A trip through Oceanic Lithosphere: 2019 international workshop and field trip of IGCP 649 in Muscat, Oman

The IGCP-649 project “Diamonds and Recycled Mantle” has held its Fifth workshop successfully on November, 12–22, 2019 in Muscat, Sultanate of Oman. Prof. Jingsui Yang (CARMA, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China) and Prof. Sobhi Nasir (UNESCO Chair for Ophiolite Studies and Director-Earth Sciences Research Centre, Sultan Qaboos University) led the workshop. The workshop consisted of a two-day conference hosted at Sultan Qaboos University, Muscat, Oman (Fig. 1) and an eight-day post-conference field trip investigating the ophiolite and chromitites in the Fanja-Al-Khodh-Somarah, Ibra and Maqsad area, southwest of Muscat, Wadi Al Jizzi volcanics, copper and chromite mines in Sohar area, northern Oman, and chromitites, carbonatite and ultramafic lamprophyre in eastern Oman ophiolite (Fig. 2). Attendees have visited the world famous Semail ophiolite (including crustal sequence, mantle sequence and the “Moho” boundary), chromite deposits, as well as the metamorphic sole (blueschists, eclogites, marble and pelitic schist in the Sifah area) in Oman.

Near 100 scientists from Oman, China, America, Germany, Austra-
eral Names (IMA-CNMMN): Jingsuiite (IMA 2018-117b), Zhiqinite (IMA 2019-076) and Badengzhuite (IMA 2019-077) (https://doi.org/10.1180/mgm.2019.73). In all, the workshop provided an excellent opportunity for geoscience communication.

Field Trip of the 2019 International Workshop of IGCP 649

The Sultanate of Oman is situated close to the north-eastern margin of the Arabian Plate. The Arabian Plate is bounded to the north-east by the Bitlis–Zagros collision zone and the Makran subduction zone, to the north-west and south-east by the Levant and Owen strike-slip faults, respectively, and to the south-west and south by the active spreading axes of the Red Sea and Gulf of Aden rifts. Convergence along the North Oman continental margin is accommodated by subduction of the Gulf of Oman oceanic lithosphere below the Makran accretionary prism and Eurasian continental lithosphere. The northern Oman Mountains extend for 700 km from the Musandam Peninsula in the north to the Batain coast in the south-east (LeMétour et al., 1990).

The Semail ophiolite Nappe represents a slice of oceanic lithosphere formed above a northward-dipping subduction zone in a marginal basin tectonic setting (Fig. 3). The Oman Neo-Tethys have formed in the early Triassic by the rifting off and migration of small continents (e.g., Iran, Tibet, Afghanistan) northward from the remainder of Gondwana. This movement stopped in the Late Campanian (70 Ma) when the buoyant crust of the Arabian continental margin could not be pushed deeper into the dense mantle. As the American plate moved away from Africa, the Atlantic Ocean began to open, causing Africa to reverse its direction of motion and move northward. As a result, the Tethys Ocean was consumed, pushing the ophiolite, above the shallow marine limestone of the Hajar Super Group. The ophiolitic nappe was detached from a Tethyan oceanic ridge at the initiation of closure of the Neo-Tethys between 96.5 and 95.5 Ma, along-strike the Semail ophiolite (Tilton et al., 1981; Hacker and Mosenfelder, 1996). Emplacement onto the Arabian plate took place at around 78 Ma (Nicolas et al., 2000). Most structural and tectonic models proposed for the emplacement of the ophiolite have involved the NE-directed subduction away from the passive continental margin of the Arabian plate (e.g., Glennie et al., 1974; Lippard et al., 1986; Goffé et al., 1988; Le Métour et al., 1990; Searle et al., 1994). The thickness of the detached oceanic crust reached 15 to 20 km.

The classic ophiolite sequence is well exposed at the Semail ophiolite. Under the headship of Prof. Sobhi Nasir and Prof. Juergen Koepke from the Leibniz University Hannover, the attendees have observed the complete oceanic crust-mantle section from residual peridotite, layered gabbro, sheeted dyke complex and effusive basaltic layer and sea sediments. This entire sequence at Semail is 12 km thick. The detailed field route is as below:

Stop 1 - Chromite mines and Maqsad Massif (Fig. 4): Chromitites in the Moho Transition Zone at Maqsad form stratiform and dyke-like bodies a few meters thick. Over 20 pods have been recognized in the 400-m thick MTZ overlying the Maqsad diapir. With a few exceptions, all chromite deposits are located in the lower part of the MTZ close to the transition from MTZ dunites to mantle harzburgites in a horizon of flat harzburgite/dunite interlayering. Chromitite deposits are dominantly concordant lenses of a few meters thickness. Chromitites in the dunitic Moho Transition Zone of the Oman ophiolite have compositions typical of those formed from a basaltic melt, and the standard interpretation of their origin has been their formation in melt channels in the mantle created by the migration of basaltic melts.

Stop 2 - Maqsad mantle diapir (Sumail block) at Mahram: Maqsad mantle diapir isolocated under the segment center of the Oman paleoridge axis on which has been superimposed an area of mantle upwelling. This is indicated by steeply dipping lineations (up to 70°) mapped in the mantle harzburgites and is one of a number of zones of mantle
upwelling or “mantle diapirs” which have been mapped in the mantle section of the Oman ophiolite (Nicolas and Boudier, 2000). The paleo-spreading axis is assumed to run south-east to north-west down the center of the massif. This section of mantle is assumed to have had a lot of melt passing through it as part of the diapir. The Maqsad diapir is characterized by a thick MTZ (Moho Transition Zone), documenting the exceptional high magma production rate under segment centers. The outcrop is 30–100 m below the MOHO. Harzburgite is the primary rock type, with areas of concentrated plagioclase and clinopyroxene. The fabric has been almost completely destroyed by melt passing through the section.

Stop 3 - Deep gabbro sills below the Moho (Fig. 5): The MTZ of the Oman ophiolite commonly includes a number of gabbro sills surrounded by dunites. The gabbros sills have millimeter-scale to tens of centimeter-scale modal layering that closely resembles layering in lower crustal gabbros of the ophiolite. These layered gabbros with wehrlite intrusions are thought to be in the transition zone below the MOHO. The petrological and geochemical observations on the gabbro sills indicate that they formed from small, open-system melt-filled lenses within the MTZ. Modal layering could develop through the expulsion cycles, probably via in situ crystallization at the margins of melt lenses.

Stop 4 - Field relations between the crustal and mantle rocks (Fig. 6): Harzburgite, gabbro and wehrlite are the primary rock type, with areas of concentrated plagioclase and clinopyroxene. At this stop, the attendees can actually put their fingers on the “Moho”, based on the field relations between the crustal and mantle rocks exposed in this stop. The layered gabbros with wehrlite intrusions are thought to be in the transition zone below the MOHO. The layered gabbros strike

Figure 3. (a) The Oman ophiolites (red area). (b) Map of the Oman ophiolite structures (Godard et al., 2003).
approximately east-west and dip to the south. Some of the gabbros are pegmatitic.

Stop 5 - Sheeted dykes of Somerah (Fig. 7): The dikes at this stop typically have a single chilled margin. They show obvious chilled margins and the coarser grained dike centers. It was observations of this type which led to the modern understanding of oceanic spreading centers at mid-ocean ridges.

Stop 6 - The plagiogranite near Somerah: Plagiogranites in oceanic
Figure 6. MOHO Transition zone.

Figure 7. Sheeted dykes of Somerah.
crust include tonalites, trondhjemites and granodiorites. Late gabbro-
plagiograntes intrusive complex form rounded intrusions, which are
normally emplaced into the sheeted dyke unit and/or the pillow lavas
of the ophiolite. These plagiograntes formed from a mafic magma by
the re-melting of previously depleted mantle harzburgite followed by
fractional crystallisation.

Stop 7 - Somerah layered gabbro: The outcrop of layered gabbro at
Somerah is World’s top site for layered gabbro. The layering is pro-
nounced by differences in modal proportions and is therefore called
modal layering. The olivine appears dark in the rock, leading to the
observed color variations depending on the olivine content. Each layer
covers an olivine-rich base and an olivine-poor top, with gradation-
ally decreasing olivine content up layer. The layer thickness varies
between 40 and 80 cm.

Step 8 - Frozen axial melt lenses (AMLs) –varitextured gabbro: The
presence of axial melt lenses was discovered at fast-spreading
mid-ocean ridges in the late 90s. This outcrop presents a whole suite of
different lithologies and complex cutting relationships: vari-textured
gabbro with relics of primitive poikilitic clinopyroxene is cut by
basaltic dykes. These gabbros are interpreted as a frozen (fossilized)
filling of the AML, which crystallized in-situ. The patchy vari-textured
gabbros containing domains of primitive poikilitic clinopyroxene and
evolved granular networks represent the record of in-situ crystallization.

Stop 9 - Listwanite: Listwanites are the hydrothermal alteration
products of mafic and ultramafic rocks composed of quartz, carbonate
minerals (calcite, dolomite, magnesite and ankerite), and/or fuchsite
(a Cr-mica) with sulfides (pyrite, chalcopyrite and tetrahedrite). Sim-
ply, listwanites are fully carbonated peridotites, in which all Mg-sili-
cates have been converted to Mg-carbonates and quartz.

Stop 10 - Dunite channels, alteration and faulting: The peridotite of
Fanja area includes many dunite channels. Most of the dunites are highly
altered to serpentine. Magnesioferrite and Ni-Fe alloys are common
product. This stop shows faulting of the mantle rocks due to seismic
activity in the mantle. Several late stage melt channels and dykes are
common.

Stop 11 - The metamorphic sole-contact with the mantle: The base
of the ophiolite nappe is sporadically but widely metamorphosed and
called “metamorphic sole”. The metamorphic sole was formed when
the hot ophiolite nappe subducted onto the oceanic sediments and effu-
sive rocks, and gave them necessary heat and obtained fluids expelled
through dehydration reactions. At the contact with the Mantle rocks,
the upper unit is made of coarse-grained dark green amphibolite, passing
down-section to fine-grained amphibolite, with intercalations of grey-
green metaquartz. The lower unit is composed mostly of greenschist-
facies white micaceous quartzite associated with grey-mica mica-chast and minor banded calcic gneiss. The metasediments are affected by
polyphase deformation.

Stop 12 - Seifa Metamorphic rocks: Metabasite, epidote amphibio-
lites and glauconephase schist: This outcrop contains interlayered
metapelites, quartz mica schists and metabasites. In this stop you can
see different types of amphibolite schist, gneiss as well as metasedi-
ments which are metamorphosed under high pressure and low to
medium pressure conditions

Stop 13 - As Sifah eclogites: The quartz + phengite + garnet calc-
schists enclosing the large ecgolite boudin and the widespread NE-
vergent asymmetric folds in massive metabasic eclogite. Crinoid ossi-
cles have been preserved in these schists above the eclogite boudin.
NE-directed C-S fabrics indicate down-to-NE motion, also called an
extensional crenulation cleavage. In reality these fabrics indicate SW-
directed exhumation of the footwall beneath a static hanging-wall
during expulsion from the NE-dipping subduction zone (Searle et al.,
2004; Agard et al., 2010). The late-stage NW-SE aligned quartz-hae-
mate veins cutting across the schistosity. Coarse-grained eclogite facies
metabasites show a prograde mineral assemblage: Garnet + clinopy-
roxene (chloromelanite) + lawsonite + phengite + glaucophane + rutile. 
Eclogite facies metametopites show: Quartz + phengite + garnet + chlo-
ritoid + clinopyroxene (aegerine-jadeite) + lawsonite. Pseudomorphs
of clinozoisite and white mica after lawsonite enclosed in garnets show a
prograde growth zoning. Eclogite garnets contain sigmoidal inclusion
trails defined by rutile and omphacite, which are continuous with the
matrix fabric. This prograde mineral fabric is overgrown by coarse-
grained static growth of crosite + epidote + chlorite. Later greenschist
facies alteration consists of albite + chlorite + biotite and narrow rims
of blue-green amphibole around crosite.

Stop 14 - Visiting Copper-Gold Mines: Mawarid Mining Company:
The Sultanate of Oman is traditionally known for mining copper ores
since 3000 BC. Several localities of the remaining slogs have been
found in different places in the Oman Mountains, particularly in the
Sohar region at al-Asil ancient mine. Other places such as Samail and
Samad were also very active in mining. Ore occurs as shallow open
pitcher copper massive sulfide deposits that dip moderately from 0 to
20 meters below the surface to a maximum depth of about 100 meters
below surface. Mines have a cut-off grade of 0.3% copper and aver-
age grades of 2–3% copper. To date, the mining operations have pro-
duced a combined total of over 2.5 million metric tons of ore at an
average stripping ratio of 4.6 since inception.

Stop 15 - Northern chromitites area: Most chromitite deposits in
northern Oman are located at various depth in the harzburgitic mantle
section. They are associated with several tens of kilometres of long
shear zones of mylonitic peridotites distributed mainly in the Fizh and
Hili mantle sections. In the Fizh massif, the mantle shear bands rotating
at depth are inferred to connect with the flat-lying metamorphic sole.

Stop 16 - Geotime pillow lava, Wadi Jizi (Fig. 8): The initial divi-
sion of the extrusive sequence into five units (Lippard et al., 1986)
has been grouped into three sequences in geological maps (Ernewin et al.,
1988). The Geotimes unit (or V1) directly overlies the sheeted dike
complex with gradational contacts. It is composed of 750–1500 m of
redish basaltic toandesitic lavas. The majority are non vesicular and
aphyric. Geotimes lavas have trace element compositions similar to
N-MORB. The classical “Geotimes” outcrop is world’s top site for pil-
low basaltal. We have seen that the structure of the lava emplacement
corresponds more to tubes, than to pillows. And observed crosscut-
ting dikes which fed the uppermost extrusive units.

Stop 17 - Carbonatite: Four occurrences of carbonatite dikes and
plugs associated with ultramafic and alkaline igneous rocks have been
discovered along Wadi Sal area within the Batinah nappes, eastern Oman.
The carbonatites display a wide petrographic and geochemical spec-
trum and range in composition from magnesiocarbonatites to ferrugi-
nous calcioarbonatites. The carbonatites are interpreted as primary
magnesiocarbonatite contaminated by mantle-derived material and
isotopically re-equilibrated with low-temperature crustal fluids. The
close spatial association of carbonatite and ultramafic igneous rocks
(aillikite and damtjernite) along with geological, petrographical and geochemical data indicates that these rocks are of intra-oceanic origin.

Stop 18 - Ultramafic lamprophyres: The lamprophyric dyke swarms of the Bomethra area comprise macrocrystic, spinel and phlogopite bearing hybabysall facies calcite aillikite/damtjernite with pelletal lapilli and globular segregationary textures. The main dyke extends in length up to 6 km and ranges in width between 1 and 30 meters.

Stop 19 - Chromitites within the Masirah melange: Several chromitite deposits have been discovered in the ophiolite of the Batain melange, Wadi Musawa, Eastern Oman. These deposits have been extensively altered and deformed, with the host pyroxenite and dunite. The chromitites occur as separated small concordant or lenticular pods outcrops (3–10 m in thickness). The chromitites show disseminated or massive textures. Most primary silicate minerals are converted to secondary chlorite, serpentinite and pargasite. Olivine and clinopyroxene occurs as inclusions in the spinel grains. Discriminant geochemical diagrams based on the mineral chemistry of harzburgites indicate a Mid-Ocean-Ridge origin.

**Summary**

IGCP-649 project “Diamonds and Recycled Mantle” (2015–2019) is aimed to carry out extensive and systematic research on the peridotites, chromitites, and related high pressure and reduced minerals such as diamond, moissanite and other unusual minerals, from different ophiolites and orogenic belts in the world, in order to understand the formation and origin of deep-mantle minerals in oceanic lithosphere, the origin of carbon for the ophiolite-hosted diamonds, the evolution of Earth’s mantle and the dynamic process of ophiolite emplacement and also to provide new model for chromitite formation and exploration. Since 2015, the IGCP-649 workshops and field excursions have been held at the world well-known classic ophiolites and chromitites exposed areas, such as the North Qilian ophiolite in China (Yang et al., 2015a), the Troodos ophiolite in Cyprus (Yang et al., 2016), the Mayari-Baracoa ophiolites and chromitites in Cuba (Yang et al., 2017), the Massif du Sud ophiolite in New Caledonia (Yang and Shen, 2018), and the Semail ophiolite in Oman this year (2019). In addition to holding workshops and field excursions, the IGCP-649 project has also organized many scientific sessions on ophiolites and chromitites in world well-known international conferences, e.g., Goldschmidt Conference (2015, 2017, 2019), Annual Meeting of Geological Society of America (2015, 2017), the International Geological Congress (2016, 2020 now postponed), and published several special issues of the journals, such as Gondwana Research (2015), Lithosphere (2018), Earth Sciences (2019), as well as abstract volumes (2015, 2016, 2017, 2018, 2020) in the journal Acta Geologica Sinica. All these scientific activities and publications provided an excellent opportunity for international geologists and earth science communications to gather and exchange their new achievements and perspectives.

*Figure 8. Geotime pillow lava, Wadi Jizi.*
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**Dr. Xiaolu Niu** is an associate Professor for petrology in Institute of Geology, Chinese Academy of Geological Sciences. She received her PhD at Peking University, China in 2011. Her main interest is the understanding of the origin and formation processes of igneous rocks.

**Sobhi Nasir** is the Director of Earth Sciences Research Centre at the Sultan Qaboos University and the UNESCO Chair for Ophiolites Studies. He is also the Chair of the Earth Resources Theme of the International Geoscience program (IGCP). Prof. Nasir is specialized in applied mineralogy and petrology, and herelishes his continued involvement in teaching and research and contributes to undergraduate and postgraduate teaching in various fields of Earth Sciences. He have published more than 320 papers and books, and he built his international reputation through his research focusing on Oman and the Arabian lithosphere. He is a member in several editorial board of international journals in earth sciences. He received many regional and international research funding for his research as well as many international awards including the EESSEO Prize for Science and Technology 2016.

**Jingsui Yang** his PhD at Dalhousie University, Canada in 1992. He became a Professor in Institute of Geology, Chinese Academy of Geological Sciences in 1995. Now he is a professor in School of Earth Sciences and Engineering, Nanjing University, and academician of Chinese Academy of Sciences. He is the leader of the Center of Advanced Research of Mantle (CARMA) and working on ophiolites, particularly on high pressure minerals in mantle rocks, as well as on ultra-high pressure metamorphic rocks in subduction zones on the Tibetan plateau and other orogenic belts. He is the author and co-author of over 300 publications in international journals and conference proceedings. He is a Fellow of the Mineralogical Society of America (MSA) and a Fellow of the Geological Society of America (GSA).

**Juergen Koepke** is Professor for petrology at the Leibniz University Hannover in Germany. His main interest is the understanding of the geodynamics of mid-ocean ridges, especially the magmatic processes and those metamorphic processes at the interface between igneous and hydrothermal processes. For this he focus on performing ship cruises to mid-ocean ridge systems of recent oceans, on field campaigns in the Oman ophiolite and on the experimental simulation of relevant magmatic processes related to the construction of the ocean crust especially with respect to the role of \(aH_2O\) and \(fO_2\) on phase equilibria and the evolution of \(SiO_2\)-rich melts within basaltic systems. He is co-PI of several IODP proposals and also of the ICDP Oman Drilling Project.