

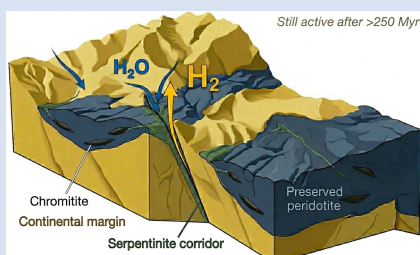
Supra-subduction zone ophiolites retain hydrogen generation potential after 300 Myr

F.V. Donzé^{1*}, L. Truche¹



<https://doi.org/10.7185/geochemlet.2614>

Abstract



The Ural Mountains host well documented natural hydrogen (H_2) emissions, yet the Palaeozoic ultramafic complexes are 250–400 Ma old and could have exhausted serpentinisation potential through progressive alteration over geological time. We revisit overlooked Soviet observations from the Kempirsay chromitite district and compare them with recent data from the younger, Jurassic Bulqizë ophiolite in Albania. In both massifs, H_2 -rich seeps (>80–90 vol. % H_2) occur within ~300 m of podiform chromitite bodies. At Kempirsay, degassing takes place at low temperatures (14–30 °C), and experiments on Kempirsay rocks show that Fe-bearing minerals can generate H_2 at near-ambient conditions. New radiocarbon data from Bulqizë methane (apparent age ~26 ka) demonstrate that associated CH_4 - H_2 inventories are renewed on 10^4 year time scales. We interpret chromitite bodies and their damage zones as catalytic and hydraulic hubs embedded in a supra-subduction zone ophiolitic architecture that localises serpentinisation and preserves reactive peridotite. This chromitite centred architecture implies that chromitite-bearing mantle slabs can retain hydrogen generation potential for hundreds of millions of years and constitute priority targets for natural hydrogen exploration and stimulated geological hydrogen production.

Received 4 December 2025 | Accepted 16 March 2026 | Published 20 April 2026

Introduction

Recent mining accidents in Kazakhstan's chromite mines have brought renewed attention to the persistent hydrogen hazard in these ancient geological formations. In February and May 2025, fires at the "Bolashak" mine injured several workers and forced temporary suspension of operations, highlighting a phenomenon that has affected these mines for decades (ISSSource, 2025). These incidents echo observations dating back to 1979 from the same mining district, when hydrogen-rich gas ignited underground, creating what miners described as "calm flames over 12 m high" (Ukhanov *et al.*, 1987). The first documented observations of H_2 -rich gas (66.5–81 % H_2) in Ural mines date from 1925–1931 (Bohdanowicz, 1934; Lidin *et al.*, 1982) in the Nizhny Tagil dunite massif during drilling at ~600 m depth. Soviet research, often overlooked in Western literature, also showed that hydrogen emissions at the Kempirsay massif occurred exclusively within 300 m of chromitite bodies and were never reported in barren ultramafic units (Lidin *et al.*, 1982).

The persistence of hydrogen degassing from Palaeozoic ophiolites in the Ural Mountains highlights gaps in our understanding of natural hydrogen systems. Despite their geological age, 250–400 Ma, these ultramafic complexes release hydrogen at rates comparable to much younger systems. These observations closely parallel those from the Bulqizë mine, hosted in a Jurassic ophiolite approximately 170 Ma old, where active hydrogen seeps persist within chromitite-bearing peridotites (Truche *et al.*, 2024, 2025; Yao *et al.*, 2025). The fact that these ophiolites, spanning a Palaeozoic to Mesozoic age range, display similar

degassing patterns suggests a common underlying control, raising the question of whether podiform chromitites play a fundamental role in natural H_2 systems of chromitite-bearing SSZ ophiolites worldwide. Without ruling out the possibility that part of the present day hydrogen emissions reflect older serpentinisation events that are no longer active, we address this question by examining several features of these ophiolites that may support long lived and still active H_2 systems. A first order observation is that both Kempirsay and Bulqizë share a common geological heritage: they are supra-subduction ophiolites that host abundant podiform chromitites. Podiform chromitites form in such settings during high degree partial melting of the mantle wedge, and concentrate chromium-rich minerals. Similar associations between chromitite bodies and hyperalkaline H_2 - CH_4 fluids have been documented in several other chromitite-bearing ophiolites worldwide (Donzé *et al.*, 2024; Pappalardo *et al.*, 2025), suggesting that chromitite-bearing ophiolites of this type may represent a coherent class of natural hydrogen systems. Here we use a comparative analysis of the Kempirsay and Bulqizë ophiolites to document this class and to discuss its implications for natural hydrogen generation and exploration.

Geological Setting and Hydrogen Occurrences in Ural and Bulqizë Chromite Mines

The Ural Mountains exhibit numerous ophiolitic complexes that originate from the oceanic lithosphere formed during the

1. Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, Univ. Gustave Eiffel, ISTerre, 38000 Grenoble, France

* Corresponding author (email: frederic.donze@univ-grenoble-alpes.fr)

Palaeozoic evolution of the Uralian Ocean between 400–250 Ma (Puchkov, 2009). These complexes were obducted during the Late Devonian–Early Carboniferous collision between the Baltica and Siberia–Kazakhstan continents. Among these, the Kempirsay massif in Kazakhstan stands out as one of Earth's largest exposed ultramafic complexes, covering over 900 km². Within the Sakmara allochthon, it represents fore-arc lithosphere formed along the Devonian Magnitogorsk Island arc (Savelieva *et al.*, 1997). To understand the significance of hydrogen emissions from such ancient rocks, we can compare them with the much younger Bulqizë ophiolite in Albania (Table 1). This Jurassic complex formed 160–165 million years ago in a Neo-Tethyan setting (Beccaluva *et al.*, 1994), providing an interesting contrast.

Kempirsay and Bulqizë share similarities with both hosting large podiform chromitites surrounded by dunite envelopes (Melcher *et al.*, 1997; Truche *et al.*, 2024). They both display persistent H₂ outgassing, with gas compositions >80 % H₂. However, they differ on some other points. Firstly, the Kempirsay ophiolitic massif exhibits exceptionally low surface heat flow values of 25–35 mW m^{−2}, well below the global continental average of ~65 mW m^{−2} (Kukkonen *et al.*, 1997). Temperature–depth profiles indicate a present day crustal gradient of ~12 °C km^{−1} in the upper 2 km. By contrast, measurements inside the Bulqizë mine show gradients of 25–30 °C km^{−1} in the upper 2–3 km, implying temperatures above 100 °C at depths of a few kilometres (Yao *et al.*, 2025). Secondly, the degree of serpentinisation also differs. Historical work, based on limited sampling from mine galleries, suggested that ~28 % of the Kempirsay peridotite was serpentinised (Lidin *et al.*, 1982), but later drilling and bulk rock LOI (“Loss On Ignition”) measurements indicate that the uppermost kilometre is now almost completely hydrated (70–100 %, LOI = 10–17 wt. %), with fresh lizardite restricted to depths >1 km (Saveliev *et al.*, 2022). At Bulqizë, most harzburgite and dunite remain largely unaltered (<2 % serpentine) over the first kilometre, with hydration focused in chromitite-bearing fault corridors (Xiong *et al.*, 2015). Inside these corridors, the alteration intensity rises from dunite envelopes to massive chromitite, reflecting multiple serpentinisation pulses and late fluid percolation.

The spatial distribution of hydrogen emissions provides insights into the controlling factors of these ancient systems. At the Kempirsay massif, underground mapping by Soviet geologists documented a clear pattern: all hydrogen occurrences cluster in the immediate vicinity of chromitite ore bodies (Lidin *et al.*, 1982). The Molodezhnaya mine exemplifies this relationship, with sustained flows reaching 20 m³ day^{−1} from

fractures adjacent to chromitite lenses. Gas composition shows extreme hydrogen enrichment (92–98 %) with minor methane (0.8–1.7 %) and nitrogen (0.4–0.6 %), plus trace helium, similar to the 84 % H₂ observed at Bulqizë (Truche *et al.*, 2025) despite the large differences in age and temperature.

Strong support for low temperature generation comes from Soviet experimental work that has received little attention in recent literature. Devirtz *et al.* (1992) reacted crushed dunite from the Kempirsay mines with controlled additions of water in sealed glass reactors and quantified H₂ in the headspace at both 100 °C and 17–24 °C, documenting concurrent Fe(II) oxidation consistent with water reduction by ferrous iron. Although low temperature serpentinisation experiments are subject to considerable rate variability and potential artefacts (Barbier *et al.*, 2020), the Devirtz *et al.* (1992) results are internally consistent across independent lines of evidence (H₂ yields, Fe²⁺/Fe³⁺ budgets, thermodynamic feasibility, and isotopic fractionation). Similar low temperature hydrogen generation has been reported from other serpentinising systems (Ellison *et al.*, 2021), although the specific role of chromitites as catalytic enhancers remains underexplored. Radiocarbon measurements on methane from Bulqizë (Truche *et al.*, 2025) provide an additional constraint on the time scales of these systems. A value of 3.76 ± 0.06 pMC, corresponding to an apparent age of ~26,000 years, shows that at least part of the CH₄ inventory is renewed on 10⁴ year time scales rather than the 10⁶ year scales occasionally discussed for ophiolitic systems (*e.g.*, Etiope and Schoell, 2014). The young age of CH₄ implies that the associated H₂ required for its synthesis must also be recently produced, indicating active hydrogen generation rather than simple release of ancient gas reservoirs. This suggests that chromitite-bearing SSZ ophiolites may play a more dynamic role in the global carbon and hydrogen cycles than previously recognised.

These observations are consistent with the idea that low temperature serpentinisation can sustain hydrogen generation under appropriate geochemical conditions, but they do not by themselves explain why active seeps in both massifs are strictly confined to the vicinity of chromitite ore bodies; this is the question we now address in the following discussion.

The Chromitite Catalytic Factory

The association between hydrogen emissions and chromitite bodies at Kempirsay and Bulqizë is supported by converging spatial, geochemical, and mineralogical evidence. In both massifs, all documented H₂-rich seeps are located within a few

Table 1 Comparative characteristics of H₂-producing ophiolitic systems (references for the values are provided in the text).

Parameter	Kempirsay (Urals)	Bulqizë (Albania)	Implications
Geological features			
Ophiolite age	250–400 Ma	160–165 Ma	200+ Myr age difference
Geothermal gradient	~12 °C/km	25–30 °C/km	Distinct thermal regimes
Temperature assessment at H ₂ source depth	14–30 °C	100–150 °C	Different generation conditions?
Degree of serpentinisation	~28 % (historical estimate)	<2 % in harzburgite	Substantial fresh rock remains
Gas characteristics			
δD-H ₂ (‰ VSMOW)	−744 to −766	−743 ± 3	Remarkably similar signatures
H ₂ concentration	92–98 %	84 ± 4 %	Both highly enriched
CH ₄ content	0.8–1.7 %	13.2 ± 0.7 %	Variable secondary processes
Maximum documented H ₂ flux	20 m ³ /day	~550 m ³ /day	Different scales or preservation?
Association with chromitite location	100 %	100 %	Comparable spatial control

hundred metres of podiform chromitite. This spatial pattern suggests that chromitites and their surrounding damage zones play a central role in both H_2 production and migration. Chromitite-bearing peridotites provide favourable redox and catalytic conditions for hydrogen generation. Dunite and harzburgite surrounding chromitite ore bodies supply the Fe^{2+} and reducing capacity required for H_2 generation. At the mineral-fluid interface, $Fe(II)$ -rich spinel surfaces (chromite, magnetite) can catalyse hydrogen generation by transferring electrons from structural and adsorbed $Fe(II)$ to water molecules and protons adsorbed on the spinel surface, thereby reducing water to H_2 while oxidising $Fe(II)$ to $Fe(III)$ (Mayhew *et al.*, 2013).

Similar associations have been reported in other chromitite-bearing ophiolites (Fig. 1). In several Neoproterozoic and Phanerozoic belts, podiform chromitites occur together with hyperalkaline H_2 - CH_4 -rich fluids and occluded gases trapped within chromitite samples (Pappalardo *et al.*, 2025). In many cases, CH_4 is interpreted as a secondary product of Fischer-Tropsch-type reactions fuelled by H_2 , further emphasising the importance of chromitite-hosted catalytic interfaces. This recurrent association suggests that the link between chromitites and reduced fluids is not restricted to Kempirsay and Bulqizë, but may be a general feature of chromitite-bearing SSZ ophiolites. However, to our knowledge, only these two massifs have been surveyed in enough detail to quantify the spatial relationship between active H_2 seeps and mapped podiform chromitite bodies at the 10^2 - 10^3 m scale.

Beyond this first order picture, several features of podiform chromitites may further enhance hydrogen generation. Chromitites are enriched in platinum group elements by one to two orders of magnitude relative to surrounding peridotites (Melcher *et al.*, 1997), creating metal-rich interfaces where catalytic water reduction and Fischer-Tropsch-type reactions may be promoted (Truche *et al.*, 2025). Quantifying the contribution of these mineralogical and catalytic effects, however, will require dedicated experimental and field studies beyond the scope of this work.

Other mineral phases, such as awaruite, native iron, and Fe-Ni alloys, have also been discussed as potential catalysts for H_2 generation and Fischer-Tropsch-type synthesis in

serpentinising systems (Foustoukos and Seyfried, 2004). While we do not claim that chromitite is the only catalytic phase involved, the striking spatial association between all documented H_2 -rich seeps and mapped podiform chromitite bodies in both case studies, combined with the catalytic, redox, and structural functions of chromitite-bearing damage zones, supports podiform chromitites as a robust exploration marker for natural hydrogen in SSZ ophiolites.

Chromitite bodies thus operate as local catalytic and hydraulic hubs. Their role can be understood within the broader framework of supra-subduction zone ophiolites, whose inherited architecture controls both the early localisation of serpentinisation and the long term preservation of reactive mantle domains.

Mineralogical and Structural Drivers of Chromite-Hydrogen Coupling in SSZ Ophiolites

Supra-subduction zone (SSZ) ophiolites create a distinctive mantle architecture in which podiform chromitites, strongly depleted peridotites and inherited permeability structures are closely linked (Dilek and Furnes, 2011). High degree melting in fore-arc settings produces harzburgite-dunite domains that are both olivine dominated and Fe^{2+} -bearing, providing a chemically favourable substrate for H_2 -producing reactions once hydration occurs. At the same time, SSZ magmatism focuses Cr-rich melts into deforming peridotite to form podiform chromitites, while faulting and dyke emplacement create a heterogeneous network of fractures and magmatic contacts that control seawater penetration into the mantle (Dilek and Furnes, 2011). In this configuration, serpentinisation is expected to be localised along a subset of these high permeability structures rather than proceeding uniformly throughout the mantle section (Mével, 2003). Early hydration along faults, shear zones, gabbro-peridotite contacts and dyke swarms, creates serpentinite corridors that become mechanically weak and highly permeable, concentrating both deformation and fluid flow during subsequent intra-oceanic subduction and obduction. Within these

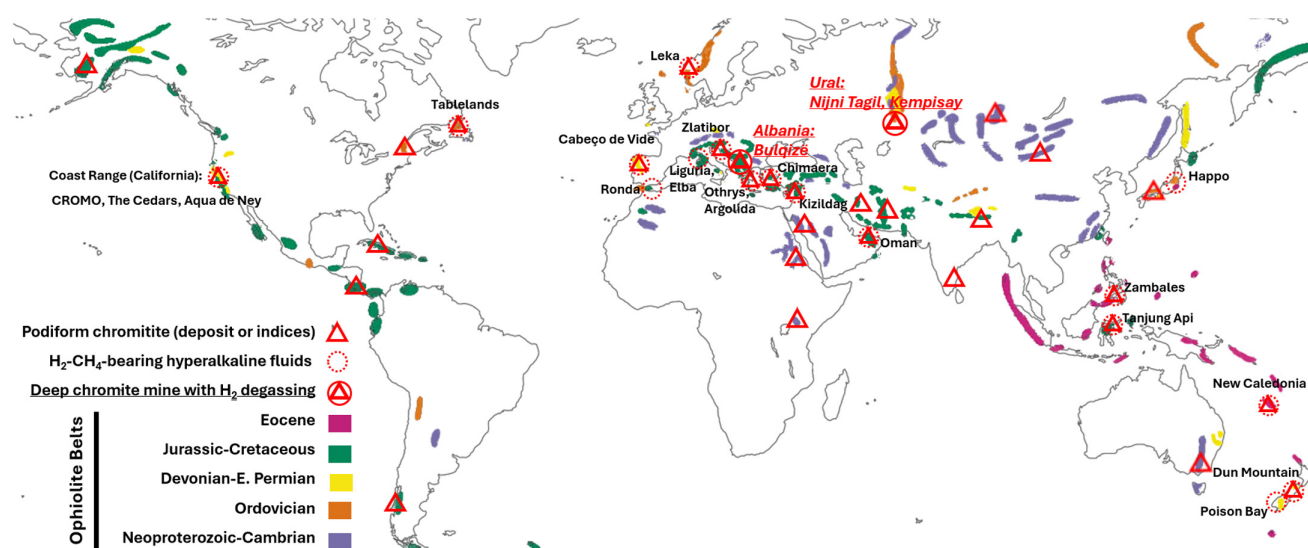


Figure 1 Global distribution of Neoproterozoic and Phanerozoic ophiolite belts, modified after Vaughan and Searrow (2003). Supra-subduction zone ophiolites that host podiform chromitites and reduced H_2 - CH_4 -rich fluids discussed in this study are highlighted, including the Kempirsay massif in the Urals (Kazakhstan), the Bulqizë ophiolite (Albania) and other chromitite-bearing peridotite massifs cited in the text.

corridors, chromitite bodies behave as mechanically stiff inclusions that focus fracturing and maintain damage zones in the more deformable serpentinite matrix (Albers *et al.*, 2019). These local damage zones provide the permeability needed to connect chromitite bodies to the massif-scale fault network, creating a two scale hydraulic architecture in which regional faults supply meteoric water to local chromitite-centred reaction sites. By contrast, intervening blocks of harzburgite-dunite and gabbro that remain less fractured and only weakly hydrated behave as more competent panels and can be translated upward largely as coherent blocks, with limited additional serpentinisation during exhumation (Dilek and Furnes, 2011).

Once obducted and exposed at shallow crustal levels, these preserved olivine-rich blocks are reconnected to meteoric water through fault networks inherited from the same tectonic history (Dilek and Furnes, 2011). At this late stage, large volumes of Fe^{2+} -bearing peridotite that escaped pervasive hydration during subduction become available for renewed low temperature serpentinisation and chromitite catalysed water reduction. Combined with the thick, permeable architecture typical of obducted SSZ mantle slabs, this interplay of early localisation of serpentinisation, mechanical partitioning of strain, and long term preservation of reactive mantle domains makes these ophiolites particularly effective natural systems for sustaining hydrogen generation potential over hundreds of millions of years.

Implications for Natural Hydrogen Systems

Chromitite-bearing SSZ ophiolites behave as poly-stage hydrogen systems. At oceanic spreading centres, mantle exhumation and seawater penetration along detachments, transform and normal faults initiate serpentinisation (Fig. 2). During active subduction, hydration of the mantle wedge along inherited faults and shear zones in the fore-arc further localises serpentinisation and the production of reduced fluids. The Mariana fore-arc provides a modern analogue: serpentinite mud volcanoes there are fed by slab-derived fluids and discharge high pH (up to 12.5) fluids enriched in abiotic H_2 , CH_4 and higher hydrocarbons (Fryer *et al.*, 2020). These reduced gases are attributed to serpentinisation-driven hydrogen production coupled with abiotic methane synthesis. Similar fore-arc processes likely operated during the SSZ stage of ophiolite formation, when podiform chromitites and their harzburgite-dunite hosts formed in the mantle wedge.

Once obducted and emplaced on continental margins, these SSZ ophiolites evolve into long lived, low temperature hydrogen systems. Their inherited architecture, with highly serpentinised, high permeability corridors flanked by thick panels of relatively weakly serpentinised, chromitite-bearing harzburgite-dunite, allows large volumes of Fe^{2+} -bearing peridotite to remain reactive for hundreds of millions of years. Where meteoric water circulates along reactivated fault zones and

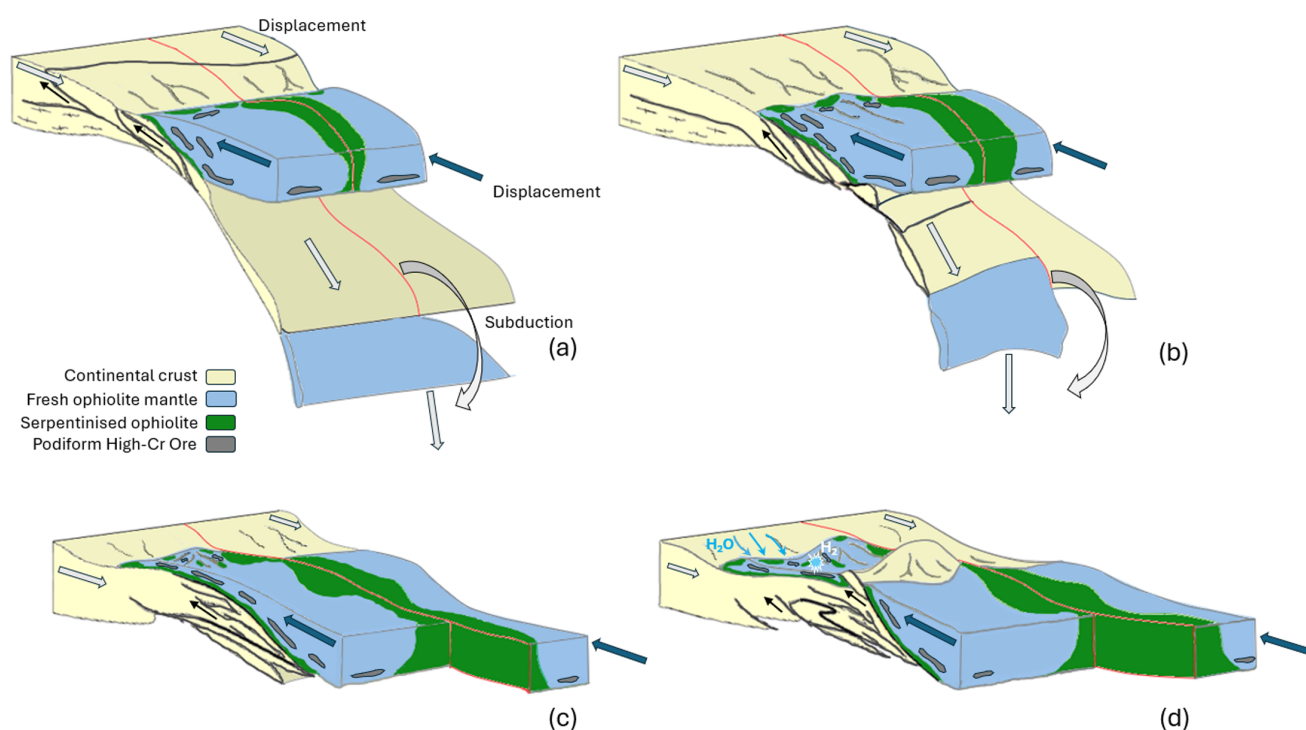


Figure 2 Conceptual 3D model for the tectonic and hydrological evolution of chromitite-bearing SSZ ophiolites and their long lived hydrogen systems. (a) Continental subduction beneath supra-subduction zone oceanic lithosphere. An inherited transform- or detachment-related fault (red) cuts the mantle wedge and localises hydration and serpentinisation along a narrow damage corridor (green), while a panel of weakly serpentinised harzburgite-dunite (light blue) with podiform chromitite lenses (dark grey) remains comparatively intact. (b–c) Subduction choking, exhumation and lateral transport. Under-thrusting of buoyant continental crust jams the subduction zone and drives uplift and translation of the ophiolite toward the foreland, while strain and fluid flow remain focused within the serpentinite corridor. The chromitite-bearing mantle panel is transported as a coherent block to shallow crustal levels with limited internal disruption. (d) Final obduction and present day configuration. The ophiolite slab is emplaced on the continental margin, with weakly serpentinised mantle panels flanking a narrow, highly serpentinised corridor. Reactivation of inherited fault networks, including the main high permeability corridor and secondary structures, by meteoric water circulation reconnects chromitite bodies to fresh fluids and sustains low temperature H_2 generation in preserved Fe^{2+} -rich mantle domains (adapted from Agard *et al.*, 2023).

fracture networks, hydrogen generation and leakage can be sustained over at least 300 Myr, provided that fracture permeability is maintained or periodically reactivated and that fresh dunite, harzburgite and chromitite bodies remain available. This behaviour is consistent with thermodynamic constraints on low temperature continental serpentinisation fluids (Leong and Shock, 2020) and with observations of sustained H₂ production in partially hydrated peridotites in the Samail ophiolite, Oman (Templeton et al., 2024). Together, these studies indicate that efficient H₂ generation does not require high temperature hydrothermal systems, but can persist under relatively cold, near surface conditions when appropriate redox gradients and catalytic phases are present.

Within this framework, podiform chromitite bodies and their surrounding damage zones emerge as prime internal targets for hydrogen exploration within such ophiolites. Our analyses emphasise that, at present, chromitite-bearing SSZ ophiolites are the best documented natural laboratories for long term, low temperature hydrogen generation and, together with their adjacent sedimentary basins, should constitute priority targets for systematic exploration. The conceptual evolution shown in Figure 2 links the fore-arc serpentinisation stage, through subduction choking, expulsion tectonics and final obduction, to the present configuration where preserved, chromitite-rich mantle panels are reconnected to meteoric fluids and operate as long lived H₂ factories.

From a practical exploration perspective, the two massifs studied here provide useful first order numbers. In both Kempirsay and Bulqizë, all documented H₂ seeps occur within damage zones surrounding mapped podiform chromitite bodies, and individual vents display instantaneous flow rates between ~20 and 550 m³ day⁻¹. These values are site specific and based on a limited number of measurements, but they illustrate the spatial extent of chromitite centred damage zones (on the order of 10² m; Lidin et al., 1982; Xiong et al., 2015) and the magnitude of local hydrogen fluxes that can be sustained over geological time scales. More broadly, SSZ ophiolites appear to be among the most fertile H₂ systems currently identified. They may locally host economically interesting accumulations, but probably of limited size because porosity is mostly fracture controlled. Surrounding and overlying sedimentary basins may represent more favourable exploration plays, as they can trap H₂ sourced from the ophiolite and are connected to the H₂ factory through active structural drains.

Editor: Ambre Luguët

Additional Information



© 2026 The Authors. This work is distributed under the Creative Commons Attribution 4.0 License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. Additional information is available at <http://www.geochemicalperspectivesletters.org/copyright-and-permissions>.

Cite this letter as: Donzé, F.V., Truche, L. (2026) Supra-subduction zone ophiolites retain hydrogen generation potential after 300 Myr. *Geochem. Persp. Let.* 40, 1–6. <https://doi.org/10.7185/geochemlet.2614>

References

- AGARD, P., SORET, M., BONNET, G., NINKABOU, D., PLUNDER, A., PRIGENT, C., YAMATO, P. (2023) Subduction and obduction processes: The fate of oceanic lithosphere revealed by blueschists, eclogites, and ophiolites. In: CATLOS, E.J., ÇEMEN, İ. (Eds.) *Compressional Tectonics: Plate Convergence to Mountain Building*. American Geophysical Union Geophysical Monograph 277. John Wiley & Sons, Inc., Hoboken, 21–45. <https://doi.org/10.1002/9781119773856.ch2>
- ALBERS, E., BACH, W., KLEIN, F., MENZIES, C.D., LUCASSEN, F., TEAGLE, D.A.H. (2019) Fluid-rock interactions in the shallow Mariana forearc: Carbon cycling and redox conditions. *Geochemistry, Geophysics, Geosystems* 20, 4361–4382 <https://doi.org/10.5194/se-10-907-2019>
- BECCALUVA, L., COLTORTI, M., PREMTI, I., SACCANI, E., SIENA, F., ZEDA, O. (1994) Mid-ocean ridge and supra-subduction affinities in the ophiolitic belts of Albania. *Ophioliti* 19, 77–96.
- BARBIER, S., HUANG, F., ANDREANI, M., TAO, R., HAO, J., ELEISH, A., PRABHU, A., AUBAUD, C., LIU, H., FAURE, K. (2020) A review of H₂, CH₄, and hydrocarbon generation in experimental serpentinization using network analysis. *Frontiers in Earth Science* 8, 209. <https://doi.org/10.3389/feart.2020.00209>
- BOHDANOWICZ, C. (1934) Natural gas occurrences in Russia (USSR). *AAPG Bulletin* 18, 746–759. <https://doi.org/10.1306/3d932c3c-16b1-11d7-8645000102c1865d>
- DEVIRTZ, A.L., GAGAUZ, F.G., GRINENKO, V.A., LAGUTINA, E.P., PEREVERZOV, V.V., SHUKOLYUKOV, Y.A. (1992) On the origin of hydrogen in ultrabasic rocks of the Kempirsay massif. *Geokhimiya* 8, 1084–1093.
- DILEK, Y., FURNES, H. (2011) Ophiolite genesis and global tectonics: Geochemical and tectonic fingerprinting of ancient oceanic lithosphere. *Geological Society of America Bulletin* 123, 387–411. <https://doi.org/10.1130/B30446.1>
- DONZÉ, F.V., LEFFEVRE, N., TRUCHE, L., YAO, Y., VUJEVIĆ, I., DUTOIT, H. (2024) Natural hydrogen exploration within Western European and the eastern Mediterranean ophiolites and ultramafic complexes. *Geochemistry: Exploration, Environment, Analysis* 24, geochem2024-043. <https://doi.org/10.1144/geochem2024-043>
- ELLISON, E.T., TEMPLETON, A.S., ZEIGLER, S.D., MAYHEW, L.E., KELEMEN, P.B., MATTER, J.M., Oman Drilling Project Science Party (2021) Low-temperature hydrogen formation during aqueous alteration of serpentinized peridotite in the Samail ophiolite. *Journal of Geophysical Research: Solid Earth* 126, e2021JB021981. <https://doi.org/10.1029/2021JB021981>
- ETIOPE, G., SCHOELL, M. (2014) Abiotic gas: Atypical, but not rare. *Elements* 10, 291–296. <https://doi.org/10.2113/gselements.10.4.291>
- FOUSTOUKOS, D.I., SEYFRIED, W.E. (2004) Hydrocarbons in hydrothermal vent fluids: The role of chromium-bearing catalysts. *Science* 304, 1002–1005. <https://doi.org/10.1126/science.1096033>
- FRYER, P., WHEAT, C.G., WILLIAMS, T., KELLEY, C., JOHNSON, K. et al. (2020) Mariana serpentinite mud volcanism exhumes subducted seamount materials: implications for the origin of life. *Philosophical Transactions of the Royal Society A* 378, 20180425. <https://doi.org/10.1098/rsta.2018.0425>
- ISSSOURCE (2025) Mine work suspended after hydrogen fire. Available at <https://www.issource.com/mine-work-suspended-after-hydrogen-fire/>. Accessed 5 March, 2026.
- KUKKONEN, I.T., GOLOVANOVA, I.V., KHACHAY, Y.V., DRUZHININ, V.S., KOSAREV, A.M., SCHAPOV, V.A. (1997) Low geothermal heat flow of the Urals fold belt—implication of low heat production, fluid circulation or palaeoclimate? *Tectonophysics* 276, 63–85. [https://doi.org/10.1016/S0040-1951\(97\)00048-6](https://doi.org/10.1016/S0040-1951(97)00048-6)
- LEONG, J.A.M., SHOCK, E.L. (2020) Thermodynamic constraints on the geochemistry of low-temperature, continental, serpentinization-generated fluids. *American Journal of Science* 320, 185–235. <https://doi.org/10.2475/03.2020.01>
- LIDIN, G.D., MATVIENKO, N.G., ZIMAKOV, B.M., GAGAUZ, F.G., VARDOLANI, E.F., PEREVERZOV, V.V. (1982) New data on natural hydrogen gas emissions from ultrabasic rocks. *Doklady Akademii Nauk SSSR* 264, 1222–1225.
- MAYHEW, L.E., ELLISON, E.T., MCCOLLOM, T.M., TRAINOR, T.P., TEMPLETON, A.S. (2013) Hydrogen generation from low-temperature water–rock reactions. *Nature Geoscience* 6, 478–484. <https://doi.org/10.1038/ngeo1825>
- MELCHER, F., GRUM, W., SIMON, G., THALHAMMER, T.V., STUMPF, E.F. (1997) Petrogenesis of the ophiolitic giant chromite deposits of Kempirsay, Kazakhstan: a study of solid and fluid inclusions in chromite. *Journal of Petrology* 38, 1419–1458. <https://doi.org/10.1093/ptro/38.10.1419>
- MÉVEL, C. (2003) Serpentinization of abyssal peridotites at mid-ocean ridges. *Comptes Rendus Geoscience* 335, 825–852. <https://doi.org/10.1016/j.crte.2003.08.006>
- PAPPALARDO, L., BUONO, G., PROCESI, M., ETIOPE, G. (2025) The link between ophiolitic chromitites, natural hydrogen and methane: Insights from 3D microtomography. *Chemical Geology* 676, 122575. <https://doi.org/10.1016/j.chemgeo.2024.122575>
- PUCHKOV, V.N. (2009) The evolution of the Uralian orogen. *Geological Society, London, Special Publications* 327, 161–195. <https://doi.org/10.1144/SP327.9>

- SAVELIEVA, G.N., SHARASKIN, A.Y., SAVELIEV, A.A., SPADEA, P., GAGGERO, L. (1997) Ophiolites of the southern Uralides adjacent to the East European continental margin. *Tectonophysics* 276, 117–137. [https://doi.org/10.1016/S0040-1951\(97\)00053-X](https://doi.org/10.1016/S0040-1951(97)00053-X)
- SAVELIEV, D.E., MAKATOV, D.K., RAKHIMOV, I.R., GATAULLIN, R.A., SHILOVSKIKH, V.V. (2022) Silicates from Lherzolites in the South-Eastern Part of the Kempirsay Massif as the Source for Giant Chromitite Deposits (the Southern Urals, Kazakhstan). *Minerals* 12, 1061. <https://doi.org/10.3390/min12081061>
- TEMPLETON, A.S., ELLISON, E.T., KELEMEN, P.B., LEONG, J., BOYD, E.S., COLMAN, D.R., MATTER, J.M. (2024) Low-temperature hydrogen production and consumption in partially-hydrated peridotites in Oman: implications for stimulated geological hydrogen production. *Frontiers in Geochemistry* 2, 1366268. <https://doi.org/10.3389/fgeoc.2024.1366268>
- TRUCHE, L., DONZÉ, F.V., GOSKOLLI, E., MUCEKU, B., LOISY, C., MONNIN, C., DUTOIT, H., CEREPİ, A. (2024) A deep reservoir for hydrogen drives intense degassing in the Bulqizë ophiolite. *Science* 383, 618–621. <https://doi.org/10.1126/science.adk9099>
- TRUCHE, L., DONZÉ, F.V., MUCEKU, B., SIVAN, M., RÖCKMANN, T., LEVY, D., MOREIRA, M., LOISY, C., CEREPİ, A., QUÉMÉNEUR, M., TISSERAND, D., DUTOIT, H., VUJEVIĆ, I., YAO, Y., LEFEUVRE, N., LAVOUÉ, A., MONNIN, C., GOSKOLLI, E. (2025) A dynamic H₂ system with multi-source methane in chromitite-rich ophiolitic settings. *Geochimica et Cosmochimica Acta* 409, 281–307, <https://doi.org/10.1016/j.gca.2025.09.039>
- UKHANOV, A.V., DEVIRTZ, A.L., IVANOV, N.D. (1987) Isotopically light hydrogen at Kempirsay (South Urals). *Doklady Akademii Nauk SSSR* 293, 700–703.
- VAUGHAN, A.P.M., SCARROW, J.H. (2003) Ophiolite obduction pulses as a proxy indicator of superplume events? *Earth and Planetary Science Letters* 213, 407–416. [https://doi.org/10.1016/S0012-821X\(03\)00330-3](https://doi.org/10.1016/S0012-821X(03)00330-3)
- XIONG, F., YANG, J., ROBINSON, P.T., XU, X., LIU, Z., LI, Y., LI, J., CHEN, S. (2015) Origin of podiform chromitite, a new model based on the Luobusa ophiolite, Tibet. *Gondwana Research* 27, 525–542. <https://doi.org/10.1016/j.gr.2014.04.008>
- YAO, Y., DONZÉ, F.V., PERSEM, M., TRUCHE, L., MUCEKU, B., GARAMBOIS, S., VUJEVIĆ, I., LEFEUVRE, N., GOSKOLLI, E. (2025) Magnetotellurics point to serpentinization as a potential source of hydrogen in the Bulqizë ophiolite. *Journal of Geophysical Research: Solid Earth* 130, e2025JB031898. <https://doi.org/10.1029/2025JB031898>