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Geochemistry and Chromium Enrichment of the Hamumah Intrusive Rocks, Khamis Mushayt, Southern Saudi Arabia

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Abstract. Jabal Hamumah is a small, isolated, intrusive plug located in the Khamis Mushayt quadrangle, southern Saudi Arabia. The pluton is composed of shonkinite (mafic syenite) intruding the Khamis Mushayt Gneiss which is the oldest known lithostratigraphic unit in the basement complex of the Saudi Arabian Shield. In the upper zone the shonkinite is composed of olivine, pyroxene (Orthopyroxene), plagioclase, perthite, and biotite, but in the lower zone the mineralogy changes drastically to produce a rock rich in hydrous minerals such as amphiboles (anthophyllite and tremolite-actinolite) and chlorite. Geochemical analysis shows that Mg, Cr, and Ni were highly enriched in the lower zone, while the other major and trace elements have been greatly depleted. Post-magmatic alteration due to the action of meteoric or hydrothermal water on the shonkinite has produced a different rock in which leaching of Ti, Al, Na, and other trace elements has resulted in a high concentration of Mg, Cr, and Ni in the lower zone.

Introduction

A fairly steep circular plutonic plug about 85 high and 100 in diameter jabal Hamumah (Fig. 1), is exposed in the Hamumah area 30 kilometer to the southeast of the city of Khamis Mushayt, one of the major urban centers in southern Saudi Arabia (Fig. 2). The area is located between latitudes of 42°48′ and 42° 55 N. and a longitude of 18° 12′ E. and forms part of the Asir Mountains. A reconnaissance geologic map of the study area, the Khamis Mushayt quadrangle was made [1] at a scale of 1:100000. This map provides a geologic framework for analysis of the plutonic plug. More than 50 samples were collected for petrographic examination of which 10 were selected for detailed chemical analysis (Fig.2 and Table 1). The study area contains chiefly three rock types: gneiss, schist, and mafic intrusive rocks (Fig.1).

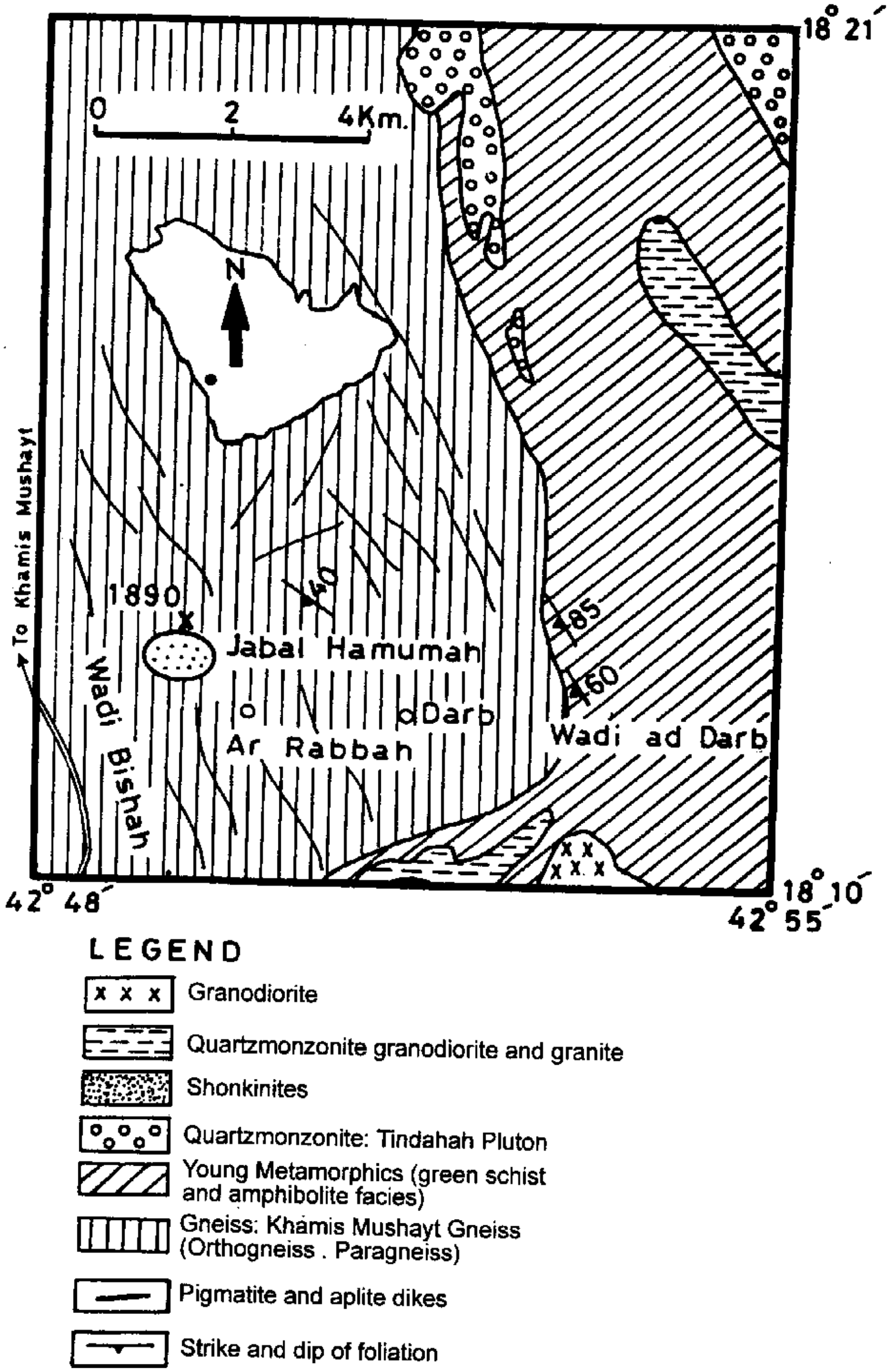


Fig. 1. Geologic map showing the location of the Jabal Hamumah plug and other rock units in the Hamumah area.

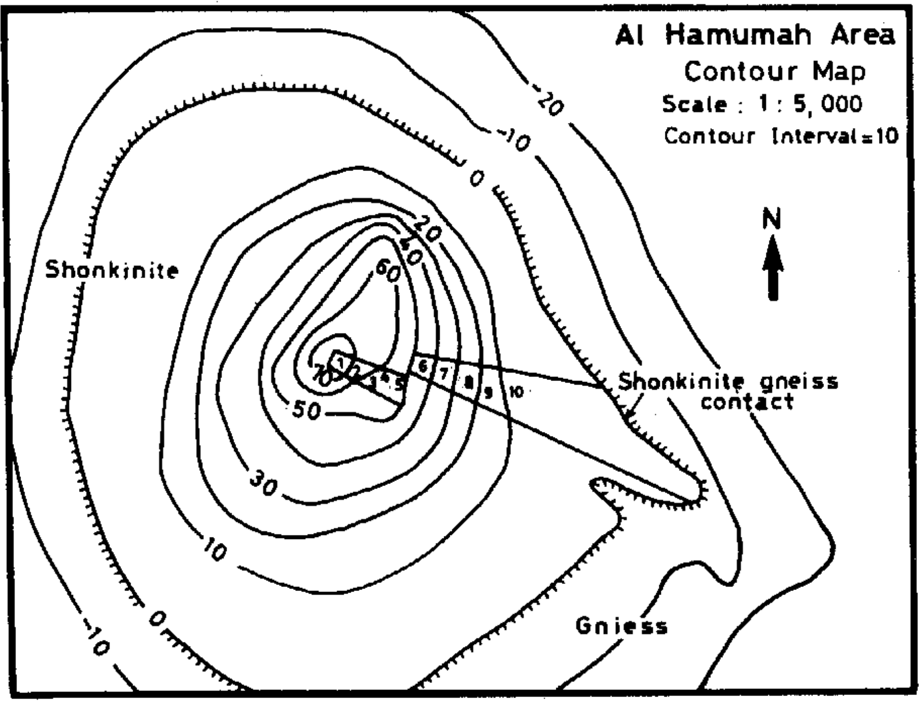


Fig. 2. Contour map of Jabal Hamumah showing sample location.

Table 1. Modal analysis of shonkinite (in volume percent)

Minerals	Top zone	Mid zone	Bottom zone
Olivine	15	10	-
Pyroxene	25	20	-
Plagioclase	20	15	2
Perthite	30	25	-
Biotite	10	15	-
Amphibole	-	10	85
Chlorite	-	-	15
Accessories	Apatite + Fe-Ti Oxides	Fe-Ti Oxides	Serpentine + Fe-Ti Oxides

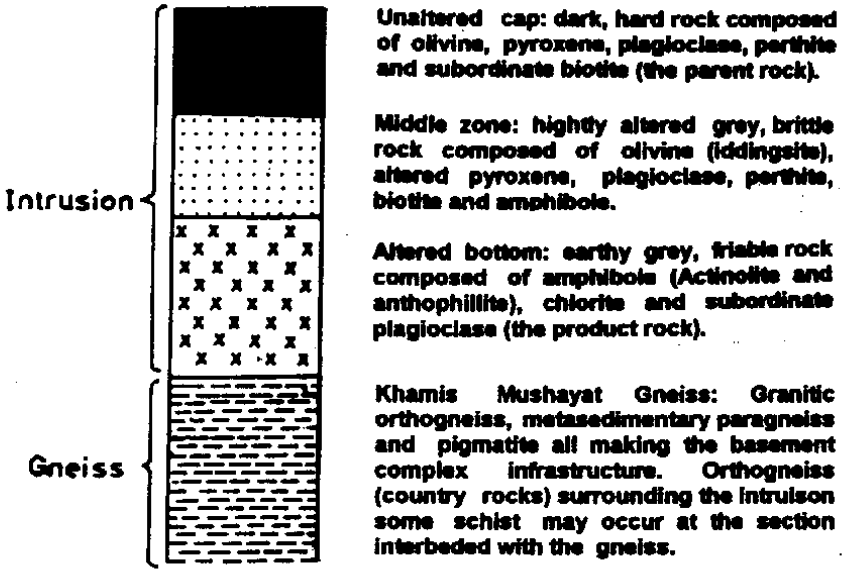
The mineralogical composition of the gneiss (that is quartz ; k – feldspars, and muscovite-biotite) suggests it is predominantly orthogneiss, of igneous affiliation but, there are minor quantities of probable metasedimentary paragneiss as shown by some relic metasedimentary minerals such as garnet . These rocks are known as the Khamis Mushyat Gneiss and represent the deepest erosional level of the basement complex in the Arabian Shield. Therefore, it is the oldest known lithostratigraphic unit in Saudi Arabia [1-3]. The second rock type in the area is younger than the gneiss. It consists of pelitic metasedimentary rocks mainly of the greenschist metamorphic facies composed of rocks such as biotite-muscovite schist, graphite schist, and chlorite schist. Generally the schist occurs as small sheets or blocks closely interbedded with gneiss and is often highly altered.

The third rock type is mafic plutonic rock that makes up the bulk of the Jabal Hamumah plug, which intrudes the Khamis Mushayt Gneiss. The plug consists of the basic igneous rock shonkinite (a mafic syenite) which is fairly fresh at its top but highly altered near its topographic base probably because of metasomatic action or hydrothermal alteration. The age of the shonkinite is Late Proterozoic, clearly younger than the gneiss it intrudes [2]. This investigation includes detailed petrologic, mineralogical, and modal analysis of the shonkinite in order to determine the effect of retrograde metasomatism, or solution addition, on the chemical-mineralogical composition of the rock. Chemical analyses of ten representative whole-rock samples of shonkinite are used to interpret the chemical evolution of the plug and the nature of mass exchanges after its emplacement.

Mineralogy of Shonkinite

Based on the hand samples and microscopic observation, the shonkinite can be broadly subdivided into two main varieties : a fairly fresh variety at the top and a highly altered variety at the bottom. Between these two zones The rock is in various alteration states. The fresh rock at the top (here termed parent rock) is hard, medium - to coarse - grained and of dark color, while the altered lithology at the bottom (here termed the product) is often friable, fine-to medium-grained and earthy gray in color.

Table 2 summarizes the modal composition of the rocks. The unaltered parent (Fig. 4) is composed mainly of olivine (10 - 15 volume percent), pyroxene (24 - 25 volume percent of the enstatite-hypersthene type), plagioclase (18 - 20 volume percent of the anorthite-labradorite type), perthite (25 - 30 volume percent), and biotite (8-10 volume percent). There is also an accessory amount of iron-titanium oxides and apatite. Olivine is essentially fresh with only slight serpentinisation along the fractures while all other minerals are entirely fresh exhibiting no alteration (Fig. 5).



Unaltered cap: dark, hard rock composed of olivine, pyroxene, plagioclase, perthite and subordinate biotite (the parent rock).

Middle zone: hightly altered grey, brittle rock composed of olivine (iddingsite), altered pyroxene, plagioclase, perthite, biotite and amphibole.

Altered bottom: earthy grey, friable rock composed of amphibole (Actinolite and anthophillite), chlorite and subordinate plagioclase (the product rock).

Khamis Mushayat Gneiss: Granitic orthogneiss, metasedimentary paragneiss and pigmatite all making the basement complex infrastructure. Orthogneiss (country rocks) surrounding the intruison some schist may occur at the section interbeded with the gneiss.

Fig. 3. Schematic stratigraphy through Jabal Hamumah plug and surrounding gneiss .

Table 2. Chemical Analysis of Major and Trace Element inThe Hamumah Shonkinite (oxides in wt percent , and trace elements in ppm)

Oxide	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
SiO_2	51.25	51.11	52.33	51.02	51.14	50.46	51.40	50.22	52.22	47.12
TiO_2	1.25	1.27	1.32	1.23	1.28	0.59	058	0.95	0.47	0.65
Al_2O_3	14.81	14.74	14.97	14.56	15.02	4.19	5.60	7.84	5.02	5.93
Fe_2O_3	10.26	10.30	10.42	10.40	10.15	9.94	9.95	1.22	8.83	15.30
MnO	0.16	0.16	018	0.17	0.15	0.17	0.18	0.21	019	0.24
MgO	8.48	8.42	8.05	8.65	7.94	19.11	17.24	14.04	17.40	23.37
CaO	7.97	8.05	7.77	8.22	7.84	12.79	12.64	12.61	14.28	2.92
Na_2O	3.33	3.39	3.50	3.28	3.43	0.62	0.80	0.94	0.80	0.50
K_2O	2.37	2.36	2.52	2.28	2.44	0.16	0.22	0.36	0.28	0.03
P_2O_5	0.37	0.41	0.49	0.40	0.44	0.03	0.05	0.09	0.07	0.12
L O I	00	00	00	0.02	0.02	2.36	1.52	1.08	0.59	3.74
Total	100.21	100.06	100.47	100.21	100.21	100.41	99.87	99.50	100.15	99.92

Trace elements in ppm

	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
Ba	1256	1157	1321	1181	1250	47	33	99	17	30
Ce	45	50	47	33	40	9	10	15	9	7
Cl	95	91	109	105	119	46	11	90	29	54
Cr	445	446	428	469	402	1430	1508	1653	3046	5490
Cu	49	50	52	48	50	75	44	18	14	14
Ga	19	21	20	18	21	10	11	14	17	13
La	12	23	18	9	15	1	1	1	1	1
Np	5	5	6	6	6	2	2	4	7	3
Nd	24	27	21	19	17	7	14	12	9	11
Ni	112	110	11	122	107	116	291	159	276	499
Pb	19	20	20	17	17	11	13	12	14	6
Rb	46	48	51	44	49	5	6	7	5	5
S	98	83	113	112	102	125	72	247	82	300
Sr	899	917	883	893	917	76	83	300	75	88
Th	1	2	2	0	1	1	2	1	1	1
V	176	194	191	195	192	232	218	314	181	250
Y	25	27	28	27	27	15	17	29	13	11
Zn	81	85	90	85	81	61	65	83	126	111
Zr	138	143	147	128	142	36	47	67	50	56

Fig. 4. Photomicrograph showing unaltered olivine (ol) , pyroxene (px) , plagioclase (pl) and perthite (per) in shonkinite (XN. x 2.5).

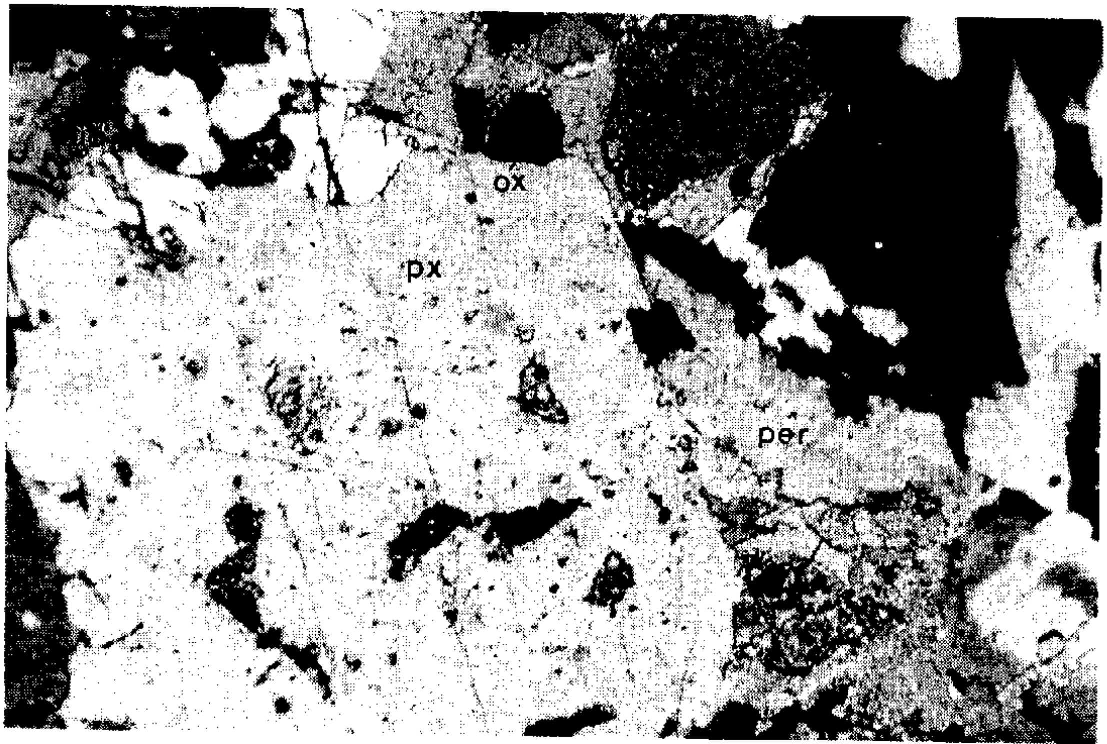


Fig. 5. Photomicrograph of unaltered shonkinite showing olivine, pyroxene, plagioclase , perthite , biotite (bio) ,and oxides (ox)(XN x 2.5) .

In the middle zone the rock is variably altered and the mineralogy has undergone visible change. The rock in the middle zone is composed of olivine (12 Percent), pyroxene (20 percent), plagioclase (15 percent), perthite (25 percent), biotite (15 percent), and amphibole (10 percent). The accessories are mainly iron -titanium oxides and chlorite. The photomicrograph, Fig. 6, shows severe alteration of some olivine to iddingsite , and of pyroxene to amphibole and chlorite.

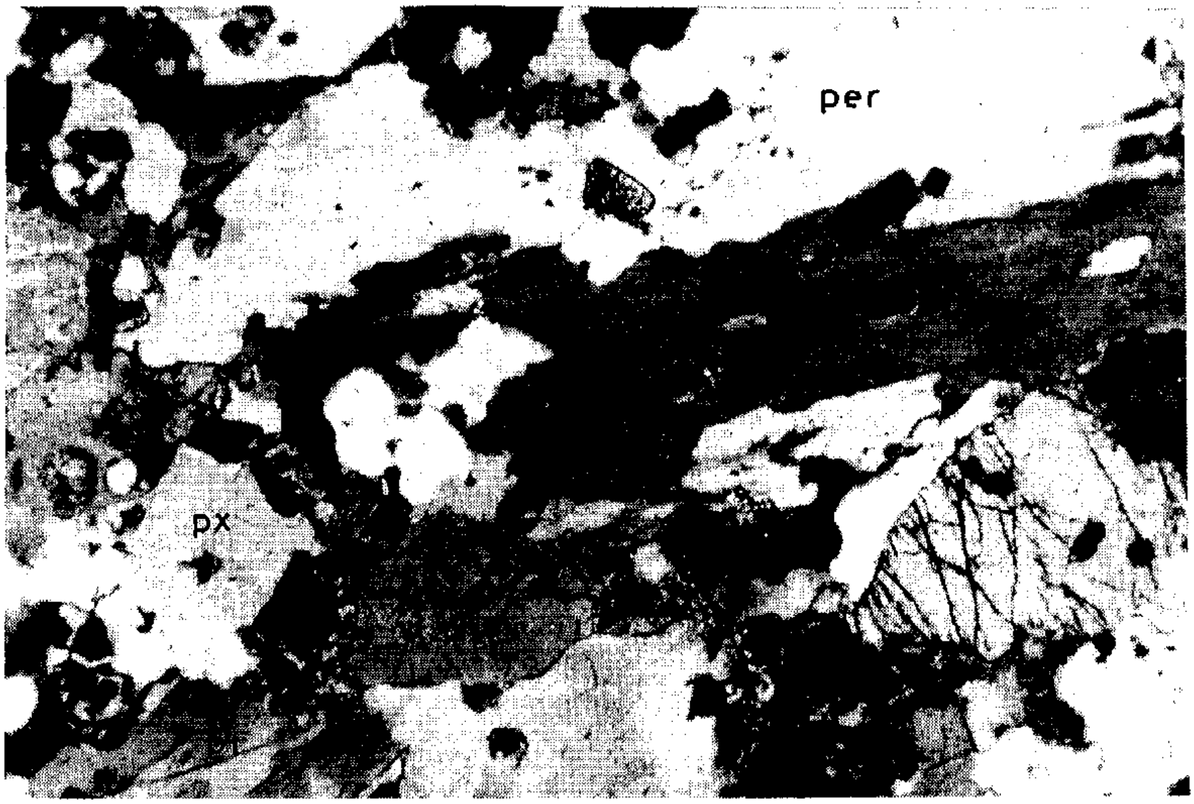


Fig. 6. Photomicrograph of unaltered olivine (ol) , pyroxene(px) , plagioclase(pl) , perthite(per) , chlorite(chl) in shonkinite within the middle zone (XN. x 2.5) .

In the lowest zone the rock has undergone an almost complete change into an amphibole-chlorite . This product rock is composed of more than 85 percent amphibole and 12 percent chlorite and serpentine with a few small elongated grains of plagioclase and perthite amounting to less than 2 percent of the total volume of the rock (Fig. 7). Olivine, pyroxene, perthite, and biotite have totally disappeared from the rock. Olivine has been altered to iddingsite and serpentine. Pryroxene has been altered to amphibole (anthophyllite) and probably to chlorite. Plagioclase and perthite have probably been altered to sericite and clay minerals. Iron - titanium oxides are the only accessories present because they have not been affected by alteration processes (Table 2). The amphiboles are mainly of the actinolite-tremolite series with variable amount of minerals such as anthophyllite. Due to the great difference between the upper and the lower zones in mineralogy and chemical composition , one may suggest that the Hamumah is divided into two different rock types. The upper zone is composed mainly of shonkinite, while the lower zone (product) is composed of some kind of ultramafic rock rich in chromium, nickel and magnesium . Later, alteration process changed the lower ultramafic zone into an amphibole - and chlorite - rich rock.

Fig.7. Photomicrograph of shonkinite in the bottom zone showing complete change of mafic minerals into fibrous amphibole (anthophyllite)(ant) and actinolite(act) and some chlorite (XN. x 2.5) .

Geochemical Evolution of Shonkinite

Table 1 shows the variation of major and trace elements in the shonkinite plug. Average chemical composition of rock in the top and bottom together with the composition of sample H1 (as an example of the parent) and H10 (as an example of product) is shown in Table 3. The chemical analysis reveals an unusual feature in the enrichment of magnesium, nickel, and chromium in the product rock while most of the other components are depleted. The loss on ignition (LOI) is also highly increased in the product. The geochemical analyses also clearly show that most of the major and trace elements were depleted from the bottom zone. For instance there is a decrease in TiO_2 (from 1.25 o 0.65 percent), Na_2O (From 3.39 to 0.73 percent), K_2O (from 2.39 to 0.20 percent),and P_2O_5 (from 0.42 to .07 percent) . Also there is a decrease in Ba (from 1223 to 42 ppm), Ce (from 42 to 10 ppm), Cl (from 104 to 46 ppm), La (from 15 to 1 ppm), Rb (from 48 to 6ppm) , Sr (from 902 to 124ppm), and Zr (from 128 to 51 ppm). By contrast there is a large enrichment in MgO (from 8.31 to 18.23), Ni (from 92 to 499 ppm), and in Cr (from 476 to 2625 ppm). It is also noticeable that SiO_2 did not change greatly (from 51.17 to 50.28 while the loss on ignition has increased substanially (From

0.41 to 1.86). Sample H10 exhibits the most extreme change in chemical composition essentially MgO (23.37), CaO (2.92), K_2O (9.03), LOI (3.74), Ni (499 ppm), Rb (5 ppm), Sr (88 ppm), and especially Cr (5490 ppm).

Table 3. Average major and trace elements in the top zone (parent), the bottom zone (product), and samples H1 and H10 as references in the Hamum ah area

Element	Parent	Product	H 1	H 10
SiO_2	51.17	50.28	51.25	47.12
TiO_2	1.25	0.65	1.26	0.65
$Al_2 O_3$	14.82	5.85	14.81	5.93
$Fe_2 O_3$	10.31	9.10	10.26	15.10
Mg O	8.31	18.23	8.48	23.17
Ca O	7.97	11.10	7.97	2.92
$Na_2 O$	3.39	0.73	3.33	0.50
$K_2 O$	2.39	0.20	2.37	0.03
$P_2 O_5$	0.42	0.07	0.37	0.12
L o I	0.41	1.86	2.00	3.74
Ba	12.33	42	1256	30
Ce	43	10	45	7
Cl	104	46	95	54
Cr	438	2625	445	5490
La	15	1	12	1
Ni	92	268	112	499
Rb	48	6	46	5
Sr	902	124	899	88
V	190	239	176	250
Y	27	17	25	11
Zr	128	51	81	56

Figure 8a is an X-Y diagram suggesting the presence of a high SiO_2 - low MgO and a low SiO_2 - high MgO variety of rock. This, with other plots namely Fig. 8b may reflect a non systematic chemical variation of the Hamumah shonkinite. When MgO content is plotted as a function of Ni (Fig. 8c) and of Cr (Fig 8d) the variation appears systematic and similar, while a plot of alkalis Na_2O and K_2O against MgO (Fig. 8e) shows a decrease of Na and K in the product rock as Mg increases . Figure 8f shows that Sr content is high in the top zone (parent) and decreases drastically with CaO increasing in the bottom zone, especially in sample H10 where Sr content reaches a minimum of 88 ppm. These facts suggest that the chemical evolution in the Hamumah shonkinite may not follow fractional crystallization scheme. In normal magmatic differentiation K_2O is likley to increase in the differentiate.

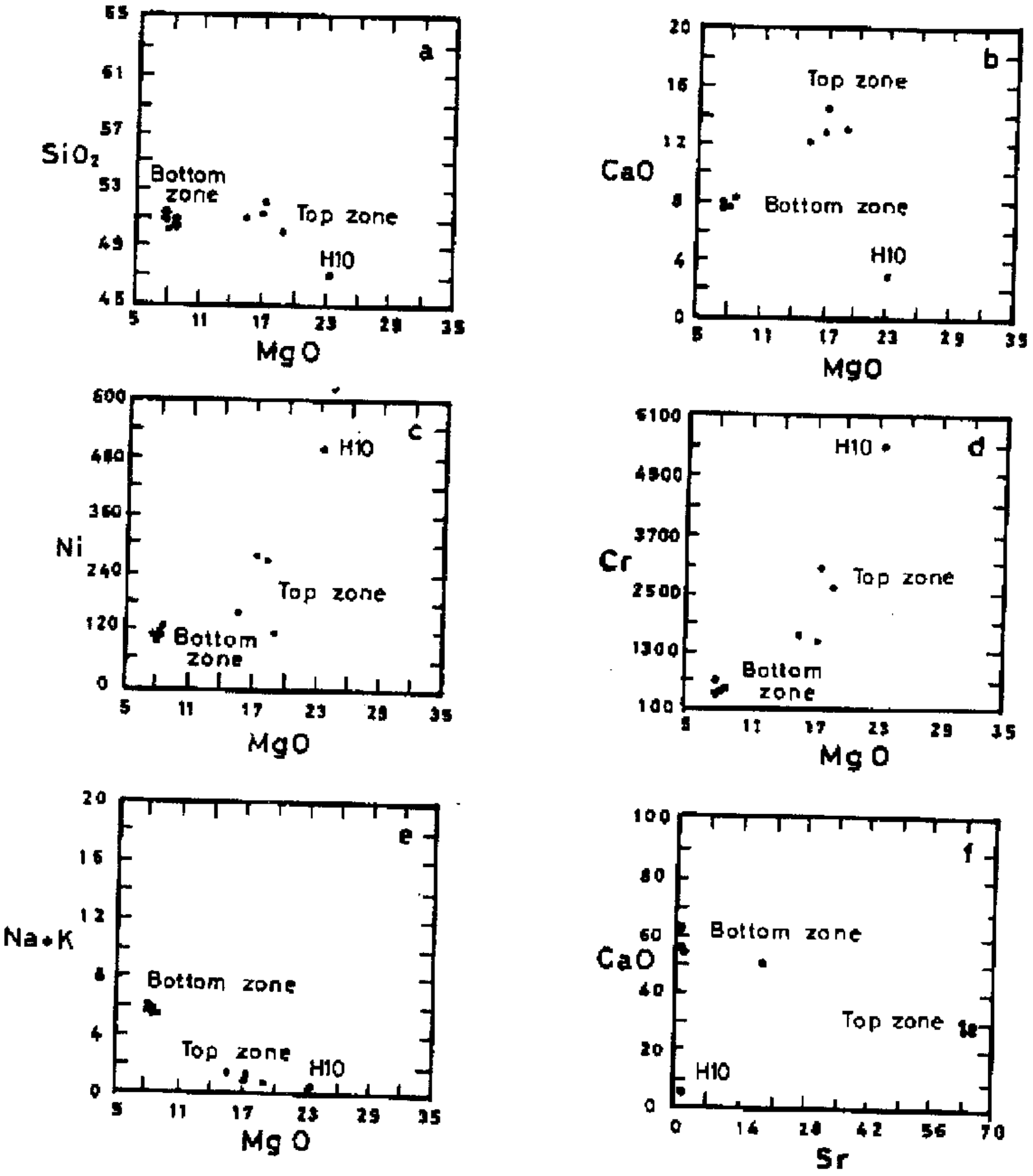


Fig. 8. Diagram showing variation in MgO as a function of SiO2 , CaO , Ni , and Cr, and alkalis. A plot of CaO versus Sr is also included .

Discussion

In an attempt to explain and clarify the nature of the observed mineralogy and chemistry of the shonkinite plug, the various processes that may be involved in its evolution are discussed and evaluated as follows:

The effects of fractional crystallization: Melt concentrations of compatible elements such as Ni, Cr, and Sr are excellent indicators of the degree of fractional crystallization or the extent of crystal fractionation of minerals olivine, clinopyroxene, and plagioclase respectively. It is suggested that the concentrations of these three elements decrease with advancing fractional crystallization [4]. Olivine .crystallization will therefore, severely deplete the residual liquid in Ni and clinopyroxene will incorporate Cr [5;4]. Furthermore, chromite minerals may be present in the early - stage differentiates associated with olivine but it will disappear in a late - stage because of the liquidus relationships that exist between chromite and clinopyroxene [6-8]. Therefore, when pyroxene begins to form it can accommodate all the Cr available from the liquid. With the decrease of compatible element contents in the residual melt, incompatible elements such as K, Ba, and Rb, (having crystal : melt partition coefficient < 1) increase as the crystallization proceeds .

In differentiated mafic magma sequences there should be an excellent fit between major elements, compatible elements, and refractory incompatible elements (such as Zr, Sr, Th, and Nb). Volatile incompatible elements such as K, Rb, Cs, and Na may show abnormally high content in the late - stage differentiates. In the Hamumah shonkinite there is no systematic agreement between compositional variations in major and trace elements. It seems that a reverse differentiation has occurred with increased MgO, FeO, Ni, and Cr in the residual melt . That caused the depletion of TiO_2, Al_2O_3, K_2O, Na_2O, Ce, La, Rb, Sr, and Zr. Hence, the observed chemical variation cannot be explained by fractionation of magmatic minerals such as olivine, pyroxene, and plagioclase. Instead of being taken out of the residual melt Ni and Cr were largely concentrated .

The effect of late-stage processes: Other processes that may have led to the observed chemical variations in the shonkinite are wall-rock reaction, magmatic contamination, volatile transfer, and alteration.

a) Wallrock reaction refers to continued interaction of melt with the walls of the conduit during the ascent of magma . It is believed that this leads to a steady increase in the concentration of incompatible elements in the residual melt [4] .This process cannot explain the large decrease of K, Na, Rb, Sr and other incompatible elements in the shonkinite.

b) Magma contamination is the addition of foreign materials to a differentiating magma and assimilation and digestion of these materials by the melt .The effect of this process is similar to that of wall - rock reaction. Assimilation of country rocks or crustal material will cause the increase of incompatible element content in the residual magma. K, Rb, and Ba content will significantly increase in a magma intruding granite - gneiss country rock [9;10]. If the added materials are of mafic origin it would be expected that compatible element content would increase and incompatible element content decrease in the current melt, but the fractional crystallization effect would mask this process. In the

Hamumah shonkinite Ni and Cr are increased and the remaining trace elements are decreased. Therefore, the chemistry can not be explained by this process. That is, because: 1) the increase in MgO, Ni, Cr, is too large to be accountable for by this process, as is the decease in Na, K, Sr, Rb, and other elements; 2) the produced mineralogy is not compatible with the addition of a mafic component ; 3) the present chemical variation does not fit the general scheme expected in a normal fractional crystallization. Therefore, magma contamination cannot be the cause of chemical variation in the Hamumah shonkinite .

c) Volatile transfer occurring in the magma chamber or in the cooling unit itself could cause increase in the concentration of K, Rb, and Th without significant variations in the concentration of major elements and trace elements such as Sr , Ba , Ni , and Cr [11;12]. The variation may be attributed to the upward movement of a very small amount of residual fluid (magmatic or volatile phase) after the crystallization of mafic magma is essentially completed [13].

d) Alteration may occur because of the upward movement of an aqueous phase or upward filtration of an intercumulus liquid during mafic rock petrogenesis after crystallization is completed. This process could have a similar effect to volatile transfer [7;14].

In the Hamumah shonkinite there is an overall variation that is not in accord with the volatile transfer or the alteration by an aqueous phase. Only a wholesale metasomatic alteration after emplacement of shonkinite can explain the observed chemical variation in the area. The effects of meteoric water, or hydrothermal solution attack have produced a rock highly enriched in hydrous minerals. Another suggestion to explain the chemical and mineralogical variation would be the presence of two rock varieties in the original plug, one of these in the lower part of the plug being rich in Cr, Ni, and Mg.

Conclusion

The Hamumah shonkinite composed of olivine, pyroxene, Ca-Na plagioclase and perthite has been subjected to severe alteration attributed to the action of meteoric waters or hydrothermal fluids which produced a new rock rich in hydrous minerals such as ferromagnesian amphiboles and chlorite. Geochemical studies reveal that the altered rock is remarkably enriched in MgO, Ni, and Cr. By contrast several major and minor elements were taken out of the product rock. Severe leaching has played a major role in mass transfer during the post-emplacement period. Meteoric and hydrothermal waters percolating through the lower part of the intrusion have dissolved most of the compatible and incompatible elements and enriched the rock with Mg, Ni, and Cr would be useful to evaluate these two paths for concentrating Platinum group elements and to evaluate the suitability of the Hamumah rock as a source of chromium ore.

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الجيوكيمياء والإشباع بالكروم في صخور الحمومة المتداخلة في خميس مشيط، جنوب المملكة العربية السعودية

جمعة عبدالرحيم العلاوي

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الرياض ١١٤٥١، المملكة العربية السعودية

(استلم للنشر في ١٤١٨/٧/٢٥هـ؛ وقبل للنشر في ١٤١٩/١١/١٢هـ)

ملخص البحث. جبل حمومة عبارة عن كتلة نارية متداخلة صغيرة معزولة واقعة ضمن مربع خميس مشيط جنوب المملكة العربية السعودية. يتركب المتداخل من صخور الشونكينايت (سيانايت ماحي) متداخل ضمن نايس خميس مشيط والذي هو أقدم وحدة صخرية استراتجرافية معروفة في المعقد القاعدي من الدرع العربي السعودي. يتركب الشونكينايت في المنطقة العليا، من الأوليفين، البيروكسين، البلاجيوكليز، البرثايت والبيوتايت، ولكن، يتغير التركيب المعدني، في المنطقة السفلى، إلى حد كبير لتكوين صخر غني بالمعادن حاملة الماء مثل الأمفيبولايت (الأنثوفيليت والتريمولايت - أكتينولايت) والكلورايت. أوضحت التحليلات الجيوكيميائية تشبعا كبيرا بالمغنسيوم، الكروم والنيكل، وانخفاضا كبيرا في كمية العناصر الأساسية والضئيلة الأخرى، في المنطقة العليا. أدى التحلل التالي للنشاط الصهيري والناتج عن فعل مياه الأمطار على صخر الشونكينايت إلى تكوين صخر مختلف تماما، تم فيه استخراج وطرد التيتانيوم، الألومنيوم، الروبيديوم، السنترونشيوم والزيركونيوم، مما أدى إلى تركيزات عالية من المغنسيوم، الكروم والنيكل.