

[MANTLE XENOLITHS OF HARRAT UWAYRID]

BY

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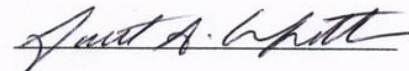
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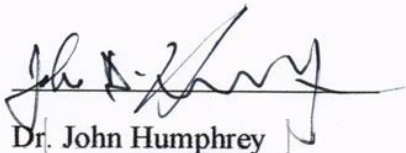
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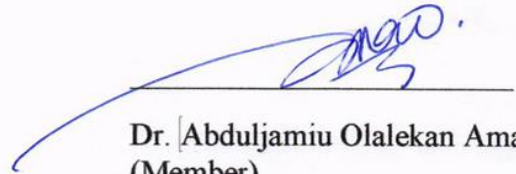
This thesis, written by **Oktarian Johan Iskandar** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN GEOLOGY**.



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[I dedicate this to Allah the Most Gracious, the Most Merciful]

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[Praise be to Allah; we seek His help and His forgiveness. We seek refuge with Allah from the evil of our own souls and from our bad deeds. Whomsoever Allah guides will never be led astray, and whomsoever Allah leaves astray, no one can guide. I bear witness that there is no (true) God but Allah, and I bear witness that Muhammad is His slave and Messenger.

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LIST OF ABBREVIATIONS

Al₂O₃	:	Aluminum oxide
Ba	:	Barium
CaO	:	Calcium oxide
Cd	:	Cadmium
Ce	:	Cerium
Co	:	Cobalt
Cr₂O₃	:	Chromium (III) oxide
Cs	:	Cesium
Cu	:	Copper (cuprum in Latin)
Dy	:	Dysprosium
EPMA	:	Electron Probe Micro-analysis
Er	:	Erbium
Eu	:	Europium
FeO	:	Iron (II) oxide
Fe₂O₃	:	Iron (III) oxide
Ga	:	Gallium

Gd	:	Gadolinium
Hf	:	Hafnium
Ho	:	Holmium
ICP-MS	:	Inductively Coupled Plasma Mass Spectrometry
ICP-OES	:	Inductively Coupled Plasma Optical Emission Spectrometry
K₂O	:	Potassium oxide
La	:	Lanthanum
LOI	:	Loss on Ignition
Lu	:	Lutetium
MnO	:	Manganese (II) oxide
MgO	:	Magnesium oxide
Mo	:	Molybdenum
Na₂O	:	Sodium oxide
Nb	:	Niobium
Nd	:	Neodymium
Ni	:	Nickel
P₂O₃	:	Phosphorus trioxide

Pb	:	Lead (plumbum in Latin)
Pr	:	Praseodymium
Rb	:	Rubidium
Sb	:	Antimony (stibium in Latin)
Sc	:	Scandium
SiO₂	:	Silica oxide
Sm	:	Samarium
Sn	:	Tin
Sr	:	Strontium
Ta	:	Tantalum
Tb	:	Terbium
Th	:	Thorium
TiO₂	:	Titanium oxide
Tm	:	Thulium
U	:	Uranium
V	:	Vanadium
Y	:	Yttrium

Yb : Ytterbium

Zn : Zinc

Zr : Zirconium]

ABSTRACT

Full Name : Oktarian Johan Iskandar
Thesis Title : Mantle Xenoliths of Harrat Uwayrid
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Numerous Upper Miocene to Quaternary harrats (alkali basalt volcanic fields) litter the western margin of Saudi Arabia along the Red Sea between Jordan and Yemen and are related to the opening of the Red Sea system. Many of these harrats have alkaline scoria bombs and lavas that bear mantle xenoliths, and one of these is Harrat Uwayrid, situated between Tabuk to the north and Al Ula to the south. This study presents new whole-rock and mineral chemistry data of Uwayrid mantle xenoliths. It provides new insights into their petrogenesis, including degrees of partial melting and oxygen fugacity of their source.

Harrat Uwayrid peridotite xenoliths are classified as spinel lherzolite, spinel harzburgite with rare wehrlites. The xenoliths range from cm-scale to fist-size and are found primarily within basanite scoria bombs that comprise cinder cones in the central Pliocene to Quaternary field; a few were recovered, for the first time, from Upper Miocene alkali basalt and hawaiiite lavas in the southern plateau. No distinctive features are apparent between peridotite xenoliths discovered in the older and younger host rocks.

Fo# of olivines from most of the Harrat Uwayrid peridotite xenoliths ranges from 83.46 – 93.05. Mg# of clinopyroxene range from 83.33 – 93.84 with an average of 91.86. Cr# values range from 2.60 – 16.90 with an average of 11.63. Mg# of orthopyroxenes ranges

from 89.40 – 93.68, with an average of 91.55, whereas orthopyroxene Cr# ranges from 3.41 – 16.34, with an average of 6.86.

Based on Cr#, calculated degrees of partial melting are low to moderate, ranging from 1 – 17 %. Rare Earth Elements (REE) analysis exhibits distinct Light REE (LREE) enrichment relative to chondritic values. Calculated based on the compositions of coexisting olivine-orthopyroxene-spinel, oxygen fugacity values are -1.89 to -0.22 (relative to fayalite-magnetite-quartz, FMQ, buffer), suggesting equilibration in reduced conditions. Thermobarometry calculations based on coexisting olivine and clinopyroxene associations suggest that the peridotite xenoliths equilibrated at ~1.72 – 3.76 GPa at temperatures of ~1090° – 1135° C, corresponding to a depth of ~50 – 105 km.

Therefore, the study establishes that the peridotite mantle xenoliths from Harrat Uwayrid were subjected to partial melting and metasomatism. They generally exhibit similar degrees of partial melting, oxidation state and metasomatism compared to other similarly aged western Arabian Harrats. This indicates the mantle below Harrat Uwayrid was subjected to similar large-scale events of the Arabian plate.]

ملخص الرسالة

الاسم الكامل: أوكتاريان جوهان إسكندار

عنوان الرسالة: وشاح الزينوليت من حرة عويرض

التخصص: جيولوجيا

تاريخ الدرجة العلمية: ربيع الآخرة 1444

العديد من الحرات البركانية التي يمتد عمرها من الميوسين العلوي إلى العصر الرباعي (الحقول البركانية البازلتية القلوية) تتواجد على الحافة الغربية للمملكة العربية السعودية على طول البحر الأحمر بين الأردن واليمن، حيث يرتبط تواجد هذه الحرات بانفتاح البحر الأحمر. العديد من هذه الحرات تمتلك أحجام كبيرة (قنابل) من الاسكوريا القلوية والطفوح البركانية المحتوية على صخور دخيله من وشاح الأرض، وإحدى هذه الحرات هي حرة عويرض، الواقعة بين تبوك في الشمال والعلا في الجنوب. تقدم هذه الدراسة بيانات مفصلة وحديثة لكيمياء الصخور والمعادن للقطع الصخرية الأتية من وشاح الأرض في منطقة عويرض. أيضا تقدم هذه الدراسة رؤى جديدة حول النشأة الصخرية، بما في ذلك درجات الانصهار الجزئي وزوال الأكسجين من مصدرهم.

تُصنّف القطع الصخرية الدخيلة المكونة من البيريدوتايت في حرات عويرض على أنها اسبينل لارزولايت، اسبينل هارزبورجيت مع نسبة ضعيفة جدا من فيرليت. تتراوح أحجام القطع الصخرية الدخيلة من السنتيمتر إلى حجم القبضة وتوجد غالبا في قنابل السكوريا الباسانية التي تشتمل على مخاريط الجمر البركاني في الحقول التي تمتد عمرها من منتصف الباليوسين إلى الرباعي؛ تم جمع عدد قليل لأول مرة، من البازلت القلوي العلوي من العصر الميوسيني والطفوح البركانية من منطقة حاويت في الهضبة الجنوبية. لا توجد سمات مميزة واضحة بين القطع الصخرية الدخيلة المكتشفة في الصخور المضيفة الأقدم والحدث منها.

تتراوح نسبة عنصر الحديد في الألفين في معظم القطع الصخرية الدخيلة المكونة من البيريدوتايت في حرات عويرض من 83.46 - 93.05 . تتراوح نسبة المغنسيوم من كلينوبيروكسين من 83.33 - 93.84 وبمتوسط 91.86. نسبة

الكروم تتراوح من 2.60 إلى 16.90 وبمتوسط 11.63. نسبة المغنسيوم من أورثوبيروكسين تتراوح من 89.40 - 93.68، وبمتوسط 91.55، في حين يتراوح نسبة الكروم أورثوبيروكسين من 3.41 - 16.34، بمتوسط 6.86. اعتمادا على نسبه الكروم فان الدرجة المحسوبة للانصهار الجزئي تكون منخفضة إلى متوسطة وتتراوح من 1 إلى 17٪. تحاليل العناصر الأرضية النادرة تظهر وفرة أكبر نسبه الى قيم الكوندريت. اعتمادا على النسبة المحسوبة أوليفين-أورثوبيروكسين-إسبنيل، قيم زوال الأكسجين هي -1.89 إلى -0.22) نسبة إلى فايوليت-كوارتز- مغنيتيت، FMQ، المخزن المؤقت)، مما يشير إلى الموازنة في ظروف منخفضة. الأعماق الحرارية التي تم حسابها اعتمادا على أساس أوليفين وتجمعات الكلينوبيروكسين تقترح ان المكونه من البيريدوتايت في حالة اتزان عند ضغط يتراوح من 1.7 - 3.8 جيجا باسكال وعند درجات حرارة تتراوح من 1100 إلى 1220 درجة مئوية تقريباً، وهو ما يقابل عمق حوالي 50-80 كم .

تظهر الدراسة أن القطع الصخرية الدخيلة المكونة من البيريدوتايت في حرات عويرض تعرضت لانصهار جزئي وعمليات تحول. هذه الحرات تظهر نتائج مشابهة بشكل عام للحررات الغربية للجزيرة العربية من ناحية الانصهار الجزئي ونسبه الأكسدة والتحول. وهذا يشير إلى أن الوشاح الموجود أسفل حرات عويرض تعرض لأحداث مماثلة واسعة النطاق مشابه لما حصل في الصفيحة العربية.

CHAPTER 1

INTRODUCTION

1.1 Background

Xenoliths are inclusions of mantle or lower crust rock fragments brought to the surface by extrusive igneous rocks ([Blatt et al., 2006](#)). They are among the few means to directly observe the Earth's mantle. Mafic and ultramafic xenoliths are regarded as fragments of the lower continental crust and upper mantle, respectively (e.g., [Stern and Johnson, 2010](#)); and are transported to the surface via extrusion of basaltic magma ([Winter, 2001](#)), predominantly of alkaline basalt ([Downes, 2021](#)), nephelinite, and basanite compositions.

The western part of the Arabian Plate has significant exposures of Neoproterozoic continental crust, which comprises the Arabian Shield ([Stern and Johnson, 2010](#)). Among younger rocks that cut the Arabian Shield are Cenozoic alkali-basalt fields, known as harrats. These harrats represent one of the largest basalt fields on Earth and extend from north to south along the coast of the Red Sea, covering parts of Jordan, Syria, the Kingdom of Saudi Arabia, and Yemen ([Camp and Roobol, 1989](#)). Additionally, these extensive lavas have been interpreted as volcanic products caused due to rifting of the Red Sea ([Coleman, 1974](#); [Ghent et al., 1980](#); [Coleman et al., 1983](#); [Bosworth, 2015](#); [Moufti and Nemeth, 2016](#)).

These Cenozoic harrats contain abundant mafic and ultramafic xenoliths ([Stern and Johnson, 2010](#)). Studies from various lava fields in Syria ([Al-Safarjalani et al., 2009](#); [Nasir](#)

[and Rollinson, 2009](#); [Stern et al., 2014](#)), Jordan ([Stern et al., 2016](#); [Nashir, 1992](#)), Saudi Arabia (specified in forthcoming chapters), and Yemen ([Baker et al., 1998](#)) have produced insight to their characteristics and provided interpretations of the nature of the mantle beneath the Arabian plate.

1.2 Problem Statement

Large volumes of xenolith-bearing harrats lie within Saudi Arabia. A total of twelve harrats have been reported in western Saudi Arabia and nine of these have been identified as containing xenoliths. Some of these xenoliths are well-studied whereas others are not ([Coleman et al., 1983](#)). Published xenolith studies in Saudi Arabia are limited to five lava fields: Harrat Khaybar, Harrat Al Birk, Harrat Kishb, Harrat Hutaymah, and Harrat Uwayrid ([Ghent et al., 1980](#); [Kuo and Essen, 1986](#); [McGuire, 1988b](#); [Henjes-Kunst et al., 1990](#); [McGuire and Stern, 1993](#); [Thornber, 1994](#); [Blusztajn et al., 1995](#); [Kaliwoda et al., 2008](#); [2007](#); [Ahmed et al., 2016](#); [Ahmed et al., 2019](#)). Details of the aforementioned studies are provided in Chapter 2.

The study aim is to provide comprehensive bulk-rock chemistry and additional mineral chemistry analysis to determine the petrogenetic processes undergone by Harrat Uwayrid mantle xenoliths.

1.3 Objectives

This study has the following objectives:

- Bulk rock chemistry by ICP-OES and ICP-MS analysis to determine major and trace element concentrations, respectively, of the xenoliths.
- Mineral chemistry documentation by EPMA analysis to determine major element compositions of the minerals in the xenoliths.
- Determine mineralogy and rock classification of the xenoliths.
- Identify petrogenetic process of the xenoliths.
- Comparisons of the study's results to other Arabian xenolith studies.
- Provide constraints on the interpretations of the nature of the mantle below Harrat Uwayrid and the Arabian plate.

1.4 Study Area

The study area, Harrat Uwayrid, is located in the northwestern area between Tabuk and Al Ula, lying between the administrative division of the Tabuk Region and the Medina Region, Saudi Arabia. The extent of the study area covers N 28° 06' – 26° 30' and E 36° 06' – 38° 00' as seen in [Fig. 1.](#)]

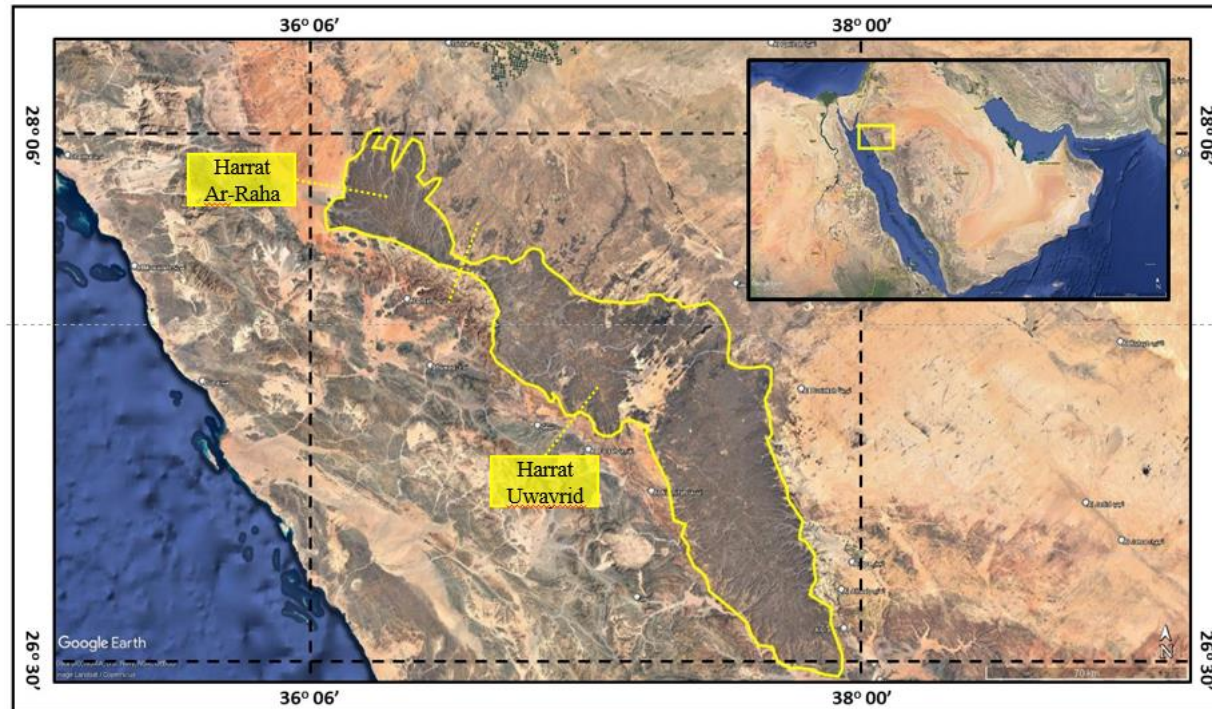


Figure 1 Map of the the volcanic fields of Ar-Raha and Uwayrid.

CHAPTER 2

LITERATURE REVIEW

2.1 Geological Background

Harrat Uwayrid is one of the intraplate Cenozoic volcanic bodies located along the western margin of the Arabian plate [Fig. 2](#). The structural trend of Harrat Uwayrid is N 30° W which is interpreted to parallel the orientation of the Najd fault and the Red Sea axis ([Coleman et. al., 1983](#)). According to the work of [Stern and Johnson \(2010\)](#), Harrat Uwayrid host rocks have an age ranging from 9 Ma-Present. More recently, K-Ar dating from [Altherr et al. \(2019\)](#) provided two age distinctions within the volcanic field, Upper Miocene (8.22 ± 0.13 Ma to 6.75 ± 0.12 Ma) and Pliocene-Quaternary (5.20 ± 0.09 Ma to 0.34 ± 0.07 Ma). The two ages are assigned to the subdivision of the harrat's host basalt established within the study (Fig. 3). The older rocks in the NW and southern sections comprise exclusively plateau lavas of alkalic basalts, hawaiites, basanites and rare transitional basalts (Whattam et. al., in preparations). In contrast, the younger rocks of the central section, are primarily scoria of basanite and their fractioned equivalents characterized by bombs and lesser lava flows ([Altherr et al., 2019](#); Whattam et. al., in preparation).

The lower most section of host basalt of Harrat Uwayrid and the underlying Paleozoic sandstone has an angular unconformity contact ([Coleman et. al., 1983](#)) suggesting that formation of the harrat postdates the tilting event in the northern Shield. In addition,

contacts between igneous and sedimentary rocks are observable elsewhere throughout the volcanic field (Fig. 4).

The heavily eroded plateau Upper Miocene basalts of the NW and southern sections are mostly devoid of mantle xenoliths, while the younger volcanic rocks with its characteristic cinder cones contain numerous mantle xenoliths and megacrysts. (Fig. 5 and Fig. 6)

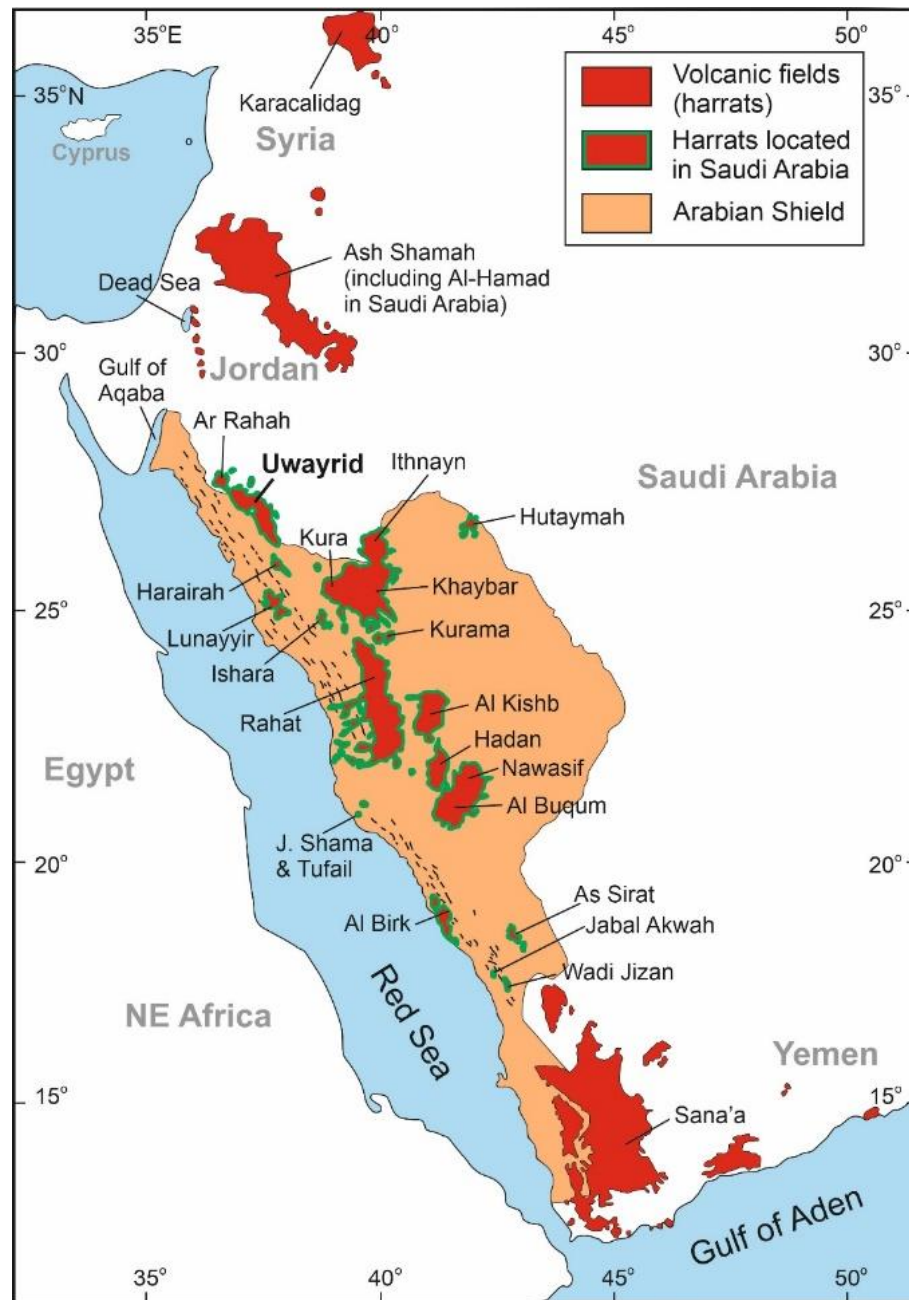


Figure 2 Location of study area Harrat Uwayrid (adopted from [Altherr et al. \(2019\)](#)).

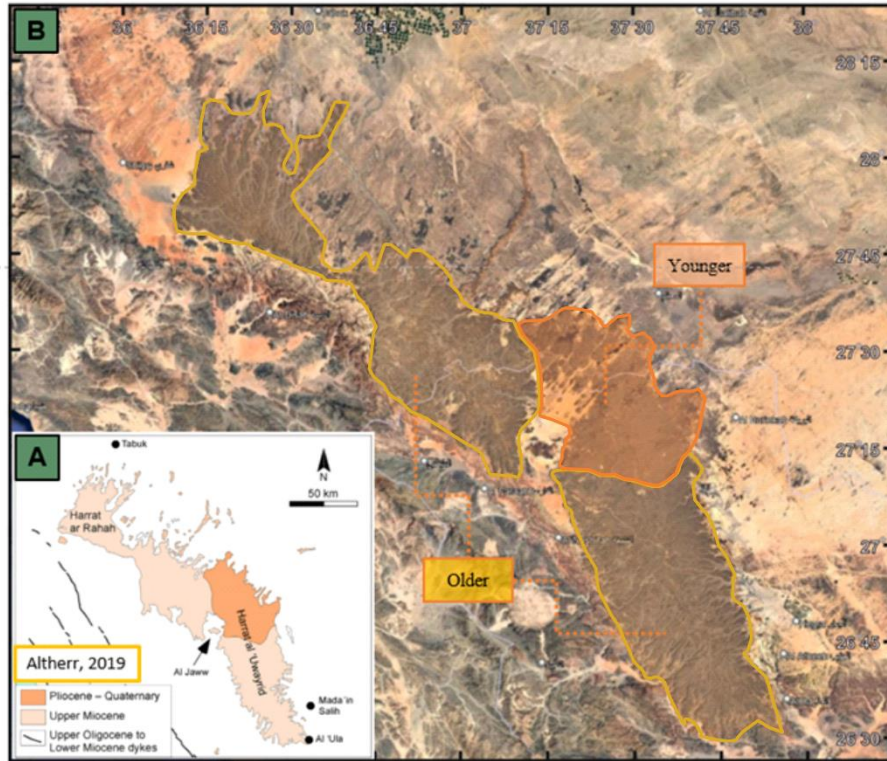


Figure 3 [A] Sketch of Harrat Uwayrid from Altherr et al. (2019). [B] Interpreted subdivision of host basalt age of Harrat Uwayrid. (adopted from [Altherr et al., 2019](#)).



Figure 4 Contact between the underlying Paleozoic (Siq Formation) Sandstone and host basalt (represented by the white dashed line).



Figure 5 Images of [A] typical older host lava, [B] typical younger host scoria.

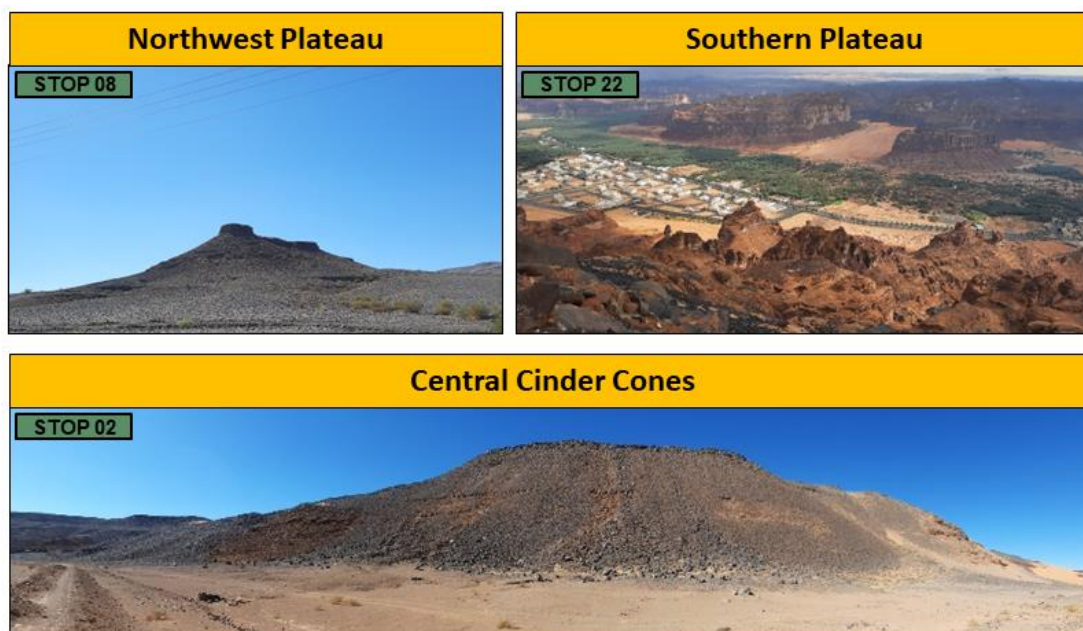


Figure 6 Images of representative host lava basalt morphology within Harrat Uwayrid.

2.2 Previous Studies

2.2.1 Xenoliths of Saudi Arabia

A summary of all previous studies of mantle and crustal xenoliths in Saudi Arabia is provided in Table 1.

2.2.2 Harrat Uwayrid Xenoliths

The presence of mantle and crustal xenoliths of Harrat Uwayrid have been reported in studies of [Ghent et al. \(1980\)](#); [Coleman et al. \(1983\)](#); [McGuire and Stern \(1993\)](#); and [Blusztajn et al. \(1995\)](#). However, two published studies which focuses on Harrat Uwayrid's xenoliths are elaborated on below.

The earliest detailed study on Harrat Uwayrid was published by [Henjes-Kunst et al. \(1990\)](#), including xenolith data from the first author's Ph.D. Dissertation ([Henjes-Kunst, 1987](#)).

[Henjes-Kunst \(1987\)](#) subdivided Harrat Uwayrids xenoliths along with xenoliths from other harrats into two main groups, IA and IB, corresponding to the xenolith classification of [Frey and Prinz \(1978\)](#). Textures of group IA range from protogranular to porphyroclastic, whereas group IB mainly display protogranular textures. Ratios of Al/Si and Mg/Si suggest xenoliths of group IA have compositions of fertile lherzolites to residual harzburgite, while type IB range from lherzolite to wehrlite. Mineral chemistry values of group IA are concluded to exhibit compositions of typical peridotite xenoliths based on comparison to the [Basaltic Volcanism Study Project \(1981\)](#). Additionally, group IB possess similar, albeit

slightly lower mineral chemistry values and are of peridotite compositions. Geothermometric calculations of Group IA and IB xenoliths estimate T conditions during equilibration of 850°-1110° C and 950°-1100° C, respectively.

Isotopic analysis was performed on Harrat Uwayrid mantle xenolith clinopyroxene, amphibole and phlogopite ([Henjes Kunst et al., 1990](#)). Group IA show positive ϵ_{Nd} and low $^{87}\text{Sr}/^{86}\text{Sr}$ compared to bulk earth. However, the $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ relationship of the ratios closely resemble those of modern mid-ocean ridge basalt (MORB), although the scatter of $^{143}\text{Nd}/^{144}\text{Nd}$ ratios exhibits values higher than modern MORB's. Furthermore, the relationship between $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of group IB that plot off the oceanic mantle array left suggests metasomatic enrichment.

The study of Henjes-Kunst et al. (1990) concluded from thermobarometric and isotopic data that the xenoliths have lithospheric origins. Moreover, petrographic and chemistry data inferred that the mantle from which the xenoliths originated was subjected to two metasomatic events. Whereas group IA mostly belongs to a mantle section unaffected by first and secondary metasomatic events, some group IA came were affected by the second metasomatic event. Meanwhile, group IB xenoliths sections were subjected to both metasomatic events. The metasomatic events were considered as related to the development of the Red Sea. Finally, an isochron obtained from the various xenoliths have Nd-Sm isotope compositions that produced an array with a 700 Ma value, corresponding to the age of crustal formation of the Neoproterozoic Arabian Shield. The interpretation was the crust and mantle represent two complimentary counterparts that both fractionated from a common source.

Table 1 List of previous studies on xenoliths in Saudi Arabia.

No	Author	Year of Publication	Location	Data Presented & Methodology						Lithologies
				Petrography	Whole Rock Chemistry	Mineral Chemistry	Thermobarometry		Isotope	
							Temperature	Pressure		
1	Ghent et. al.	1980	Harrat Al Birk, Jizan Area	Petrographic descriptions, and mode analysis	Rapid rock methods, normative and semiquantitative spectrographic analyses	Electron microprobe, and semiquantitative spectrographic analyses	Revision of Wood and Banno (1973) two-pyroxene geothermometer (Wells, 1977); calibration of two-pyroxene (Mori, 1977); correction of two pyroxene (Herzberg 1978).	Coexistence of clinopyroxene-orthopyroxene-spinel-olivine and the lack of stable olivine-plagioclase (Irving, 1974b); estimation from experimental work on plagioclase (Green and Hibberson, 1970b). Absence of garnet and estimation from experiments by O'hara et. al., 1971; Green and Wood 1967b, respectively).	X	Harzburgites, spinel clinopyroxene websterites
2	Coleman et. al.	1983	Harrat Al Birk, Harrat Harairah, Harrat Khaybar, Harrat Hutaymah, Harrat Kishb, Harrat Nawasif/Al Buqum, Harrat Rahat, Harrat Uwayrid, Jizan Area	Petrographic descriptions	X	X	X	X	X	Lherzolites, dunites, harzburgites, websterites, and gabbros which existence varies within the different volcanic bodies.

No	Author	Year of Publication	Location	Data Presented & Methodology						Lithologies
				Petrography	Whole Rock Chemistry	Mineral Chemistry	Thermobarometry		Isotope	
							Temperature	Pressure		
3	Kuo and Essen	1986	Harrat Kishb	Petrographic descriptions, point counting and normative analysis.	X	ARL-EMX electron microprobe	The two pyroxene thermometers (Mysen, 1976; Lindsley, 1983), olivine-spinel thermometer (Engi, 1983), olivine-orthopyroxene-spinel thermometer (Sachtleben and Seck (1981), and single pyroxene thermometer (Herzberg, 1978),.	Phase boundaries from the stability field of spinel peridotite, (O'Hara et al. 1971; Herzberg 1978 and Obata 1976). Experimental studies of O'Neill, 1981; Jenkins and Newton, 1979. Single-pyroxene barometer (Mercier, 1980).	X	Two spinel Harzburgites
4	McGuire	1988	Harrat Kishb, Harrat Al Birk, Harrat Hutaymah,	Petrographic descriptions	X	Electron microprobe JEOL JXA-733. Major element compositions of pyroxenes (clino and ortho), olivine, garnet, spinel, amphibole, mica and plagioclase.	Diopside - Enstatite miscibility gap (Wells, 1977); Fe-Mg partitioning between olivine and spinel (Fabries, 1979), and Al contents of orthopyroxene or clinopyroxene coexisting with olivine and spinel (Mori, 1977; Lane and Ganguly, 1980; Gasparik and Newton, 1984).	Al content of orthopyroxene coexisting with garnet (Wood and Bando, 1973; Wood, 1974; MacGregor, 1974; Harley, 1984). Experiment and study on spinel peridotite existence and stability (Herzberg, 1978; O'Neill 1981; Gasparik, 1984; Chatterjee and Terhart, 1985)	X	Spinel dunite, spinel harzburgites, spinel lherzolite, websterites (with/without spinel, plagioclase, amphibole, olivine), clinopyroxenites (with/wihtout spinel, garnet), pyroxenites (with/without spinel, garnet), two-pyroxene gabbro, rare amphibole-bearing spinel harzburgite, wehrlite.
5	Henjes-Kunst et. al.	1990	Harrat Al Birk, Harrat Hutaymah, Harrat Kishb, Harrat Lunayyir, Harrat Uwayrid, Jizan Area	Petrographic descriptions	X	Mg# of olivine, orthopyroxene, clinopyroxene and spinel. Cr# of pyroxenes (ortho and clino) and spinel.	Two-pyroxene (Wells, 1977; Sachtleben and Seek, 1981; Bertrand and Mercier, 1986; Brey, 1989.)	X	Microprobe mass spectrometer. Rb, Sr, Sm and Nd isotopic compositions.	Lherzolites, harzburgites, wehrlites, a granulitic xenolith.

No	Author	Year of Publication	Location	Data Presented & Methodology						Lithologies
				Petrography	Whole Rock Chemistry	Mineral Chemistry	Thermobarometry		Isotope	
							Temperature	Pressure		
6	McGuire and Stern	1993	Harrat Uwayrid, Harrat Al Kishb, Harrat Al Birk, Harrat Ithnayn, and Harrat Harairah	Petrographic descriptions	Thermo Jarrell Ash ICP Spectrometer and XRF. Major and trace elements of the two-pyroxene granulites and garnet granulites.	JEOL 733 automated electron microprobe. Major elements of granulite plagioclase, pyroxenes (clino and ortho) and garnet.	Two-pyroxene thermometer (Wells, 1977); garnet-clinpyroxene (Ellis and Green, 1979) and gamet-orthopyroxene (Wood and Banno, 1973).	Based on experimental results from Irving, 1974.	Finnigan MAT 261 mass spectrometer. Rb, Sr, Sm and Nd isotopic compositions.	Two pyroxene granulites and garnet bearing granulites
7	Thornber	1994	Harrat Hutaymah	Petrographic descriptions, modal analysis	XRF	ARL-SEMQ electron microprobe	Two-pyroxene thermometer (Wells, 1977)	Based on experiments from Takahashi, 1980; Arculus, 1975; Thompson, 1974; Green, 1973b; and Green and Ringwood, 1970, 1967, 1967b). Al solubility of orthopyroxene coexisting with garnet (Wood, 1974); and experiments of Irving, 1974. Experiment and study on spinel peridotite existence and stability (Herzberg, 1978; O'Neill 1981; Gasparik, 1984; Chaterjee and Terhart, 1985; Webb and Wood, 1986)	X	Peridotite, olivine-bearing pyroxenite, clinopyroxenites, websterites, orthopyroxenites (+/- brown spinel, pargasitic amphibole and phlogopite), kaersutitic amphibolite and wehrlites (+/- garnet, green or black spinel, sapphirine, calcic plagioclase and kaersutite).
8	Blusztajn et. al.	1995	Harrat Al Birk, Harrat Hutaymah, Harrat Kishb, Harrat Uwayrid	Brief petrographic descriptions.	X	Cameca® IMS 3f ion microprobe and isotope dilution. Trace element compositions.	Two-pyroxene thermometer (Wells, 1977)	X	Mass spectrometer. Isotope dilution for Sm, Nd, Rb, and Sr isotopic compositions.	Spinel Lherzolites, spinel harzburgites and a wehrlite.

No	Author	Year of Publication	Location	Data Presented & Methodology						Lithologies
				Petrography	Whole Rock Chemistry	Mineral Chemistry	Thermobarometry		Isotope	
							Temperature	Pressure		
9	Kaliwoda, et. al.	2007	Harrat Uwayrid	Petrographic descriptions	X	Cameca SX51 electron microprobe. Mg# of orthopyroxene, clinopyroxene olivine, and spinel. Cr# of pyroxenes (ortho and clino) and spinel.	Composition of coexisting orthopyroxene and clinopyroxene (Brey and Kohler, 1990)	Two-pyroxene temperature (Brey and Kohler, 1990) and spinel compositions (Webb and Wood, 1986)	X	Spinel lherzolites, spinel websterites, spinel olivine clinopyroxenite and spinel wehrlite.
10	Kaliwoda, et. al.	2008	Harrat Uwayrid	X	X	Cameca® IMS 3f ion microprobe equipped with a primary beam mass filter. Concentrations of Li, Be an B.	X	X	Cameca® IMS 3f ion microprobe equipped with a primary beam mass filter. Li isotope analysis.	Spinel peridotite, spinel websterites, spinel-olivine clinopyroxenite, spinel-clinopyroxene orthopyroxenite and spinel-pargasite-phlogopite-olivine websterite.
11	Ahmed et. al.	2016	Harrat Kishb	Petrographic descriptions, and CIPW normative analysis.	ICP-MS. Major and trace element compositions.	JEOL electron-probe microanalyzer JXA-8200. Major element composition from Ol, Opx, Cpx and Spl.	Two-pyroxene (Brey and Kohler, 1990; Putrika, 2008; Putrika et. al., 2003) and olivine-spinel Mg-Fe ²⁺ exchange (Ballhaus et. al., 1991)	Two-pyroxene from Kohler and Brey (1990) and Putika (2008)	X	Pyroxene bearing lherzolites-harzburgite and spinel rich wehrlite
12	Ahmed et. al.	2019	Harrat Hutaymah	Petrographic descriptions	ICP-MS. Major and trace element compositions.	JEOL 8900 super probe and JEOL JXA-8200 electron-probe micro analyzer (EPMA). Silicate and oxide minerals compositions from olivine, pyroxenes, spinels, amphiboles, and plagioclase.	Olivine-spinel Mg-Fe ²⁺ exchange (Ballhaus et. al., 1991 and two-pyroxene (Brey and Kohler, 1990; Putrika et. al., 2003; Putrika, 2008) and)	Two-pyroxene (Brey and Kohler, 1990; Putrika et. al., 2003; Putrika, 2008) and olivine-spinel Mg-Fe ²⁺ exchange (Ballhaus et. al., 1991). Hornblende-plagioclase of (Blundy and Holland, 1990; Holland and	X	Lherzolite, harzburgite, spinel rich Clinopyroxene and Hornblendite

No	Author	Year of Publication	Location	Data Presented & Methodology						Lithologies
				Petrography	Whole Rock Chemistry	Mineral Chemistry	Thermobarometry		Isotope	
							Temperature	Pressure		
								Blundy, 1994) and Al-in-hornblende of Schmidt (1992) and Anderson and Smith (1995)		

The most recent xenolith research from Harrat Uwayrid was published by [Kaliwoda et al. \(2008\)](#). The former study was of selected samples of peridotites (spinel lherzolites, spinel wehrlites) and pyroxenites (spinel websterites, and spinel olivine clinopyroxenite). The xenoliths fall under the “Cr-diopside” group based on the classification of [Wilshire and Shervais \(1975\)](#), which is equivalent to the “Group I” classification of [Frey and Prinz \(1978\)](#). Textural characteristics of the xenoliths range from heterogranular to weakly porphyroclastic. In addition to essential minerals of ultramafic rocks, accessory amphibole (paragsite/kaersutite) was identified. Magnesium-iron ratio (Mg#, cationic Mg / Mg+Fe²⁺) of olivine (0.87 – 0.91), clinopyroxene (0.86 – 0.93), orthopyroxene (0.87 – 0.91), and spinel (0.61 – 0.83) in selected peridotite samples were calculated. Additionally, chromium-aluminum ratio (Cr#, cationic Cr / Cr+Al) from clinopyroxene (0.05 – 0.34), orthopyroxene (0.04 – 0.19), and spinel (0.07 – 0.64) were also produced. Mg# and Cr# calculated from pyroxenites display slightly lower values than the peridotites.

Observation of Ca and Al concentrations within zoning patterns of the olivine and pyroxene suggest three different thermal stages, consisting of simple cooling, cooling followed by heating, and finally, simple heating. Petrographic analysis identified two enrichment events. Geothermobarometric calculations estimated *T* and *P* ranging from ~800° – 1140° C and 1.5 to 3.3 GPa, respectively, with the *P* estimates corresponding to depths of ~30 - 65 km. The study concluded that the upper part of the lithospheric mantle beneath Harrat Uwayrid at the calculated depths was subjected to regional heating originating from Afar plume activity (beginning about 40 Ma), followed by slow cooling. The final stage was exposure to the second heating event caused by stagnated or rising magma.

Table 2 Summary of [Henjes-Kunst et. al \(1990\)](#) study.

Results						
Lithologies	Petrography	Whole Rock Chemistry	Mineral Chemistry	Thermobarometry		Isotope
				Temperature	Pressure	
Lherzolites, harzburgites and wehrlites. Classified under group IA and IB	Protogranular – Porphyroclastic texture	IA : low Al/Si and high Mg/Si ratios IB : high Mg/Si and low Al/Si ratios	Mg# of olivine (0.862 - 0.916), pyroxene (0.875 - 0.948) Cr# from Cpx (0.045 - 0.365) and spl (0.022 - 0.430)	850° - 1100°	x	Isochron from Nd-Sm produced an array with a 700 Ma Value

Table 3 Summary of [Kaliwoda et. al \(2007\)](#) study.

Results						
Lithologies	Petrography	Whole Rock Chemistry	Mineral Chemistry	Thermobarometry		Isotope
				Temperature	Pressure	
Spinel lherzolites, spinel wehrlites, spinel websterites and spinel olivine clinoproxenite. Categorized under group IA.	Heterogranular – Porphyroclastic texture	x	Mg# from ol (0.868 - 0.911), cpx (0.864 - 0.931), opx (0.873- 0.914), and spinel (0.614 - 0.834). Cr# from cpx (0.050 - 0.342), opx (0.040 - 0.191), and spl (0.074 - 0.636)	~800° - 1140°	1.5 to 3.3 Gpa	x

CHAPTER 3

METHODOLOGY

This section describes the methodology to achieve the aforementioned objectives. A simple flow chart adapted from [Rollinson, and Pease \(2021\)](#) summarizes the steps (Fig. 7). Further elaborations of each step are discussed in the following sub-sections.

3.1 Sample Processing

Host lavas, cinders and entrained xenoliths were collected during a field trip to Harrat Uwayrid under the guidance of Dr. Scott Whattam and Mr. Mutasim Osman in November 2020. The study of [Altherr et al. \(2019\)](#) was used as a basis for stop locations. Xenoliths were primarily encountered in multiple cinder cones in the Al-Jauww area, positioned in the middle (central) section of the harrat body (Fig. 3).

Xenolith samples were retrieved from lavas and scoria by breaking host rocks with a geological hammer. Sampling of these ultramafic nodules and basalts were carefully chosen, choosing fresh samples with little alteration. Collected samples were then placed in plastic sample bags and tagged according to stop name and host type. A handheld GPS device performed geotagging of each stop location.

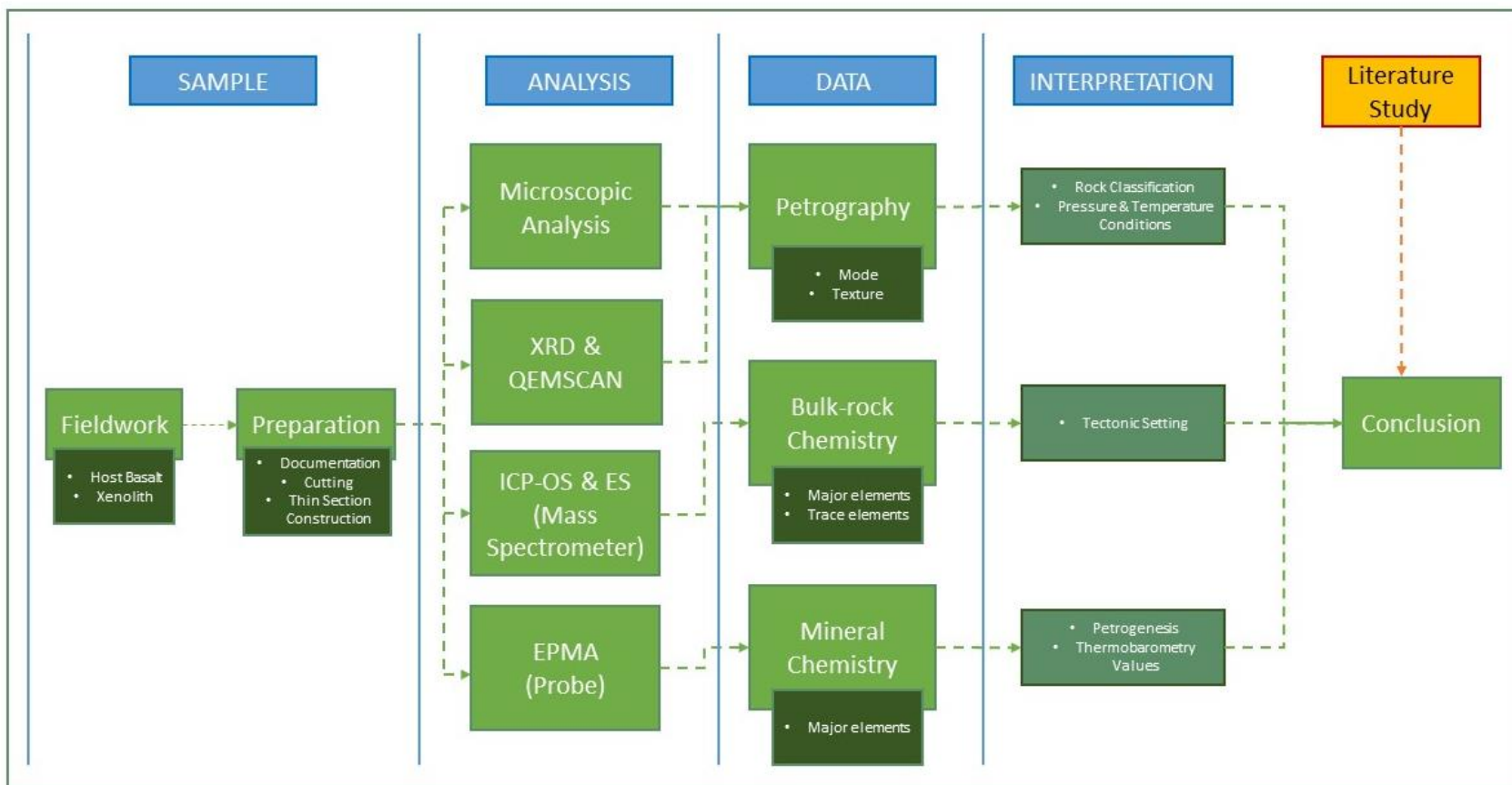


Figure 7 Flowchart of study.

Field descriptions and interpretations were made according to the recommendations of [Thorpe and Brown \(1991\)](#). Recording of color, texture, grain size, fabric, mineralogy of the hand specimens was performed.

3.2 Sample Processing

3.2.1 Sample Documentation

All samples were photographed using a 30 cm metal ruler in the background for scale to document and highlight textural features of the samples.

3.2.2 Sample Preparation

A Felker Bay rock saw machine (Fig. 8) housed in the Center for Integrative Petroleum Research (CIPR) sample preparation laboratory, College of Petroleum and Geosciences (CPG), King Fahd University of Petroleum and Minerals (KFUPM), was used to cut the rocks and xenoliths.

Representative peridotite xenolith samples were then selected for thin section construction and geochemical analysis. The samples were cut into rectangle shaped pucks and small cubes, respectively with a total weight of 20 – 30 g (Fig. 8).

Eighteen rectangle shaped pucks were then separated and sent to Vancouver Petrographics, Vancouver, Canada for polished thin section construction. Meanwhile, eleven samples of

small cubes were sent to Bureau Veritas, Vancouver, Canada for bulk rock chemistry analysis by ICP spectrometry.

As not all locations yielded abundant peridotite xenoliths for multiple analyses, some peridotite samples were chosen for selected analysis only.



Figure 8 Rock saw machine and prepared peridotite xenolith samples.

3.3 Sample Analysis

3.3.1 Petrographic Microscopy

Identification of petrographic characteristics and qualitative modal mineralogy (mode) of polished thin sections was acquired by using a Zeiss microscope (Fig. 9).

The eighteen constructed thin sections from the selected peridotite xenoliths, were observed under the microscope utilizing objective lens with 10x or 20x magnification. Interchanging between microscopic views of plane polarized light (PPL) and crossed polarized light (XPL) depended on the detail required.

Imaging of representative sections from the thin sections was assisted by Zeiss software connected to the microscope which allows for the capturing of images observed under the microscope.

3.3.2 Inductively Coupled Plasma (ICP) Spectrometry

Bureau Veritas, Vancouver, Canada utilized ICP-OES and ICP-MS to determine major and trace element contents (bulk rock chemistry), respectively, of selected peridotite samples. The protocol used was Lithogeochemical Whole Rock Fusion, BVM Code LV 200. (<http://acmelab.com/pdfs/FeeSchedule-2016.pdf>).

Following trimming to remove weathered surfaces from the small cube peridotite xenolith samples, they were then pulverized before being analyzed for major and trace elements. The samples were prepared and mixed with a $\text{LiBO}_2/\text{Li}_2\text{B}_4\text{O}_7$ flux. Crucibles were fused in

a furnace, followed by ICP-OES analysis of the melts after dissolution in ACS-grade nitric acid. Oxides of most major elements were detected at 0.01 percent except Cr_2O_3 , which was 0.002 percent, and Fe_2O_3 and K_2O , which were 0.04 percent. The loss on ignition (LOI) was calculated from the weight loss after cooling a sample split at 1050°C. The ICP-MS technique was used to analyze trace and rare earth elements on the same digestions as the major elements, with detection limits as low as 0.01 g/g for most trace elements.

3.3.3 Electron Probe Micro-analysis (EPMA)

After petrographic analysis and documentation, the eighteen-peridotite xenolith thin sections were sent for EPMA analysis to Korea University in Seoul, South Korea. The analyses were performed using a JEOL JXA-8600 SX EPMA (Fig. 10) with energy dispersive spectroscopy (INCA-6025, Oxford Instruments).

The microprobe is run at an accelerating voltage of 15.0 kV, a beam current of 3.0 nA, a live time of 100 s, and a probe diameter of 3 μm , as per standard procedures. Calibration was performed using manganesite (Mn) quartz (Si), rutile (Ti), eskolaite (Cr), hematite (Fe), K-feldspar (K), wollastonite (Ca), jadeite (Na), corundum (Al), and periclase (Mg). The analyses were done to determine mineral major element chemistry.



Figure 9 Petrographic microscope and peridotite xenolith thin sections.



Figure 10 Electron Probe Micro-Analyser, JEOL JXA-8600 SX.

3.4 Data and Interpretation

Petrography and geochemistry results are presented in tables, bivariate and ternary plots, primitive mantle-normalized multi-element diagrams, and chondrite-normalized rare earth element (REE) diagrams. Figures were constructed with the aid of IgPet software ([Carr and Gazel, 2017](#)). The software allows users to input geochemical data to produce geochemical variation diagrams. Further edits were applied by Affinity Designer software.

Reference data were extracted when presented in original source. Additional data was also acquired by accessing the opensource geochemical database websites GEOROC and PetDB.

3.4.1 Petrography

i. Modal Mineralogy

Modal mineralogy forms the basis for the classification of ultramafic rocks (e.g., [Downes, 2021](#)). Based on the ultramafic modal classification scheme of [Le Maitre et al. \(2002\)](#), the modal mineralogy (mode) of xenoliths may be achieved by point counting of thin sections or mass balancing techniques ([Pearson et al., 2014](#)).

Mode in this study is provided from semi-qualitative analysis, acquiring estimation of the mineral distribution under optical microscope observation, and quantitative analysis. The quantitative approach utilized normative (norm) method with usage of the CIPWFULL software ([Al-Mishwat, 2015](#)).

Results from the mode and norm are then further constrained by comparing results from the XRD analyses.

ii. Texture

The textural character of a xenolith reflects the geological process that it was subjected to, specifically pressure (P) and temperature (T) ([Pearson et al., 2014](#)). Identification and description of the texture, grain size, and relationships between minerals was performed on selected Harrat Uwayrid peridotite xenoliths.

3.4.2 Bulk Rock Chemistry

Bulk rock chemistry of major, and trace elements from the xenolith samples were acquired by ICP-AES and ICP-MS analysis at Bureau Veritas commercial geochemistry lab, Vancouver, Canada.

These major element oxides results were used for the CIPW norm calculation utilizing CIPWFULL ([Al-Mishwat, 2015](#)). CIPWFULL is a FORTRAN program designed for processing norm data based on original CIPW procedure which was initiated by Cross, Iddings, Pirsson and Washington ([Cross et al., 1902](#); [1903](#)).

Subsequent plots were employed and variation between oxides and elements were used to identify processes such as breakdown of magnesian or decrease of MgO due to partial melting ([Rollinson and Pease, 2021](#)) (see Section 3.3.4, Partial Melting and Melt Extraction).

3.4.3 Mineral Chemistry

Essential minerals of ultramafic rocks consist chiefly of olivine ($[\text{Mg}, \text{Fe}]_2\text{SiO}_4$), orthopyroxene (enstatite; $\text{Mg}_2\text{Si}_2\text{O}_6$), and clinopyroxene (diopside; $[\text{Ca}, \text{Mg}]_2\text{Si}_2\text{O}_6$). Accessory minerals such as plagioclase, spinel ($[\text{Mg}, \text{Fe}] [\text{Al}, \text{Cr}]_2\text{O}_4$), garnet, biotite, and amphibole may also be present ([McDonough and Rudnick, 1998](#); [Downes, 2021](#)).

Major elemental composition contents of olivine, orthopyroxene, clinopyroxene, spinel, and other accessory minerals were acquired via EPMA analysis at Korea University.

Subsequent plots were constructed to determine degrees of melt extraction (Section 3.3.4, Partial Melting and Melt Extraction), fugacity (Section 3.3.5, Oxidation state) and pressure and temperature of formation (Section 3.3.6., Thermobarometry).

Atomic and molecular weights calculation from recalculation of the major elements were performed under protocols found in [Deer et. al. \(1992\)](#), while stoichiometric calculations from [Droop \(1987\)](#) were utilized for estimation of Fe^{3+} .

3.4.4 Partial Melting and Melt Extraction

Magnesium number (Mg#) which is the magnesium-iron ratio is defined as

$$\text{Mg\#} = 100 \times \frac{\text{Mg}^{2+}}{\text{Mg}^{2+} + \text{Fe}^{2+\text{tot}}}$$

and calculated in atomic proportions. Furthermore, chromium number (Cr#) is defined as

$$\text{Cr\#} = 100 \times \frac{\text{Cr}}{(\text{Cr} + \text{Al})}$$

The values of Mg# and Cr# values are used as an index that reflects depletion of mantle due to partial melting. ([Rollinson and Pease, 2021](#), [Downes, 2021](#)).

Based on moderately incompatible heavy rare earth elements (MREE) in abyssal peridotite clinopyroxene showing high correlation with Cr# of coexisting spinel, [Hellebrand et al. \(2001\)](#) developed an empirical equation that describes the extent of fractional melting (F) of mantle peridotite as a function of spinel Cr#. The formula is defined as

$$F = 10\ln(\text{Cr\#})_{\text{spl}} + 24$$

which was used to calculate degrees of partial melting undergone by Uwayrid peridotite.

3.4.5 Mantle Oxidation State

Knowledge of the oxidation state of the Earth's mantle is critical for understanding the processes of magma genesis and the composition of deep-seated volatiles. ([Arculus and Delano, 1980](#)).

Oxygen fugacity (f_{O_2}) of the study peridotite xenoliths were calculated using relations between coexisting olivine-orthopyroxene-spinel associations from the study of [Ballhaus et al. \(1990\)](#) whereby:

$$\begin{aligned}\Delta \log (f_{O_2}) = & 0.27 + \frac{2505}{T} - \frac{400 * P}{T} - 6 * \log \left(\frac{Fe^{2+}}{(Mg + Fe^{2+})} \right)_{ol} \\ & - \frac{3200 * (1 - X)^2}{T} + 2 * \log \left(\frac{Fe^{2+}}{(Mg + Fe^{2+})} \right)_{spl} + 4 * \log \left(\frac{Fe^{3+}}{\sum R^{3+}} \right) \\ & + \frac{2630 * (\frac{Al^{3+}}{\sum R^{3+}})^2}{T}\end{aligned}$$

3.4.6 Thermobarometry

Calculation of P conditions are based on [Kohler and Brey \(1990\)](#), which uses calcium (Ca) exchange between coexisting olivine and clinopyroxene as the geobarometer.

$$P_{KB} = \frac{(-T * \ln(\frac{Ca_{ol}}{Ca_{cpx}}) - 11982 + 3.61 * T)}{56.2}$$

$$\text{for } T > (1275.25 + 2.827 * P)$$

and

$$P_{KB} = \frac{(-T * \ln(\frac{Ca_{ol}}{Ca_{cpx}}) - 5792 - 1.25 * T)}{42.5}$$

$$\text{for } T < (1275.25 + 2.827 * P).$$

At the same time, T analysis is based on the study of [Brey and Kohler \(1990\)](#), which uses coexisting orthopyroxene and clinopyroxene compositions as the geothermometer.

$$T_{BKN} = \frac{23664 + (24.9 + 126.3 * (\frac{Fe}{(Fe + Mg)})_{cpx}) * P}{13.38 + (\ln(\frac{1 - Ca_{cpx}}{1 - Ca_{opx}}))^2 + 11.59 * (\frac{Fe}{(Fe + Mg)})_{opx}}$$

Further constraints are provided from experimental studies regarding phase stability of accessory minerals such as plagioclase, spinel, and garnet ([Webb and Wood, 1986](#)). Among these includes the experimental pyrolite study of [Green and Ringwood \(1967\)](#).

CHAPTER 4

Results

4.1 Petrography

Twenty-five locations were visited (Fig. 11), and 66 rock samples, consisting of 36 ultramafic xenolith samples were collected. Rock samples of lavas and scoria with entrained xenoliths vary from fist-sized to boulder; some loose mantle peridotite xenoliths that were not embedded in the host rocks and located on the ground were also collected.

The peridotite xenolith samples were commonly found in the younger host scoriaceous basalts in the central region of the harrat. In contrast, xenoliths were rarely found in older host plateau basalts located in the NW and southern segments of Harrat Uwayrid. Peridotite xenoliths entrained in the older basalts tend to be very small in size (~1cm). An exception was one xenolith suite located in the southern segment of the harrat near Al Ula under stop number UH-24.1 (Fig. 11), where the sizes of the peridotite xenoliths were approximately fist sized.

The retrieved xenoliths display similar physical characteristics, typically showing protogranular textures (Fig. 12), with grain size > 2 mm, and grain boundaries which range from straight to smoothly curving. In hand specimen, the xenoliths are predominantly light green to dark green (Fig. 12), reflecting the characteristic minerals of olivine, and pyroxene. Some parts of the xenolith samples are light brown color, which is interpreted as the result of alteration (hydration) of olivine to iddingsite.

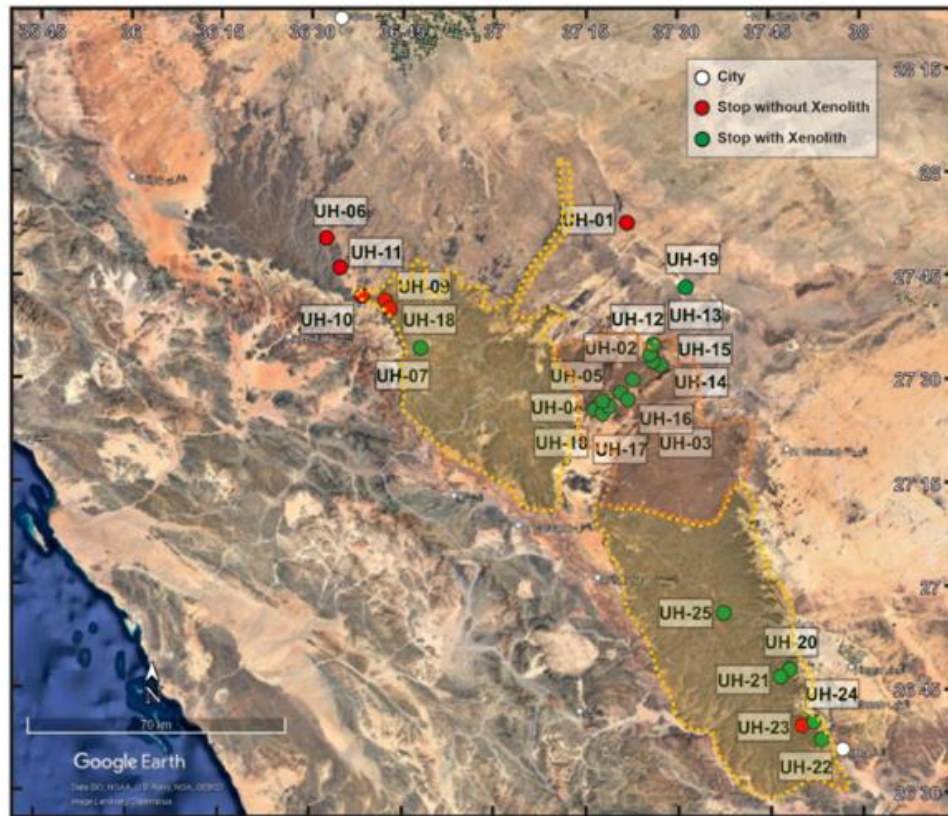


Figure 11 Study stop locations within the subdivision of the harrat's host basalt, adapted from the study of [Altherr et al., \(2019\)](#).



Figure 12 Hand specimens of selected peridotite xenoliths and host rock. Dashed green lines delineate xenoliths.

No distinctive features are apparent between the xenoliths retrieved from the young scoracious basanite basalts from the xenoliths collected from the older alkalic basalts

4.1.1 Modal Mineralogy

Semi-qualitative quantification of mode from representative xenolith thin sections resulted in the identification of olivine (ol), orthopyroxene (opx), and clinopyroxene (cpx) in varying proportions (Fig. 14).

All samples yield between 75-80 % olivine, and 15-20 % pyroxenes (opx and cpx). In the case of samples UH-3.2 and UH-3.4, olivine and clinopyroxene are the dominant minerals. Spinel is scarcely found and is estimated as below 5 % of the mode.

The modal mineralogy (mode) of the xenoliths classifies them predominantly as spinel lherzolites, under the scheme of [Le Maitre et al. \(2002\)](#). Samples UH-3.2 and UH-3.4 with their lack of orthopyroxene, however, are classified as wehrlites.

Normative calculations performed on the peridotite xenolith samples from whole rock geochemistry results provides additional constrains to further aid in classification. Based on CIPW normative calculations, the compositions of Harrat Uwayrid peridotite xenoliths are approximately 53.53 – 78.25 % olivine, 2.43 – 15.12 % clinopyroxene, and 13.15 – 31.74 % orthopyroxene.

The qualitative analysis projected on Fig. 13 show that seven of the peridotites are lherzolites (UH-2.1X, UH-2.1X2, UH-13.2, UH-14.1, UH-17.2, UH-17.3, and UH-17.6), and four are harzburgites (UH-4.1, UH-5.1, UH-16.1, and UH-24.1).

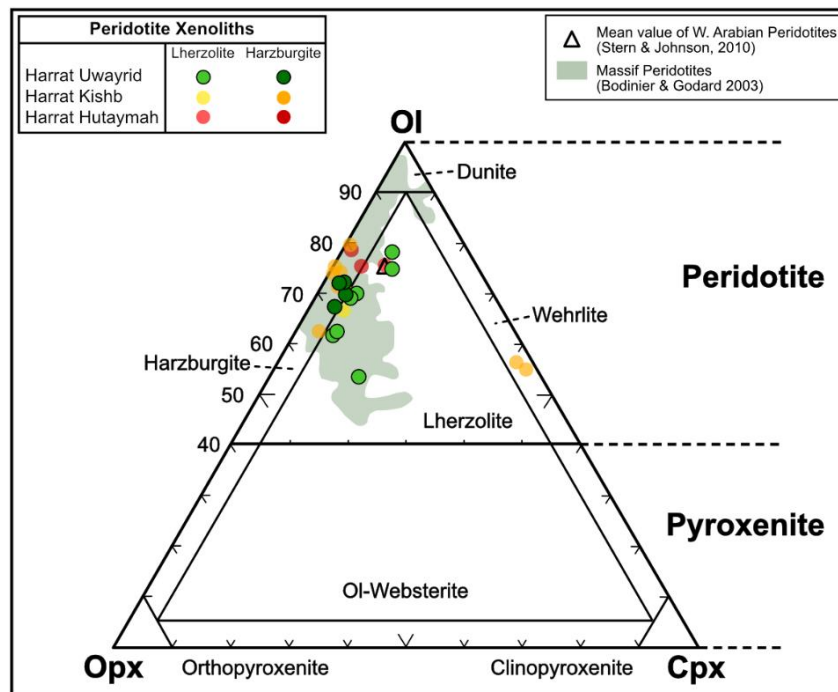


Figure 13 Classification scheme of ultramafic rocks (Le Maitre et al. 2002). The plotted Harrat Uwayrid peridotite xenoliths are based on normative calculations (norm).

Fig. 13 shows that the compositions of the peridotite xenoliths lie near the boundary between lherzolite and harzburgite on the basis of varying clinopyroxene contents. However, the majority of samples are in accordance to the general findings of peridotites located in western Arabian peridotites which are lherzolites ([Stern and Johnson, 2010](#)).

Apart from two wehrlites, comparison alongside the norm calculated plots of Harrat al-Kishb peridotite xenoliths and Harrat Hutaymah peridotite xenoliths ([Ahmed et. al. 2016; 2019](#)) on Fig. 13 shows that Harrat Uwayrid peridotite xenoliths of this study have broadly similar lithologies.

Harrat Uwayrid spinel facies peridotite xenoliths of this study are therefore lherzolites, with lesser harzburgites and rare wehrlites.

i. Spinel Lherzolite

Harrat Uwayrid spinel lherzolite peridotites are light to dark green and exhibit protogranular textures (Fig. 14). Norm calculations yield the following ranges: orthopyroxenes (13 % – 31 %), clinopyroxenes (4 % – 15 %) and olivine (53 % – 78 %).

ii. Spinel Harzburgite

Samples are predominantly light green and display a mixture of weak porphyroclastic and predominant protogranular textures (Fig. 14). Percentages of the norm calculations are orthopyroxene (24 % – 30 %), clinopyroxene (2 % – 4 %) and olivine (62 % - 72 %),

showing less cpx abundances in comparison to the Harrat Uwayrid spinel lherzolites peridotites.

iii. Wehrlite

Wehrlite peridotites are the least common type from the collected xenolith samples.

Wehrlites are dark green and display porphyroclastic texture (Fig. 14). Semi-qualitative analysis by petrographic microscope from thin sections established the presence of olivine and clinopyroxenes, with very little to no orthopyroxenes. Bulk rock chemistry analyses were not possible, due to small sample size.

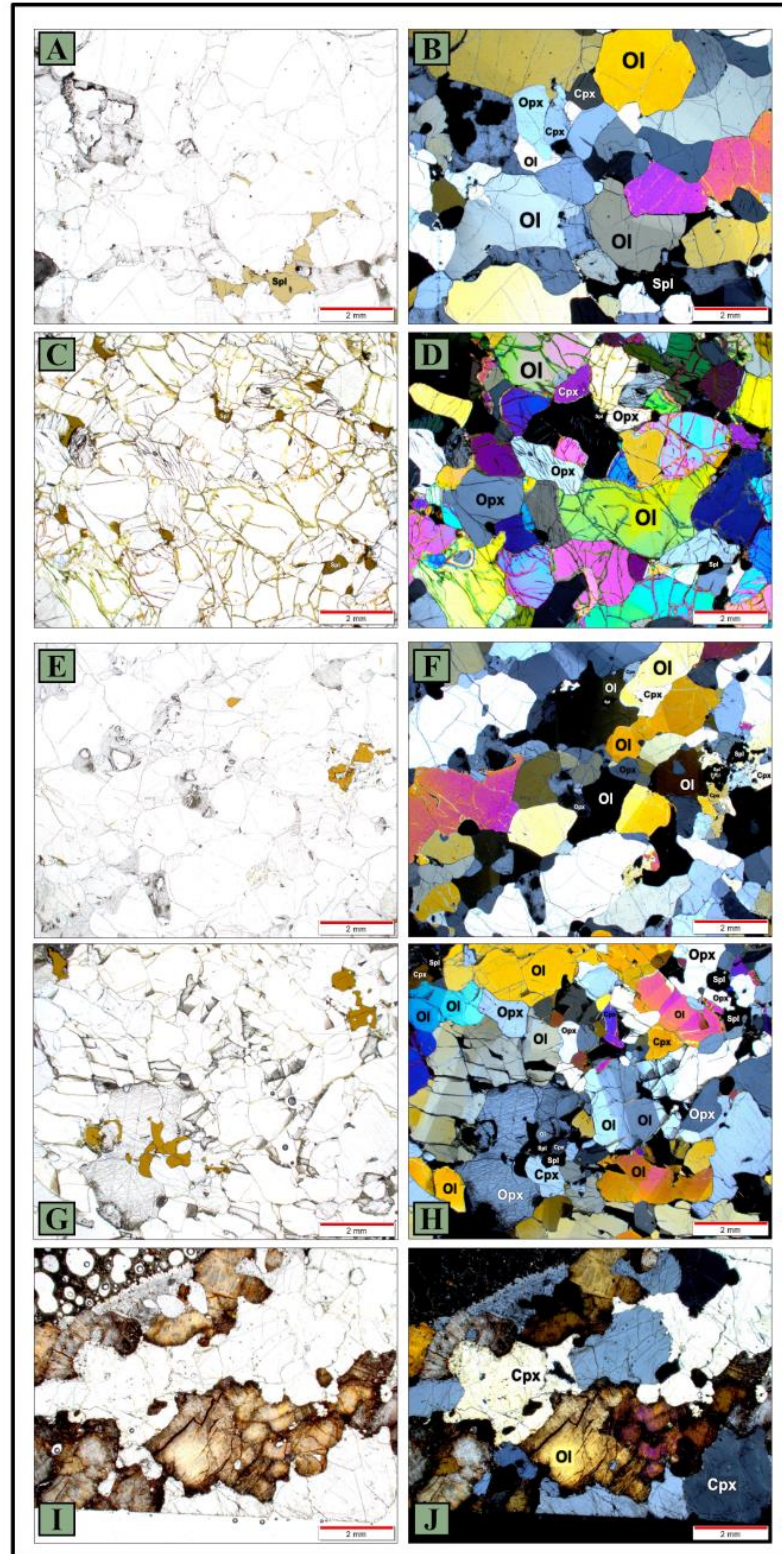


Figure 14 Selected petrographic images showing textural features of protogranular to weak porphyroclastic of Harrat Uwayrid peridotites (Left side PPL, Right side XPL). [A], [B], [C], [D] Lherzolites. [E], [F], [G], [H] Harzburgites. [I], [J] Wehrlites.

4.1.2 Major Elements

Whole rock chemistry of the peridotite xenoliths is given in Table 4. An important observation of the peridotite xenoliths is the loss on ignition (LOI) values, all of which are below 1%, which attests to the exceptional freshness of the samples. The Mg# range of Harrat Uwayrid peridotite xenoliths (88.2 – 90.5), is similar to-western Arabian peridotite xenoliths average (Mg# of 88.8 [Stern and Johnson, 2010](#)). Furthermore, the Mg# values are also similar to the average bulk-rock Mg# of worldwide spinel peridotite xenoliths (Mg# of 89.8, [McDonough, 1990](#)).

Harker diagrams (Fig. 15) of major oxides against MgO of Harrat Uwayrid peridotite xenoliths, demonstrate the variation between major oxides. Possible crystal fractionation processes are further elaborated on in Chapter 5. Plotted alongside the data from this study are whole-rock chemistry data from other western Arabian peridotite xenoliths.

Table 4 Whole-rock major and trace element compositions of selected xenolith samples.

<i>Sample</i>	<i>UH-2.1X</i>	<i>UH-2.1X2</i>	<i>UH-4.1</i>	<i>UH-5.1</i>	<i>UH-13.2</i>	<i>UH-14.1</i>	<i>UH-16.1</i>	<i>UH-17.2</i>	<i>UH-17.3</i>	<i>UH-17.6</i>	<i>UH-24.1</i>
<i>Location</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>south</i>
<i>Mode Classification</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>
<i>Norm Classification</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl hrzbg</i>	<i>spl hrzbg</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl hrzbg</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl hrzbg</i>
<i>Host Extrusive Rock</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>hawaiiite</i>
<i>Major oxides wt.%</i>											
<i>SiO₂</i>	45.73	44.64	44.44	44.57	43.68	45.7	44.65	43.62	46.81	44.64	44.76
<i>TiO₂</i>	0.12	0.12	0.04	0.01	0.04	0.12	0.08	0.17	0.14	0.12	0.12
<i>Al₂O₃</i>	4.24	3.61	2.12	1.75	1.78	3.12	2.82	2.74	3.09	2.32	2.05
<i>Fe₂O₃</i>	9.43	9.63	9.41	8.78	9.25	8.96	9.59	9.93	8.5	9.61	9.03
<i>MnO</i>	0.14	0.14	0.13	0.13	0.14	0.13	0.14	0.15	0.13	0.14	0.13
<i>MgO</i>	35.9	37.89	41.32	42.39	40.94	38	39.55	38.67	35.04	39.61	40.54
<i>CaO</i>	3.47	3.07	1.82	1.46	2.8	3.11	2.47	3.55	4.76	2.54	1.96
<i>Na₂O</i>	0.31	0.25	0.16	0.13	0.4	0.2	0.18	0.28	0.31	0.26	0.11
<i>K₂O</i>	<0.01	<0.01	<0.01	<0.01	0.06	<0.01	<0.01	0.04	0.05	0.05	<0.01
<i>P₂O₅</i>	0.02	0.03	0.02	0.04	0.19	0.02	0.02	0.04	0.03	0.04	0.01
<i>Cr₂O₃</i>	0.404	0.388	0.388	0.386	0.445	0.423	0.453	0.387	0.382	0.421	0.419
<i>Total</i>	99.93	99.92	99.93	99.94	99.91	99.93	99.93	99.93	99.92	99.92	99.93
<i>LOI</i>	-0.1	-0.1	-0.2	0	-0.1	-0.1	-0.3	0.1	0.4	-0.1	0.6
<i>Mg #</i>	88.25	88.59	89.65	90.5	89.72	89.32	89.05	88.48	89.05	89.05	89.85
<i>Trace elements ppm</i>											
<i>Sc</i>	19	17	13	11	12	17	15	17	20	15	12
<i>V</i>	95	84	60	45	49	80	66	80	92	67	65
<i>Ni</i>	1943	1981	2171	2315	2205	2006	2118	2066	1875	2098	2254
<i>Co</i>	108.5	108.5	121	115.4	112.9	105.1	114.4	107.9	94.1	112.1	115.2
<i>Cu</i>	20.4	22.9	6.6	7.4	6.5	18.8	12.8	11.7	44.2	14.8	5.8
<i>Zn</i>	20	32	28	32	39	21	27	39	24	32	29
<i>Ga</i>	4	3.2	1.5	1	1.3	2.2	1.8	1.8	1.7	1.6	0.6
<i>Rb</i>	<0.1	<0.1	0.1	<0.1	0.9	<0.1	<0.1	0.2	0.7	0.9	<0.1
<i>Sr</i>	6.9	7.5	20.4	18.2	153.9	13.6	7.8	34.7	19.8	31.1	25.3
<i>Y</i>	3.7	3.3	1.5	1.1	4.1	2.6	2.5	4	3.4	2.1	0.8
<i>Zr</i>	5.4	4.6	2.8	2.9	12.7	5.5	4.1	8.5	5.9	13.6	3.8
<i>Nb</i>	0.2	0.1	0.2	1.3	5	0.2	<0.1	1.4	0.7	2.3	0.3
<i>Mo</i>	<0.1	<0.1	<0.1	<0.1	0.3	<0.1	<0.1	0.1	<0.1	0.2	0.1
<i>Cd</i>	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
<i>Sn</i>	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
<i>Sb</i>	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
<i>Cs</i>	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
<i>Ba</i>	5	2	56	22	52	8	5	53	10	19	2
<i>La</i>	0.2	0.6	1.1	1.3	11	0.3	0.3	1.2	0.6	2.3	1.5
<i>Ce</i>	0.4	1.2	1.7	2.7	22.1	0.7	0.2	3.2	1.7	4.3	2.1

<i>Sample</i>	<i>UH-2.1X</i>	<i>UH-2.1X2</i>	<i>UH-4.1</i>	<i>UH-5.1</i>	<i>UH-13.2</i>	<i>UH-14.1</i>	<i>UH-16.1</i>	<i>UH-17.2</i>	<i>UH-17.3</i>	<i>UH-17.6</i>	<i>UH-24.1</i>
<i>Location</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>central</i>	<i>south</i>
<i>Mode Classification</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>
<i>Norm Classification</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl hrzbg</i>	<i>spl hrzbg</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl hrzbg</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl lhrz</i>	<i>spl hrzbg</i>
<i>Host Extrusive Rock</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>basanite</i>	<i>hawaiiite</i>
<i>Pr</i>	0.08	0.14	0.14	0.31	2.65	0.09	0.04	0.48	0.21	0.49	0.14
<i>Nd</i>	0.4	0.7	0.5	1.2	10.1	0.7	<0.3	2.5	1.3	2.1	0.4
<i>Sm</i>	0.25	0.23	0.12	0.21	1.7	0.23	0.14	0.65	0.36	0.38	<0.05
<i>Eu</i>	0.11	0.09	0.04	0.07	0.51	0.08	0.06	0.24	0.15	0.14	<0.02
<i>Gd</i>	0.44	0.41	0.17	0.24	1.32	0.37	0.29	0.82	0.51	0.43	0.06
<i>Tb</i>	0.09	0.07	0.02	0.02	0.16	0.06	0.05	0.12	0.08	0.06	<0.01
<i>Dy</i>	0.64	0.49	0.21	0.17	0.9	0.43	0.39	0.71	0.53	0.42	0.09
<i>Ho</i>	0.15	0.12	0.05	0.03	0.13	0.09	0.08	0.13	0.13	0.08	<0.02
<i>Er</i>	0.46	0.39	0.15	0.09	0.38	0.3	0.26	0.38	0.37	0.22	0.06
<i>Tm</i>	0.07	0.06	0.02	0.01	0.04	0.04	0.04	0.05	0.05	0.04	<0.01
<i>Yb</i>	0.44	0.33	0.16	0.1	0.28	0.3	0.24	0.34	0.34	0.25	0.11
<i>Lu</i>	0.06	0.05	0.02	<0.01	0.03	0.04	0.04	0.05	0.05	0.03	0.01
<i>Hf</i>	0.2	0.2	<0.1	<0.1	0.2	0.2	0.1	0.2	0.2	0.3	<0.1
<i>Ta</i>	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
<i>Pb</i>	0.1	0.6	0.3	0.3	0.6	0.2	0.4	0.4	1.4	0.2	0.2
<i>Th</i>	<0.2	<0.2	<0.2	<0.2	1.1	<0.2	<0.2	<0.2	<0.2	0.3	0.3
<i>U</i>	<0.1	<0.1	<0.1	<0.1	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

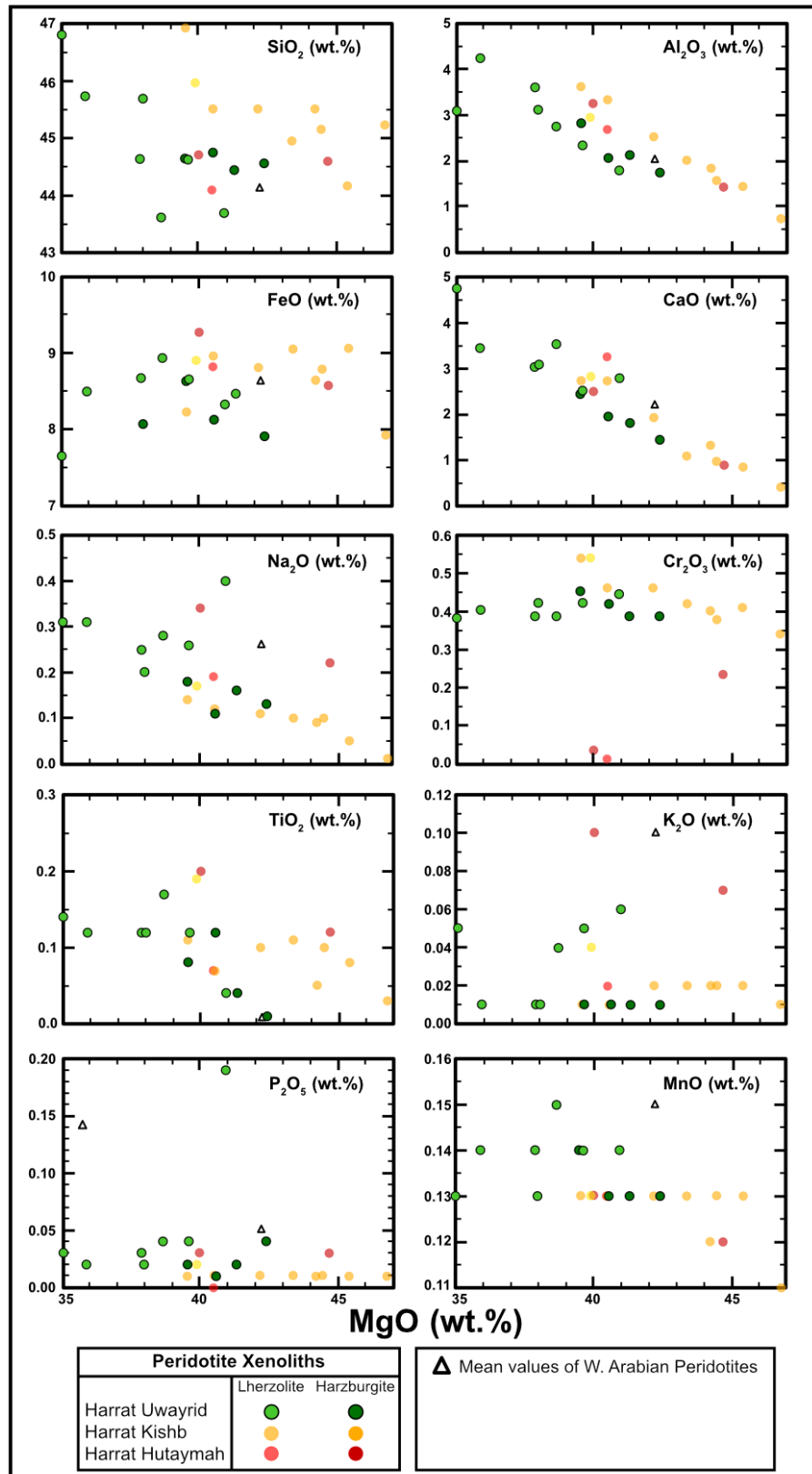


Figure 15 Harker diagrams of plotted major oxides weight percentages against MgO weight percentage.

Among the oxides, SiO_2 , TiO_2 , Al_2O_3 , FeO , MgO , Na_2O display a negative correlation with MgO . However, no correlations are displayed between MgO and MnO , K_2O_5 , P_2O_5 , and Cr_2O_3 .

SiO_2 contents of Harrat Uwayrid peridotite xenoliths range from 43 - 45 wt. %, and MgO ranges from 35 - 42 wt. %. These values are relatively higher and lower, respectively, compared to the mean values of western Arabian peridotite xenoliths. Other major element oxides of the Uwayrid peridotite xenoliths are relatively higher than the mean values of the western Arabian peridotite xenoliths. Exceptions are P_2O_5 and MnO which are slightly lower, and K_2O which is significantly lower than the mean of western Arabian peridotite xenoliths.

A comparison of major element compositions of Harrat Uwayrid peridotite xenoliths with worldwide xenoliths is shown on a plot of Mg/Si versus Al/Si (Fig. 16). The Harrat Uwayrid peridotite xenoliths lie along the peridotite trend line as defined in a study by [Nasir and Rollinson \(2009\)](#), which utilized data of worldwide mantle peridotites as compiled by [Pearson et al. \(2014\)](#).

Harrat Uwayrid peridotite xenoliths are generally similar to global lherzolites with Mg/Si of $\sim 0.95 - 1.2$ and Al/Si of $0.04 - 0.12$, indicative of low to moderate degrees of melt extraction. However, some samples -UH-2.1X, UH-14.1, and UH-17.3- plot anomalously as they lie further away from the peridotite trend than the other samples.

Further discussion of interpretations related to observations within this section is carried out in the following chapter (Chapter 5).

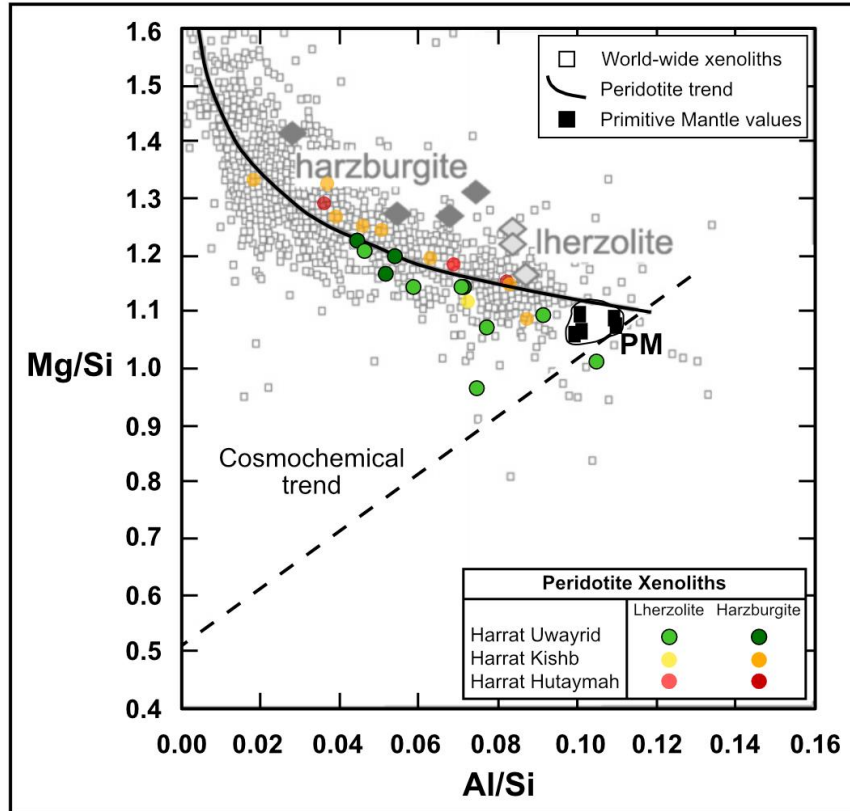


Figure 16 Elemental Mg/Si ratios vs. Al/Si ratios modified from [Nasir and Rollinson \(2009\)](#). Primitive upper mantle (PUM) values from [McDonough and Sun \(1995\)](#); [McDonough \(1990\)](#); [Hart and Zindler \(1986\)](#); [Palme and Nickel \(1985\)](#); and [Jagoutz et. al. \(1979\)](#).

4.1.3 Trace Elements

Trace element contents from whole-rock geochemistry analysis of the peridotite xenoliths are given in Table 4. A REE diagram normalized to CI Carbonaceous Chondrite is shown in Fig. 17. The diagram exhibits two general trends.

The first trend shows a fractionated pattern with high light REE (LREE) abundances ranging from chondritic-like values up to a 1.5 order magnitude higher. In contrast, the heavy REE (HREE) displays chondritic-like values.

The second trend displays a flat pattern with LREE and HREE abundances similar to chondritic values.

This first trend is shown by peridotite xenolith samples UH-4.1, UH-5.1, UH-13.2, UH-17.2, UH-17.6, and UH-24.1. Meanwhile, the second trend is shown by peridotite xenolith samples UH-2.1X, UH-2.1X2, UH-14.1, UH-16.1, and UH-17.3.

Also, a constructed Primitive Upper Mantle-normalized plot of the Uwayrid peridotite xenoliths is shown in Fig. 18. Patterns of the Harrat Uwayrid peridotite xenoliths, which show fractionated and flat REE patterns, generally exhibit similar PM-normalized patterns.

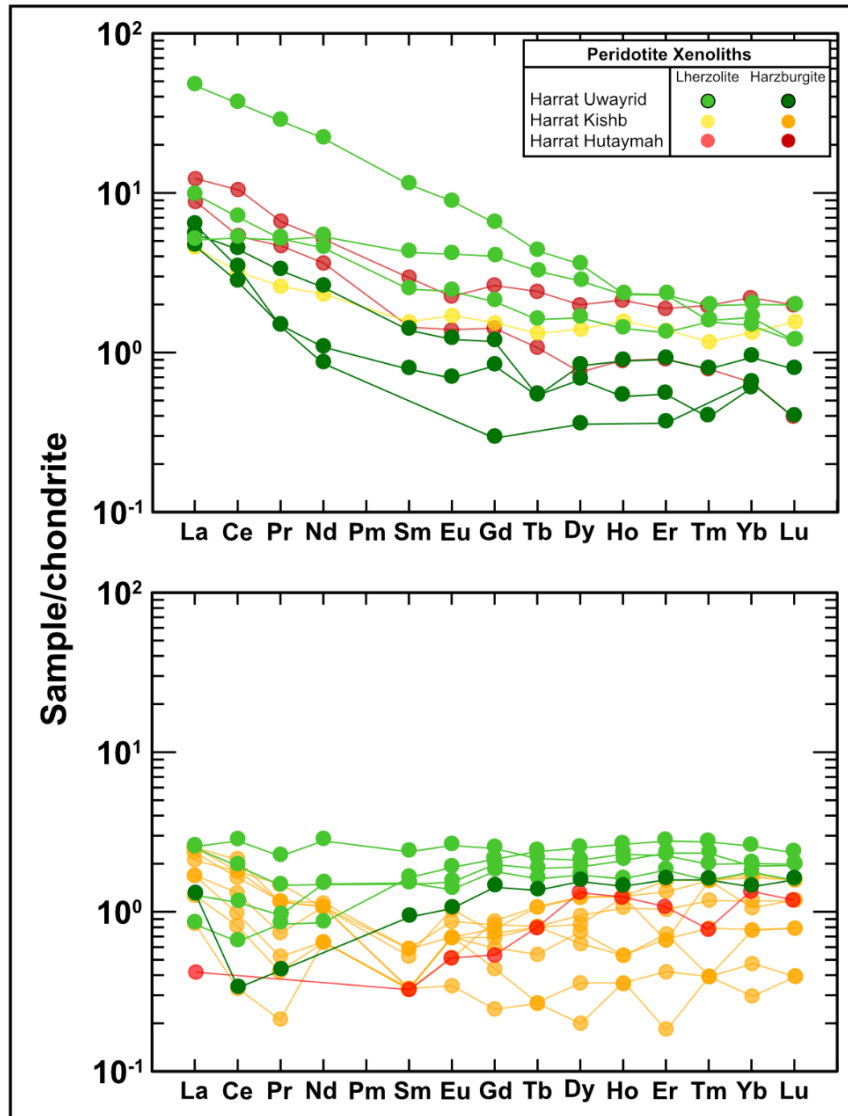


Figure 17 REE diagrams of Harrat Uwayrid peridotite xenoliths normalized to CI Carbonaceous Chondrites (chondrite values from [Sun and McDonough, 1989](#)).

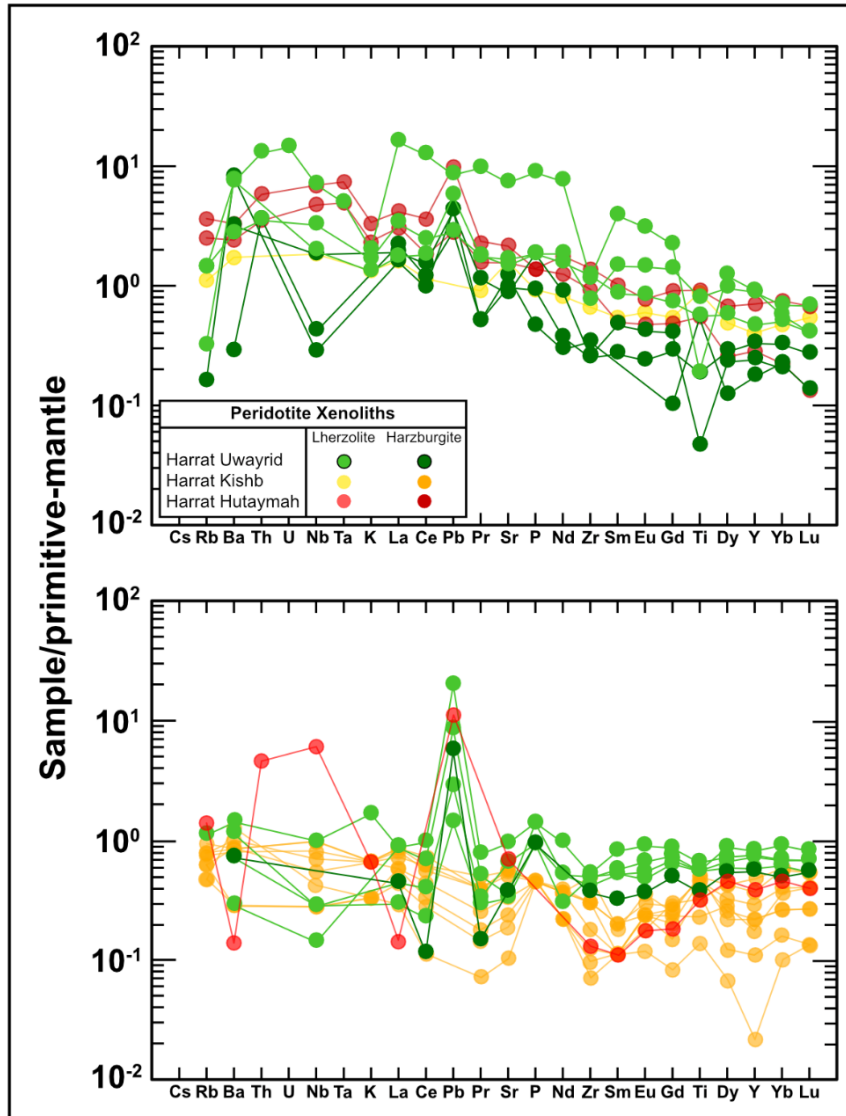


Figure 18 Multi-element diagrams normalized to Primitive Mantle (PUM values of [McDonough and Sun, 1995](#)).

4.1.4 Mineral Chemistry

i. Olivine

Major elements compositions of olivine are provided in Table 5. A total of 90 analyses were obtained on olivine of Harrat Uwayrid peridotite xenoliths.

Fo# of olivines from most of the Harrat Uwayrid peridotite xenoliths range from 83.5 – 93.0, predominantly which fall within a range of 88 – 94 which are considered as peridotitic ([McDonough & Rudnick, 1998](#)); [Pearson, 2014](#); and [Downes, 2021](#)).

Major element composition of all olivine are similar and have the following average values; 40.86 wt. % SiO₂, 0.18 wt. % Al₂O₃, 10.54 wt. % FeO, 0.09 wt. % CaO, 48.78 wt. % MgO, 0.03 wt. % CoO, 0.03 wt. % Cr₂O₃ and 0.37 wt. % NiO.

ii. Pyroxene

Major element compositions of clinopyroxene are provided in Table 6. A total of 34 analyses were obtained on clinopyroxene of Harrat Uwayrid peridotite xenoliths.

Mg# of the clinopyroxene have an average value of 91.86 and range from 83.33 – 93.84. Cr# ranges from 2.60 – 16.90 and have an average of 11.63. Major elements show a small range, e.g., SiO₂ (49.61-54.37 wt. %), Al₂O₃ (2.36-6.84 wt. %), FeO (1.95-5.46 wt. %), CaO (18.58-22.72 wt. %), MgO (14.91-17.98 wt. %), CoO (0.00-0.06 wt. %), Cr₂O₃ (0.32-1.56 wt. %) and NiO (0.00-0.14 wt. %).

Major elements compositions of orthopyroxene are provided in Table 7. A total of 53 analyses were obtained on orthopyroxene of Harrat Uwayrid peridotite xenoliths.

Mg# of orthopyroxene from Harrat Uwayrid peridotites are between 89.40 – 93.68, with an average of 91.55 and Cr# ranges from 3.41 – 16.34, with an average of 6.86. Similar to clinopyroxene, major elements show small variation, e.g., SiO₂ (52.55-57.25 wt. %), Al₂O₃ (1.23-4.48 wt. %), FeO (5.09-6.95 wt. %), CaO (0.27-1.03 wt. %), MgO (32.84-35.57 wt. %), CoO (0.00-0.08 wt. %), Cr₂O₃ (0.27-1.11 wt. %) and NiO (0.03-0.18 wt. %).

Table 5 Major element mineral chemical data of olivine from Harrat Uwayrid peridotite xenoliths.

Sample	Lithology	Analysis Number	SiO ₂	Al ₂ O ₃	FeOt	CaO	MgO	CoO	Cr ₂ O ₃	NiO	Total	Fo#
UH-2.1X	Lherzolite	6	41.21	0.05	10.78	0.09	49.25	0.05	0.06	0.36	101.84	89.06
		7	40.92	0.15	10.56	0.08	49.31	0.00	0.02	0.45	101.50	89.27
		8	41.73	0.13	10.23	0.07	49.39	0.00	0.01	0.28	101.84	89.59
		9	40.53	0.16	10.90	0.08	49.42	0.00	0.02	0.45	101.56	88.99
		10	40.99	0.14	10.72	0.00	48.97	0.03	0.00	0.42	101.26	89.06
		11	40.60	0.14	10.72	0.00	48.99	0.03	0.00	0.42	100.89	89.07
		15	41.10	0.13	10.43	0.07	49.17	0.04	0.01	0.33	101.28	89.37
		16	40.71	0.13	10.43	0.07	49.19	0.04	0.01	0.33	100.91	89.37
		17	40.23	0.13	10.23	0.07	49.42	0.00	0.01	0.28	100.37	89.60
		18	40.82	0.05	10.43	0.09	49.20	0.05	0.06	0.36	101.05	89.37
UH-2.1X2	Lherzolite	24	40.49	0.14	10.30	0.02	48.96	0.05	0.05	0.37	100.38	89.44
		27	40.80	0.03	10.54	0.05	49.53	0.08	0.00	0.43	101.46	89.34
		28	40.69	0.05	10.40	0.05	49.38	0.02	0.00	0.48	101.06	89.43
UH-3.2	Wehrlite	31	40.21	0.10	13.80	0.07	46.88	0.00	0.32	0.00	101.39	85.83
UH-3.4	Wehrlite	35	40.05	0.15	15.99	0.14	45.09	0.02	0.05	0.27	101.77	83.41
		36	39.88	0.19	15.74	0.21	44.97	0.00	0.00	0.17	101.15	83.59
		37	39.50	0.19	15.74	0.21	45.00	0.00	0.00	0.17	100.80	83.60
		38	39.67	0.16	15.99	0.14	45.12	0.02	0.05	0.27	101.42	83.42
		39	39.37	0.09	15.34	0.18	45.54	0.08	0.00	0.24	100.83	84.11
		40	39.45	0.16	15.55	0.07	44.90	0.03	0.01	0.24	100.41	83.73
		41	39.90	0.19	15.74	0.14	45.01	0.02	0.00	0.26	101.26	83.60
		42	39.30	0.07	15.83	0.15	45.21	0.06	0.01	0.21	100.84	83.58
		104	39.14	0.16	15.83	0.16	44.98	0.03	0.03	0.29	100.62	83.51
		105	39.54	0.15	15.83	0.16	44.94	0.03	0.03	0.29	100.98	83.50
		106	39.14	0.15	15.67	0.14	45.13	0.01	0.01	0.20	100.46	83.70
		109	39.28	0.05	15.97	0.09	45.20	0.06	0.03	0.21	100.89	83.46
		110	39.44	0.17	15.59	0.23	45.14	0.08	0.03	0.29	100.98	83.77
		111	39.23	0.11	15.41	0.11	45.19	0.00	0.00	0.22	100.27	83.94
UH-5.1	Harzburgite	47	40.80	0.09	8.45	0.07	50.21	0.07	0.05	0.44	100.17	91.37
		48	40.90	0.09	8.81	0.13	50.21	0.01	0.04	0.51	100.69	91.04
		56	41.17	0.06	9.17	0.07	50.70	0.03	0.02	0.48	101.69	90.79
		57	41.40	0.01	8.89	0.14	50.29	0.04	0.00	0.45	101.22	90.98
		60	40.84	0.02	8.94	0.03	50.50	0.00	0.00	0.42	100.75	90.97
UH-24.1	Harzburgite	68	41.07	0.08	8.83	0.03	50.40	0.00	0.05	0.55	101.00	91.05
		69	40.67	0.08	8.83	0.03	50.43	0.00	0.05	0.55	100.63	91.06
		73	41.24	0.15	8.85	0.05	50.47	0.03	0.00	0.49	101.27	91.04
		74	40.47	0.03	9.07	0.05	50.72	0.05	0.03	0.41	100.83	90.88
		77	40.99	0.07	8.78	0.08	50.20	0.05	0.00	0.38	100.56	91.07
		78	40.58	0.07	8.78	0.08	50.23	0.05	0.00	0.38	100.18	91.07
		81	41.15	0.16	8.65	0.07	50.38	0.04	0.02	0.38	100.83	91.21
		82	40.35	0.16	8.65	0.06	50.44	0.04	0.02	0.38	100.10	91.22

Sample	Lithology	Analysis Number	SiO ₂	Al ₂ O ₃	FeOt	CaO	MgO	CoO	Cr ₂ O ₃	NiO	Total	Fo#
		83	40.50	0.10	8.84	0.02	50.30	0.00	0.00	0.37	100.13	91.03
		84	40.61	0.21	8.85	0.06	50.50	0.00	0.03	0.35	100.61	91.05
		85	41.02	0.21	8.85	0.06	50.47	0.00	0.03	0.35	100.99	91.04
		86	40.76	0.11	8.84	0.11	50.52	0.02	0.00	0.56	100.91	91.06
		95	40.59	0.10	8.83	0.10	50.51	0.00	0.00	0.41	100.55	91.07
		96	40.99	0.10	8.83	0.10	50.48	0.00	0.00	0.41	100.92	91.06
		97	54.91	3.76	5.48	0.89	33.51	0.05	0.28	0.16	99.04	91.60
		98	55.45	3.75	5.48	0.89	33.50	0.05	0.28	0.16	99.56	91.59
		101	40.53	0.08	9.06	0.07	50.63	0.01	0.04	0.43	100.85	90.88
UH-14.1	Lherzolite	114	40.77	0.00	9.48	0.04	49.62	0.00	0.02	0.41	100.34	90.32
		115	40.29	0.08	9.74	0.12	49.65	0.08	0.00	0.39	100.34	90.09
		116	40.40	0.14	9.75	0.03	49.76	0.06	0.06	0.36	100.56	90.10
		119	40.60	0.00	9.57	0.04	49.35	0.05	0.01	0.42	100.03	90.19
		120	40.46	0.13	9.51	0.06	49.71	0.06	0.01	0.31	100.25	90.31
		124	40.37	0.07	9.88	0.00	49.92	0.00	0.06	0.26	100.57	90.01
		125	40.39	0.08	9.61	0.03	49.60	0.07	0.00	0.37	100.16	90.20
		126	40.34	0.10	9.75	0.03	49.69	0.07	0.01	0.46	100.44	90.08
		129	40.28	0.13	9.64	0.00	49.62	0.00	0.00	0.35	100.02	93.05
		132	40.29	0.08	9.62	0.03	49.63	0.10	0.00	0.42	100.17	90.19
		140	40.65	0.08	9.66	0.00	49.93	0.02	0.00	0.51	100.85	90.21
UH-16.1	Harzburgite	144	40.52	0.12	10.09	0.03	49.81	0.09	0.00	0.44	101.10	89.80
		145	40.55	0.05	9.77	0.04	49.61	0.03	0.04	0.41	100.49	90.05
		146	40.48	0.05	9.98	0.13	49.85	0.06	0.05	0.31	100.91	89.90
		147	40.91	0.04	9.98	0.09	49.66	0.02	0.01	0.46	101.16	89.87
		148	40.51	0.15	10.32	0.09	49.83	0.05	0.00	0.40	101.34	89.59
		149	40.54	0.08	10.05	0.09	50.04	0.09	0.00	0.46	101.35	89.87
		155	40.60	0.11	9.85	0.00	49.69	0.01	0.00	0.51	100.76	89.99
		161	40.54	0.06	10.03	0.08	49.66	0.00	0.08	0.52	100.97	89.82
		163	40.61	0.06	9.78	0.07	49.45	0.03	0.04	0.30	100.33	90.01
		185	41.24	0.05	10.50	0.04	49.80		0.02	0.30	101.94	89.42
		186	40.90	0.09	10.24	0.09	49.59	0.04	0.03	0.30	101.28	89.62
		197	40.66	0.09	10.32	0.06	49.81		0.03	0.41	101.38	89.59
		198	40.83	0.07	10.11	0.06	50.00	0.06	0.05	0.37	101.55	89.81
		199	40.88	0.04	10.15	0.04	49.89	0.03		0.36	101.39	89.76
		200	40.87	0.09	10.31	0.07	50.14	0.05	0.04	0.40	101.98	89.66
		204	41.00	0.08	10.15	0.06	49.68		0.05	0.51	101.52	89.72
		205	40.78	0.09	10.25	0.09	50.14	0.12		0.49	101.97	89.71
		206	40.50	0.07	10.01	0.18	49.62	0.08		0.43	100.90	89.83
		209	41.03	0.11	10.49	0.04	49.88	0.03		0.34	101.91	89.45
		210	41.01	0.07	10.18	0.04	49.72	0.05	0.07	0.39	101.52	89.70
		211	41.03	0.07	10.20	0.02	49.92	0.02	0.06	0.47	101.79	89.72
		214	40.99	0.07	10.21	0.07	49.90	0.10	0.02	0.31	101.66	89.70
		215	41.06	0.11	10.03	0.05	49.90	0.05		0.43	101.62	89.87

Sample	Lithology	Analysis Number	SiO ₂	Al ₂ O ₃	FeOt	CaO	MgO	CoO	Cr ₂ O ₃	NiO	Total	Fo#
		218	40.03	0.03	10.29	0.01	49.94		0.04	0.44	100.79	89.64
UH-17.3	Lherzolite	170	40.86	0.09	8.34	0.09	50.97	0.03	0.05	0.47	100.90	91.59
		173	40.72	0.09	8.04	0.01	50.88	0.00	0.00	0.38	100.13	91.86
		174	40.64	0.05	8.19	0.02	50.77	0.01	0.00	0.46	100.14	91.70
		175	40.68	0.11	8.03	0.00	50.78	0.00	0.00	0.46	100.06	91.85
		177	40.80	0.08	7.94	0.01	50.63	0.05	0.01	0.38	99.89	91.91

Table 6 Major element mineral chemical data of clinopyroxene from Harrat Uwayrid peridoite xenoliths.

Sample	Lithology	Analysis Number	SiO ₂	Al ₂ O ₃	FeOt	CaO	MgO	CoO	Cr ₂ O ₃	NiO	Total	Mg#	Cr#
UH-2.1X	Lherzolite	4	52.14	6.51	3.27	20.48	15.12	0.01	0.83	0.00	98.36	89.18	7.90
		5	51.72	6.49	3.16	20.44	14.91	0.00	0.60	0.08	97.39	89.37	5.80
UH-2.1X2	Lherzolite	19	51.81	6.21	3.05	20.74	15.09	0.04	0.75	0.08	97.77	89.82	7.50
		22	51.52	6.18	3.24	20.30	15.21	0.02	0.64	0.05	97.16	89.33	6.50
		23	51.45	6.17	3.24	21.17	15.22	0.02	0.64	0.05	97.96	89.33	6.50
UH-3.2	Wehrlite	30	49.72	8.02	5.29	18.79	15.55	0.00	0.40	0.00	97.77	83.97	3.30
		32	49.61	8.23	5.46	18.58	15.31	0.01	0.32	0.00	97.52	83.33	2.60
UH-5.1	Harzburgite	49	52.99	3.43	2.00	22.04	16.59	0.04	0.88	0.12	98.09	93.67	14.70
		50	53.10	3.36	1.95	22.23	16.66	0.02	1.02	0.04	98.37	93.84	16.90
		51	53.26	3.56	1.99	22.22	16.53	0.00	0.99	0.09	98.64	93.67	15.70
		52	53.78	3.55	1.99	22.22	16.53	0.00	0.90	0.09	99.06	93.67	14.50
		53	53.62	3.35	1.95	22.23	16.65	0.02	1.02	0.04	98.87	93.84	16.90
		54	54.37	2.36	2.15	22.72	17.28	0.00	0.60	0.01	99.48	93.48	14.50
		55	53.60	3.45	2.19	22.30	16.61	0.01	0.96	0.09	99.21	93.11	15.70
		62	54.07	3.28	2.14	22.20	16.62	0.01	0.77	0.00	99.09	93.26	13.60
UH-24.1	Harzburgite	70	52.78	4.75	2.93	20.84	16.48	0.00	1.10	0.03	98.91	90.93	13.50
		71	52.78	4.75	2.93	20.84	16.48	0.00	1.10	0.03	98.91	90.93	13.50
		72	52.99	4.47	2.65	20.93	16.55	0.02	0.96	0.01	98.58	91.76	12.60
		87	52.54	5.00	2.79	20.60	16.57	0.04	0.97	0.00	98.50	91.37	11.50
		99	52.82	4.80	2.86	20.48	16.69	0.06	0.95	0.12	98.78	91.23	11.70
		100	52.91	4.88	2.87	21.09	16.58	0.00	0.82	0.00	99.15	91.15	10.10
		102	52.78	4.86	2.59	20.58	16.53	0.05	0.90	0.08	98.36	91.92	11.00
UH-14.1	Lherzolite	117	53.03	4.92	2.50	21.63	15.44	0.00	0.58	0.10	100.34	91.67	7.33
		118	52.57	5.45	2.55	21.88	15.33	0.04	0.78	0.04	100.56	91.46	8.71
		121	51.81	5.68	2.39	21.50	15.20	0.00	0.59	0.14	97.31	91.89	6.52
		122	52.19	5.43	2.37	21.60	15.07	0.04	0.68	0.05	97.43	91.89	7.70
		123	50.19	6.84	2.62	21.33	15.15	0.00	0.93	0.07	97.13	91.16	8.34
		141	52.77	4.92	2.58	22.12	15.55	0.00	0.72	0.09	98.76	91.48	8.97
UH-16.1	Harzburgite	154	53.06	4.41	2.69	21.25	16.39	0.00	0.93	0.01	98.74	91.57	12.37
		156	53.16	4.94	2.79	21.02	16.14	0.00	0.69	0.04	98.78	91.16	8.58
		219	52.55	4.55	2.58	21.41	16.24	0.06	0.86	0.06	98.31	91.82	11.30
		220	52.71	4.65	2.64	21.18	16.24	0.06	1.01	0.06	98.54	91.64	12.71
		221	50.68	6.83	3.17	20.28	16.38	0.02	1.56	0.08	99.00	90.21	13.29

Sample	Lithology	Analysis Number	SiO ₂	Al ₂ O ₃	FeOt	CaO	MgO	CoO	Cr ₂ O ₃	NiO	Total	Mg#	Cr#
		222	53.02	4.47	2.81	20.87	16.24		0.81	0.07	98.29	91.15	10.83

Table 7 Major element mineral chemical data of orthopyroxene from Harrat Uwayrid peridotite xenoliths.

Sample	Lithology	Analysis Number	SiO ₂	Al ₂ O ₃	FeOt	CaO	MgO	CoO	Cr ₂ O ₃	NiO	Total	Mg#	Cr#
UH-2.1X	Lherzolite	1	55.69	4.45	6.95	0.64	32.87				100.60	89.40	0.00
		2	55.61	4.36	6.67	0.64	32.99				100.27	89.81	0.00
		3	55.18	4.46	6.71	0.64	32.84				99.83	89.72	0.00
UH-2.1X2	Lherzolite	25	55.01	4.38	6.54	0.63	32.92	0.05	0.33	0.04	99.90	89.97	4.80
		29	55.24	4.48	6.74	0.61	33.07	0.00	0.30	0.13	100.58	89.74	9.40
UH-5.1	Harzburgite	58	56.77	2.74	5.41	0.48	34.46	0.02	0.37	0.12	100.37	91.91	8.40
		59	56.82	2.65	5.53	0.57	34.25	0.00	0.36	0.07	100.26	91.69	8.40
		61	56.92	2.61	5.57	0.53	34.30	0.00	0.40	0.07	100.40	91.65	9.20
UH-24.1	Harzburgite	65	55.73	3.75	5.88	0.84	33.69	0.06	0.53	0.17	100.65	91.08	8.70
		66	55.95	3.91	5.73	0.98	33.41	0.00	0.43	0.17	100.58	91.22	6.90
		67	55.95	3.91	5.73	0.99	33.41	0.00	0.43	0.17	100.59	91.22	6.90
		75	56.40	3.42	5.34	0.82	33.84	0.00	0.43	0.18	100.43	91.87	7.70
		76	55.89	3.43	5.34	0.82	33.85	0.00	0.43	0.18	99.93	91.87	7.70
		79	55.85	3.92	5.89	0.67	33.90	0.00	0.49	0.10	100.82	91.12	7.80
		80	54.80	3.94	5.89	0.67	33.93	0.00	0.49	0.10	99.82	91.13	7.70
		93	55.36	3.54	5.75	0.86	34.17	0.00	0.39	0.15	100.22	91.37	7.00
		94	55.90	3.53	5.75	0.86	34.15	0.00	0.39	0.15	100.73	91.37	7.00
		103	55.26	3.44	5.89	0.74	34.12	0.02	0.37	0.13	99.97	91.17	6.70
UH-14.1	Lherzolite	127	54.70	4.48	6.10	1.03	32.84	0.00	0.34	0.15	99.64	91.60	4.80
		128	54.49	4.16	6.40	0.45	33.63	0.03	0.42	0.08	99.67	93.05	6.33
		130	55.50	3.42	6.30	0.42	33.83	0.00	0.14	0.05	99.66	91.67	2.76
		131	55.00	3.60	6.36	0.50	33.83	0.01	0.34	0.13	99.77	92.85	5.90
		134	55.17	4.00	6.37	0.43	33.60	0.00	0.28	0.13	99.99	91.80	4.55
		139	55.42	3.66	6.44	0.46	33.77	0.00	0.27	0.08	100.10	91.80	4.70
UH-16.1	Harzburgite	150	55.44	3.75	6.27	0.61	33.72	0.03	0.30	0.16	100.27	92.08	5.01
		151	56.34	3.71	6.15	0.50	33.62	0.00	0.37	0.12	100.81	90.69	6.32
		152	55.39	3.60	6.41	0.57	33.58	0.00	0.42	0.14	100.11	91.52	7.24
		153	55.30	3.52	6.17	0.72	33.38	0.00	0.41	0.14	99.64	91.46	7.32
		160	54.88	3.96	6.31	0.69	33.03	0.05	0.41	0.18	99.51	91.29	6.55
		162	52.55	5.76	6.59	0.58	33.28	0.00	1.11	0.12	99.99	95.75	11.46
		179	56.67	3.38	6.40	0.68	33.58	0.01	0.31	0.08	101.11	90.34	5.72
		180	56.32	3.62	6.30	0.63	33.56		0.41	0.08	100.92	90.47	7.12
		181	56.46	3.62	6.36	0.58	33.70	0.02	0.43	0.10	101.27	90.43	7.43
		182	56.23	3.56	6.59	0.56	33.49		0.38	0.11	100.93	90.06	6.71
		183	56.02	3.53	6.42	0.52	33.84		0.43	0.06	100.81	91.08	7.55
		184	55.84	3.57	6.26	0.49	33.58	0.08	0.30	0.05	100.17	90.70	5.38
		194	55.79	3.50	6.42	0.65	33.55		0.40	0.03	100.35	90.83	7.17
		195	55.76	3.55	6.56	0.70	33.62	0.00	0.39	0.10	100.68	91.26	6.81

<i>Sample</i>	<i>Lithology</i>	<i>Analysis Number</i>	<i>SiO₂</i>	<i>Al₂O₃</i>	<i>FeOt</i>	<i>CaO</i>	<i>MgO</i>	<i>CoO</i>	<i>Cr₂O₃</i>	<i>NiO</i>	<i>Total</i>	<i>Mg#</i>	<i>Cr#</i>
		196	56.05	3.39	6.45	0.58	33.78		0.28	0.04	100.58	90.94	5.27
		201	55.71	3.68	6.60	0.54	33.76	0.02	0.37	0.05	100.74	91.38	6.33
		202	55.90	3.54	6.42	0.54	33.81		0.38	0.11	100.69	91.25	6.72
		203	56.09	3.50	6.53	0.60	33.73	0.03	0.31	0.18	100.98	91.01	5.65
		207	55.58	3.82	6.58	0.77	33.54	0.04	0.40	0.16	100.88	91.63	6.52
		208	55.56	3.58	6.57	0.75	33.53	0.05	0.32	0.08	100.43	91.45	5.62
		212	56.02	3.42	6.54	0.59	33.99		0.30	0.13	100.99	91.60	5.50
		213	55.99	3.48	6.58	0.56	33.93	0.07	0.44	0.08	101.14	91.54	7.90
		216	54.74	3.30	6.42	0.68	33.70	0.02	0.32	0.14	99.32	93.23	6.06
		217	54.68	3.31	6.44	0.68	33.72	0.02	0.33	0.15	99.33	93.33	6.33
<i>UH-17.3</i>	Lherzolite	169	56.71	1.62	5.21	0.37	35.29	0.00	0.40	0.07	99.68	93.57	14.23
		171	57.23	1.34	5.12	0.39	35.27	0.01	0.39	0.07	99.82	92.68	16.34
		172	56.93	1.23	5.55	0.28	35.48	0.03	0.06	0.06	99.62	93.52	3.41
		176	56.95	1.32	5.09	0.27	35.57	0.00	0.32	0.08	99.60	93.68	14.08
		178	57.25	1.32	5.33	0.35	35.55	0.01	0.29	0.16	100.25	93.40	12.69

Most clinopyroxene of Harrat Uwayrid peridotite xenoliths from this study plot similarly to other Harrat Uwayrid peridotite clinopyroxenes such as from the study of [Henjes-Kunst et. al. \(1990\)](#) and [Kaliwoda et. al. \(2007\)](#) in Mg# vs. Cr# space (Fig. 19). All plot in a similar area with comparable values of Mg# ranging from 0.89 – 0.93 and Cr# of 0.6 - 1.8. One outlier from Harrat Uwayrid peridotite xenolith sample UH-3.2 of this study, plots to the lower left of the diagram with an anomalously low Mg# of ~0.84. This low Mg# is characteristic of wehrlite / pyroxenite ([Frey and Green, 1974](#); [Frey and Prinz, 1978](#); [Pearson et al., 2014](#)), hence supporting the mode classification for sample UH-3.2 in section 4.1.

Compared to other western Arabian peridotite xenoliths, those of Harrat Kishb have higher Cr# values of ~0.8, and slightly higher Mg# and so exhibit a dissimilar trend. Further discussions on the degrees of partial melting and depletion are discussed in Chapter 5.

iii. Spinel

Major elements compositions of spinel are provided in Table 8. A total of 35 analyses were obtained on spinel of Harrat Uwayrid peridotite xenoliths.

The Al₂O₃ and Cr₂O₃ content of Harrat Uwayrid peridotite xenolith spinel plot within the general mantle array field (Fig. 20). Al₂O₃ ranges from 41.51 – 58.64 wt. %, and Cr₂O₃ varies from 8.23 – 27.78 wt. %.

Mg# of the spinel from Harrat Uwayrid peridotite xenoliths are homogeneous with values ranging between 75.80 – 81.40. Cr# of spinel's have values between 8.90 – 30.70. These values lie within Mg# and Cr# field of spinel peridotites from [McDonough & Rudnick \(1998\)](#).

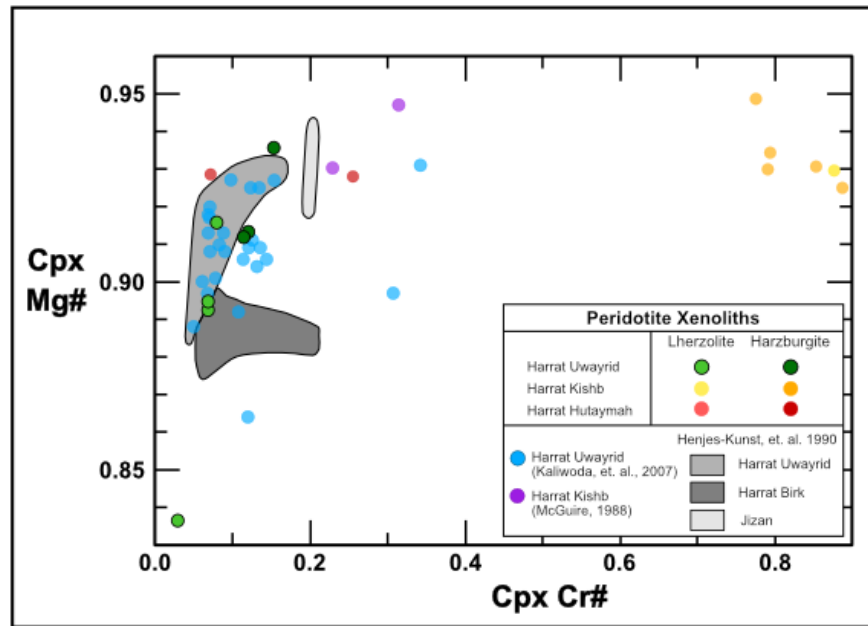


Figure 19 Mg# vs. Cr# of clinopyroxene in peridotites from various Saudi Arabian Harrats (modified from [Henjes-Kunst et. al. \(1990\)](#)).

The Harrat Uwayrid peridotite mantle xenoliths are further discriminated and plotted in comparison to the defined fertile and refractory peridotite fields from the study of [Zheng et. al. \(2001\), \(2007\)](#). Harrat Uwayrid peridotite xenoliths have representative samples in each field, with samples UH-2.1X, and UH-2.1X2 lying in the fertile mantle field, and samples UH-5.1, UH-14.1, and UH-16.1 falling within both the fertile and refractory mantle field. Sample UH-24.1 is positioned in refractory field mantle (Fig. 21).

A study by [McDonough and Rudnick \(1999\)](#) mentioned that lherzolites are considered fragments of the primitive mantle and that harzburgites are primitive mantle subjected to high partial melting. The results above imply that lherzolites and harzburgites of Harrat Uwayrid mantle peridotite xenoliths generally originate from a fertile mantle, a relatively undepleted mantle. In comparison, only two harzburgites are shown to be categorized as a refractory mantle, the part of the mantle considered to be the residue of extensive partial melting. These findings are consistent with Harrat Uwayrid mantle peridotites mineralogy classification.

Table 8 Major element mineral chemical data of spinel from Harrat Uwayrid peridotite xenoliths.

Sample	Lithology	Analysis Number	SiO ₂	Al ₂ O ₃	FeOt	CaO	MgO	CoO	Cr ₂ O ₃	NiO	Total	Mg#	Cr#
UH-2.1X	Lherzolite	12	0.09	58.12	11.84	0.04	21.06	0.04	8.42	0.48	100.08	76.02	8.90
		13	0.12	58.06	11.49	0.05	21.02	0.06	8.49	0.56	99.86	76.53	8.90
		14	0.11	58.64	11.76	0.00	20.82	0.00	8.23	0.46	100.02	75.94	8.90
UH-2.1X2	Lherzolite	20	0.09	58.23	11.49	0.00	20.92	0.01	8.88	0.43	100.05	76.45	9.30
		21	0.18	58.37	11.76	0.00	20.80	0.00	8.91	0.42	100.44	75.92	9.30
		26	0.12	57.92	11.39	0.00	20.91	0.00	8.94	0.52	99.80	76.59	9.40
UH-5.1	Harzburgite	44	0.15	42.06	11.53	0.02	18.39	0.04	27.78	0.25	100.22	73.98	30.70
		45	0.13	41.51	11.89	0.00	18.38	0.06	27.43	0.20	99.60	73.37	30.70
		46	0.08	42.60	11.23	0.01	18.74	0.07	27.27	0.16	100.16	74.84	30.00
UH-24.1	Harzburgite	63	0.10	48.89	11.83	0.00	20.11	0.00	18.53	0.43	99.89	75.19	20.30
		64	0.22	48.96	11.39	0.05	20.10	0.03	18.09	0.45	99.29	75.88	19.90
		88	0.10	49.14	11.58	0.05	20.22	0.08	18.73	0.43	100.34	75.68	20.40
		89	0.27	49.36	11.49	0.00	20.36	0.00	18.04	0.39	99.91	75.95	19.70
		90	0.15	48.74	11.70	0.01	20.10	0.06	18.19	0.39	99.33	75.38	20.00
		91	0.13	48.88	11.32	0.01	20.20	0.00	17.47	0.30	98.31	76.08	19.30
		92	0.13	49.14	11.71	0.05	20.24	0.03	17.86	0.38	99.54	75.50	19.60
UH-14.1	Lherzolite	112	0.06	56.15	11.48	0.00	20.62	0.07	11.22	0.48	100.07	80.41	11.82
		113	0.15	56.58	11.23	0.07	20.68	0.04	11.07	0.36	100.19	80.11	11.60
		133	0.11	56.50	11.30	0.00	20.38	0.02	10.61	0.38	99.30	79.48	11.19
		135	0.17	56.31	11.31	0.03	20.54	0.03	10.89	0.31	99.59	79.89	11.48
		136	0.18	56.39	11.77	0.02	20.60	0.09	10.87	0.46	100.39	79.79	11.45
		137	0.11	56.54	11.45	0.03	20.58	0.06	10.87	0.40	100.04	80.02	11.42
		138	0.13	56.41	11.43	0.06	20.62	0.02	10.84	0.48	100.00	80.28	11.42
		142	0.17	51.24	11.89	0.00	20.04	0.09	15.98	0.32	99.73	79.49	17.30
UH-16.1	Harzburgite	143	0.15	51.67	11.52	0.00	19.99	0.05	15.51	0.41	99.31	79.55	16.76
		157	0.10	51.35	11.92	0.00	20.11	0.06	16.01	0.46	100.01	79.83	17.30
		158	0.07	51.46	11.66	0.04	20.03	0.01	15.64	0.33	99.24	79.80	16.94
		159	0.11	51.41	11.73	0.00	20.09	0.09	16.21	0.37	100.01	79.65	17.46
		187		50.70	12.21		20.10	0.05	15.87	0.32	99.25	80.41	17.35
		188		50.66	12.09		19.99	0.05	15.92	0.29	99.00	80.15	17.41
		189		50.72	12.02		20.02	0.02	16.31	0.35	99.44	80.05	17.74
		190		50.73	11.98		19.91	0.07	15.91	0.33	98.93	80.01	17.38
		191		50.82	12.28		20.08	0.05	15.24	0.34	98.81	80.64	16.75
		192		50.93	12.21		20.18	0.07	15.53	0.31	99.23	80.69	16.98
		193		50.92	12.00		20.15	0.11	15.44	0.36	98.98	80.83	16.90
UH-17.3	Lherzolite	164	0.08	20.90	17.43	0.07	14.39	0.02	43.50	0.11	97.08	67.77	58.27
		165	0.11	21.05	17.59	0.00	14.38	0.06	43.47	0.02	97.25	67.24	58.08
		166	0.01	20.71	17.75	0.10	14.44	0.00	43.83	0.19	97.67	68.08	58.67
		167	0.16	21.39	17.66	0.00	14.61	0.00	42.78	0.14	97.35	68.12	57.30
		168	0.78	21.73	15.42	0.03	15.95	0.07	43.40	0.18	98.03	71.92	57.26

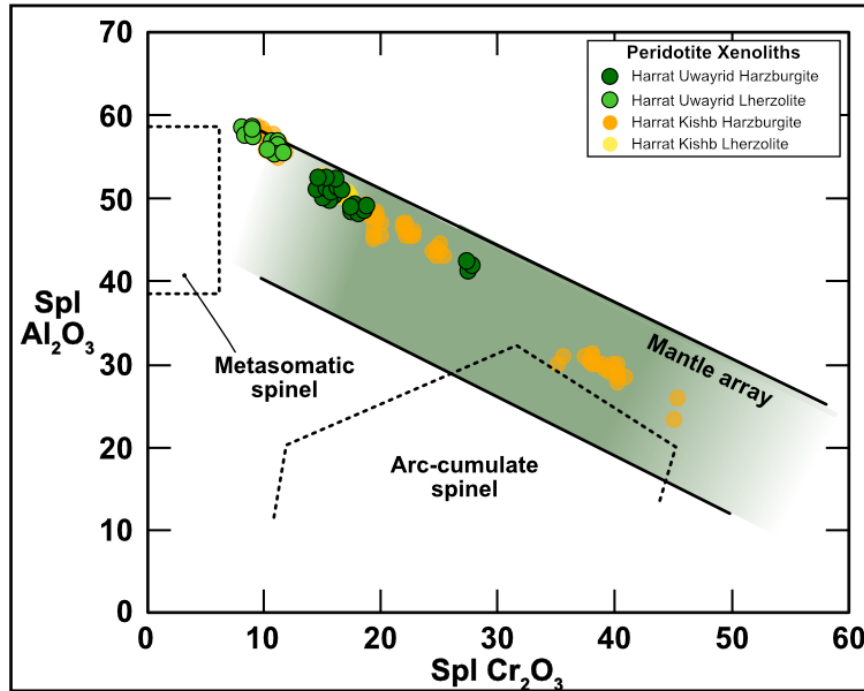


Figure 20 Al_2O_3 vs Cr_2O_3 contents of spinel in the studied mantle xenoliths (modified from [Ahmed et al. \(2016\)](#)). Fields of metasomatic, and arc-cumulate spinel from [Franz and Wirth \(2000\)](#) and [Rajesh et al. \(2013\)](#).

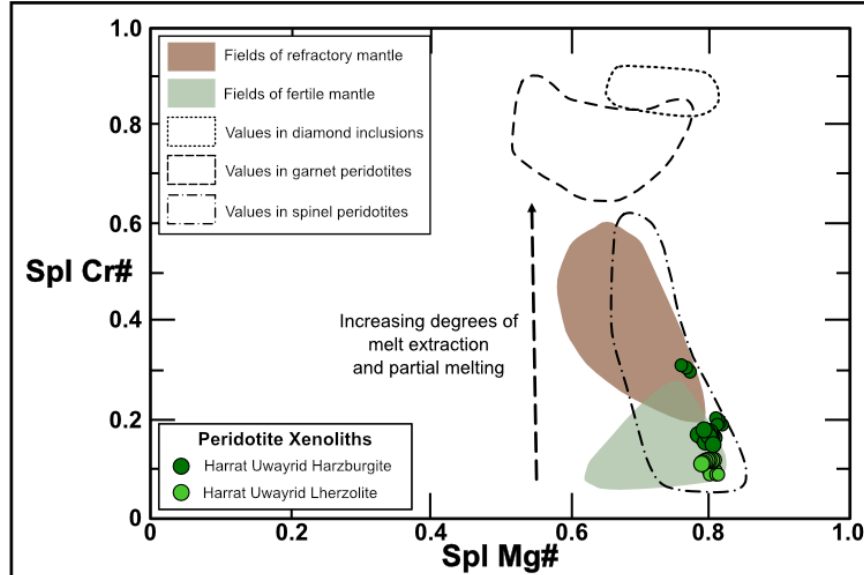


Figure 21 $\text{Mg\#}$ vs $\text{Cr\#}$ contents of the peridotite xenoliths. The spinel, garnet and diamond peridotite values are compiled in the study of [McDonough and Rudnick \(1998\)](#). The fertile and refractory mantle fields are from [Zheng et al. \(2001\)](#); (2007).

CHAPTER 5

DISCUSSION

5.1 Degrees of Partial Melting and Melt Extraction

Bulk-rock CaO and Al₂O₃ concentrations can be used to assess the degree of mantle depletion and partial melting (e.g. [Frey and Green, 1974](#); [Stern and Johnson, 2010](#); [Pearson et al., 2014](#); [Downes, 2021](#)) since CaO and Al₂O₃ preferentially partition into melt during partial melting and so are removed from the residual peridotite. Fig. 22 shows the Harrat Uwayrid peridotite xenoliths samples was subjected to ~1% to ~17% partial melting.

Mineral chemistry data is also utilized to quantify the degree of mantle depletion using the olivine – spinel (OSMA) mantle array diagram shown in Fig. 23, which utilizes spinel Cr# against olivine Fo#. The diagram shows that mantle depletion percentages vary between ~1% - ~13% for the Harrat Uwayrid peridotite xenoliths, with sample UH-17.3 - harzburgite- plotting as an outlier with anomalously high depletion (~29%).

Additionally, higher precision values of melt extraction degrees were also produced utilizing the formula of [Hellebrand et. al. \(2001\)](#), defined as $F = 10 * \ln(\text{Cr\#}_{\text{spl}}) + 24$. Calculations from the formula resulted in melt extraction with a range of 0.26% - 12.12%. Similar to the OSMA diagram (Fig. 23), sample UH-17.3 is dissimilar to the other samples, displaying anomalously high degree of melt extraction of 18.54%.

Comparison of bulk-rock, mineral chemistry and melt extraction calculation of each sample show similar results (Table 9), except sample UH-17.3 which show varying results.

Table 9 Comparison of degrees of partial melting and melt extraction of Harrat Uwayrid peridotite xenoliths.

Sample	Lithology	F CaO vs Al₂O₃ WR	F Cr#_{spl} vs Fo#_{ol}	F Cr#_{spl}
UH-2.1X	Lherzolite	1 %	0 %	-
UH-2.1X2	Lherzolite	5 %	1 %	0.26 %
UH-4.1	Harzburgite	14.9 %	-	-
UH-5.1	Harzburgite	17 %	13 %	12.12 %
UH-13.2	Lherzolite	14 %	-	-
UH-14.1	Lherzolite	6%	3%	2.36 %
UH-16.1	Harzburgite	9 %	7 %	6.39 %
UH-17.2	Lherzolite	6 %	-	-
UH-17.3	Lherzolite	2%	29 %	18.54 %
UH-17.6	Lherzolite	12.5 %	-	-
UH-24.1	Harzburgite	14.8 %	8 %	7.8 %

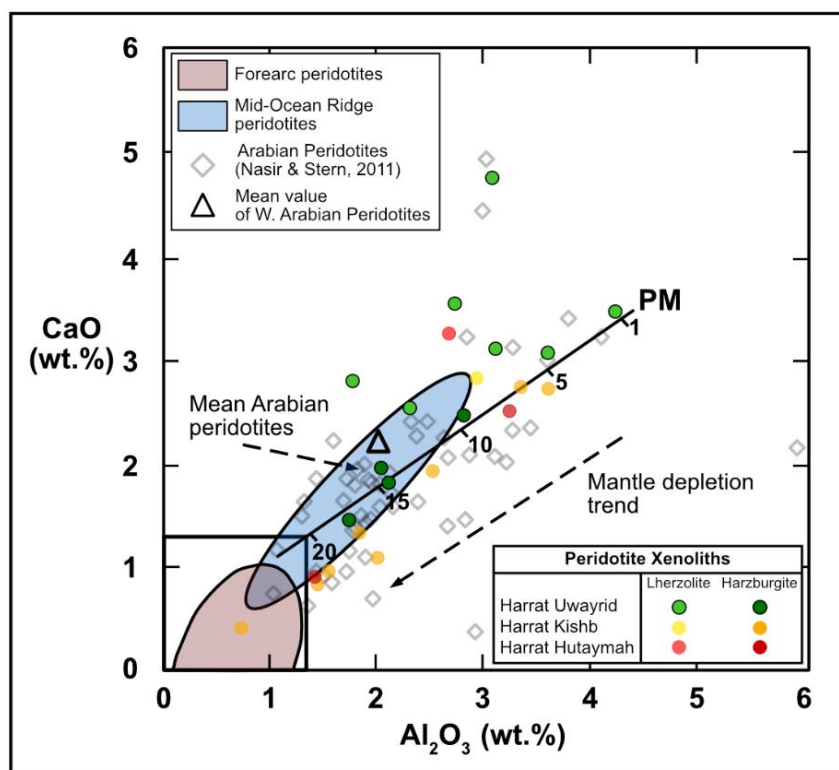


Figure 22 CaO vs Al₂O₃ plot of whole rock chemistry of Harrat Uwayrid peridotite xenoliths among other western Arabian (Stern and Johnson, 2010) and Arabian peridotites (Nasir and Stern, 2012). Primitive mantle (PM) values from McDonough and Sun (1995).

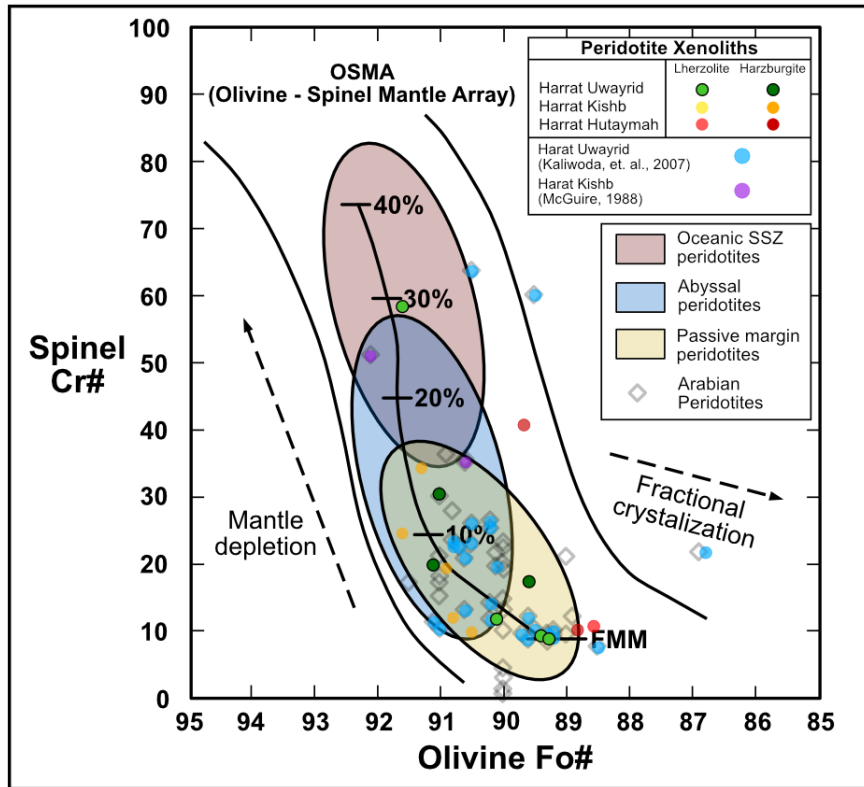


Figure 23 The olivine - spinel mantle array (OSMA) diagram from [Arai \(1994\)](#) indicating percentage of mantle depletion in peridotite xenoliths based on Fo# vs Cr#.

Overall, Harrat Uwayrid peridotite xenoliths are similar to other western Arabian and Arabian peridotite xenoliths, which were subjected to low to moderate (~1% - 17%) degrees of partial melting and melt extraction consistent with their formation in a within-plate setting.

Distinction between the degrees of melt depletion between the Harrat Uwayrid lherzolites and harzburgites are readily apparent (Table 9). Whereas the former is relatively less depleted and more similar to primitive mantle, the latter shows relatively higher degrees of depletion akin to mid-ocean ridge peridotites (Fig. 22). The results suggests that the Harrat Uwayrid harzburgites were subjected to higher degrees of partial of melting in comparison to Harrat Uwayrid lherzolites, consistent with the mineralogy.

5.2 Oxidation State

The calculated oxygen fugacity (f_{O_2}) values of the Harrat Uwayrid peridotite xenoliths are presented in Table 10. The f_{O_2} calculated with the oxygen barometer of [Ballhaus et al. \(1990\)](#) which employs interaction of coexisting olivine-orthopyroxene-spinel compositions

Harrat Uwayrid peridotite xenolith f_{O_2} are plotted against spinel Cr# taking into consideration their positions relative to the fayalite-magnetite-quartz (FMQ) buffer (Fig. 24). The f_{O_2} values range from -1.89 to -0.22.

Harrat Uwayrid samples fall into 2 fields. All Harrat Uwayrid lherzolites (UH-2.1X, UH-2.1X2 and UH-14.1) lie within the primitive mantle field whereas all harzburgites (UH-5.1,

UH-24.1, and UH-16.1), which were subjected to higher degrees of melt extraction fall within the abyssal peridotite field.

Fig. 24 show that Harrat Uwayrid lherzolites and harzburgites display oxygen fugacity similar to other global mantle peridotite xenolith suites. Harrat Kishb peridotite xenoliths however display f_{O_2} that deviates somewhat from their equivalent global mantle peridotite xenolith fields.

An important point is that the original mantle in which the peridotites originated from equilibrated in a reduced environment, consistent with a within-plate environment.

1.1 Thermobarometry

Calculation of the temperature (T), T_{BKN} and $T_{Ca-in-Opx}$ are from the two-pyroxene thermometer of [Brey and Kohler \(1990\)](#) and are presented in Table 11 below.

Methods of calculation of pressure (P) for the spinel phase are limited to the barometer of [Kohler and Brey \(1990\)](#) (P_{KB}). The method utilizes Ca exchange between olivine and clinopyroxene. However, because this barometer has a high temperature sensitivity ([Pearson et. al., 2014](#)), significantly different results occur when there exist even slightest differences in temperature. Results of these calculations are provided in Table 12.

Table 10 Summary of range and mean of oxygen fugacity of Harrat Uwayrid peridotite xenoliths.

Sample	Lithology	$\Delta\log(fO_2)$
UH-2.1X	Lherzolite	[-0.47] - [-0.22] (-0.34)
UH-2.1X2	Lherzolite	[-1.15] - [-0.85] (-0.97)
UH-5.1	Harzburgite	[-1.89] - [-1.21] (-1.63)
UH-24.1	Harzburgite	[-0.56] - [-0.39] (-0.47)
UH-14.1	Lherzolite	[-1.11] - [-0.73] (-0.89)
UH-16.1	Harzburgite	[-1.24] - [-0.55] (-0.86)

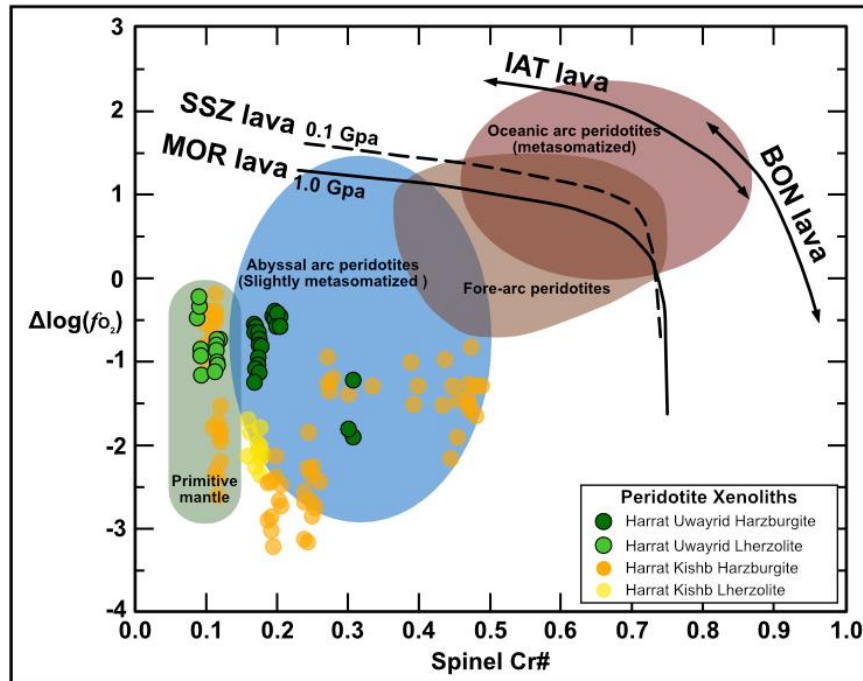


Figure 24 Bivariate plot of $\Delta\log fO_2$ fayalite-magnetite-quartz (FMQ) vs spinel Cr# (Dare et al., 2009) of western Arabian peridotite xenoliths. Fields of various mantle peridotites are from Ballhaus (1993), Parkinson and Pearce (1998), and Arai and Ishimaru (2008).

Calculated T and P (T_{BKN} and P_{KB}) are plotted on Fig. 25. Two of the six geothermobarometry results lie similarly to the Harrat Uwayrid peridotite xenoliths from [Kaliwoda et al. \(2007\)](#). Temperature results from T_{BKN} values between 1019° - 1135° C, while pressure values from P_{KB} are shown ranging from 1.72 – 3.76, corresponding to equilibration at approximately 50 km - 105 km depth.

The other four samples in Fig. 25 suggests their formation at higher pressure and depth. UH 2.1X2 and UH-16.1 are the anomalous exhibiting pressures below 3 GPa and depths below 90 km. Harrat Uwayrid lherzolites and harzburgites show similar equilibrium temperatures and pressures (depths). The results suggest heterogeneity of the regions of the mantle below Harrat Uwayrid.

Fig. 26 shows the Harrat Uwayrid peridotite xenoliths calculated depths plotted on an interpretation of the Western Arabian plate crust cross-section. The peridotite xenoliths mainly originated in asthenospheric mantle, with few from the sub-lithospheric mantle. However this result does differ slightly with the previous studies, in which mention that the xenoliths have lithospheric origins ([Henjes-Kunst et al., 1990](#)).

Table 11 Calculated Thermometry of Harrat Uwayrid peridotite xenoliths.

Sample	Lithology	$T_{BKN} (C^{\circ})$	$T_{Ca-in-Opx} (C^{\circ})$
UH-2.1X	Lherzolite	1135.38	946.73
UH-2.1X2	Lherzolite	1168.23	1050.80
UH-5.1	Harzburgite	1019.41	824.70
UH-24.1	Harzburgite	1143.76	1047.94
UH-14.1	Lherzolite	1090.62	907.28
UH-16.1	Harzburgite	1174.18	1015.95

Table 12 Calculated Thermobarometry of Harrat Uwayrid peridotite xenoliths.

Sample	Lithology	$P_{KB} (Gpa)$
UH-2.1X	Lherzolite	1.78
UH-2.1X2	Lherzolite	3.76
UH-5.1	Harzburgite	1.72
UH-24.1	Harzburgite	2.87
UH-14.1	Lherzolite	2.59
UH-16.1	Harzburgite	3.27

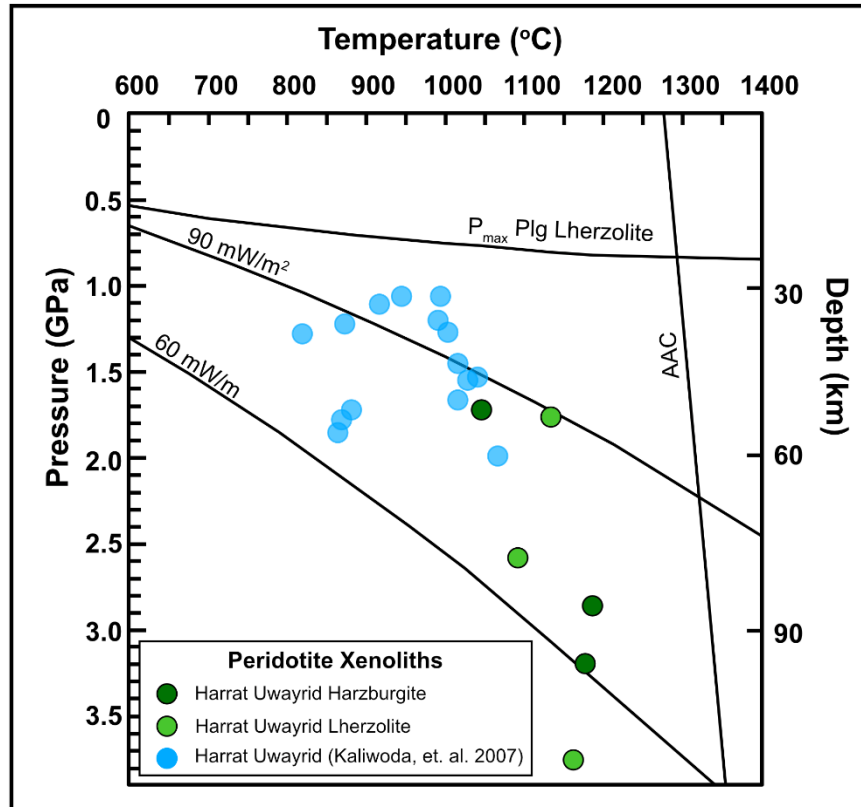


Figure 25 Diagram adapted from [Kaliwoda et al. \(2007\)](#), which consists of thermobarometry results and the calculated transitional depth of plagioclase bearing lherzolite boundary from the study. Heat geotherms are from the study of [Pollack and Chapman \(1977\)](#).

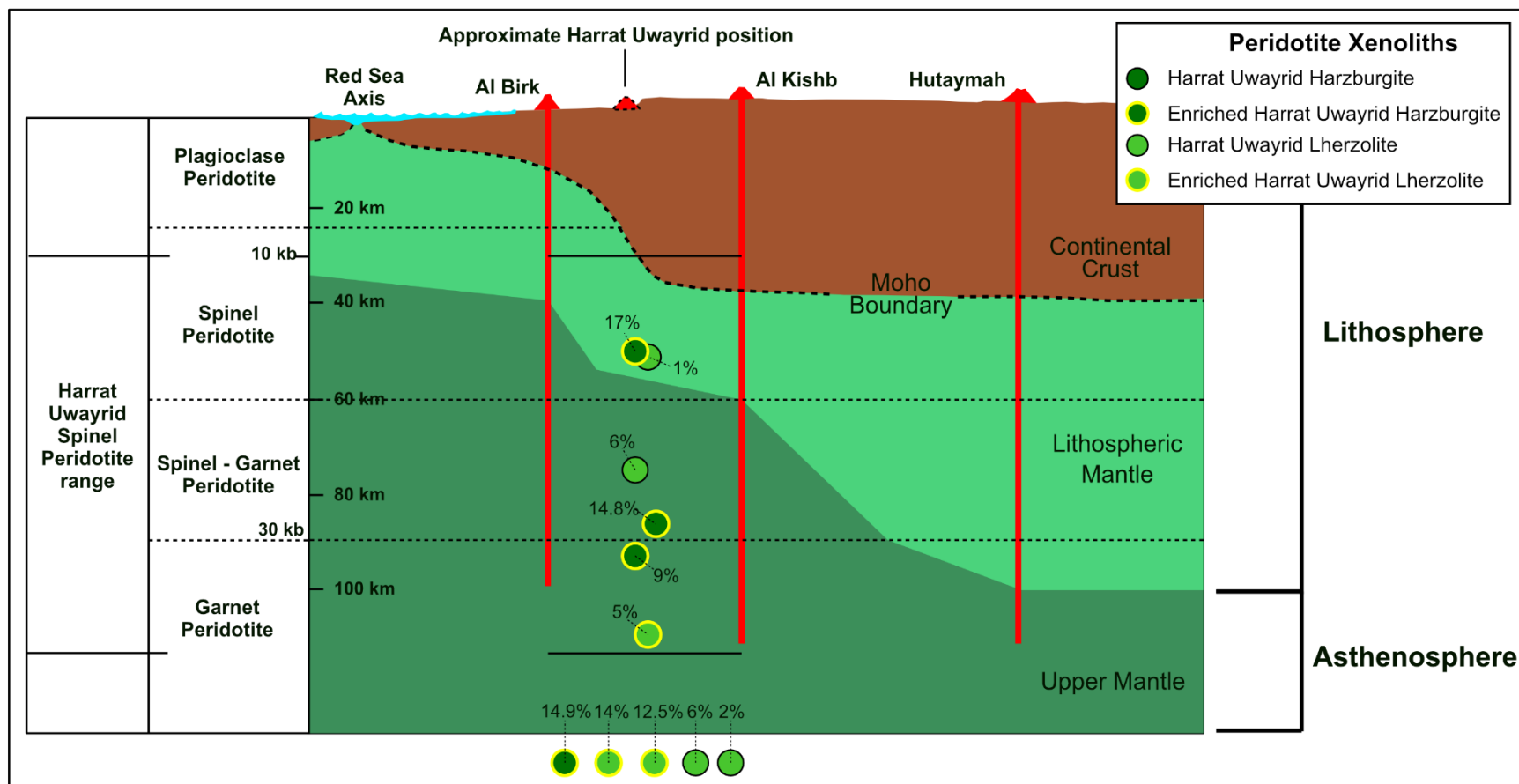


Figure 26 Harrat Uwayrid peridotite xenoliths and the interpretation of Western Saudi Arabia's lithospheric mantle (adapted from [McGuire, 1988b](#)). Moho and lithosphere–asthenosphere boundaries adapted from the shear-wave velocity profile study of [Park et al. \(2008\)](#).

5.4 Enrichment and Metasomatism

[Frey and Green \(1974\)](#) recognized that incompatible rare earth elements (REE) provide insights into second-stage enrichment processes. Incompatible elements in the REE group are defined as the light REE (LREE) La to Sm by [Gill \(2010\)](#), whereas [Rollinson and Pease \(2021\)](#) include Pm. As shown in Fig. 27, several Harrat Uwayrid peridotite xenolith samples display high LREE, particularly La and Ce. Enrichment in these LREE attests that the original mantle from which the LREE-enriched samples were derived was subjected to secondary metasomatic enrichment.

Enrichment of the LREE in Harrat Uwayrid peridotite xenoliths are observed in both Harrat Uwayrid spinel lherzolite and Harrat Uwayrid spinel harzburgite samples (Fig. 28). The enrichments are generally more pronounced in the Harrat Uwayrid spinel harzburgites, as 3 of 4 samples display relatively high chondrite-normalized La/Yb (La_{cn}/Yb_{cn}) of 2.95 – 7.49. However, a fourth harzburgite has La_{cn}/Yb_{cn} of 0.64, like most of the Harrat Uwayrid spinel lherzolites.

Apart from an outlier with very high Ce_{cn}/Yb_{cn} of 21.88 (sample UH-13.2), the Harrat Uwayrid spinel lherzolites display relatively lower Ce_{cn}/Yb_{cn} values in comparison to the harzburgites and are closer to chondritic values, ranging from 0.25 – 4.76.

A study by [Menzies \(1983\)](#) subdivided patterns of LREE enrichment (type 1A) and LREE depletion (type 1B) based on clinopyroxene REE. As whole-rock REE patterns represent their clinopyroxene REE patterns ([Pearson et al., 2014](#)), Harrat Uwayrid Cr-diopside lherzolites group are primarily categorized as type IB ($Ce_n/Yb_n > 1$), with a few 1A types ($Ce_n/Yb_n < 1$).

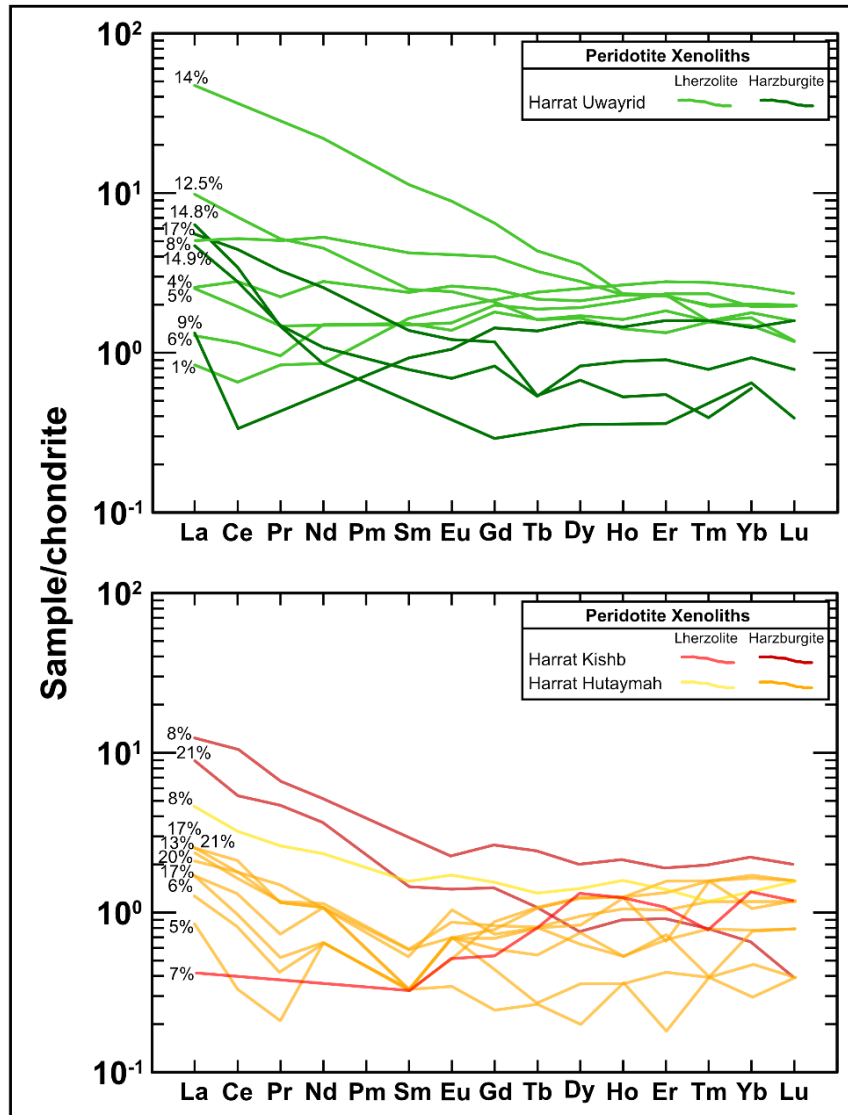


Figure 27 REE values from Harrat Uwayrid, Al-Kishb and Hutaymah normalized to CI Carbonaceous Chondrite. Depletion percentage values estimated from bulk-rock CaO vs Al₂O₃ contents.

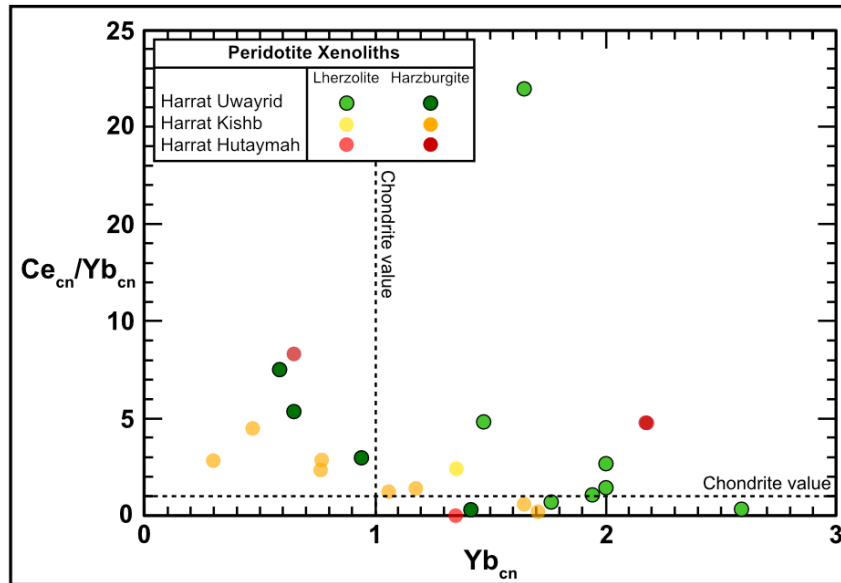


Figure 28 Ce/Yb vs Yb chondrite-normalized from whole rock chemistry of peridotite xenoliths in young (Upper Miocene and younger) western Arabian lava suites.

Harrat Al-Kishb peridotite xenoliths generally show lower Ce_{cn}/Yb_{cn} and Yb_{cn} compared to the Harrat Uwyarid lherzolites and harzburgites. Meanwhile, Harrat Hutaymah peridotite xenoliths range from relatively enriched to moderately enriched with Ce_{cn}/Yb_{cn} of 0.13, 5.68, and 13.83.

Furthermore, [McDonough \(1990\)](#) showed that the continental lithospheric mantle is generally characterized by incompatible element enrichment. Peridotite xenoliths of Harrat Uwayrid and other western Arabian harrats well exhibit such characteristics. It is established that peridotite xenoliths from the young harrats, less than ~30 Ma ([Stern and Johnson, 2010](#)), record degrees of enrichment that range from slight to pronounced.

An important observation from comparison of degrees of partial melting percentages to LREE enrichment (Fig. 27). Peridotite samples with a higher degree of depletion percentage (gauged by whole-rock CaO and Al_2O_3 abundances) generally show LREE enrichment. Conversely, samples with a lower depletion percentage are mostly not LREE enriched. Harrat Uwayrid harzburgites generally exhibit the former, and the lherzolites display the latter.

However, samples that differ from the trend also exist, such as a harzburgite with a relatively low degree of depletion and two lherzolites showing a relatively high degree of depletion. These minor trends may be related to the various petrogenetic sequences to which the peridotite xenoliths were subjected.

5.5 Petrogenesis of Harrat Uwayrid Mantle Xenoliths

The mantle beneath Saudi Arabia (western Arabian plate) has been identified to have been subjected to a multi-stage history ([Henjes Kunst et al., 1990](#); [Blustzajn et al., 1995](#)). In their study, [Frey and Green \(1974\)](#) proposed an interpretation of the multi-stage history while explaining continental peridotite xenolith LREE enriched signatures. Peridotites were initially melt-depleted due to basalt extraction and this residue was later enriched by small amounts of incompatible element-enriched melt or late-stage melt/fluid infiltration before/during an eruption.

This study has established partial melting degrees and melt extraction from mantle xenoliths originating from the mantle below Harrat Uwayrid as 1 – 17%. Further observations show that degrees of melting for 1A samples, which represent residues of varying degrees of melt extraction for long-period depletion of the sub-continental mantle ([Blustzajn et al., 1995](#)), differ and are generally lower than the degree of melt extraction from 1B samples. This suggest that the mantle under Harrat Uwayrid was subjected to two periods of separate partial melting processes.

The first partial melting event is related to tectonic events involving accretion of the Arabian plate during the Neoproterozoic. However, suggestions as to the exact age of the depletion differ, from 850 – 650 Ma ([Henjes Kunst et al., 1990](#)) to 670 – 430 Ma ([Blustzajn et al., 1995](#)). The the second partial melting is suggested to have occurred during rifting of the Red Sea due to Afar plume head emplacement ([Henjes Kunst et al., 1990](#); [Stein and Hofmann, 1992](#); [Blustzajn et al., 1995](#)) caused by ascension of host magmas by decompression and infiltration of fluids ([Kaliwoda et al., 2007](#)).

Although this study does not manage to identify the periods of metasomatism, a study by [Henjes Kunst et al., 1990](#) has proposed the occurrence of the enrichment during the large-scale phenomena of rifting of the Red Sea, with LREE enrichment which is observed in samples IB as evidence. The agent that carried the incompatible elements and enriched the LREE of the type 1B sample is suggested to be a H₂O rich fluid ([Blustzajn et al., 1995](#); [Kaliwoda et al., 2008](#)), as [Meen et al. \(1989\)](#) discovered that CO₂-rich fluids could not cause LREE enrichment. Furthermore, as high-field strength element depletion is seen within the peridotite xenoliths (Fig. 21), this suggest that the agent of fluid enrichment is related to subduction processes ([Downes, 2001](#)). Also, there exists no other evidence to suggest alternative enrichment agents, such as silicate melts or carbonatite magmas, as the cause of metasomatism.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

- The Harrat Uwayrid peridotite xenoliths of this study are identified as spinel lherzolite, spinel harzburgite and wehrlite.
- No distinctive features are apparent between the xenoliths retrieved from the young scoracious basanite with the xenoliths collected from the older alkalic lavas.
- Petrogenesis of the peridotite xenoliths consists of depletion, enrichment, and metasomatic events.
- Peridotite xenoliths of the study exhibit low to moderate degrees of partial melting, ranging from 1 - 17 %.
- Oxygen fugacity values of peridotite xenoliths range from -1.89 to -0.22, indicative of equilibration in a reduced (non-oxidized) environment.
- Calculated geothermobarometry establishes the last equilibration of the studied peridotites xenoliths at pressures of $\sim 1.72 - 3.76$ GPa corresponding to depths of $\sim 50 - 105$ km and temperatures between $\sim 1019^\circ - 1135^\circ$ C.
- The mantle below Harrat Uwayrid was subjected to similar large-scale events of the Arabian plate.

- The studied peridotite xenoliths exhibit generally similar degrees of partial melting, oxidation state and metasomatism in comparison to other similarly aged western Arabian Harrats.

6.2 Recommendations

- Perform point counting as a method for mode classification.
- Provide XRD and QEMSCAN results for classification constraints.
- Isotope analysis for age determination and better petrogenesis analysis constraints.
- Correlate the determined petrogenesis to the major tectonic events.
- Apply the study's methodology to other less studied mantle peridotite xenoliths from Cenozoic-aged harrat in Western Saudi Arabia.

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