Journal of Nepal Geological Society, 1995, Kathmandu, Vol. 11, Special Issue, pp. 237-252

Khewra Trap: An Unusual Ultrapotassic Rock in the Salt Range of Pakistan

M.Q. Jan[1] and S.H. Faruqi[2]
[1]National Centre of Excellence in Geology, University of Peshawar, Pakistan.
[2] 11, Street 39, F-7/1, Islamabad, Pakistan.

ABSTRACT

The classical stratigraphic sequence of the Salt Range contains thin flows of an ultrapotassic rock at its base. Commonly known as Khewra trap, it occurs at the top of the very late Proterozoic to Early Cambrian rocks consisting of marly anhydrite/gypsum, and oil shales overlying evaporites. The trap is an unusual rock consisting of euhedral to skeletal, spinifex, stellate phenocrysts in a very fine-grained to cryptocrystalline, locally glassy, matrix. The phenocrysts (up to 3 cm long) are considered to be Mg-rich enstatite now completely pseudomorphed by a mineral aggregate principally made up of talc with subordinate amounts of Mg-rich clays and, locally, quartz. The matrix is unaltered and almost entirely made up of Na-Ca-poor and Mg-Fe-rich K-Feldspar (sanidine-orthoclase), with granules, specks and dendroids of Fe-Oxide. Talc, Mg-rich clays, quartz, dolomite, and Fe-oxide constitute the amygdules.

Chemical analyses of the rock samples from the trap are remarkably similar in composition except for some variation in iron oxide due, probably, to leaching during alteration. The rocks consist approximately of 60 wt% SiO_2, 0.7% TiO_2, 11% Al_2O_3, 2-5% Fe_2O_3 (total), 0.02% MnO, 10% MgO, 0.4% CaO, 0.5% Na_2O, 9% K_1O, and 0.04% P_2O_5. Normatively the rocks are essentially made up of orthoclase and orthopyroxene. The volcanism may be related to Late Proterozoic-Early Paleozoic rifting which also resulted in deposition of the evaporites, however, the major element chemistry casts doubts on such an interpretation. Detailed trace- and rare earth element geochemistry is in progress to throw light on the petrogenesis of these highly unusual rocks.

INTRODUCTION

The Salt Range of central north Pakistan (72^0 E, 32.5^0 N) has been known for long as a classical area for stratigraphic studies. It displays a nearly complete sequence of fossiliferous sedimentary rocks ranging from Early Permian to Pleistocene, which rest unconformably over Middle (to Early?) Cambrian and Eocambrian rocks (Fatmi 1984, Gee 1989). Khewra trap, representing the only igneous activity in the entire Salt Range, occurs as thin sheets within the gypsiferous stage at the top of the evaporites of the Eocambrian Salt Range Formation. Since first reporting by Fleming (1853), the trap has attracted the attention of several geologists because of its highly unusual composition, texture and paragenesis.

The Salt Range is located within the northwestern part of the Indian plate (Fig.1). Although the range is thought to have moved at least 20 km to the south along the Salt Range Thrust (Gee 1989), it is not an allochthonous block in strict sense. Based on a bore-hole log data at Karampur, 280 km to the south, Gee (1989) proposed that the basement to the Salt Range is akin to the Kirana Hills outcrops, some 80 km SE of the range. The Kirana Hills are made up of sedimentary and volcanic rocks which have a Rb-Sr whole rock isochron age of 870 ± 40 m.y. (Davies and Crawford 1971). The age of the Khewra trap is not known, but its confinement to the Eocambrian rocks below the Cambrian strata is revealing.

In this paper, the petrography of the trap is reviewed with support from XRD and electron microprobe analytical data. Martin (1956) and Mosebach (1956) have presented detailed petrographic accounts of the trap. Many dozen mineral analyses were performed with a Jeol superprobe model JC 733, using wavelength dispersive system, and suitable mineral and synthetic standards for cali-

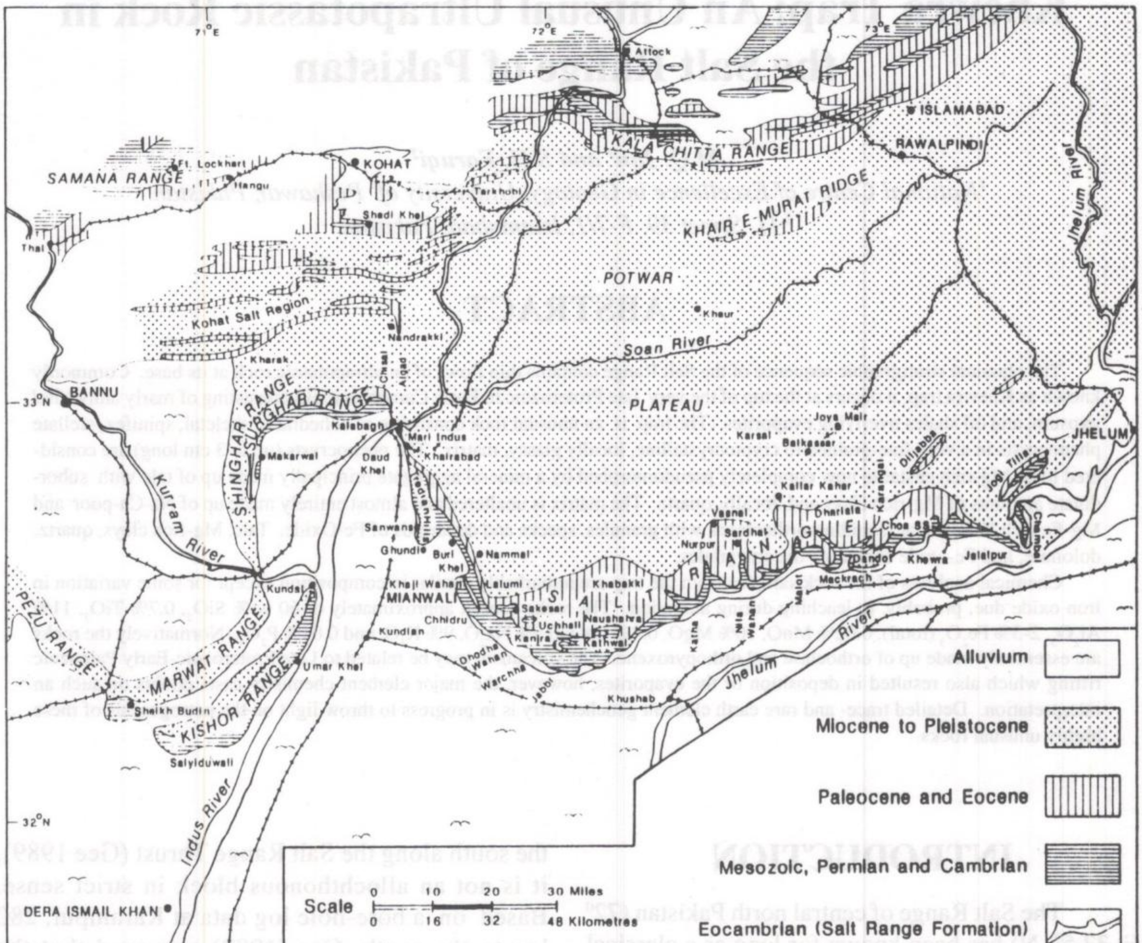

Fig. 1 Location map of the Salt Range and related areas. After Gee (1983)

bration. The geochemistry of the rocks is in progress and details will be presented in a separate publication. In the meanwhile, major elements in five samples were analysed for gaining a preliminary insight. These are briefly discussed.

FIELD ASPECTS

The Khewra trap was initially reported in a few places (Khewra Gorge, Nilawan ravine, etc.) in the form of beds ranging from some centimeters to 5 meters in thickness (Wynne 1878). It is associated with altered rocks such as dolomitic and marly anhydrite/gypsum, and oil shales (Gee 1980, Faruqi 1986). Many years of studies by one of us (SHF), however, have shown that the trap occurs throughout the Salt Range. Drilling at Dalmial, 20 km NW of Khewra, shows two zones of mostly altered trap (total core length 96.6 m) separated by 23.8 m of rock salt, dolomite, anhydrite and bitumen (Faruqi 1986).

Following initial reporting by Fleming (1853) and Theobald (1854), Wynne (1878) described the Khewra trap in some detail. According to him it is a dark purple, compact to earthy, volcanic-looking rock associated with purple volcanic tuff or ash and occurs in irregular patches and lenticular layers up to 2 m thick. He noted that the trap is crowded with stellate acicular crystals (Fig.1) and contains stringers and nests of talc, small geodes of reddish and clear quartz and chalcedony, minute cavities filled with reddish calcite, stringers of quartz and white specks of a decomposed mineral. Although Theobald had reported that the trap occurs in dykes, most workers (e.g., Fleming 1853, Pascoe 1920, Chhibber 1944, Sahni 1944, Mosebach 1956) considered it volcanic in origin and erupted in shallow lacustrine environment (Martin 1956). More recently, however, Faruqi (1986) reproposed an intrusive (dykes and sills) mode of occurrence for the trap.

The discordant relations noted by Theobald (1854) and Faruqi (1986) may, however, have resulted from salt diaprism and/or tectonic deformation. On top of that, the neighboring rock, especially the evaporites, display extensive weathering which could have led to further exacerbation of the contact relationships. Textural characteristics and the presence of ash beds suggest very rapid cooling and a volcanic origin for the trap. It displays a variety of colours and colour mottling. The rocks range from buff to brown, dark purple, red and, rarely, dark green. These colours appear to be related to a complete alteration of the phenocrysts and release of iron oxide. The red and dark purple rocks contain abundant granules of hematite whereas in the buff rocks much of this hematite has leached away. In some cases, the following gradation occurs within a few to more than 10 cm distances: deep purple or red rock passing into a similar one with buff patches, buff or orangy rock with red spherules measuring a few millimeter to over 1.5 cm, buff rock with orangy spherules and, finally, buff rock without spherules (Fig.2).

Martin (1956) presented additional details and noted that "the trap is gently dipping, and shows layering parallel to the overlying beds of marl and gypsum and the underlying beds of laminate carbonaceous dolomite". He reported the following trap succession (in descending order) in the exposures on the right bank of the Khewra Gorge:

5) 30 cm of light pumaceous tuff, mottled in buff and light maue colours.

4) 30 cm of dark purplish trap with hackly fracture, fine networks of greenish grey to white needles up to 3 mm long and irregular shaped, and pink amygdules up to 2 mm.

3) 30 cm of orange buff trap, spotted with spherular patches of the dark purple trap. The latter are the centres from which needles, up to 2 cm long and of the same material as in 4, radiate outwards into the lighter rock. In addition to the amygdules reported in 4, there are irregular amygdules lying along side the needles and consisting of a dull grey to blue grey cryptocrystalline material.

2) 1.2 m of light purple trap with slight colour mottling. Similar to 3, but the needles are coarsely radiating and up to 2.6 cm in length.

1) 30 cm of trap similar to 4, but softer and lighter in colour.

Martin (1956) also studied the 3.35 m long core of the trap recovered from borehole at Dhariala, 24 km NW of Khewra. Here the rock lacks layering and consists of brown amygdaloidal trap at bottom and top, passing into 2.4 m of hard, purple trap which is more coarsely crystalline towards the centre.

PETROGRAPHY AND MINERAL CHEMISTRY

During the course of this investigation representative rocks from widely scattered localities were petrographically studied. Chemical analyses were performed on five samples, together with electron microprobe and XRD analyses on seven. In the following, the texture, phenocrysts, groundmass and vesicles are described.

TEXTURE

The Khewra trap under the microscope is a very fine-grained, porphyritic, vesicular to amygdaloidal rock (Fig.3). It contains up to 3 cm long and 1.5 mm broad phenocrysts altered to a whitish to light grey colour material. Some of the

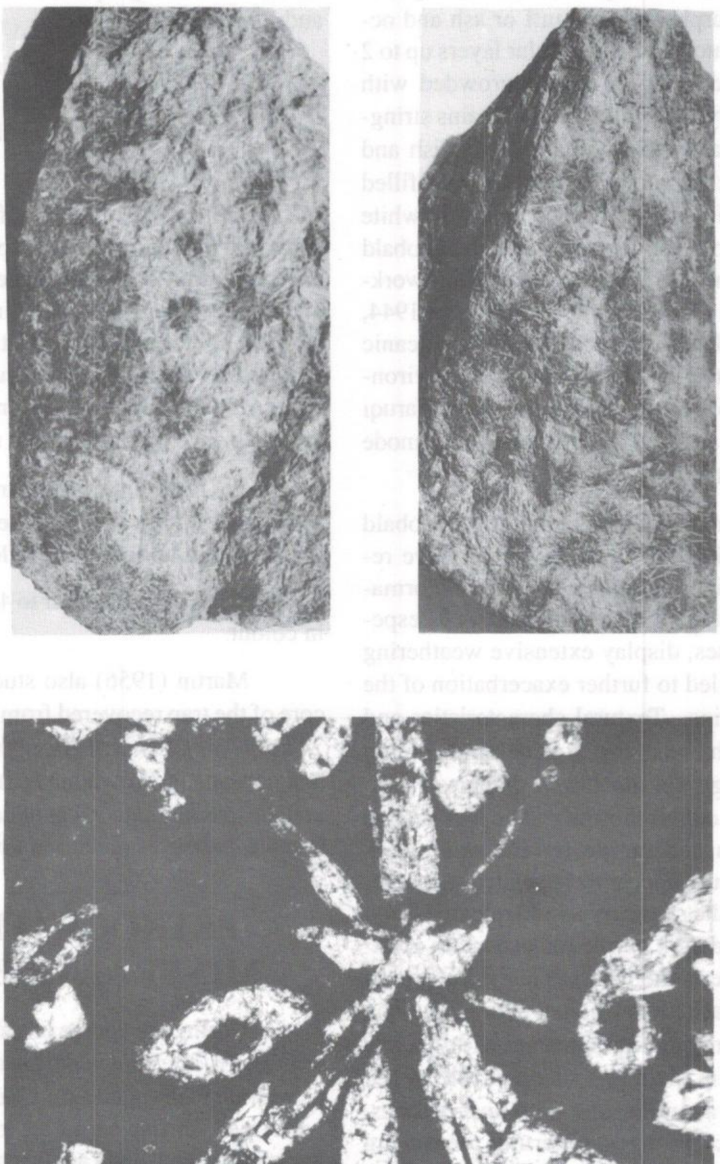

Fig. 2 Top left: A specimen of the Khewra trap showing acicular (locally radial) phenocrysts in a very fine-grained matrix ranging from dark maroon (left) to buff with maroon spots (right). The buff colour is due to leaching of iron oxide, as is also evident in a ring in the lower left of the photo. Top right is also a buff coloured trap, containing abundant maroon-red spots, tiny vesicles (centre) and acicular phenocrysts. Both photos are 15 cm in length. Bottom: Photomicrograph of the trap showing stellate (radial) phenocrysts in a cryptocrystalline groundmass of K-feldspar composition (looking black). The euhedral to skeletal phenocrysts may contain inclusions of the groundmass and are completely pseudomorphed by Mg-rich hydrous silicates, mainly talc. Length of the photograph is 2.24 mm.

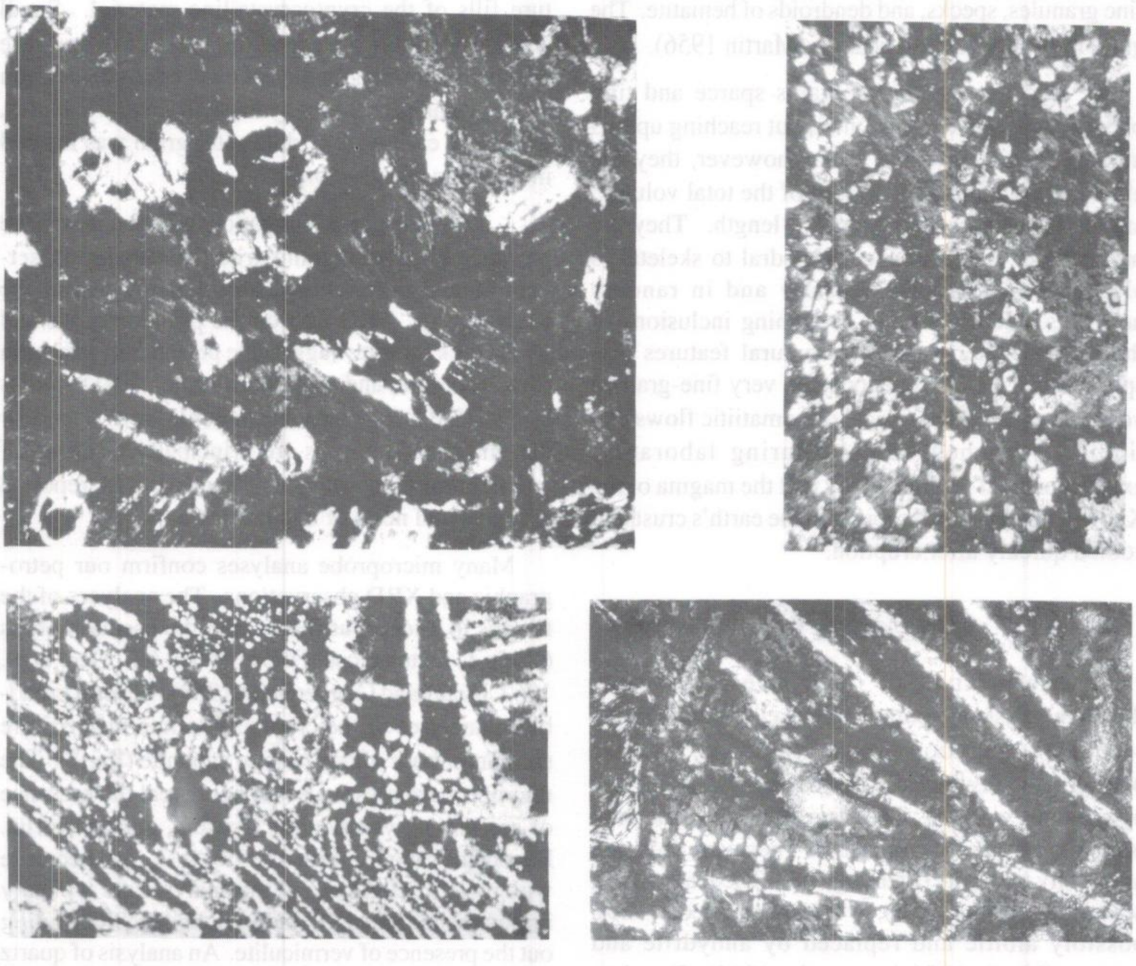

Fig. 3 Textures in the Khewra trap
Top left: Skeletal to subhedral, altered phenocrysts in a micro-to cryptocrystalline matrix. Dark interiors of the phenocrysts are mostly fallen parts. Length of the photograph is 2.2 mm. some phenocrysts contain secondary quartz interiors. Top right: Euhedral to subhedral microphenocrysts in micro- to cryptocrystalline matrix. The totally altered phenocrysts in some cases contain quartz cores. Length of photo is 1.7 mm. Bottom left: Skeletal and beady phenocrysts in a cryptocrystalline matrix. Scale as in top right. Bottom right: Photomicrograph showing phenocrysts ranging from euhedral (extreme lef, only half grain), acicular/skeletal, to aligned beads (bottom) in an amygdaloidal matrix. The amygdules (centre and right) have clear talcosic cores and clear to Fe-stained cryptocrystalline margins of Mg-rich clays. Length of photo is 1.7 mm. Note that irrespective of size and shape, all the phenocrysts are totally altered to talc + Mg-rich clays, whereas the groundmass is of K-feldspar composition (for details, see text). All photomicrographs were taken under crossed polars.

samples also contain rare, microphenocrysts of magnetite. The phenocrysts are set in a microcrystalline to cryptocrystalline, locally glassy, groundmass of K-feldspar composition, dusted with fine granules, specks, and dendroids of hematite. The glass may show devitrification (Martin 1956).

Locally, the trap contains sparce and tiny phenocrysts, mostly 1 to 3 mm, but reaching up to 5 mm in length. In most rocks, however, they are abundant (making up to a third of the total volume) and commonly exceed 5 mm in length. They are prismatic to needle-shaped, euhedral to skeletal to aligned beads, grown radially and in random networks, and commonly containing inclusions of the matrix material. These textural features (i.e. spinifex and stellate phenocrysts, very fine-grained vesicular matrix) are typical of komatiitic flows and liquids quenched quickly during laboratory experiments. It is, thus, likely that the magma of the Khewra trap travelled rapidly in the earth's crust and cooled quickly after eruption.

PHENOCRYSTS

Irrespective of their size and shape, the phenocrysts are completely pseudomorphed by secondary alteration product in all the samples petrographically investigated during this study and by previous workers. Therefore, their identification is merely a matter of conjecture. They were regarded as initially tremolite (Fleming 1853, Theobald 1854), actinolite (Wynne 1878), or feldspar (Pascoe 1920), possibly albitic and replaced by anhydrite and gypsum (Martin 1956, but see also 1962). Based on a considerably detailed petrographic study and a chemical analysis of the trap, Mosebach (1956) concluded that the phenocrysts were initially orthopyroxene altered hydrothermally according to the following reaction:

enstatite → antigorite + vermiculite + quartz.

A correct identification of even the alteration product has proven very difficult. Much of it consists of tiny, soft, micaceous to fibry grains displaying strong interference colours. In several thin sections, these are randomly accompanied by a very fine-grained (cryptocrystalline) aggregate showing whitish to dark grey interference colours. In one sample, the cores of some pseudomorphs are made up of the strongly birefringent material with margins and fracture fills of the cryptocrystalline material. Small amounts of a silica mineral (quartz, but in one case consisting of fine granules of chalcedony?) and iron oxide granules accompany these in several samples, whereas a carbonate (? dolomite) grain was located in only one pseudomorph.

The present investigation did not confirm the presence of gypsum, anhydrite (Martin 1956), serpentine and vermiculite (Mosebach 1956) in the Khewra trap. XRD data on the pseudomorphs and whole rock samples suggest the presence of talc, with some sepiolite, and montmorillonite. XRD studies by S.A.H. Baqri (personal communication) also show that the pseudomorphs are principally made up of talc. It is worth repeating that Wynne (1878) reported stringers and nests of talc in the trap.

Many microprobe analyses confirm our petrographic and XRD observations. The analyses of the fibrous to micaceous material in the pseudomorphs (Table 1) match closely those of talc (cf., Deer et al. 1962, Evans and Guggenheim 1988). Several broad-beam analyses of the cryptocrystalline material are similar to those of hectorite or saponite (Fig.4). The microprobe analyses also do not reveal the presence of serpentine, vermiculite, gypsum, and anhydrite. Except the saponite with 8 to 9% Al_2O_3, and hectorite with up to 3.3% Al_2O_3, all the analyses are typically impoverished in Al_2O_3 and enriched in SiO_2, ruling out the presence of vermiculite. An analysis of quartz grain in a pseudomorph is quite pure except for 0.66% TiO_2 and 0.28% Al_2O_3. In summary then, the pseudomorphs are apparently made up mostly of talc with some hectorite, saponite, quartz and local carbonate. The Mg-rich clays developed during low-temperature alteration following the replacement of the phenocrysts by talc at higher temperature.

Many of the basal sections of the pseudomorphosed phenocrysts are squarish in outline and, like Mosebach (1956), the authors also regard them to have been Mg-rich enstatite initially. Despite the presence of some rhombic sections, we

Table 1 Representative analyses of the material occupying the phenocrysts

	1	2	3	4	5	6	7	8	9
SiO_2	60.71	61.54	62.25	60.70	59.38	54.29	41.51	100.09	0.34
TiO_2	0.00	-	-	-	-	0.01	-	0.66	3.30
Al_2O_3	1.35	0.22	0.89	0.93	1.99	2.38	8.91	0.28	0.32
Fe_2O_3	0.00	0.66	0.00	-	-	-	-	-	60.80
FeO	2.49	2.70	4.47	4.39	2.57	2.69	4.43	0.00	32.62
MnO	0.02	0.01	-	-	-	0.03	-	0.00	0.24
MgO	29.18	29.93	28.24	28.53	30.80	25.97	24.65	0.00	0.42
CaO	0.16	0.00	0.11	0.05	0.00	0.33	0.64	0.01	0.16
Na_2O	0.18	0.06	0.45	0.25	0.14	0.15	0.25	0.00	0.04
K_2O	0.14	0.03	0.00	0.05	0.12	0.26	0.37	0.03	0.00
Total	94.32	95.15	96.41	94.90	95.00	86.12	80.76	101.07	98.24
					Number of cations*				
Si	7.79	7.91	7.94	7.88	7.65	7.73	6.51	0.993	0.00
Ti	0.00	-	-	-	-	0.00	-	0.005	0.10
Al	0.20	0.03	0.13	0.14	0.30	0.40	1.65	0.002	0.01
Fe^{3+}	0.00	0.06	0.00	0.00	0.05	0.00	0.00	0.000	1.77
Fe^{2+}	0.27	0.29	0.48	0.48	0.22	0.32	0.58	0.000	1.01
Mn	0.00	0.00	-	-	-	0.00	-	0.000	1.06
Mg	5.58	5.73	5.37	5.52	5.91	5.51	5.76	0.000	0.02
Ca	0.02	0.00	0.02	0.01	0.00	0.05	0.11	0.000	0.01
Na	0.04	0.02	0.11	0.06	0.04	0.04	0.08	0.000	0.00
K	0.02	0.00	0.00	0.01	0.02	0.05	0.08	0.000	0.00

1: Talc sample Kt1200; total contains 0.09% Cr_2O_3, giving 0.09 Cr in the formula.
2-4: Talc in Kt201; 2: after main phenocryst, 3: after skeletal phenocruyst,
4: after beady phenocryst.
5: Talc in Kt 1199.
6: Cryptocrystalline ?hectorite in KT6, Total contains 0.01% Cr_2O_3.
7: ? Saponite after main phenocryst in KT 1199.
8: Quartz grain in a pseudomorph of KT 1204.
9: Titano-magnetite phenocryst in KT 1202.
* cations based on 22 (O) in 1-7, 2 (O) in 8, and 4(O) in 9.
In Tables 1 to 3, total iron determined as FeO, was normalised into Fe_2O_3 and FeO according to charge balance requirements.

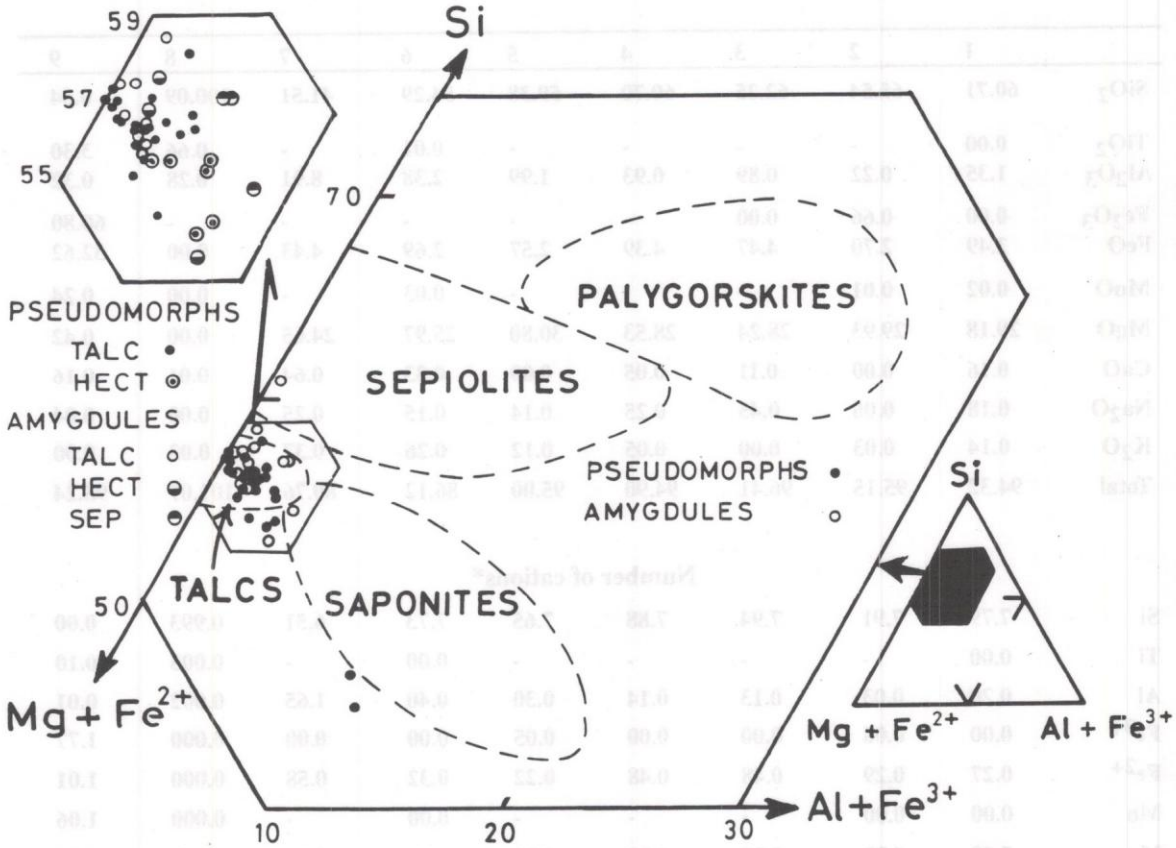

Fig. 4 Plots of the Mg-rich hydrous silicate analyses in terms of Si-Mg+Fe^{2+} -Al+ Fe^{3+} (octahedral) components. Field of talc analyses is based on compilation of Deer et al. (1962), whereas those of palygorskites, sepiolites, and saponites are adapted from Jones and Galan (1988, Fig. 19a, p. 662).

exclude the possibility of a Ca-rich amphibole because the analy of the trap in general and those of the pseudomorphs in particular are typically impoverished in CaO. Although CaO could have been dissolved and carried away, evidence of Ca-metasomatism is lacking in the neighboring rocks. Chemical analyses of the trap are remarkably uniform in composition, negating substantial chemical changes during the alteration of the phenocrysts. The only changes which may have taken place include a slight increase of silica, and variable decrease of iron oxide due to leaching.

Chhibber (1944) suggested that the trap is silicified and contains fine secondary quartz crystals, but these could neither be confirmed by Martin (1956) nor are visible in the present set of samples. "Silicification" is essentially restricted to the formation of quartz in some amygdules and pseudomorphs, and could not have contributed more than a few percent of SiO_2. The total lack of silica deficient phases in the trap suggests that the small amount of normative quartz (0.8 to 5.4%) owes itself to the essentially saturated nature of the magma, although one rock analysis is silica deficient and olivine normative. Some redistribution and possible leaching away of iron oxide is indicated by the abnormally high Mg# (Mg/(Mg + Fe)) and variation in the colour of the trap. The more altered, and lighter colour (buff and orange) trap contains lower total iron and higher Mg# than the less altered and deeper colour (purple, red, green) trap.

GROUNDMASS

In contrast to the phenocrysts, the groundmass is little altered (Mosebach 1956), except for the development of hematite granules, specks, and dendroids, probably at the expense of magnetite/titanomagnetite and the phenocrysts. Forty microprobe analyses reveal that the groundmass is essentially of K-feldspar composition and XRD studies suggest the presence of sanidine and orthoclase. The groundmass inclusions in the pseudomorphs are of identical composition. Representative analyses are listed in Table 2. The chemical data show that the feldspar consists essentially of orthoclase component, with low CaO and BaO contents. The anorthite content is mostly below 1.4 mole % and ranges from 0.0 to 2.2, with one value of 4.2 mole %. In general, the anorthite content increases with albite content of the analyses (Fig.5). Celsian content (determined in seven analyses) ranges from 0.0 to 2.0 mole %. The average composition of the 40 analyses is $An_{0.8} Ab_{8.9} Or_{89.8} Cn_{0.5}$.

There are considerable variations in the proportions of orthoclase and albite components in the feldspar analyses within the domain of a thin section (Fig.5). The maximum noted range is from pure orthoclase ($Or_{99.9}$) to $An_{4.2} Ab_{33.4} Or_{62.3}$. The highly potassic nature of the rocks (with average K_2O/Na_2O ratio of 12) would suggest that K-feldspar compositions with more than about 10 mole % albite must be rare. Potash feldspars with similarly low contents of albite have been reported from some other ultrapotassic rocks. For example, sanidines from the Leucite Hills, Wyoming, contain less than 2 mole % albite, whereas those of the Spanish lamproites contain an average of 6 mole % albite (Sahama 1974). An interesting aspect of the feldspar analyses is their high contents of MgO (up to 4.0 wt%; average 0.94 %) and Fe_2O_3* (up to 2.6 wt %, average 0.90%). Sanidine relatively rich in iron has been analysed in other ultrapotassic rocks (Carmichael 1967, Edgar 1974).

The opaque grains in the matrix and pseudomorphs are nearly pure iron oxide containing 0.03 to 0.4 % SiO_2, 0.0 to 0.05 % TiO_2, 0.0 to 0.1 % Al_2O_3, and 0.0 to 0.3 MgO, but one unusual analysis contains 3.3% TiO_2, 0.3% Al_2O_3, 0.24% MnO, and 0.42 % MgO. The bulk analyses of the trap contain 0.7 to 0.8 wt % TiO_2, however, none of the analysed minerals contains appreciable amounts of TiO_2. Two analyses of the matrix under broad beam, however, contain 3.9 and 5.4% TiO_2, the former also containing 11.7 % FeO, suggesting the presence of tiny grains of titanomagnetite.

VESICLES/AMYGDULES

All the studied samples contain highly irregular to rounded vesicles ranging from microscopic to a

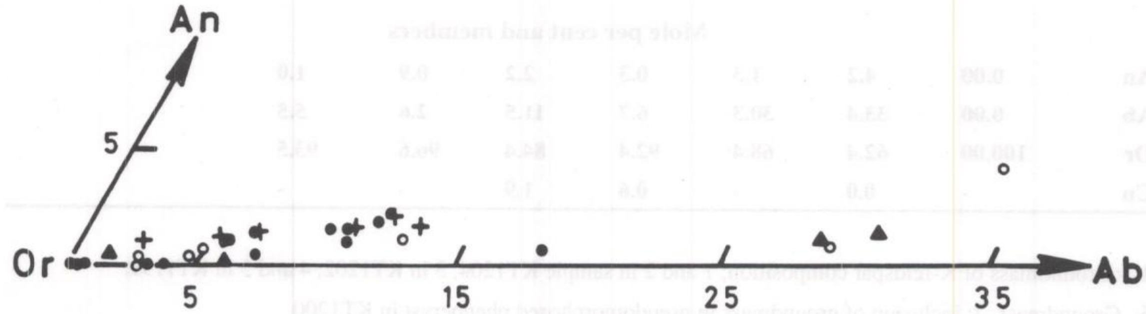

Fig .5 Mole per cent anorthite-orthoclase-albite plots of the K-feldspar analyses in groundmass and inclusions in the phenocrysts. In order to show intra-granular compositional variation, analyses from four different samples are shown by different symbols.

Table 2 Representative analyses of the material in groundmass

	1	2	3	4	5	6	7	8	9
SiO_2	65.64	66.32	65.37	65.02	65.00	66.80	66.21	0.35	0.12
TiO_2	-	-	0.16	0.18	0.02	0.01	0.06	0.12	1.20
Al_2O_3	17.83	18.39	17.56	17.37	17.50	16.74	17.80	0.03	0.77
Fe_2O_3	0.18	0.75	1.68	0.83	0.58	0.53	0.73	100.84	66.84
FeO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	29.55
MnO	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.00	0.09
MgO	0.00	0.25	0.18	0.98	2.60	2.39	0.89	0.03	1.21
CaO	0.00	0.78	0.30	0.05	0.34	0.14	0.21	0.00	0.01
Na_2O	0.00	3.43	3.29	0.61	1.02	0.26	0.59	0.00	0.00
K_2O	15.15	9.70	11.32	12.59	11.30	14.72	15.46	0.00	0.00
BaO	-	0.01	-	0.34	0.86	-	-		-
Total	98.80	99.86	99.62	97.97	99.22	101.62	101.96	101.38	99.79
					Number of cations*				
Si	12.16	12.01	11.96	12.07	11.93	12.07	11.98	0.01	0.00
Ti	-	-	0.03	0.03	0.00	0.00	0.01	0.00	0.03
Al	3.90	3.93	3.79	3.80	3.76	3.56	3.80	0.00	0.03
Fe^{3+}	0.03	0.10	0.23	0.12	0.08	0.05	0.10	1.99	1.91
Fe^{2+}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.94
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.07	0.05	0.27	0.71	0.64	0.24	0.00	0.07
Ca	0.00	0.15	0.05	0.01	0.07	0.03	0.04	0.00	0.00
Na	0.00	1.20	1.17	0.22	0.36	0.09	0.21	0.00	0.00
K	3.59	2.24	2.64	3.05	2.65	3.39	3.57	0.00	0.00
Ba	-	0.00	-	0.02	0.06	-	-	-	-
					Mole per cent and members				
An	0.00	4.2	1.3	0.3	2.2	0.9	1.0		
Ab	0.00	33.4	30.3	6.7	11.5	2.6	5.5		
Or	100.00	62.4	68.4	92.4	84.4	96.6	93.5		
Cn	-	0.0	-	0.6	1.9	-	-		

1-5:Groundmass of K-feldspar composition; 1 and 2 in sample KT1204, 3 in KT1202, 4 and 5 in KT1199.

6: Groundmass, 7: inclusion of groundmass in pseudomorphosed phenocryst in KT1200.

8: Hematite granule in KT1200.

9: Titanomagnetite on the edge of an amygdule in KT1200.

* 1-7 based on 32(O), 8 on 3(O), and 9 on 4(O).

centimeter in dimension. Most of them are entirely occupied by secondary minerals, but a few have marginal fillings and empty cores. The amygdules commonly do not exceed a few percent of the rocks by volume, but in a few samples they reach up to 10%. They can be divided into three main groups.

1) Grayish green to dark green in handspecimens, these are by far the most abundant, show a range of textural and mineralogical variation, and completely occupy the vesicles. Some of these are entirely made up of a pale yellow to orange, cryptocrystalline material of grey interference colour. Others are zoned, with margins of the yellow cryptocrystalline material and cores of a colourless, very fine-grained, strongly birefringent material. A few consist of alternating shells of the two, some of which are stained brown.

Some of these amygdules contain quartz which is much coarser grained than the rest of the material. There are tiny (<0.3 mm) amygdules one side of which is occupied by a grain or two of quartz, and the other by the crystalline material too fine-grained to discern. A few of the amygdules are zoned and, from centre to periphery, consist of: quartz core, a thin film of hematite, a shell of the more birefringent material and an outer envelope of the cryptocrystalline material. Some amygdules of this group have an outer lining of hematite, but there may also be well-formed grains of iron oxide (hematized magnetite?) discretely grown within the interior or along the periphery of the amygdules.

Microprobe analyses were performed on several of these amygdules. The strongly birefringent material is talcosic in composition and similar to that occurring in the pseudomorphs, but containing slightly higher FeO* and lower Al_2O_3 (Table 3). The cryptocrystalline material, considered chalcedonic by Martin (1956) and Mosebach (1956), is chemically sepiolite (Jones and Galan 1988) or hectorite. The XRD data are in conformity with the probe analyses which are plotted in Fig.4. The analyses of quartz and iron oxide are quite pure.

2) Irregular amygdules are of reddish colour, some of which have empty cores. These consist commonly of a core of dolomite (average composition: Ca 52.1, Mg 44.2, Fe^{2+} 3.5, Mn 0.1, Na 0.1 mole %), a middle shell of quartz, and an outer shell of a yellow cryptocrystalline talc or hectorite with or without an outermost lining and discrete grains of hematite similar to 1. Both the carbonate and quartz grains may exceed a milimeter in dimension.

3) Black, tiny masses of iron oxide intermixed with a minor amount of the cryptocrystalline material form the third group of amygdules.

The rocks may also contain fracture fillings of red quartz and grayish white carbonate (calcite and dolomite), up to 2 mm thick. In one sample, there are local pools of milky white carbonate measuring up to 30 x 10 x 3 mm.

NOMENCLATURE AND PRELIMINARY GEOCHEMISTRY

Although according to the 1972 edition of the AGI Glossary of Geology (Gray et al. 1972), the term trap refers to "any dark-colored, fine-grained hypabyssal or extrusive rock", most of the workers have regarded the Khewra trap as volcanic in origin. Pascoe (1920, p.474) referred to it as a volcanic rock consisting "of an andesitic felt-like mass of feldspar laths..." Martin (1956) described it as "a variolitic basalt, but like the spilites and mugearites... difficult to place in a petrographic system".

The detailed study of Mosebach (1956) was revealing in that the trap was categorised to consist essentially of orthopyroxene (now totally altered) and K-feldspar. The texture, mineral and chemical composition of the trap are sufficiently peculiar to tempt Mosebach in assigning it a new name, Khewraite. He considered that this highly potassic rock is intermediate between trachyte and leucitanite. On the basis of SiO_2 vs. total alkalis, the trap analyses classify as potassic trachyte according to Le Bas et al. (1986), and tristanite following Cox et al. (1979). None of the common rock systematics, however, is adequate for classifying rocks so highly enriched in potassium.

Chemical analyses of six rocks, presented in Table 4, are remarkably similar. The high K_2O, K_2O/

Table 3 Representative analyses of the material in amygdules

	1	2	3	4	5	6	7	8	9
SiO_2	61.54	62.35	60.48	50.27	50.09	53.51	100.12	0.00	0.03
TiO_2	-	-	0.04	0.00	0.03	0.00	0.00	0.00	0.06
Al_2O_3	0.22	0.06	0.33	0.99	1.19	3.20	0.01	0.00	0.06
Fe_2O_3	0.66	0.00	0.00	3.60	1.10	0.00	0.03	0.00	99.99
FeO	2.70	5.05	3.08	2.27	1.52	4.36	-	3.11	-
MnO	0.01	-	0.00	0.00	0.01	0.04	0.00	0.10	0.48
MgO	29.93	28.04	23.97	24.06	23.00	26.77	0.00	22.48	0.02
CaO	0.00	0.00	0.00	0.02	0.08	0.39	0.00	33.84	0.00
Na_2O	0.06	0.07	0.84	0.26	0.21	0.16	0.00	0.02	0.00
K_2O	0.03	0.00	0.94	0.12	0.11	0.06	0.00	0.00	0.00
Total	95.15	95.57	89.68	81.59	77.34	88.49	100.16	59.55	100.64
					Number of cations				
O =	22	22	22	32	32	22	2	6	3
Si	7.91	8.03	8.25	11.14	11.49	7.50	1.00	0.00	0.00
Ti	-	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.03	0.01	0.05	0.26	0.32	0.53	0.00	0.00	0.00
Fe^{3+}	0.06	0.00	0.00	0.60	0.19	0.00	0.00	0.00	1.99
Fe^{2+}	0.29	0.54	0.35	0.42	0.29	0.51	-	3.36	-
Mn	0.00	-	0.00	0.00	0.00	0.00	0.00	0.18	0.01
Mg	5.73	5.38	4.87	7.94	7.86	5.59	0.00	42.22	0.00
Ca	0.00	0.00	0.00	0.00	0.02	o;[0.06	0.00	54.09	0.00
Na	0.02	0.02	0.22	0.11	0.09	0.04	0.00	0.04	0.00
K	0.00	0.00	0.16	0.03	0.03	0.01	0.00	0.00	0.00

1: Colourless to pale microcrystalline talcosic centre of an amygdule in sample KT1201.

2: Colourless to pale microcrystalline talcosic centre of an amygdule in KT1200.

3: Unusual ?sepiolite in an amygdule in KT1201.

4,5: Yellow cryptocrystalline sepiolite marginal zones of amyugdules around quartz in KT1199.

6: Yellow brown cryptocrystallines (?hectorite) margin of a carbonate-quartz amygdules in KT6.

7: Quartz core of an amygdule in KT1204.

8: Dolomite core of an amyugdule in KT6.

9: Hematite in an amygdule in KT1201.

Na_2O, and Mg# classify them as ultrapotassic. They are also characterised by high Fe_2O_3/FeO, and abnormally low MnO, CaO, Na_2O and P_2O_5. For their high Mg# (>75), they have rather high SiO_2 and very low Cr and Ni. The high Fe_2O_3/FeO ratios are common in ultrapotassic rocks and have been attributed to oxidation during emplacement (Foley et al. 1987), however, in the Khewra trap post-emplacement alteration probably also played an important role. Table 4 also shows that in the more weathered rocks (compare 5B with 5A) much of iron has been leached, but the remaining oxides are similar to those of the other analyses. Sample 1494 is the freshest, and hence dark green in colour.

The unique major element characteristics of the trap analyses are clearly reflected in their unusual CIPW norms, consisting essentially of orthoclase and orthopyroxene with subordinate amounts of quartz, plagioclase and Fe-Ti oxides. In fact the modal and normative compositions of the rocks match closely, if the assumption that the pseudomorphs have formed at the expense of orthopyroxene phenocrysts is correct.

A variety of nomenclature has been used for ultrapotassic rocks (Barton 1979, Bergman 1986, Peccerillo 1993). Foley et al. (1987) classified them into three chemical groups:

1) Group I consists of lamproites characterised by high Mg# (mostly 70 to 85), TiO_2, K_2O; low Al_2O_3, CaO, Na_2O; and variable SiO_2. These occur in stable continental areas, but non-standard members may occur in orogenic areas.

2) Group II rocks have low SiO_2 and Al_2O_3, their TiO_2 contents are comparable to and CaO contents higher than lamproites. Their Mg# are mostly above 60. These rocks occur predominantly in rift-zone environments.

3) Group III rocks are rich in Al_2O_3, CaO, and poor in TiO_2. They have lower Mg# than the other groups (only rarely above 70), and their SiO_2 content is commonly below 50 wt%. These rocks occur essentially in active orogenic environments.

Foley et al. (1987) showed that the three groups can be distinguished on several diagrams based on major elements. The Khewra trap analyses plot consistently in the field of group I rocks. The latter, however, contain >1.0% TiO_2; the lower TiO_2 content of the trap analyses is akin to group III rocks.

PETROGENESIS

A number of hypotheses have been presented for the generation of ultrapotassic magmas. Their high K_2O, Cr and Ni contents and Mg# have led to a growing consensus that they are a partial melting product of a metasomatised, phlogopite-bearing upper mantle (Kuehner et al. 1981, Edgar and Prima 1984, Oberhansli 1986, Foley et al. 1987, Peccerillo 1993). Locally, fractionation seems to have played variable roles in the evolution of the ultrapotassic rocks (Rogers et al. 1985, Thompson and Fowler 1986), but some workers have also suggested the assimilation of crustal material (cf. Gupta and Yagi 1980, Mitchell and Bergman 1991). The Khewra trap analyses contain much higher MgO/FeO* and lower CaO, Na_2O, MnO, P_2O_5 than the crustal material (Taylor and McLennan 1981). Thus, we regard that despite the rather high SiO_2, the magma composition of the trap was not contaminated much by crustal assimilation.

The trap analyses display two distinct and mutually contradictory features: (1) their Mg numbers (75 to 83, ignoring the very altered rock KT5B) are very highy, like the group I rocks of Foley et al. (1987), and (2) their Cr and Ni contents are low like some of the most evolved magmas. The former trait, as mentioned in the proceeding section, can be attributed at least partly to loss of iron due to leaching. It is worth noting that the least altered rock (1494) has the lowest Mg# and the most altered rock (5B) the highest. As far as depletion in Cr, Ni, CaO and P_2O_5 is concerned, it could have been effected by separation of spinel, plagioclase, apatite and some olivine and/or orthopyroxene during fractional crystallization. Separation of these minerals will also explain the rather high amount of SiO_2 (although some of it may have been added during alteration, as suggested by the lower SiO_2 in the least altered rock 1494) and low amounts of Na_2O and TiO_2 in all the rocks. But keeping in view the considerable variation in the composition of ultrapotassic rocks the

Table 4 Analyses of the Khewra Trap from Khewra gorge

	M	KT1494	KT7	KY6	KT 5A	KT 5B
SiO_2	58.87	55.69	59.67	60.38	60.29	60.35
TiO_2	0.62	0.67	0.72	0.74	0.67	0.78
Al_2O_3	13.29	12.22	10.63	10.08	10.56	12.14
Fe_2O_3	2.45	7.45	4.06	4.73	4.61	0.83
FeO	1.23		-	0.65	0.65	0.72
MnO	0.02	0.00	0.01	0.02	0.01	0.01
MgO	8.04	11.34	10.24	11.19	9.12	10.78
CaO	0.45	0.30	0.56	0.33	0.33	0.48
Na_2O	0.91	0.46	1.05	0.61	0.55	0.78
K_2O	9.78	9.00	9.22	9.22	9.51	9.94
P_2O_5	0.08	0.04	0.11	0.15	0.15	0.10
LOI	3.98	3.00	3.36	2.68	3.07	2.98
Total	99.72	100.17	99.63	100.78	99.52	99.89
Mg#	80.7	75.1	83.3	80.2	77.2	92.9
Cr	-	38	-	24	23	20
Ni	-	34	-	20	23	20
CIPW Norms (Anhydrous)						
Q	1.54	-	3.59	3.87	5.40	0.78
Or	60.55	55.16	57.13	56.01	58.65	60.69
Ab	8.05	4.03	3.37	0.39	1.27	6.85
An	1.79	1.27	-	-	0.00	0.18
C	0.58	1.29	-	-	-	
Ac	-	-	1.65	2.17	2.17	-
Di	-	-	1.72	0.57	0.52	1.29
Hy	25.28	27.60	30.86	35.21	30.31	28.12
Ol	-	7.73	-	-	-	-
Mt	0.79	1.50	-	-	-	0.33
Il	1.23	1.32	1.43	1.45	1.33	1.54
Ap	0.18	0.09	0.24	0.33	0.35	0.22-

All the samples are from Khewra Gorge. M (Mosebach 1956), KT7 (greyish maroon), 6 and 5A (deep purple) are samples from which some Fe may have leached away. KT5B, buff-coloured with sparse purple spots, shows strong Fe leaching. Note that 5A and 5B are two ends of the same sample and show a gradual transition. KT 1494 is dark green trap which Fe leaching may not have taken place (XRF analysis by N. Marsh. Total iron as Fe_2O_3, KT7, 5A and 5B wet chemically analysed by M. T. Shah. CIPW norms on anhydrous basis, adjusting iron as Fe_2O_3: FeO = 0.15 following Irvine and Baragar (1971). Mg# = 100 Mg/(Mg + Fe).

world over, it would not be surprising if these chemical peculiarities are characteristic of the magma of the Khewra trap. Irrespective of their Mg#, the high MgO contents of the rocks suggest derivation from the upper mantle, and the high K/Ti and K/Na ratios are suggestive of the presence of phlogopite in the source region (Hawksworth et al. 1984, Rogers et al. 1985).

Khewra trap represents the only igneous activity in the entire Salt Range, and there are no ultrapotassic rocks in the region which can be equated with it. There are diamondiferous conglomerates of Late Proterozoic age in central India (Pascoe 1965), where diamonds have been derived from still older (ultra) potassic rocks. However, these are too far removed in space (>1000 km) and time (? Vindhyan) to be equated with the Khewra trap. The Malani series rhyolites, dacites, andesites, and minor basalts cover more than 50,000 km^2 area in western Rajasthan. These and their related granitic plutons have a whole-rock Rb-Sr isochron age of 735 ± 15m.y. (Crawford 1975). Kochhar (1980) thought that the Malani rocks are plume-related, but Srivastava et al. (1989) suggest that they are crustal melts. Although some of the Malani rhyolites have high K_2O contents, their very low MgO and Mg#, and high SiO_2 do not group them with ultrapotassic rocks and the Khewra trap, some 600 km to the north west.

Several evaporite deposits of the world can be related to rifting and continental fragmentation (cf. Windley 1984). The Salt Range evaporites and ultrapotassic rocks are closely associated in space and time, and it is tempting to relate them also to rifting. However, the major element geochemistry of the rocks group them with ultrapotassic rocks of stable continental areas rather than with those of rift-zone environments, whereas their TiO_2 content is similar to K-rich rocks of orogenic areas. Until the age of the Khewra trap is precisely known and Precambrian tectonics of the region well-understood, a sound hypothesis for the plate tectonic configuration of the Khewra trap is hard to be put forward.

ACKNOWLEDGEMENTS

Much of the analytical work for this paper was performed at the NCE Geology, University of Peshawar. We are thankful to Barkatullah Khan for microprobe analyses, M. Tahir Shah for whole-rock analyses, and M. Rafiq and Irshad Ahmad for XRD work. N. Marsh (Leicester University) analysed one sample by XRF. Some XRD data was collected at the University of Oklahoma during the tenure of a Fulbright Fellowship to M. Q. Jan. We are grateful to Doug Powell for the XRD and the U.S. Education Foundation in Pakistan for financial support.

REFERENCES

Barton, M., 1979, A comparative study of some minerals occurring in the potassium-rich alkaline rocks of the Leucite Hills, Wyoming, the Vico Volcano, Western Italy, and the Toro Ankole region, Unganda. Neues Jahrb. Mineral. Abh., v.137, pp.113-134.

Bergman, S. C., 1986, Lamproites and other potassium-rich rocks:a review of their occurrence, mineralogy and geochemistry. In: Fitton, J.G., and Upton, B.G.J., eds., Alkaline Igneous Rocks. Geol. Soc. Lond. Spec. Paub. v. 30, pp. 108-190.

Carmichael, I. S. E., 1967, The mineralogy and petrology of the volcanic rocks from the Leucite Hills, Wyoming. Contrib. Mineral. Petrol., v. 15, pp.24-66.

Chhibber, H. L., 1944, The age of the Saline Series of the Salt Range, Punjab. Proc. Nat. Acad. Sc. India, v.14, pt.6, pp. 244-248

Cox, K. G., Bell, J. D., and Pankhurst, R. J., 1979, The Interpretation of Igneous Rocks. Allen ad Unwin, London.

Crawford, A. R., 1975, Rb-Sr age determinations for the Mount Abu Granite and related rocks of Gujrat. J. Geol. Soc. India, v.16, pp. 20-28.

Davies, R.G., and Crawford, A.R., 1971, Petrography and age of the rocks of the Bulland Hill, Kirana Hills, Sargodha district, West Pakistan. Geol. Mag., v.108, pp. 235-246.

Deer, W. A., Howie, R. A., and Zussman, J., 1962, Rock-forming Minerals, V.3. Longman, London, 270p.

Dostal, J., Dupu, C., Carron, J. P., de Kerneizon, M. L. G., and Maury, R. C., 1983, Partition coefficients of trace elements: application to volcanic rocks of St. Vincent, West Indies. Geochem. Cosmochim. Acta, v. 47, pp. 525-533.

Edgar, A. D., 1974, Experimental studies. In: Sorensen, H., ed., The Alkaline Rocks. Wiley, New York, pp. 355-389.

Edgar, A. D., and Arima, M., 1984, Experimental studies on K metasomatism of a model pyrolite mantle and their bearing on the genesis of ultrapotassic magmas. Proc. 27 Int. Geol. Cong., v. 9, pp. 509-541.

Evans, B. W., and Guggenheim, S., 1988, Talc, pyrophyllite, and related minerals. Min. Soc. Amer. Reviews in Mineralogy, v.19, pp. 225-294.

Faruqi, S. H., 1986, Precambrian oil in the Salt Range and Potwar, Pakistan. Kashmir J. Geol., v. 4, pp. 33-50.

Fatmi, A. N., 1984, Geology of Salt Range. Guide Book, Ist Geol. Cong. Pakistan.

Fleming, A., 1853, On the Salt Range in the Punjab. Quart. J. Geol. Soc. Lond., v. 9, pp. 189-200.

Foley, S. F., Venturelli, G., Green, D. H., and Toscani, L., 1987, The ultrapotassic rocks: characteristics, classification, and constraints for petrogenetic models. Earth Science Rev., v. 24, pp. 81-134.

Gary, M., McAfee, R., Jr., Wolf, C. L., 1972, Glossary of Geology. Amer. Geol. Inst., Washington, D.C.

Gee, E. R., 1980, Pakistan, Salt Range geological map series. Directorate Overseas Surv., U.K.

Gee, E. R., 1989, Overview of the geology and structure of the Salt Range, with observations on related areas of northern Pakistan. In: Malinconico, L.L. and R.J. Lillie, R.J., eds., Tectonics of the western Himalayas. Geol. Soc. Amer. Spec. Pap., 232, pp. 95-112.

Gupta, A. K., and Yagi, K., 1980, Petrology and Genesis of the Leucite-Beering Rocks. Springer-Verlag, Berlin, 252 p.

Hawksworth, C. J., Rogers, N. W., Van Calsteren, P., and Menzies, M. A., 1984. Mantle enrichment processes. Nature, Lond., v. 311, pp. 331-335.

Irvine, T. N., and Baragar, W. R. A., 1971, A guide to the classification of the common volcanic rocks. Canad. J. Earth Sciences, v. 8, pp. 523-549.

Jones, B. F., and Galan, E., 1988, Sepiolite and palygorskite. Min. Soc. Amer. Reviews in Mineralogy, v.19, pp. 631-674.

Kochhar, N., 1980, Malani igneous suite: hot spot magmatism and cratonization of the northern part of the Indian shield. J. Geol. Soc. India, v. 25, pp.154-161.

Kuehner, S. M., Edgar, A. D., and Arima, M., 1981, Petrogenesis of the ultrapotassic rocks from the Leucite Hills, Wyoming. Amer. Mineral, v. 66, pp. 663-677.

Le Bas, M.J ., Le Maitre, R. W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkalis-silica diagram. J. Petrol., v. 27, pp. 45-750.

Martin, N. R., 1956, The petrography of Khewra trap rocks, Salt Range, West Pakistan. Geol. Surv. Pak., Rec., 8, pt.2, pp. 45-48.

Martin, N. R., 1962, Mosebach on the Khewra trap. Geol. Bull. Punjab Univ., v. 2, pp. 57-58.

Mosebach, R., 1956, Khewrait vom Khewra Gorge, Pakistan, ein neuer typus kalireicher effusivgesteine. Neues Jb. Mineral. Abh., v. 89, pp.182-209.

Mitchell, R.H., and Bergman, S. C., 1991, Petrology of Lamproites. Plenum Press, New York, 447p.

Oberhansli, R., 1986, Geochemistry of meta-lamprophyres from the Central Swiss Alps. Schweiz. Mineral. petrol. Mitt., v. 66, pp. 315-342.

Pascoe, E. H., 1920, Petroleum in the Punjab and North-West Frontier Province. Mem. Geol. Surv. India, v. 40, pt.3., pp. 331-493.

Pascoe, E.H., 1965, A Manual of Geology of India, vol.1. Govt. of India Press, 485 p.

Peceerillo, A., 1993, Potassic and ultrapotassic rocks compositional characteristics, petrogenesis, and geological significance. Episodes, v.15, pp. 243-251.

Rogers, N. W., Hawkesworth, C.J., Parker, R. J., and Marsh, J. S., 1985, The geochemistry of potassic lavas from Vulsini central Italy and implications for mantle enrichment processes beneath the Roman region. Contrib. Mineral. Petrol., v. 90, pp. 244-257.

Sahama, T. G., 1974, Potassium-rich alkaline rocks. In: Sorensen, H., ed., The Alkaline Rocks. Wiley, New York, pp. 96-109.

Sahni, B., 1944, Microfossils and problems of Salt Range geology. Proc. Nat. Acad. Sci., v.14, pp.1-32.

Srivastava, R., Maheshwari, A., and Upadhyaya, R., 1989, Geochemistry of felsic volcanics from Gurapratap Singh and Diri, Pali district, Rajasthan. (Part-I major elements, Part-II trace elements). J. Geol. Soc. India, v. 34, pp. 467-485, 617-631.

Taylor, S. R., and McLennan, S. M., 1981, The composition and evolution of the continental crust: rare-earth element evidence from sedimentary rocks. Phil. Trans. R.Soc. Lond., v. A301, pp. 381-399.

Theobald, W., 1854, Notes on the geology of the Punjab Salt Range. Jour. Asiatic Soc. Bengal, v. 33, pp. 651.

Thompson, R. N., and Fowler, M. B., 1986, Subduction-related shoshonitic and ultrapotassic magmatism. A study of Siluro-Ordovician syenites from the Scottish Caledonides. Contrib. Mineral. Petrol. v. 94, pp. 507-522.

Wilson, M., 1989, Igneous Petrogenesis. Unwin Hyman, London, 466 p.

Windley, B. F., 1984, The Evolving Continents. Wiley, New York, 399p.

Wynne, A. B., 1878, On the geology of the Salt Range in the Punjab. Geol. Surv. India Mem., v.14, pp.1-305.