr}$ values in the Moon Volcanics and Berangan Andesite and fractional crystallisation in the Mandi and Arfak volcanics and Lembai Diorite. Errors for all samples are too small to plot (e.g., smaller than the symbols used).

Figure 6

$^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ binary isotope mixing models showing the extend of crustal contamination in the Moon Volcanics and Berangan Andesite. a) Mixing model using the most depleted sample from the Moon Volcanics (MW16-021) as a starting composition and samples MW16-034, BJ-02, and 12JD332A as potential contaminants. b) Mixing model using MORB (Sun & McDonough, 1989) as a starting composition and samples BJ-028 & BJ-138 as
potential contaminants. Errors for all samples are too small to plot (e.g., smaller than the symbols used).

**Figure 7**

Inverse distance weighted (IDW) interpolation maps using $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$ isotopic data as well as $^{2}\text{T}_{\text{DM}}$ Nd model ages for samples from this study to understand the northern extent of Australian continental crust in the Bird’s Head Peninsula, its relationship to regional structures, and the isotopic signature of different terranes in the peninsula. a) $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic data and sample location map. b) IDW interpolation map using $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic data. c) $\varepsilon_{\text{Nd}}$ isotopic data and sample location map. d) IDW interpolation map using $\varepsilon_{\text{Nd}}$ isotopic data. e) $^{2}\text{T}_{\text{DM}}$ Nd model ages and sample location map. f) IDW interpolation map using $^{2}\text{T}_{\text{DM}}$ Nd model ages.

**Figure 8**

Crustal domain map of the Bird’s Head showing the location of autochthonous and allochthonous terranes, polygons defining the location of different formations within them, and their classification as continental crust, transitional magmatic rocks, or oceanic crust based on their $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$ isotopic data and $^{2}\text{T}_{\text{DM}}$ Nd model ages from this study. The location of terranes and the geology within them are derived from Pieters et al. (1983) and Dow and Sukamto, (1984).

**Figure 9**

Inverse distance weighted (IDW) interpolation and P-wave velocity maps for New Guinea. a) Inverse distance weighted (IDW) interpolation maps for New Guinea using $\varepsilon_{\text{Nd}}$ isotopic data
from both this study and previous studies in New Guinea (Hamilton et al., 1983; Richards et
al., 1990; Hegner & Smith, 1992; Weiland, 1999; Housh & McMahon, 2002; Crowhurst et al.,
2004). The individual data were also used to identify isotopic ranges for underlying crustal
domains across New Guinea (Australian continental crust; transitional magmatic rocks;
oceanic/island arc crust). b) P-wave velocity data at 23 km depth imaging the nature of the
crust beneath New Guinea, P-wave velocity data were taken from Li et al. (2008). Blues and
greens show the location of higher velocity waves through dense, cold continental crust,
while oranges and reds show the location of lower velocity waves from thinner oceanic
crust or hot mantle material.

Supplementary Data File 1

All TIMS Sm–Nd and Rb–Sr isotopic and supplementary data for samples and standards used
in this study.

Supplementary Data File 2

Binary isotope mixing models and AFC models for $^{143}$Nd/$^{144}$Nd vs. $^{87}$Sr/$^{86}$Sr including
parameters for all potential melt sources.
Isotopic mapping reveals the location of crustal fragments along a long-lived convergent plate boundary.

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Abstract

New Guinea has acted as the boundary between the Australian and Pacific plates for hundreds of millions of years. Strike-slip movement and arc–continent collisions along this boundary during the Cenozoic have shuffled rocks of different age and composition in a series of terranes along the plate boundary making mapping them a considerable challenge.

Here we report results of Sr–Nd isotopic data obtained from rock samples from western New Guinea that are representative of the different terranes. These isotopic data reveal the crustal affinity of the terranes and we have used these data to map their spatial distribution. The isotopic data show three distinct crustal domains underlying western New Guinea; Palaeozoic–Mesozoic Australian continental crust (${^{87}\text{Sr}}/{^{86}\text{Sr}} = 0.719594$ to 0.710921; $\varepsilon_{\text{Nd}} = -13.85$ to 1.373); thinned transitional crust intruded by Miocene–Pleistocene magmatic rocks (${^{87}\text{Sr}}/{^{86}\text{Sr}} = 0.706524$ to 0.704019; $\varepsilon_{\text{Nd}} = 6.67$ to 2.13); and accreted island arc crust (${^{87}\text{Sr}}/{^{86}\text{Sr}} = 0.704053$ to 0.703759; $\varepsilon_{\text{Nd}} = 6.63$ to 4.97). These data, together with crustal contamination models, indicate that the northern-most extent of Australian continental crust exists beneath the northern-most section of western New Guinea. We also combined our isotopic data with existing data across New Guinea and used these to develop an isotopic map that shows the position of the ancient Australian–Pacific Plate boundary, producing results that are also consistent with broad-scale seismic tomography imagery. Our findings provide a framework for mapping other plate boundaries, particularly ancient systems where only fragmentary data exist.
Keywords:
Sr–Nd isotopes; New Guinea; Continental crust; Crustal contamination; Australian Plate
1. Introduction

Convergent plate boundaries are complicated zones where slices of the Earth’s crust of different age and composition (‘terranes’) are often juxtaposed. Unravelling the history of these zones is key to understanding what the Earth looked like in the past. New Guinea is recognised as one of the world’s youngest arc–continent collisional orogens (Ali & Hall, 1995; Hall, 2002; Hill & Hall, 2003; Baldwin et al., 2012; Davies, 2012; Holm et al., 2016), but has acted as a plate boundary to the northern margin of the Australian Plate since the Triassic (Hill & Hall, 2003; Jost et al., 2018). If we can understand the tectonic evolution of New Guinea in its current setting, then we can use this knowledge to better understand other much older plate boundary systems.

The island of New Guinea marks the meeting point of the Australian, Philippine Sea, and Caroline tectonic plates (Milsom et al., 1992; Bird, 2003; Hall & Spakman, 2003; Tregoning & Gorbatov, 2004). The interaction of these plates during the Cenozoic saw the production of subduction-related volcanism, the collision and accretion of island arc volcanoes, as well as extensive strike-slip faulting. All of this tectonic activity has resulted in the island’s current geological configuration, that is a complicated region of juxtaposed sections of oceanic and continental crust. The complicated tectonic history, together with large areas of difficult to access terrain (e.g., mountains, dense tropical rainforest, vegetated wetlands) has meant it has been difficult to identify the location of ancient plate boundaries.

Australian continental crust was initially proposed to extend no further north than the New Guinea Fold and Thrust belt in eastern New Guinea (Abers & McCaffrey, 1988). Recent studies from eastern New Guinea, however, show that underthrust Australian continental
crust may continue north beneath the New Guinea Mobile Belt and be in contact with
oceanic or island arc crust of the Marum Ophiolite and Adelbert–Finisterre–Huon Block
along the Ramu–Markham Fault (Crowhurst et al., 1996). Isotopic studies from central New
Guinea indicate that ancient Archaean or Proterozoic Australian continental crust extends
north beneath the Central Range to at least the 4th parallel South (based on the location of
crustally contaminated Pliocene–Pleistocene igneous rocks) (Housh & McMahon, 2000).

In addition, limited geophysical data exist in this region of the world. This means it is difficult
to map the variation of crustal thicknesses across New Guinea. Those data that do exist
(e.g., seismic tomography) have typically been applied to only eastern New Guinea (Abers &
McCaffrey, 1988; Abers, 1991; Abers & Roecker, 1991) or used to image subducted slabs
deeper in the mantle (Hall & Spakman, 2003), while other work has focussed on looking at
upper crustal structures that may control the location of ore deposits (White et al., 2013) –
however, all of this work has relied on predominately coarse resolution data. It therefore
presents a significant challenge as to how one could map the crustal structure of New
Guinea.

Recent Nd isotopic studies of the Australian continent have been used to isotopically map
different geological domains, from Archaean–Proterozoic cratons to Palaeozoic arc and
orogenic terranes (Champion, 2013; Mole et al., 2015; Champion & Huston, 2016). Such
work has also been applied in the Himalaya (Ahmad et al., 2000; Richards et al., 2005), the
western United States (Bennett & DePaolo, 1987), the Central Asian Orogenic Belt (Wang et
al., 2009; Wang et al., 2015), and Antarctica (Borg & DePaolo, 1994), providing insight into
the age and isotopic signature of juxtaposed terranes and the underlying crust. Here we
take a similar approach using $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ whole-rock isotopic data from a
series of Devonian–Carboniferous and Permian–Triassic basement rock granitoids, metamorphosed Mesozoic passive margin sedimentary rocks, Oligocene oceanic island arcs, and Miocene–Pleistocene magmatic rocks from NW New Guinea. Using these isotopic data, we define isotopic signatures for and map different crustal domains across the region. We then compared our data with existing isotopic data available from other parts of New Guinea to map the northern-most extent of Australian continental crust and other crustal fragments.

2. Regional Background

2.1. The crustal domains and tectonics of New Guinea

The island of New Guinea was largely formed by a long history of continental growth along an Andean-type subduction system during the Palaeozoic and Mesozoic, and the accumulation of multiple terranes along its northern margin throughout the Cenozoic (Figure 1a). The number of terranes and their crustal affinities vary depending on individual studies. For instance, one article indicates that New Guinea consists of up to thirty-two separate terranes (Pigram & Davies, 1987). However, more recent work shows that many of those thirty-two terranes are equivalent to one another, and after reflecting on these similarities, there are essentially four distinct belts that strike broadly east–west, along the length of the island (Figure 1a) (Baldwin et al., 2012; Davies, 2012). These include: a stable platform in the south composed of both Proterozoic (western New Guinea) and Palaeozoic (eastern New Guinea) continental crust overlain by thick carbonate sequences (Hill & Hall, 2003); the New Guinea Fold and Thrust Belt, consisting of Jurassic–Neogene sedimentary rocks, which have been deformed and uplifted since the Oligocene in response to at least
two arc–continent collisions (Pigram & Panggabean, 1984; van Ufford & Cloos, 2005; Cloos, 2005; Mahoney et al., 2019; Webb et al., 2020); the New Guinea Mobile Belt, a highly active region composed of terranes of both continental and oceanic crust (Hill & Hall, 2003), including Late Cretaceous to early Paleocene ophiolites (Davies & Jaques, 1984; Weiland, 1999); and a series of oceanic island arcs (Figure 1). These arcs formed during the Eocene–early Miocene in the Philippine Sea and Pacific plates above the northwards subducting Australian Plate (Hill & Hall, 2003; Webb et al., 2020) and collided with the northern margin of New Guinea during the Miocene (Hill & Hall, 2003; Cloos, 2005; Webb et al., 2019).

The Bird’s Head Peninsula of westernmost New Guinea is composed of three crustal zones containing rocks of similar affinities and deformation styles to those four regional tectonic belts (Pieters et al., 1983; Dow & Sukamto, 1984). These zones are: the continental zone consisting of Australian continental crust; the transition zone, made up of rocks derived from both continental and oceanic crust; and the oceanic zone, which includes obducted and accreted oceanic and island arc crust (Figure 1b). Understanding how these zones in the Bird’s Head and the rocks therein correlate with the major tectonic belts of the rest of New Guinea and how they relate to the underlying crust will improve our understanding of the tectonic evolution of NW New Guinea and the northern margin of the Australian Plate.

2.2. The geology of NW New Guinea

Previous mapping campaigns by Indonesian and Australian government geologists subdivided the rocks of the region into a series of tectonostratigraphic blocks belonging to different crustal zones (Figure 1b) (Pieters et al., 1983; Dow & Sukamto, 1984; Pigram & Davies, 1987). The Kemum Block (continental zone) in the south represents Australian continental crust and is composed of Siluro–Ordovician metaturbidites, intruded by
Devonian–Triassic granitoids, and overlain by Jurassic–Cretaceous passive margin sedimentary rocks (Dow & Sukamto, 1984; Gunawan et al., 2012; Jost et al., 2018). It should be noted that while some seismic and modern-day GPS plate motion studies indicate that the Kemum Block forms part of a separate microcontinental block (termed the Bird’s Head Block) that separated from the Australian continent during Late Triassic rifting (Pigram & Panggabean, 1984; Dow et al., 1988; Stevens et al., 2002; Bailly et al., 2009), studies of the Palaeozoic granitic rocks of the Kemum Block indicate that they formed as part of the Australian Plate during subduction beneath eastern Gondwana (Crowhurst et al., 2004; Webb & White, 2016; Jost et al., 2018). Immediately north and east of the Kemum Block are the Sorong and Ransiki fault zones, respectively, these are large strike-slip fault zones up to ~15 km across (Figure 1b). These fault zones contain fault bounded fragments of both continental and oceanic affinity and may have transported these fragments from up to ~300 km westwards (Pieters et al., 1983; Dow & Sukamto, 1984; Webb & White, 2016; Jost et al., 2018; Webb et al., 2019). North of the Sorong Fault Zone is the Tamrau Block (transition zone), which represents an allochthonous block that has been transported along the fault zone (Figure 1b). The block has a deformed metasedimentary basement (Jurassic–Cretaceous protolith), overlain by Palaeogene metacarbonate, both of which have been intruded by middle Miocene arc volcanic rocks, and unconformably overlain by Miocene–Pleistocene sedimentary rocks (Pieters et al., 1983; Webb et al., 2019). Along the northern and eastern coasts lie the Tosem and Arfak blocks (oceanic zone), these are composed of Eocene–Miocene oceanic island arc volcanic rocks, which collided with the northern margin of the Australian Plate throughout the Miocene (Pieters et al., 1983; Dow & Sukamto, 1984; Black & McCulloch, 1990; Webb et al., 2019).
The rocks analysed in this study include Devonian–Triassic granitoids of the Kemum Block (Mariam Granodiorite, Wasiani Granite, Wariki Granodiorite, and Anggi Intrusive Complex), Sorong Fault Zone (Sorong Granite and Netoni Intrusive Complex) and Bird’s Neck regions (Maransbadi and Kwatisore granites), Jurassic–Palaeogene metasedimentary rocks and Miocene–Pleistocene volcanics of the Tamrau Block (Tamrau Formation, Ajai Limestone, Moon Volcanics, and Berangan Andesite), middle Miocene diorites in the Ransiki Fault Zone (Lembai Diorite), and oceanic island arc rocks from the Tosem and Arfak blocks (Mandi and Arfak Volcanics, respectively).

3. Methods

3.1. Whole-rock Sr–Nd isotopic analysis

Twenty-two samples were analysed for their whole-rock Sr–Nd isotopic compositions and LREE concentrations. For both Sr and Nd analyses, 0.1 g of bulk rock powder was dissolved using HF–HNO₃ in Teflon beakers for 24 hrs at 180°C, they were then evaporated and converted to nitrate by digestion in HNO₃ before undergoing total dissolution in 10% HNO₃. Twenty-five percent of the resulting solution was then removed for analysis of the light rare earth elements (LREEs). Strontium isotopes were determined on an Isotopx Phoenix thermal ionisation mass spectrometer (TIMS) at Royal Holloway University using the multidynamic method of Thirlwall (1991b). During the period of analysis, SRM987 gave \(^{87}\text{Sr}/^{86}\text{Sr}\) values of 0.71023 ± 9 and 0.710234 ± 8 (2SD). Neodymium isotopes were determined on a Thermo Scientific Triton TIMS at the University of Leeds; during these analyses the La Jolla standard gave \(^{143}\text{Nd}/^{144}\text{Nd}\) of 0.511860 ± 16 and 0.511876 ± 11 (2SD), both within published ranges for La Jolla 0.511858 ± 20 (Lugmair et al., 1978; 1983). The LREE samples were prepared and analysed using the same isotope dilution (ID) methods and multi-element spike as in
Thirlwall 1982, and were analysed on the RHUL IsoProbe MC-ICP-MS. Major and trace element data for the samples in this study were used to further support isotopic modelling and interpretation. These data were collected on fusion disks and pressed pellets, respectively. These were analysed using a 2010 PANalytical Axios sequential X-ray fluorescence spectrometer at RHUL. These data and a full account of the analytical methods used during data collection are presented in full in previous related studies (Jost et al., 2018; Webb et al., 2020).

All additional calculations made to the measured Sr–Nd isotopic data (e.g., age corrections and model ages) were made using the geochemical data modelling software GCDkit (Janoušek et al., 2006). Epsilon Nd data was calculated from the $^{143}\text{Nd}/^{144}\text{Nd}$ data using the present-day CHUR value - 0.512638 (chondritic uniform reservoir) (DePaolo & Wasserburg, 1976; Jacobsen & Wasserburg, 1980; DePaolo, 1988). Age corrections have been performed on all samples to correct for radiogenic ingrowth over time and yield $^{87}\text{Sr}/^{86}\text{Sr}(i)$ and $\varepsilon_{\text{Nd}}(i)$ values based on U–Pb zircon geochronology and apparent stratigraphic ages reported in recent studies of the region (Webb & White, 2016; Jost et al., 2018; Webb et al., 2019; Webb et al., 2020). Either single-stage or two-stage $T_{DM}$ Nd model ages were calculated for the samples in GCDkit (Janoušek et al., 2006) to model when the melts that formed these rocks separated from the depleted mantle model reservoir (DePaolo, 1988). The use of single-stage or two-stage $T_{DM}$ Nd model ages was dependent on if the sample was suspected of being partially or completely crustally contaminated (based on field observations, geochemistry, and U–Pb zircon geochronology) (Webb et al., 2020) or if the single-stage model age did not make geological sense (e.g., when they generate minus values or ages over 4.5 Ga). Calculation of two-stage $T_{DM}$ Nd model ages in GCDkit requires the input of a measured $^{147}\text{Sm}/^{144}\text{Nd}$ ratio (obtained during this study) and a crystallisation age (U–Pb
zircon ages for all samples are reported in Webb et al., 2019; 2020) for each sample, an
assumed crustal evolution curve (\(^{147}\text{Sm} /^{144}\text{Nd}\) ratio of 0.12 - Liew & Hofmann, 1988) is then
used to determine when the sample separated from the depleted mantle (e.g., the two-
stage \(T_{\text{DM}}\) Nd model age). The two-stage \(T_{\text{DM}}\) Nd model age is used to correct for a range of
crustal processes (including crustal contamination) (Liew & McCulloch, 1985).

4. Results

4.1. Whole-rock Sr–Nd isotopic analysis

Twenty-one samples of volcanic, plutonic, metamorphic, and sedimentary rocks from the
Bird’s Head where analysed for whole-rock \(^{87}\text{Sr} /^{86}\text{Sr}\) isotopic data, twenty of these samples
were also analysed for whole-rock \(^{147}\text{Sm} /^{144}\text{Nd}\) and \(^{143}\text{Nd} /^{144}\text{Nd}\) data (Supplementary Data
File 1). The remaining sample (MW15-024) did not contain enough Nd for \(^{147}\text{Sm} /^{144}\text{Nd}\) and
\(^{143}\text{Nd} /^{144}\text{Nd}\) analyses. The results were sub-divided into six groups based on their isotopic
values and their geographic location. These groups are summarised in Supplementary Data
File 1 and Figure 1b.

4.1.1. The Kemum Block and continental basement (continental zone)

Eight granitoids analysed from the Kemum Block and surrounding areas of continental crust
in West Papua (e.g., the Netoni Fragment and Lengguru Fold and Thrust Belt; Figure 1b)
display relatively enriched isotopic values consistent with their formation within Australian
continental crust (\(^{87}\text{Sr} /^{86}\text{Sr} = 0.719594\) to \(0.710921;\) \(^{143}\text{Nd} /^{144}\text{Nd} = 0.512208\) to \(0.511928;\) \(\varepsilon_{\text{Nd}}\n = −13.85\) to \(−8.39;\) Supplementary Data File 1). Age corrections yield a significant change in
\(^{87}\text{Sr} /^{86}\text{Sr}(i)\) values (0.713538 to 0.703029), resulting from ingrowth of radiogenic Sr, while
$\varepsilon_{Nd(i)}$ values remain relatively unchanged ($-11.32$ to $-7.15$). The two samples with the most significant change in values and lowest $^{87}\text{Sr}/^{86}\text{Sr(i)}$ (MW14-11 = 0.703029; MW15-024 = 0.703444) also have the highest $^{87}\text{Rb}/^{86}\text{Sr}$ values and have been extensively deformed and partially recrystallised (Webb & White, 2016; Jost et al., 2018). These processes may have altered the $^{87}\text{Sr}/^{86}\text{Sr(i)}$ values of these samples. Single-stage $T_{DM}$ model ages for the Kemum Basement rocks are dominantly Archaean–Proterozoic (2.91–1.205 Ga) along with an anomalous and unrealistic age of 6.206 Ga (BJ-121). Given this anomalous age and earlier evidence for crustal contamination in these rocks (Jost et al., 2018), we consider that the two-stage $T_{DM}$ Palaeoproterozoic model ages are more reliable (1.988–1.564 Ga), these ages also correlate well with inherited Proterozoic zircons within these granitoids (Jost et al., 2018).

### 4.1.2. The Tamrau Block (transition zone)

#### 4.1.2.1. Basement Rocks

The metapelite (Tamrau Formation; BJ-028) and metacalc-silicate (Ajai Limestone; MW16-034) basement rocks of the Tamrau Block yield moderately enriched isotopic values ($^{87}\text{Sr}/^{86}\text{Sr} = 0.713279$ to $0.707256$; $^{143}\text{Nd}/^{144}\text{Nd} = 0.512866$ to 0.512252; $\varepsilon_{Nd} = -7.53$ to 4.45; Supplementary Data File 1). As they represent metasedimentary rocks derived from multiple age sources, age corrections on rocks from the Tamrau Block basement are not necessarily representative of the initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{Nd}$ values for the entire sample and as such should be treated with caution ($^{87}\text{Sr}/^{86}\text{Sr(i)} = 0.707247$ to $0.707104$; $\varepsilon_{Nd(i)} = -5.95$ to 4.72; Supplementary Data File 1). The ages obtained from these samples are derived from a youngest detrital zircon age from the Tamrau Formation ($150.3 \pm 7.4$ Ma; 2σ) and a stratigraphy-based age for the Ajai Limestone ($\sim 40$ Ma) (Webb et al., 2019). Model ages for
the two samples from the Tamrau Block differ significantly. Sample BJ-028 of the Tamrau
Formation yields older Mesoproterozoic single-stage (1.304 Ga) and two-stage (1.373 Ga)
T$_{DM}$ ages, while sample MW16-034 of the Ajai Limestone has younger Cambrian to
Neoproterozoic ages (single-stage: 0.580 Ga; two-stage: 0.449 Ga).

4.1.2.2. Moon Volcanics

Intermediate–felsic intrusive and extrusive rocks of the middle Miocene Moon Volcanics
display variable isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr} = 0.706524$ to $0.704019$; $^{143}\text{Nd}/^{144}\text{Nd} = 0.512980$ to
0.512806; $\varepsilon_{\text{Nd}} = 3.28$ to $6.67$; Supplementary Data File 1). Given the relatively young ages for
all Cenozoic volcanic rocks presented here (Eocene to Miocene for the Mandi and Arfak
volcanics, middle Miocene for the Lembai Diorite and Moon Volcanics, and Plio-Pleistocene
for the Berangan Andesite, Pieters et al., 1983; Webb et al., 2020), age corrections for these
rocks have little effect (Supplementary Data File 1) and as such, we have used their
measured values to better understand the present-day isotopic signature of crustal blocks in
the Bird’s Head Peninsula. Single-stage T$_{DM}$ model ages for the Moon Volcanics are
Mesoproterozoic to Mesozoic (1.036 to 0.236 Ga, including another unrealistic age of 9.12
Ga; MW15-078). Given this anomalous age, as well as the potential crustal contamination
within the Moon Volcanics (Webb et al., 2020) we consider the Palaeozoic two-stage model
ages (0.543 to 0.262 Ga) as being the most reliable for the Moon Volcanics.

4.1.2.3. Berangan Andesite

The Plio-Pleistocene Berangan Andesite yields moderately depleted isotopic data ($^{87}\text{Sr}/^{86}\text{Sr} =
0.704951$; $^{143}\text{Nd}/^{144}\text{Nd} = 0.512842$; $\varepsilon_{\text{Nd}} = 3.98$; Supplementary Data File 1), which are
consistent with it being a crustally-contaminated mantle-derived melt (Webb et al., 2020).
The single-stage and two-stage $T_{DM}$ model ages from sample MW15-054 of the Berangan Andesite give Ordovician ages of 0.476 to 0.458 Ga, respectively.

4.1.3. Island arc and oceanic crust (oceanic zone)

4.1.3.1. Mandi Volcanics

Mafic–intermediate intrusive and extrusive rocks of the Oligocene Mandi Volcanics have depleted isotopic values indicative of their formation within an island arc ($^{87}\text{Sr}/^{86}\text{Sr} = 0.704053$ to 0.703759; $^{143}\text{Nd}/^{144}\text{Nd} = 0.512964$ to 0.512893; $\varepsilon_{\text{Nd}} = 4.97$ to 6.36; Supplementary Data File 1). Single-stage model ages for the Mandi Volcanics again yield an anomalous age of −0.525 Ga (MW15-034). We therefore consider the Devonian–Carboniferous two-stage $T_{DM}$ model ages (0.392 to 0.330 Ga) as being the most reliable results for the Mandi Volcanics.

4.1.3.2. Lembai Diorite and Arfak Volcanics

Coeval middle Miocene quartz diorites from the Lembai Diorite (MW15-050, MW15-051) and the Arfak Volcanics (MW15-058) yield relatively depleted isotopic values ($^{87}\text{Sr}/^{86}\text{Sr} = 0.704575$ to 0.704304; $^{143}\text{Nd}/^{144}\text{Nd} = 0.512892$ to 0.512747; $\varepsilon_{\text{Nd}} = 2.13$ to 4.95; Supplementary Data File 1). Single-stage model ages for the Lembai Diorite samples yield an anomalous age of −0.224 Ga (MW15-050). We have therefore used the two-stage $T_{DM}$ model ages (Devonian ages of 0.466 to 0.438 Ga). The single-stage $T_{DM}$ age for the quartz diorite within the Arfak Volcanics (0.351 Ga; MW15-058) is comparable to the Devonian–Carboniferous two-stage ages obtained from the coeval Mandi Volcanics, while its two-stage $T_{DM}$ model age is Neoproterozoic (0.612 Ga).

5. Discussion
5.1. The isotopic signature and tectonic evolution of NW New Guinea

Determining the Sr–Nd isotopic composition of the rocks of NW New Guinea and what they indicate for their source has implications for understanding the nature of the crust beneath NW New Guinea and determining the northern-most extent of Australian continental crust. It also provides a distinct isotopic signature for each of the terranes studied, allowing for the correlation of isotopic signatures and allochthonous terranes across New Guinea. This can in turn be coupled with tectonic reconstructions to better understand the tectono-stratigraphic evolution of New Guinea.

The Devonian–Triassic granitoids of the Kemum Block formed during two periods of continental arc magmatism; intruding into the Palaeozoic basement of the Kemum Block at middle to upper crustal levels (Jost et al., 2018). These granitoids display high \(^{87}\text{Sr}/^{86}\text{Sr}\) values (0.719594 to 0.710921) and low negative \(\epsilon_{\text{Nd}}\) values (−13.85 to −8.39) consistent with rocks derived from ancient continental crust, this is supported by a Proterozoic inheritance in the U–Pb zircon age spectra of these granitoids (Jost et al., 2018). Figure 2a-b shows that these granitoids lie close to the field of isotopic compositions obtained from Palaeozoic–Proterozoic crustal rocks in NE Australia (Black & McCulloch, 1990; Knutson et al., 1996; Blewett et al., 1998), which are likely comparable in age and isotopic composition to the underlying basement of the Kemum Block. This is supported by the Palaeoproterozoic two-stage \(T_{\text{DM}}\) model ages of the Devonian–Carboniferous granitoids (Figure 3a) and suggests that Palaeozoic and Proterozoic Australian continental crust underlies the Kemum Block at middle to upper crustal levels.

The Tamrau Formation forms the Mesozoic basement of the Tamrau Block and formed during a period of extensive rifting and passive margin development that occurred along the
northern margin of New Guinea and eastern Australia in the Late Triassic to Cretaceous (Pigram & Panggabean, 1984; Hill & Hall, 2003). This led to the thinning of continental and transitional crust along this margin that now underlies the Tamrau Block. Radiogenic $^{87}$Sr/$^{86}$Sr (0.713279) and $\varepsilon_{Nd}$ (-7.53) values and the Proterozoic two-stage TDM model age (Figure 3a) from the Tamrau Block basement (Tamrau Formation – BJ-028) are consistent with its derivation from both Proterozoic–Palaeozoic Australian continental crust (comparable to crustal rocks exposed in NE Australia; Figure 2) and Palaeozoic–Mesozoic granitoids of the Kemum Block ($^{87}$Sr/$^{86}$Sr: 0.719594 to 0.710921; $\varepsilon_{Nd}$: -13.85 to -8.39). This is supported by its U–Pb detrital zircon spectra (Webb et al., 2019), which contains Triassic, Devonian, and Neo- to Mesoproterozoic ages, indicating potential sourcing from the Kemum Block basement (Decker et al., 2017; Jost et al., 2018) or NE Australia (Holm et al., 2020).

The Ajai Limestone of the Tamrau Block (MW16-034) is a calc-silicate rock containing both carbonate and siliciclastic material. It shows relatively high $^{87}$Sr/$^{86}$Sr (0.70756) compared to more depleted $\varepsilon_{Nd}$ (4.72) values and does not reflect the more radiogenic, older crustal signature of the underlying Tamrau Formation and Tamrau Block basement. This is likely the result of the introduction of seawater Sr during precipitation of its carbonate component, the $^{87}$Sr/$^{86}$Sr isotopic composition of seawater during deposition of the Ajai Limestone (~40 Ma; Webb et al., 2019) was ~0.70760 (Koepnick et al., 1985), comparable to the $^{87}$Sr/$^{86}$Sr composition of sample MW16-034.

The Moon Volcanics represent a suite of intrusive and extrusive rocks that formed within a continental arc along the northern margin of New Guinea in the middle Miocene and intruded through the Mesozoic basement of the Tamrau Block (Webb et al., 2020). These rocks display variable and moderately radiogenic $^{87}$Sr/$^{86}$Sr (0.704019 to 0.706524) and $\varepsilon_{Nd}$ values (3.28 to 6.67). These data lie outside the mantle array and the field representing
present-day oceanic basalts and island arc volcanics (Hawkesworth et al., 1991; Hofmann, 1997), trending to more radiogenic values (Figure 2a, b). These moderately radiogenic values indicate the addition of a continental crust component to an originally mantle-derived melt but are significantly less radiogenic than other examples of magmatism through thickened ancient Australian continental crust in New Guinea (Housh & McMahon, 2000). This is because the Moon Volcanics have instead intruded through the thinned continental or transitional Mesozoic crust underlying the Tamrau Block (the Tamrau Formation). Other isotopic studies of arc volcanism through thinned continental crust yield comparable isotopic data to the Moon Volcanics (Kurile Basin, Russia; \(^{87}\text{Sr}/^{86}\text{Sr}: 0.70652–0.70287\)) (Tararin et al., 2003) as do Pleistocene volcanics from the Sorong Fault Zone west of the Bird’s Head Peninsula, which have erupted through both oceanic crust and faulted slices of fragmented continental crust \(^{87}\text{Sr}/^{86}\text{Sr}: 0.7087–0.7058\) (Morris et al., 1983). Two-stage \(T_{\text{DM}}\) model ages in the Moon Volcanics increase from N–S (MW16-021; 0.262 to MW15-078; 0.543; Figure 1b) indicating a change in crustal age from younger Triassic crust in the north to older and potentially thicker Cambrian crust in the south.

The Berangan Andesite erupted through the Sorong Fault Zone (which separates the Kemum and Tamrau blocks) during the Plio-Pleistocene following a period of crustal thickening and terminal arc–continent collision (Webb et al., 2020). Field and petrographic evidence, as well as inheritance in its U–Pb zircon ages indicate that the Berangan Andesite underwent crustal contamination during its formation. This is supported by \(^{87}\text{Sr}/^{86}\text{Sr}\) (0.704951) and \(\varepsilon_{\text{Nd}}\) (3.98) values that plot outside both the mantle array and present-day oceanic basalt and arcs field (Figure 2a, b), this along with its early Ordovician two-stage \(T_{\text{DM}}\) model age (0.476 Ga; Figure 3b) indicate the incorporation of a Palaeozoic crustal component into the original melt.
Eocene to Miocene volcanic and intrusive rocks from the Mandi and Arfak volcanics and
Lembai Diorite display low $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.704575 to 0.703505) and positive $\varepsilon_{\text{Nd}}$ values (2.13 to 6.36) consistent with mantle-derived rocks in volcanic arcs. They plot within, or close to the mantle array and the field denoting most present-day oceanic basalts and island arc volcanic rocks (Figure 2a, b) (Hawkesworth et al., 1991; Hofmann, 1997), consistent with their formation within or intrusion into the Eocene–Oligocene oceanic island arcs of the Philippine Sea Plate (Webb et al., 2020).

### 5.2. Evidence for crustal contamination

Previous field, petrographic, and U–Pb zircon geochronology studies of the Moon Volcanics and Berangan Andesite (Webb et al., 2020) indicate that they have undergone some degree of crustal contamination. The Moon Volcanics formed within a continental arc resulting from subduction of the Philippine Sea Plate beneath the Australian Plate in the middle Miocene (Webb et al., 2020). Field evidence shows granitoids associated with these volcanics in intrusive contact with metasedimentary rocks of the Tamrau Formation, pockets of granitic melt can be observed in the surrounding country rock and indicate ongoing partial melting and possible contamination during the intrusion of these peraluminous granitoids (Figure 4; Webb et al., 2020). The Berangan Andesite formed during continued crustal thickening, uplift, and strike-slip faulting during the Pliocene to Pleistocene following late Miocene to Pliocene island arc–continent collision in NW New Guinea (Webb et al., 2020). Both field and petrographic observations indicate the presence of granitic xenoliths and quartz aggregate xenocrysts in the Berangan Andesite, these xenocrysts are deformed (showing evidence for grain-boundary migration) and are likely derived from granitic basement rocks in the underlying Kemum Block (Figure 4; Webb et al., 2020). In addition, U–
Pb zircon geochronology from the Berangan Andesite shows the presence of Triassic, Devonian–Carboniferous, and Neoproterozoic inherited zircons, these ages correspond to those found in the underlying Tamrau and Kemum Blocks and further support crustal contamination (Webb et al., 2020).

To assess the degree of crustal contamination in these rocks we plotted their SiO$_2$ wt. % vs. $^{87}\text{Sr}/^{86}\text{Sr}$ values. Figure 5 shows that samples from the Mandi Volcanics, Arfak Volcanics, and Lembai Diorite have relatively stable $^{87}\text{Sr}/^{86}\text{Sr}$ values below $\sim$0.7405 with increasing SiO$_2$ wt. %, indicating fractional crystallisation from a mantle-derived source (Downes, 1984). The same is true for three samples from the Moon Volcanics (MW16-021; MW16-022; MW15-074), they show uniform $^{87}\text{Sr}/^{86}\text{Sr}$ values below $\sim$0.7405 (reflecting a mantle source) with increasing SiO$_2$ indicating fractional crystallisation. However, two samples from the Moon Volcanics (MW15-031; MW15-078) are offset from the trend with both increased $^{87}\text{Sr}/^{86}\text{Sr}$ with SiO$_2$ values of $\sim$0.7064 and $\sim$69 wt. %, respectively.

This indicates that these samples have likely undergone some degree of crustal contamination, increasing their $^{87}\text{Sr}/^{86}\text{Sr}$ values and plotting them closer to those of the Tamrau Formation (Figure 5), into which the Moon Volcanics intrude (Webb et al., 2020). This crustal contamination appears to be temporally controlled, samples with low $^{87}\text{Sr}/^{86}\text{Sr}$ values formed at $\sim$14 Ma at the onset of subduction beneath the Moon Volcanics (MW16-021 – 14.5 ± 2.5 Ma) (Webb et al., 2020) while those with higher $^{87}\text{Sr}/^{86}\text{Sr}$ values formed at $\sim$12 Ma (MW15-078 – 12.4 ± 0.4 Ma, MW15-031 – 12.8 ± 1 Ma) (Webb et al., 2020) and therefore crustal contamination may reflect increasing crustal thickness during formation of the arc. Sample MW15-054 of the Berangan Andesite is also offset from the horizontal
fractional crystallisation trend (Figure 5), again indicating some degree of crustal contamination.

Binary isotope models ($^{143}$Nd/$^{144}$Nd vs. $^{87}$Sr/$^{86}$Sr) were used to further test the degree of crustal contamination in the Moon Volcanics and Berangan Andesite and to identify potential sources of contamination (Figure 6a, b; Supplementary Data File 2). The $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd isotopic ratios for the samples and contaminants were recalculated to initial values at 12 Ma to better reflect their isotopic signatures during magmatism in the Moon Volcanics. Two starting compositions were used for modelling, the first was the most depleted and oldest sample analysed from the Moon Volcanics (MW16-021; andesite; Figure 6a), to determine to what degree assimilation of crustal materials has affected the isotopic composition of the Moon Volcanics through time. A MORB starting composition (Figure 6b) (Sun & McDonough, 1989) was also used to model crustal contamination in the Berangan Andesite (which is likely mantle-derived much like other Plio–Pleistocene magmatic rocks in New Guinea) (Housh & McMahon, 2000) and as a secondary starting composition for modelling the Moon Volcanics to mitigate against potential crustal contamination in even the most depleted sample (MW16-021). The potential contaminants used include the Devonian–Triassic granitoids of the Kemum Block basement (which represent the middle to upper crust of the Kemum Block) (Jost et al., 2018) and the Jurassic–Cretaceous Tamrau Formation (BJ-028) of the Tamrau Block. Isotopic and geochemical data for all mixing components as well as parameters for the mixing models can be found in Supplementary Data File 1.

Figure 6a shows that mixing curves can be modelled for samples BJ-02 and 12JD332A of the Kemum Block basement (both Triassic granitoids). The more depleted samples of the Moon
Volcanics (MW16-022 & MW15-074) lie along this curve indicating that they may well have been partially contaminated with ~10% to 15% partial melt from the granitoids, however, the most contaminated samples (MW15-031 & MW15-078) show no relationship with this line. The Berangan Andesite also lies along this line, indicating potentially ~20% contribution from the Triassic granitoid contaminants (this is supported by the presence of Triassic age zircons and quartz aggregate xenocrysts in the Berangan Andesite; Figure 4a, b) (Webb et al., 2020).

Figure 6b shows a model of mixing between the MORB starting composition and potential contaminants. A mixing curve can be modelled between MORB and sample BJ-028 of the Tamrau Formation in the Tamrau Block basement (Figure 6b). All samples of the Moon Volcanics lie broadly along this curve, indicating that even the most depleted samples of the Moon Volcanics have undergone some degree of crustal contamination. This mixing curve indicates up to ~25% contribution in the most contaminated samples (MW15-078 & MW15-031) and ~5% to 15% contribution in the least contaminated (MW16-021; MW16-022; MW15-074; Figure 6b). This model is supported by field relationships, particularly the intrusion of granitic rocks of the Moon Volcanics into the Tamrau Formation (Figure 4c, d) as well as pockets of partial melt in the Tamrau Formation (Figure 4e, f). The Berangan Andesite also lies close to this mixing line and may have been contaminated by the Tamrau Formation (BJ-028) by ~15% to 20% (Figure 6b). A mixing curve can also be modelled to potential contaminant BJ-138. Sample MW15-078 of the Moon Volcanics lies along this curve indicating that it may have received ~10% to 15% contamination contribution from BJ-138 (Figure 6b).
Finally, AFC modelling (based on the model provided in Ersoy & Helvacı, 2010) was used to determine which of these potential contaminants were most likely. AFC models were produced using the two starting compositions (MW16-021 & MORB) and all proposed contaminants (12JD332A, BJ-02, BJ-138, and BJ-028), a target composition was set at $^{143}\text{Nd}/^{144}\text{Nd} = 0.512806$ and $^{87}\text{Sr}/^{86}\text{Sr} = 0.706524$ based on the most enriched sample from the Moon Volcanics (MW15-078) (Supplementary Data File 2). Modelling between MW16-021 and BJ-02 (Figure 6a) produced the target composition at ~35% assimilation ($r = 0.4$). Whilst modelling between MORB and BJ-028 (Figure 6b) produced the target composition at ~30% assimilation ($r = 0.3$).

These models show that for the Moon Volcanics most of the crustal contamination (~25% to 30%) could be derived from partial melting of the Tamrau Formation into which they intrude (Figures 6b & 4c–f). There is also evidence for contamination of ~35% from Triassic granitoids in the middle to upper crust of the Kemum Block indicating that it continues north of the Sorong Fault Zone beneath the Tamrau Block (Figure 6a, b). The Berangan Andesite shows evidence for contamination of up to 20% from the Tamrau Formation or ~20% from the Triassic granitoids (Figure 6a, b), which is reflected in its U–Pb zircon spectra and the presence of deformed quartz aggregates (Webb et al., 2020; Figure 4a, b).

Contamination of the Moon Volcanics and Berangan Andesite of the Tamrau Block by Triassic granitoids of the Kemum Block basement indicates that Australian continental crust (represented by the basement rocks of the Kemum Block) may extend further north than previously thought, underlying at least some of the Tamrau Block (Figure 7).

5.3. The northern limit of Australian continental crust in New Guinea
The isotopic data presented herein show that Proterozoic to Mesozoic Australian continental crust does occur beneath New Guinea, however, the exact location of this underlying crust has often been disputed. Previous field studies have proposed that Australian continental crust does not occur north of the E–W striking Sorong Fault Zone (Pieters et al., 1983; Dow & Sukamto, 1984). They proposed that the region north of the Sorong Fault Zone (the Tamrau Block) is a so-called transitional zone of rocks derived from both the continental crust to the south and oceanic crust to the north. In contrast, the results from this study, including $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$ isotopic data, Nd model ages, and previously published inherited zircon ages (e.g., Webb et al., 2020), indicate that the Tamrau Formation, Moon Volcanics, and Berangan Andesite of the Tamrau Block do indeed overlie Australian continental crust (Figure 7). However, it should be noted that any inference on this northern limit of Australian crust is based on the current location of an allochthonous fault bounded block (the Tamrau Block). While the Tamrau Block is underlain by the same Proterozoic–Palaeozoic continental crust as the rest of western New Guinea, it was moved into its current position by ~300 km of westwards strike-slip movement in the Plio-Pleistocene (Dow & Sukamto, 1984; Gold et al., 2014; Webb et al., 2019; 2020), following the onset of displacement along the Sorong Fault Zone in the late Miocene (Dow & Sukamto, 1984).

Inverse distance weighted (IDW) interpolation maps were produced for the $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$ isotopic data and $^{2}\text{T}_{\text{DM}}$ Nd model ages for both the samples analysed in this study (Figure 7). These IDW maps delineate the approximate location of the different crustal blocks of the Bird’s Head Peninsula as well as the overall crustal signature of each block. The blue to green colours shown in Figure 7 define the highly radiogenic isotope signature and Proterozoic $^{2}\text{T}_{\text{DM}}$ model ages of the continental crust (i.e., the Kemum Block, as well as...
sections of the Tamrau Block and Lengguru Fold and Thrust Belt). A more simplified image is shown in Figure 8. The pale orange and yellow colours shown in Figure 7 define transitional Miocene to Pleistocene magmatic rocks (Moon Volcanics, Lembai Diorite, and Berangan Andesite) which have intruded through both oceanic and continental crust and display moderately radiogenic isotopic data and Cambrian–Triassic $^{2}\text{T}_{DM}$ model ages. These transitional magmatic rocks differ from the ‘Transition Zone’ (Pieters et al., 1983; Dow & Sukamto, 1984) as they exclude the Tamrau Formation (derived entirely from continental clastic sources) and mark the change from continental crust to transitional or oceanic crust of the Australian Plate beneath the Tamrau Block (shown by the N–S change in the Moon Volcanics from mantle-derived material to crustal contamination and partial melting of the Tamrau Formation). Finally, the red areas in Figure 7 indicate the depleted and mantle-derived isotopic data and Devonian–Carboniferous $^{2}\text{T}_{DM}$ model ages of the accreted oceanic island arcs (Dore, Mandi, and Arfak Volcanics).

The $^{2}\text{T}_{DM}$ model age and $\varepsilon_{\text{Nd}}$ IDW maps (Figures 7d & f) provide a better visual representation of the isotopic composition of the crust than the $^{87}\text{Sr}/^{86}\text{Sr}$ map (Figure 7b). These maps clearly define the structural boundaries between the Kemum and Arfak blocks (the Ransiki Fault), the Kemum and Dore Volcanics (the Sorong Fault), the Tamrau and Tosem blocks (the Koor Fault), the Netoni Fragment, and the south to north transition from continental to oceanic/transitional crust in the Tamrau Block (Figures 7 & 8). The transition from crustally contaminated magmatic rocks to mantle-derived volcanic rocks in the Moon Volcanics occurs at roughly the midpoint of the mapped extent of this unit and the northern boundary of the Tamrau Formation. This can be correlated with the outcrop locations of crustally contaminated granitoids in the south (samples MW15-031 & MW15-078; Figure 2b) and mantle-derived volcanic rocks in the north (samples MW16-021; Figure 2b). These
data indicate that Australian continental crust exists beneath the Bird’s Head Peninsula and extends northwards to at least latitude 0°30’ S at the present-day (Figure 7).

5.4. Correlating isotopic data across New Guinea

We compared our isotopic data with other data from across New Guinea with the aim of mapping the position of different isotopic domains (Figure 9). The Devonian–Triassic granitoids that intrude the Kemum Block represent the Palaeozoic–Mesozoic basement of the Bird’s Head at middle to upper crustal levels (Jost et al., 2018). Their isotopic data correlate well with Proterozoic–Palaeozoic continental crust in NE Australia (Figure 2c), which likely extends beneath the Arafura Sea and into western New Guinea (Hill & Hall, 2003) and represents a source of contamination in these granitoids. The Devonian–Carboniferous samples (BJ-121 & BJ-93) represent the oldest samples analysed for isotopic data from across New Guinea and magmatic rocks of that age are only found in the Bird’s Head. Samples of Triassic meta-diorite from the Amanab Block in eastern New Guinea have been analysed for their Sr–Nd isotopic signature, however, these have much less radiogenic isotopic signatures than our Triassic samples and have been interpreted to have formed during a period of post-subduction rifting in the Triassic (Crowhurst et al., 2004). Samples MW14-11, BJ-138, and BJ-93, have Sr–Nd isotopic values comparable to Pliocene intrusive rocks in the Central Range (Figure 2c), this is indicative of their shared contamination from an underlying Proterozoic continental crust source (Housh & McMahon, 2000).

No other Sr–Nd isotopic studies have been conducted on Palaeogene calc-silicate or carbonate rocks within New Guinea, so there are no data to directly compare with that obtained from sample MW16-034. However, early Palaeogene phyllites from the Frieda Province in eastern New Guinea have relatively depleted Sr–Nd isotopic compositions
(0.70585–0.70689 $^{87}\text{Sr}/^{86}\text{Sr}$; 5.29–6.59 $\varepsilon_{\text{Nd}}$) reflecting their derivation from arc-related volcaniclastics (Crowhurst et al., 2004). The clastic component in MW16-034 may be in part derived from arc-related volcaniclastics shedding onto the northern New Guinea margin in the Palaeogene, reflecting its depleted isotopic composition despite the introduction of seawater Sr. The more radiogenic Sr–Nd composition of sample of BJ-028 of the Jurassic–Cretaceous Tamrau Formation reflects its derivation from a Proterozoic–Palaeozoic continental crust source (similar to that observed in NE Australia; Figure 2). These data are comparable to other Jurassic–Cretaceous passive margin sedimentary rocks of the Om Formation from eastern New Guinea (Richards et al., 1990) indicating that continent-derived Jurassic–Cretaceous passive margin sedimentary rocks can be traced along the length of New Guinea (including the Kembelangan Formation of the Bird’s Neck and Central Range) (van Ufford & Cloos, 2005; Warren & Cloos, 2007; Decker et al., 2017).

Samples from the middle Miocene Moon Volcanics show the same trend towards more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ values as late Miocene to Pliocene intrusive rocks and hydrothermal fluids from the Porgera Intrusive Complex in Papua New Guinea (Richards et al., 1990; 1991). The Porgera samples with a more radiogenic isotopic composition were considered to be derived from mixing between depleted mantle melts and Jurassic Australian passive margin sedimentary rocks in a back-arc setting above a southward dipping subduction zone following arc–continent collision (Richards et al., 1990; 1991). The tectonic setting and isotopic data obtained from the Porgera samples are comparable to those of the Moon Volcanics with the mixing between mantle-derived melts and the Jurassic–Cretaceous Tamrau Formation above a southward dipping subduction zone (Webb et al., 2020). Hafnium on zircon isotopic studies from the Miocene–Pliocene Maramuni Arc in eastern New Guinea also show the continued crustal contamination of mantle-derived melts by
Mesozoic sedimentary rocks in the upper crust (Holm et al., 2015). However, these magmatic rocks are proposed to have formed following a period of continent–continent collision in the middle to late Miocene (Holm et al., 2015).

The low $^{87}\text{Sr}/^{86}\text{Sr}$ and moderate $\varepsilon_{\text{Nd}}$ values obtained from the Oligocene Mandi Volcanics in this study are comparable with isotopic data from early Miocene mafic intrusive rocks in the Bewani–Torricelli Mountains that also reflect an accreted island arc (Crowhurst et al., 2004). The intrusive rocks of the Arfak Volcanics (MW15-058) and Lembai Diorite (MW15-050 & 051) have $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$ values comparable to Miocene intrusive rocks of the Bugalaga Traverse in the Central Range (Weiland, 1999). The rocks of the Bugalaga Traverse intruded through both the Irian Ophiolite and accreted mafic arc volcanic rocks, their field observations and isotopic data are consistent with the middle Miocene intrusives of the Arfak Volcanics (Figure 2c; Webb et al., 2020), indicating that they too may have intruded through previously accreted arc volcanic rocks and ophiolites (e.g., Webb et al., 2020).

Isotopic studies of Plio-Pleistocene magmatism across New Guinea reveal two distinct groups of data. Those in the east yield relatively depleted isotopic values, only slightly more radiogenic than MORB, and are proposed to have been formed by the crustal contamination of mantle-derived melts during either subduction or continental collision (Hamilton et al., 1983; Richards et al., 1990; Hegner & Smith, 1992; van Dongen et al., 2010; Holm et al., 2015). These data differ from the highly radiogenic isotopic values obtained from rocks in the Central Range of western New Guinea. These highly radiogenic data are thought to be the result of mixing of an ancient enriched mantle reservoir and Archaean or Proterozoic Australian continental crust (Housh & McMahon, 2000).
The youngest volcanic analysed in this study was from the Plio-Pleistocene Berangan Andesite. The isotopic data obtained for these rocks are comparable to data obtained from Pleistocene volcanoes of the Fly-Highlands in eastern New Guinea (Figure 2c) (Hamilton et al., 1983). These Pleistocene volcanoes are interpreted to have formed from the crustal contamination of mantle-derived magmas during Pliocene uplift following arc–continent collision (Hamilton et al., 1983). This mechanism is consistent with the crustal contamination of the Berangan Andesite by middle–upper crustal Palaeozoic–Mesozoic granitoids following late Miocene–Pliocene arc–continent collision in the Bird’s Head Peninsula (Webb et al., 2019).

We created a broader scale IDW interpolation of the $\varepsilon_{Nd}$ isotopic data from this study and those from earlier studies to capture the variation of isotopic values across New Guinea and map the extent of crustal fragments with different affinities (Figure 9a). Australian continental crust across New Guinea yields $\varepsilon_{Nd}$ values of −20 to 0; transitional magmatic rocks yield $\varepsilon_{Nd}$ values of 0 to 5; and oceanic/island arc crust yields $\varepsilon_{Nd}$ values of 5 to 10 (Figure 9a). These values are comparable to the isotopic ranges derived from crustal fragments in the Bird’s Head Peninsula (Figure 8) indicating that $\varepsilon_{Nd}$ isotopic data can be used to track the nature of the underlying crust across New Guinea. There is a systematic change in the $\varepsilon_{Nd}$ values from west to east in New Guinea (Figure 9a). The west is dominated by negative $\varepsilon_{Nd}$ values indicative of contamination by the underlying Proterozoic Australian continental crust (Housh & McMahon, 2000). Isolated regions of positive values in the centre of the island correspond to the location of island arc material along the northern and central ranges (Figures 1a and 9a). However, the comparative lack of isotopic data obtained from central New Guinea (in particular the northern ranges) and the extremely negative continental crust values taken from samples in the New Guinea Fold and Thrust Belt (Housh...
means that the distinction between continental, oceanic, and transitional crust is less obvious here. In the east, the IDW map is dominated by positive $\varepsilon_{Nd}$ values (indicative of partially contaminated transitional material, primary mantle, or island arc material; e.g., Figure 8) with isolated negative values corresponding to Triassic granitoids and Jurassic–Cretaceous passive margin sedimentary rocks (Richards et al., 1990; Crowhurst et al., 2004). This isotopic variation is likely the result of both different degrees of crustal contamination in magmatic rocks across the island and the age and nature of the underlying continental crust (e.g., Proterozoic in the west vs. Palaeozoic in the east).

The level of contamination in New Guinea is governed by two factors: the thickness of Australian continental crust beneath New Guinea (with thicker crust corresponding to greater crustal contamination); and the age of the crust beneath New Guinea (with regions of particularly old continental crust giving more negative $\varepsilon_{Nd}$ values than regions of younger crust, irrespective of crustal thickness) (Housh & McMahon, 2000). To further test the isotopic mapping of continental vs. oceanic/island arc crust, we compared the interpolated $\varepsilon_{Nd}$ value map with P-wave velocity data generated for a depth of ~23 km (Figure 9b) (Li et al., 2008). The tomographic imagery highlights a band of faster velocities (shown in blue and green colours; Figure 9b) that strike east to west across the island. This region of higher velocities likely corresponds to dense, cold, continental lithosphere beneath New Guinea and shows little variation from east to west, indicating that the density and composition of continental crust remains relatively constant from east to west across the centre of the island. Regions of slower velocities are also present across New Guinea. These typically correspond to the locations of accreted island arc material and high positive $\varepsilon_{Nd}$ values (indicative of oceanic/island arc crust) along the northern margin of New Guinea (Figures 1a & 9a). We propose that these zones of slower velocity define zones of oceanic/island arc
crust thrust onto the leading edge of the Australian Plate (i.e., relatively thinner Australian continental crust than is found further to the south). Given that there is no apparent change in crustal density from east to west across New Guinea (Figure 9b), it is likely that the age of the underlying crust is the primary cause of variations in the $\varepsilon_{Nd}$ data. The presence of Archaean or Proterozoic Australian continental crust beneath central New Guinea has been previously proposed (Housh & McMahon, 2000), and the results from this study indicate that Devonian–Triassic granitoids in the Bird’s Head have intruded through Proterozoic continental crust. The positive $\varepsilon_{Nd}$ data in eastern New Guinea may represent the presence of younger Palaeozoic continental or transitional crust underlying this part of the island (Crowhurst et al., 2004). This can be compared to the transition from Archaean–Proterozoic stable cratons to Proterozoic–Mesozoic rifted and arc-related crust observed in eastern Australia (Aitchison et al., 1992; Simons et al., 1999; Debayle et al., 2000; Hill & Hall, 2003). We determined the isotopic ranges for different crustal domains based on the data generated in this study and their correlation with similar rocks across New Guinea. Continental crust is defined by $^{87}\text{Sr}/^{86}\text{Sr}$: 0.719594–0.710921; $\varepsilon_{Nd}$: −13.85 to −7.53; $^{2}T_{DM}$: 1.988–1.373, transitional Miocene–Pleistocene magmatic rocks are defined by $^{87}\text{Sr}/^{86}\text{Sr}$: 0.706524–0.704019; $\varepsilon_{Nd}$: 6.67 to 2.13; $^{2}T_{DM}$: 0.612–0.262, and oceanic island arc crust is defined by $^{87}\text{Sr}/^{86}\text{Sr}$: 0.704053–0.703759; $\varepsilon_{Nd}$: 6.63 to 4.97; $^{2}T_{DM}$: 0.392–0.330. Our aim here was to provide a framework for future workers to use when interpreting the extent of crustal domains using isotopic data, particularly in difficult to access regions.

6. Conclusions
• Sr–Nd isotopic data from rocks in the Bird’s Head can be correlated with the isotopic compositions of coeval and cogenetic rocks across New Guinea and indicate the shared tectonic history of eastern and western New Guinea since at least the Triassic.

• Binary isotope mixing models combined with field and petrographic studies show that the middle Miocene Moon Volcanics erupted through thinned continental crust and have been contaminated by up to ~25% partial melt of the underlying Tamrau Formation and ~10–15% partial melt from the middle–upper Australian continental crust. The Berangan Andesite also shows evidence for crustal contamination by both the Tamrau Formation (~20%) and the middle–upper crust of the Kemum Block (~20%).

• Sr–Nd isotope and \(^{2}T_{DM}\) model age signatures have been determined for Proterozoic–Palaeozoic middle–upper continental crust (\(^{87}\text{Sr}/^{86}\text{Sr}: 0.719594–0.710921; \varepsilon_{Nd}: -13.85 \text{ to } -7.53; \, ^{2}T_{DM}: 1.988–1.373\)), Eocene–Miocene oceanic island arc crust (\(^{87}\text{Sr}/^{86}\text{Sr}: 0.704053–0.703759; \varepsilon_{Nd}: 6.63 \text{ to } 4.97; \, ^{2}T_{DM}: 0.392–0.330\)), and transitional Miocene–Pleistocene magmatic rocks (\(^{87}\text{Sr}/^{86}\text{Sr}: 0.706525–0.704019; \varepsilon_{Nd}: 6.67 \text{ to } 2.13; \, ^{2}T_{DM}: 0.612–0.212\)), which intrude through both continental and oceanic rocks in the Bird’s Head. These isotopic crustal signatures can be used to map the extent of Australian continental crust and accreted oceanic island arc crust across New Guinea.

• The northern-most extent of Australian continental crust has been determined to continue further than its previously proposed termination along the Sorong Fault Zone. Continental crust in the Bird’s Head extends beneath the Tamrau Block to at least latitude 0°30’ S.
• The age of underlying Australian continental crust beneath New Guinea varies from Archaean–Proterozoic in the west to Palaeozoic in the east.

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References


**Figure Captions**

**Figure 1**

Overview maps of the geology, terranes, and crustal domains of New Guinea and the Bird’s Head. a) Overview map of the geology and terranes that can be correlated along the length of New Guinea (the location of the different terranes has been adapted from Baldwin et al., 2012 & Davies, 2012). Included in the map are the locations of previous isotopic studies in New Guinea used for comparison with data from this study. b) Map of the Bird’s Head displaying the different crustal domains present (continental zone, transition zone, and oceanic zone), along with sample locations, terranes, and structures. The locations of crustal domains are based on Pieters et al. (1983).

**Figure 2**
Plots showing $\varepsilon_{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic data for all samples from this study. a) Plot of measured $\varepsilon_{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic data for all samples, with fields representing most present-day oceanic basalts and arcs (Hawkesworth et al., 1991; Hofmann, 1997) and NE Australia Palaeozoic and Proterozoic continental crust (Black & McCulloch, 1990; Knutson et al., 1996; Blewett et al., 1998) and the mantle array. b) Plot of age corrected initial $\varepsilon_{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic data for all samples, fields are the same as those from Figure 2a. c) Plot showing measured $\varepsilon_{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic data for all samples in this study with fields showing Sr-Nd isotopic from across New Guinea for comparison. Errors for all samples are too small to plot (e.g., smaller than the symbols used).

Figure 3

Two-stage $T_{DM}$ Nd model ages for all samples from this study. a) Two-stage $T_{DM}$ Nd model ages for all Cenozoic magmatic rocks and sample MW16-034 of the Tamrau Block basement. b) Two-stage $T_{DM}$ Nd model ages for granitoids from the Kemum Block basement and sample BJ-028 of the Tamrau Block basement. Errors for all samples are too small to plot (e.g., smaller than the symbols used).

Figure 4

Field photos and photomicrographs from the Moon Volcanics, Tamrau Formation, and Berangan Andesite showing evidence for crustal contamination and partial melting of country rocks. a) Hand specimen of the Berangan Andesite (MW15-054) showing the presence of aggregates of quartz xenocrysts reflecting crustal contamination. b) Photomicrograph of the Berangan Andesite (MW15-054) with deformed aggregates of quartz xenocrysts showing bulging and sub-grain rotation recrystallisation within and andesitic groundmass. c) Intrusive relationship between a microtonalite (MW15-078) of the
Moon Volcanics and a schist of the Tamrau Formation. d) Intrusive relationship between a granite (MW15-031) of the Moon Volcanics and a mylonitic schist of the Tamrau Formation (BJ-028), discordant ptygmatic veins of partial melt radiate from the contact. e) Contact between MW15-031 (Moon Volcanics granite) and BJ-028 (Tamrau Formation mylonitic schist), the schist contains pockets of quartzose partial melt concordant to the dominant fabric. f) Photomicrograph of sample BJ-028 showing pockets of quartzose partial melt crystallised in veins concordant to the main mylonitic fabric.

Figure 5

$^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\text{SiO}_2$ wt. % plot for the Cenozoic magmatic rocks and the Tamrau Block basement. The plot shows the effects of crustal contamination on increasing $^{87}\text{Sr}/^{86}\text{Sr}$ values in the Moon Volcanics and Berangan Andesite and fractional crystallisation in the Mandi and Arfak volcanics and Lembai Diorite. Errors for all samples are too small to plot (e.g., smaller than the symbols used).

Figure 6

$^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ binary isotope mixing models showing the extent of crustal contamination in the Moon Volcanics and Berangan Andesite. a) Mixing model using the most depleted sample from the Moon Volcanics (MW16-021) as a starting composition and samples MW16-034, BJ-02, and 12JD332A as potential contaminants. b) Mixing model using MORB (Sun & McDonough, 1989) as a starting composition and samples BJ-028 & BJ-138 as
potential contaminants. Errors for all samples are too small to plot (e.g., smaller than the symbols used).

**Figure 7**

Inverse distance weighted (IDW) interpolation maps using $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$ isotopic data as well as $^{2}\text{T}_{\text{DM}}$ Nd model ages for samples from this study to understand the northern extent of Australian continental crust in the Bird’s Head Peninsula, its relationship to regional structures, and the isotopic signature of different terranes in the peninsula. a) $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic data and sample location map. b) IDW interpolation map using $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic data. c) $\varepsilon_{\text{Nd}}$ isotopic data and sample location map. d) IDW interpolation map using $\varepsilon_{\text{Nd}}$ isotopic data. e) $^{2}\text{T}_{\text{DM}}$ Nd model ages and sample location map. f) IDW interpolation map using $^{2}\text{T}_{\text{DM}}$ Nd model ages.

**Figure 8**

Crustal domain map of the Bird’s Head showing the location of autochthonous and allochthonous terranes, polygons defining the location of different formations within them, and their classification as continental crust, transitional magmatic rocks, or oceanic crust based on their $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$ isotopic data and $^{2}\text{T}_{\text{DM}}$ Nd model ages from this study. The location of terranes and the geology within them are derived from Pieters et al. (1983) and Dow and Sukamto, (1984).

**Figure 9**

Inverse distance weighted (IDW) interpolation and P-wave velocity maps for New Guinea. a) Inverse distance weighted (IDW) interpolation maps for New Guinea using $\varepsilon_{\text{Nd}}$ isotopic data
from both this study and previous studies in New Guinea (Hamilton et al., 1983; Richards et al., 1990; Hegner & Smith, 1992; Weiland, 1999; Housh & McMahon, 2002; Crowhurst et al., 2004). The individual data were also used to identify isotopic ranges for underlying crustal domains across New Guinea (Australian continental crust; transitional magmatic rocks; oceanic/island arc crust). b) P-wave velocity data at 23 km depth imaging the nature of the crust beneath New Guinea, P-wave velocity data were taken from Li et al. (2008). Blues and greens show the location of higher velocity waves through dense, cold continental crust, while oranges and reds show the location of lower velocity waves from thinner oceanic crust or hot mantle material.

**Supplementary Data File 1**

All TIMS Sm–Nd and Rb–Sr isotopic and supplementary data for samples and standards used in this study.

**Supplementary Data File 2**

Binary isotope mixing models and AFC models for $^{143}$Nd/$^{144}$Nd vs. $^{87}$Sr/$^{86}$Sr including parameters for all potential melt sources.
Most present-day oceanic basalts and arcs.

NE Australia Proterozoic and Palaeozoic continental crust

- Kemum Basement
- Tamrau Basement
- Mandi Volcanics
- Arfak Volcanics
- Lembai Diorite
- Moon Volcanics
- Berangan Andesite

Figure 2

- Porgera deposit host rocks; Richards et al., 1990a
- Porgera deposit intrusives; Richards et al., 1990a
- Cenozoic metamorphic and igneous rocks central and eastern New Guinea; Crowhurst et al., 2004
- Triassic metamorphic rocks central and eastern New Guinea; Crowhurst et al., 2004
- Pleistocene volcanics PNG; Hamilton et al., 1983
- Miocene Central Range intrusives; Weiland, 1999
- Central Range metabasics; Weiland, 1999
- Pliocene Central Range intrusives; Housh & McMahon, 2000
- NE Australian continental crust; Black & McCulloch, 1990; Knutson et al., 1998; Blewett et al., 1998

Arfak Volcanics
- Lembai Diorite
- Moon Volcanics
- Berangan Andesite
Figure 3

- Kemum Basement
- Tamrau Basement
- Mandi Volcanics
- Arfak Volcanics
- Lembai Diorite
- Moon Volcanics
- Berangan Andesite

- Measured $^{147}$Sm/$^{144}$Nd ratio (this study)

U-Pb zircon age (Jost et al., 2018; Webb et al., 2019)

$^{147}$Sm/$^{144}$Nd ratio - 0.12 (Liew & Hofmann, 1988)

U-Pb zircon age (Webb et al., 2019; 2020)

$^{147}$Sm/$^{144}$Nd ratio - 0.12 (Liew & Hofmann, 1988)
Figure 4

- Berangan Andesite MW15-054
  - Quartz xenocryst contamination

- Granite MW15-031
  - Ptygmatic veins

- Microtonalite MW15-078
  - Tamrau Formation

- Pockets of partial melt

- Tamrau Formation BJ-028
  - Pockets of partial melt
  - Cf. Fig 6 f
Figure 5

- Tamrau Basement
- Mandi Volcanics
- Arfak Volcanics
- Lembai Diorite
- Moon Volcanics
- Berangan Andesite

Fractional crystallisation
Crustal contamination

Increasing crustal contamination with time in the Moon Volcanics

MW15-031
MW15-078
~12 Ma

MW16-022
~14 Ma

SiO₂ wt.%

\( \frac{\text{Sr}}{\text{Sr}^*} \)
Figure 6

a. Starting composition -
MW16-021 (Moon Volcanics)

\[
\begin{array}{c|c|c|c}
\text{Sr/Sm} & \text{Sr ppm} & \text{Nd/Sm} & \text{Nd ppm} \\
0.704019 & 915 & 0.51298 & 21.2 \\
\end{array}
\]

AFC parameters -
Assimilant = BJ-02
\( r = 0.3 \)  Increments = 5%
Crystallisation ends at 45%

AFC target composition reached at 35% assimilation

b. Starting composition -
MORB (Sun & McDonough, 1989)

\[
\begin{array}{c|c|c|c}
\text{Sr/Sm} & \text{Sr ppm} & \text{Nd/Sm} & \text{Nd ppm} \\
0.70317 & 104 & 0.513101 & 11 \\
\end{array}
\]

AFC parameters -
Assimilant = BJ-028
\( r = 0.4 \)  Increments = 5%
Crystallisation ends at 45%

AFC target composition reached at 30% assimilation
Figure 7

a. Tosem Block
b. Tamrau Block
c. Kemum Block
d. Kemum Basement High
e. Arfak Block
f. Lengguru Fold and Thrust Belt

g. Extent of underlying Australian crust

**Sr/Sr data**
- 0.704056 to 0.703759
- 0.707256 to 0.704304
- 0.710921 to 0.710921

**εNd data**
- 4.97 to 6.67
- 5.01 to 2.13
- -7.53 to -13.85

**2T$_{206}$ (Ga) data**
- 0.397 to 0.262
- 0.612 to 0.438
- 1.988 to 1.373

**Isotopic data**
- 0.704056 to 0.703759
- 0.707256 to 0.704304
- 0.710921 to 0.710921
Figure 8

Isotopic ranges for outcropping crustal domains:

Palaeozoic to Mesozoic Australian continental crust
- $^{87}\text{Sr}/^{86}\text{Sr}$: 0.719594 to 0.710921
- $\varepsilon\text{Nd}$: -13.85 to -7.53
- $\delta T_{DM}$ (Ga): 1.988 to 1.373

Miocene to Pleistocene transitional magmatic rocks
- $^{87}\text{Sr}/^{86}\text{Sr}$: 0.706524 to 0.704019
- $\varepsilon\text{Nd}$: 6.67 to 2.13
- $\delta T_{DM}$ (Ga): 0.612 to 0.262

Eocene to Miocene accreted oceanic island arc crust
- $^{87}\text{Sr}/^{86}\text{Sr}$: 0.704053 to 0.703759
- $\varepsilon\text{Nd}$: 6.63 to 4.97
- $\delta T_{DM}$ (Ga): 0.392 to 0.330
Isotopic ranges for underlying crustal domains (symbols):

- Australian continental crust: $\varepsilon$Nd: −20 to 0
- Transitional magmatic rocks: $\varepsilon$Nd: 0 to 5
- Oceanic/island arc crust: $\varepsilon$Nd: 5 to 10

- Proposed northern limit of Archean to Proterozoic Australian continental crust
- Proposed northern limit of thinned Palaeozoic to Mesozoic crust

Figure 9
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: