Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL087484

Arc-Type Magmatism Due to Continental-Edge Plowing Through Ancient Subduction-Enriched Mantle

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Key Points:

- "Postsubduction" arc magmatism on New Guinea results from the Australian cratonic margin plowing through a previously enriched mantle wedge
- Mantle wedges may appear to remain semistationary in the mantle for tens of million years or even longer times and produce subduction signatures if remelted
- Absolute plate motions juxtapose mantle and crustal rocks with very different geological histories

Supporting Information:

- Supporting Information S1
- Movie S1

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Citation:
van Hinsbergen, D. J. J., Spakman, W., de Boorder, H., van Dongen, M., Jowitt, S. M., & Mason, P. R. D. (2020). Arc-type magmatism due to continental-edge plowing through ancient subduction-enriched mantle. *Geophysical Research Letters*, *47*, e2020GL087484. https://doi.org/10.1029/2020GL087484

Received 13 FEB 2020
Accepted 11 APR 2020
Accepted article online 23 APR 2020

Abstract

The puzzling <7 Ma old "postsubduction" arc magmatism of New Guinea contains geochemical subduction-type signatures yet did not occur above an active subduction zone. Here we show that these arc magmas formed at the North Australian continental lithospheric edge when it plowed northward through mantle above the detached Arafura slab remnant. This mantle preserved its subduction signature and the edge plowing process generated new melts that ascended via an active transform fault. Arafura slab subduction occurred at an intraoceanic subduction zone that ended ~30–25 Ma ago, when the Australian continental edge was still ~1,000 km to the south. Our absolute plate tectonic reconstruction of continental-edge plowing suggests that ancient mantle wedges remain semistationary in the upper mantle and can preserve their geochemical signature for tens of Ma, explaining previously enigmatic "postsubduction" arc magmatism.

Plain Language Summary

During subduction, downgoing plate lithosphere ("slab") releases water to the overlying mantle causing so-called "arc volcanism." A puzzling class of "postsubduction" arc magmatism bears geochemical signatures of subduction but occurs in a setting without subduction. Here we show that this magmatism is the result of remelting of mantle portions that were previously enriched by ancient subduction zones, slab relics of which are now found with seismological techniques below these enriched portions. From famous postarc magmatic rocks on New Guinea we identify that the "plowing" of the edge of a thick, continental lithosphere through a previously enriched mantle portion may provide a cause of melting, producing arc-like magmatism. We also identify that pathways for the melts to rise to (close to) the surface, provided by major faults, are essential. The "New Guinea recipe" also explains magmatism on the Fiji Islands, California, and Colombia. A major implication of our work is that asthenospheric upper mantle rocks appear to move much slower than plates, such that lithosphere may have undergone a very different geological history than the currently underlying mantle.

1. Introduction

The subduction of oceanic lithosphere introduces fluids into the mantle, causing hydration-type or "wet" melting and the formation of distinct "arc-type" magmas, that is, calc-alkaline magmatic rocks with an enrichment in large ion lithophile relative to high field strength elements that are found above almost all subduction zones (McCulloch & Gamble, 1991; Wilson, 1989). Enigmatically, there are also so-called "postsubduction" arc magmas (Richards, 2009). The specific tectonic origin of postsubduction arc magmatism remains puzzling because of the paradox that the geochemistry of these magmas, and associated ore deposits, records the activity of melts and fluids derived from subduction-enriched mantle wedge material, while the magmas formed in temporal and spatial isolation from active subduction (Richards, 2009). Here, we focus on the tectonic setting of postsubduction magmatism in New Guinea, an area where we identified diagnostic geodynamic events. We subsequently test the predictive value of our inferences from New Guinea elsewhere, in the Americas, Caribbean, Tethyan, and SW Pacific realms.

The western and central parts of the island of New Guinea host late Miocene-Pleistocene (<7 Ma) postsubduction arc magmatism (Figure 1; supporting information Movie S1) associated with the world-class Grasberg-Ertsberg and Ok Tedi porphyry copper-gold deposits (Richards, 2009). Volcanics in west central New Guinea are calc-alkaline to ultrapotassic with bulk geochemical characteristics typical of magmas generated in a subduction environment (Housh & McMahon, 2000; van Dongen et al., 2010). Intrusives in the

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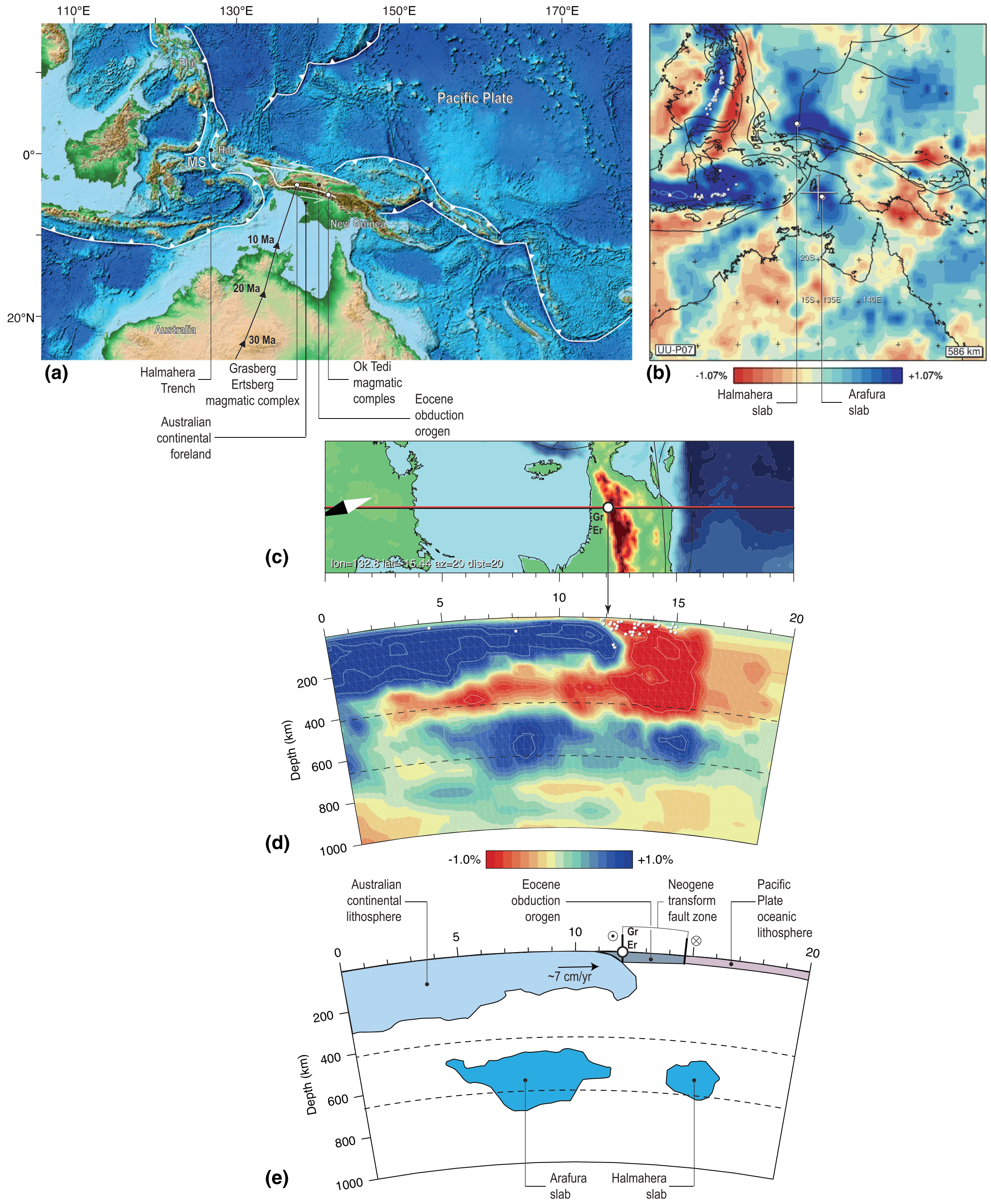

Figure 1. Plate tectonic setting of the New Guinea post-subduction arc magmatic complexes of Grasberg-Ertsberg, and Ok Tedi. (a) Absolute plate motion of Australia indicated for the location of Grasberg-Ertsberg in 10 Ma intervals using a global moving hot spot reference frame (Doubrovine et al., 2012). Hal = Halmahera Island; MS = Molucca Sea Plate; Phil = Philippines. (b) Horizontal seismic tomogram at 586 km depth based on the UU-P07 model (Amaru, 2007; Hall & Spakman, 2015). Blue areas are regions of higher seismic velocities interpreted as lithosphere of the Australian continent, and of the Arafura and Halmahera Slabs (van der Meer et al., 2018). (c) Location of seismic tomographic cross section of Figure 1d. (d) Seismic tomogram of vertical section parallel to Neogene absolute Australian plate motion. White dots represent earthquake hypocenters. Gr/Er = Grasberg-Ertsberg magmatic complexes. (e) Interpretation of seismic tomogram of Figure 1d, indicating the locations of the Arafura and Halmahera Slabs, and Australian continental lithosphere. Note that the thickness of this continental lithosphere in the uppermost part of the mantle tends to be overestimated in *P* wave tomographic images.

central part of New Guinea are of dioritic to quartz monzonitic composition (Pollard et al., 2005) and were emplaced in a fold-and-thrust belt related to the Eocene (~50 Ma) obduction of ophiolites over the northern Australian continental margin (Hall, 2002; Schellart & Spakman, 2015) (Figure 1a).

Paradoxically, while late Cenozoic subduction is well known from eastern New Guinea (Hall, 2002), plate kinematic reconstructions that are independent of geochemical observations indicate that the Plio-Pleistocene melts on west central New Guinea formed long after the termination of subduction in the Eocene (Hall, 2002, 2012; Schellart & Spakman, 2015).

Eocene ophiolite obduction marked the arrest of a northward dipping subduction zone consuming oceanic lithosphere of the Australian plate formerly present to the north of the New Guinea passive margin (Hall, 2002; Schellart & Spakman, 2015). This gap between Eocene subduction and the much-later Plio-Pleistocene genesis of arc-type magmas on New Guinea indicates that new insights and observations are required to determine the geodynamic processes that triggered the genesis of these magmas by melting of a previously subduction-enriched region of the asthenosphere.

One hitherto understudied element in the genesis of postsubduction magmatism is the movement of tectonic plates relative to the underlying mantle, so-called absolute plate motions, in a mantle frame of reference such as provided by moving hot spot frames (Doubrovine et al., 2012; O'Neill et al., 2005). Models of absolute plate motion place the Eocene subduction that tectonically affected New Guinea along the northern Australian continental edge ~3,000 km to the south of the modern location of the Plio-Pleistocene New Guinea magmatic rocks (Schellart & Spakman, 2015).

The northward movement of Australia in this mantle frame since the Eocene means it is unlikely that the New Guinea magmas formed from mantle enrichment associated with this Eocene subduction. Instead, our study explores for paleosubduction into the mantle now overlain by New Guinea that may have caused subduction-related enrichment of this mantle material when the North Australian continental edge was still located far to the south. We then assess whether plate models may provide new insights into the mechanisms triggering postsubduction arc-type magmatism. Crucially, the New Guinea region represents an ideal natural laboratory for the development of these ideas as the present-day mantle structure of this region can be directly correlated with the recently formed arc magmas in this area with no need for assumptions that would be required in geologically older areas with more obscure tectonic histories. In addition, our work benefits from previous research that determined the subduction-enriched mantle origin and its composition directly underpinning the magmatic units and mineral deposits in this region.

2. Results

Following a period of intraoceanic subduction (Figure 2a), the ~50 Ma detachment of the Eocene northward subducting slab along the North Australian margin of New Guinea, at a latitude of ~30°S (Figure 2a) was followed at around 50–45 Ma by the generation of an intraoceanic subduction zone to the far north of New Guinea, around 10–15°S (Hall, 2002; Schellart & Spakman, 2015) (Figure 2b). This intraoceanic subduction in turn ceased around 30–25 Ma in an intraoceanic position, when there was still ~500–1,000 km distance between this trench and the northern continental edge of Australia (Figure 2c). The arc associated with this intraoceanic subduction drifted west with oceanic plates of the Pacific realm and is thought to currently be found around Halmahera and the southern Philippines (Hall, 2002; Zahirovic et al., 2014) (see Figure 1 for location). Next, Australia-Pacific *relative* plate motion, which has been E-W directed since 25 Ma, was associated with the development of the southwest and northwest dipping subduction zones in eastern New Guinea, as well as the eastward dipping and westward retreating Halmahera subduction zone that generated a N-S trending trench initially located to the north of New Guinea that retreated westward by consuming Molucca Sea plate lithosphere (Hall, 2002) (Figures 1a and 2d). Halmahera slab retreat, relative to the eastern New Guinea subduction systems, was associated with the formation of a left-lateral transform plate boundary zone across northern New Guinea (Sapiie & Cloos, 2004) along the Eocene obduction-related orogen of west central New Guinea, and along the edge between the northern Australian continental foreland to the south and oceanic lithosphere to the north (Hall, 2002) (Figure 1; Figures 2c and 2d).

The kinematic history described above is a *relative* plate motion history where one can take any plate as a fixed reference plate, which is commonly used in conceptual models of subduction-related magmatism

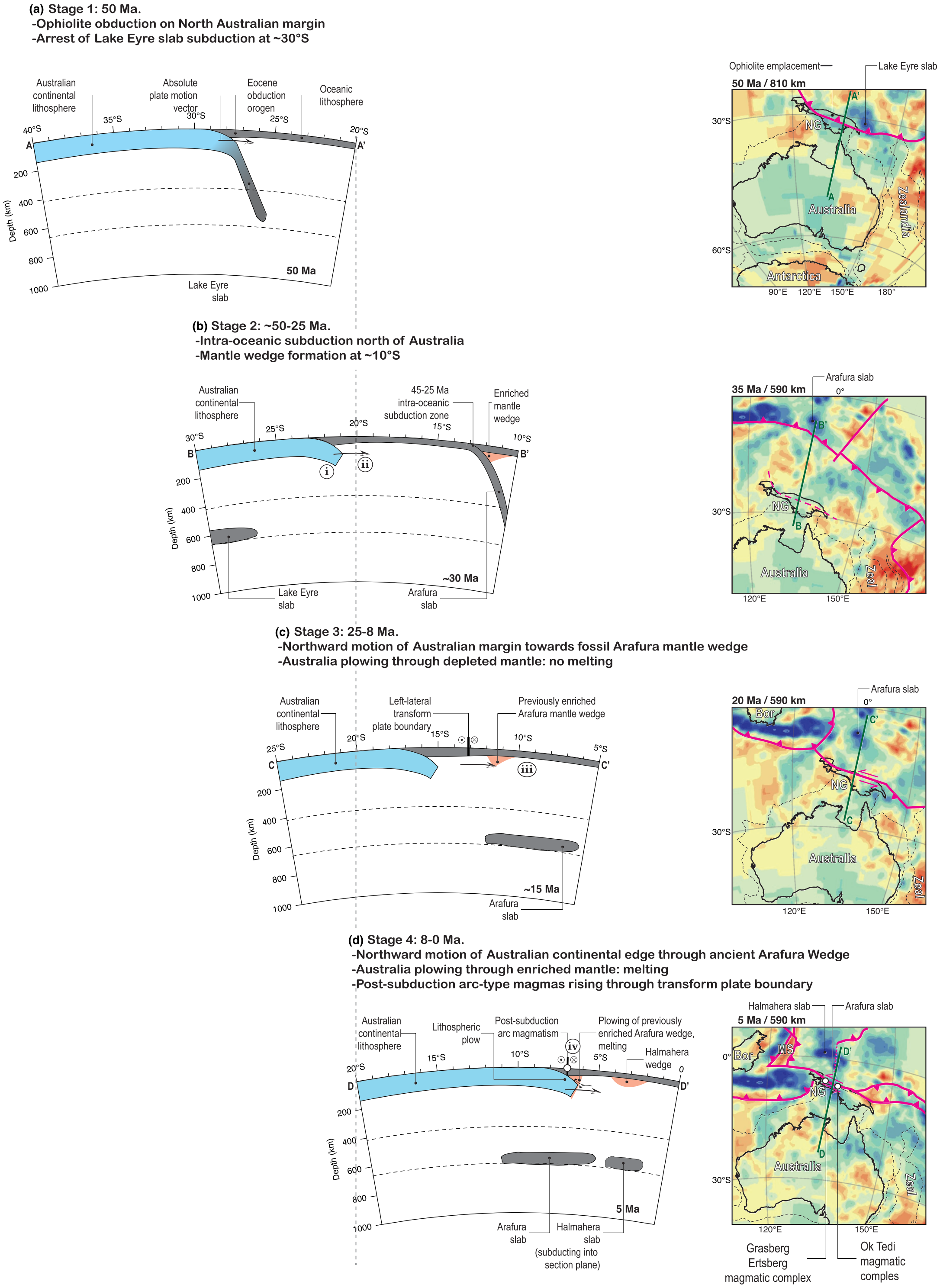

Figure 2. Schematic model illustrating the "recipe" for the formation of the postsubduction arc magmatic centers on New Guinea, containing four elements: (i) a lithospheric edge that formed by slab break-off following Eocene ophiolite obduction that due to (ii) its motion relative to the mantle plowed through (iii) a previously subduction-enriched mantle wedge from which partial melt was emplaced into the crust along (iv) a transform fault that was active during mantle plowing. Reconstructions are based on Hall (2002) and van de Lagemaat et al. (2018) and are placed in the global moving hot spot reference frame of Doubrovine et al. (2012). Tomography from the UU-P07 model (Amaru, 2007; Hall & Spakman, 2015) at 810 km (a) and 590 km (b–d) with the Lake Eyre and Arafura slabs indicated. For interpretations of other slabs, see van der Meer et al. (2018). At 35 Ma, subduction zones in the SW Pacific realm do not correlate with slabs portrayed in the tomography at 590 km, but instead with slabs that reside deeper in the mantle conversely, the slabs portrayed at 590 Ma correspond to subduction stages younger than 35 Ma (see, e.g., Schellart et al., 2009; van de Lagemaat et al., 2018). Bor = Borneo; NG = New Guinea; Zeal = Zealandia.

(Richards, 2015; Wilkinson, 2013; Wilson, 1989). In reality, however, almost all plates on Earth move relative to the deep mantle (Doubrovine et al., 2012; O'Neill et al., 2005; Torsvik et al., 2008; van der Meer et al., 2010). This means that geological records of former subduction may become displaced relative to their ancient mantle wedges and detached subducted slab remnants (van der Meer et al., 2010). This suggests that a region in the shallow mantle that was at some position and time enriched during a phase of past subduction can at a much later geodynamic stage be overridden by lithosphere that is void of any subduction evidence related to the underlying enriched mantle.

Various moving hot spot references frame models predict that the Australian plate has moved northward relative to the deeper mantle at a high rate of ~6 ± 2 cm/a (Doubrovine et al., 2012; O'Neill et al., 2005; Torsvik et al., 2008) since 50 Ma. This predicts that the slab that detached from northern Australia following Eocene obduction should, if it sank near vertically through the mantle after detachment, now be located some 3,000 km to the south of New Guinea, a location coincident with an imaged slab remnant below Lake Eyre in southern Australia. The "Lake Eyre" slab is located within the upper part of the lower mantle (Schellart & Spakman, 2015; van der Meer et al., 2018) and is at a depth consistent with globally reconstructed average lower-mantle slab sinking rates of ~1–2 cm/yr (van der Meer et al., 2010, 2018).

Seismic tomographic images of the mantle below the New Guinea region also reveal evidence of past subduction (Hall & Spakman, 2015; van der Meer et al., 2018) (Figure 1; supporting information Movie S1). Two clear anomalies are present in the mantle transition zone around 660 km, the northernmost of which connects westward to active east dipping Halmahera subduction (Hall, 2002; Zahirovic et al., 2014). The southern of the two slabs, which is disconnected from the surface plates, is presently located below the Sea of Arafura between the island of New Guinea and mainland Australia and is therefore called the Arafura slab (Hall & Spakman, 2015; van der Meer et al., 2018) (Figure 1). This slab has been linked to the above mentioned south dipping intraoceanic subduction zone (Hall, 2002; Zahirovic et al., 2014) and broke off around 30–25 Ma, when the North Australian margin of New Guinea was still located 500-1,000 km to the south of the southern edge of the Arafura slab (Figure 2). The mantle structure further shows no evidence of recent or active subduction below New Guinea, agreeing with the overall transform nature of the New Guinea plate boundary since ~25 Ma. We note that an earlier interpretation of an actively southward subducting flat slab under New Guinea (Tregoning & Gorbatov, 2004) conflicts with the absence of significant relative N-S plate convergence between the Pacific and west central New Guinea but can be explained as an image of the thick Australian cratonic lithosphere as shown here (Figure 1; Movie S1) and in recent high-resolution surface wave tomography (Schaeffer & Lebedev, 2013).

The deep flat-lying portion in Figure 1 of the Halmahera slab is now partly found under New Guinea also as a result of northward absolute motion of Australia. We note that this cannot be inferred from the westward *relative* transform motion of the Pacific Plate with respect to Australia because the common northward component of absolute plate motion of both plates is canceled in the relative plate motion frame. The westward rollback of the Molucca Sea subduction occurred after 25 Ma, while the Australian plate was overriding the detached Arafura slab. The Molucca Sea subduction system was dragged northward with Australian absolute plate motion, explaining the location of the Halmahera slab remnant within the mantle to the north of the Arafura Slab even though the former subducted closer to northern Australia (Figures 1b and 1c). This exemplifies why mantle structures need to be interpreted in a mantle reference frame as it reveals the implications of slab dragging (Spakman et al., 2018; van de Lagemaat et al., 2018).

The absolute plate motion of Australia (Doubrovine et al., 2012) (Figure 1a) indicates that New Guinea started to move above the tomographically imaged location of the Arafura slab at ~9–6 Ma and was located above the slab during the formation of the Plio-Pleistocene Ertsberg-Grasberg and Ok Tedi arc-type magmas and mineral deposits. This strongly suggests that the source of the arc-type signature of Plio-Pleistocene west central New Guinea magmatic rocks is the ancient mantle wedge of the Arafura slab. These magmas were emplaced within the northern continental lithospheric edge of the Australian continent, where the continental edge of the advancing thick (>200 km; Kennett & Blewett, 2012; Schaeffer & Lebedev, 2013) Australian lithosphere may have laterally, but importantly, also vertically displaced, or "scooped up," this earlier enriched mantle material (Figures 2c and 2d). This caused decompression, which led to melting when it started involving the hydrous, subduction-metasomatized former Arafura mantle wedge during transient remobilization events (Hronsky et al., 2012; Johnson et al., 1978), as schematically indicated in Figure 2d.

We suggest that this upward plowing of the previously fertilized mantle wedge generated *postsubduction* magmatism with calc-alkaline to highly alkaline *subduction-type* signatures that led eventually to emplacement in the shallow subsurface along the steep transform plate boundary zone that cuts through northern New Guinea (Hall, 2002; Sapiie & Cloos, 2004).

This scenario explains the subduction-type geochemistry of the Plio-Pleistocene New Guinea magmas despite the absence of Plio-Pleistocene subduction along the edge of the protruding Australian lithosphere. This model, which we call the "New Guinea Recipe" for the previously enigmatic formation of the postsubduction arc magmas thus involves: (i) a continental lithospheric edge that (ii) plowed through (iii) a previously subduction-enriched region of the mantle, causing partial melting leading to magmatism in the overlying crust (iv) a trans-lithospheric pathway here provided by an active transform fault system (Figure 2). Asthenospheric upwelling in areas containing cratonic edges are thought to be commonly associated with the genesis of major gold-enriched mineral deposits (Hou et al., 2017), as is certainly the case for Grasberg-Ertsberg (Jowitt et al., 2013). In addition, there is no reason to conclude that this central and western New Guinea magmatic scenario is in some way unique, therefore, the sequence of processes provides a causal scenario for the genesis of "postsubduction" magmatism, that is, in absence of concurrent subduction. This model of postsubduction magmatism provides a new geodynamic framework for the genesis of porphyry copper and associated mineralization, which may prove beneficial in global exploration, as well as geochemical fingerprinting, for postsubduction type magmas and their associated mineralizing systems.

3. Testing the New Guinea Model Elsewhere

We tested the "New Guinea recipe" outlined above for postsubduction arc magmatism in three other regions during times when the four elements given as i-iv in the section above (Figure 2) coexisted without any associated active subduction (Figure 3). In addition, we assessed whether postsubduction arc magmas also exist if one of these elements is lacking.

First, the New Guinea recipe applies to the Fiji Islands (Figure 3a). These are located in a Miocene, ENE-WSW trending transform system at the northern end of the Cenozoic Tonga arc (Hall, 2002) (Figure 3a). Until the Middle Miocene, the Tonga-Kermadec trench continued from the Fiji Islands to the west as the south dipping Vitiaz Trench (Figure 3a), but the ~10 Ma collision with the Ontong-Java plateau arrested this trench and flipped subduction polarity behind the Vitiaz arc associated with the Vitiaz Trench, subsequently forming the New Hebrides subduction zone. Relative motion between the westward retreating New Hebrides slab and the eastward retreating Tonga-Kermadec slab was accommodated along the North Fiji Fracture Zone that has acted as transform plate boundary since ~10 Ma (Hall, 2002). The Tonga arc basement that forms part of the Australian plate is plowing northward (van de Lagemaat et al., 2018) through the enriched wedge of the former Vitiaz and the Late Miocene New Hebrides subduction zones (Pitcairn et al., 2014). This tectonic setting thus has all four ingredients of the New Guinea recipe. Fiji hosts a series of upper Miocene-Pliocene (up to 5 Ma old) arc magmatic intrusions that ascended along faults associated with the North Fiji Fracture Zone. These postsubduction intrusions have subduction-type geochemical characteristics despite not forming above an active subduction zone and host world-class porphyry-copper-gold and associated mineralization (Orovan et al., 2018; Tanaka et al., 2010).

Second, the New Guinea recipe may apply to the western margin of North America. This margin recorded the long-lived eastward subduction of the Farallon plate (Boschman et al., 2018; Wakabayashi, 2015) and associated formation of a subduction-enriched mantle wedge. Subduction terminated upon arrival of the Farallon-Pacific ridge in the western North American trench between the Late Oligocene and Middle Miocene (Atwater, 1989). The North America-Pacific plate boundary subsequently became the San Andreas-Gulf of California transform and pull-apart fault system within the North American continent, merging Baja California with the Pacific plate (Atwater, 1989; McQuarrie & Wernicke, 2005) (Figure 3a). Taking both extension in the Basin and Range region within the North American continental crust (McQuarrie & Wernicke, 2005) and absolute plate motions (Doubrovine et al., 2012) into account indicates that this transform system moved westward relative to the mantle at ~4 cm/yr during the Neogene. This plowed the western North American continental margin through the previously enriched mantle wedge that was generated during Farallon plate subduction. This is coeval with Pliocene postsubduction magmatism along the wider San Andreas transform zone in the Coast Ranges of California and in Baja California

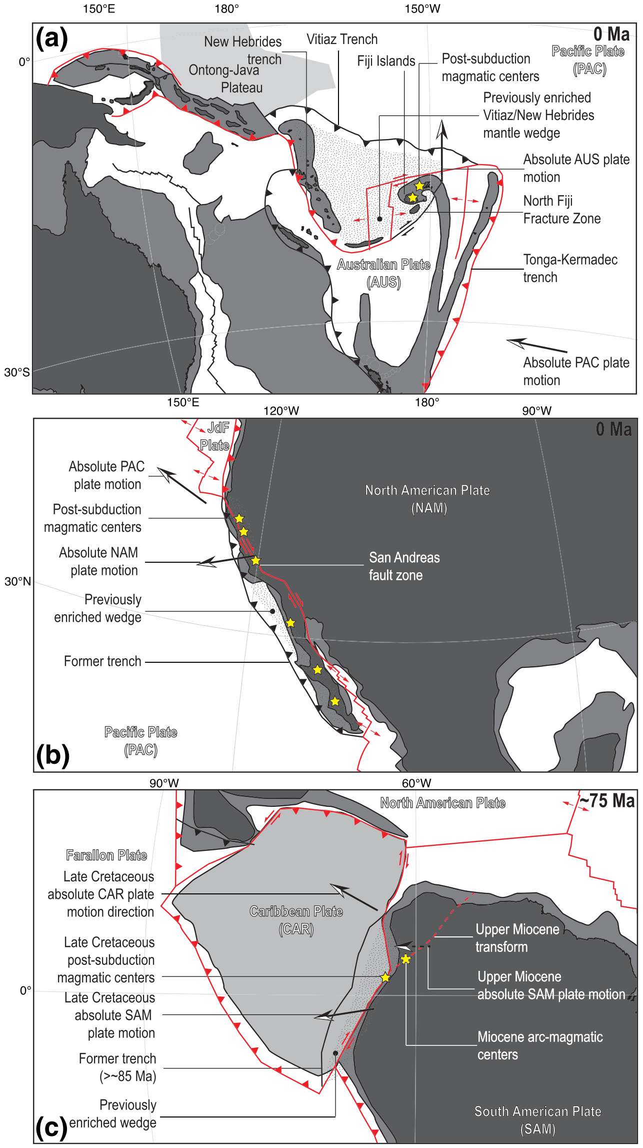

Figure 3. Three examples where the New Guinea "recipe" may apply. (a) Fiji since the Late Miocene; (b) Western North America in the Neogene; (c) NW South America in the late cretaceous (reconstruction at 75 Ma [Boschman et al., 2014] cast in the global moving hot spot reference frame [Doubrovine et al., 2012]; CLIP = Caribbean Large Igneous Province). Plate boundaries in red are active at the time of the snapshot; black indicates fossil plate boundaries.

(Calmus et al., 2011; Castillo, 2008; Desonie, 1992; Negrete-Aranda & Cañón-Tapia, 2008) and although local tectonic deformation likely played a role in triggering melting, the "New Guinea recipe" also may well apply here.

A third region where all ingredients of the New Guinea recipe may exist in in the Cretaceous of NW South America. There, subduction between the Caribbean and South American plates terminated around 85 Ma upon collision of the Caribbean Large Igneous Province with NW South America (Boschman et al., 2014) (Figure 3b). This was followed by break-off of the Venezuela Slab (van der Meer et al., 2018) and a subsequent ~85–50 Ma phase of dextral transform motion between the Caribbean and South American plates was accommodated along major NNE striking transform faults now found in Colombia (Boschman et al., 2014). The northeastward motion of the Caribbean plate relative to the Americas between 85 and 50 Ma is also reflected by left-lateral transform motion at this time of the Caribbean plate relative to North America, for example, along the Belize margin (Boschman et al., 2014; Rosencrantz, 1990) after which the Caribbean plate started to move eastward relative to the Americas and subducted below the Colombian margin since the Early Eocene (Boschman et al., 2014). Between 85 and 70 Ma absolute motion of the South American plate was ~6 cm/yr to the west (followed by very slow absolute plate motion between 70 and 50 Ma) (Doubrovine et al., 2012), plowing the NW South American continental margin through a previously enriched region of mantle wedge. In the 85-70 Ma interval, this transform system recorded arc magmatism (Jaramillo et al., 2017) during the lull in subduction (Boschman et al., 2014) analogous to the New Guinea situation.

Other magmatic provinces previously identified as "postsubduction" (Richards, 2009) include middle-upper Miocene magmatic rocks in southern Tibet (Hou, 2005) and Iran (Densmore et al., 2007) and Eocene magmatic rocks in eastern Turkey (İmer et al., 2016). Recent kinematic restorations indicate that subduction below the eastern Pontides and the Taurides continued until well after the Eocene (Gürer & van Hinsbergen, 2019; van Hinsbergen et al., 2020), meaning that the eastern Anatolian deposits are no longer classified as postsubduction. However, the magmatism in Iran and Tibet is associated with the edges of the underthrusting Arabian and Indian cratons, respectively, both of which have been imaged below the overriding plate plateaus (Li & Song, 2018; Nabelek et al., 2009; Paul et al., 2010). Restoring the location of these edges through time using plate reconstructions that include upper plate deformation (McQuarrie & van Hinsbergen, 2013; van Hinsbergen et al., 2019) reveals that at the time of formation, magmas in both belts were located above cratonic edges that were moving northward through previously enriched mantle wedges, suggesting a link between our plowing model and the genesis of these magmas. The Iranian plateau is associated with widespread strike-slip deformation (Allen, 2010), whereas the Miocene south Tibetan deposits formed in normal fault systems (Hou, 2005) that formed in an intensely deformed upper plate lithosphere with ample opportunity for magmas to rise from the sub-Tibetan mantle (Li & Song, 2018).

These examples demonstrate that regions that contain the ingredients of our New Guinea recipe have also undergone postsubduction magmatism. The opposite is also true in that regions that contain postsubduction arc magmas also appear to have the ingredients of the New Guinea recipe. This may therefore provide a first-order causal link between postsubduction magmatism, mantle structure, and plate tectonics.

Regions in which key elements of the New Guinea recipe are lacking, such as Oman and the Belize margin do not contain postsubduction arc magmas and lack associated mineralization. In Oman, the emplacement of ophiolites onto the Arabian continental margin in the Late Cretaceous was followed by break-off of the Arabia Slab (Duretz et al., 2016; van der Meer et al., 2018). Ongoing absolute northward plate motion of Arabia (Doubrovine et al., 2012) must have caused the plowing of this continental edge through a previously enriched mantle wedge resulting from preobduction intraoceanic subduction. Yet postsubduction magmatism from this setting of continental-edge plowing is absent from the Semail ophiolite. The element missing from the New Guinea recipe is a transform fault systems or other active translithospheric fault in Oman at this time, which we infer prevented magmatic ascent to the (shallow subsurface) surface.

The Paleocene Caribbean-North America transform plate boundary of the Belize Margin (Boschman et al., 2014; Rosencrantz, 1990) formed a continental edge bordering the Yucatán continental lithosphere in the northwest from the oceanic Caribbean plate in the southeast. Southeastward subduction below the northern Caribbean plate recorded in the geology of Cuba (Boschman et al., 2014; Iturralde-Vinent et al., 2008) must have created a subduction-enriched region of the asthenosphere just to the southeast of the continental edge (Figure 3c). However, Yucatán absolute plate motion, as part of North America, was westward and away from this enriched asthenosphere and no Paleocene or younger magmatism is present in eastern Yucatán.

4. Implications for Geodynamics

Our explanation for the formation of the New Guinea postsubduction arc magmatism and the tests of the predictive value of this hypothesis in Fiji and the Americas suggests that former mantle wedges are preserved as geochemical heterogeneities in the shallow asthenosphere long (>20 Ma) after subduction has ceased. How long such heterogeneities may survive in the asthenosphere, how deep “plows” may need to extend into the mantle, and whether other melting mechanisms may also remobilize ancient mantle wedges preserved within the asthenosphere, remains open for future (particularly modeling) research. It is interesting to note, however, that it has been shown that geochemical heterogeneities in the shallow asthenospheric mantle may exist for even much longer times than inferred for the New Guinea case. Young magmatic rocks melted due to decompression below the SE Indian ridge, contain a signature of plume volcanism that occurred in this location as long as 90 Ma ago (Park et al., 2019). This also suggests that not only subduction-enriched, but also plume-modified asthenospheric anomalies may be long-lived and could therefore be eventually juxtaposed with lithosphere that came from thousands of kilometers away or that formed much later. Such long-term survival of geochemically anomalous asthenospheric regions may provide a potential avenue for explaining other enigmatic findings such as ancient zircons within modern mid-ocean ridge settings (Cheng et al., 2016; Pilot et al., 1998; Bea et al., 2020). Reworking of subducted zircons in arcs has, for instance, been demonstrated in the Caribbean region (Rojas-Agramonte et al., 2016, 2017; Torró et al., 2018) showing that zircons survive mantle wedge pressure and temperature conditions. A geochemical heterogeneity at the Atlantic mid-oceanic ridge between 31°N and 41°N also contains Proterozoic to Early Mesozoic zircons (Pilot et al., 1998; Bea et al., 2020) as well as geochemical evidence that continental material contributed to this geochemical anomaly suggesting a subduction influence (Snow et al., 1993), isotopically estimated to have formed ~250 Ma ago (Dosso et al., 1999). The Atlantic ridge geochemical anomaly is located above the Atlantis Slab, which is located at the core-mantle boundary and most likely subducted between ~290 and 210 Ma along the western margin of North America (van der Meer et al., 2010, 2018). Although admittedly speculative, a link between Atlantis slab subduction and the Atlantic 31–41°N anomaly would indicate that the asthenosphere mixes only slowly, suggesting an efficient decoupling from overriding lithosphere plates, and consistent with relative plume motions of only a few mm/yr as predicted by moving hot spot reference frames (Doubrovine et al., 2012; O'Neill et al., 2005; Torsvik et al., 2008). Insignificant mixing and motion of the asthenosphere on time scales of 10–100 Ma is inconsistent with models based on plate motions that are predominantly driven by upper mantle or whole mantle flow (Becker & Faccenna, 2011) and would instead suggests an upper mantle convection rate that is much lower than that of plate motions. Integration between absolute plate kinematic, mantle geochemical, and geodynamic research may thus provide novel constraints on the relationship between the moving plates and the convecting mantle.

Acknowledgments

M. v.D. thanks his former PhD advisors Roberto Weinberg and Andrew Tomkins. We appreciated reviews of Peter Cawood and anonymous reviewer. Funding: DJJvH acknowledges NWO Vici Grant 865.17.001. Data and materials availability: Gplates reconstruction files for several regions discussed in this paper are available online (http://www.geologist.nl/reconstructions/). For tomographic model and sections, see this website (http://www.atlas-of-the-underworld.org).

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