Karstic structural development of the aquifers in the ophiolitic ranges of New Caledonia

H. Camus [(1)] ; D. Leveneur [(2)]; F. Bart [(3)].
1) CENOTE ; 2) MICA environnement ; 3) LE-NICKEL-SLN
camus.hubert@cenote.fr ; d.leveneur@mica-environnement.com, f.bart@eramet-sln.nc

I. Hydrogeological context of karstified peridotite in New Caledonia

Grande Terre, the main island of New Caledonia, presents the remains of an ophiolitic sheet resulting from obduction in the Late Eocene and reposing on a serpentinite overthrust in abnormal contact with the basement. The principal sheet covers the south (Massif du Sud) while on the west coast, a series of klippes lies along the West Caledonian fault zone (WCFZ – figure 1). Tectonic forces have resulted in severe fracturing of the ophiolites and marked uplift dated to 19-22 million years ago (B. Sevin, 2014), which led to the formation of the mountain belts and the general current aspect of the relief (Y. Lagabrielle, 2008). Since their immersion during the Oligocene, these ophiolites have been subjected to supergene alteration; this has given rise to nickel and cobalt deposits in volumes of global importance in lateritic profiles (B. Pelletier, 2003).

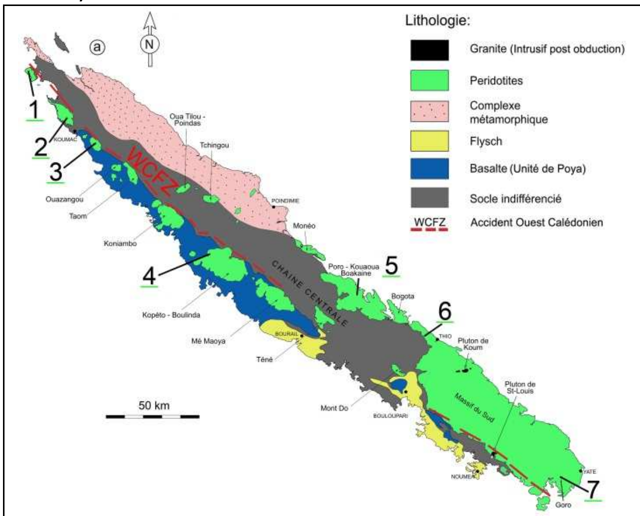

Figure 1: Geological map of New Caledonia, based on V. Chevillotte (2005)- Observed massifs:: (1) Poum,(2) Tiébaghi,(3)Kaala,(4) Kopéto,(5) Méa and Kiel, (6) Thio Plateau, (7) Plaine des Lacs.

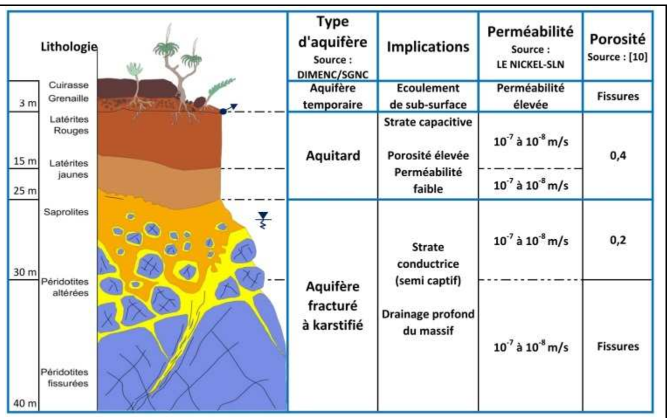

Figure 2: Alteration profile in peridotite, based on B. Pelletier (2003) and hydrogeological context (SGNC)

At the scale of the reference alteration profile, a multilayer-type aquifer occupies the alterite up to the level of the fractured bedrock (figure 2). This comprises, beneath the crust, a subsurface strata through which temporary flows occur, then an aquitard in the lateritic profile overlying conductive strata in the fractured saprolitic and peridotitic profiles which feed hillside springs and allow sub-drainage. These strata form a continuous hydraulic entity, as shown in the Tiébaghi Massif (J-L Joins, 2005).

On a larger scale, that of the massifs and the mining operations, this multilayer model is severely disrupted by vertical karstic structures which means that the hydrogeological circulation system – especially the phenomenon of concentrated infiltration into the endorheic drainage basins – remains unexplained. At this scale, the drainage systems sometimes exceed the limits of the topographical watersheds and feed a small number of outflows, which is typical of a karst aquifer: wherever karst phenomena are found to exist, they exceed the dimensions or limits of the different aquifer layers either by the size of the features and/or by extent of the drainage systems. The karstic functioning of the ophiolitic massifs also results in their characteristic topography, reminiscent of the karst landscapes of limestone areas, with the occurrence of closed depressions (dolines) with subterranean drainage some of which are very large in size (cf. the poljes of Plaine des Lacs) and confined by rocky buttes with lapiaz surfaces on the slopes: karst butte (figure 3)

Figure 3:

Photo of the Aubin doline worksite – Illustration of karst butte relief (Kopéto B2 mine).

II. CHARACTERIZATION OF KARSTIC PHENOMENA

II.1 – Resorption cell structure – Concept models.

Mining boreholes show that the hanging wall of the unaltered rock has an undulating topography, with cockpit-type depressions ("boîte à oeufs"), formed according to L. Guillou-Frottier (2014-[8])by karstogenesis beneath a lateritic overburden by means of hydrothermal convection (figure 4). This hypothesis does not explain the development of buttes, nor the resulting groundwater flow. The development of these crypto-depressions was investigated by A. Genna (2004), who defined the notion of "resorption cells" (figure 5). He argues that isovolumic "ghost rock"-type alteration processes (Quinif, 2014) give rise to an upper karst in the resorption cells and an underlying lower karst in the unaltered peridotite. He explains the resulting discontinuity and hydrosedimentary movements of material within the resorption cell and drainage from the latter through the lower karst as phenomena contemporary with ghost rock weathering by diffusion, which is contradictory.

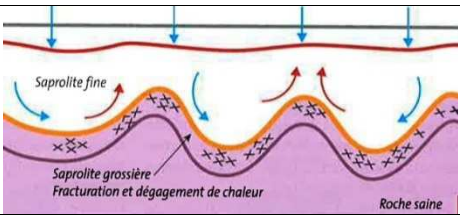

Figure 4: Hypothesis of L. Guillou-Frottier (2014) of formation of "cockpits" by hydrothermal convection in a lateritic environment; heat generated in the saprolite fosters convection and maintains a high rate of permeability.

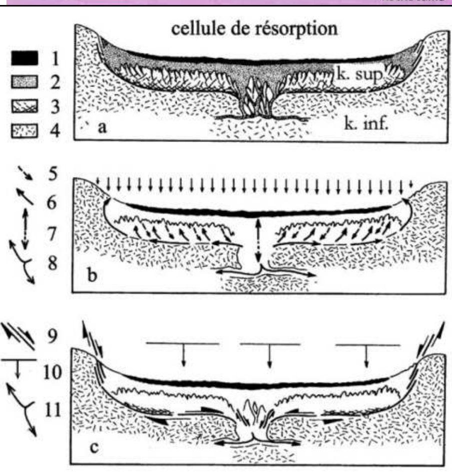

Figure 5: Model showing development of a resorption cell acc. to A. Genna, 2004.

(a) Interpretive cross-section of a resorption cell: (1) crust (2) laterite, (3) saprolite, (4) peridotite.
(b) Fluid dynamics: (5) movement per descensum, (6) movement per ascensum, (7) water table fluctuations, (8) evacuation of fluids through the lower, subterranean karst.
(c) *Material kinematics: (9) normal listric fault, (10) global resorption of the peridotite, (11) evacuation of material through the lower karst.*

II.2 – Karstification of the aquifer in three phases.

Work carried out since 2010 (MICA Environnement - CENOTE) on 7 mining sites belonging to LE NICKEL-SLN has shown that the karstification of the massifs occurs in three phases, common to all sites.

II.2.1 - Initial formation phase of a ghost-rock-type karst aquifer

Ghost-rock weathering of the bedrock spreads by diffusion from the fractures. Whether the resorption cell is more or less bowl-shaped or has an oblong gutter shape depends on how long it is confined and how long the substratum is exposed to isovolumic alteration. The longer the diffusion processes, the more isotropic the alteration kinematics, tending to the formation of a half-sphere. Over a shorter period of time, or if the alteration kinematics are controlled by a slow rate of drainage into the reservoir, the cells tend to fit to the shape of the fracture network. The size of the cells thus appears to vary by zone between the central areas of the massifs and the decreasingly confined periphery (figure 6).

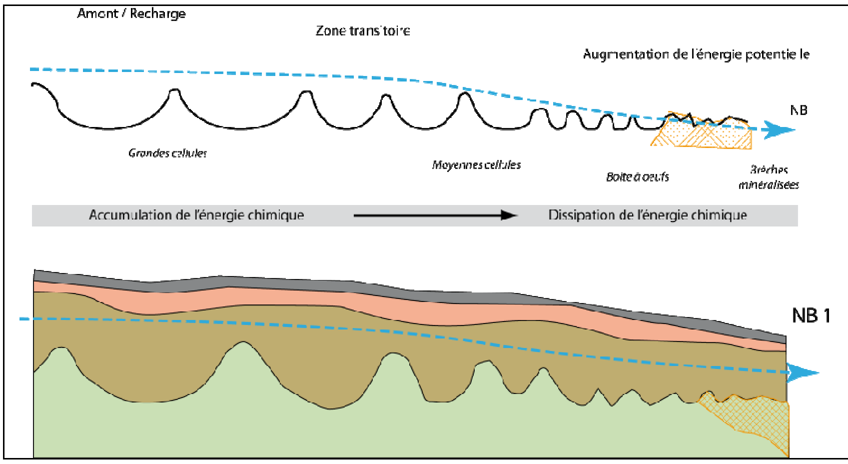

Figure 6:

Principle of zonal variations in the size of the saprolitic resorption cells

NB: base level

The boundaries and major discontinuities are marked by masses of mineralized breccia, the result of the downstream drainage of these ghost-rock-type reservoirs, the form of which is the result of long development under the effect of a close base level with a low hydraulic gradient.

II.2.2 Phase 2 - Phase 2 – Formation of a cryptokarst system

The ghost-rock reservoir is then dismantled by vertical cryptokarstic dynamics caused by tectonic uplift with simultaneous rapid lowering of the base level and lateritic alteration front; this results in a hydraulic gradient and accelerated circulation. These cryptokarstic structures, which pierce the saprolite down to the unaltered peridotite, highlight the dominant role of crypto-alteration dynamics, which result in large volumes of laterite being transported from the surface (figure 7) down to the saprolite boundary, where they join breccia corridors – a transfer area of choice – which contain cavities and feed downstream conduits.

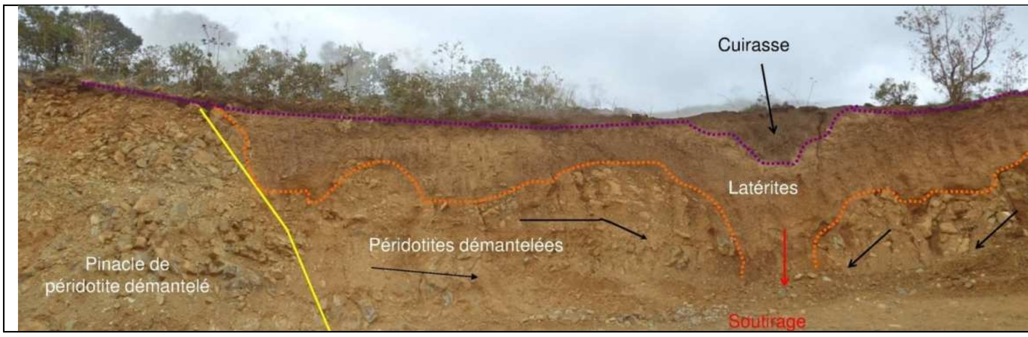

Figure 7:
Figure 7: Photo of a cryptokarstic structure – the alterite is dismantled. Chantier Pionnier sur la mine de Méa (Le Nickel-SLN)

These cryptokarstic systems evolve over a shorter time frame than ghost-rock systems. They rely on vertical flows exploiting breccia corridors (figure 8).

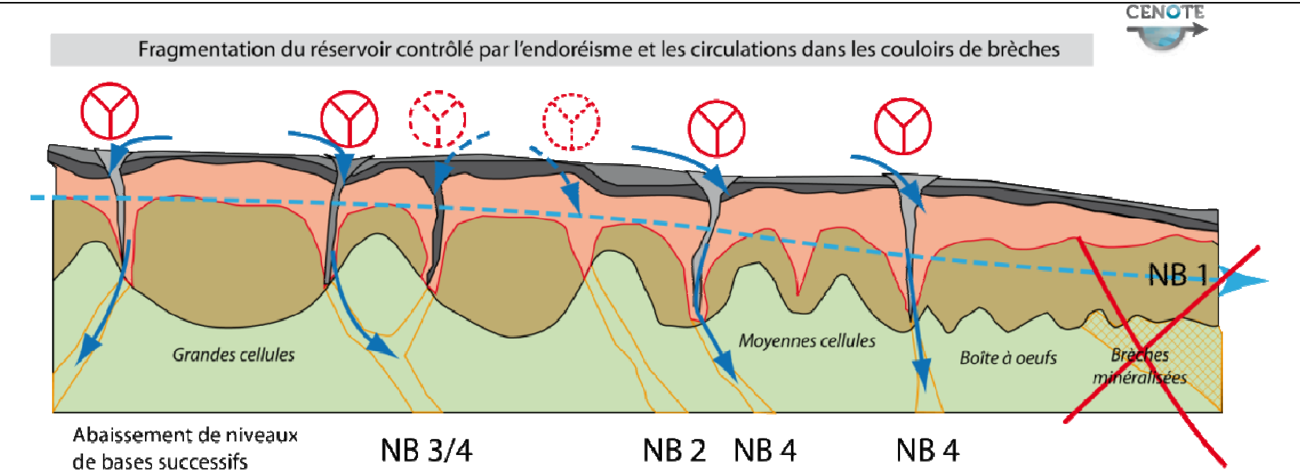

Figure 8: Schematic diagram showing fragmentation of the initial aquifer reservoir - Distribution of the cryptokarstic sinkholes in the resorption cells and flows into the breccia corridors

The now disappeared Picot doline in the Tiébagh mine illustrates the major role of the breccia corridors in the structural evolution of ancient ghost rock aquifer systems. Observations carried out in this mega-doline, of complex form (500m in length) and currently mined, provide an illustration of the extent of the hydrosedimentary processes resulting from recurrent cryptokarstic phases. The principal appendix to this mega-doline is a vast bowl of sedimentary clay deposits. These deposits show evidence of hydrosedimentary cycles in a cryptokarstic megastructure associated with the doline (figure 9). These cycles comprise lengthy phases of flooding in the doline and cryptokarstic phases evidenced by deformation and syn-sedimentary faults in the clay. The sinkhole dynamics in Picot go hand in hand with deformation and palaeoslides in the different layers of clays and alterites; these are the result of the recurrent hydrodynamics of the breccia corridors which determine the volume and position of sinkholes. The breccia corridor exposed by the mining operations nearly 80m below the natural surface topography, presented absorption cavities.

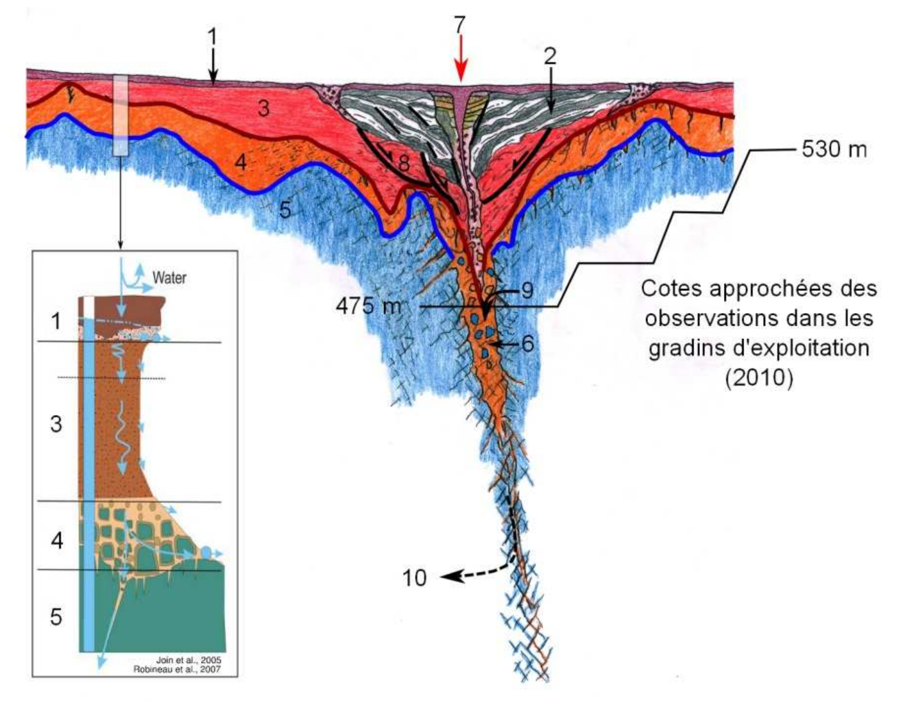

Figure 9: Principle cross-section of the Picot doline (Tiébagh Mine)

1 : Iron Pan, clasts
2 : Deformed clay infilling with several sealed faults between sequences
3 : Laterite
4 : Saprolite
5 : Unaltered peridotite
6 : Breccia corridor with open cavities
7 : Sinkhole
8 : Palaeoslides
9 : Active seepage at mine bottom
10 : Drainage into collapsed breccia halfway down slope (level 350?)

II.2.3. Phase 3 – Structuring of "current" circulation systems through retreat of valleys: karstic indications of water recharge and outflow:

A phase of retrogressive erosion then isolates or partitions off the massifs and dismantles the bottom of the geological structures. The regression of the slopes exposes ancient drainage features and allows settlement of the outflow points at the junction between the fractured and unaltered peridotites or in the altered breccia masses. In certain cases, this declogged material is evacuated by an endokarstic network which takes on a predominant role. The outlets of these systems correspond to conduits fed by the interconnected cavities of the breccia corridors.

Figure 10: Sinkhole in an open conduit – Creek Salé, Kopéto B2 Massif

Figure 11: Doline known as "Trou du Tahitien", flooding of which (photo CNRT) can last several months with levels of up to 16m of water which is discharged through a single outlet (arrow)

These successive karstification phases and their current impact on the massifs have resulted in an unusual distribution of seepages in the recharge areas. In natural zones, there are three types of seepage by concentrated infiltration in the alterites and karstified peridotite:

- Conduits carved out by corrosion of the bare rock beneath the laterite, forming lapiaz (figure 12);
- Sinkholes at the centre or at the edge of the dolines, depending on the size of the resorption cells. These seepages drain endorheic drainage basins, connect with the cavities in the breccia corridors and sometimes allows water to change from one drainage basin to another, as illustrated by the Trou du Tahitien (figure 11): this is emptied through a single sinkhole which recurrently alternates between flooding and rapid discharge;
- Sinkholes in the thalwegs beneath the alterite footwall on karstified faults or breccia corridors that have been evacuated by circulating water (figure 10).

The mining operations allow us to observe the horizontal and vertical transfer areas by exposing karstified faults with open conduits (figure 13) and/or vertical cryptokarstic structures connected to the infiltrating breccia corridors (figure 14).

Figure 12: Photo of cavities beneath lateritic overburden - Belvédère Est site at Thio Plateau (Le Nickel-SLN)

Numerous cavities and conduits can be observed beneath the lateritic overburden and are an advantage for mining operations. These features correspond to a lapiaz beneath iron pan with wide open cavities and fissures.

Figure 13: Photo (left) of an open conduit on fault N150° - Thio Plateau Massif (Belvédère Est)

Figure 14: (right) Breccia corridor at Kopéto B2 capable of absorbing several tens of L/s

The outlets of the drainage units in the peridotite massifs show signs of karstification, such as conduits in unaltered peridotite (figure 15), cavities in mineralized breccia corridors (figure 16) and concentrated groundwater circulation at the junction between unaltered and karstified peridoitites.

There are also contact springs at the laterite hanging wall. These are related to the charging of the iron pan with water. In sometimes difficult observation conditions, we also noted a large number of water outlets in the alluvial deposits; however these are only temporary outflow points. The serpentinite overthrust forms a screen which is impervious to sub-drainage of the massifs. Consequently, the contact breccias of the overthrust form an area of emergence.

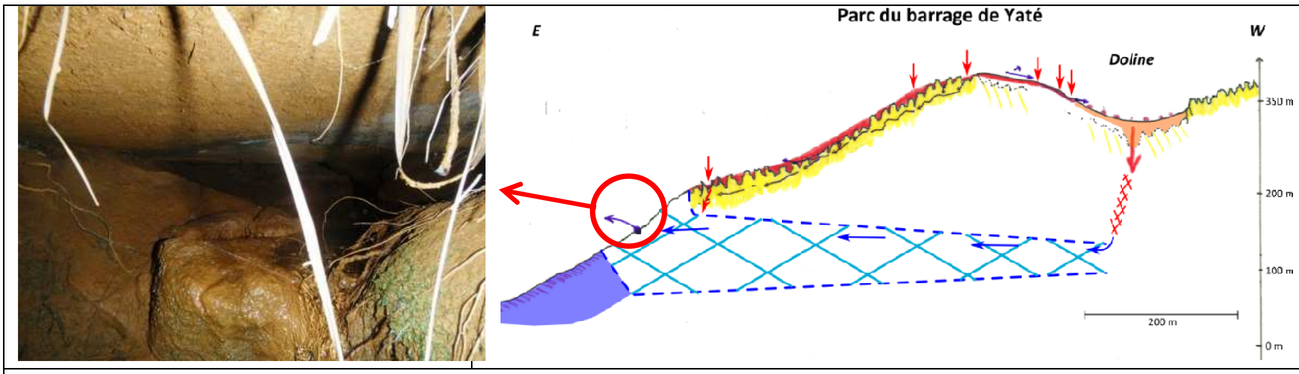

Figure 15: Photo of an outflow in a karst conduit (Yaté Dam park – at Yaté) – Cross-section key in figure 16.

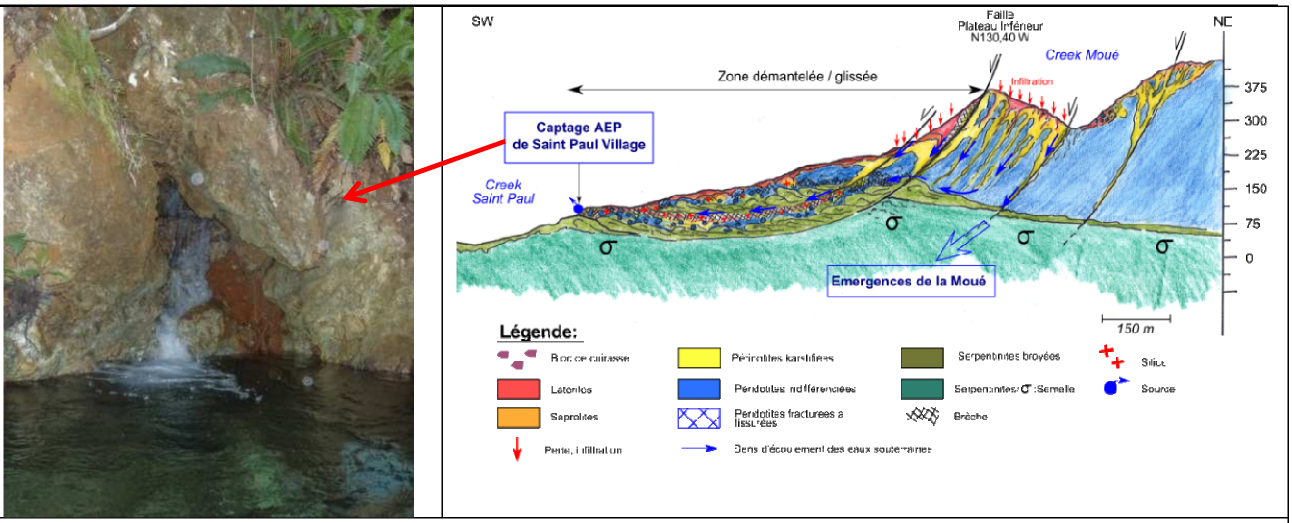

Figure 16: Outflows in cavernous silica breccia at Thio Plateau – St Paul Village water capture

The Thio Plateau mining massif presents all the typical elements of a karst system, both in its landscape and in its hydrogeology, the drainage units showing the following signs of karstification: an area of recharge by seepage at concentrated flow rates, the presence of cavities in the vertical and horizontal transfer areas exposed by the mining operations, and outflows with concentrated flow rates the catchment areas of which exceed the limits of the topographical watersheds (figure 17). Some of the principal outflows on the plateau are not aligned with the creeks but are situated on slopes where ancient geological structures have been exposed through retrogressive erosion.

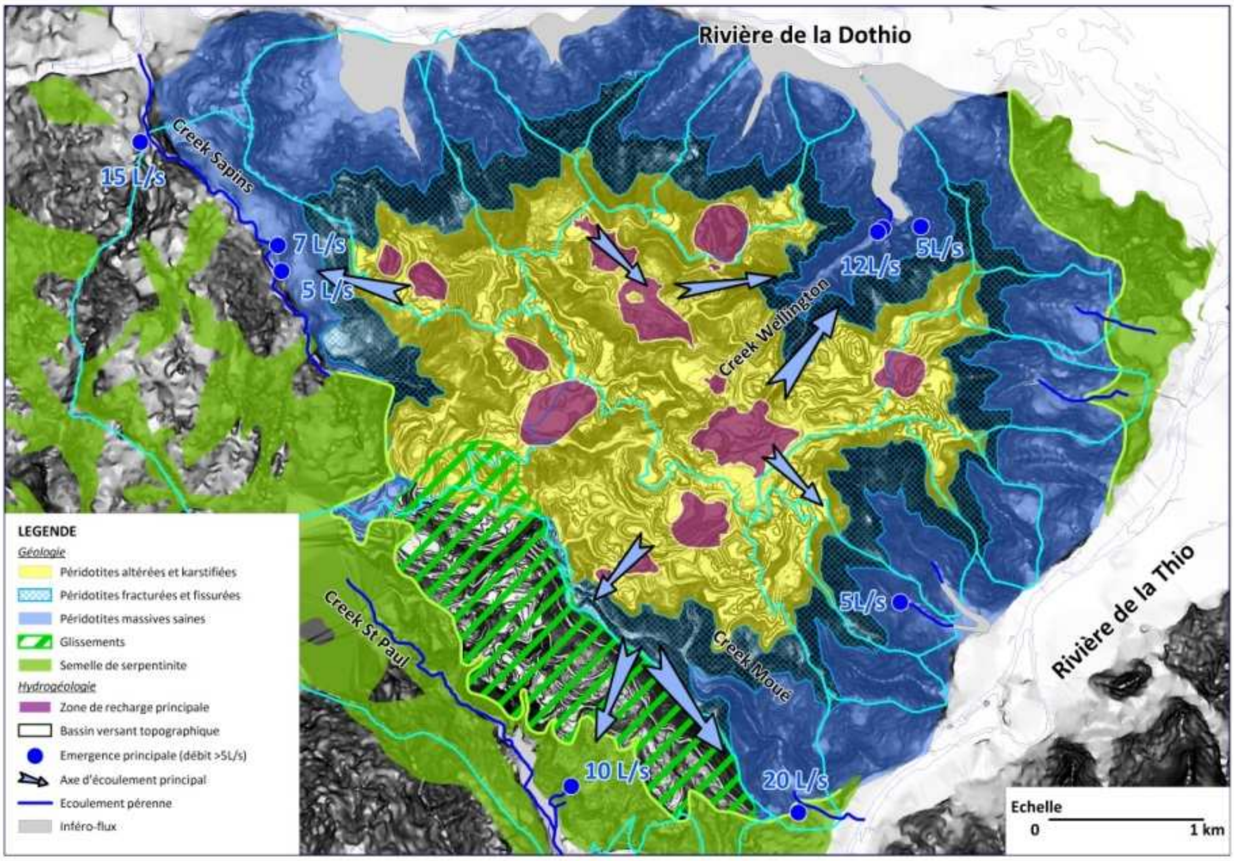

Figure 17: Position and flow of the principal springs on Thio Plateau Massif (July 2014)

III. STRUCTURAL KARSTIC DEVELOPMENT OF THE RESERVOIRS AND APPLICATION IN MINING OPERATIONS

The study of seven massifs mined by LE NICKEL-SLN confirmed the diagnostic criteria of karstification features on all the observed peridotite massifs not only of the landforms but also the hydrogeology. This karstification is expressed differently from one massif to another and the models of their functional dynamics are varied and non-reproducible. However, they have in common a multiphase structural development with successive karstification processes over time, in which the drainage units extend beyond those of the resorption cell beneath the saprolite footwall. The initial ghost-rock weathered reservoir is dismantled by hydrosedimentary evolution and the verticalization of subterranean groundwater flows, initiated by the formation of the massifs as a result of neogene uplift. This resulted in the development of lateritic sinkholesstructures with the all the functional dynamics of a cryptokarst drainage system. These cryptokarstic structures pierce the saprolite down to the unaltered peridotite and connect with breccia corridors. They supply a new drainage system which is capable of transporting the ferruginous clasts and laterite masses to the cavities of the breccia corridors, then from the karst conduits to the springs downstream. Exploitation of these breccia corridors by the cryptokarst systems causes fragmentation of the ancient ghost-rock weathered aquifers, but itself evolves due to purging during valley incision. This three-phase dynamic determines the distribution and functional dynamics of seepages and concentrated infiltration areas on the edge or in the centre of the resorption cells, depending on their size.

This study has provided a diagnostic methodology for identifying hydrokarst contexts in pits and mining installations which generally fall within a more extensive drainage unit. Based mainly on field observation, this method has enable us to define the hydrogeological units and rapidly situate sinkholes in the resorption cell and how they connect with the massif's subterranean outlets. Karstological diagnostic assessment of these massifs constitutes a decisionmaking tool for water management strategy options in mining operations, as it allows the possible consequences of the operations on groundwater circulation to be foreseen. This study also provided new arguments and criteria for stability diagnostics both for the pits and long-term mining installations, and for the peripheral slopes of the mined massifs.

Bibliography:

[1] PELLETIER B., 2003 – Les minerais de nickel de Nouvelle-Calédonie*, Bulletin de l'Union Française des Géologues.*
[2] TRESCASES J-J., 1973 – L'évolution géochimique supergène des roches ultrabasiques en zone tropicale et la formation des gisements nickélifères de Nouvelle-Calédonie, *thesis, Louis Pasteur University, Strasbourg, 1973.*
[3] LATHAM M., 1986 – Altération et pédogénèse sur roches ultrabasiques en Nouvelle-Calédonie, Genèse et évolution des accumulations de fer et de silice en relation avec la formation du modelé, *ORSTOM,*
[4] GENNA A., MAURIZOT P., LAFOY Y., AUGE T., 2005 – Contrôle karstique des minéralisations nickélifères de Nouvelle-Calédonie, *C.R Géosciences 337 (2005), 367-374.*
[5] CHEVILLOTTE V., 2005 – Morphogénèse tropicale en contexte épirogénique modéré – Exemple de la Nouvelle-Calédonie, *thesis of University of New Caledonia*.
[6] QUINIF Y., BAELE J-M., DUBOIS C., HAVRON C., VERGARI A., 2014 – Fantômisation: un nouveau paradigme entre la théorie des deux phases de Davis et la théorie de la biorhexistasie d'Erhart, *Géologica Belgica (2014)17/1: 66-74.*
[7] SEVIN B., 2014 – Cartographie du régolithe sur massifs ultrabasiques de Nouvelle-Calédonie: distribution dans l'espace et le temps des gisements nickelifères. *thesis of University of New Caledonia 2014*.[8] MAURIZOT P., SEVIN B., QUESNEL F., WYNS R., 2014 – Les sols et les altérites comme ressources minérales. *Revue Géosciences, July 2014*.
[9] LAGABRIELLE Y., CHAUVET A., 2008 – The role of extensional tectonics in shaping Cenozoïc New-Caledonia, *Bull. Soc. géol. Fr. 2008, t.179, n°3 pp 315-329.*
[10] JOINS J-L., ROBINEAU B., AMBROISI J-P., COSTIS C., COLIN F., 2005 – Système hydrogéologique d'un massif minier ultrabasique de Nouvelle-Calédonie. *C.R Geoscience*.