Evidence for Element Mobility in Some Metavolcanic Rocks in the Vicinity of Mineralized Areas in the Arabian Shield

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ABSTRACT. Forty-three samples of volcanic rocks were selected from 5 widely spaced mineralized areas within the Hulayfah Group in the Arabian Shield. These samples were analysed for major and minor oxides as well as Nb, Zr, Y, Ti and P. The analyses were plotted on some of the commonly used petrochemical discrimination and variation diagrams in a trial to test the mobility of elements, but not to deduce tectonic setting or magma type. Nb and Y showed the highest mobility, Ti and Zr showed relatively moderate mobility with Ti being somewhat more mobile, but P showed the least mobility. It is suggested that the partial pressure of carbon dioxide, and whether it is buffered by an external source or not, have a considerable effect on the mobility of these elements during metamorphism and alteration.

Introduction

Discrimination diagrams based on major and minor oxides as well as trace elements are frequently used to identify magma types and geotectonic settings (Barker and Arth 1976, Pearce and Cann 1973, Pearce 1975, Pearce and Gale 1976, Winchester and Floyd 1976, Pearce *et al.* 1977, Garcia 1978, Beccaluva *et al.* 1979, Fox 1979, Mullen 1983, Pharaoh and Pearce 1984, and Soliman 1988). Some of these diagrams are designed for unaltered rocks and others are designed for rocks of a certain range of composition (e.g. Pearce and Cann 1973, Beccaluva *et al.* 1979, Mullen 1983, Pharaoh and Pearce 1984 and Soliman 1988). On the other hand, Floyd and Winchester (1975) and Winchester and Floyd (1976 and 1977) have devised other diagrams based on immobile elements for use with altered and metamorphosed rocks. In addition, Harker and other triangular variation diagrams have also been utilized to

identify magma series and to assign petrographic names to volcanic rocks. In the Arabian Shield, several workers applied some of these diagrams for various purposes in their study of the volcanic rocks; from these we mention Shanti (1982), Roobol *et al.* (1983 and 1984), Qadhi and Hussein (1984), Tofig and Al Shanti (1984), Duyverman (1984) and Tayib and Al Shanti (1984). In the present work, it was found that basaltic rocks around five mineralized areas in the Arabian Shield do not plot within the expected fields on some discrimination diagrams. This was interpreted as due to mobility of some trace elements, which probably took place during alteration associated with mineralization. So, forty-three samples, ranging from basaltic to rhyolitic in composition, were selected from the five mineralized areas to investigate the mobility of some trace elements by using variation and discrimination diagrams. Thus, it should be emphatically stated at the outset that: it is not intended here to use the variation and discrimination diagrams to determine the tectonic setting or the magma type of the studied rocks, but the aim of this contribution is to indicate that these diagrams could be very helpful in disclosing element mobility.

Samples of the Present Study

Five volcanogenic sulphide occurrences within the Hulayfah Group volcanics and its equivalents in the Arabian Shield (Fig. 1) were selected for the present study. The five areas are Ash Shizm, Um Ad Dammar, As Safra, Al Musayna'ah and Um Ash Shalahib. They differ in their detailed geologic setting and nature of mineralization. Forty-three samples of volcanic rocks from these areas were analysed for major oxides and the trace elements Zr, Nb and Y (Table 1). The petrographic identification of these samples is given in Table 2. In the present routine identification of the studied samples, dacite, rhyodacite and rhyolite were grouped together as acidic rocks and collectively given one symbol on some of the diagrams. Previous workers (e.g. Delfour 1983, Tayib and Al Shanti 1983, and Qadhi and Hussein 1984) indicated that the Hulayfah volcanics are dominantly calc-alkaline. All the investigated samples are affected by low grade regional metamorphism with the development of greenschist facies minerals, mostly epidote, chlorite, albite, calcite and to a lesser extent actinolite. Epidote is the most abundant metamorphic mineral and occurs in all the rocks, even in the most fresh rhyolite. Chlorite is specially abundant in the basaltic rocks, which occur only in Ash Shizm. Sericite and kaolinite also occur as minor alteration products in some samples. In spite of this, the original textures and relics of the parent volcanic minerals are preserved in many cases. The analyses were recalculated on a water free basis before plotting on the diagrams. The chemical analyses were carried out at the Laboratories of the Faculty of Earth Sciences, King Abdulaziz University. Zr, Nb, Y, Ti, P, Si, Al, Ca and K were determined by XRF technique. Mg, Mn, Na and total Fe were determined by atomic absorption technique. Water and FeO were determined by wet chemical techniques. Precision and accuracy are estimated to be 3% or better.
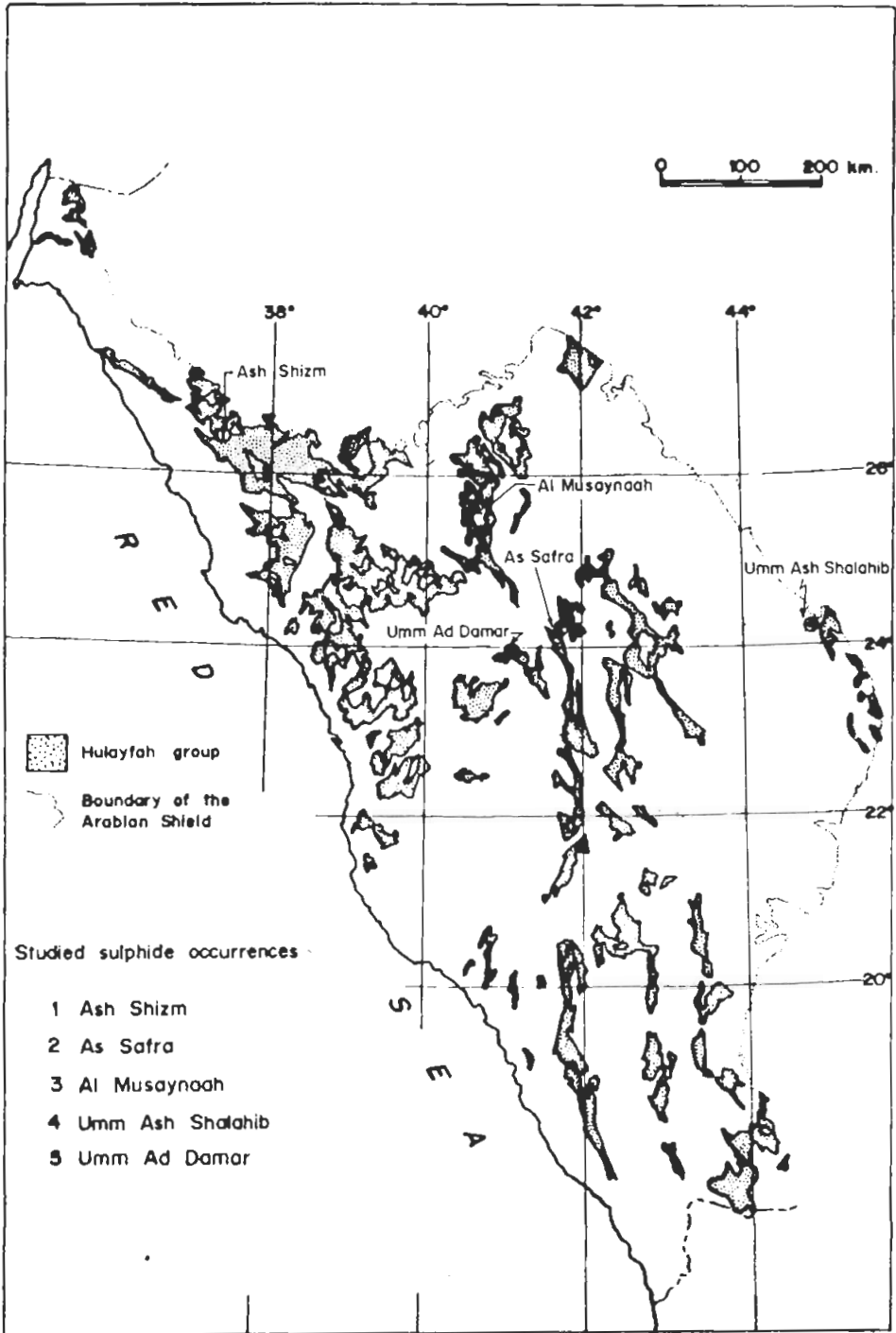
FIG. 1. Location of the studied sulphide occurrences.

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TABLE 1. Chemical analyses of the studied samples.

Sample	1	2	3	4	5	6	7	8
Weight Percent								
SiO_2	49.40	49.86	47.72	44.47	51.06	47.49	55.20	74.17
TiO_2	0.88	0.75	1.29	1.29	0.96	0.76	1.24	0.27
Al_2O_3	13.99	14.45	14.42	14.99	13.54	14.75	14.08	11.51
Fe_2O_3	2.92	3.83	3.55	4.50	5.02	5.11	3.59	1.90
FeO	7.61	6.10	8.26	7.40	5.40	4.74	8.44	2.30
MnO	0.21	0.22*	0.20	0.20	0.14	0.20	0.26	0.11
MgO	7.93	6.57	6.51	5.05	6.66	7.38	4.27	0.71
CaO	8.81	12.53	6.00	10.52	7.52	14.57	7.01	2.52
Na_2O	2.70	2.64	3.40	2.66	2.95	0.82	2.98	4.41
K_2O	0.76	0.03	0.93	0.15	0.20	0.09	0.70	0.15
P_2O_5	0.13	0.16	0.11	0.15	0.12	0.19	0.13	0.08
sum	95.34	97.14	92.39	91.38	93.57	96.10	97.90	98.13
PPM								
Nb	12	12	23	21	10	15	15	25
Zr	31	31	17	29	7	55	50	48
Y	5	5	5	5	5	5	5	11

TABLE 1. (Contd)

Sample	9	10	11	12	13	14	15	16
Weight Percent								
SiO_2	73.15	74.65	68.28	74.15	25.80	78.60	74.66	66.14
TiO_2	0.20	0.21	0.35	0.24	1.08	0.11	0.16	0.60
Al_2O_3	11.35	11.69	13.03	11.82	16.76	6.77	11.46	15.08
Fe_2O_3	1.93	1.53	2.04	1.84	4.15	1.80	1.04	1.70
FeO	1.36	1.44	2.59	1.94	21.73	5.82	2.62	3.16
MnO	0.11	0.10	0.10	0.05	0.66	0.16	0.10	0.11
MgO	0.96	1.09	1.63	1.02	13.11	2.96	4.46	2.58
CaO	4.09	3.80	3.83	3.40	1.40	0.23	0.21	5.74
Na_2O	3.37	1.85	5.78	3.99	0.91	0.56	0.67	2.91
K_2O	0.34	2.02	0.19	0.26	0.02	0.41	1.80	0.87
P_2O_5	0.09	0.09	0.09	0.08	0.05	0.06	0.06	0.11
sum	96.95	98.47	97.91	98.79	85.67	97.48	97.24	99.00
PPM								
Nb	30	31	23	24	12	5	16	16
Zr	91	63	79	52	38	7	7	29
Y	12	14	16	10	10	5	5	5

TABLE 1. (Contd)

Sample	18	19	20	21	22	23	24	25
Weight Percent								
SiO_2	65.78	54.14	70.82	77.70	65.50	76.10	73.82	76.54
TiO_2	0.28	0.26	0.51	0.11	0.36	0.08	0.09	0.12
Al_2O_3	11.07	15.88	13.68	11.52	12.06	11.80	11.82	11.87
Fe_2O_3	3.16	4.03	1.06	0.28	2.72	1.36	1.17	1.43
FeO	2.08	5.35	2.87	0.32	1.44	0.29	0.22	0.29
MnO	0.07	0.23	0.08	0.02	0.10	0.03	0.03	0.01
MgO	8.38	5.76	1.34	0.10	7.78	0.20	0.22	0.16
CaO	0.27	8.89	1.67	0.64	0.58	0.48	1.10	0.26
Na_2O	0.56	3.81	7.06	7.29	0.58	3.78	3.87	3.54
K_2O	0.42	0.30	0.42	0.50	2.89	4.24	4.18	4.80
P_2O_5	0.08	0.14	0.08	0.06	0.06	0.06	0.06	0.06
sum	92.15	98.79	99.59	98.54	94.07	98.42	96.58	99.08
PPM								
Nb	14	15	12	15	5	78	105	66
Zr	8	7	7	5	25	39	72	73
Y	5	5	5	8	5	22	27	20

TABLE 1. (Contd)

Sample	26	27	28	29	30	31	32	33
Weight Percent								
SiO_2	76.59	74.98	61.35	55.73	53.07	57.18	53.47	49.70
TiO_2	0.15	0.16	1.38	1.18	1.12	1.12	1.08	0.82
Al_2O_3	11.83	11.81	12.50	15.36	16.46	13.89	15.42	12.53
Fe_2O_3	1.02	1.12	3.05	3.04	1.62	8.66	5.51	2.13
FeO	0.72	0.65	3.48	4.85	6.82	4.31	3.52	14.90
MnO	0.01	0.01	0.08	0.13	0.16	0.02	0.03	0.04
MgO	0.20	0.23	2.17	5.54	4.95	3.28	3.30	5.25
CaO	0.60	0.74	3.70	7.91	8.51	0.47	1.91	0.34
Na_2O	2.99	3.23	4.36	3.84	3.49	2.00	2.10	0.64
K_2O	5.18	5.15	2.51	0.69	1.30	6.84	8.11	5.95
P_2O_5	0.06	0.06	0.12	0.15	0.15	0.07	0.07	0.06
sum	99.35	98.14	94.70	98.42	97.65	97.84	94.52	92.36
PPM								
Nb	66	63	33	5	5	5	15	18
Zr	138	71	92	62	103	12	43	42
Y	24	17	13	5	5	5	12	31

TABLE 1. (Contd)

Sample	34	35	36	37	38	39	40	41
Weight Percent								
SiO_2	59.55	49.43	53.78	64.37	55.76	78.82	72.84	76.98
TiO_2	0.73	1.08	1.40	1.35	1.07	0.31	0.53	0.35
Al_2O_3	11.95	14.17	15.40	11.74	13.97	11.12	11.13	10.87
Fe_2O_3	2.72	2.68	2.38	10.69	5.31	0.30	4.22	0.26
FeO	9.73	8.51	5.31	1.29	4.63	0.72	0.36	0.72
MnO	0.03	0.03	0.13	0.01	0.02	0.02	0.00	0.02
MgO	5.19	7.65	4.18	0.39	3.86	1.78	0.12	0.72
CaO	0.39	3.50	7.39	0.86	4.52	2.20	0.36	2.03
Na_2O	1.05	2.34	3.06	4.76	3.65	4.48	3.40	7.25
K_2O	5.75	6.18	0.87	0.57	3.00	0.36	3.45	0.30
P_2O_5	0.06	0.10	0.13	0.06	0.01	0.08	0.06	0.07
sum	97.15	95.67	94.03	96.09	95.80	100.19	96.47	99.57
PPM								
Nb	10	12	5	5	10	12	5	10
Zr	198	22	28	17	64	27	27	22
Y	5	8	8	5	11	5	5	5

TABLE 1. (Contd)

Sample	43	44	45
Weight Percent			
SiO_2	55.82	72.62	65.90
TiO_2	0.71	0.28	0.36
Al_2O_3	16.27	10.56	9.23
Fe_2O_3	1.72	0.84	6.06
FeO	3.30	1.11	4.49
MnO	0.11	0.21	1.49
MgO	5.60	1.98	4.01
CaO	8.42	6.04	4.84
Na_2O	1.55	3.61	1.50
K_2O	1.46	1.78	0.64
P_2O_5	0.15	0.06	0.11
sum	98.11	99.09	98.63
PPM			
Nb	10	16	12
Zr	37	30	109
Y	5	5	16

TABLE 2. Comparison of petrographic and chemical identification of the studied rocks.

	Petrographic Identification	Chemical Identification		
		TAS diagram (Fig. 2)	Zr/TiO_2-SiO_2 (Fig. 3)	Nb/Y-Zr/TiO_2 (Fig. 4)
1	altered basalt	basalt	subalk. basalt	alkali basalt
2	altered basalt	basalt	subalk. basalt	alkali basalt
3	altered basalt	basalt	subalk. basalt	alkali basalt
4	altered basalt	basalt	subalk. basalt	basanite nephelinite
5	basalt	basaltic andes.	andesite	–
6	metabasalt	basaltic andes.	subalk. basalt	basanite nephelinite
7	altered basalt	basaltic andes.	andesite	basanite nephelinite
8	altered rhyolite ⁺	rhyolite	rhyolite	basanite nephelinite
9	altered rhyolite	rhyolite	rhyolite	basanite nephelinite
10	altered rhyolite	rhyolite	rhyolite	basanite nephelinite
11	altered rhyolite	dacite	dacite	basanite nephelinite
12	altered rhyolite	rhyolite	rhyolite	basanite nephelinite
13	chloritite	–	–	alkali basalt
14	metarhyolite	rhyolite	rhyolite	alkali basalt
15	metarhyolite	rhyolite	rhyolite	basanite nephelinite
16	metarhyolite	dacite	dacite	basanite nephelinite
17	deleted*	–	–	–
18	metarhyolite	dacite	dacite?	basanite nephelinite
19	andesite	basaltic andes.	andesite	basanite nephelinite
20	metarhyolite	rhyolite	dacite?	alkali basalt
21	metarhyolite	rhyolite	rhyolite	alkali basalt
22	metarhyolite	dacite	dacite	alkali basalt
23	metarhyolite	rhyolite	rhyolite	trachyte
24	metarhyolite	rhyolite	rhyolite	trachyte
25	metarhyolite	rhyolite	rhyolite	trachyte
26	metarhyolite	rhyolite	rhyolite	trachyte
27	metarhyolite	rhyolite	rhyolite	trachyte
28	metarhyolite	rhyolite	rhyolite	alkali basalt
29	meta-andesite	basaltic andes.	andesite	alkali basalt
30	meta-andesite	basaltic andes	andesite	alkali basalt
31	andesite	trachyandesite	andesite	–
32	andesite	trachyandesite	andesite	alkali basalt
33	andesite	trachyandesite	andesite	subalk. basalt
34	andesite	andesite	andesite	subalk. basalt
35	andesite	phonotephrite	basalt	subalk. basalt
36	andesite	andesite	andesite	subalk. basalt
37	andesite	dacite	dacite?	–
38	andesite	andesite	andesite	alkali basalt
39	altered rhyol.	rhyolite	rhyolite	alkali basalt
40	rhyol. tuff	rhyolite	rhyolite	alkali basalt
41	rhyol. tuff	rhyolite	rhyolite	alkali basalt
42	deleted*	–	–	–
43	metarhyolite	trachyandesite	andesite	alkali basalt
44	rhyolite	rhyolite	dacite	alkali basalt
45	rhyolite	dacite	dacite	trachyandesite

Sample Locations

1 to 13: Ash Shizm

14 to 21: Umm Ad Damar

22 to 30: As Safra

31 to 38: Al Musayna'ah

39 to 45: Umm Ash Shalaheeb

⁺ Including dacite and rhyodacite.

* Deleted for extreme silicification.

Diagrams for
Chemical Classification of Volcanic Rocks

Three diagrams used for the chemical classification of volcanic rocks were selected for plotting the present analysis.

1. TAS diagram (Fig. 2, after Le Bas et al. 1986)

The studied samples were plotted on this diagram, which was proposed by the IUGS for the chemical classification of the volcanic rocks to see how the major chemistry of these rocks conform with the petrographic identification. From this diagram, we note the following :

1.1) The SiO_2 content of the majority of the samples lies within the range specified by the petrographic identification, except few basalt and andesite samples, which show slight enrichment in silica.

1.2) Several samples show a clear enrichment in alkalis and are thus separated from the calc-alkaline field and moved to the alkaline field or even to the feldspathoidal field, while the rest of the samples lie in the calc-alkaline field. Although there is no dividing line between the rhyolite and alkali rhyolite field, the samples from As Safra (encircled) show moderate enrichment in alkalis with respect to other rhyolites. So, various degrees of alkali metasomatism is indicated in, at least, some of the studied samples.

2. SiO_2 vs Zr/TiO_2 diagram (Fig. 3, after Winchester and Floyd 1977)

The shift of some samples from the calc-alkaline field would be expected to be towards the alkaline field, if there were a mutual consistency among the chemical parameters of these rocks in indicating their nature. But here, the shift is further away from the alkaline field, bringing some samples outside the realm of the diagram. This is clearly due to the decrease of the Zr/TiO_2 ratio in, at least, some of the studied rocks, indicating the mobility of one or both elements.

3. Zr/TiO_2 vs Nb/Y diagram (Fig. 4, after Winchester and Floyd 1977)

The effect of decreased Zr/TiO_2 ratio is quite clear in shifting the samples downwards in the diagram. At the same time, the effect of increased Nb/Y ratio is also very clear in shifting most of the samples to the alkaline and feldspathoidal fields.

Thus, from these three simple diagrams we demonstrate the mobility of, at least, two of the four "thought immobile" trace elements, namely Zr and Ti. We will now use some other diagrams to investigate the mobility of these elements.

Discrimination Diagrams

1. P_2O_5 vs Zr diagram (Fig. 5, after Winchester and Floyd 1976)

This diagram was proposed to discriminate between tholeiitic and alkalic basalts. The studied basalts plot where they would be expected from petrographic identifica-
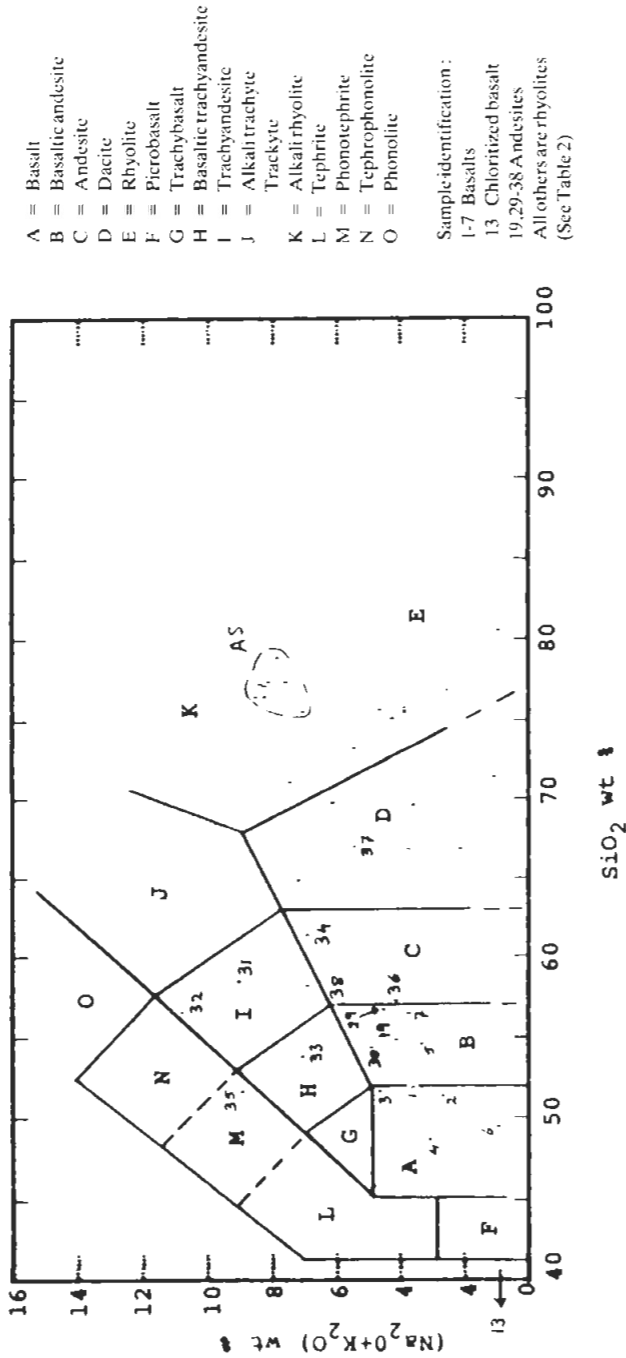
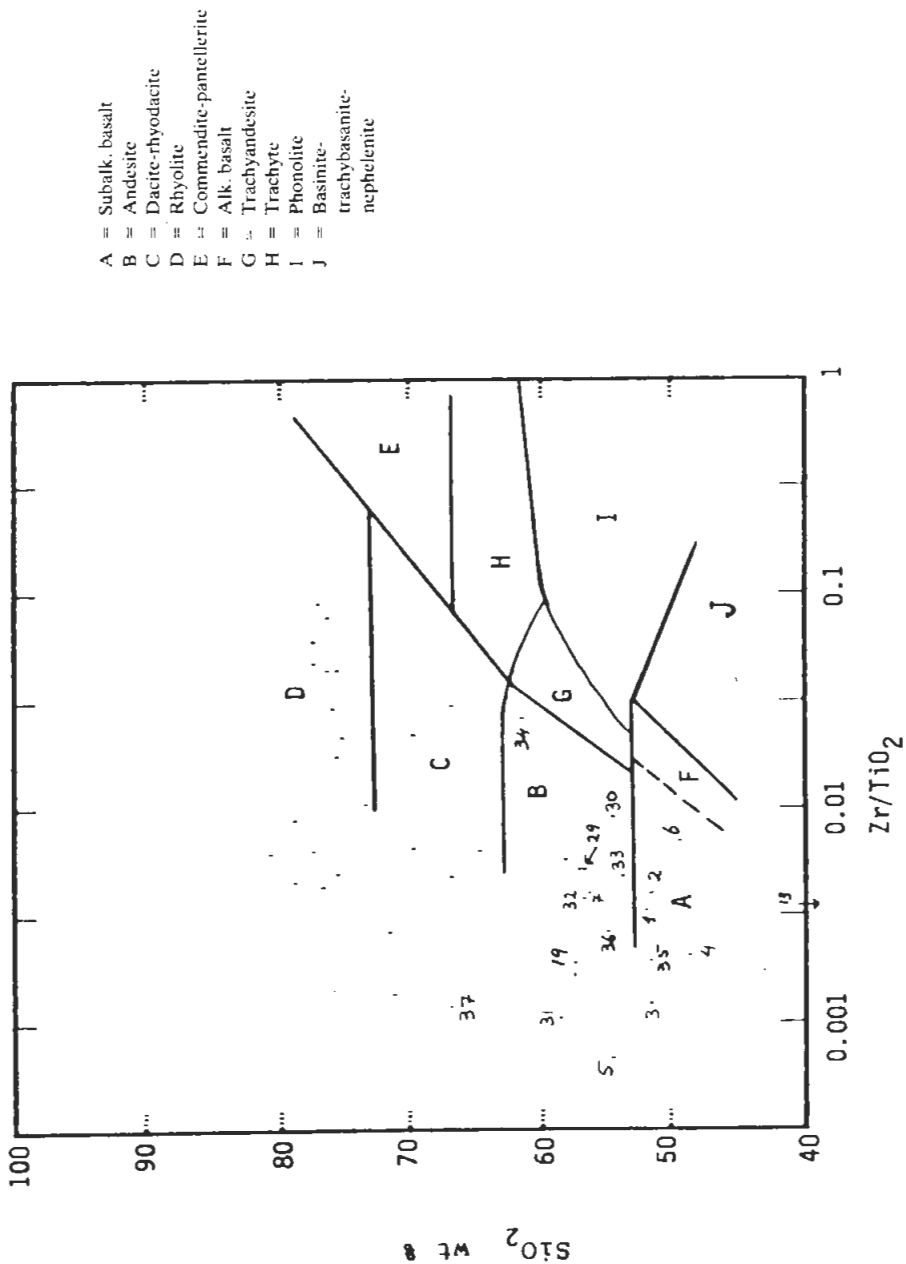FIG. 2. TAS diagram of the studied rocks, after Le Bas *et al*. 1986.

A = Basalt
B = Basaltic andesite
C = Andesite
D = Dacite
E = Rhyolite
F = Picrobasalt
G = Trachybasalt
H = Basaltic trachyandesite
I = Trachyandesite
J = Alkali trachyte
    Trachyte
K = Alkali rhyolite
L = Tephrite
M = Phonotephrite
N = Tephrophonolite
O = Phonolite

Sample identification :
1-7   Basalts
13   Chloritized basalt
19,29-38 Andesites
All others are rhyolites
(See Table 2)

A = Subalk. basalt
B = Andesite
C = Dacite-rhyodacite
D = Rhyolite
E = Commendite-pantellerite
F = Alk. basalt
G = Trachyandesite
H = Trachyte
I = Phonolite
J = Basinite-
    trachybasanite-
    nephelenite

FIG. 3. SiO_2 against Zr/TiO_2 diagram for the studied rocks, after Winchester and Floyd, 1977. (Sample identification as in Fig. 2).

A = Subalk. basalt
B = Andesite-basalt
C = Andesite
D = Dacite-rhyodacite
E = Rhyolite
F = Commendite-pantellerite
G = Alk. basalt
H = Trachyandesite
I = Trachyte
J = Phonolite
K = Basanite-nephelinite
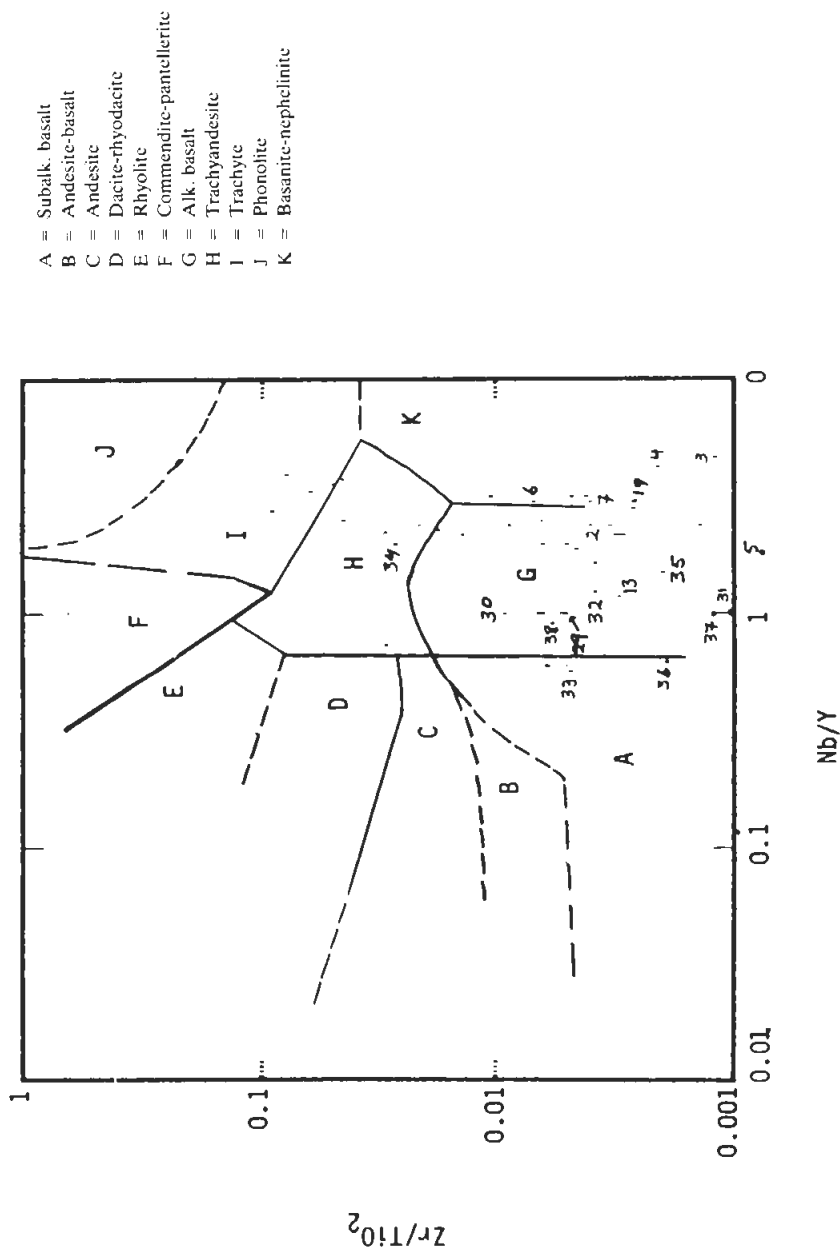
FIG. 4. Zr/TiO$_2$ against Nb/Y diagram for the studied rocks, after Winchester and Floyd, 1977.

tion and from previous works. This result indicates that phosphorous was not mobilized to the extent to alter the signature of the rocks. This diagram was first used here because any mobilization of Zr would not affect the position of samples at the level of P_2O_5 content. Furthermore, nonbasaltic rocks were also plotted here as well as in diagrams to follow, merely to show their relative position within the different fields. This diagram also shows the variation of Zr content in the studied samples.
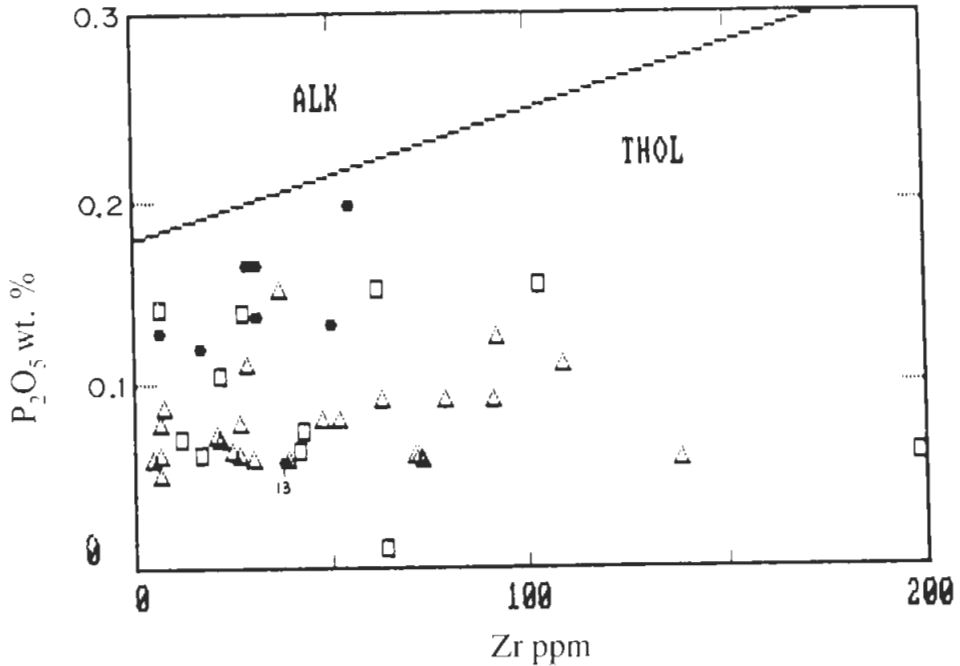
FIG. 5. P_2O_5 against Zr diagram for the studied rocks, after Winchester and Floyd, 1976.
Dot = Basalt
Square = Andesite
Triangle = Rhyolite

2. TiO$_2$ vs Zr/P$_2$O$_5$ (Fig. 6) and Nb/Y vs P$_2$O$_5$ (Fig. 7) diagrams (after Winchester and Floyd 1976)

In Fig. 6, about half the basalts and andesites are shifted from the subalkalic field to the alkalic field, which suggests that either Ti had increased or Zr had decreased in the studied rocks. Three samples plot beyond the right limit of the diagram due to their higher value of Zr/P$_2$O$_5$ ratio. Fig. 7 shows the effect of the increase of Nb/Y ratio in most of the studied rocks.
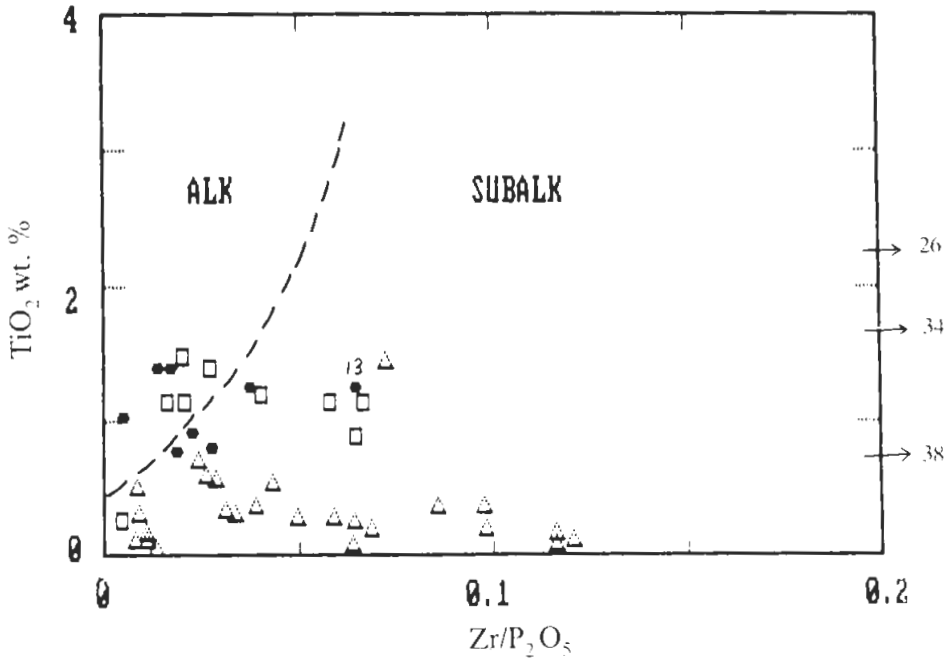
FIG 6. TiO$_2$ against Zr/P$_2$O$_5$ diagram for the studied rocks, after Winchester and Floyd 1976 (symbols as in Fig. 5).
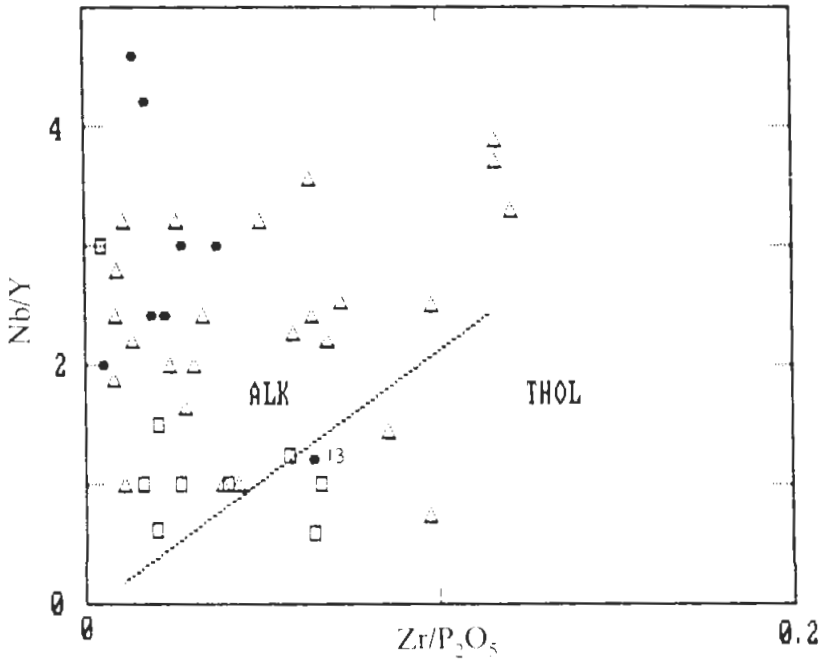
FIG 7. Nb/Y against Zr/P$_2$O$_5$ diagram for the studied rocks, after Winchester and Floyd 1976 (symbols as in Fig. 5).

3. Ti vs Zr diagram (Fig. 8, after Pearce and Cann 1973)

This diagram was proposed to identify several magma types of basaltic rocks. In the light of field and petrographic data, this diagram would suggest a LKT magma type for basalts of Ash Shizm (1 to 7) and a CAB magma type for the andesites (33, 38, 30). However, eight samples of both the basalts and andesites fall outside the realm of the diagram towards the increase of Ti coupled to a lesser extent with a decrease of Zr. The distribution of the points representing rhyolites also shows a wide dispersion of both elements independent of each other. So, Ti and Zr were both mobilized in the studied rocks to various degrees, and this, we believe, is the cause of the inconsistency observed in Fig. 2 and 3.
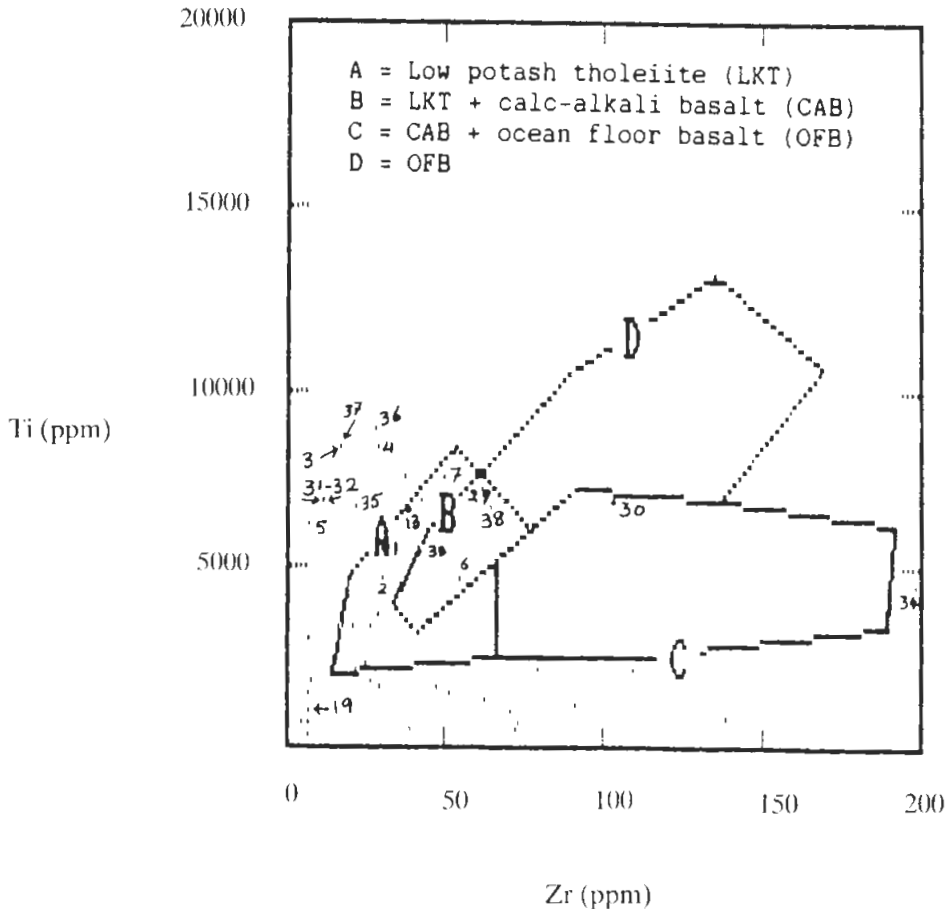
FIG. 8. Ti against Zr diagram for the studied rocks, after Pearce and Cann 1973 (Sample identification as in Fig. 2).

4. *Relation between Nb and Y*

The relation between these two elements may be illustrated by plotting each of them against silica as shown in Fig. 9 and Fig. 10, respectively, as well as plotting them against each other in Fig. 11. Figure 9 was proposed by Pearce and Gale (1976) to discriminate between volcanic and within plate magma types for basaltic rocks.
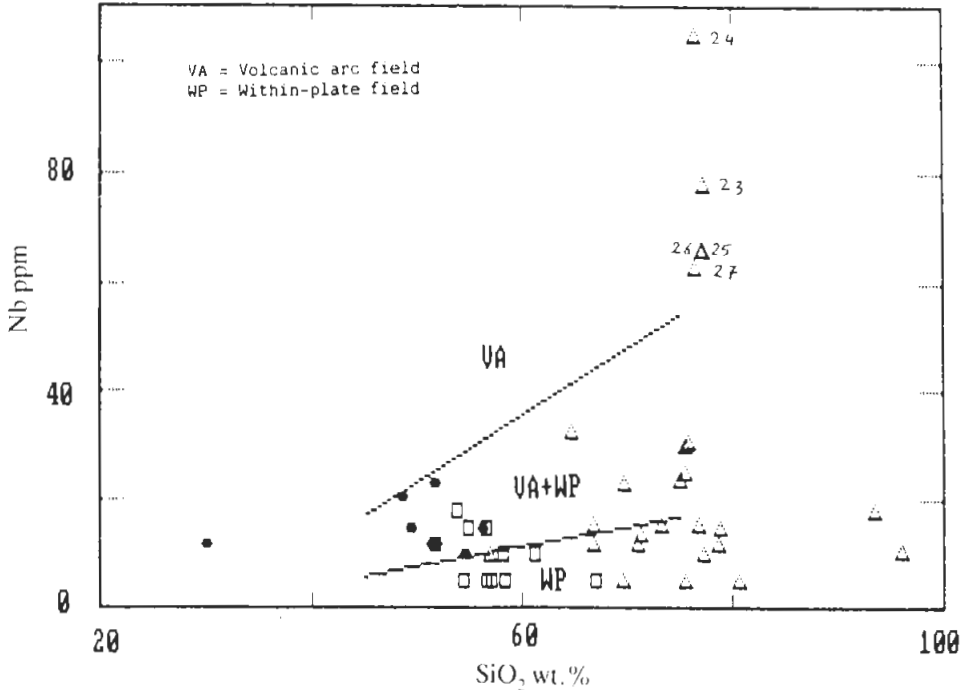

FIG. 9. Nb against SiO_2 diagram for the studied rocks, after Pearce and Gale 1976 (Symbols as in Fig. 5).

Most of the studied basalts and andesites fall in the area of overlap between the fields of volcanic arc basalt and within plate basalt due to increased Nb content so that there is an ambiguity in identifying the magma type. It also shows the wide variation of Nb content in the rhyolitic samples, particularly in most of As Safra samples (23 to 27, note also that these samples showed effects of alkali metasomatism in Fig. 2). Figure 10 shows that Y was coherent with Nb during mobilization, but to a lesser degree. In other words, both the two elements increase in at least some of the studied rocks, but with different rates so as the net result is a decrease of Nb/Y ratios. The precision of analyses decreases towards lower values and in case of Y, 22 samples have Y content below detection limit (10 ppm) and were plotted as having 5 ppm Y. The coherence between Nb and Y in the range of their high values is further illustrated in Fig. 11, where they show positive correlation.
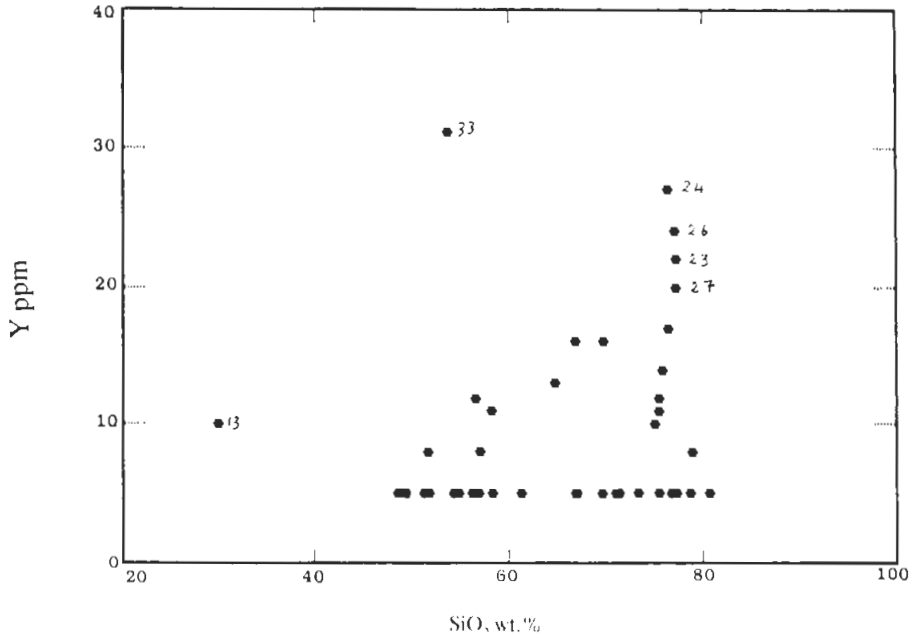
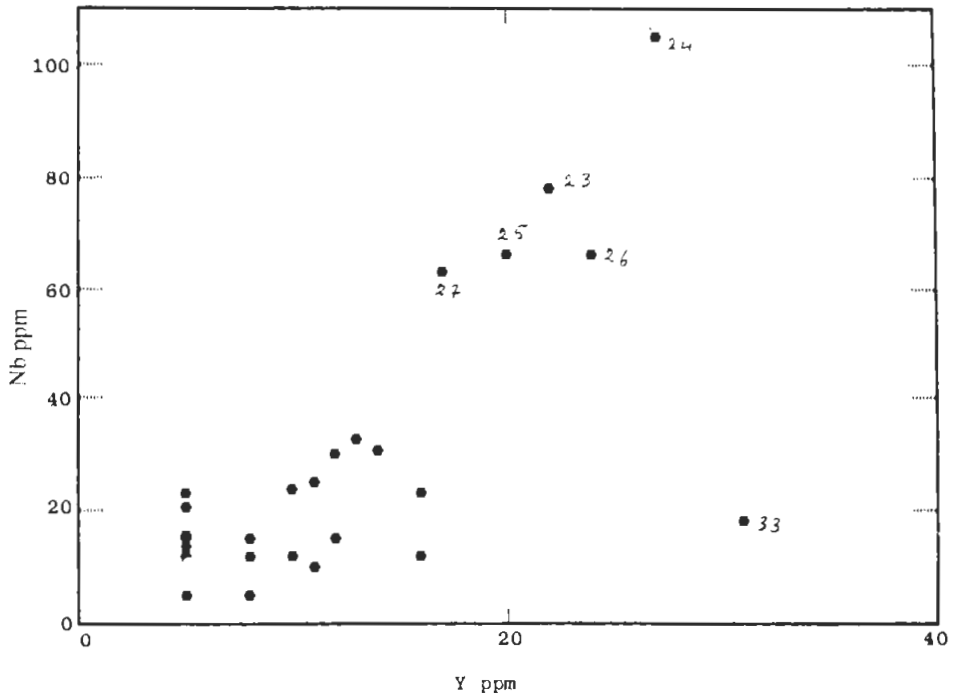FIG. 10. Variation of Y against SiO$_2$ in the studied rocks.

FIG. 11. Variation of Nb against Y in the studied rocks.

Conclusion

Applying the discrimination diagrams to the studied rocks revealed some chemical characteristics which may be summarized in the following points :

1. Alkali metasomatism is well displayed in the samples of Al Musayna'ah (andesites), As Safra (rhyolites) and to a lesser degree in the remaining areas.

2. Nb and Y showed the highest mobility, Ti and Zr showed relatively moderate mobility with Ti being somewhat more mobile, while P showed the least mobility.

3. The discrimination diagrams used here are very effective in revealing some of the chemical variations induced upon the studied rocks since their formation; both basaltic and rhyolitic rocks may be treated in the same way. We propose and encourage this trend with the application of as many diagrams as possible in a trial to establish some specific procedures for testing element mobility. In this respect, it should be noted that the mobility of a certain element is only noticed when the respective sample plots outside its expected field. If the sample moved within its field, the mobility of the causing element would pass unnoticed. This effect can be largely overcome by plotting each element or oxide against several other parameters in independent diagrams.

4. Searching for a reason of mobility of elements which are supposed to be immobile, Hynes (1980) and Murphy and Hynes (1986) found that the partial pressure of carbon dioxide and whether it is buffered by an external source or not, have a considerable effect on the mobility of these elements during alteration and metamorphism.

Acknowledgement

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أدلــة تحرك بعض العنـاصـــر في بعض الصخـور البركـانيــة المتحـولــة بجــوار مناطـــق تمعـــدن في الـدرع العـــربي

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مستخلص .　　تم اختيار أربعة وثلاثين عينة من صخور بركانية من خمس مناطق تمعدن متباعدة من صخور مجموعة الحُلَيْفَة في الدرع العربي . وتم تحليل هذه العينات للأكاسيد الرئيسة والقليلة بالإضافة إلى عناصر النيوبيوم والزركونيوم واليتريوم والتيتانيوم والفوسفور ، ثم وُقّعت هذه التحـاليل على بعض الأشكـال المستخـدمـة عادة في التمييز والتغاير البتروكيميائي لاستجلاء مدى تحرك هذه العناصر ، بعيدًا عن استنباط الوضع البنيوي أو النوعية الصهارية . وقد أظهر كل من النيوبيوم واليتريوم أقصى درجة تحرك ، بينما أظهر كل من التيتانيوم والزركونيوم تحركًا متوسطًا ، وكان التيتانيوم أكثر تحركًا إلى حد ما من الزركونيوم . أما الفوسفور ، فقد أظهر أقل درجة تحرك من بقية العناصر . ويرى الباحثون أن الضغط الجزئي لثاني أكسيد الكربون ، وإذا كان هذا الضغط الجزئي مثبّتًا بمصدر خارجي ، هما من الأسباب التي لها تأثير مباشر على تحرك هذه العناصر أثناء عمليتي التحوُّل والتغيُّر .