Workshop on New Caledonian Peridotite Amphibious Drilling Project
January 22-24, 2019 – Genopolys - Montpellier France

Proponents: Julien Collot (Service Géologique de Nouvelle-Calédonie, New Caledonia), Marguerite Godard (Host, CNRS Université de Montpellier, France), Rupert Sutherland (Victoria University of Wellington, New Zealand), Juerg Matter (University of Southampton, UK)

Summary

The Workshop on New Caledonian Peridotite Amphibious Drilling Project was organized in January 22-24, 2019 at Génopolys (Montpellier, France) by M. Godard (GM), J. Collot (SGNC) and C. Clerc (Université de Nouvelle-Calédonie), with the objective to develop an amphibious proposal for drilling the onshore peridotites of New Caledonia and their offshore extension. The workshop brought together scientific communities associated with the Integrated Ocean Drilling Program (IODP) and the International Continental Scientific Drilling Program (ICDP), representatives of the operators of these science drilling programs, specialists in marine tectonics, geophysics and geology, (bio-)geochemistry, and borehole (hydro-)geophysics with interests in geodynamics, georesources, paleoclimatology and the origin of Life, as well as representatives from the mining and related industries, and policy makers. The workshop gathered 90 participants from 15 countries. It was sponsored by MagellanPlus, Université de Montpellier, Service Géologique de Nouvelle-Calédonie and INSU CNRS; travel support for selected participants was also provided by USSSP, Ifremer and ANZIC.

The workshop commenced with a series of presentations that provided an updated view of the geodynamics of northern Zealandia, tectonics of New Caledonia and the development of carbonate reefs in this context, and on the hydrogeology of H_2-generating, serpentinite-hosted hydrothermal fields in the New Caledonia ophiolite and related microbial communities. This was followed by discussions that allowed defining and developing the science questions to be addressed by drilling offshore and onland the New Caledonia ophiolite, around three main integrative themes: (1) Geodynamics of Northeastern Zealandia and the mechanisms driving obduction of mantle-dominated units, with a focus on both mantle dynamics and underlying HP metamorphic units; (2) Serpentinization, fracturation, flow and transport in peridotite basements: impact on carbon trapping, hydrogen production, volatile and metal fluxes and deep biosphere; and (3) Age, mechanisms of formation and evolution of carbonate reefs; Impact of climate change and/or interactions with mantle derived fluids. The workshop also allowed proposing paths for realistic coordinated drilling strategies, identifying synergies between scientific communities, industry (mining and petroleum) and policy makers to raise complementary funding for the onshore ICDP project and building a pluridisciplinary proponent team for a multiplatform IODP (non-riser drilling, MSP) – ICDP Amphibious Drilling Proposal, coordinated by J. Collot (SGNC) and M. Godard (Géosciences Montpellier).

Scientific rationale & Workshop Goals

The scientific analyses of the wealth of marine data recently acquired in the Western Pacific and Tasman Sea regions as part of EEZ exploratory programs (France/New Caledonia, New Zealand and Australia) have reinvigorated the debate around the geodynamic evolution of Zealandia. Its evolution, from the Gondwana break-up during the Cretaceous to the subduction-dominated tectonics in the Cenozoic, led to the obduction of a string of peridotite massifs marking the eastern limits of Zealandia, from Southern New Zealand to the Papuan Ultramafic Belt Ophiolite. Amongst these, the best exposed and most extensively researched is the New Caledonian Ophiolite which has been explored and mined for mineral resources, mainly Nickel and Cobalt, for more than a century.

The New Caledonian Ophiolite exposes one of the largest obducted peridotite massifs in the world: its present-day topography exceeds 1.6 km and it makes up a quarter of the 500x80 km island of Grande Terre and stretches offshore over more than 400 km (Fig 1). This massive mantle nappe was tectonically emplaced onto the north-eastern edge of the Zealandia continent during the Eocene. The onshore exposures are weakly deformed and structurally not imbricated within an orogenic belt. An Eocene HP/LT eclogitic metamorphic complex is found at its northeastern boundary. Obduction also preceded the formation, during the Quaternary, of the world's second largest rimmed carbonate platform. The offshore continuation of the allochthon has been identified to the South of New Caledonia in 2000 m water-depth by seismic imaging (Fig. 1). In this area, the peridotite nappe occurs as a flat-topped continuous body, capped by carbonate reefs. It is bounded by major normal faults, and lies within a 150 km wavelength depression associated to a set of sedimentary archives (Patriat et al., Tectonics, 2018). East of the offshore peridotite nappe, the 350 km long Felicité Ridge is interpreted as the southern extension of the HP/LT metamorphic complex observed onland. West of the nappe is the Norfolk Ridge along which compressional deformation is observed.

At the same time as new marine data were bringing new insights on the geodynamic evolution of Zealandia, the growing environmental concerns related to terrestrial mining in New Caledonia led local institutions and mining companies to fund new research to develop tools to study the ophiolite and, in particular, to understand the alteration processes taking place in the peridotites as well as their potential to achieve carbon capture and storage via in situ mineral carbonation (e.g. "Expertise on CO_2 Storage in peridotites" *CNRT Nickel 2013*). In June 2017, the participants of the Australasian IODP Regional Planning Workshop (Sydney, Australia) identified several unresolved fundamental questions relating to ophiolite emplacement, to exchanges between solid Earth and its external envelopes and to the deep biosphere that could be addressed by drilling the New Caledonian Ophiolite and its offshore extension:

Fig. 1 Geological map of New Caledonia ; in light green the onshore & offshore New Caledonian Peridotite Nappe (after Patriat et al., Tectonics 2018); in purple the HP/LT metamorphic complex.

- The emplacement mechanisms of mantle-dominated allochthons and their relations with underlying exhumed HP metamorphic units are still debated. These mechanisms could be addressed by deep drilling the ultramafic sequence and associated sedimentary records, metamorphic sole and underlying basement. The contractional phase which led to obduction of the ophiolite is contemporaneous with the initiation of the Tonga-Kermadec subduction. What are the relationships between these two outstanding tectonic processes? The available geochemistry also indicates that regionally the peridotites of New Caledonia have a highly depleted chemistry. What causes this depletion?

- Several alteration processes are observed onshore throughout the massifs and are associated with serpentinization, fracturation, flow and transport in fractured peridotite basement aquifers. They involve carbon trapping, methane and hydrogen-rich fluid production, volatile and metal fluxes and abiotic vs biotic processes. Archaeal and eubacterial communities are known to develop in these alkaline systems which could have several similarities with hydrothermal environments at the beginning of life on Earth.
- Carbonate reefs that overlie the allochthon are one of the world's largest rimmed platform. What is the age of their formation and their relation to other Pacific reefs? Was their initiation associated with climate changes? What is the contribution of ultramafic alteration-derived fluids on the carbonate reef development?

Finally, significant discrepancies exist between geological records, phylogenetic evolution and biogeography. Indeed, endemism of New Caledonia and New Zealand biota are thought to be inherited from Gondwana, whereas current studies of geological records indicate deep sea environments were prevalent during the Paleocene and Eocene. Refining paleogeography and identifying land gateways would help resolve this major issue.

The long term goal of the workshop was to assess the interest of developing a land-to-sea drilling strategy to address these questions. The main objectives of the workshop were (1) defining and developing the science questions to be addressed by drilling offshore and onland the New Caledonia ophiolite, (2) proposing realistic coordinated drilling strategies, (3) identifying synergies between scientific communities, industry (mining and petroleum) and policy makers to raise complementary funding for the onshore ICDP project and (4) building a strongly involved and pluridisciplinary proponent team for an Amphibious Drilling Proposal for the peridotites of New Caledonia and their southern offshore extension.

Workshop: participants, program & discussions

The workshop brought together scientific communities associated with the Integrated Ocean Drilling Program (IODP) and the International Continental Scientific Drilling Program (ICDP), representatives of the operators of these science drilling programs, as well as representatives from the mining and related industries, and policy makers. The workshop, initially dimensioned for ca. 50 participants, gathered 90 participants, including 29 PhD and post-docs, from 15 countries (see List of Participants; Fig. 2). It was supported primarily by MagellanPlus; complementary funding was provided by Service Géologique de Nouvelle-Calédonie, Université de Montpellier and INSU CNRS. This funding allowed hosting the workshop without registration fees (rental of amphitheatre, breakout session rooms and poster hall, administrative costs). It covered also the cost of lunches and coffee breaks for all participants, plus travel and accommodation for keynote speakers. Several participants were also supported by travel grants from USSSP, ANZIC, Ifremer and Service Géologique de Nouvelle Calédonie.

The workshop took place from January 22 to 24 at the CNRS Genopolys Centre, France. The first day and the morning of the second day were dedicated to a series of keynote talks and general questions on the main topics of the workshop with the aim to stimulate synergies among the different disciplines. First, Julien Collot (SGNC, New Caledonia), Yves Lagabrielle (Géosciences Rennes, France) and Martin Patriat (IFREMER, France) provided an updated view of the tectonics and geodynamic settings of the South West Pacific with a focus on the New Caledonia ophiolite; then, Peter Blum (IODP-JRSO, USA), Ulrich Harms (ICDP, Germany), David McInroy (BGS, UK) and Philippe Pézard (U. Montpellier, France) presented the drilling and logging facilities available as part of the ICDP and IODP programs. In the afternoon, Brice Sevin and Julien Collot (SGNC, New Caledonia) presented an overview of the drilling capabilities available in New Caledonia, and of the existing onshore and offshore geological and geophysical datasets on this region. The last series of talks followed with the aim to introduce the main scientific themes of the workshop. Othmar Muntener (UNIL, Switzerland), Rupert Sutherland (VUW, New Zealand) and Philippe Agard (UPMC, France) introduced Theme 1 "Mechanisms driving obduction of mantle-dominated units : the New Caledonia ophiolite". Theme 2 "Serpentinization, flow and transport in New Caledonia peridotite basements: impact on carbon trapping, hydrogen production, volatile and metal fluxes and deep biosphere" was presented by Ivan Savov (U. Leeds, UK), Benedicte Menez (IPGP, France), Alain Prinzhofer (GEO4U, Brazil) and Julie Jeanpert (SGNC, New Caledonia). Theme 3 "Age, mechanisms of formation and evolution of carbonate reefs; Impact of climate change and/or interactions with mantle derived fluids" was introduced by Colin Woodroffe (U. Wollongong, Australia), Francois Fournier (CEREGE, France) and Aurélien Virgone (TOTAL, France).

Fig. 2. Group photo of participants to Workshop on New Caledonian Peridotite Amphibious Drilling Project that was organized in January 22-24, 2019 at Génopolys (Montpellier, France)

Poster sessions were organized on Day 1 and Day 2: they allowed each participant to present his/her most recent works of relevance to the goals of the workshop (see List of Posters). An Icebreaker was organized at the end of Day 1 to facilitate interactions and discussions between the different groups of experts, as well as between young and senior scientists.

The last part of the workshop was dedicated to discussions in break-out groups on the different themes alternating with plenary sessions. The main objectives of these discussions were to identify the scientific questions that would justify the development of an Amphibious Proposal, and to define a strategy, writing groups and leaders to develop such a proposal. Two presentations on the Oman Drilling Project by Peter Kelemen (LDEO, U. Columbia, USA) and Juerg Matter (U. Southampton, UK) provided the background on the logistical challenges of drilling ophiolites. The breakout groups were coordinated by Philippe Agard (UPMC, France), Othmar Muntener (UNIL, Switzerland) and Jessica

Warren (U. Delaware, USA) for Theme 1, Frieder Klein (WHOI, USA) and Juerg Matter (U. Southampton, UK) for Theme 2 and Francois Fournier (CEREGE, France) and Samuel Etienne (SGNC, New Caledonia) for Theme 3.

Outcome of breakout sessions and summary of the drilling strategy proposed during the workshop

The breakout group discussions allowed the participants to propose and discuss a wealth of ideas, sometimes contradictory, to identify a body of questions to be addressed and hypotheses to be tested, and determined associated drilling strategies. These different items were summarized by the coordinators of the break-out groups and discussed during the plenary wrap-up sessions.

During plenary sessions, consensus was rapidly reached that an ICDP-IODP coordinated proposal would offer an exciting and innovative opportunity to explore the lateral heterogeneities of the mantle-dominated New Caledonia ophiolite onshore and offshore, their associated lithologies and sedimentary records with the potential to advance significantly our understanding of:

(i) the formation and emplacement of ophiolites in the context of incipient subductions, with a strong focus on identifying and measuring deformation and fluxes in the mantle wedge, as preserved by the New Caledonia peridotites, and studying the protracted processes forming the metamorphic sole;

(ii) the closely interdependent tectonic, hydrogeological, geochemical and biological processes that control the development of H_2-rich ultramafic hosted hydrothermal systems, together with their environmental and economic impacts over time;

(iii) the Oligo-Miocene oceanographic and climate changes and the onset of the reefal communities in the Western Pacific for which the New Caledonia carbonates provide a unique record.

Drilling strategies common to the three break-out groups were discussed to provide samples to address these themes. The need to develop observatories to acquire time series to investigate linkages between active processes of flow, fluid-rock interactions and the development of life was also emphasized. The proposed Land2Sea approach is summarized in Figure 3. It combines

(i) onland drilling (ICDP) at 3 primary sites (white contour circles), including one multi-borehole site in the Prony area (white bold contour circle) where would be developed an observatory and that could become a legacy site; a fourth alternate site is also identified on the east coast;

(ii) 1 possible shallow water site (ICDP/MSP?) close to the coast in Prony Bay

(iii) 3 offshore sites in ca 300 m water-depths (JR?) targeting a drowned carbonate platform and the offshore extension of the peridotite massifs beyond the barrier reef; and

(iv) 4 primary deep water sites (JR) to explore Pines and Felicity ridges to the South of the island where the continuity of the New Caledonia ophiolite has been recently demonstrated, the main targets being two deep holes (white bold contour circles) down to basement (500 – 1000 m bsf; minimum 200 m into basement), allowing to sample the carbonate-peridotite interface and the peridotite basal thrust, and an E-W transect in the adjacent sedimentary records. An alternate site is also identified in the South Loyalty Basin.

A general consensus emerged from discussions that an onshore-offshore approach was essential/vital to solve the science questions. For instance, this complementary approach would allow (i) comparing seawater vs freshwater serpentinisation and investigate the differences in associated geochemical processes (role of ionic strength, temperature, pH, …), and the linkages with the development of microbiological communities in these different environments, as well as (ii) combining the results of the project with already available offshore (e.g., marine sedimentary records, seismic imaging) and onshore (geological maps…) data and industry exploration data to build the first 3D geological models of the New Caledonia ophiolite associated allochtonous units, and their structural relationship with the autochtonous basement.

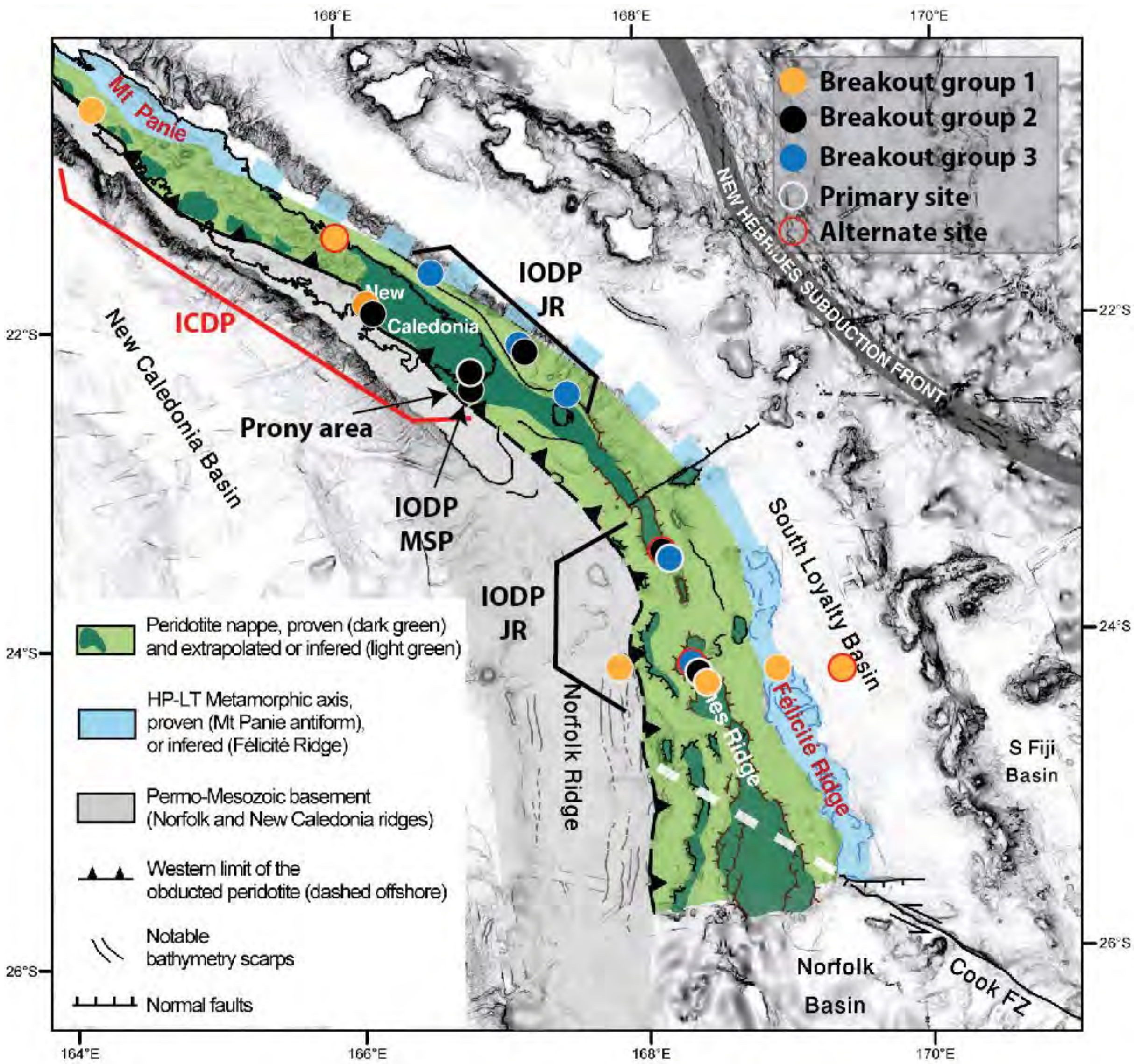

Fig. 3: Summary of drilling sites identified during the workshop. ICDP: Sites to be drilled through the International Continental Drilling Program; MSP & JR: Sites to be drilled using the facilities provided by the International Ocean Discovery Program facilities, i.e. the Mission Specific Platform for shallow water drilling and the Joides Resolution for deep sea drilling, respectively. Basemap is structural map of the mantle peridotite massifs after Patriat et al., 2018, Tectonics.

The complexity of the proposed drilling program, both in terms of science (should we simplify the range of projects and put forward a limited number of themes and ideas?) and implementation (multi-platform project, seeking funds and academic and industrial collaborations, permitting) was acknowledged during the discussions. It was concluded that the submission of a successful proposal would require long term planning and adaptability: Marguerite Godard (Géoscience Montpellier) and Julien Collot (SGNC) were designated to follow up on the result of the workshop and lead the future drilling proposal(s). In this context, to keep the workshop scientific momentum and preserve all the ideas that has arisen during the discussions, each break-out group wrote, over the weeks following the workshop, a full summary of the questions and drilling strategies as well as possible illustrations (drafts) for the future proposal (see Appendix A4).

Assessment of the results and impact of the event on the future direction of the field

The main outcomes of the workshop are

(i) establishing the scientific bases for a future drilling proposal focussing on the New Caledonia ophiolite;
(ii) bringing together a pluri-disciplinary team of researchers with common scientific interests who will form the core of the proponent team for this project,
(iii) raising the awareness of the international scientific ocean drilling community and of the New Caledonia industrial and governmental organizations on the main scientific questions and hypotheses that remained to be addressed for the New Caledonia ophiolite as well as the importance of a better understanding of these questions for the environment and economy of New Caledonia.

Following the NCDP workshop, the results of the workshop were presented and discussed with scientists and science operators who didn't attend the workshop (e.g., ECORD FB, The University of Sydney, France-Japan deepsea observatory Workshop in Nouméa, IODP 371 science workshop…). Also, funding from Service Géologique de Nouvelle-Calédonie and Victoria University of Wellington was obtained over the period 2019-2022 to:

(i) deploy a network of seismometers over the Massif du Sud (now underway) as part of a project led by Martha Savage, John Townend, Rupert Sutherland (Victoria University of Wellington) and Julien Collot (SGNC) to better characterize the onshore structure and thickness of the ophiolite with the objective to better constrain drilling strategy (in particular, borehole locations and depth)
(ii) conduct a fission track study on zircons, apatites from sediments located onshore beneath the ophiolite with Diane Seward (VUW) and Julien Collot (SGNC) to estimate the maximum thickness of the ophiolite. Preliminary results show that the ophiolite was likely over 5 km in thickness during its emplacement.

On the basis of the results of the NCDP workshop and the following discussions, and following the recent update of the IODP Proposal Submission Guidelines that clarify the procedure for coordinating an ICDP/IODP project, a Land-2-Sea pre-proposal to drill the New Caledonia ophiolite is now in preparation to be submitted in January 2021.

Appendix 1 : List of participants

Workshop on New Caledonian Peridotite Amphibious Drilling Project - January 22-24, 2019 – Montpellier France

List of Participants (1/2)

Last Name	First name		Institution	Country
Agard	Philippe	**S, C**	Sorbonne Université, Paris	France
Allard	Mael	*	Géosciences Montpellier	France
Aitchison	Jonathan		University of Queensland	Australia
Aquino	Karmina	*	ETH Zurich	Switzerland
Bailly	France		CNRT Nickel and its environment	New Caledonia
Benezeth	Pascale		Géosciences Environnement Toulouse	France
Biedermann	Andrea Regina	*	ETH Zurich / University of Bern	Switzerland
Blum	Peter	**S**	TAMU IODP	USA
Bordenave	Aurélien		SGNC / ADECAL / ENSEGID	France
Bosch	Delphine		Géosciences Montpellier	France
Boudier	Françoise		Géosciences Montpellier	France
Boulvais	Philippe		Géosciences Rennes	France
Calassou	Sylvain		TOTAL S.A.	France
Carter	Elliot	*	University of Manchester	UK
Celle-Jeanton	Hélène		Bourgogne France-Comté University	France
Chatzaras	Vasileios		University of Sydney	Australia
Clerc	Camille	**C**	ISEA, UNC	New Caledonia
Cluzel	Dominique		UNC	New Caledonia
Collot	Julien	**S, C**	SGNC	New Caledonia
Decrauzaz	Thierry	*	Géosciences Montpellier	France
Dewandel	Benoit		BRGM	France
Erauso	Gaël		Mediterranean Institute of Oceanography	France
Etienne	Samuel	**C**	ADECAL / SGNC	New Caledonia
Farough	Aida		Kansas State University	USA
Ferre	Eric		University of Louisiana at Lafayette	USA
Fournier	François	**S, C**	Aix-Marseille University	France
Früh-Green	Gretchen		ETH Zurich	Switzerland
Garrido	Carlos		CSIC - UGR	Spain
Gaucher	Eric		TOTAL S.A.	France
Gautier	Pierre		Géosciences Rennes, University of Rennes 1	France
Godard	Marguerite	**C**	Géosciences Montpellier	France
Gouze	Philippe		Géosciences Montpellier	France
Gürer	Derya		The University of Queensland	Australia
Harms	Ulrich	**S**	ICDP	Germany
Harris	Daniel		The University of Queensland	Australia
Ildefonse	Benoît		Géosciences Montpellier	France
Iseppi	Marion	*	ISEA, UNC	New Caledonia
Jeanpert	Julie	**S**	SGNC	New Caledonia
Johnson	Kevin		NSF	USA
Habault	Christian		CNRT Nickel and its environment	New Caledonia
Kadar	Mohamed		Société Le Nickel SLN-ERAMET	New Caledonia
Kelemen	Peter		LDEO Columbia University	USA
Klein	Frieder	**C**	Woods Hole Oceanographic Institution	USA
Lafay	Romain		Géosciences Montpellier	France
Lagabrielle	Yves	**S**	CNRS - Géosciences Rennes	France
Laporte-Magoni	Christine		ISEA, UNC	New Caledonia
Lee	Eun Young		Chonnam National University	Republic of Korea
Le Guen	Monique		ERAMET	France
Malvoisin	Benjamin		University of Lausanne	Switzerland
Manzanares	Sarah		Syndicat des Industriels de la Mine de Nouvelle-Calédonie	New Caledonia
Marques	Jose Manuel		University of Lisbon	Portugal
Matter	Juerg		University of Southampton	UK

* Early career scientists: S Speaker; C Convener

Workshop on New Caledonian Peridotite Amphibious Drilling Project - January 22-24, 2019 – Montpellier France

List of Participants (2/2)

Maurizot	Pierre		SGNC	New Caledonia
McInroy	David	**S**	British Geological Survey	UK
Menez	Benedicte	**S**	Institut de Physique du Globe de Paris	France
Monnin	Christophe		Geosciences Environnement Toulouse	France
Montanini	Alessandra		Università di Parma	Italy
Moretti	Isabelle		ENGIE	France
Morris	Anthony		University of Plymouth / ESSAC Chair	UK
Munoz	Manuel		Géosciences Montpellier	France
Müntener	Othmar	**S, C**	University of Lausanne	Switzerland
Nicolas	Adolphe		Géosciences Montpellier	France
Noel	Julie	*	Géosciences Montpellier	France
O'Neil	Hugh		ANU	Australia
Palazzin	Giulia		NeoGeo	Italy
Patriat	Martin	**S**	Ifremer	France
Petriglieri	Jasmine Rita		UNC / Univ. Milano-Bicocca	Italy
Pezard	Philippe	**S**	Géosciences Montpellier	France
Piller	Werner		University of Graz / ESSAC	Austria
Postec	Anne		Mediterranean Institute of Oceanography	France
Price	Roy		Stony Brook University	USA
Prinzhofer	Alain	**S**	GEO4U	Brazil
Quemeneur	Marianne		IRD, Aix-Marseille Univ.	France
Reagan	Mark		University of Iowa	USA
Rey	Patrice		The University of Sydney	Australia
Savov	Ivan	**S**	University of Leeds	UK
Secchiari	Arianna	*	Parma University	Italy
Selmaoui-Folcher	Nazha		ISEA, UNC	New Caledonia
Sevin	Brice	**S**	SGNC	New Caledonia
Shervais	John		Utah State University	USA
Shrenk	Matthew		Michigan State University	USA
Sissman	Olivier		IFP Energies Nouvelles	France
Sutherland	Rupert	**S**	Victoria University of Wellington	New Zealand
Suzuki	Shino		JAMSTEC	Japan
Takazawa	Eiichi		Niigata University	Japan
Tamura	Yoshihiko		JAMSTEC	Japan
Teagle	Damon		University of Southampton	UK
Tichadou	Camille	*	Géosciences Montpellier	France
Tournadour	Elsa	*	IFREMER / SGNC	New Caledonia
Tourneur	Enora	*	Géosciences Montpellier	France
Ulrich	Marc		IPGS-EOST	France
Virgone	Aurélien	**S**	TOTAL S.A.	France
Warren	Jessica	**C**	University of Delaware	USA
Woodroffe	Colin	**S**	University of Wollongong	Australia
Yamada	Yasuhiro		JAMSTEC	Japan

* Early career scientists: S Speaker; C Convener

Appendix 2 : Workshop program

Workshop on New Caledonian Peridotite Amphibious Drilling Project
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Program

DAY 1 - *Tuesday 22 January*

8h15-9h00 Registration

9h00 Objectives and organization of the workshop (Chairperson: Godard M.): *Developing an Amphibious Proposal on the New Caledonia Peridotite: Scientific Questions and how to address them*

9h15 New Caledonia in the context of the South West Pacific (Chairperson: Godard M.)

- COLLOT J. (SGNC, New Caledonia): Geodynamics of the southwest Pacific: a brief review and relation to ophiolite emplacement (15')
- ~~CLUZEL D. (UNC, New Caledonia): An outline of the Geology of New Caledonia (15')~~
- LAGABRIELLE Y. (Géosciences Rennes, France): Geometry and structure of the New Caledonia ophiolitic sheet, clues to its syn- and post-obduction evolution (15')
- PATRIAT M. (Ifremer, France): Obduction to post-obduction evolution of the New Caledonia ophiolite inferred from its offshore continuation (15')
- Questions / Discussion (15')

10h30 Coffee Break

11h00 IODP/ICDP facilities (Chairperson: Collot J.)

- BLUM P. (IODP-JRSO, USA): Joides Resolution Drilling Capabilities (15')
- MCINROY D. (BGS, UK): Mission Specific Platforms ESO (15')
- HARMS U. (ICDP, Germany): ICDP Drilling capabilities (15')
- PEZARD Ph. (U. Montpellier, France): ICDP/IODP borehole logging & hydrogeology facilities (15')
- Questions (15')

12h15 General discussion and questions (Chairperson: Collot J.) (15')

12h30 Lunch Break & Posters

14h00 New Caledonia: Existing datasets and facilities (Chairperson: Clerc C.)

- SEVIN B. (SGNC, New Caledonia): Drilling Capabilities in New Caledonia (15')
- COLLOT J. (SGNC, New Caledonia): Presentation of the existing offshore dataset (15')
- SEVIN B. (SGNC, New Caledonia): Presentation of the existing dataset on New Caledonia Geology: Onshore data (15')
- Questions / Discussion (15')

15h00 Break

15h15 Developing an Amphibious Proposal on the New Caledonia Peridotite (Chairpersons: Collot J., Godard M.): *Introduction to Science themes* (15')

15h30 Introduction to Theme 1: Mechanisms driving obduction of mantle-dominated units : the New Caledonia ophiolite (Chairperson: Clerc C.)

- MÜNTENER O. (U. Lausanne, CH): Petrology and geochemistry of mantle from extension to subduction: does extension control future subduction (15'+5')
- SUTHERLAND R. (VUW, NZ): Cenozoic ophiolites and allochtons of Zealandia (15'+5')
- AGARD Ph. (UPMC, Paris): Obduction, from start to finish (15'+5')

16h30 – 19h00 Icebreaker & Poster session *Geology of New Caledonia, science themes 1, 2 & 3*

DAY 2 - *Wednesday 23 January*

9h00 Summary of previous day & Introduction to the day's program (Chairperson: Collot J.)

9h10 Introduction to Theme 2: Serpentinization, flow and transport in New Caledonia peridotite basements: impact on carbon trapping, hydrogen production, volatile and metal fluxes and deep biosphere (Chairperson: Collot J.)

- SAVOV I. (U. Leeds, UK): Serpentinization in subduction environments: a mineralogical and geochemical Caledonian perspective (15'+5')
- MENEZ B. (IPGP, France) : Deep biosphere associated to ultramafic hosted hydrothermal vents : Results from New Caledonia studies (15'+5')
- PRINZHOFER A. (GEO4U, Brazil / IFPEN, France): Natural hydrogen and associated gas compounds in the New Caledonian ophiolite (15'+5')
- JEANPERT J. (SGNC, New Caledonia): Hydrogeology of New Caledonia peridotite basement (15'+5')

10h30 Coffee Break

11h00 Introduction to Theme 3: Age, mechanisms of formation and evolution of carbonate reefs; Impact of climate change and/or interactions with mantle derived fluids (Chairperson : Clerc C.)

- WOODROFFE C. (U. Wollongong, AU) : Quaternary reefs in the Pacific (15'+5')
- FOURNIER F. (CEREGE, France): Miocene post-obduction carbonate system development in New Caledonia (15'+5')
- VIRGONE A. (Total, Pau) Geochemistry of carbonates in relation to basements: Toward a process-oriented facies interpretation (15'+5')

12h00 Discussion and Organization of break-out sessions on Themes 1, 2 & 3 (Chairpersons: Collot J., Godard M.) (30')

12h30 Lunch Break & Posters

14h00 Break-out sessions: *Objective : Identify main science questions*

15h30 Coffee Break

16h00 Theme chairs report back on their themes and discussion (Chairpersons: TBD)

16h30 – 18h30 Poster session: *Geology of New Caledonia, science themes 1, 2 & 3*

DAY 3 - *Thursday 24 January*

9h00 Summary of previous day & Introduction to the day's program (Chairperson: Godard M.)

9h15 Lessons to be learned from previous projects (Chairperson: Godard M.)

- MATTER J. (U. Southampton, UK) : The Oman Drilling Project (25'+5')
- KELEMEN P. (LDEO, USA): Main scientific results of the Oman Drilling Project (25'+5')

10h15 General discussion and questions (Chairperson: Godard M.) (15')

10h30 Coffee Break

10h45 Break-out sessions on Themes 1, 2 & 3: *Best strategy to address scientific questions (*1h15)

12h00 Lunch Break & Posters

14h00 Strategy for developing an Amphibious Proposal on the New Caledonia Peridotite (Chairpersons: Collot J & Godard M.): Plenary session

- Theme chairs report back on their themes
- Development of one (or more) drilling proposal(s): rationale, identification of PI(s) and lead writing team(s), discussion of drilling strategy (including discussion of drilling targets in relation to existing site surveys and opportunities to acquire new data); identifications of funding opportunities for ICDP proposal

15h30 Coffee Break

16h00 Strategy for developing an Amphibious Proposal on the New Caledonia Peridotite (Chairpersons: Collot J & Godard M.): Plenary session (Ctd')

- Development of one (or more) drilling proposal(s): rationale, identification of PI(s) and lead writing team(s), discussion of drilling strategy (including discussion of drilling targets in relation to existing site surveys and opportunities to acquire new data); identifications of funding opportunities for ICDP proposal

16h30 Breakout sessions: writing teams

17h00 Discussion - Strategy for developing an Amphibious Proposal on the New Caledonia Peridotite (Chairpersons: Collot J & Godard M.):

- Feed-back from break-out sessions by leaders;
- Discussion

17h45 Summary and end of meeting (Chairpersons: Godard M., Collot J.)

Appendix 3 : Poster session

THEMES 1 & 3

Please refer to your poster number to locate your poster emplacement. X-Y where X refers to floor number and Y to emplacement

Last Name	First Name	Title	Poster number
Aitchison	Jonathan	New Caledonia: somewhere all geologists working on continent/continent collision should visit	3-1
Bailly	France	New Caledonia, a land of nickel - research and innovation acting for the sustainable development	3-2
Biedermann	Andrea Regina	Understanding the sources of magnetic fabrics in shear zones from the New Caledonia ophiolite: Bogota peninsula and Tontouta valley shear zones	3-3
Bordenave	Aurélien	Onshore and offshore tectono-stratigraphic evolution of New Caledonian paleogene sedimentary basins: influence and recording of the onset of the New Caledonian ophiolite	3-4
Chatzaras	Vasileios	Stress variations in the mantle section of an oceanic transform fault: Bogota peninsula shear zone, New Caledonia	3-5
Clerc	Camille	Syn- and post obduction thermal history of New Caledonia age of emplacement, thickness, weathering and erosion of the peridotite nappe	3-6
Etienne	Samuel	The drowned carbonate platform of the Lansdowne Bank (New Caledonia): preliminary results from the SEDLAB cruise	3-7
Ferre	Eric	Strain, melt extraction, and serpentinization gradients in the Humboldt peridotite shear zone, Massif du Sud, New Caledonia	3-8
Garrido	Carlos	Fluid-assisted strain localization weakening in peridotite beyond serpentinite stability as a potential mechanism for subduction initiation and mantle obduction	3-9
Gautier	Pierre	The emplacement of the Peridotite Nappe of New Caledonia	3-10
Gürer	Kanchana	Reconstructing past intra-oceanic subduction from the upper plate geological record in the eastern Mediterranean	3-11
Harris	Daniel	Oceanographic, climate, and sea level influence on quaternary coral reef and coastal development	3-12
Iseppi	Marion	Internal structure of the New Caledonian ophiolite imaged by heliborne electromagnetic survey	3-13
Maurizot	Pierre	Substrate diversity of the Peridotite Nappe (New Caledonia); tectonic inferences	3-14
Montanini	Alessandra	The geochemical message from the New Caledonia gabbronorites: insights on depletion and contamination processes of the sub-arc mantle in a nascent arc setting	3-15
Morris	Anthony	Can the magnetism of ophiolite metamorphic sole rocks be used to constrain exhumation mechanisms?	3-16
Nicolas	Adolphe	New Caledonia ophiolite obduction: a new model	3-17
Palazzin	Giulia	Syn- to post-obduction tectonic evolution of the Nouméa peninsula and first attempt of correlation with offshore observations	3-18
Patriat	Martin	Obduction to post-obduction evolution of the New Caledonia ophiolite inferred from its offshore continuation	3-19
Rey	Patrice	Towards a self-consistent numerical model of obduction	3-20
Savage	Martha	Seismic structure of the New Caledonia peridotite from passive seismology	3-21
Secchiari	Arianna	Geochemical and Sr-Nd-Pb isotope investigation of the New Caledonia peridotite nappe: unravelling the history of a poorly known mantle section	3-22
Selmaoui-Folcher	Nazha	Examples of large and complex data analysis	3-23
Shervais	John	Ophiolite emplacement by accretionary uplift	3-24
Tamura	Yoshihiko	Nishinoshima volcano in the Ogasawara arc: andesites and their crust-mantle connections	3-25
Tournadour	Elsa	Architecture and facies evolution of mixed carbonate-siliciclastic systems in a post-obduction margin context (Népoui formation, Lower Miocene, New Caledonia)	3-26
Yamada	Yasuhiro	Strength profile across the crust-mantle transition at Samail Oman Ophiolite	3-27

THEME 2

Please refer to your poster number to locate your poster emplacement. X-Y where X refers to floor number and Y to emplacement

Last Name	First Name	Title	Poster number
Aquino	Karmina	Serpentinization and weathering of peridotite from the Zambales Ophiolite, Philippines	1-1
Boulvais	Philippe	Carbonation and silicification of the New Caledonia peridotite nappe: a stable isotope survey	1-2
Carter	Elliot	Exploring hydration and carbonation of lithospheric peridotites through the noble gas isotope and halogen systematics of ophiolites	1-3
Dewandel	Benoit	Inferring the heterogeneity, transmissivity and hydraulic conductivity of crystalline aquifers from a detailed water-table map. Application to the peridotite aquifer of the Tiébaghi Massif - NC	1-4
Erauso	Gaël	Microprony: microbial ecosystem functioning in the serpentinizing-hydrothermal system of prony, New Caledonia	1-5
Farough	Aida	The correlation between evolution of physical properties and degree of serpentinization in ophiolites from Point Sal, California: implications for strength of oceanic lithosphere	1-6
Iseppi	Marion	Internal structure of the New Caledonian ophiolite imaged by heliborne electromagnetic survey	1-7
Jeanpert	Julie	Karstic flow in peridotite of the Massif du Sud, New Caledonia	1-8
Kelemen	Peter	Main scientific results of the Oman drilling project	1-9
Klein	Frieder	Abiotic synthesis of methane in olivine-hosted fluid inclusions	1-10
Kularatne	Kanchana	CO_2 storage and H_2 production from olivine bearing mine tailings	1-11
Lafay	Romain	Coupled dissolution and precipitation as a prerequisite for intra-crystalline reaction-induced cracking: evidence from experimental olivine hydration and carbonation	1-12
Lamérand	C.	Olivine dissolution and hydrous Mg-carbonate and -silicate precipitation in the presence of microbial consortium of photo-autotrophic and heterotrophic bacteria	1-13
Laporte-Magoni	Christine	Weathering influence on fiber release of asbestos type minerals	1-14
Marques	Jose Manuel	Present-day serpentinization and related Na-Cl/Ca-OH hyperalkaline CH_4-rich mineral waters in continental peridotites (cabeço de vide – portugal)	1-15
Matter	Juerg	The hydrogeology of an active serpentinization system in the Oman Ophiolite	1-16
Monnin	Christophe	Chemical composition of on-land alkaline springs in southern New Caledonia	1-17
Moretti	Isabelle	Hydrogen solubility in aqueous NaCl solutions	1-18
Noel	Julie	Origin and significance of “fingerprint” textures in serpentinized Batin dunite (Wadi Tayin, Oman Ophiolite)	1-19
Petriglieri	Jasmine Rita	Asbestos hazard in New Caledonia. Understanding the rock fabric evolution of serpentinite before weathering.	1-20
Price	Roy	Methane cycling in the alkaline serpentinizing vents of the Prony hyrothermal field, New Caledonia	1-22
Quemeneur	Marianne	Hydrostatic pressure helps to cultivate original and anaerobic bacteria from the Atlantis Massif subseafloor: caracterization of petrocella atlantisensis gen. Nov, sp. Nov.	1-21
Quemeneur	Marianne	Microbial diversity in terrestrial alkaline springs of New Caledonia	1-23
Schrenk	Matthew	A framework linking hydrogeology and microbial activities in continental serpentinites	1-24
Shervais	John	Ophiolite emplacement by accretionary uplift	1-25
Sissman	Olivier	Abiogenic formation of light hydrocarbons and other short-chain organic compounds within a serpentinite mud volcano over the Marianna Trench (IODP exp. 366)	1-26
Suzuki	Shino	Microbial life at serpentinization settings	1-27
Tichadou	Camille	Serpentinization and potential for natural hydrogen in north-western pyrenees	1-28
Tourneur	Enora	Ultramafic context and Co-Ni-rich arsenides mineralization: a case study from the Bou Azzer mining disctrict (Anti-Atlas, Morocco).	1-29
Ulrich	Marc	Dissolution–precipitation processes governing the carbonation and silicification of the serpentinite sole of the New Caledonia Ophiolite	1-30
Ulrich	Marc	Geochemistry of the New Caledonia serpentinites: evidences for multiple serpentinization events at various depths	1-31
Yoshida	Y.	Alteration of the mantle peridotite in the northern Fizh Block, Oman Ophiolite - serpentinized peridotites, especially directly above the basal thrust	1-32

Appendix 4 : Reports of Break-out Groups on Science Themes 1, 2 and 3

[NCDP Workshop, Montpellier]
Report THEME 1 — Mechanisms driving obduction of mantle-dominated units

Chairs & Scribes of Breakout Group 1 (*Coordination of report): P. Agard (*), O. Müntener, J. Warren, H. O'Neill, C. Clerc, E. Takazawa, R. Sutherland, D. Teagle, A. Secchiari, M. Patriat, D. Guerer

SCIENTIFIC RELEVANCE AND TIMELINESS

Being one of the largest ophiolite fragments on earth (with Oman, Turkey, Newfoundland), the New Caledonia (NC) ophiolite is a unique witness of plate tectonics. NC hosts a rare example of ophiolite perfectly preserved from collision with well-constrained kinematics (Cluzel et al., 2011; Maurizot et al., 2018; Patriat et al., 2018). And is therefore a key location to understand ophiolite emplacement ('obduction' s.s.), i.e. the enigmatic process leading to the overthrusting of large, several hundred of km long piece(s) of lithosphere on top of continents (Coleman 1981, Nicolas 1989). Ophiolites are also crucial to study processes creating (and modifying) the oceanic crust and shallow mantle, mantle upwelling in fore-arc regions, or fluid and mass transfer from variably altered subducted material into the overlying mantle wedge peridotites (with implications for economic mineral deposits).

Two specific features make the NC ophiolite an optimal, compelling target for an amphibious drilling project (the NCDP project):
— the link between the obducted ophiolite and the adjacent oceanic lithosphere has never been studied anywhere in the world and can only be studied through an onshore-offshore connection. This has not been (and cannot easily be) done north of the iconic Oman ophiolite, largely due to geopolitical reasons (the Oman Drilling Project, for example, is onshore only). NC also preserves an exceptional sedimentary record (including for tracking vertical movements), and reconnaissance, high-resolution geophysical data exist (Collot et al., 2008; Patriat et al., 2018).
— there are major along strike NS variations in ophiolite type (much more so than in Oman), allowing to assess the geodynamic environment in which obduction did nucleate (back-arc or fore-arc, spontaneously or not) and the influence of the nature of the ophiolite on the emplacement process (e.g., thickness of the ophiolite and serpentinized sole, extent of overthrusting and burial of the continental margin).

The NCADP project targets two key scientific questions:

***Q1.* The mechanisms of ophiolite emplacement during 'obduction'**
>>> To which extent is this lithospheric-scale emplacement linked to subduction initiation and/or subduction termination? How much continental subduction is needed? What is the extent of gravity-driven processes?

***Q2.* The nature and type of ophiolitic fragment(s)**
>>> What was the initial composition/structure of the oceanic lithosphere? Where and how (long) did it form? To which extent are the documented NS contrasts pristine or

related to the obduction process, and how did they influence the whole ophiolite emplacement process?

>>> *State of the art and unresolved issues*

Obduction results in the mysterious emplacement of a dense, rigid, oceanic lithosphere on top of a buoyant, deformable and thicker continental margin. Some observations are firmly established (for the sake of clarity, a generic evolution is shown in Fig.1):

- Obduction generally ensues from some geodynamic (mantle-scale) plate reorganization (Vaughan and Scarrow, 2003; Agard et al., 2007; Jolivet et al., 2016; Sutherland et al., 2017).
- Below large-scale obducted ophiolites are metamorphic soles (MS) attached to the mantle base, that attest to subduction initiation at some stage (Wakabayashi and Dilek, 2003; Cluzel et al., 2012; Agard et al., 2016). The MS and mantle base represent a unique example of a frozen-in (warm) subduction interface (Prigent et al., 2018).
- Ophiolites evidence a subduction imprint (e.g., V2 lavas in Oman, late calc-alkaline plutons in NC; Godard et al., 2003; Cluzel et al., 2001, respectively), if not fully supra-subduction-derived (Whattam and Stern, 2011; McLeod et al., 2013).
- Continental subduction to depths of 30 to 60 km in a cold, subduction regime, is attested by the presence, below all large-scale obducted ophiolites, of rocks metamorphosed at high-pressure low-temperature conditions (HP-LT; for NC: Clarke et al., 1997; Agard and Vitale-Brovarone, 2013). Radiometric constraints indicate that they transformed ~10-15 My after the MS (Baldwin et al., 2007; Vitale-Brovarone et al., 2018), which are in places overprinted by HPLT metamorphism (Plunder et al., 2016).
- Widespread extension shortly follows or accompanies the termination of ophiolite emplacement (Fournier et al., 2006; Lagabrielle et al., 2005).

A number of unresolved or debated issues nevertheless remain, which all can be addressed in NC:

— Emplacement requires underthrusting of the continent, but mechanisms and/or polarity have been debated ever since the discovery of obduction in the 1970s (e.g., Dewey, 1976; Searle et al., 2004; Boudier and Nicolas, 2019). In NC, underthrusting (and/or subduction) polarity is commonly inferred to be eastward (Cluzel et al., 2001; Gautier et al., 2016), but the sense of displacement is debated (Sutherland et al.?).

— How much continental subduction is needed? Is the apparent along strike variation in HP-LT metamorphism/underthrusting (exhumed eclogites in the north, none in the south) and in the nature of the ophiolite (lherzolites to the north, harzburgites in the south) only a mere coincidence, and/or what does it tell us in terms of (paleogeo)dynamics?

— Does emplacement relate to gravity sliding, in part or for all (Lagabrielle et al., 2013; Gautier et al., 2016)? More generally, what is the role and timing of serpentinization on ophiolite emplacement, especially given the existence of a thick serpentinized/listvenitized horizon at the base of the ophiolite (including the extensive 50-100m thick 'mur à silice'; Ulrich et al., 2014; Quesnel et al., 2016)? The NC case study potentially contrasts with Oman, where serpentinization is essentially late with respect to most of the transport (being discontinuous at the mantle base, overprinting deformation at $650°<T<900°C$, and never a large-scale weak decollement decoupling the MS from the mantle base).

— How is the late uplift/exposure of the nappe stack achieved and what are the forces involved? What are the cause(s) and driving mechanism(s)? Slab break-off? Far-field forces? Isostasy? Flexural rebound? (Chemenda et al., 1996; Agard et al., 2014; Duretz et al., 2016) And what are

the respective roles of mechanical/tectonic erosion, rainfall and chemical erosion/dissolution (weathering) on this evolution (Sevin et al., 2012; Gautier, 2016)?
— Some (intraoceanic) subduction initiation is documented, but was it spontaneous or induced (Stern, 2004)? Is the ophiolite/oceanic lithosphere preexisting (i.e., intra-oceanic subduction comes second) or is it entirely formed by supra-subduction upwelling (i.e., intra-oceanic subduction comes first)?
— Despite evidence for subduction, there is no real volcanic arc (nor significant arc sediments) and the precise setting of subduction nucleation is still unclear (i.e., former ridge, transform or detachment? Nicolas and Le Pichon, 1981; Hacker et al., 1996; Maffione et al., 2015, McCarthy et al., 2018). Although most obducted ophiolites are young and warm (<5-30 My; for NC: 85-80 Ma crystallization ages vs 55 Ma for the MS marking subduction initiation), their petrological nature and origin is poorly constrained (supra-subduction? slow-spreading? OCT-type?).

>>> ***Q1 Scientific Objectives*** *(see below for specific Drill targets)*

→ The sole of the ophiolite (ie, of the 'Peridotite Nappe'): Characterize the mantle base, metamorphic sole (MS) and serpentinized/listvenitized horizons near or reworking the contact (early and late during the ophiolite emplacement?). To which extent is the MS reworked? Is the Peridotite Nappe a relatively continuous massif obducted as a single entity or rather adjacent, disrupted mantle piece?
→ Deformation: Constrain the detailed emplacement, vergence and evolution through time, from subduction to effective emplacement, and the extent of gravity sliding. Assess the direction and distance of transport based on structures from the drill core (deformation patterns, EBSD). Constraining the convergence direction is a key question for tectonic models of the region (and for the location of the paleo-subduction zone represented by the MS). How much early (ductile) vs ductile to brittle deformation? Is displacement systematically associated to a (paleo-) subduction interface? If not, along which other thrust plane and is it substantial (Boudier and Nicolas, 2019)? Can we determine the paleo-taper angle of the nappe during its emplacement (Sutherland et al., 2017?)?
→ Restoration: Can we determine the maximum overburden (paleo-thickness) of the nappe before erosion, using the sedimentary record beneath the nappe (e.g., Bourail flysch; thermochronology on sediments beneath the nappe to access post-emplacement exhumation ages/rates; provenance data for source to sink approach; Maurizot et al., 2011; e.g., Goodenough et al., 2014 for the UAE ophiolite).
→ Timing: Provide constraints on the timing of these processes (including U-Th-He dating of serpentinization through chromite and magnetite?, e.g. Cooperdock and Stockli, 2018). Estimate the along strike time contrast/delay of emplacement (probably earlier from north to south; Cluzel et al., 2001).

>>> ***Q2: Scientific Objectives*** *(see below for specific Drill targets)*

→ Variability and type of ophiolite: Study the striking contrast between the fertile lherzolite northern massifs lacking crust (Tiebaghi and further north; Augé, 1988, Ulrich et al. 2010; Secchiari et al. 2016) and the ultra-depleted harzburgite massifs in the south (Massif du Sud; Marchesi et al., 2009; Pirard et al., 2013) where a limited crustal sequence is found. Sampling the north, south, and off-shore massifs would constrain the large-scale variability of mantle composition and the type of mantle (arc, forearc, continental). For example, do plagioclase-bearing peridotites in the north relate to shallow refertilized and exhumed mantle?

- → Inherited vs newly formed: Constrain the role of inherited compositions versus melting/refertilization processes (Ulrich et al., 2010) from small-scale variations in mantle composition in each drill core and comparison across sites. This may also help detect changes associated with potential rotations and differential exposure to subduction fluids (e.g., Oman: Morris et al., 2016).
- → Oceanic/continental: Assess the role of subduction zone processes (e.g., boninites and refertilized peridotites at subduction initiation sites; Marchesi et al., 2009; Ulrich et al., 2010), and/or mantle upwelling, versus possibly inherited Zealandia sub-continental mantle (Mortimer et al., 2017; Scott et al., 2019; with regional-scale implications for the mantle evolution).
- → Serpentinization processes: Determine variation through space (apparently decreasing from N to S but uncorrelated with the harzburgite/lherzolite transition; Gautier et al., 2016), through time (oceanic or subduction-related, early or late during emplacement) and as a function of seawater versus meteoric water.
- → Carbon sequestration: assess its efficiency by comparing the onshore/offshore settings (Quesnel et al., 2013). Evaluate differences if related to deep or surface processes, and to marine or fresh water.

AN AMPHIBIOUS DRILLING STRATEGY

Most of the scientific questions listed above can only be addressed by continuous sampling, hence drilling both onshore and offshore, and through the comparison of both. The key profiles identified here target the sole contact, the sedimentary record and the nature of the ophiolite.

On-land drilling would:

- Provide a continuous transect across the metamorphic sole (near Thio; Cluzel et al., 2012) and the base of the Peridotite Nappe.
- Constrain thickness, structure and variability of the northern massif, particularly whether composition is lherzolitic throughout.
- Recover material further from the Moho in the southern massif.

Off-shore drilling would:

- Delineate the extent of the Massif du Sud.
- Determine uplift/subsidence (and weathering) history of the massif through analysis of offshore sedimentation history (thin sedimentary platform on the Pines Ridge horst; KNCN4747).
- Connect mantle across the debated Zealandia 'continent' (Mortimer et al., 2017), from New Caledonia south towards New Zealand.
- Provide constraints on the timing of the formation of the flexural sedimentary basin formed at the front of the obducted complex (on the eastern flank of the Norfolk Ridge).

Target locations:

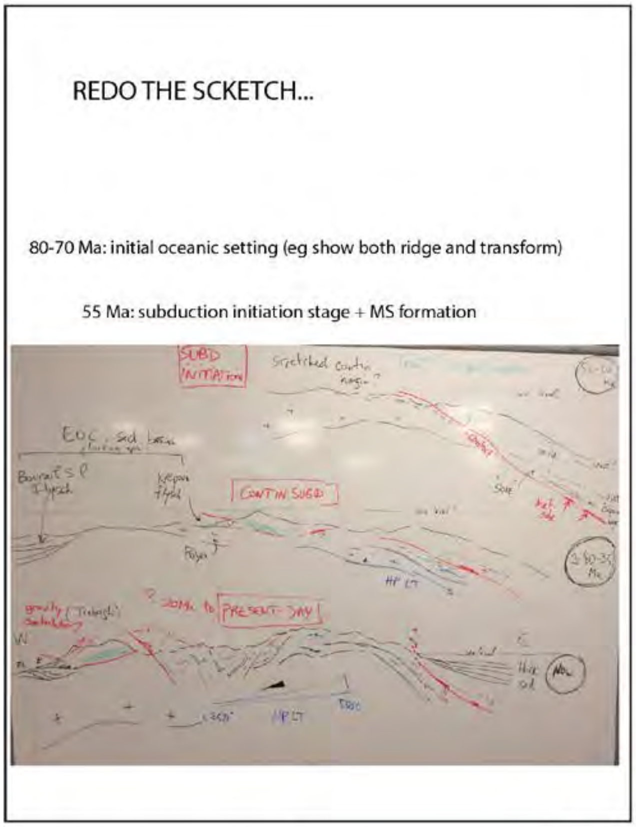
1. Onshore, Northern massif - Tiebaghi is a good location to drill into lherzolite, as current model is that it overlies harzburgite; location is wide and relatively unweathered. It’s a good test for length-scale of variations. Also interesting for chromite formation.
2. Onshore, Massif du Sud - near Thio (and/or Bogota Peninsula), in an area where it is possible to drill through the ophiolite massif, the metamorphic sole and into the underlying HP-LT rocks.
3. Offshore – Eastern flank of Norfolk Ridge (thrust wedge and flexural basin) sedimentary records of obduction
4. Offshore - Pines Ridge. Very few locations where (serpentinized) mantle has been drilled (Bach et al., 2006), especially deeper than 200 m... is there antigorite?
5. Offshore – Félicité Ridge

WARNINGS

!!!! some deep marine geophysical imagery missing to locate/address coring, site-survey needed
!!!! careful with orientations lost through drilling... for inferring the vergence!!
!!! impossible to drill in the NE, alas... !!!

CONCEPTUAL FIGURE (Draft)

Fig1: tentative evolution / 5 steps placing key processes and unknowns (as on the board!)



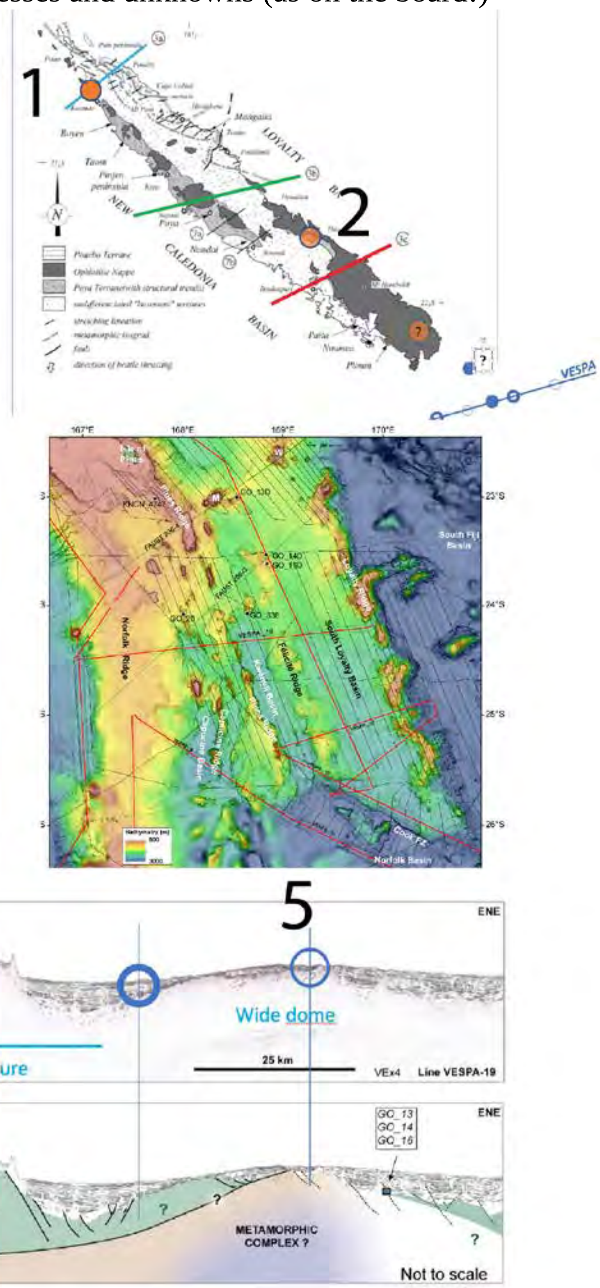


Fig. 2 a-b-c : location of the target profiles with respect to major structures

Additional comments/suggestions (A. Secchiari):

1. Q2: Scientific Objectives

- Serpentinisation processes: apparently decreasing from N to S but uncorrelated with the harzburgite/lherzolite transition → not completely true, the northern lherzolites are quite serpentinised, as well as the southern Massif du Sud harzburgites. It does not seem that serpentinisation display a gradient moving from the northern lherzolitic massifs toward south.

2. Target locations

- Tiébaghi massif cannot be properly indicated as a “relatively unweathered” site. We have some samples in our dataset from Tiébaghi that display high LOI values (up to ~10%), consistent with the LOI reported by Ulrich et al. 2010 for samples from the same locality (LOI ~ 9-16%).

Q2 Scientific Objectives:

- The relationship among subduction zones and the occurrence of important ore deposits has been recognized since long time. For the New Caledonia ophiolite, there are some (old) papers attesting the presence of important ores deposits (i.e. chromitite, placers, mineralizations within the harzburgite bodies etc…, see Augé et al., 1988; Augé and Maurizot, 1995; Augé et al., 1999). Maybe it could be worthwhile to add something about to the origin of such deposits, in the wider context of how subduction factories globally work in element cycling and in the genesis of economically relevant ore deposits.

To conclude, we are all aware that drilling sites have to be limited and that we cannot manage to obtain more than 10-11 sites in total. Anyway, on the sketch map there is one drilling location in the Massif du Sud excluded from the “wish list”, which maybe needs to be reconsidered.

New Caledonia represents one of the few sites worldwide (together with the Jurassic Talkeetna arc in south-central Alaska and the Cretaceous Kohistan arc in northern Pakistan) where a well-preserved section of a lower crust arc is exposed (Marchesi et al., 2009; Pirard et al., 2013; Secchiari et al., 2018). In addition, this sequence is believed to have formed during the first phases of subduction inception in a nascent arc environment. This constitutes an exceptional opportunity to investigate the processes related to subduction initiation, as well as the main petrological and geochemical features (and their variability) of the first magmatic products generated during subduction. In fact, while a discrete knowledge on how subduction zones work during their “maturity” is available in the scientific literature, the processes occurring during subduction “infancy” are still poorly known, due to the difficulty of sampling the modern forearc regions.

[NCDP Workshop, Montpellier]

Report Theme 2: Serpentinization and related processes

Chairs & Scribes of Breakout Group 2 (*Coordination of report): F. Klein(*), J. Matter, A. Farough, C. Monnin, B. Menez, S. Suzuki, J. Jeanpert, P. Kelemen

The New Caledonian Peridotite features subaerial and submarine exposures of partly to completely serpentinized peridotite and active vent sites in the Prony Bay area that discharge serpentinization fluids of meteoric origin. The continuum of related subaerial, intertidal, and shallow submarine vent sites in the Prony Bay area uniquely positions this system for scientific amphibious drilling to address the following fundamental questions in current serpentinization research.

Q1. Low-temperature serpentinization - what is it, how is it expressed, and what are the timescales?

Serpentinization occurs over a wide range of temperatures (~550 °C to ambient conditions) in diverse geodynamic settings including mid-ocean ridges, passive margins, subduction zones, and ophiolites, which result in a broad array of serpentinization reactions (e.g., Früh-Green et al., 2004; Jöns & Bach, 2013). There is field-evidence for serpentinization at low temperatures from gas seeps and alkaline springs (e.g., Okland et al., 2012) however, we have been struggling to replicate low-temperature serpentinization reactions under well-constrained laboratory conditions (e.g., Miller et al., 2017) and our current understanding of serpentinization is largely based on reactions taking place at much higher temperatures (beyond the known temperature limit of life, 121°C). Dissolution rates of primary minerals strongly decrease with decreasing temperature (Martin and Fyfe, 1970; Malvoisin et al., 2012; McCollom et al., 2016), which raises the question as to what reactions dominate serpentinization at low temperatures and how do they relate to volatile concentrations and fluxes? Which factors control the reaction progress? How do reactions change spatially and temporarily from the recharge to the discharge zone? What are the chemical and mineralogical effects of fluid composition (meteoric water vs. seawater) on low-temperature serpentinization reactions? How do lithological heterogeneities affect serpentinization processes? What of transport vs reaction kinetics controls serpentinization and carbonatization reactions and does this dominant mechanism evolve along flow path? How does low-temperature serpentinization affect the physical properties of the altered rock (and vice versa)?

Scientific drilling of the New Caledonia ophiolite, from subaerial to submarine, across the gradient of the Prony bay plumbing system, would provide direct access to site(s) of low-temperature serpentinization. It would allow for systematic investigation with depth and proximity to discharge sites. Because it is well established that fluids are of meteoric origin, likely recharged within a 50km (most likely 15 km) radius of Prony bay, it may be possible to follow fluids along the flow path and trace their compositional modulations with time. In turn, changes in fluid chemistry along the flow path may be recorded in the geochemistry, mineralogy, and physical properties of altered rocks. The anticipated geochemical, mineralogical, and hydrological data can then be compared to datasets from other sites, like the Samail ophiolite in Oman which was recently drilled during the Oman Drilling Program, and the proposed offshore drill site (see Q4 below). The Oman and New Caledonia sites of low-temperature serpentinization show similar protolith compositions and general fluid chemistry (high pH, enriched in

H_2), but they differ in climate (tropics vs. desert) and hydrogeology (subaerial vs subaerial & submarine discharge). Any serpentinization at the proposed offshore drill site is entirely due to interaction of peridotite with seawater. Therefore possible effects of meteoric fluids on low-temperature serpentinization on land processes may become discernible.

Q2. How do microbial communities, biomass, and metabolic activities change in an amphibious serpentinization system?

Serpentinization in New Caledonia bridges land and sea. Meteoric water enters the weathered and serpentinized peridotite on land, reacts with minerals in the root zone, and discharges in subaerial, intertidal, and submarine sites. The associated changes in fluid chemistry provide distinct challenges and opportunities for microbial communities, which likely adapted to these conditions over geologic (?) timescales. While the microbial ecology of the Prony Hydrothermal Field (PHF) has been evaluated (e.g., Frouin et al., 2018; Quéméneur et al., 2014' Postec et al., 2015), much less is known about which microbes are associated with the continental and marine serpentinizing aquifers. Do these microbes follow geochemical contours? Is biomass focused where geochemical gradients are steepest, e.g., at lithological contacts or in mixing zones? Do microorganisms migrate within the system? What are the energy and nutrient fluxes for microbial life in an amphibious serpentinization system? How do microbes exists within the native aquifer? What are their vertical distributions in the subsurface (i.e. are they concentrated in particular aquifers)? Do the solids play specific roles in their metabolism and physiology? At present, it is not possible to systematically address these questions because there is no direct access to the subsurface biosphere. Scientific drilling is currently the only known approach to examine subsurface microbial communities in situ. We will target specific drill sites from the recharge to the discharge zone, as well as lithological contacts, which will allow us to comprehensively address these questions.

Q3. What are the major biological and geological processes, sources, and sinks in the carbon cycle of low-temperature serpentinization systems?

Carbon plays a central role in serpentinization systems (e.g., Grozeva et al., 2017; Kelemen and Matter, 2008; Lang et al., 2018). Dissolved inorganic carbon is reduced to methane and other hydrocarbons, which has important ramifications for our understanding of prebiotic synthesis and the sustenance of microbial life in extreme environments (Martin et al., 2008; Schrenk et al., 2013). Dissolved inorganic carbon can also precipitate as carbonate during heating of meteoric fluids, mixing of serpentinization fluids with seawater, or reaction with primary and secondary minerals (de Obeso and Kelemen, 2018; Eickmann et al., 2009; Hansen et al., 2005; Klein et al., 2015). The interplay of geological and biological processes and their effects on the carbon cycle remain poorly understood. A key example is methane formation, which can be abiotic or biogenic. What are the sources and pathways of methane formation in a low-temperature amphibious serpentinization system? Does methane oxidation cause carbonate precipitation? What is the relative contribution of biogenic (i.e. microbial) versus abiotic methane in the subsurface serpentinizing aquifer, and does this change across the gradient of meteoric versus marine water serpentinization? Because the meteoric recharge zone is relatively well known (at least compared to other serpentinization systems), biology-mediated changes in fluid compositions (e.g. N, P, Fe, and S) could be tracked and correlated to fluid-rock interactions along pathways. Also, changes in carbon speciation can be traced and correlated with changes in carbonate mineralizations. An amphibious drilling program at New Caledonia would us to address the geological, geochemical and biological connections across the land-sea interface.

Q4. Is our understanding of (deep) oceanic serpentinization biased?

The deepest hole drilled into the altered oceanic mantle to date is Ocean Drilling Program Leg 153 Hole 920D (200.8 m) south of the Kane Fracture Zone on the Mid-Atlantic Ridge (Cannat et al., 2014). Much of our knowledge related to submarine serpentinization relies on this and other relatively shallow drillholes. Because peridotite and its serpentinized equivalents are prone to weathering at or near the seafloor (Snow & Dick, 1995; Jöns et al., 2017; Klein et al., 2017), studying igneous and hydrothermal processes is challenged by overprinting chemical and mineralogical modifications. Another issue where limited access to deep oceanic serpentinites may have resulted in a fundamental bias in our understanding of serpentinization is the formation of antigorite in the oceanic lithosphere. Lizardite and chrysotile appear to be the dominant serpentine minerals in oceanic serpentinites drilled thus far, but there is 'scattered' evidence for antigorite in oceanic serpentinite from tectonic windows such as oceanic core complexes (e.g., Atlantis Massif), or the Puerto Rico Trench (Aumento and Loubat, 1971; Groberty, 2003; Beard, 2009; Früh-Green et al., 1996; Klein et al., 2017; Ribeiro da Costa, 2008; Rouméjon et al., 2018). Moreover, there is field-, geophysical, and theoretical evidence for serpentinization of peridotite at much greater depth (e.g, Grevemeyer et al., 2018). This raises the question as to whether shallow serpentinized peridotites are representative of serpentinized peridotites deeper in the oceanic basement? If for example, antigorite is a major reaction product of serpentinization in the oceanic lithosphere, this has important consequences for the water, trace element, and redox budgets of subduction zones (Lafay et al., 2013; Debret et al., 2014). Another important question which may be addressed in a deep (>500m deep) borehole in oceanic serpentinite: Are there systematic changes in the reaction pathways, chemical, or isotopic composition with depth? If so, this would have profound implications for element cycling between the oceanic basement and seawater, for prevailing redox conditions, and the subsurface biosphere. To date, all microbiological studies in oceanic serpentinite focus on samples recovered from shallow depth. This begs the question whether microbial communities change with depth as temperatures, pressure, and fluid composition change. One may also ask whether microbial communities in the submarine (offshore) basement are related to the ones in nearshore and onshore environments. An amphibious drilling program at New Caledonia would allow us to better assess the effects of fluid composition (meteoric vs seawater derived) on serpentinization of the same (or similar) protolith, which would be a fundamental contribution to our understanding of ongoing processes and inherited serpentinization signatures.

Q5. (How) does serpentinization affect obduction? How do serpentinization processes differ?

Obduction of oceanic crust remains a poorly understood process. How does serpentinization processes and products differ in a subduction zone vs. a supra subduction zone vs. a detachment fault system? Generation of serpentinites may significantly change the mechanical properties of obducting crust, yet, there has been no systematic study of related marine and continental serpentinites, specifically those near the basal thrust zone. An amphibious drilling program at New Caledonia would us to compare obducted serpentinites with their unobducted marine counterparts. These efforts would focus on structural and geophysical properties in a drill hole that penetrates serpentinite and the underlying basal thrust. An assessment of the unobducted counterparts as well as comparing obducted lherzolites versus harzburgites, north and south NC, respectively, would probably yield important information about mechanics of obduction and the possible involvement of serpentinites.

Q6. What are the societal implications of serpentinization and weathering of serpentinized peridotite in New Caledonia?

Serpentinization of peridotite generates molecular H_2. There is a strong effect of reaction temperature on the rate of serpentinization with decreasing rates with decreasing temperature. Given that serpentinization is ongoing in the Prony Bay plumbing system, likely at low temperatures (<50˚C), what exactly is the rate of H_2 formation? Are they sufficient to be exploited on an industrial scale as a source of energy? Or is the Prony Bay system tapping an existing resource of H_2, which formed at some point earlier in time and not actively replenished by low-temperature serpentinization (see Q1)? How do rates of H2 generation differ in continental and marine settings? An amphibious drilling project would provide quantitative constraints on past and ongoing H2 generation.

Weathering of serpentinized peridotite under warm and humid tropical conditions leads to the formation of Ni-laterites. In New Caledonia these deposits represent ~30% of the global Ni resources (Sévin et al., 2012). Mining exploration in New Caledonia produced shallow (20 to 80 m) boreholes through the laterite and the saprolite and, more rarely, into the serpentinites. If mining companies would provide access to existing boreholes, this would present an opportunity to gain in-depth preliminary information about New Caledonian basement lithologies and associated alteration processes, which is important specifically for the preparation of the proposal. It may be possible to strategically tie-in these existing boreholes with planned ones to provide complementary information for NCDP and the mining industry.

Another aspect of NCDP with societal implications is the possibility of monitoring water quality and hydraulic properties of ultramafic-hosted aquifers in the basement accessed through deep boreholes. Wells could be monitored for chemical contaminants and pathogens. Serpentinization and mineral carbonation are theoretically exothermic reactions; monitoring locally heat fluxes would allow assessing their actual contribution to regional heat flow and evaluate possible applications for geothermic energy. Mineral carbonation of peridotite, serpentinite, and laterite is yet another aspect which can be explored through amphibious drilling. Natural mineral carbonation is evident at NC from magnesite concretions associated with serpentinite (e.g., Ulrich et al., 2014). Would it be possible to adapt naturally occurring mineral carbonation processes for industrial-scale mineral carbonation? The warm tropical climate may facilitate mineral carbonation at rates faster than in cold and/or arid climate (e.g., Bucher et al., 2015). The efficiency and mineralogical expressions of mineral carbonation processes could be explored in 3-D in distinct lithological units.

Drilling Strategy:

Difficult outcrop conditions, dense vegetation, and weathering on New Caledonia challenge systematic research efforts related to geological processes operating at depth that affect shallow processes with environmental implications. The key questions identified here can only be addressed through strategic scientific drilling at five onshore and three offshore sites.

a) Tontouta: The main goal of this site is to establish the pre-existing records of serpentinization, which is key to differentiating past (high-T) serpentinization from recent (low-T) serpentinization (Q1). The hole would penetrate the high deformation zone and go through the metamorphic sole and therefore address Q5. There are geologically similar areas on New Caledonia which makes the site selection negotiable.

b) Plain de lacs: Except for Tontouta, this site is farthest from the discharge zone and would presumably penetrate rocks and fluids in the recharge zone. This site would be the first one of three in a transect to the discharge zone in Prony Bay. This borehole would be part of a series of drill sites to address Q1-Q3 and Q6.

c) Near Grande Terre: This is the second site in a transect from the recharge zone to the discharge zone. It would help us understand how fluid and rock compositions change along the flow path. Links to gas seeps close by? This borehole would be part of a series of drill sites to address Q1-Q3 and Q6.

d) Prony Bay: This site would penetrate the discharge zone and complete the transect from Tountouta and Plain des Lacs. It would likely be onshore. This borehole would be part of a series of drill sites to address Q1-Q3 and Q6.

e) Goro: This site would penetrate a gabbro-peridotite contact. It is located near a major normal fault. This borehole would be part of a series of drill sites to address Q1-Q3 and Q6.

f) Offshore South of Prony: This offshore site would be the first one to penetrate serpentinized oceanic peridotite deeper than 200m. It would complement the on- and near-shore sites and establish whether / how oceanic and continental serpentinization processes differ. It would allow us to gain access to unweathered serpentinite, which is crucial for accurate mass transfer estimates between seawater and the oceanic mantle. It would also allow us to constrain whether mineralogy, geochemistry, fluid chemistry, and microbiology change as a function of depth. This borehole would primarily address Q5. It would be the marine endmember to address Q1-4, and Q6.

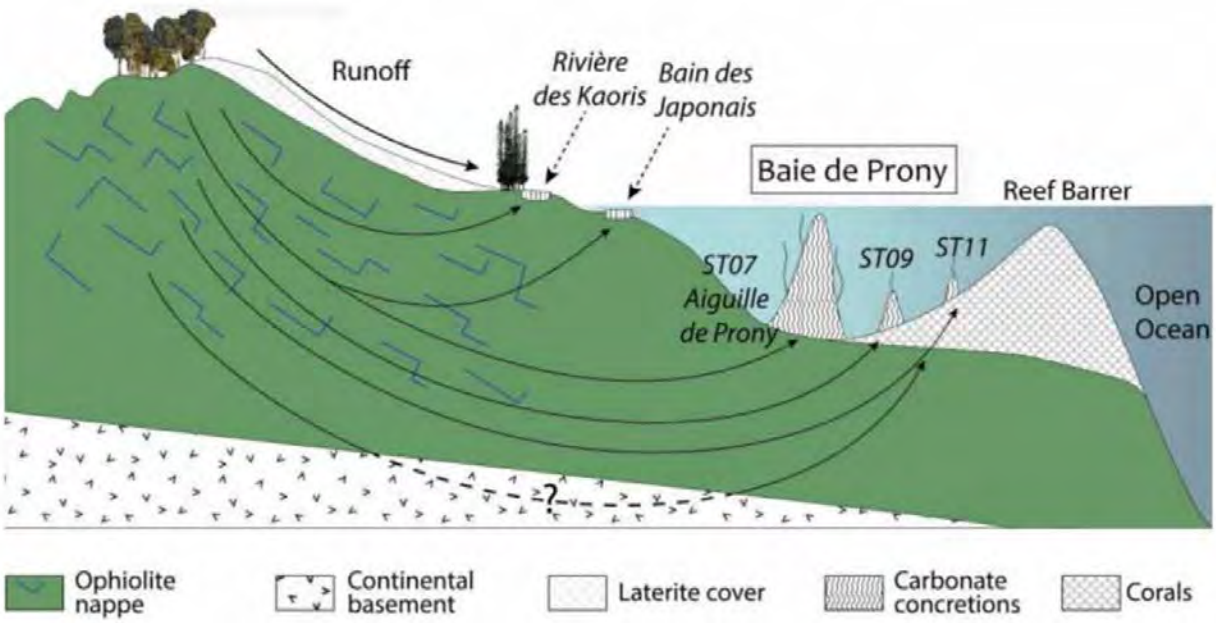


Figure 1: Possible illustrations: Expected flow paths at Prony (C. Monnin)

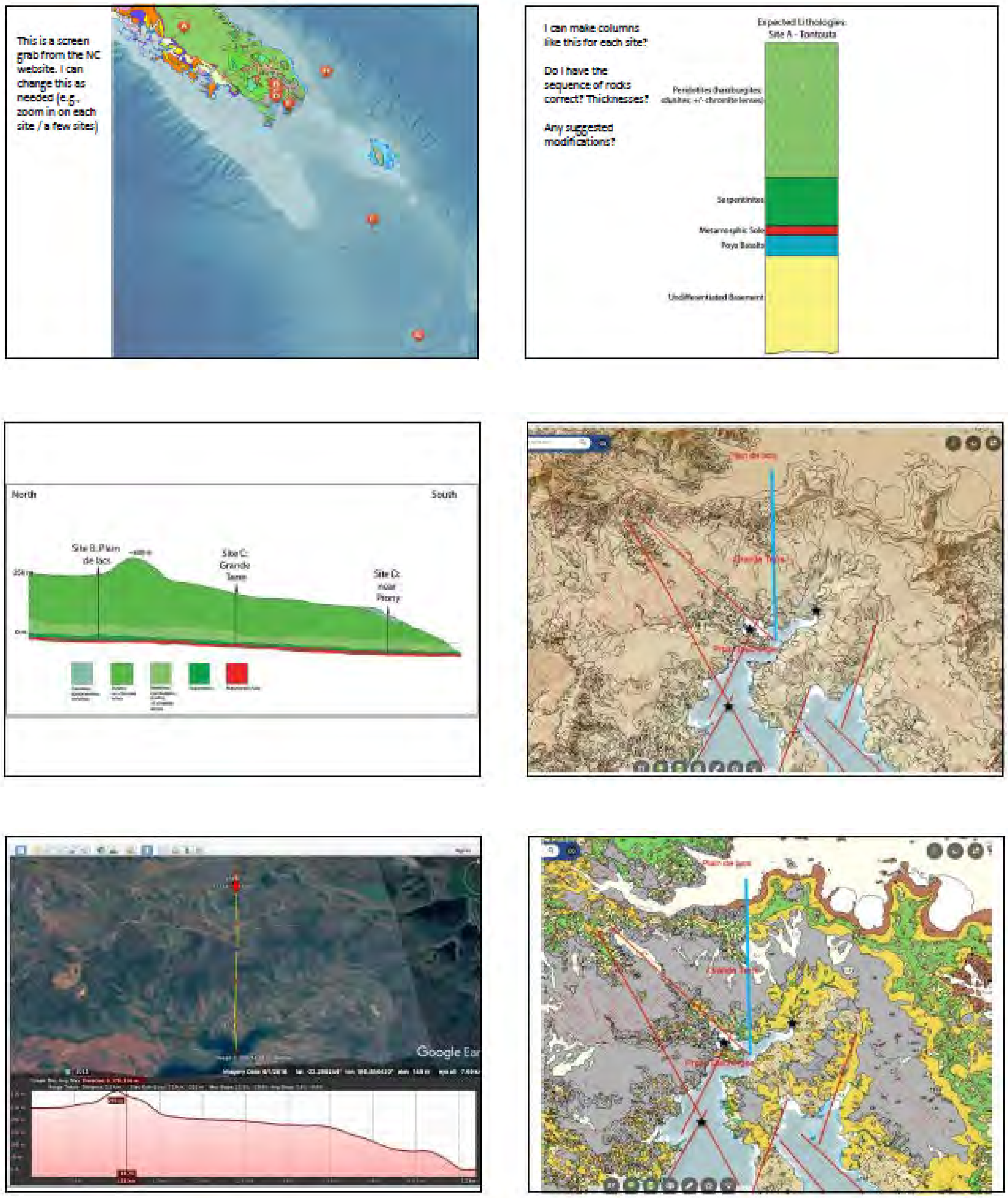
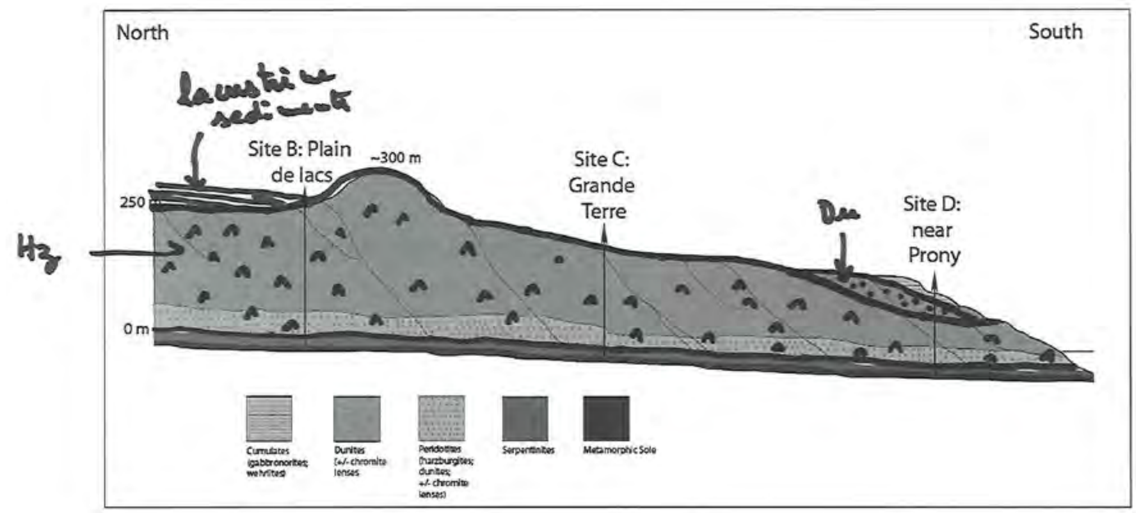


Figure 2: Possible illustrations of borehole locations and expected lithologies



I can make columns like this for each site?

Do I have the sequence of rocks correct? Thicknesses?

Any suggested modifications?

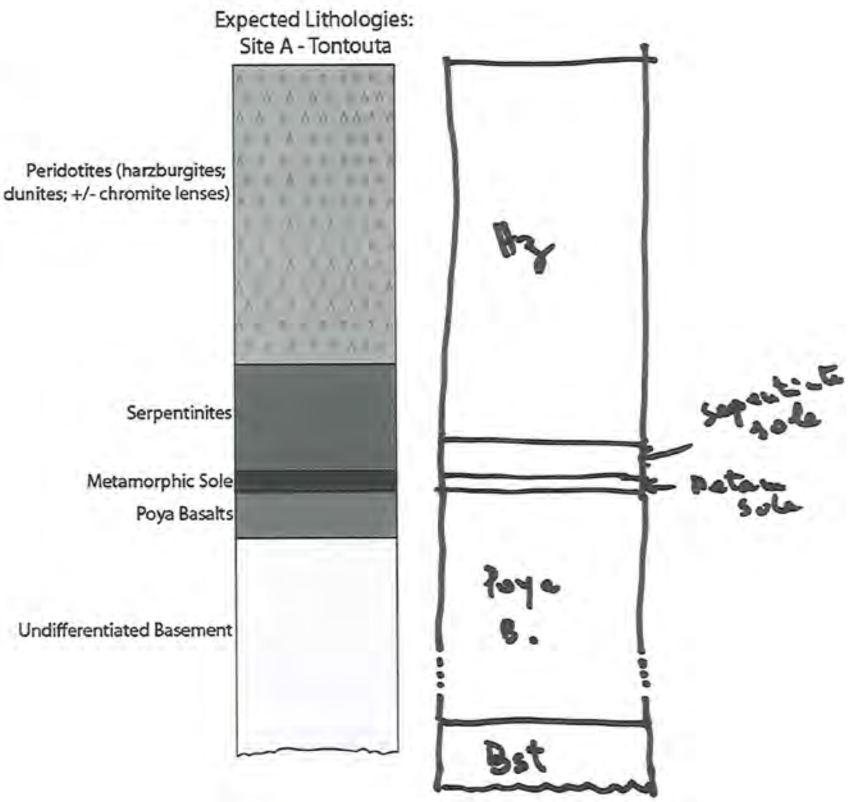


Figure 3: Discussions on possible illustrations

[NCDP Workshop, Montpellier]

Theme 3: Age, mechanisms of formation and evolution of shallow-water carbonate systems; Impact of climate change and/or interactions with mantle derived fluids

Chairs & Scribes of Breakout Group 3 (*Coordination of report): F. Fournier (*), S. Etienne, E. Tournadour

1- State of the Art and main scientific questions

The Oligocene and Miocene periods represent the most important phase in the long-term and stepwise global cooling. Such a climatic transition led from a greenhouse to an icehouse Earth. Shallow water carbonates have been shown to represent a relevant archive of the paleoclimatic and paleoceanographic changes through times (e.g. Mutti *et al*., 2010) since: 1) Neritic carbonate can be reliably dated by biostratigraphic (e.g. planktonic and benthic foraminifera), chemostratigraphic (e.g. Sr isotope stratigraphy) or absolute dating methods (U / Pb), 2) stable isotope or trace element measurements on carbonate skeletons can be used as proxy of climate changes and associated earth surface processes and properties such as continental weathering, current circulations and sea-surface temperatures, and 3) changes in dominant carbonate producers are indicative of changes in sea-water composition (including Mg/Ca ratio), nutrient concentration, paleocurrent circulation and sea-surface temperature.

The Oligo-Miocene is also a major key period in terms of evolution of surface sea-water composition since it corresponds to the transition from calcitic sea (low Mg/Ca) to aragonitic sea (high Mg/Ca). It is also a period of drastic turn-over in shallow-water carbonate producing communities, which is marked by the worldwide onset of coral reef ecosystems in tropical shallow-water area. Knowledge of the paleo-environmental events and corresponding development of reefal ecosystems in the Indo-West Pacific is embryonic when compared with other area such as the Caribbean and the eastern Pacific (Pandolfi, 2011). The rise of the modern IWP reefal biota is thought to have occurred during the critical interval spanning the transition from the Late Oligocene to the Early Miocene (Wilson, 2002) during large fluctuations in global ice volume (Zachos et al. 2001) and regional changes in tectonics. For other researchers (Pomar and Hallock, 2008), the coral capacity in building modern-type of reefal structures in the euphotic, shallow-water environments occurred later during the Late Miocene and would be likely related to the conjunction of various factors such as the major diversification of extant Symbiodinium zooxanthellae and the overall global cooling with associated increased thermal bathymetric gradients.

In addition, neritic carbonates have been proven to be relevant and reliable tools for reconstructing relative sea-level changes and therefore for quantifying vertical movements (e.g. Munch et al., 2014). The paleoenvironmental reconstructions performed from post-obduction carbonate ramp systems from the south-western margin of New Caledonia revealed the occurrence of a significant uplift during the early Burdigalian and allowed the subsidence rates to be estimated (Maurizot et al., 2015; Fournier et al., 2015).

Finally, the detailed analysis of geochemical signal (trace elements, stable isotopes) of primary carbonates and diagenetic products could make it possible to trace the evolution of the circulations of subsurface fluids, **particularly those related to serpentinization processes (cf. Theme 1 and 2)**, through the carbonate formations during the post-obduction phase.

As a result, the completion of a core drilling through an oligo-miocene carbonate build-up of exceptional thickness would provide answers to the following 4 scientific problematics:

1) **The evolution of carbonate production during the Oligo-Miocene in the Pacific domain and the onset of reefal communities;**
2) **The record of Oligo-Miocene paleoceanographic and paleoclimatic changes;**
3) **The quantification of vertical movements during the post-obduction phase;**
4) **The impact of fluids seeps on the carbonate development and diagenesis of carbonates.**

2- Drilling strategy.

The interpretation of the seismic data available on the northeastern New Caledonian margin made it possible to determine four main drilling targets, located along the Ridge of Pines (**Figure 1**):

-**DS-1**: seismic profile FAUST 206 (**Figure 2**) shows the occurrence of an exceptionally thick post-obduction carbonate buildup (averaging 500 ms TWT), overlying peridodites. By considering common velocity values in carbonate sediments and rocks (3000-6000 m/s), the estimated thickness of the carbonate buildup ranges from 750 to 1500 m. The carbonate buildup is drowned below a water-depth of 350m thus suggesting a pre-Quaternary age. The DS-1 drilling site is therefore a good candidate for a long-scale, carbonate sedimentary record covering a significant part of the Oligo-Miocene interval. It would therefore represent a potential reference site for the Oligo-Miocene paleoclimatic and paleoceanographic archive in Western Pacific area.

-DS-2, DS-3 and DS-4: bathymetrical map (**Figure 3A**) and sparker seismic profile NEOMARGE (Chardon et al., 2006)(**Figure 3B**) show an horizontal, flat surface at about 300 m water depth along the eastern margin. Some samples collected on scarp of this terrace indicate Miocene ages (Chardon et al., 2008). Currently, biostratigraphic analyses on the new thin section material are in progress and preliminary observations indicate similar depositional environments and facies compared to Nepoui carbonate-siliciclastic mixed systems previously identified on the western margin (Maurizot et al., 2016; Tournadour et al., in review). These observations suggest the establishment of Miocene carbonate system and the subsidence of the eastern margin during the Neogene. The DS-2 to DS-4 drilling sites could allow quantifying the vertical motion of the eastern margin in the continuity of Ridge of Pines.

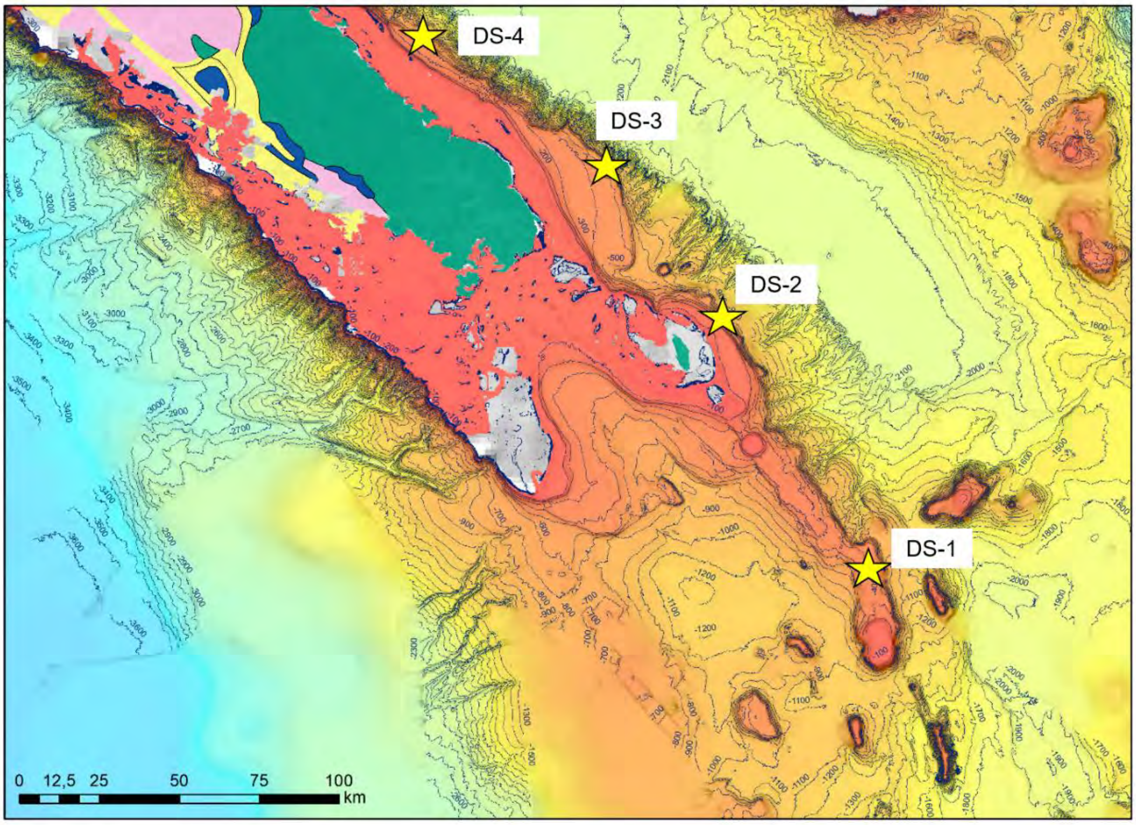


Figure 1: Location map of the proposed drilling sites.

RIDE DES PINS CARBONATE BUILDUP

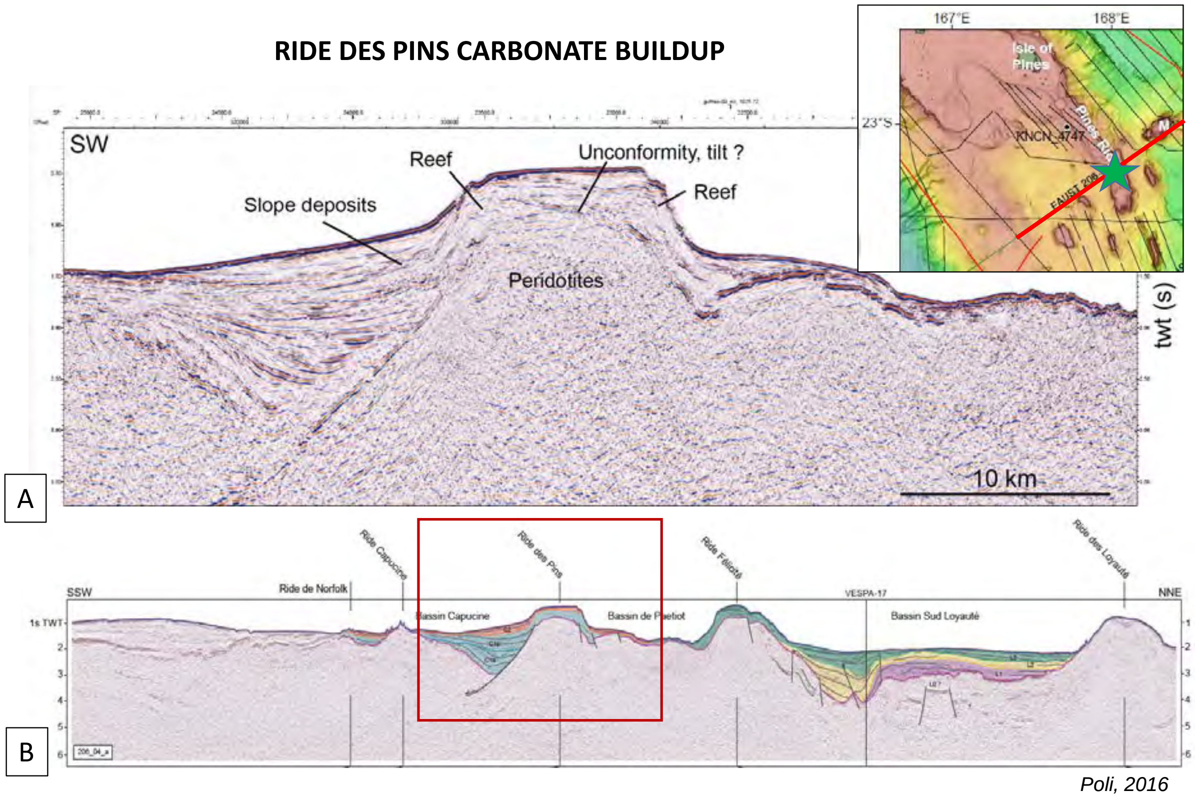


Figure 2: Ride des Pins carbonate buildup. A : focus on seismic profile FAUST 206 ; B : line drawing of the regional 2D seismic profile FAUST 206 (Lafoy et al., 1998; Poli, 2016)

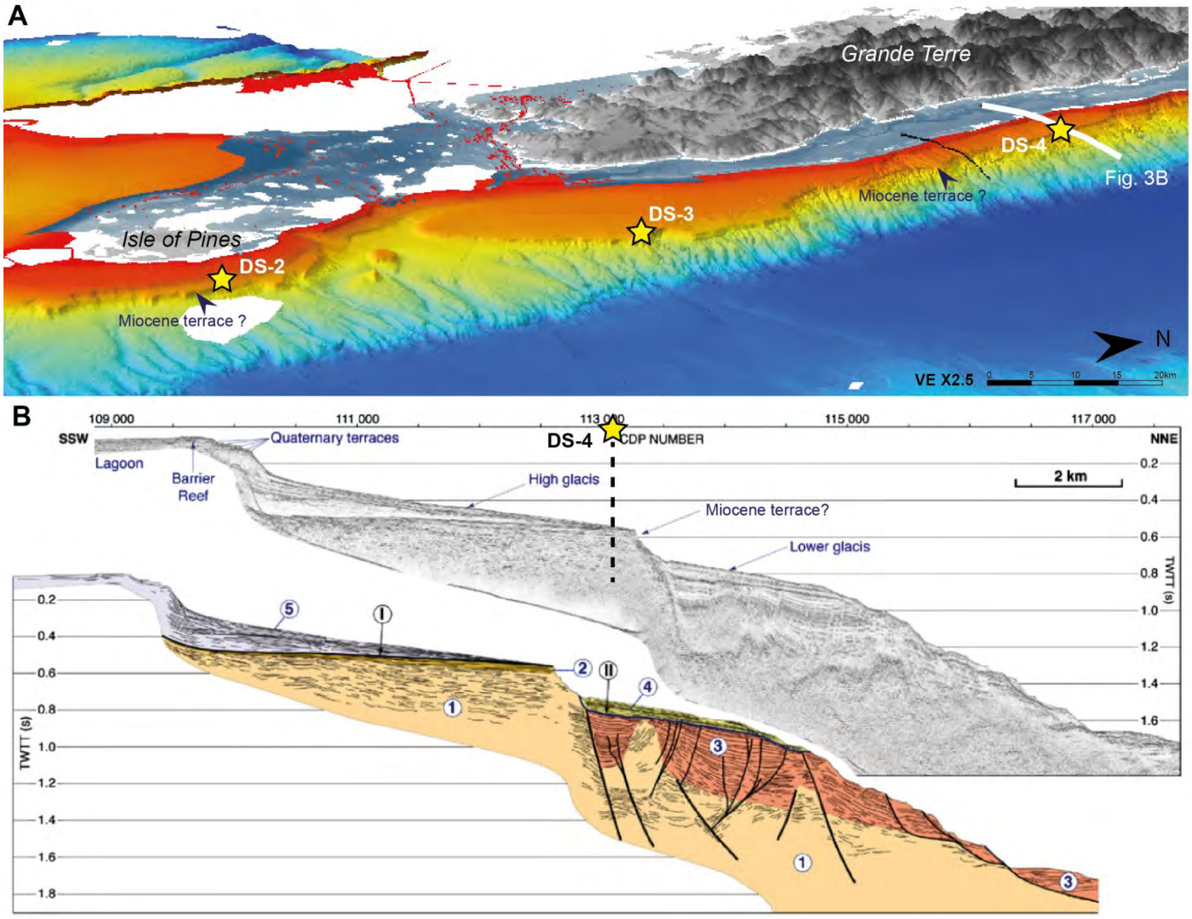


Figure 3: A. 3D view of the bathymetrical map of the eastern margin and location of the drilling sites DS-2 , DS-3 and DS-4. **B**. Sparker seismic profile NEOMARGE and location of the drilling site DS-4 (modified from Chardon et al., 2008).

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