Plio-Pleistocene river drainage evolution in New Guinea. Implications for reservoir mineralogy predictions

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SUMMARY

The drainage of New Guinea has evolved rapidly since Pliocene time. Relief growth initiated in accreted oceanic terranes in the north and migrated into the Australian margin interior over time. The present-day drainage retains inherited elements of an ancient fluvial system that routed sediments from these northern terranes through the Central Highlands into foreland flexural basins, epicontinental seas, and deep oceanic basins. The rise of the Highlands and of the Papuan Peninsula spurred drainage reorganization, such that today little of the oceanic terranes still drains through the mountain range. This evolution has strongly affected the composition of the clastic sediments delivered to the shelves.

The topography retains the memory of some of the most recent changes. Most of the relief of the Papuan Peninsula formed during the past 5 Ma, driven by tectonic removal of the load of the peninsular ophiolites, accompanied by contractional collapse along the Aure-Pocklington trough. In the eastern Central Highlands, rapid drainage reversal results from flexural back-tilting under the load of the colliding Huon-Finisterre Range. Northward reversal is also observed at the western end of the Highlands. In the south, the Fly platform has experienced recent, widespread, non-tectonic and non-flexural uplift of deep origin that will ultimately close the Torres Strait.

The Quaternary drainage evolution will be used to calibrate the Badlands software developed by the Basin Genesis Hub, as a first step for simulating the evolution of topography and sediment delivery to the Australian shelf and Gulf of Papua in earlier times.

Key words: Tectonics, Drainage evolution, New Guinea, Sediments

MOTIVATION

The drainage of New Guinea has evolved rapidly since Pliocene time as a result of the rapid growth of the New Guinea fold and thrust belt. Relief growth initiated in accreted oceanic terranes to the north of the present-day drainage divide, progressively migrating into the continental Australian terranes farther south. The composition of the fluvial sediments delivered to the New Guinea foreland and the Gulf of Papua evolved accordingly, affecting in particular the composition of sandy deposits that potentially trap hydrocarbons.

The Basin Genesis Hub at the University of Sydney has developed *Badlands*, a surface process model that simulates the evolution of topography and river drainages under the effects of uplift and precipitation, together with sediment deposition at sea. The software is versatile and amenable to the incorporation of modules aimed at incorporating more specific processes of landscape evolution. It can, in particular, generate the production of different grain sizes populations according to rock type and erosion rate, and investigate the effects of sediment fluxes on river incision. This production function is currently adapted to generate and calibrate transfer functions between source rock composition and sand fraction mineralogy in terminal sinks. A first application of this development is to predict the evolution of sand mineralogy in space and time along the New-Guinea-Papua orogen.

Its implementation involves two consecutive steps. First, we use a recent quantification of sediment delivery to the Gulf of Papua and present-day distributions of rock types, rock uplift rates, and precipitation to calibrate *Badlands*' sediment flux delivery to the gulf (see AEGC presentation 'Constraining upland erodibility in catchments delivering sediment to the Gulf of Papua' by Garrett *et al.*, Figure 1).

The mineralogy of Early Pleistocene sandy turbidites is then used to calibrate the production of mineral populations on the slopes of their feeding catchments. This calibration will be used to predict the evolution of the sand composition along the strike of the orogen, especially along the Papuan Peninsula.

Implementation of this second step requires foreknowledge of how drainage boundaries have migrated over time, as this affects source rock contributions. Understanding drainage evolution is also critical for simulations aimed at modelling sediment fluxes and sediment composition farther back in time. Migration of water divides is a slow (10^5-10^7 years), variously delayed adaptation of drainage patterns to changing tectonics and climate. Tectonics, mountain building, and orographic precipitations in New Guinea have evolved over remarkably short timescales (10^5-10^6 years). Therefore, the recent evolution of the divides encapsulates the interference of several, sometimes antagonistic and often short-lived tectonic pulses.

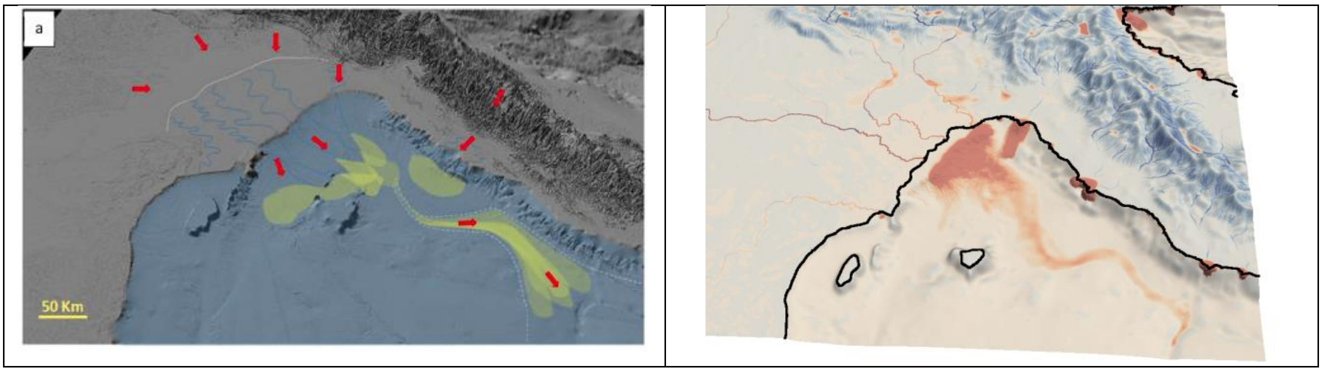

Figure 1: *Calibration of erosion and sediment delivery in Badlands (Garrett et al., 2017), using sedimentary fluxes over the past 20 kyrs. Left panel: observed turbiditic depocenters in the Gulf of Papua. Right panel: Badlands prediction of final cumulated erosion (blue) and deposition (red).*

INTRODUCTION

Tectonic evolution of the Papuan Peninsula and eastern Highlands

The last phase of mountain building in New Guinea probably started in the Oligocene, culminating during the Pliocene uplift of the Highlands and of the Papuan Peninsula (see AEGC presentation 'Tectonics and geodynamics of the eastern Tethys and northern Gondwana since the Jurassic' by Zahirovic *et al.*). In the Late Jurassic, New Guinea was the northern active margin of the Australian continent, above a south-dipping subduction zone. Slab rollback in the latest Jurassic likely caused opening of a Sepik back-arc basin, with these supra-subduction zone ophiolites now forming the Central Ophiolite Belt of New Guinea (Permana, 1998), north of the modern drainage divide. The ophiolite is bordered by the Sepik composite terrane to the north (microcontinental fragments within a dominant mass of oceanic island arcs), and the Australian continental margin to the south. Most of this back-arc ophiolite is thought to have been subducted northward below the Sepik composite terrane. Arrival of the Sepik terrane produced the obduction of the Central ophiolite belt onto the Australian margin (~55 Ma), followed by continent-arc collision of the Sepik terrane presumably in the Oligocene (Davies and Jaques, 1984). Convergence was then accommodated by a change in subduction polarity, allowing for southward subduction of the Caroline Plate below New Guinea. Subduction generated the Maramuni volcanic Arc (~18 to 8 Ma) across all accreted terranes. Oblique arrival of the Melanesian Arc in the subduction zone in the Late Miocene subsequently led to diachronous, east-younging, and still ongoing continental arc-island arc collision along the margin, with successive accretion of the Cyclops, Bewani-Torricelli, Amanab, Finisterre and Huon Peninsula terranes (Hill and Hall, 2003).

Deformation associated with this later collision is partitioned between dominantly strike-slip, left-lateral structures north of the Sepik-Mamberamo terrane and ophiolites, which themselves behaves semi-rigidly, and contractional deformation and uplift much farther south, in the continental terranes of the New Guinea fold and thrust belt (Baldwin et al., 2012; Cloos et al., 2005; Hill and Hall, 2003; Wallace et al., 2004).

'Docking' of the Finisterre-Huon Peninsula against the mainland involves a phase of strike-slip docking along the Ramu-Markham fault zone (Hill and Hall, 2003), followed by the current frontal, orthogonal convergence (Abers and McCaffrey, 1994; Wallace et al., 2004). This later sees the arc-arc collision turn at the advantage of the Finisterre-Huon terrane, with thrusting of the Huon Peninsula over New Guinea, accompanied by downward flexure of the New Guinea lithosphere below the Finisterre-Huon terrane (Abers and McCaffrey, 1994).

Together with subduction at the Solomon trench, arrival of the Ontong Java plateau at the Solomon Island trench has been held responsible for the opening of the Woodlark (3.6 – 0 Ma) and Bismark Sea (3.5-0 Ma) spreading centres in an overall context of oblique convergence (Holm et al., 2016). The Woodlark basin currently propagated westwards across the Papuan Peninsula, triggering exhumation of deep crustal core complexes in the d'Entrecasteaux Islands (Little et al., 2011) and within the Papuan peninsula Suckling-Dayman dome (Daczko et al., 2011). Farther west, extension generates upper crustal normal faulting along the Owen-Stanley fault, which reactivates the former suture between the Owen-Stanley continental metamorphic sole to the SW and the overlying Papuan ophiolite to the NE. Recent (0.5 Ma) change in the opening direction at the Woodlark spreading centre (Taylor et al., 1999), may explain the contractional inversion of the Owen-Stanley fault towards its NW termination (Ott and Mann, 2015), although such inversion thus far remains a mere prediction of rigid plate rotation models (Wallace et al., 2014; Wallace et al., 2004).

The Aure Trough, between the New Guinea mainland and the Papuan Peninsula is a mobile belt which has accommodated successive episodes of extension and contraction between New Guinea and the peninsula. Since the Pliocene, it is the locus of continued contraction, which has been interpreted as a consequence of the rigid rotation of the microplate that supports the Peninsula (Ott and Mann, 2015).

Topographic evolution of the Papuan Peninsula and eastern Highlands

Little is known about the topography of New Guinea before the spread of siliciclastic detritus over the southern foreland carbonate shelf ~12 Ma ago (van Ufford and Cloos, 2005). By ~15 Ma unroofing had started north of the modern main water divide, within the Sepik composite terrane, and within the underlying ophiolitic belts and continental metamorphic sole (Cloos et al., 2005; Hill and Raza, 1999). Shortening and unroofing along the present water divide had started by 7 Ma in Western New Guinea and 4 Ma in the Western Island, accompanying the southward propagation of fold and thrust belts and causing 3-4 km of denudation (Crowhurst et al., 1996). Contraction seems to have slowed in Western New Guinea since 4 Ma (Cloos et al., 2005), allowing for a better expression of left-lateral components, both within the range (Cloos et al., 2005), and in the southern foothills. In Eastern New Guinea, contraction in the foothills still goes on, together with lesser amounts of wrenching, and includes recent basement fault inversions in the foreland. Overall, the very high elevations of the Highlands (4-5 km) cannot be easily reconciled with the limited amount of shortening (a few 10s of kilometres) that has taken place on visible geologic structures (folds and faults). This discrepancy has been explained by lithospheric mantle delamination under the Highlands (Cloos et al., 2005). During the Quaternary, a pulse of alkaline intraplate volcanism created a cluster of shield volcanoes that straddle all pre-existing structural domains, from the foreland to the Highlands. The volcanoes built on top of the range have been extensively glaciated (Barrows et al., 2011). Normal sequences of moraine imbrication imply no significant growth of ice feeding areas from a glaciation to the other, suggesting limited uplift of the Highlands during the late Pleistocene. Flexural loading studies have shown that building of the Papuan fold and thrust belt induces limited flexural subsidence across the southern foreland (Abers and Lyon-Caen, 1990), implying decoupling across large normal Jurassic faults (Hanani et al., 2016).

Farther east, a short-lived (6-4 Ma) andesitic volcanic arc grew along the strike of the Papuan Peninsula (Pain, 1983). We mapped the areal extent of these volcanic units (Figure 2) and found that they consist dominantly of low-angle volcanoclastic sheets emplaced over subdued topography (paleovalleys < 100 m deep). Toward the southwest, volcanogenic sediments have been incorporated into a narrow fold-and thrust belt that accommodates shortening between the Peninsula and the floor of the Gulf of Papua, across the flexural Pocklington trough. Farther inland, within the Papuan peninsula, the volcanogenic sediments exhibit a dramatic upwarp. They project to the elevation of a series of widespread remnants of a formerly extensive subdued surface (Loffler, 1974) that crowns the highest mountain tops (Figure 2). These observations implies most of the 4 km of relief growth since the Early Pliocene, when the peninsula was near sea level. Remnants of the summit surface are found at much lower elevation on the oceanic terranes to the northeast of the Owen Stanley fault, indicating that topographic growth was likely coeval to fault activation. For this reason we consider that most of the uplift in the Owen-Stanley range results from tectonic removal of the Papuan ophiolite, which covers most of the footwall over considerable thicknesses. In the d’Entrecasteaux Islands, the Papuan ophiolite is more than 10 km thick (Little et al., 2011) and constitutes an heavy lid over less dense rocks exhumed within the metamorphic cores. The coeval formation of the flexural Pocklington Trough and coastal contraction is therefore interpreted as gravitational collapse of the Owen-Stanley footwall over the Papuan Gulf sea floor, rather than stalled rigid block rotation (Ott and Mann, 2015), although it may mark the resumption of convergence over an ancient subduction zone (Schellart and Spakman, 2015).

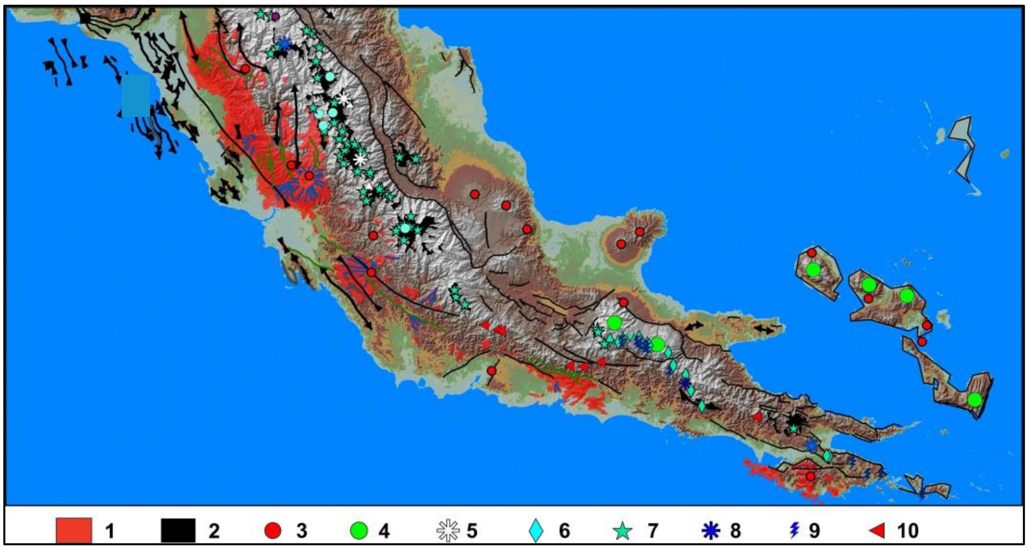

Figure 2: *Markers of surface uplift and drainage evolution used to reconstruct the evolution of the Papuan Peninsula.*
1: Pliocene volcanics, 2: perched relict low-relief surface, 3: volcanic centre (Pliocene and Quaternary), 4: metamorphic core complexes, 5: moraines, 6: windgaps, 7: river knickpoints, 8: river diversion, 9: drainage reversal, 10: rapid watershed migration.

DRAINAGE EVOLUTION

The drainage of New Guinea evolved in this context of complex, intertwined pattern of contraction and extension-driven uplift and subsidence. Owing to the youth of mountain building (<5 Ma), and in spite of high rainfall and erosion rates, its relief retains an incompletely eroded memory of its evolution which allows us to reconstruct the most recent phases of drainage evolution. The most useful elements are volcanic deposits fossilizing past topographies, perched low-relief surfaces, uplifted shorelines, drowned topographies, and diagnostic elements of drainage rearrangement such as windgaps, underfit streams, capture elbows and associated canyons, barbed tributaries, alluviated, back-tilted valleys, and perched alluvial deposits (e.g. Figure 3). These features allow reconstruction of drainage divide migration along the strike of the New Guinean fold and thrust belt as well as along the Papuan Peninsula (Figure 4). The drainage evolution can then be superposed to tectonic evolution to identify the main drivers of drainage rearrangement.

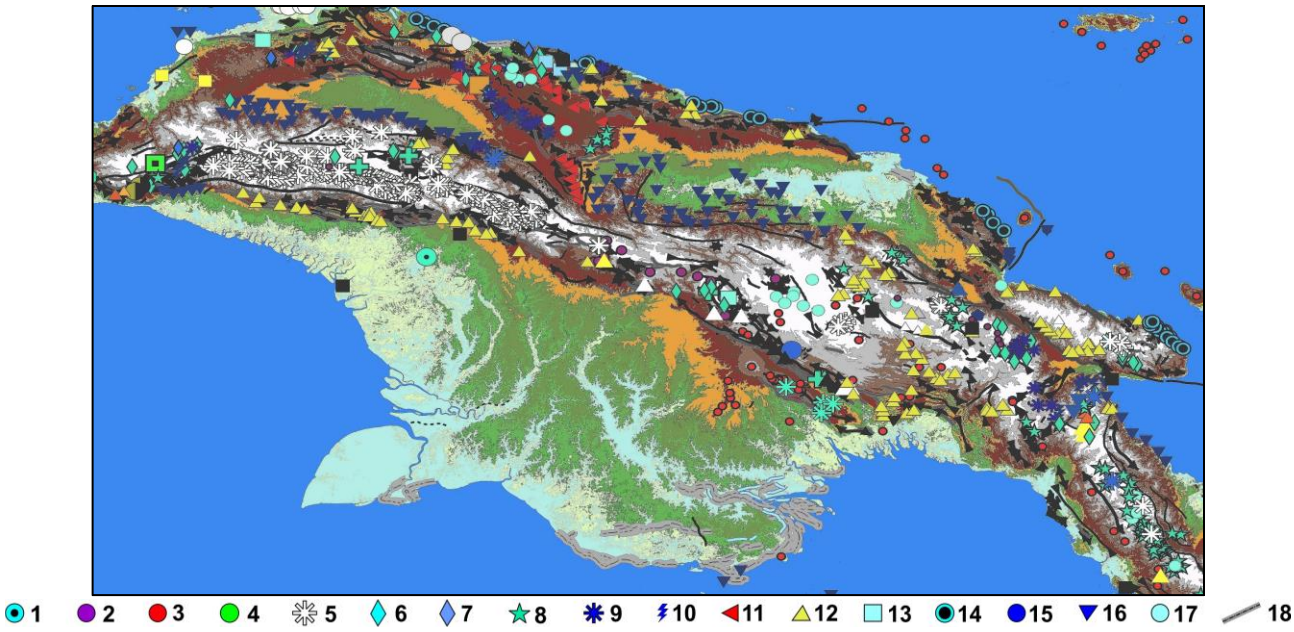

Figure 3: Markers of surface uplift and drainage evolution used to reconstruct the evolution of the New Guinea fold and thrust belt. 1: Inner delta, gravel-sand transition, 2: shallow intrusive, 3: volcanic centre (Pliocene and Quaternary), 4: metamorphic core, 5: moraines, 6: windgaps, 7:paleovalley, 8: river knickpoint, 9: river diversion, 10: drainage reversal, 11: highly dissymmetric watershed, 12: perched fan,13: polje, 14: perched shoreline, 15: polje lake, 16: drowned topography, 17: alluviated valley, 18: inactive sand/gravel bar.

The dominant trend in drainage migration is southwards, from within the oceanic terranes to entirely within the continental terranes. At present the oceanic terranes are almost no longer drained by south-flowing streams. The corresponding expected outcome is a decrease in the amount of graywackes delivered to the basin and possibly an increase in the occurrence of clean, mature sands, although this will vary considerably from one catchment to the other.

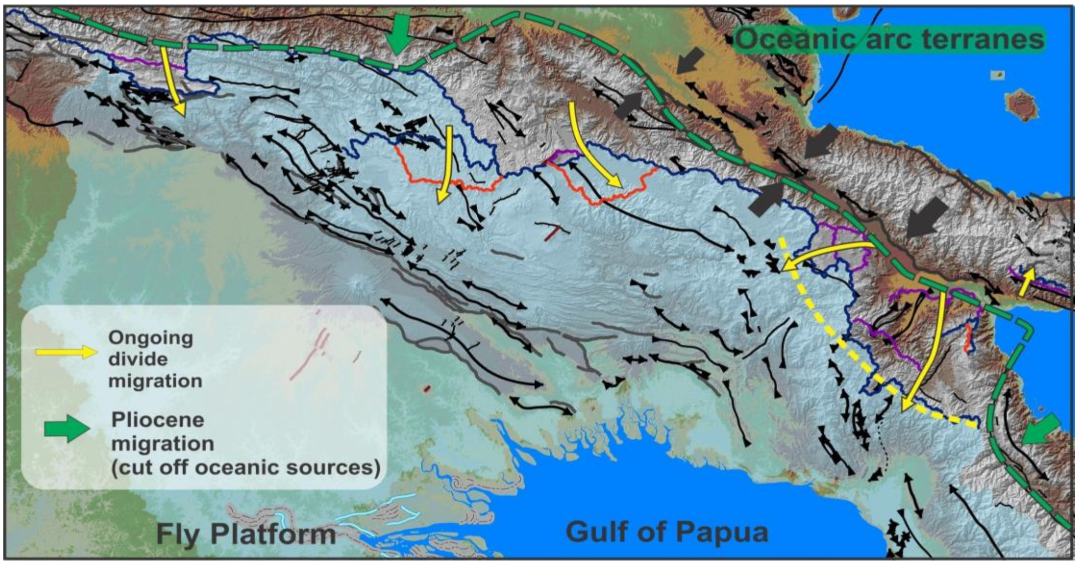

Figure 4: Evolution of the main drainage divide, over the central Highlands: Dashed green line: southern limit of the ophiolitic belts, dashed yellow line: inferred southern extent of the flexure related to the loading of the Huon Peninsula. Purple lines: past drainage divide positions, blue: modern drainage divide extent (light blue: catchments draining to the Gulf of Papua), red lines: projected position of the divide in the near future.

The overall southward migration of the divide is well expressed all along the strike of the Central fold-and-thrust belt. It is likely a response to uplift along the southern foothills, and subsidence in the north, along the southern border of sepik-Mamberamo terranes, which generate an apparent northward backtilting of the range. This uplift pattern probably results from lithospheric contraction. In addition, however, longer wavelength uplift has affected the southern foreland, exposing a platform that had remained submerged until the past few 100s of thousands of years, and allowing for the Fly River system to prograde dramatically seawards. This uplift probably originates in deeper, mantle-driven processes, possibly related to the pulse of Quaternary intraplate volcanism. Quaternary volcanism is responsible for some derangement of the drainage lines. It does not, however, counteract the overall migration of the divide southwards, and may have helped it at places.

Southward migration of the divide is occurring more rapidly, by drainage inversion, across from the Finisterre-Huon range, in a mountainous area affected by flexural downwarping (Fig.4). The extent of the reversal matches the predictions of the forebulge crest position produced by this loading (Abers and McCaffrey, 1994).

Conversely, along the Papuan Peninsula, the divide is stabilized over the entire length of the Owen-Stanley fault, which effectively cuts off the delivery of ophiolitic material to the Gulf of Papua. The absence of windgaps across the fault scarp suggests that, if a through-going drainage once existed, it was cut off soon after the fault started developing a normal component of slip, and that this happened during the Early Pliocene (4 Ma). The bimodal distribution of volcanic rock ages in the volcanic rocks of the Early Pliocene volcanic arc (RJ Holm, pers. comm.) suggests a possible Miocene source that could be the continuation of the Maramuni Arc in now flooded areas, NE of the Owen Stanley fault. However at this stage no definitive evidence of a through-going drainage can be provided.

CONCLUSIONS

Inspection of indices of drainage evolution reveals rapid, Plio-Quaternary adjustments of the river drainages. These will affect predictions of the sediment composition delivered to the Gulf of Papua in a significant manner for simulations aimed at addressing pre-Quaternary sediment routing.

Several drivers contribute to these changes, over different time and spatial scales: lithospheric thickening, flexural loading, tectonic denudation and unloading, gravitational collapse, volcanic derangement and mantle convection. There is no clear specific signal that can be related to narrow lithospheric mantle delamination (Cloos et al., 2005), at least over the past million of years. It should be noted, however, that the uplift field produced by such a narrow delamination may be difficult to distinguish from that produced by lithosphere thickening.

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