RATIONALE FOR THE SCIENTIFIC DRILLING PROJECT "INTERACTION": INTERACTIONS BETWEEN LIFE, RIFTING AND CALDERA TECTONICS IN OKATAINA

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KARAKIA WHAKAWĀTEA

Unuhia unuhia
Unuhia te urutapu nui kia wātea
Kia māmā te ngākau, te tinana me te wairua
Koia rā e Rongo, whakairia ake ki runga
Kia tīna! Tīna
Haumi e, Hui e, Tāiki e

Draw away, draw away.
Draw away the sacredness and let us be free.
Let our hearts, bodies and spirit be unburdened.
Oh Rongo suspend this plea up high
And let it be affirmed
Let it be binding, together, all in agreeance

Keywords: *scientific drilling, mātauranga Māori, interactions, caldera, rift, biosphere, hydrology, Okataina Volcanic Centre*

ABSTRACT

The Okataina Volcanic Centre (OVC) in Aotearoa, New Zealand is of high cultural significance to Māori. The OVC is also a nested caldera complex, one of two giant active calderas of the Taupō Volcanic Zone (TVZ), ranked as New Zealand's highest threat volcano. In-situ, sub-surface observations required to better understand interactions between volcanism, rifting, fluid circulation and the deep biosphere are sparse. We propose the INTERACTION (Interactions between life, rifting and caldera tectonics in Okataina) scientific drilling programme to provide rock and fluid samples, downhole measurements and a base for a long-term observatory. Downhole samples and data, and new high-resolution ground-based surveys near the borehole will refine and fill gaps in the extensive geophysical, geological and geochemical datasets collected across the OVC and wider TVZ region since the 1950s, and advance fundamental concepts of caldera systems globally.

Scientific drilling at the OVC, coupled with extensive stakeholder engagement will lead to improved resilience to natural hazards and sustainable management of groundwater and geothermal resources. Close collaboration with Māori will achieve both scientific and cultural outcomes. New geothermal concepts (heat source, permeability and recharge), geophysical data acquisition and new technology deployment, will help future geothermal development in the central TVZ and elsewhere. Altogether, scientific drilling at the OVC will advance our understanding of: (1) drivers to volcanic eruptions, feedbacks between volcanic and seismic events, caldera evolution; (2) large-scale hydrology and magmatic systems; and (3) diversity, function, and geological processes that support deep subsurface microbial activity and response to a highly active geosphere. At these early stages of planning, we invite contributions to the concept of this project in the exceptional OVC settings and strengthen linkages with other ongoing research and geothermal drilling programmes.

1. NGĀ KŌRERO MŌ RŪAUMOKO (NGATI RANGITIHI)

I te tīmatanga o te orokohanga, nā te aroha nui o Ranginui rāua ko Papatuanuku, i piritahi rāua i te tauawhinga mutunga kore. Heoi e noho ana ā rāua tamariki i roto i te pōuri, ā, ka puta, e ai ki ētahi, te whaikōrero tuatahi i waenganui i a Tāne Mahuta, i a Whiro, i a Tāwhirimātea me ētahi atu, mō tō rātau āhua noho. Ko tā Tāne, kia wehea ngā mātua. Kāore a Whiro rāua ko Tāwhirimātea i whakaae. I reira ka tautohetohetia te take rā, engari i te mutunga iho ka whāia ko tā Tāne. Ka whakamahia e ia ōna waewae hei pana i a Rangi ki runga, i wehe ai ōna mātua. I a koe e whakatau ana i tētahi rākau hei mahi Taiaha, me anga te ūpoko ki te papa. Ko te ūpoko hoki o Tāne Mahuta i piri ki te papa, ko ōna waewae ngā peka, otirā koinei te āhua i māwehea ai ōna mātua.

Nō muri i te wehetanga a Tāne i ōna mātua, he wā kōuaua anō i a rātau e tirotiro haere ana. Waipuketia ana ngā tama i ngā roimata a Ranginui mō tōna whaiāipo a Papatūānuku. Ka whakaaro iho a Tāne Mahuta me ōna kaitautoko kia hurihia a Papatūānuku kia kore a ia e kitea mai e Ranginui, ā, kia mutu ai te tangi. Ka hurihia e ia tōna whāea, ā, ka mutu. Engari i roto tonu a Rūaumoko i te kōpū o tōna whāea, nā, ka mau ia ki roto mō āke tonu. I Te Ao Māori, e noho pukuriri ana ia. Ko ngā rū whenua ērā. E kore hoki a Whiro e hākoakoa, ā, ka ahu mai i a Tāwhirimātea te āwhā, te marangai me te hau, nā tana riri ki te wehenga o ō rātau mātua.

In the beginning of creation, Ranginui and Papatūānuku were so in love that they were locked in an eternal embrace. However, their children were in complete darkness and so began, some say, the first whaikōrero (public speaking) between Tāne Mahuta, Whiro, Tāwhirimātea and others, about their situation. Tane suggested that they part their father and mother. Whiro and Tāwhirimātea were against the separation. There was kōrero tautohetohe (argument) about doing this, but in the end Tāne Mahuta won the argument. He used his legs to separate his mother and father. When you select your wood to make the Taiaha (Māori long club), the Upoko (head of the Taiaha) has to be the end from the ground. Tāne Mahuta's head is in the ground and his legs are the branches, that's how he separated them.

When Tāne Mahuta succeeded in separating his parents there was a time of rain as they looked at each other. The tears of Ranginui for his Whaiaipo (sweetheart), Papatūānuku, created a flood for the tamariki (children). Tāne Mahuta and his supporters decided to turn Papatūānuku over so that Ranginui would not be able to see her and the crying would stop. He turned his mother over and the crying stopped. Unfortunately, Rūaumoko was still in his mother's whare tangata (womb), so he is trapped there forever. In Te Ao Māori, the Māori world, he is not happy. That's how we get rūwhenua (earthquakes). Whiro the god of evil is never happy and Tāwhirimātea brings us bad weather, storms and winds because he also is not happy about their parent's separation.

This kōrero has been provided by Tiipene Marr and translated by Tamati Waaka.

2. INTRODUCTION

2.1. Benefits of scientific drilling

Scientific drilling provides high-resolution and *in-situ* recording of geological and biological changes through time and in response to volcanic or tectonic events not available from surface-based surveys. Downhole rock and fluid sampling are the only way to investigate subsurface microbial communities, their growth rates and responses to environmental changes imposed by sudden events (e.g, eruption, earthquake) within the extremely nutrient and substrate-poor deep subsurface.

Scientific drilling and associated studies in volcanic and geothermal regions have significantly improved our understanding of geological processes (including the Iceland Deep Drilling Project (IDDP): Elders et al., 2014; Friðleifsson et al., 2020); Campi Flegrei: Carlino et al., 2015; Unzen Scientific Drilling Project: Nakada et al., 2005; and Brothers Volcano in the Kermadec Arc offshore New Zealand: De Ronde et al., 2019). For example, the first phase of IDDP yielded the world's hottest well during flow test, which advanced concepts of hydrothermal systems and plate tectonics in mid-ocean ridge settings (Elders et al., 2014; part of a special issue of the Geothermics journal). IDDP-1 improved the magmatic and conceptual model of the Krafla Geothermal Field and magma plumbing beneath collapse calderas (e.g., Kennedy et al., 2018) alongside drilling, downhole measurements and geophysical technology advancement (Asmundsson et al. 2014; Pálsson et al. 2014) which are increasingly used in conventional geothermal operations. The second phase of IDDP at Reykjanes successfully drilled into a supercritical geothermal system and has provided opportunities to investigate water-rock interaction in the active roots of an analog of a submarine hydrothermal system. The Long Valley exploratory well (U.S.A.) provided data on the Long Valley caldera structure and evolution (Rundle and Eichelberger 1989), including downhole stress measurements (Moos and Zoback 1993) from the, then recently developed, ultrasonic borehole televiewer (Zemanek et al. 1970). Borehole televiewer logs are increasingly used in geothermal fields to map fractures and *in-situ* stress, which also inform on plate tectonic processes (e.g., Ziegler et al. 2016). In intra-arc rifts such as Kyushu, Japan (Kamata and Kodama 1999), and the Trans-Mexican Volcanic Belt (Ferrari et al. 2012), which host a large geothermal potential (Bertani 2016), it is important to pursue efforts to better understand magmatic and tectonic processes, and the role of the subducted slab in fluid chemistry and circulations through the crust.

2.2. The Okataina Volcanic Centre: natural laboratory to explore interactions between life, rifting and caldera tectonics

The Okataina Volcanic Centre (OVC) is a nested caldera complex (Cole et al., 2014) located within the continental intra-arc Taupō Rift which has rapid extension rates (5-15 mm/year; Wallace et al., 2004; Lamb, 2011; Villamor and Berryman, 2001) and has evolved significantly faster than comparative intracontinental rifts such as the African Rift (Macgregor 2015; Villamor et al. 2017) (Figure 1). Voluminous silicic volcanism in the Taupō Volcanic Zone (TVZ) is fueled by melting caused by basalt flux from the mantle that is unusually high for its continental arc setting (Wilson et al. 2009), facilitated by rapid rift extension rates (Villamor and Berryman 2001; Smith et al., 2005). Numerous eruptions of varied size and style, common basalts and the rapidly extending Taupō Rift make the OVC ideal for studying eruption's frequency-magnitude relationships and drivers to eruptions. Hydrothermal manifestations are dominantly located on some, but not all, parts of the caldera margins and sometimes occur beneath lakes (Nairn 2002; Tivey et al. 2016). This configuration will allow the entire groundwater-geothermal system and geological controls on up- and down-flows to be studied. Microbiology community composition and function have been documented in hot springs across the TVZ (Power et al. 2018), but their extent and diversity remain unknown in the subsurface.

In this paper, we present the concept and wide-ranging benefits that will stem from the proposed scientific drilling project: INTERACTION: (Interactions between life, rifting and caldera tectonics in Okataina). We are preparing a preliminary proposal for future support from the International Continental Drilling Program (ICDP). To develop a compelling programme, we seek to build strong relationships with Māori communities; assemble a multi-disciplinary national and international team; and engage with the geothermal industry.

3. SCIENTIFIC OBJECTIVES

The INTERACTION international scientific drilling project will unravel how volcanism, tectonism, fluid circulations and microbiota interact at the OVC, an active caldera within a fast intra-arc rift. We will conduct drilling, coring, extensive downhole measurements and install observatories at two sites: one in the centre of the caldera and another on the caldera margin. We will integrate knowledge gained from the drilling and post-drilling monitoring with the extensive existing surface-based datasets and New Zealand's national geohazards monitoring programme Geonet. The project will be co-produced with tangata whenua (local Māori) to integrate mātauranga Māori (indigenous knowledge) and kaitiakitanga (guardianship of the land) including protection of treasured fresh- and hydrothermal water features (taonga). The new multi-disciplinary knowledge derived from international partnerships and disseminated through stakeholder engagement and outreach will lead to benefits globally.

The complex interactions occurring in rift/caldera settings can be described in three themes:

- Theme 1 - Rocks: identify drivers to eruptions, feedbacks between volcanic and seismic events, timing and rates of deformation and crustal properties.

- Theme 2 - Fluids: explore the hydrology resulting from the 3D relationships between magmatic heat input, fault architecture, stratigraphy and permeability (aquifers and aquitards) and topography.
- Theme 3 - Life: determine the deep subsurface microbial community structure and function, and how this community interacts with and responds to underlying geological and hydrogeological processes.

The themes are linked, e.g., fluids affect the thermal and mechanical states of the crust which in turn affect magma eruptibility and fault rupture tendency. The nature and activity of the deep biosphere depends upon the fluid types and temperature, modulated by volcano-tectonic activity (Colman et al. 2017; Fullerton et al. 2020).

Outcomes will be linked with findings from existing data on microbial communities sampled from surface geothermal hot springs; extensive regional geophysics; shallow (<100 m) intra-caldera groundwater boreholes; and deep (2-3 km) geothermal wells outside the caldera. The proposed scientific drillholes will provide the first TVZ sub-surface biosphere exploration; and complete a transect of drillholes along the TVZ arc which currently lacks subsurface data in the active calderas.

This research is aligned with the ICDP science goals (Horsfield et al. 2014); key targets of the UNDRR (Sendai framework For Disaster risk reduction 2015-2030); the UNFCC aiming to reduce CO_2 emissions under the Paris Agreement; the NSF-funded Subduction Zones in four dimensions (SZ4D); the NSF decadal vision for Earth Sciences; and the Convention of Biological Diversity goals of quantifying, describing and conserving global biological diversity.

3.1 Drilling strategy

We propose to drill and install observatories in two boreholes to record long-term geological and biological changes through time and in response to volcanic or tectonic events. Drill Target 1, in the central portion of the OVC, will examine the extensive volcanic record and thermal conditions above the inferred magma reservoir. Drill Target 2, in a section of the caldera margin oblique to the rift, will examine the structural and permeability architecture of the fault zone, at a greater distance from the inferred magma. Drill target 2 will also focus on the biosphere and any variability due to faulting or volcanic activity. Discovering and comparing the geological and biosphere context in both holes will reveal any variety of life due to different geological conditions. Exact drilling locations will be set together with local Māori communities, and based on high-resolution geophysical surveys (magnetics, resistivity, heat flow, seismicity, gravity) in the context of existing regional surveys.

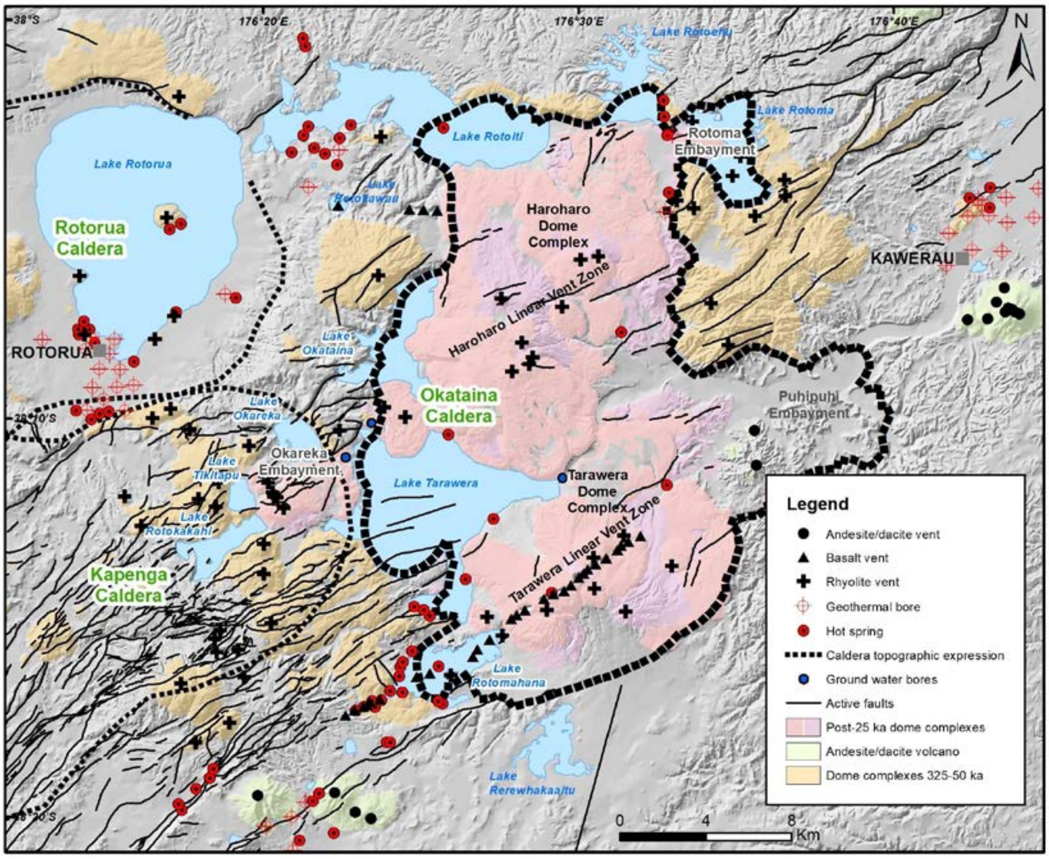

Figure 1. Simplified volcanic geology of the Okataina Volcanic Centre including lava dome complexes (all of which were deposited in association with multiple pyroclastic eruptions; Nairn 2002) and their general ages, locations of the main faults; geothermal boreholes; Lake Tarawera Groundwater Investigation drillholes (Thorstad et al., 2011; Rose et al., 2011; Lovett et al., 2012); and hot springs.

Contrary to the geothermal drillholes located outside the caldera, the sites will be targeted for low-temperature and limited hydrothermal alteration conditions, to maximise findings from analysing recovered cores and cuttings (using textures, dating, isotopes...) and explore fluid recharge zones while relying on conventional drilling systems and sensors. The caldera margin drillhole will be targeted in an area <120°C to provide long-term access for biosphere studies. This strategy will provide critical and extensive insights into fundamental geo-, hydro- and biological processes occurring in active calderas. Basalt crystals in core samples will provide windows into deeper, past mantle processes. Monitoring of possible changes in magma (fluid or melt) both intra-caldera and through a caldera margin (potentially directly connected to the mid-crust) will also inform on contemporary deep processes, and effects on sub-surface biosphere.

By targeting low-temperature conditions, this project is complementary to other scientific drilling projects aimed at supercritical and magma systems (including at Newberry (NDDP), Krafla (KMT, IDDP), Japan (JBBP)). With the clear Taupō rift expression, this project is also complementary to the ICDP/IODP proposal at Campi Flegrei (Sacchi et al. 2019). A recently funded W.M. Keck Foundation proposal (PI: E. Boyd and T. Onstott; https://onstott.princeton.edu/node/102) aims to evaluate the hydrothermal fluids and microbial activity in response to seismic activity in several existing boreholes at Yellowstone National Park, WY, USA. A comparison of these two subsurface communities from different tectonic settings (intra-arc rift and hotspot) will provide an unparalleled insight into seismobiological interactions in the deep biosphere.

Outreach activities will involve decision-makers, industry and local communities including Māori, leveraging off existing framework developed as part of ongoing New Zealand government funded research.

3.2 Target 1: The inner depths of the OVC

Drilling into the central portion of the OVC to at least 2 km depth will provide a complete stratigraphic record of eruptions. This will provide a suite of samples that can be analysed within a time-constrained sequence to assess the magmatic processes that occur prior to caldera eruptions. We will then be able to identify the drivers of small and large eruptions and reveal variations in the magma plumbing through the ~700 Kyr magmatic history of the OVC. This drilling target will aim to address the following questions:

- Theme 1 - Rocks: What is the eruption frequency-magnitude? How do mafic injections and nearby faults drive eruptions? How do caldera eruptions disrupt the magma plumbing?
- Theme 2 - Fluids: What controls the 3D cold-water and hot-water flow systems, hence fluid recharge zone? How is fluid flow impacted by deep aquitards (e.g., pre-historic caldera lakes)?
- Theme 3 - Life: What are the environmental limitations for subsurface life?

3.3 Target 2: Caldera margin zone where the rift and caldera intersect

Drilling into the OVC caldera margin to ~800 m depth to define the fault zone's architecture and monitoring changes in response to tectonic and magmatic activity will test the hypothesis that these major structures strongly affect the thermal, stress states and permeability of the mid-upper crust by connecting the mid-crust to the surface vertically, and tectonic to magmatic rift segments horizontally. This drilling target will aim to address the following questions:

- Theme 1 - Rocks: What is the thermal and stress state of the crust near caldera margins? Are caldera margin segments seismogenic? Do they contribute to accommodating extension?
- Theme 2 - Fluids: What is the permeability structure of the caldera margin through space and time? What are the hydrogeological connections between the OVC and surrounding TVZ structural elements?
- Theme 3 - Life: Can geological activity e.g. slips on the caldera margin or nearby tectonic faults, and/or changes in magmatic fluids, induce change in microbiological growth or activity?

A kinetically-activated subsurface microbial sampler (KASMS) (designed and developed by T. Onstott and colleagues) will be deployed in this drillhole. This device can capture samples or geochemistry, microbiology (i.e. cultivation studies); and molecular community (metagenomics and diversity) and functional (metatranscriptomics) analysis. Critically, the KASM Sampler will trigger autonomously with the onset of a seismic event. This ability substantially increases the chances of successfully capturing water samples/microbial communities following a seismic event by removing the requirement for human operation.

4. RELEVANCE TO SOCIETY AND TO THE GEOTHERMAL INDUSTRY

4.1 Global societal relevance

This research addresses global issues and scientific questions. The outcomes of this research interweave indigenous knowledge with modern science to provide a strong societal narrative of the importance of combining modern and traditional knowledge.

- Volcanic and earthquake hazards:

Conversion of scientific knowledge into tailored hazard planning advice will allow decision-makers worldwide to better anticipate and assess the volcanic and seismic hazards through optimised monitoring programs, leading to improved community resilience.

- Energy resources; water quality and availability:

The project will foster the sustainable management and protection of hydrothermal and groundwater resources by addressing challenges of geothermal development: 1) challenges in imaging heat sources and flow pathways (Huttrer 2020); 2) limited understanding of meteoric water recharge through space and time; and 3) risk of affecting culturally and economically (tourism) important surface hydrothermal features by altering the deep fluid circulation.

- Deep biosphere ecology and function:

Understanding the caldera- and fault-associated deep biosphere diversity and function will inform strategies on conservation and potential use of subsurface biota, and sustainable management of hydrothermal and groundwater resources.

4.2 Relevance to Māori

Māori will gain from the knowledge and relationships developed during the project:

- Education at all ages, from primary schools to university students and adults. There will be opportunities for visiting the drill site and learning about engineering and science. Scientists from New Zealand and overseas will also get opportunities to learn about Mātauranga Māori.

- Better preparation for future potential earthquake or volcanic activity, including contribution to early warning systems.

- Better understanding of geothermal systems for future sustainable energy.

- Support for tourist information explaining both the geology and Mātauranga Māori (Māori science).

4.3 Relevance to the geothermal industry

This project will support the geothermal industry in New Zealand and globally even though it is not aimed at producing geothermal energy.

This project will improve knowledge on heat transfer and geothermal systems in calderas which have a large heat source but poorly understood fluid pathways. We will unravel the hydrology resulting from the specific 3-D relationships between magmatic heat input, unit type, fault architecture, stratigraphy, permeability types and topography. This project will have a geothermal focus on: (1) recharge by meteoric fluids, a required input to geothermal reservoir models; (2) measuring a wide range of physical and hydrological properties for calibrating geophysical surveys; and (3) quantifying formation type, aquifer permeability and fracture/fault permeability.

The project will deploy new exploration technologies in collaboration with international partners before, during and after drilling, within the borehole and in the vicinity. The boreholes will be available for testing new downhole technologies. The project will also foster opportunities to test interpretation methods developed elsewhere, e.g. integrated geophysical interpretation. High-resolution surveys will be conducted to locate the depth of basement in the centre of the caldera, and the precise location of a caldera margin zone, which are relevant to many commercial geothermal exploration efforts. Altogether, this project will provide opportunities for industry to test the applicability of technologies and methods for geothermal resource exploration and sustainable management.

The new data and outreach activities will facilitate decisions on future possible development in the region. Long-term access to these monitoring wells may also support environmental monitoring for potential future new venture in the region.

5. CONCLUSION

The proposed INTERACTION scientific drilling project will increase knowledge on the biosphere and geosphere in the Okataina Volcanic Centre, with wide-ranging benefits to local communities, policy-makers, industry and scientists in New Zealand and overseas. We are developing (and inviting new) collaborations with stakeholders, scientists and engineers to assist in prioritising the research objectives, planning project goals and identifying potential well targets, and funding the project. We are building relationships with Māori communities so that we can develop a strong programme of scientific and Māori indigenous cultural importance. We also seek to strengthen links with other ongoing scientific drilling programmes in geothermal and volcanic areas.

This project is complementary to past and ongoing drilling projects targeting super-hot geothermal resources by targeting conventional temperatures; and to the Campi Flegrei drilling programme by focusing on the interactions between the caldera and the rapidly extending Taupō rift.

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KARAKIA WHAKAWĀTEA

Kia tau ngā manaakitanga a Te Mea Ngaro
Ki runga i tēnā, i tēnā o tātau
Kia mahea ai te hua mākihikihi
Kia toi te kupu, toi te mana, toi te whenua
Tūturu whakamaua kia tīna. Tīna!
Haumi e, Hui e, Tāiki e.

Bestow the blessings of the unseen force
upon each and everyone
Clear our path of any obstructions
And the words, the prestige and the land flourish
Indeed let it be affirmed
Let it be binding, together, all in agreeance

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