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Jean-Louis Grimaud [a,*], Yoram Teitler [b,c], Sylvain Favier [b], Yaël Guyomard [d], Fabrice Golfier [b], Michel Cathelineau [b]

[a] PSL University, MINES Paris, Centre de Géosciences, 35 rue St Honoré, 77305 Fontainebleau Cedex, France
[b] Université de Lorraine, CNRS, GeoRessources, Nancy, France
[c] CSIRO Mineral Resources, 26 Dick Perry Avenue, Kensington, WA 6151, Australia
[d] SGNC DIMENC, Nouméa, Nouvelle Calédonie, France

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ABSTRACT

Constraining the evolution of river networks under external forcings is critical because drainage evolution and landscape dissection control the redistribution of regolith, which has implications for mining resources. In this study, several Neogene geomorphic evolution stages of the Southern Massif of New Caledonia, where supergene nickel ore is exploited, are reconstructed by combining Digital Elevation Model (DEM) analysis with field mapping of abandoned lateritic paleo-landsurfaces. Results show that the drainage has been mostly exorheic, and that stream capture and piracy have slowly modified the landscape over the past 20 million years. The river long profiles are still adjusting to ongoing uplift, as demonstrated by southward island tilting and the uplift of quaternary reefs to the North of the study area. Ranges of drainage area changes and river incisions are assessed. Neogene incision rates are very low in the vicinity of the Goro pit (i.e., 1–15 $m.Myr^{-1}$), the classic basin-type Nickel deposit of New Caledonia, compared to other places (i.e., up to 15–30 $m.Myr^{-1}$). We propose that such low incision rates can explain the singularly high thickness of oxide Ni deposits in the area due to enhanced polygenetic weathering on lateritic profiles during the Neogene.

1. Introduction

Constraining the rates and mode of evolution of river networks under external forcings is important to bio-geoscientists. Indeed, the establishment and evolution of drainage systems set up ecological boundaries, which influence, for instance, fish speciation and control drainage area, thus the amount of sediment exported to the sea by rivers (Bishop, 1995; Montgomery, 2004; Grimaud et al., 2018; Barreto et al., 2022). Drainage evolution and landscape dissection also control surface morphologies for the redistribution of the regolith by erosion and chemical weathering, with implications for mining resources in the case of ore-bearing regolith (Ouangrawa et al., 2000; Thomas et al., 1985; Grimaud et al., 2015; Chardon et al., 2018; Salama et al., 2022).

Besides Ni-sulphide ores, principal world nickel ores formed with the supergene evolution of ultramafic rocks (Berger et al., 2011; Butt and Cluzel, 2013), such as in New Caledonia, where lateritic ore deposits also contain other mineral resources (e.g., Sc, Co; Trescases, 1975; Butt and Cluzel, 2013; Cathelineau et al., 2016, 2017, 2023; Maurizot et al., 2019, 2020; Teitler et al., 2019). There, nickel is accumulated either at the base (i.e., hydrous Mg-silicate type in the saprock) of the resulting lateritic weathering profile or higher in the weathering profile (i.e., oxide-type in the fine saprolite) (Maurizot et al., 2019; Sevin et al., 2020). A classic approach to exploration geology in New Caledonia is to classify sites according to their morphology, which is associated with different types of nickel deposits (Trescases, 1975; Bailly et al., 2014; Trotet et al., 2015; Maurizot et al., 2019). ***Basins*** correspond low-grade oxide-type ore sites where thick lateritic profiles dominate. ***Slope*** sites are usually dominated by Mg-rich hydrous silicate-ore type, and ***plateau*** sites (also dominated by hydrous Mg silicate ores) are intermediate between basins and slopes.

In early geomorphic models, Trescases (1975) considered that basins were formerly endorheic and that a karstic system evacuated erosion products. Such karstic systems are commonly found in ultrabasic rocks (Nunez et al., 1967; Hope, 2015), although the associated groundwater paths must be clarified (Jeanpert et al., 2019). The endorheic basins would then be captured by an externally drained river system and

* Corresponding author.
E-mail address: jean-louis.grimaud@minesparis.psl.eu (J.-L. Grimaud).

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inverted due to tectonic uplift, leading to the dismantling and redistribution of nickel in weathering profiles (Trescases, 1975; Maurizot et al., 2019, 2020). Hence, these models show a close relationship between tectonic uplift, drainage evolution, and Ni-laterite ore type. These models remain, however, conceptual: no study precisely documents the transition from an endorheic to an exorheic drainage in a basin-type Ni-deposit. Thus, refining drainage evolution in such a context is useful for a better understanding of mineralization processes and the validation of these models.

Landscape evolution modelling supports that drainage divides may be mobiles under different kinds of climatic and tectonic forcings (i.e., Willett et al., 2001; Bonnet, 2009; Guerit et al., 2018) although in some cases, drainage networks are stable for millions of years (Bishop, 1986; Chardon et al., 2016). When a disequilibrium arises, catchments defined as *aggressors* may capture the upstream drainage area of their *victims* through headward erosion (Willett et al., 2014). The χ metric, which aims to quantify such disequilibrium across shared drainage divides (Perron and Royden, 2013; Willett et al., 2014; Whipple et al., 2017), has been applied in many contexts. The usefulness of χ is debated, i.e., from its relevance compared to other metrics to its limitation when using inappropriate parameters for χ estimates across drainage divides (e.g., Whipple et al., 2017; Gailleton et al., 2021). In general, χ-maps must be compared against field data to robustly assess drainage changes (e.g., Fan et al., 2018). In that sense, i.e., to be tested against field evidence, it is a useful metric to quantify anomalies in the drainage.

In this study, the Neogene surface evolution of the Southern Massif in SE New Caledonia, an area typically described as dominated by basin-type morphologies, is investigated. Incision rates are estimated and drainage changes (i.e., captures) are identified based on lateritic regolith mapping and river long profiles analysis combined with χ -maps. These results are discussed with regards to the tectonic evolution as well as the formation of supergene mineralization in the area. In particular, we challenge the paradigm that the drainage was formerly endorheic during the lateritic weathering stage when the nickel ore found in the study area formed.

2. Geomorphic context

2.1. Geological settings of New Caledonia

Grande Terre, New Caledonia's main island, is located on the Australian plate within the SW Pacific, to the NE of Australia and the E of the Coral Sea (Fig. 1). It corresponds to the Northern end of the Norfolk ridge as part of the 94 % submerged Zealandia continent (Mortimer et al., 2017; Collot et al., 2020). Its present-day geodynamics is controlled by the subduction of the NE of the Australian plate below the Pacific plate (Fig. 1). This convergence is accommodated by the New Hebrides-Vanuatu Trench (Dubois et al., 1974, 1977; Pelletier et al., 1998, 2001).

New Caledonia geologic substrate may be divided into a volcano-sedimentary basement, composed of Gondwana terranes covered by Late Cretaceous to Eocene sediment, overlaid by a peridotite nappe (Paris, 1981; Maurizot et al., 2020). Evidence of high-pressure, low-temperature metamorphism is interpreted as Paleocene subduction before exhumation and obduction in the Late Eocene (Cluzel et al., 2001; Lagabrielle et al., 2013; Gautier et al., 2016). The timing of obduction is constrained between the age of (marine) sediments deposited below the Peridotite Nappe (34 Ma) and the age of magmatic intrusions in the Nappe (27 Ma) (Sevin et al., 2014, 2020). The emersion of the Grande Terre of New Caledonia has been attested since at least 25 Ma based on paleomagnetic dating of ferricretes (Sevin et al., 2012, 2014, 2020). During the Neogene, a change in the regional directions of constraints from extension to transtension is suggested from micro-tectonic analyses (Chardon and Chevillotte, 2006; Lagabrielle et al., 2005, 2013; Mortimer et al., 2014). During the Late Neogene to Quaternary, a southwestward tilt of the island of Grande Terre is supported by (i) the

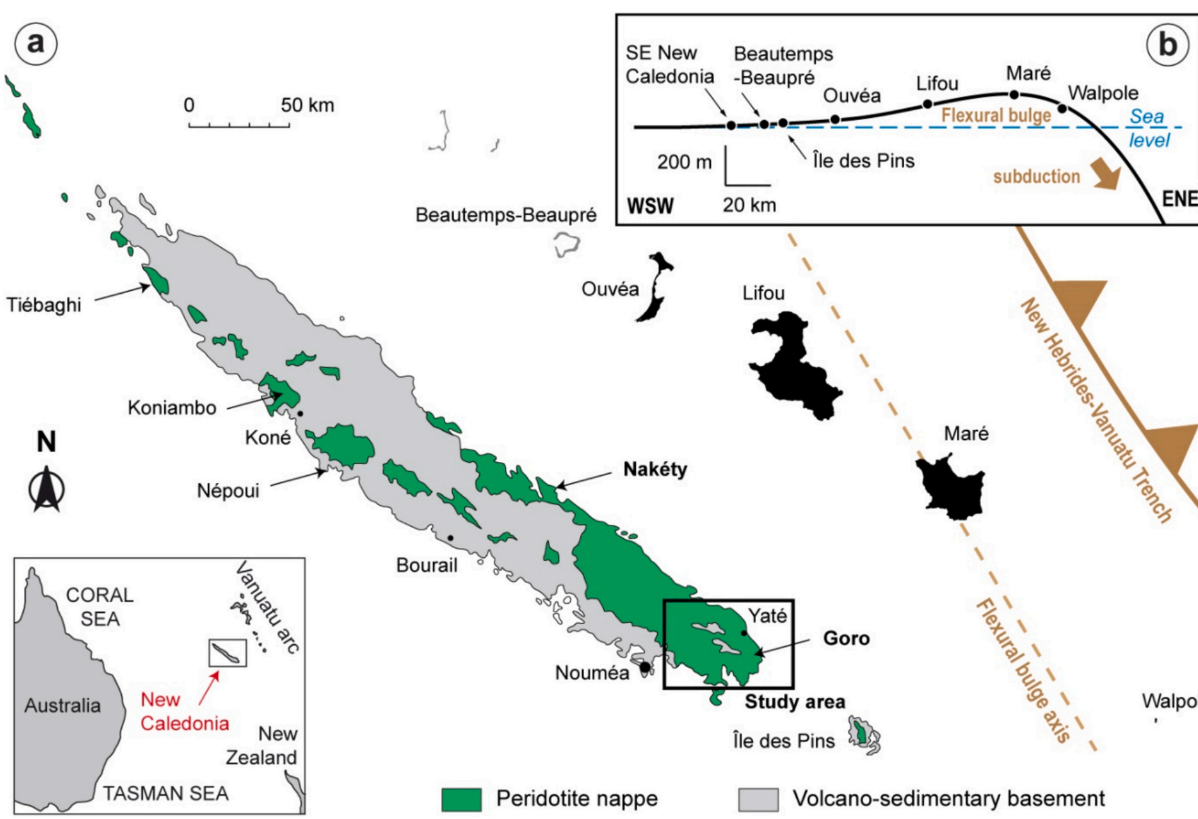

Fig. 1. (a) Simplified geological context (Cathelineau et al., 2023). (b) Cross-section orthogonal to the New Hebrides-Vanuatu Trench with the elevations of the different islands highlighting the flexural bulge (Dubois et al., 1974).

elevations of ~125 kyr-old reef remnants relative to the sea level across the island and (ii) the differential elevation of Tertiary continental deposits (Davis, 1925; Cabioch et al., 1999; Chardon and Chevillotte, 2006; Cluzel et al., 2012) (Fig. 1).

2.2. Incision chronology from lateritic paleo landforms

During Meso-Cenozoic times, intense weathering led to the formation of thick lateritic profiles, particularly in the intertropical zone (Grandin and Thiry, 1983; Tardy and Roquin, 1998; Wirthmann, 2000; Beauvais and Chardon, 2013). In response to climatic oscillations leading to river incision and changes in rock uplift, lateritic weathering profiles -capped by duricrusts- may be inverted and abandoned. They thus correspond to the relicts of interfluves, which connected to river levels. When correctly dated and correlated, such as in West Africa (Beauvais et al., 2008), India (Jean et al., 2020) and South America (Vasconcelos et al., 1994; Allard et al., 2018), lateritic weathering relicts can be powerful to study drainage evolution and river incision (Grimaud et al., 2014; Chardon et al., 2016; Beauvais et al., 2016; Grimaud et al., 2018). In New Caledonia, Davis (1925) was the first to describe relict surfaces at high elevation (i.e., an old "peneplain") that he interpreted as being inverted by tectonic uplift. Following the pioneering work of Trescases (1975), Chevillotte et al. (2006) defined a lateritic sequence composed of 8 paleo-landsurfaces in New Caledonia (Fig. 2). Each sequence member is found at a different elevation range, the upper ones being the oldest and the lower ones being the youngest. Chevillotte et al. (2006) further distinguished each sequence member based on its surface morphology and some variations of the weathering profile features (thickness, type of duricrust, degree of dismantling, organization, etc.).

The three upper members of the sequence (so-called A, B and C; Fig. 2) are primarily located in the inner mountain range of the Grande Terre between 1100 and 1600 m. Limited remnants of lateritic profiles are associated with surfaces A and B. In contrast, surface C, which is interpreted as the relictual incipient portion of the oldest lower surface S1, is characterized by thick, continuous weathering profiles associated with hydrous Mg silicate ore (Chevillotte et al., 2006).

S1 to S5 surfaces are found at lower elevations (< 800 m) at the periphery of the inner mountain range. They are well preserved on the ultrabasic rocks of the Peridotite Nappe (Figs. 1 and 2). S1 and S2 have similar weathering profiles, the main difference being that the S1 weathering profile is thicker. S3 surface corresponds to an erosional pediment surface mostly observed at the piedmont of peridotites massifs, and subsequently affected by weathering and development of ferricrete. It is the dominant surface of the Southern Massif. S4 and S5 correspond to glacis or pediment surfaces that connect locally to alluvial terraces. The former can be locally silicified, while the latter is only moderately ferruginized in the upper meters near the topographic surface (Chevillotte et al., 2006). Chevillotte et al. (2006) proposed a chronology as old as 34 Ma for the upper surfaces based on the relation between its members and sedimentary deposits in the Népoui area. Paleomagnetic dating in the Tiébaghi area is consistent with a Late Oligocene age for the S1-S2 surfaces (Fig. 2) (Sevin et al., 2012; Sevin et al., 2014; Cathelineau et al., 2023). In the Southern Massif area, near Goro, paleomagnetic ages are widespread, ranging from 25 Ma to the present.

2.3. Geology and morphology of the study area

The Southern Massif corresponds to a low-lying, relatively dry area of SE New Caledonia. The bedrock is mainly composed of peridotites (i.e., either dunite or harzburgite), apart from some layered gabbro found in Prony Bay and granitoids located upstream of the Pirogues River (Pirard et al., 2013) (Fig. 3c). Bedrock lithology is therefore very homogeneous in this part of the island. The Southern Massif is further characterized by the great extension of its lateritic cover, with very thick weathering profiles (~50 m; Bailly et al., 2014). It is thus a typical area of basin-type nickel deposits dominated by oxide ore (Trescases, 1975). There, weathering profiles are in contact with the widespread, so-called "Fluvio lacustrine" formation, notably around the Yaté Lake (Fig. 3c). The deposition timing of this Neogene formation has yet to be precisely constrained (Folcher et al., 2015).

Compared to the rest of the Grande Terre Island, the SE area has a lower elevation (< 400 m) and is characterized by several subcatchments organized into a "honeycomb" pattern. These catchments were interpreted as formerly endorheic (Trescases, 1975). The subcatchments may be divided into several elevation ranges delimited by different color ranges on the DEM (Fig. 3): along the coast (ex: Port-Boisé) with elevation of 0–100 m (light blue), in a transition zone (ex: the area to the North of the Prony town) with elevations of 150–200 m (yellow) and in an elevated zone (ex: Plain of the Lakes) with elevations of 250–300 m (light green). In the latter, it is worth noting that the larger lakes are all located South of the topographic depression. This distribution is consistent with the tilting of the Grande-Terre towards the SW in response to differential uplift between the northern and the southern coasts, as advocated by uplifted reefs near the Yaté Bay along the northern part of the study area (Fig. 3) (Cabioch et al., 1999; Chardon and Chevillotte, 2006; Sevin et al., 2020).

3. Methods

3.1. Lateritic (paleo)-landsurface mapping

Mapping of lateritic remnants was based on the combined analysis of aerial pictures, Digital Elevation Model (DEM) (Fig. 3) and Google Earth ® views with field observations (Fig. 4) and data from the literature (Chevillotte, 2005; Chevillotte et al., 2006; Sevin et al., 2020). Low relief and low slope duricrusted surfaces were targeted. These surfaces are not horizontal but slightly tilted towards the sea or, more generally, towards

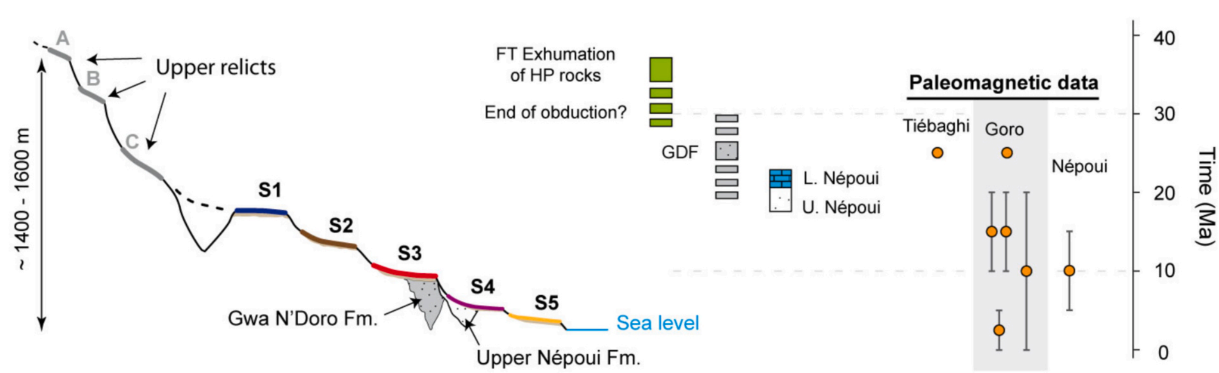

Fig. 2. Incision chronology, including a synthetic distribution of the lower paleolandsurface relicts (Chevillotte et al., 2006) and some chronological constraints from Sevin et al. (2014). GDF: Gwa N'Doro Formation, FT: Fission tracks, HP: High pressure.

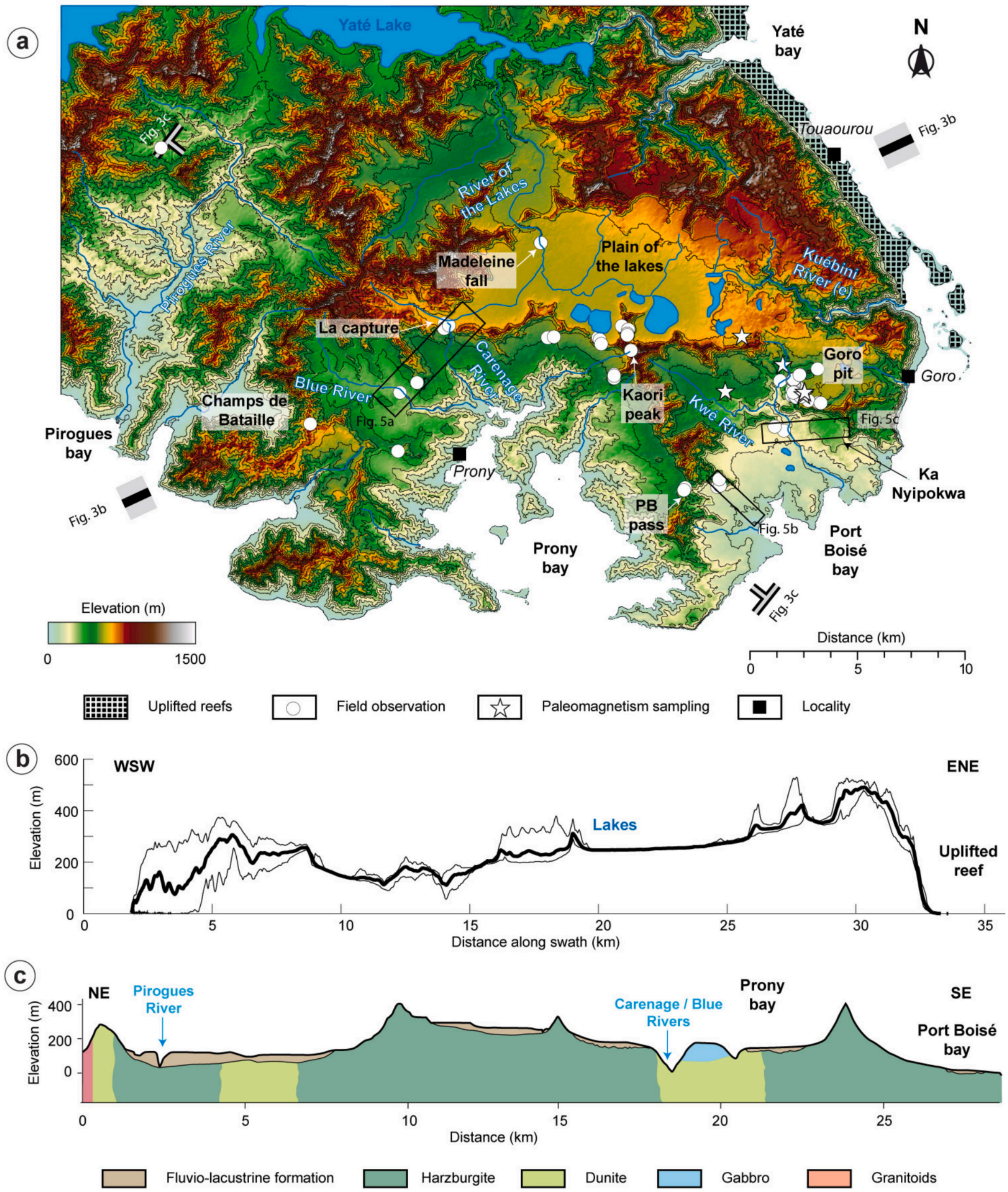

Fig. 3. (a) Topographic map of the study area with the locations cited in the text. The locations of photographs and topographic profiles in Figs. 4, 5 and 6 are also shown. Paleomagnetic sampling corresponds to the ages shown in Fig. 2. (b) Swath profile across the study area, showing tilting of the island to the SW, consistently with the flexural bulge (see Fig. 1b). (c) Geological cross-section of the study area (after Chardon and Chevillotte (2006) and Pirard et al. (2013)). PB: Port-Boisé.

the streams. These surfaces were correlated into different generations of lateritic paleo-landsurfaces based on their regional elevation ranges, their shape (e.g., concave up) and the characteristics of their duricrust (thickness, hardness, composition, content) (Figs. 5 and 6). Importantly, correlations between surfaces were made by considering the local diminution of the elevation of the surfaces. The distinction between one surface and another was made by identifying topographic steps into DEM, which could be locally verified on the field. Observations of the reworking of duricrust elements were further substantial evidence of the transition from a surface generation to the next one (Fig. 4f).

3.2. Topographic and topologic analysis

For topographic analyses, we used a DEM acquired in 2016 with a 10 m horizontal resolution and an average error on elevation of 2.16 m (https://georep-dtsi-sgt.opendata.arcgis.com/documents/356e41a416664d2d9ecca13067c847c2/about). The Topographic Analysis Toolbox (TAK; Forte and Whipple, 2019, based on the TopoToolbox Matlab

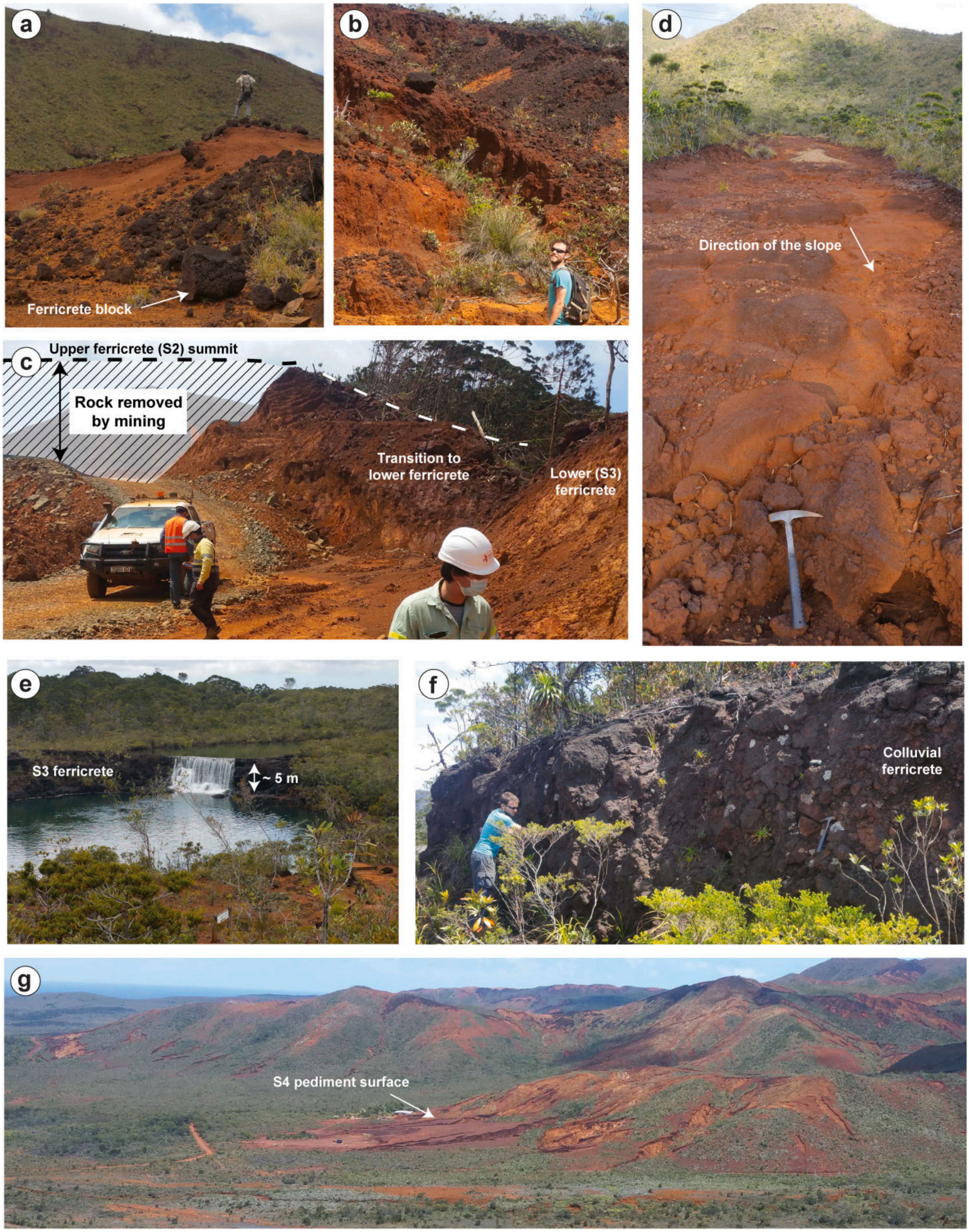

Fig. 4. Photos of typical lateritic landforms and profiles. (a-b) Surfaces B to S1. (a) Relict the top of a weathering profile with some remaining blocks of dismantled ferricrete found along the NW flank of the Kaori peak (above the lake). In the background, a higher surface with similar but older remnants was found. (b) Dismantled ferricrete above the weathering profile associated with a reduced relict of the S2 surface found to the NE of the Port Boisé pass. (c) Transition from the S2 to the S3 landsurface marked by stepping into the ferricrete. Evidence of reworking was found in S2 ferricrete pebbles contained in the S3 ferricrete. (d) View on the top of the S3 surface in the Prony area. (e) La Madeleine waterfall, where the top of the S3 ferricrete is cropping out. (f) Outcrop of the thick S2 ferricrete containing colluvium from S1 ferricrete, NW of the Prony town. (g) The typical morphology of surface S4 in the Port-Boisé is characteristic of an incised, abandoned pediment. Note that this picture was taken from the S2 surface in Fig. 4b.

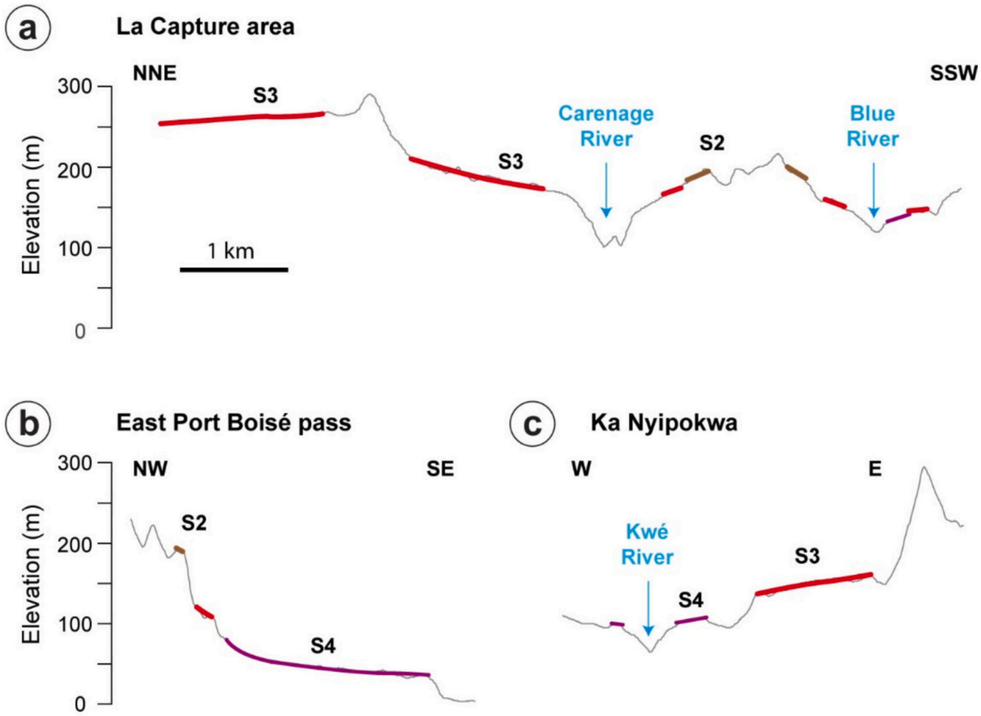

Fig. 5. Interpreted topographic cross sections across the study area (see location in Fig. 3).

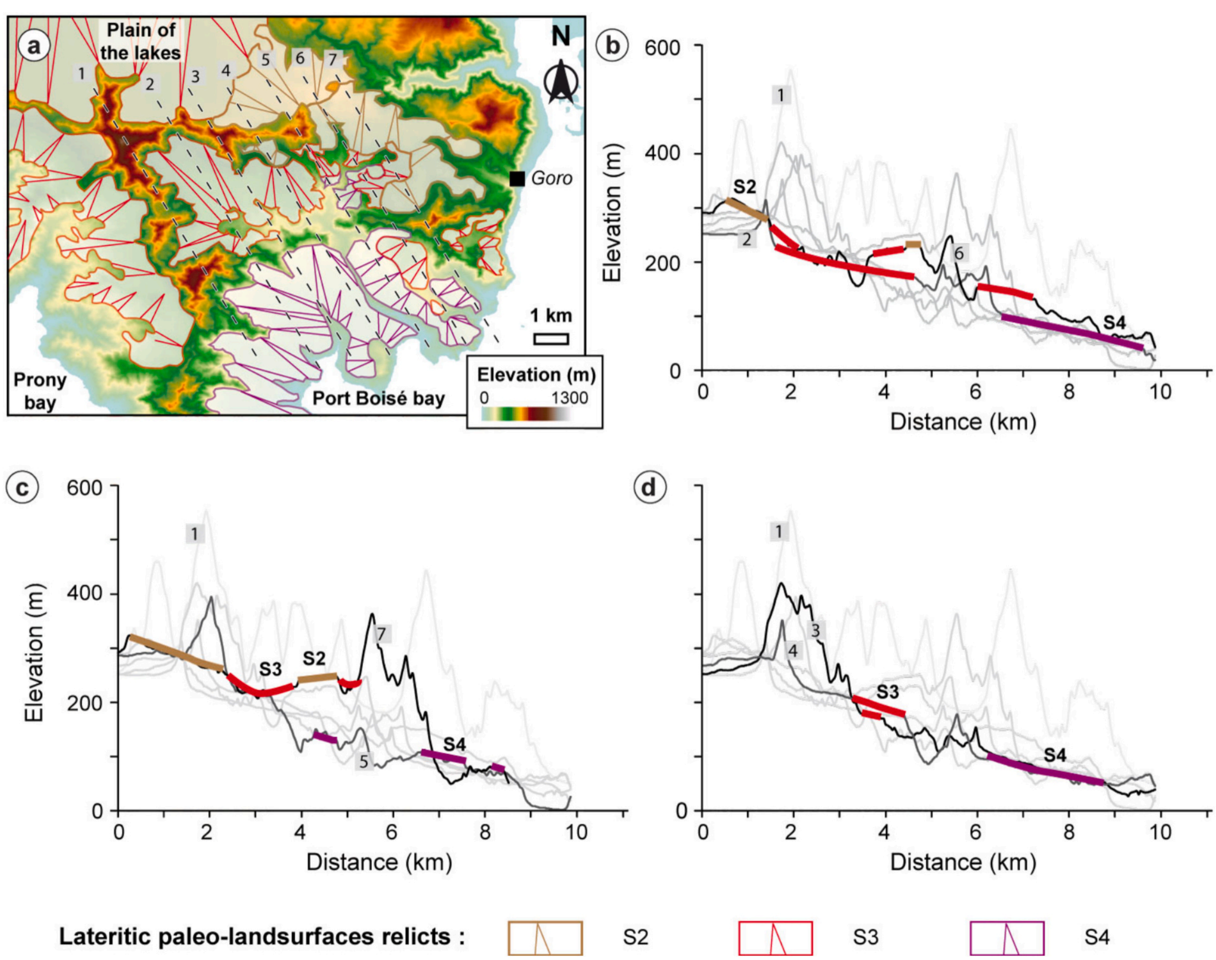

Fig. 6. Detailed geomorphic map (a) and interpreted topographic cross sections (b-d) across the Goro pit and Ka Nyipopkwa areas.

library of Schwanghart and Kuhn, 2010; Schwanghart and Scherler, 2014) was used to build the swath profiles of the study area (Fig. 3b), the river-long profile (Fig. 7) and the χ-map (Figs. 8 and Fig. 9). A threshold area of 0.001 km^2 was selected for delimiting streams.

3.2.1. Projection of the lateritic remnant's elevations along river-long profiles

To better analyze incision dynamics in different places of the Southern Massif and to further discuss drainage evolution, the elevations of the base levels of lateritic remnants were projected along modern river-long profiles, following the method of Grimaud et al. (2014). Locally, topographic profiles crossing lateritic ferricretes (i.e., ferruginized pediments) were taken orthogonally to the river. The ferricrete-bearing part of the section was isolated, and its down-dip section was projected towards the river using the following fitting formula:

$$z = z_0 + H.e^{-x/\sigma}$$

where x is the horizontal distance to the river, z is the elevation of the paleo landscape remnant, $z0$ is the minimum elevation of the fitting function, H is a constant, and σ a measure of the inverse concavity of the surface. The associated elevation error is calculated following the method of Ku (1966) using the derivative:

$$dz = dz_{DEM} + dz_0 + e^{-x/\sigma_{op}}\, dH + H_{op}\, \frac{x}{\sigma_{op}^2} e^{-x/\sigma_{op}}\, d\sigma$$

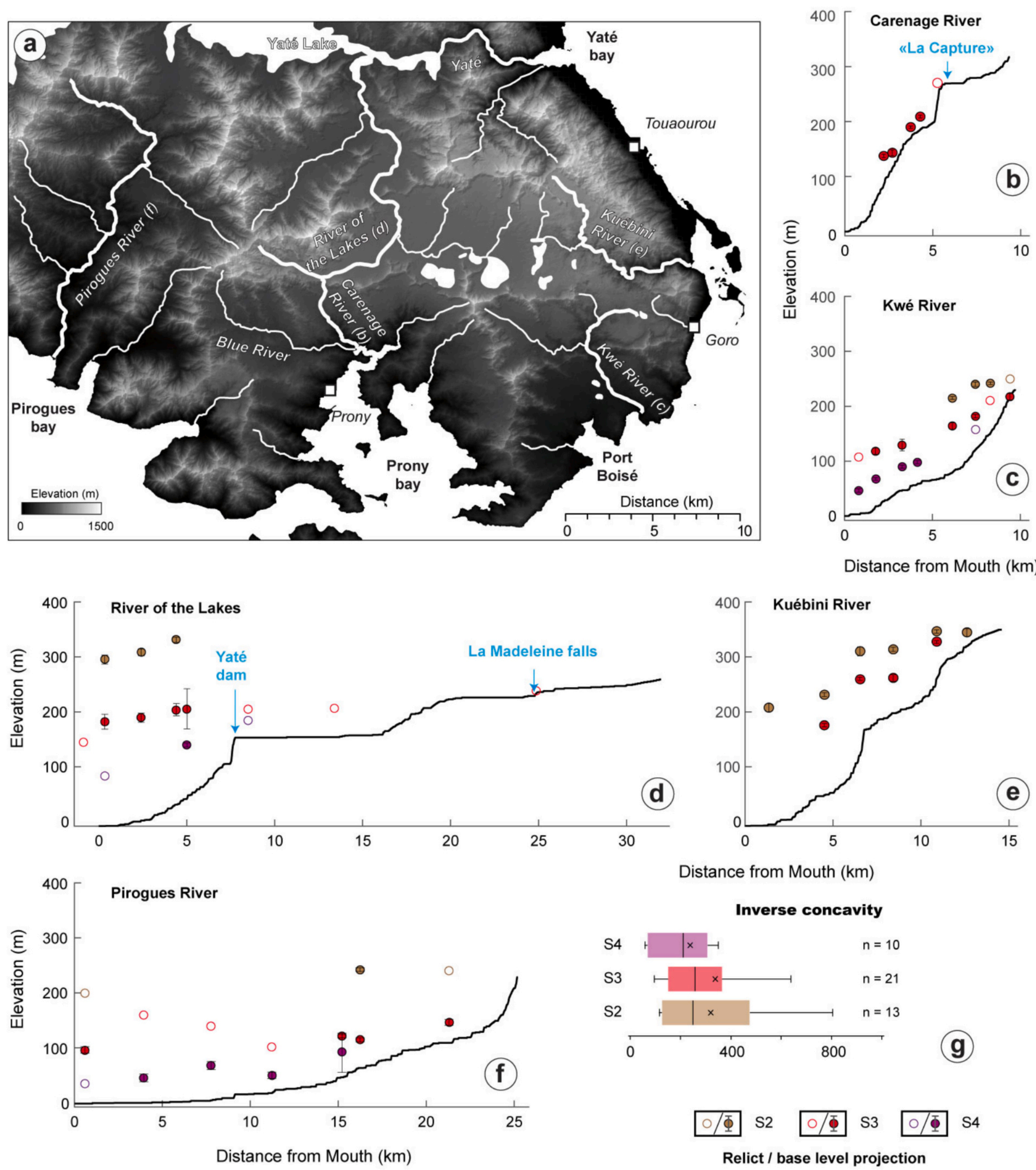

Fig. 7. River long profiles analysis. (a) Map with the location of studied rivers. (b-f) River long profiles with the projections of lateritic paleo-landsurfaces relicts/base levels for the studied rivers. (g) Distribution of the inverse concavity index σ_{op} for each lateritic landsurface.

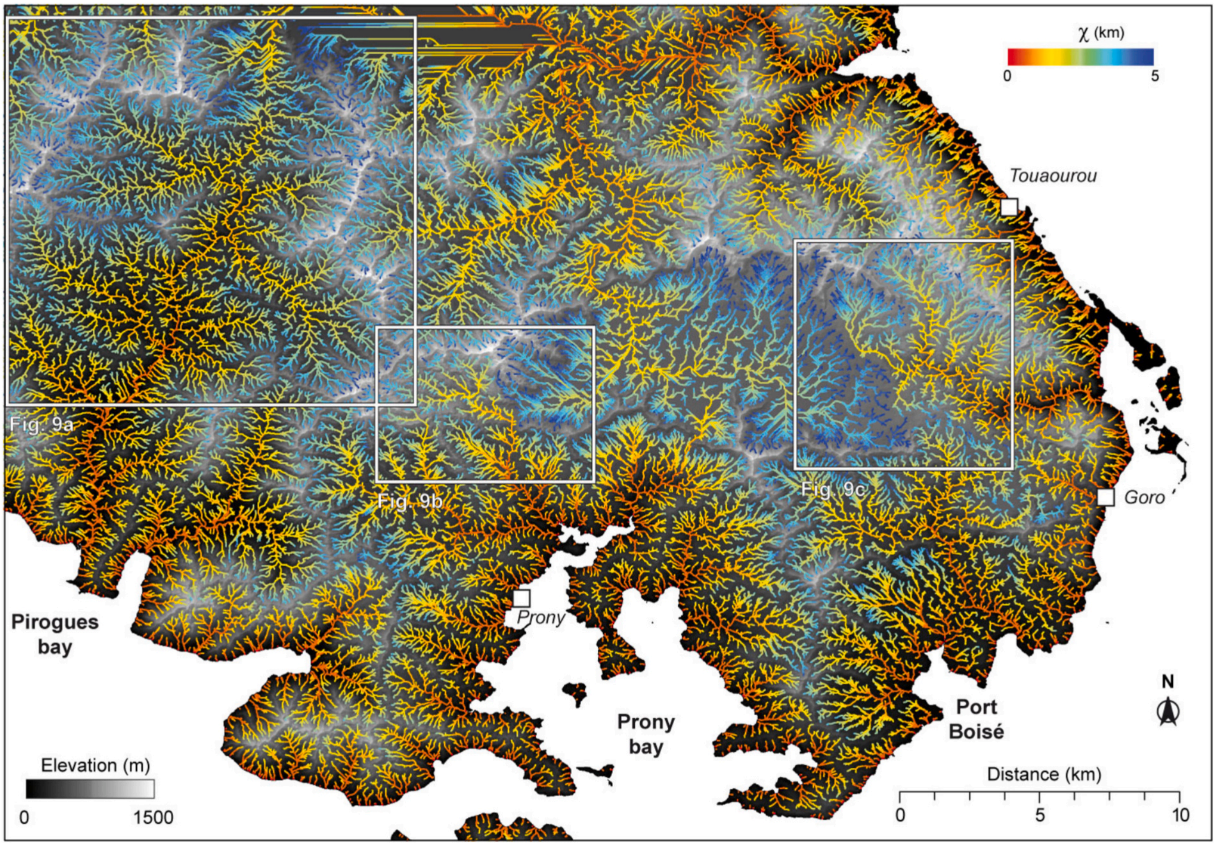

Fig. 8. Regional χ-map of SE New Caledonia.

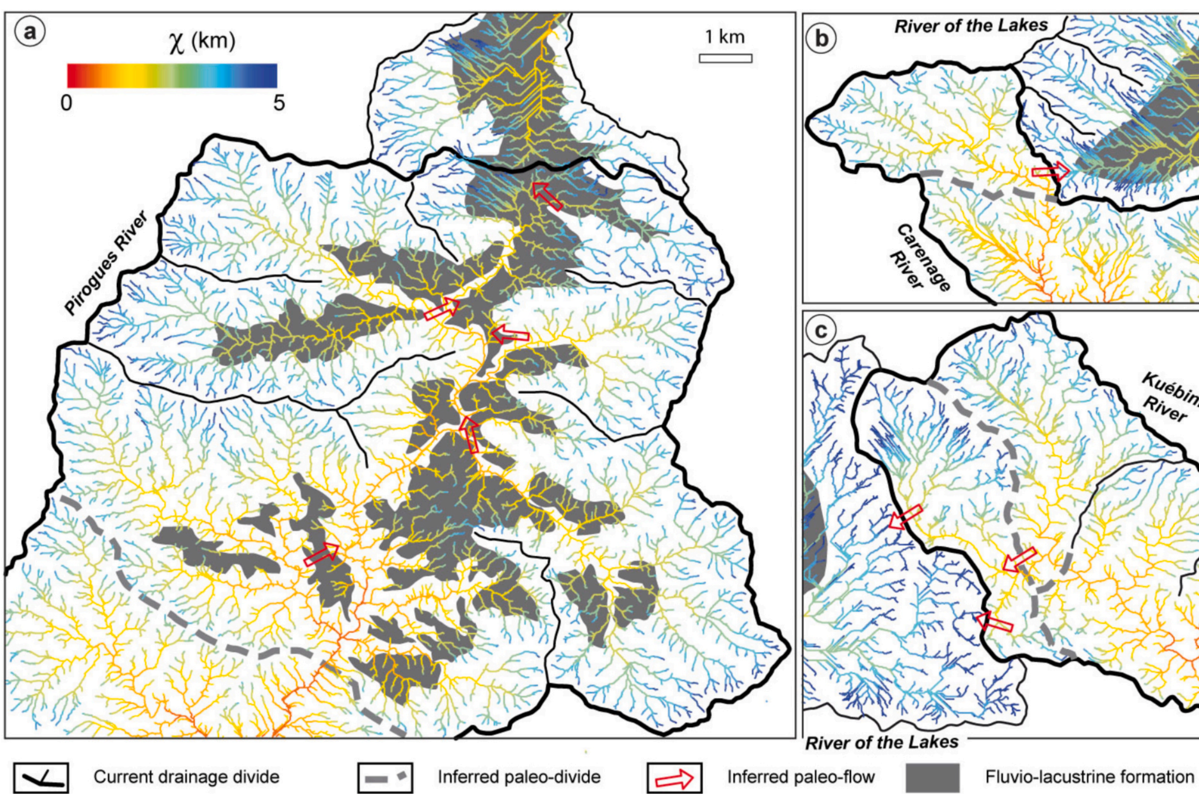

Fig. 9. Details of the drainage of SE New Caledonia showing evidence of drainage reconfiguration in the past and current disequilibrium from χ-map.

where dz_{DEM} is the DEM error (2.16 m), dz_0 is the error on the minimum elevation of the fitting function, and H_{op} and σ_{op} are the optimum values resulting from the interpolation.

The values of the estimated base level projections were replaced along modern river-long profiles together with their uncertainties (Fig. 7). Most often, these uncertainties were <5–10 m. In some cases, estimating the base level was impossible when relict surfaces were well eroded. In that case, the elevation of lateritic surface remnants <500 m away from the river was simply reported as an indirect, maximum, estimation of the base level. Finally, the values of the inverse concavities index for relict surfaces were reported (Fig. 7g). The means and averages of these values range between 200 and 400 for the S2, S3 and S4 surfaces, which is very consistent with the average of 300 reported by Grimaud et al. (2014).

3.2.2. χ-map

The χ approach originated from Perron and Royden (2013), who suggested that transforming the river long profile coordinates and linearizing them was better to analyze rivers, particularly with noisy digital elevation models. These metrics also allow for characterizing the geometry and topology of a drainage network (Willett et al., 2014). Assuming constant uplift rate U and substrate erodibility K, river elevation z as a function of distance x can be expressed as follows:

$$z(x) = z_b(x_b) + \left(\frac{U}{KA_0^m}\right)^{1/n}\chi$$

and

$$\chi = \int_{x_b}^{x} \left(\frac{A_0}{A(x)}\right)^{\frac{m}{n}} dx$$

where m and n are empirical constants, $z_b(x_b)$ is the elevation at a reference base level, A is the drainage area, and A_0 is a reference drainage area (set to unity). The χ metric is thus the integral of the inverse of drainage area calculated from x_b to x.

According to Willett et al. (2014), at equilibrium, χ must have the same value for river drainage located apart from a divide when χ is calculated from an equal base level elevation. Different values of χ suggest that the drainage network is in disequilibrium. Small values of χ mean a "deficit" of drainage area that the corresponding drains may obtain by capturing drainage area across the divide. In this study, we used simple parameters to build the χ-map (m/n ratio set to 0.5, constant U and constant K) as a metric to compare with field evidence for drainage changes. A constant K value is justified by the rather homogenous geology of the study area where bedrock lithology is often made of peridotite.

The application of χ-maps and profiles is subject to scrutiny. For instance, in settings where erosion processes can rapidly adjust to drainage change (i.e., bedrock with high erodibility), this adaptability may counteract the effects of drainage disequilibrium (Whipple et al., 2017). However, lateritic non-orogenic regions, such as New Caledonia, do not exhibit rapid responses to changes in drainage. As demonstrated in this study, the resurfacing time is on the order of at least 20 Ma (see also Grimaud et al., 2015 in West Africa). Another limitation of χ-maps is their sensitivity to unsuitable parameter choices, such as variations in the m/n ratio between drainage basins sharing divides (Gailleton et al., 2021). In such cases, the magnitude of disequilibrium may be underestimated, and in extreme scenarios, the direction of drainage divide migration can be reversed. Gailleton et al. (2021) note that these basin inversions, where aggressor and victim basins are misidentified, rarely occur when a constant m/n ratio is applied (i.e., as in the present study). Instead, only the magnitude of the χ offset is affected.

4. Results and interpretation

4.1. Distribution of lateritic paleo-landsurfaces

4.1.1. Observations

The identification of lateritic paleo-landsurfaces relicts was realized in SE New Caledonia near and within the Prony Ressources nickel mine, called "Goro pit". The area was investigated directly on the field: mainly in the flat, low-lying areas (Plain of the lakes, Prony area and Port-Boisé areas) and locally on some of the summits (e.g., Kaori peak, La Capture, Point de Vue du champ de bataille) (Fig. 3).

At the highest locations of the study (i.e., Port-Boisé pass or Kaori peak; Fig. 3), the oldest surface relicts may be found (Fig. 4a and b). These surfaces are very eroded and thus not well preserved. Along the flank of the Kaori peak, remnants of lateritic surfaces are found in the form of weathering profiles with blocs of dismantled ferricrete (Fig. 4a). There, two levels can be identified between 350 and 450 m.

In the Plain of the lakes area, a major lateritic landsurface is locally overlain by deposits from the Fluvio-lacustrine formation (Chardon and Chevillotte, 2006). The ferricrete capping the surface is massive, as shown at the Madelaine waterfall where its top 5 m portion is cropping out. This surface is also found in the La Capture area, incised by a steep stream. In the Prony Bay area, relics of lateritic paleo landforms are found at different elevations. Near the streams, ferricretes are observed (Figs. 4 and 5). Locally, these ferricretes may be slightly incised, as illustrated by an erosion surface that is itself capped by a second type of ferricrete along the Blue River (Fig. 5a). In the Goro pit, despite the intense mining and the removal of the weathering profiles, the morphology of the site could be deciphered using the DEM of 2016 combined with observations along the Southern edge of the pit. There, it was possible to observe the transition between two stepped surfaces in a limited elevation range (ca. 250 m). At this transition, there is a continuity between the upper and the lower ferricretes capping the paleosurfaces (Fig. 4c). Blocks from the upper ferricrete are found recemented in the lower one, indicating subsequent episodes of erosion and weathering.

In the Port-Boisé area, the dominant lateritic paleo-landform is capped by a ferricrete that is thinner (ca. 2–4 m) than the one found in the Prony and Plain of the lakes' areas. It is furthermore located at a lower elevation (< 100 m) (Fig. 5b). This surface is a pediment, i.e., a low-slope and concave-up surface formed by erosion of the surrounding reliefs and transport of the resulting colluvium. Field observations indicate that this surface has been incised, as attested by rills cutting across the ferricrete (Fig. 4g). A similar surface is observed in the Lower Pirogue River. Near the Port-Boisé pass (Figs. 4b and 5b), the remnants of two stepped lateritic relict surfaces dominating the pediment surface are found at about 200 m and 100 m. To the East, in the so-called Ka Nyipopkwa area (Fig. 3), another elevated and well-preserved relict surface capped by thick ferricretes (ca. 5 m) is found (Fig. 5c). There, two stepped surfaces may be identified. The upper one is found at 150–200 m (in continuity with the lower surface found in the Goro pit), while the lower one is found at 150 m and connects laterally to the pediment surface observed to the East of the Port-Boisé pass (Fig. 5b and c).

4.1.2. Interpretation

Based on previously published work (Trescases, 1975; Chevillotte, 2005; Sevin et al., 2012), the lowest elevated surface in the North Prony area can be attributed to the S4 and S5 surfaces defined by Chevillotte et al. (2006). The dominant surface in the area found in a 100–220 m elevation range corresponds to the S3 surface. It is the same S3 surface found in the Plain of the Lakes area, particularly at the Madeleine waterfall (Fig. 5).

By comparison with the neighboring Prony Bay area, some correlations can be made between the Port-Boisé area and the Lower Pirogue River area. The pediment surface below 100 m can thus be attributed to the S4 surface. The S3 surface is in a 120–160 m elevation range (i.e., near the Port-Boisé pass) and up to 180 m in the upstream Ka Nyipopkwa area. There (Fig. 5c), we attribute the two stepped surfaces to two different generations (i.e., S3 and S4), while others (i.e., Sevin et al., 2020) hypothesized that they could be the same surface offset by a fault, which would be found at the topographic transition between the two surfaces. We choose to discard this possibility based on the following: (i) no evidence exists of the prolongation of this fault towards the North and the Goro area, (ii) the lower surface can be well correlated with the S4 pediment surface near the Port-Boisé pass, and (iii) the upper surface is in an elevation range consistent with that of the S3 surface in the Prony area and near the Port-Boisé pass.

A series of NW-SE evenly spaced topographic profiles allow us to visualize these correlations in the Goro pit area (Fig. 6). The S3 surface in the Ka Nyipopkwa area correlates well with the lower surface in the Goro pit. Consequently, the upper surface in the Goro pit can thus be attributed to S2. The profiles show that the S3 and S4 surfaces are dipping to the SE towards the sea. Interestingly, a surface with a similar southeastward dipping may be found in a 450–250 m elevation range. It corresponds to the top of the hills that compose the divides between watersheds in the area (Figs. 3 and 6). It may thus be correlated to the surface observed along the flank of the Kaori peak. Their attribution to a given stage of the sequence defined by Chevillotte et al. (2006) is more speculative. It is hypothesized that they belong to surface S1 or even older (A, B or C surface of Chevillotte et al. (2006)).

4.2. River incision

The projection of the base level of lateritic paleo-landsurfaces along river-long profiles allowed measuring incisions since the abandonment of the S2 and S3 surfaces (Fig. 7). One should note that base levels are derived from the current elevation of paleosurface remnants. Given that the topography of the Southern massif has likely evolved since the formations of these profiles (i.e., due to heterogeneous uplift), the reconstructed paleo-profiles have probably been distorted (Grimaud et al., 2014).

4.2.1. Observations

Incision heights since S3 are 150–200 m along the Lower portion of the River of the Lakes and decrease upstream (<100 m when entering the Yaté Lake and <10 m at La Madeleine fall). A similar trend with slightly lower incision heights can be found along the Kuébini River (i.e., 100–150 m since S3 along the coast and decreasing when going upstream). A knickpoint visible along the modern river profile can also be identified in the S2 and S3 profiles. This indicates stability, i.e., no upstream propagation, of this knickpoint. Incision heights are even lower (50–100 m since S3) along the Pirogues and Kwé Rivers. Finally, the lowest incision height since S3 is found along the Carenage River (<20 m).

4.2.2. Interpretation

Rivers exhibit contrasting dynamics, which can be attributed to drainage reorganization and variations in uplift rates. Along the Pirogues River, a bump is observed for the S3 remnants, suggesting a drainage reorganization after the S3 stage. Overall, incision rates are higher along rivers flowing to the NE compared to rivers flowing to the SW (Fig. 7). This may be interpreted as the result of the uplift rate increasing to the north.

4.3. Evidence for drainage rearrangements

4.3.1. Description

Field observations evidence drainage reorganization in SE New Caledonia. For instance, Trescases (1969) pointed out that the Pirogue River captured a “closed-depression” filled with the Fluvio-Lacustrine Formation. This event led to the reorientation of the drainage to the South (Figs. 3 and 9a). In the Pirogues River catchment, many of the upstream basin heads have their drains flowing towards the North (Fig. 9a), supporting a Northward drainage in the past (Fig. 10). Trescases (1969) and later Sevin et al. (2020) suggested that the Southern limit of preservation of the Fluvio-Lacustrine formation marked the ancient position of a divide. The existence of this divide is further indicated by elevated S3 relicts around the 5th kilometer of the long profile of the Pirogue River (Figs. 8 and 7f). Such results support a post-S3 establishment of the current limit of the Pirogue River catchment. At present, χ values are very similar across the divide of the Pirogues River with the Yaté Lake.

Another place of drainage reorganization is the so-called “La capture” or “Col de la Laverie” (Figs. 3 and 9b). There, the Carenage River displays a 90° turn from the East towards the River of the Lakes and to the South (Fig. 11). Our field observations confirm those of Chardon and Chevillotte (2006), who showed that S3 is the dominant surface in this area. The associated S3 ferricrete is cropping at a waterfall (Fig. 4e). Water flows to the South while the ferricrete caps deposits of the Fluvio-Lacustrine Formation dipping towards the North (Chardon and Chevillotte, 2006; Folcher et al., 2015). Such configuration supposes capturing drainage area from the River of the Lakes by the Carenage River after the abandonment of the S3 surface. Currently, χ values are smaller in the Carenage River network, suggesting that the current drainage divide may continue progressing towards the North and further capture drainage heads from the River of the Lake catchment.

The χ -map also suggests drainage instability between the Kuébini River and the River of the Lakes (Figs. 8 and 9c). There, smaller χ values are found in the Kuébini drainage, supporting again that the River of the Lakes may lose drainage area in the future. Also, a close look at the upstream part of the Kuébini River long profile shows that the S2 surface is flat to inverse to the current river slope. Although the slope change is subtle, it may be another evidence of a capture of drainage from the plain of the Lakes by the Kuébini River, i.e., after the abandonment of the S2 surface this time.

In the Goro pit area (Fig. 3a and 7c), however, there is no evidence of such reorganization, and the drainage of the Kwé River seems to be exorheic since at least the S2 surface.

4.3.2. Interpretation

The combined analysis of the distribution of paleosurface relicts and χ-maps highlights three captures (Figs. 7–11). Along the Pirogues River (Fig. 10), the drainage divide shifted approximately 10 km northward. Such phenomenon is consistent with the tilting of the island to the SW, which redirected the upstream Yaté-River of the Lakes catchment towards the SE. The other two captures involved more limited divide migration (maximum 5 km) but similarly resulted in a loss of drainage area by the Yaté-River of the Lakes catchment and displacement of the divide to the NE (Fig. 11). The capture by the Kuébini catchment occurred between the S2 and S3 stages while the captures by the Carenage and Pirogues Rivers occurred after the S3 stage.

5. Discussion

This study investigates the drainage evolution of the Southern Massif in SE New Caledonia - an area typically described as dominated by basin-type sites - through lateritic regolith mapping, river long profiles analysis, and χ -maps (Fig. 9). The results indicate that the drainage network is actively, albeit very slowly, adjusting to ongoing uplift through the capture of northward drainage by southward drainages. This suggests that the drainage has been exorheic for at least 13 Ma, i.e., prior to the development of significant weathering surfaces associated with oxide-type nickel ore formation.

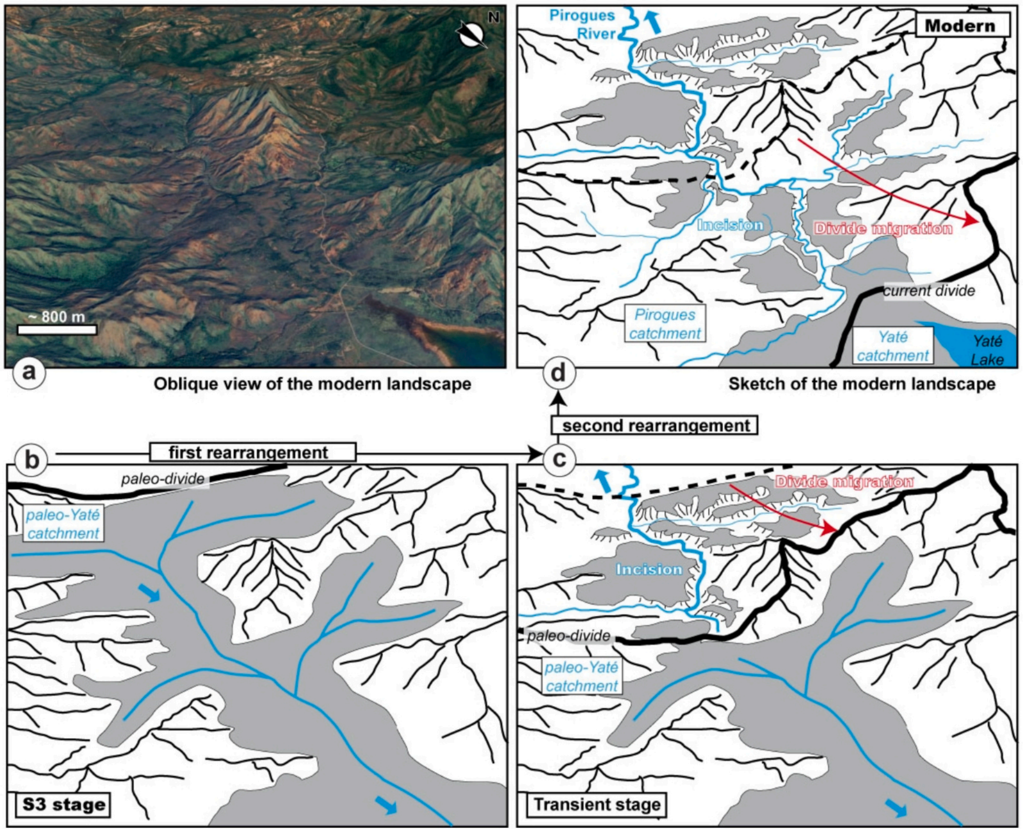

Fig. 10. Oblique view (a) of the Pirogues River catchment, where a capture is identified (image: 2025 Airbus and Maxar Technologies). (b-d) Interpretation.

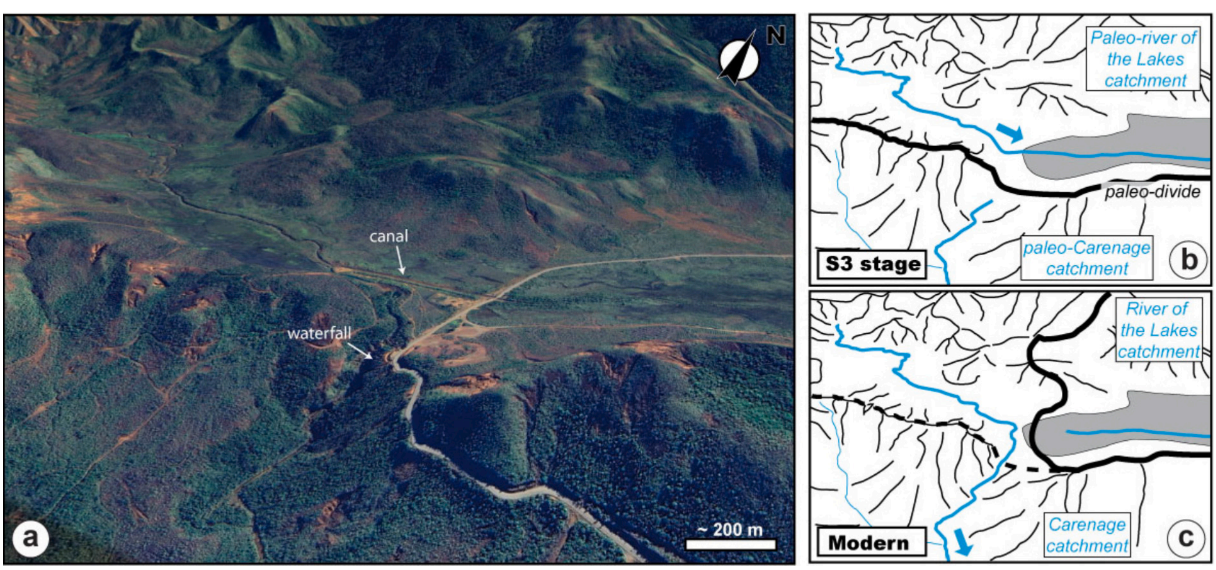

Fig. 11. Oblique view (a) of the Carenage River catchment, where a capture is identified (image: 2025 Airbus). (b-c) Interpretation.

5.1. Uplift pattern in the Southern Massif deduced from the geomorphic evolution

In New Caledonia, differential uplift and tilting of the Grande Terre Island has been suggested by many authors (e.g., Davis, 1925; Cluzel et al., 2012). Such evolution is thought to have occurred since the Miocene, triggered by a regional tectonic change, as shown by the differential preservation of lateritic paleo-landsurfaces between the North and the South of the island. These results further agree with extensive faulting and the development of the offshore New Caledonia basin to the South of Grande Terre (Chardon and Chevillotte, 2006). Considering the differential uplift of abandoned reefs (Cabioch et al., 1999), particularly in the Yaté area (Figs. 1 and 3), it can be deduced that such differential uplift is still active and extends to the island to the North of Grande Terre in response to flexure of the NE of the Australian plate related to the active subduction (Dubois et al., 1977).

The present geomorphic analysis is in line with these findings. First, the position of the major lakes to the South of the Plain of the Lakes supports that uplift is more pronounced to the North (Fig. 3) and has shifted water accumulation to the South. Second, incisions reported to the North (i.e., 100 to 200 m along the downstream Yaté and Kuébini rivers) are greater than those to the South (i.e., <100 m to <20 m along the Kwé, Pirogue and Carenage rivers) (Fig. 8), supporting more important uplift along the northern coast.

Similarly, the migration of the drainage divides of the Pirogue River to the North, attested by the remnants of the Fluvio-lacustrine formation (Trescases, 1969), supports the reorientation of drainage heads towards the South in response to a southward tilt of the Grande Terre (Fig. 10). The reconstruction of the Pirogue River long profile associated with the S3 surface (Fig. 7d), which overlays the Fluvio Lacustrine formation, suggests that the location of the divide was about 5 km North of the current river outlet (Fig. 10). In its current geometry, the S3 northern river long profile is tilted towards the South, and the paleo-divide corresponds to a high along this profile. Only by correcting for the tilting can the northern profile be oriented towards the North and the Yaté Lake, further supporting the existence of a southward tilting. The beheading of the upstream drainage of the River of the Lakes by the Carenage River is also consistent with this southward tilting and the reorientation of parts of the drainage to the South (Figs. 9b and 11).

The capture of the head of the River of the Lakes drainage by the Kuébini River differs from those mentioned above. First, this capture occurred earlier (i.e., between the S2 and S3 surfaces) than the ones caused by the Pirogue and Carenage rivers (i.e., after the S3 surface). Second, it reorientated the drainage to the West rather than the South. It can thus be interpreted as an early capture caused by the rapid incision of the Kuébini River in response to the initiation of the tilting of the Grande Terre to the South.

5.2. Evolution of drainage networks

Following the tectonic and morphoclimatic evolutions of the Grande Terre, paleo-captures and rearrangement of the drainage can be tracked, as shown in the previous section. Drainage reconstitutions support that a larger Yaté-River of the Lakes drainage system originally existed during stage S2 and the deposition of the Fluvio-lacustrine formation (Fig. 12a). Thus, the shallow Fluvio-lacustrine deposits must not be interpreted as the markers of an endorheic stage. In its modern configuration, the River of the Lakes drainage is exorheic, and alluvial and lacustrine deposition occurs. It was likely not different during stage S2. At that time, the divide that separated northward from southward drainages was positioned further south compared to its present location. The subsequent drainage capture and diversion resulted in the northward migration of this divide and the shrinking of the River of the Lakes watershed (Fig. 12b).

Establishing a chronology for the morphoclimatic sequence has proven challenging, although much progress has been made in the last two decades (Fig. 2). In their early model, Chevillotte et al. (2006) proposed that the morphoclimatic sequence started 34 Myrs ago with

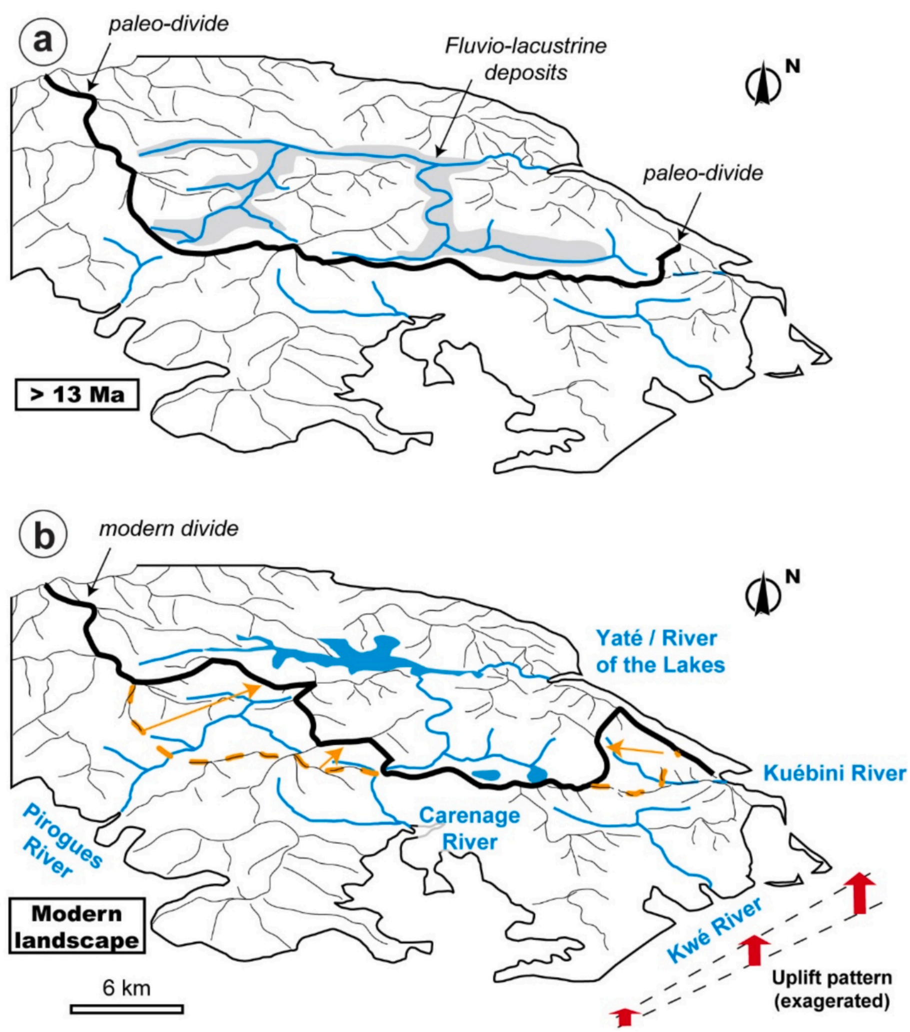

Fig. 12. Synthetic 3D sketch of the evolution of Southern New Caledonia showing the migration of the main drainage divide to the NE in response to flexural uplift increasing northward.

the A, B C, S1 and S2 surfaces all occurring between 34 and 29 Ma on the basis that they occurred before the Gwa N'Doro Formation, which is loosely dated as Oligocene (Chevillotte, 2005; Folcher et al., 2015). They further suggested that the S3 surfaces occurred 24 Ma ago, i.e., before the deposition of the Népoui formation based on geomorphic mapping near the Népoui peninsula. According to Chevillotte et al. (2006), the S4 and S5 surfaces would have developed from 16 Ma until now. Later, Sevin et al. (2012, 2020) obtained a consistent age of ca. 25 Ma based on several samples dated using paleomagnetism on the Tiébaghi plateau, where remnants of S1 and S2 could be found. These data support an age younger than initially thought by Chevillotte et al. (2006) for the S1-S2 surfaces. In the Southern Massif, paleomagnetic ages show a continuum from 25 Ma to the present for the lower surfaces near the Goro pit (Sevin et al., 2020). Finally, unpublished ages on manganese oxides based on the work of Pierre Maurizot, Florence Quesnel, Johan Yans et Gilles Ruffet (and reported in Bailly et al. (2014) and Sevin et al. (2020)) range from 22 to 13 Ma in the St Louis granitic massif, in the vicinity of where remnants of the S1/C, S2 and S3 surfaces can be found (Chevillotte, 2005). A minimum age of 22 Ma for the S1 surface and 13 Ma for the S3 surface could therefore be proposed. Unfortunately, lateritic remnants are poorly preserved on these granitic terranes, complexifying any interpretation of their geomorphic evolution.

Therefore, the exact chronology of the geomorphic evolution of New Caledonia remains to be further constrained. New dating of iron oxides associated with the Fluvio Lacustrine Formation could help (Mathian et al., 2024). Above all, the most suited approach involves systematic geomorphic mapping coupled with lateritic remnants dating. Based on the minimum and maximum ages proposed by the authors mentioned above, a broad range from 25 to 13 Ma can be suggested for the S3 surface. The S2 surface would be older, i.e., supposedly older than 20 Ma. Thus, the captures shown in the present study are several million years old. The fact that the drainage and incision evolved slowly in this area is not surprising as it explains the excellent preservation of lateritic profiles.

The χ-map (Figs. 8 and 9) further indicates that the Carenage and Kuébini River drainages are still in disequilibrium, demonstrating that the Southern Massif of New Caledonia drainage network is actively -albeit very slowly- adjusting. This evolution aligns with the northward migration of the main divide, towards the region of maximum uplift (Willett et al., 2001). Although the χ-map in the Pirogue River suggests (Fig. 9a) that the drainage has reached a stable configuration, one should keep in mind that a constant uplift rate was used to build this χ-map. In the future when the data is available, using a map that considers the increasing uplift rate to the North should improve the estimation of drainage (dis-)equilibrium. Under constant tectonic forcing, drainage rearrangement will continue in the future, likely leading to further contraction of the River of the Lakes catchment.

5.3. Implications for mineral resources

Along the Kwé River and as shown by the river long profile (Fig. 7c), the drainage has been exorheic since the S3 surface, which is the dominant surface of the Ni deposit of the Goro pit (Fig. 6). Thus, there is no evidence of an internal drainage there before at least 13 Ma. The Goro pit area may have been endorheic during or before the S2 surface, but there is limited evidence to demonstrate it. The existence of an externally drained basin since the S3 surface in the area questions the model of Trescases (1969, 1975) who suggested that the thick weathering profiles of basin-type deposits are due to aggradation during an initial endoreic stage. Indeed, our results support that an essential part of the morphology of these deposits is acquired during an exorheic stage.

Using the measured incision heights since S3, together with the two limiting ages of 25 and 13 Ma for the S3 surface, incision rates can be estimated from about 1 to 15 m.Myr^{-1} in the Southern Massif (Figs. 7 and 10). These incision rates can be tentatively compared with recent Quaternary estimates of uplift rates. Based on the 6 m elevation of uplifted reefs abandoned since about 125 kyr (Cabioch et al., 1999), an uplift rate of about 50 m.Myr^{-1} can be inferred for the northern part of the study area, where uplift rate is maximal. This value is of the same order as the incision rates observed along the lower reach of the River of the Lakes, albeit three times higher. The discrepancy between these estimates is reasonable given the uncertainties associated with both calculations. Furthermore, as previously noted, the low incision rates are consistent with the preservation of lateritic paleolandscapes in the study area.

Incision rates are particularly low along the upstream Kwé River -where the basin-type nickel ore of Goro is located- during the S2 to S4 surface stages. In other areas of New Caledonia such as Koniambo or Opoué, considered as plateau and slope deposits, respectively, 300–400 m of incision has been reported since the abandonment of the S3 surface (Fig. 13). This implies higher incision rates (i.e., range of about 15–30 m.Myr^{-1}). In Koniambo and Opoué, supergene deposits are dominated by Mg-rich hydrous silicate-ore type with a very shallow oxide type, lateritic profile compared to the Southern Massif, as confirmed by field observations. In Koniambo, Quesnel et al. (2017) demonstrated that part of the Ni ore was enriched by lateral transfer from an upper (S1) to a lower surface (S2), similarly to Goro (with S2 and S3 surface; see Fig. 13). Hence, our results highlight significant similarities among so-called basin, slope and plateau Ni-ore deposits. The primary distinction lies in the intensity of incision following the early stages of Ni enrichment, which can influence subsequent Ni transfer and/or degradation of the upper lateritic profile.

The low incision rate near Goro can probably explain why the palaeomagnetic ages range from 25 Ma to the present there (Fig. 2). Weathering profiles with limited incision can be reactivated at each stage, leaving a polygenetic imprint on soils. This can result in the partial to total recrystallisation of iron oxides formed during previous weathering stages and, consequently, in the spreading of recorded ages. On the contrary, in the Tiébaghi plateau (i.e., similar to Koniambo in Fig. 13), higher incision rates after ca. 25 Ma likely prevented polygenesis and age overprinting. We suggest that the low incision rate of the Southern Massif may also be responsible for the thick Ni deposits in the Goro pit and weathering reactivation, leading to a thicker weathering profile. Such a hypothesis would have to be carefully verified on the field. It is, however, very consistent with the syntheses of Cathelineau et al. (2017, 2023, 2024), who showed that the same ore deposit successions can be found across New Caledonia -including Goro- and that the differences in observed deposit geometries depend on local incision rates.

6. Conclusions

This study reconstructed Neogene geomorphic evolution stages of the Southern Massif of New Caledonia by combining DEM analysis with field mapping of abandoned lateritic remnants. Results show that the drainage has been mostly exorheic, and that stream capture and piracy have slowly modified the landscape over the past 20 million years. The river long profiles are still adjusting to ongoing uplift, as demonstrated by southward island tilting and the uplift of quaternary reefs to the North of the study area. Ranges of drainage area changes and river incisions are assessed. Neogene incision rates are very low in the vicinity of the Goro pit (i.e., 1–15 m.Myr^{-1}), the classic basin-type Nickel deposit of New Caledonia, compared to other places (i.e., up to 15–30 m.Myr^{-1}). Such low incision rates can explain the spreading of paleomagnetic ages between 25 Ma and present and the singularly high thickness of the weathering profile in the area.

CRediT authorship contribution statement

Jean-Louis Grimaud: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Yoram**

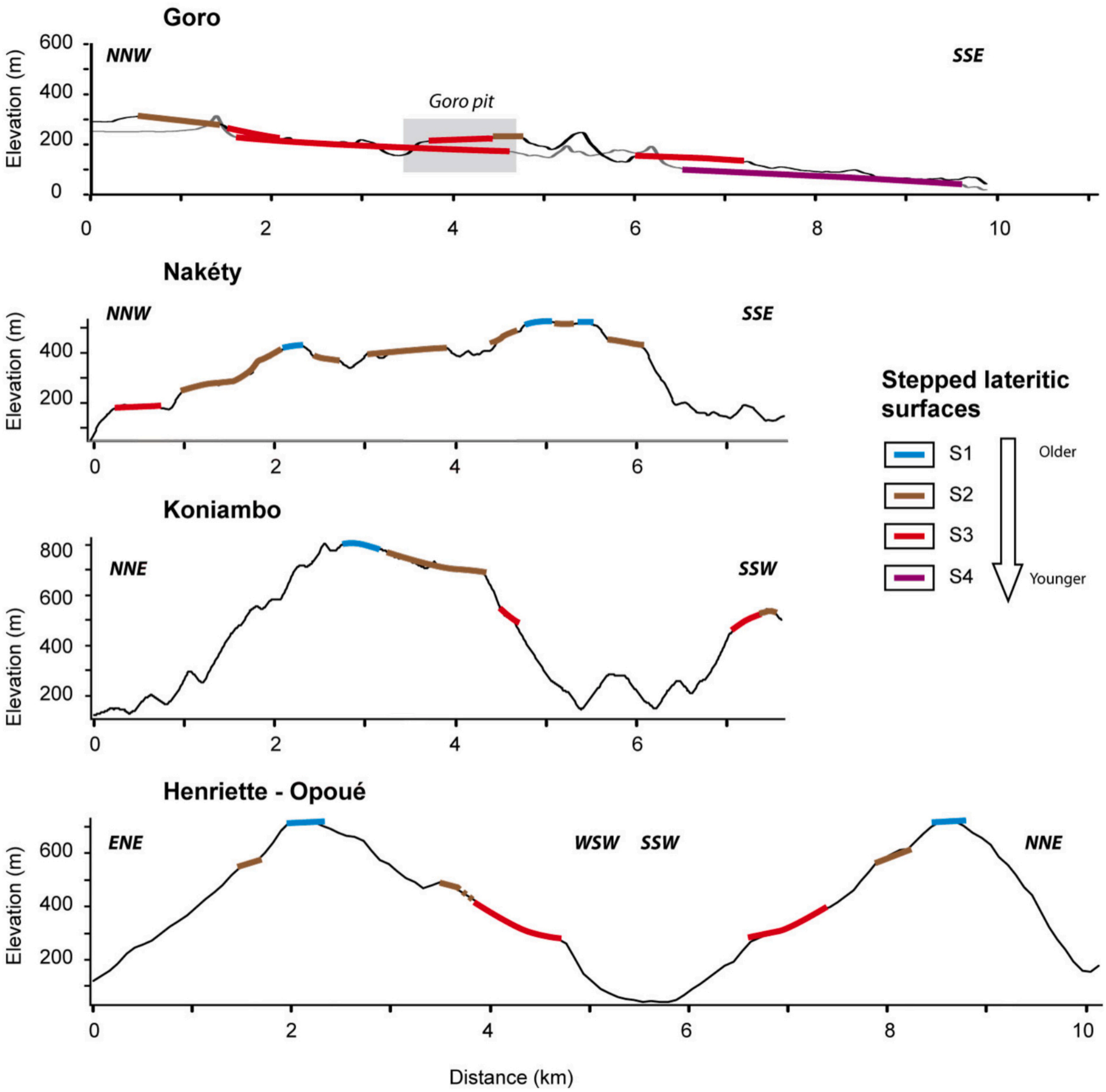

Fig. 13. Comparison of the Goro area with other locations in New Caledonia (after Cathelineau et al., 2024).

Teitler: Writing – review & editing, Investigation. **Sylvain Favier:** Writing – review & editing, Formal analysis. **Yaël Guyomard:** Writing – review & editing, Visualization, Validation, Investigation. **Fabrice Golfier:** Writing – review & editing, Validation, Funding acquisition. **Michel Cathelineau:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jean-Louis Grimaud reports financial support was provided by CNRT. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

Allard, T., Gautheron, C., Riffel, S.B., Balan, E., Soares, B.F., Pinna-Jamme, R., Derycke, A., Morin, G., Bueno, G.T., Do Nascimento, N., 2018. Combined dating of goethites and kaolinites from ferruginous duricrusts. Deciphering the Late Neogene erosion history of Central Amazonia. Chem. Geol. 479, 136–150.

Bailly, L., Ambrosi, J.-P., Barbarand, J., Beauvais, A., Cluzel, D., Lerouge, C., Prognon, F., Quesnel, F., Ramanaïdou, E., Ricordel-Prognon, C., 2014. Nickal-Typologie des minerais latéritiques de Nouvelle-Calédonie et facteurs de concentration de Co et Ni. Rapport scientifique final. Les gisements de nickel latéritique de Nouvelle-Calédonie, volume II.

Barreto, S.B., Knowles, L.L., Mascarenhas, R., Affonso, P.R.A. de M., Batalha-Filho, H., 2022. Drainage rearrangements and in situ diversification of an endemic freshwater fish genus from north-eastern Brazilian rivers. Freshw. Biol. 67, 759–773. https://doi.org/10.1111/fwb.13879.

Beauvais, A., Chardon, D., 2013. Modes, tempo, and spatial variability of Cenozoic cratonic denudation: the West African example. Geochem. Geophys. Geosyst. 14, 1590–1608. https://doi.org/10.1002/ggge.20093.

Beauvais, A., Ruffet, G., Hénocque, O., Colin, F., 2008. Chemical and physical erosion rhythms of the West African Cenozoic morphogenesis: the 39Ar-40Ar dating of supergene K-Mn oxides. J. Geophys. Res.: Earth Surf. 113 (F4).

Beauvais, A., Bonnet, N.J., Chardon, D., Arnaud, N., Jayananda, M., 2016. Very long-term stability of passive margin escarpment constrained by 40Ar/39Ar dating of K-Mn oxides. Geology 44, 299–302.

Berger, V.I., Singer, D.A., Bliss, J.D., Moring, B.C., 2011. Ni-Co laterite deposits of the world: database and grade and tonnage models (No. Reston, VA, USA). US Department of the Interior, US Geological Survey.

Bishop, P., 1986. Horizontal stability of the Australian continental drainage divide in south Central New South Wales during the Cainozoic. Aust. J. Earth Sci. 33, 295–307. https://doi.org/10.1080/08120098608729367.

Bishop, P., 1995. Drainage rearrangement by river capture, beheading and diversion. Prog. Phys. Geogr. 19 (4), 449–473.

Bonnet, S., 2009. Shrinking and splitting of drainage basins in orogenic landscapes from the migration of the main drainage divide. Nat. Geosci. 2, 766–771. https://doi.org/10.1038/ngeo666.

Butt, C.R.M., Cluzel, D., 2013. Nickel Laterite Ore deposits: Weathered Serpentinites. Elements 9, 123–128. https://doi.org/10.2113/gselements.9.2.123.

Cabioch, G., Correge, T., Turpin, L., Castellaro, C., Recy, J., 1999. Development patterns of fringing and barrier reefs in New Caledonia (Southwest Pacific). Mar. Benthic Habitats Their Living. Resour. Monit. Manag. Appl. Pac. Isl. Ctries. 22, 567–578. https://doi.org/10.1016/S0399-1784(00)88948-3.

Cathelineau, M., Quesnel, B., Gautier, P., Boulvais, P., Couteau, C., Drouillet, M., 2016. Nickel dispersion and enrichment at the bottom of the regolith: formation of pimelite target-like ores in rock block joints (Koniambo Ni deposit, New Caledonia). Miner. Deposita 51, 271–282. https://doi.org/10.1007/s00126-015-0607-y.

Cathelineau, M., Myagkiy, A., Quesnel, B., Boiron, M.-C., Gautier, P., Boulvais, P., Ulrich, M., Truche, L., Golfier, F., Drouillet, M., 2017. Multistage crack seal vein and hydrothermal Ni enrichment in serpentinized ultramafic rocks (Koniambo massif, New Caledonia). Miner. Deposita 52, 945–960. https://doi.org/10.1007/s00126-016-0695-3.

Cathelineau, M., Boiron, M.-C., Grimaud, J.-L., Favier, S., Teitler, Y., Golfier, F., 2023. Pseudo-Karst Silicification Related to late Ni Reworking in New Caledonia. Minerals 13. https://doi.org/10.3390/min13040518.

Cathelineau, M., Teitler, Y., Grimaud, J.-L., Favier, S., Golfier, F., Ramanaidou, E., Grangeon, S., Kerreveur, Y., Jeanpert, J., Étienne, S., 2024. Peridotite Weathering and Ni Redistribution in New Caledonian Laterite Profiles: Influence of climate, Hydrology, and Structure. Minerals 14, 1082.

Chardon, D., Chevillotte, V., 2006. Morphotectonic evolution of the New Caledonia ridge (Pacific Southwest) from post-obduction tectonosedimentary record. Tectonophysics 420, 473–491. https://doi.org/10.1016/j.tecto.2006.04.004.

Chardon, D., Grimaud, J.-L., Rouby, D., Beauvais, A., Christophoul, F., 2016. Stabilization of large drainage basins over geological time scales: Cenozoic West Africa, hot spot swell growth, and the Niger River. Geochem. Geophys. Geosystems 17, 1164–1181. https://doi.org/10.1002/2015GC006169.

Chardon, D., Grimaud, J.-L., Beauvais, A., Bamba, O., 2018. West African lateritic pediments: Landform-regolith evolution processes and mineral exploration pitfalls. Earth Sci. Rev. 179, 124–146. https://doi.org/10.1016/j.earscirev.2018.02.009.

Chevillotte, V., 2005. Morphogenèse tropicale en contexte épirogénique modéré: exemple de la Nouvelle-Calédonie (Pacifique Sud-Ouest). PhD Université de la Nouvelle-Calédonie. 166 pp.

Chevillotte, V., Chardon, D., Beauvais, A., Maurizot, P., Colin, F., 2006. Long-term tropical morphogenesis of New Caledonia (Southwest Pacific): Importance of positive epeirogeny and climate change. Geomorphology 81, 361–375. https://doi.org/10.1016/j.geomorph.2006.04.020.

Cluzel, D., Aitchison, J.C., Picard, C., 2001. Tectonic accretion and underplating of mafic terranes in the late Eocene intraoceanic fore-arc of New Caledonia (Southwest Pacific): geodynamic implications. Tectonophysics 340, 23–59. https://doi.org/10.1016/S0040-1951(01)00148-2.

Cluzel, D., Jourdan, F., Meffre, S., Maurizot, P., Lesimple, S., 2012. The metamorphic sole of New Caledonia ophiolite: 40Ar/39Ar, U-Pb, and geochemical evidence for subduction inception at a spreading ridge. Tectonics 31. https://doi.org/10.1029/2011TC003085.

Collot, J., Patriat, M., Sutherland, R., Williams, S., Cluzel, D., Seton, M., Pelletier, B., Roest, W.R., Etienne, S., Bordenave, A., Maurizot, P., 2020. Chapter 2 Geodynamics of the SW Pacific: a brief review and relations with New Caledonian geology. Geol. Soc. Lond. Mem. 51, 13–26. https://doi.org/10.1144/M51-2018-5.

Davis, W.M., 1925. Les côtes et les récifs coraliens de la Nouvelle-Calédonie. Ann. Géographie 34, 423–441.

Dubois, J., Launay, J., Recy, J., 1974. Uplift movements in New Caledonia-Loyalty Islands area and their plate tectonics interpretation. Tectonophysics 24, 133–150. https://doi.org/10.1016/0040-1951(74)90134-6.

Dubois, J., Launay, J., Récy, J., Marshall, J., 1977. New Hebrides trench: subduction rate from associated lithospheric bulge. Can. J. Earth Sci. 14 (2), 250–255.

Fan, N., Chu, Z., Jiang, L., Hassan, M.A., Lamb, M.P., Liu, X., 2018. Abrupt drainage basin reorganization following a Pleistocene river capture. Nat. Commun. 9, 3756. https://doi.org/10.1038/s41467-018-06238-6.

Folcher, N., Sevin, B., Quesnel, F., Lignier, V., Allenbach, M., Maurizot, P., Cluzel, D., 2015. Neogene terrestrial sediments: a record of the post-obduction history of New Caledonia. Aust. J. Earth Sci. 62, 479–492. https://doi.org/10.1080/08120099.2015.1049207.

Forte, A.M., Whipple, K.X., 2019. Short communication: the Topographic Analysis Kit (TAK) for TopoToolbox. Earth Surf. Dyn. 7, 87–95. https://doi.org/10.5194/esurf-7-87-2019.

Gailleton, B., Mudd, S.M., Clubb, F.J., Grieve, S.W.D., Hurst, M.D., 2021. Impact of changing Concavity Indices on Channel Steepness and divide Migration Metrics. Case Rep. Med. 126, e2020JF006060. https://doi.org/10.1029/2020JF006060.

Gautier, P., Quesnel, B., Boulvais, P., Cathelineau, M., 2016. The emplacement of the Peridotite Nappe of New Caledonia and its bearing on the tectonics of obduction. Tectonics 35, 3070–3094. https://doi.org/10.1002/2016TC004318.

Grandin, G., Thiry, M., 1983. Les grandes surfaces continentales tertiaires des régions chaudes. Succession des types d'altération. Cah ORSTOM Sér Géol 13, 3–18.

Grimaud, J.-L., Chardon, D., Beauvais, A., 2014. Very long-term incision dynamics of big rivers. Earth Planet. Sci. Lett. 405, 74–84. https://doi.org/10.1016/j.epsl.2014.08.021.

Grimaud, J.-L., Chardon, D., Metelka, V., Beauvais, A., Bamba, O., 2015. Neogene cratonic erosion fluxes and landform evolution processes from regional regolith mapping (Burkina Faso, West Africa). Geomorphology 241, 315–330. https://doi.org/10.1016/j.geomorph.2015.04.006.

Grimaud, J., Rouby, D., Chardon, D., Beauvais, A., 2018. Cenozoic sediment budget of West Africa and the Niger delta. Basin Res. 30, 169–186. https://doi.org/10.1111/bre.12248.

Guerit, L., Goren, L., Dominguez, S., Malavieille, J., Castelltort, S., 2018. Landscape 'stress' and reorganization from χ-maps: Insights from experimental drainage networks in oblique collision setting. Earth Surf. Process. Landf. 43, 3152–3163. https://doi.org/10.1002/esp.4477.

Hope, G., 2015. Extended vegetation histories from ultramafic karst depressions. Aust. J. Bot. 63, 222–233.

Jean, A., Beauvais, A., Chardon, D., Arnaud, N., Jayananda, M., Mathe, P.E., 2020. Weathering history and landscape evolution of Western Ghats (India) from 40Ar/39Ar dating of supergene K–Mn oxides. J. Geol. Soc. London 177, 523–536. https://doi.org/10.1144/jgs2019-048.

Jeanpert, J., Iseppi, M., Adler, P.M., Genthon, P., Sevin, B., Thovert, J.-F., Dewandel, B., Join, J.-L., 2019. Fracture controlled permeability of ultramafic basement aquifers. Inferences from the Koniambo massif, New Caledonia. Eng. Geol. 256, 67–83. https://doi.org/10.1016/j.enggeo.2019.05.006.

Ku, H.H., 1966. Notes on the use of propagation of error formulas. J. Res. Natl. Bur. Stand. 70.

Lagabrielle, Y., Maurizot, P., Lafoy, Y., Cabioch, G., Pelletier, B., Régnier, M., Wabete, I., Calmant, S., 2005. Post-Eocene extensional tectonics in Southern New Caledonia (SW Pacific): Insights from onshore fault analysis and offshore seismic data. Tectonophysics 403, 1–28. https://doi.org/10.1016/j.tecto.2005.02.014.

Lagabrielle, Y., Chauvet, A., Ulrich, M., Guillot, S., 2013. Passive obduction and gravity-driven emplacement of large ophiolitic sheets: the New Caledonia ophiolite (SW Pacific) as a case study? Bull. Société Géologique Fr. 184, 545–556. https://doi.org/10.2113/gssgfbull.184.6.545.

Mathian, M., Danišík, M., Cluzel, D., Pattier, F., Maurizot, P., Parmentier, J.-B., Delbes, L., Pina-Jamme, R., Foulcher, W., Baptiste, B., 2024. Post-Obduction History Of New Caledonia: New Temporal Constraints From Goethite (U-Th)/He Dating Of Duricrusts In Reworked Laterites. In: Presented at the 61st Annual Meeting of The Clay Minerals Society.

Maurizot, P., Sevin, B., Iseppi, M., Giband, T., 2019. Nickel-Bearing Laterite Deposits in Accretionary Context and the Case of New Caledonia: From the Large-Scale Structure of Earth to Our Everyday Appliances. GSA Today 29, 4–10. https://doi.org/10.1130/GSATG364A.1.

Maurizot, P., Sevin, B., Lesimple, S., Collot, J., Jeanpert, J., Bailly, L., Robineau, B., Patriat, M., Etienne, S., Monnin, C., 2020. Chapter 9 Mineral resources and prospectivity of non-ultramafic rocks of New Caledonia. Geol. Soc. Lond. Mem. 51, 215–245. https://doi.org/10.1144/M51-2016-9.

Montgomery, D.R., 2004. Geology, Geomorphology, and the restoration ecology of salmon. GSA Today 14, 4. https://doi.org/10.1130/1052-5173(2004)014<4:GGATRE>2.0.CO;2.

Mortimer, N., Gans, P.B., Palin, J.M., Herzer, R.H., Pelletier, B., Monzier, M., 2014. Eocene and Oligocene basins and ridges of the Coral Sea-New Caledonia region: Tectonic link between Melanesia, Fiji, and Zealandia. Tectonics 33, 1386–1407. https://doi.org/10.1002/2014TC003598.

Mortimer, N., Campbell, H.J., Tulloch, A.J., King, P.R., Stagpoole, V.M., Wood, R.A., Rattenbury, M.S., Sutherland, R., Adams, C.J., Collot, J., Seton, M., 2017. Zealandia: Earth's Hidden Continent. GSA Today 27, 27–35. https://doi.org/10.1130/GSATG321A.1.

Nunez, J.A., Korin, Z., Finko, V.I., Formell Cortina, F., 1967. Notas preliminares acerca del carso en peridotita, Sierra de Moa. Oriente. Rev. Geol. Cuba 1, 5–28.

Ouangrawa, M., Grandin, G., Parisot, J.-C., Delaune, M., 2000. Evolution des particules d'or en milieu lateritique soudano-sahelien; alluvions et colluvions dans l'environnement d'un gite filonien, Piela, Burkina Faso. Bull. Société Géologique Fr. 171, 397–405. https://doi.org/10.2113/171.4.397.

Paris, J.P., 1981. Géologie de la Nouvelle-Calédonie, un essai de synthèse. Mém. Bur. Rech. Géologiques Minières, 113.

Pelletier, B., Calmant, S., Pillet, R., 1998. Current tectonics of the Tonga–New Hebrides region. Earth Planet. Sci. Lett. 164, 263–276. https://doi.org/10.1016/S0012-821X(98)00212-X.

Pelletier, B., Lagabrielle, Y., Benoit, M., Cabioch, G., Calmant, S., Garel, E., Guivel, C., 2001. Newly identified segments of the Pacific–Australia plate boundary along the

North Fiji transform zone. Earth Planet. Sci. Lett. 193, 347–358. https://doi.org/10.1016/S0012-821X(01)00522-2.
Perron, J.T., Royden, L., 2013. An integral approach to bedrock river profile analysis. Earth Surf. Process. Landf. 38, 570–576. https://doi.org/10.1002/esp.3302.
Pirard, C., Hermann, J., O'Neill, H.S.C., 2013. Petrology and geochemistry of the crust–mantle boundary in a nascent arc, Massif du Sud ophiolite, New Caledonia, SW Pacific. J. Petrol. 54 (9), 1759–1792.
Quesnel, B., de Veslud, C.L.C., Boulvais, P., Gautier, P., Cathelineau, M., Drouillet, M., 2017. 3D modeling of the laterites on top of the Koniambo Massif, New Caledonia: refinement of the per descensum lateritic model for nickel mineralization. Miner. Deposita 52, 961–978.
Salama, W., Anand, R.R., Tunmer, W., Aspandiar, M., 2022. Regolith characterization and landscape evolution for geochemical exploration of the covered Yamarna Terrane, Western Australia. J. Geochem. Explor. 232, 106881. https://doi.org/10.1016/j.gexplo.2021.106881.
Schwanghart, W., Kuhn, N.J., 2010. TopoToolbox: a set of Matlab functions for topographic analysis. Environ. Model. Software 25, 770–781.
Schwanghart, W., Scherler, D., 2014. TopoToolbox 2–MATLAB-based software for topographic analysis and modeling in Earth surface sciences. Earth Surf. Dyn. 2, 1–7.
Sevin, B., Ricordel-Prognon, C., Quesnel, F., Cluzel, D., Lesimple, S., Maurizot, P., 2012. First palaeomagnetic dating of ferricrete in New Caledonia: new insight on the morphogenesis and palaeoweathering of 'Grande Terre. Terra Nova 24, 77–85. https://doi.org/10.1111/j.1365-3121.2011.01041.x.
Sevin, B., Cluzel, D., Maurizot, P., Ricordel-Prognon, C., Chaproniere, G., Folcher, N., Quesnel, F., 2014. A drastic lower Miocene regolith evolution triggered by post obduction slab break-off and uplift in New Caledonia. Tectonics 33, 1787–1801. https://doi.org/10.1002/2014TC003588.
Sevin, B., Maurizot, P., Cluzel, D., Tournadour, E., Etienne, S., Folcher, N., Jeanpert, J., Collot, J., Iseppi, M., Meffre, S., Patriat, M., 2020. Chapter 7 Post-obduction evolution of New Caledonia. Geol. Soc. Lond. Mem. 51, 147–188. https://doi.org/10.1144/M51-2018-74.
Tardy, C., Roquin, Y., 1998. Dérive des continents, paléoclimats et altérations tropicales. BRGM, 473pp.
Teitler, Y., Cathelineau, M., Ulrich, M., Ambrosi, J.P., Munoz, M., Sevin, B., 2019. Petrology and geochemistry of scandium in New Caledonian Ni-Co laterites. J. Geochem. Explor. 196, 131–155. https://doi.org/10.1016/j.gexplo.2018.10.009.
Thomas, M.F., Thorp, M.B., Teeuw, R.M., 1985. Palaeogeomorphology and the occurrence of diamondiferous placer deposits in Koidu, Sierra Leone. J. Geol. Soc. London 142, 789–802. https://doi.org/10.1144/gsjgs.142.5.0789.
Trescases, J.-J., 1969. Géochimie des altérations et des eaux de surface dans le Massif ultrabasique du Sud de la Nouvelle-Calédonie. Sci. Géologiques Bull. Mém. 22, 329–354.
Trescases, J.-J., 1975. L'évolution géochimique supergène des roches ultrabasiques en zone tropicale: formation des gisements nickélifères de Nouvelle-Calédonie. Mémoires ORSTOM, 259 pp.
Trotet, F., Kadar, M., Marini, D., 2015. Typology of the New Caledonian Ni-laterite deposits: from natural to industrial processes. In: The Society for Geology Applied to Mineral Deposits. Presented at the 13th SGA Meeting.
Vasconcelos, P.M., Brimhall, G.H., Becker, T.A., Renne, P.R., 1994. 40Ar39Ar analysis of supergene jarosite and alunite: Implications to the paleoweathering history of the western USA and West Africa. Geochim. Cosmochim. Acta 58, 401–420.
Whipple, K.X., Forte, A.M., DiBiase, R.A., Gasparini, N.M., Ouimet, W.B., 2017. Timescales of landscape response to divide migration and drainage capture: Implications for the role of divide mobility in landscape evolution. J. Geophys. Res.: Earth Surf. 122, 248–273. https://doi.org/10.1002/2016JF003973.
Willett, S.D., Slingerland, R., Hovius, N., 2001. Uplift, shortening, and steady state topography in active mountain belts. Am. J. Sci. 301, 455–485.
Willett, S.D., McCoy, S.W., Perron, J.T., Goren, L., Chen, C.-Y., 2014. Dynamic Reorganization of River Basins. Science 343, 1248765. https://doi.org/10.1126/science.1248765.
Wirthmann, A., 2000. Geomorphology of the Tropics. Springer Science&Business Media, 314pp.