

Volatile Alteration and Metamorphic Facies: Release of H₂O and CO₂ in the Panjal Volcanics of the NW Himalaya

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ABSTRACT

Whilst the bulk rock geochemistry of a basalt, subjected to progressively increasing metamorphic grade, may remain on the whole isochemical, it has been long known that volatiles are likely to be released. Three volatiles which should change through an increase in metamorphic grade are H₂O, CO₂ and O₂. The various metamorphic grades of the Panjal Volcanics in the NW Himalayas (unmetamorphosed, greenschist, amphibolite and eclogite facies) provide an ideal opportunity to test these ideas and possibly act as chemical indicators of the prograde metamorphism. Direct and indirect determination of CO₂ and H₂O were made on numerous samples. Direct determination of CO₂ content in a rock sample has been made by coulometric titration for five main groups: Zaskar Tethyan Shelf - Panjal Volcanic basalts (Ba); Lesser Himalaya - Panjal Volcanic basalts (PJ); Higher Himalaya Second Cover - Panjal Volcanic amphibolites (A); Higher Himalaya Second Cover - Panjal Volcanic dolerites (D) and Higher Himalaya Second Cover - Panjal Volcanic eclogites (E). The main observation on the occurrence of % CO₂ in the Panjal Volcanics with increasing metamorphic grade is that there is a decrease in CO₂ that appears to be fairly gradual. This therefore suggests that with increasing metamorphism, CO₂ is being driven off by decarbonation reactions. Estimation of the volatile content in a sample can be made by the simple weight loss on ignition, and used as a method of indirect determination of H₂O. The loss on ignition (L.O.I.) and the H₂O (+ FeO) in the Panjal Volcanics show that with an increase in metamorphic grade there is a decrease in the L.O.I. and H₂O (+ FeO) content. This therefore suggests that with increasing metamorphism, volatiles are being removed by dehydration reactions. Comparison of the results of this work with the results of some published theoretical calculations are made for the wt. % H₂O of a subducting, and therefore dehydrating, oceanic crust or tholeiitic basalt. Here, predictions were made by combining calculated pressure - temperature paths with a model of metabasalt phase equilibria, where a progression (for the upper parts of the oceanic crust) pass through greenschist to amphibolite to eclogite facies. The agreement between these two independently produced sets of data is clearly apparent.

INTRODUCTION

It has been long known that the bulk rock geochemistry of a basalt subjected to metamorphism may remain on the whole isochemical. However, during prograde metamorphism, volatiles would be released. Three volatiles which should change (in their weight % content) with an increase in metamorphic grade are H₂O, CO₂ and O₂. This has been discussed in the work of Irvine and Baeggar (1971) and Miyashiro (1973), suggesting that these volatiles could also act as a chemical indicator of the state of progressive change of the rock's composition. The various metamorphic grades of the Panjal Volcanics in the NW Himalayas (unmetamorphosed, greenschist, amphibolite and eclogite facies; see Greco, 1989; Greco et al., 1989; Greco and Spencer,

1993; Pognante and Spencer, 1991; Spencer et al., 1990, 1991; Spencer, 1993) provide an ideal opportunity to test these ideas and possibly act as chemical indicators of the state of transformation of the rock (Fig. 1). Direct and indirect determination of CO₂ and H₂O were made on numerous samples for this purpose.

COULOMETRIC TITRATION DETERMINATION OF CARBONDIOXIDE CONTENT

A method of direct determination of CO₂ content in a rock sample can be made by coulometric titration. Analysis of CO₂ content was carried out on a Ströhlein Coulomat 7012, which is an automated

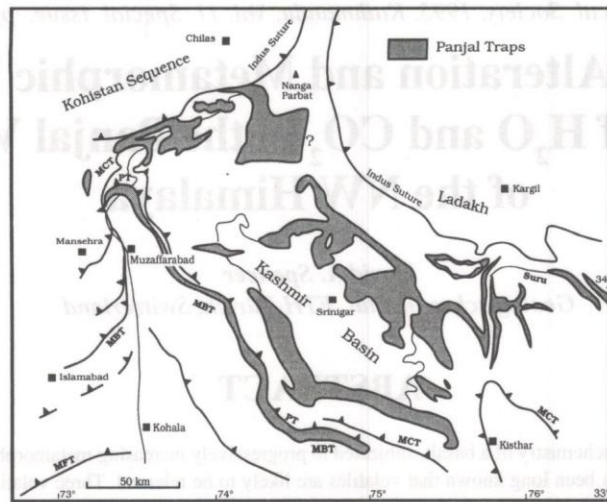


Fig. 1 The Panjal Volcanics of the NW Himalaya (Map redrawn from Papritz and Rey, 1989 with the new locations of the Panjal Volcanics in the Upper Karghan area shown)

carbon analyser (Fig. 2). The equipment consists of a double pump, thermostated absorption and titration vessel with an inlet tube, basket-stirrer, indication glass-calomel electrode, separated anode space, electrodes of a generation circuit, pH-meter and coulometric control with digital output. A device for acid decomposition is attached to the analyser. The instrument functions by nitrogen being passed through the flow meter and a column of solid KOH then enters the apparatus in excess, thus ensuring a slightly elevated pressure in the system. The excess nitrogen escapes through a T-tubing and through a water overflow valve out of the system, while the main volume is driven through the apparatus using the double pump. The gas enters the spherical bulb situated at the top of the inlet condenser and is led to the 250 ml conical flask with boiling concentrated H_3PO_4 . The inlet condenser with the bulb prevents the back escape of the gases during the vigorous gas development while the sample was decomposed. The gas flow then continued through the outlet condenser and the gas washing bottle filled with 1% v/v $HClO_4$ to the Hydrogen Sulphide trap containing granulated $AgVO_3$. The gas mixture was delivered by the double pump into the absorption vessel where CO_2 is absorbed in alkaline (pH 10.1) 20% solution of $Ba(ClO_4)_2$. The temperature of heating in the nitrogen gas atmosphere is $1300^\circ C$. The volume of the gas mixture analysed was reduced, on occasions, to one

tenth by the piston cock situated on the double pump system. In this way, the determinable amount of CO_2 was 10 times increased. Absorbed CO_2 was continuously titrated with electronically generated $Ba(OH)_2$ under the glass-calomel electrode control. The time period of continuous coulometric titration of incoming CO_2 is about 10 minutes. Full details of these analytical techniques of coulometric titration are given by Herrmann and Knake (1973) and Sixta (1977).

METHOD

Approximately 100 mg of rock sample, with a grain size of < 0.125 mm, was placed in a small ceramic container. It is then inserted into the inlet in the bulb and inlet condenser into the boiling concentrated H_3PO_4 . While the stopper is removed, excess nitrogen escapes through the inlet to prevent the contamination of the inner space by atmospheric CO_2 . Reading of the measurements from the digital display is usually displayed within 10 minutes. Standardisations, controls and pH settings were controlled at the beginning, after every six sample measurements and at the end of the analytical runs. Blank samples were run at full sensitivity after every sample measurement (total gas volume delivered to the absorbing solution). The H_3PO_4 was changed after every 12 samples. Each sample was measured three

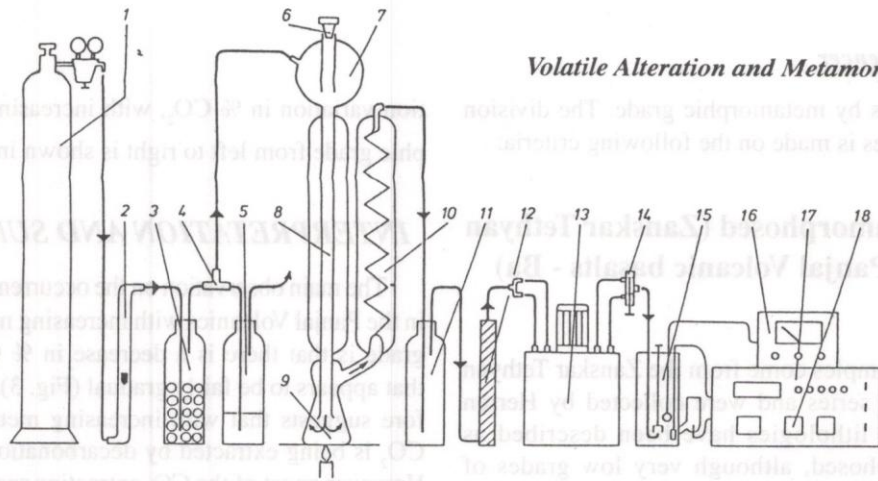


Fig. 2 Coulometric determination apparatus (from Sixta, 1977). 1: Steel cylinder with N₂; 2: Flow meter; 3: Solid KOH column. 4: T-Tubing; 5: Water overflow valve; 6: Inlet with ground glass stopper; 7: Spherical bulb; 8: Inlet condenser; 9: Conical flask with H₃PO₄; 10: Outlet condenser; 11: Gas washing bottle with 1% HClO₄; 12: H₂S trap with AgVO₃; 13: Double pump; 14: Piston cock; 15: Absorption and titration vessel; 16: pH-meter; 17: Coulometer control unit with digital display; 18: Time switch and detector

times and the result is the mean value of the three analysis.

The CO₂ content is calculated by:

$$\% \text{CO}_2 = (N - B) \cdot f / W \quad (\text{Equation 1})$$

where,

N = Display reading

B = Display reading of the blank

f = 0.073285 at 100% gas volume absorbed

= 0.73285 at 10% gas volume absorbed

W = Weight of the sample in mg

Alternatively, % carbon content is calculated by:

$$\% \text{C} = (N - B) \cdot f / W \quad (\text{Equation 2})$$

where,

N = Display reading

B = Display reading of the blank

f = 0.2 at 10% gas volume absorbed

W = Weight of the sample in mg

From equation 2., % CO₂ is calculated by:

$$\% \text{CO}_2 = \% \text{C} \times 3.66408 \quad (\text{Equation 3})$$

From equation 2., % CaCO₃ is calculated by:

$$\% \text{CaCO}_3 = \% \text{C} \times 8.33307 \quad (\text{Equation 4})$$

OBJECTIVES AND SAMPLES

The aims of the work with the coulometric titration analysis in the Northwest Himalaya is to compare the Panjal Volcanics basaltic CO₂ variation with metamorphic grade. The importance of this work lies in the recognition that the Panjal Volcanics volcanics are lithologies found that can be recognised at five different metamorphic facies (Spencer, 1993):

1. Unmetamorphosed
2. Greenschist facies
3. Amphibolite facies
4. Amphibolite-eclogite facies
5. Eclogite facies

Therefore, the coulometric titration of samples in the Kaghan Valley of greenschist, amphibolite, amphibolite - eclogite and eclogite facies, as well as those of the unmetamorphosed Zanskar Sedimentary shelf can be used to evaluate the change in CO₂ content by metamorphic facies. They, therefore, provide an excellent example of modelling the CO₂ variations in the complex collision zone dynamics to note

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the variations by metamorphic grade. The division of the samples is made on the following criteria:

1. Unmetamorphosed (Zanskar Tethyan Shelf - Panjal Volcanic basalts - Ba)

All samples come from the Zanskar Tethyan Sedimentary series and were collected by Herren (1987). The lithologies have been described as unmetamorphosed, although very low grades of metamorphism (up to prehnite - pumpellyite facies) have been ascribed to them.

2. Greenschist facies (Lesser Himalaya - Panjal Volcanic basalts - PJ)

These samples come from the Lesser Himalayan Unit of Kaghan valley which have a pervasive greenschist facies metamorphism (Papritz, 1989; Rey, 1989). The 8 samples which were collected by Papritz and Rey (1989), Papritz (1989) and Rey (1989).

3 - 5. Amphibolite, amphibolite-eclogite and eclogite facies (Higher Himalaya Second Cover - Panjal Volcanic amphibolites (A), dolerites (D) and eclogites (E))

These samples come from the Higher Himalayan Unit of Kaghan valley which has a variable amphibolite to eclogite facies metamorphism (Spencer, 1993). Recognition of the metamorphic grade was made by mineral assemblages.

RESULTS

Fifty samples were analysed and the results are shown in Table 1. All calculations, including the maximum, minimum and mean values with their standard deviation of each group, are also shown. A summary diagram with % CO₂ variation, from left to right with increasing metamorphic grade, is shown in Fig. 3A. Group means with their standard deviation

variation in % CO₂, with increasing metamorphic grade from left to right is shown in Fig. 3B.

INTERPRETATION AND SUMMARY

The main observation on the occurrence of % CO₂ in the Panjal Volcanics with increasing metamorphic grade is that there is a decrease in % CO₂ content that appears to be fairly gradual (Fig. 3). This therefore suggests that with increasing metamorphism, CO₂ is being extracted by decarbonation reactions. However, most of the CO₂ extraction seems to occur in the low temperature metamorphic grades and by the high temperature amphibolite / eclogite facies, most of the CO₂ seems to have been removed. Similar interpretations were made based on the evidence of the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ analysis of the marbles interlayered with the Panjal Volcanics (Spencer-Cervato and Spencer, 1991; Spencer, 1993).

VOLATILE (AND WATER) CONTENT

An estimation of the volatile content in a sample can be made by the simple weight loss on ignition. Calculation of the loss on ignition (% L.O.I.) which is the total volatile content of the rock is made by:
% Loss on Ignition (% L.O.I.) = [(Weight of cubicle + sample) - (Weight of sample + drying)] /

$$\frac{[(\text{Weight of cubicle} + \text{sample}) - (\text{Weight of cubicle})]}{(\text{Equation 5})}$$

The loss on ignition is essentially made up of H₂O, CO₂, F, Cl, S and O₂ from FeO, although F, Cl, S concentrations are usually extremely small. However, it is generally considered that the volatile content have little geochemical significance as:

1. The maximum temperature used in the methods is not sufficiently high to decompose all hydrated minerals.
2. Some samples gain weight after ignition (i.e., a negative loss on ignition due to the oxidation of the ferrous iron in the sample).
3. Some loss by volatilisation of alkalis metals occurs (e.g., fluorine and oxides of sulphur).

Volatile Alteration and Metamorphic Facies

Table 1 Table to show the calculated weight % carbon, carbondioxide, and calcium carbonate content by coulometric titration for selected Panjal Volcanics from different metamorphic grades. The mean, minimum (min.) value, maximum (max.) value and standard deviation (SD) of each group are also shown. BA: Zanskar Tethyan Shelf- Panjal Volcanic basalts (Mainly unmetamorphosed); PJ: Lesser Himalaya-Panjal Volcanic basalts (Greenschist facies); A: Higher Himalaya Second Cover-Panjal Volcanic amphibolites (Amphibolite facies); D: Higher Himalaya Second Cover- Panjal Volcanic dolerites (Amphibolite facies); E: Higher Himalaya Second Cover - Panjal Volcanic eclogites (Amphibolite-eclogite and eclogite facies)

	BA01	BA02	BA03	BA04	BA05	BA06	BA07	BA08	BA09	BA10										
Weight (mg)	104	118	115	107	102	99	107	104	143	149										
Control	25	25	25	25	25	25	25	0	25	0										
Counts	198	249	64	87	209	184	56	199	92	263										
Calculation for 100%	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2										
Gas level (%)	10	10	10	10	10	10	10	10	10	10										
C %	0.33	0.38	0.07	0.12	0.36	0.32	0.06	0.38	0.09	0.04	Min BA	0.04	Max BA	0.38	Mean BA	0.22	SD BA	0.15		
CO2%	1.22	1.39	0.25	0.42	1.32	1.18	0.21	1.40	0.34	0.14	0.14	1.40	0.79	0.55						
CaCO3%	2.77	3.16	0.57	0.97	3.01	2.68	0.48	3.19	0.78	0.33	0.33	3.19	1.79	1.25						
	PJ01	PJ02	PJ03	PJ04	PJ05	PJ06	PJ07	PJ08												
Weight (mg)	126	110	102	108	114	122	118	110												
Control	25	25	25	25	25	25	25	25												
Counts	148	156	104	142	116	98	142	102												
Calculation for 100%	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2												
Gas level (%)	10	10	10	10	10	10	10	10												
C %	0.20	0.24	0.15	0.22	0.16	0.12	0.20	0.14	Min PJ	0.12	Max PJ	0.24	Mean PJ	0.18	SD PJ	0.04				
CO2%	0.72	0.87	0.57	0.79	0.58	0.44	0.73	0.51	0.44	0.87	0.65	0.15								
CaCO3%	1.63	1.98	1.29	1.81	1.33	1.00	1.65	1.17	1.00	1.98	1.48	0.34								
	AO1	AO2	AO3	AO4	AO5	AO6	AO7	AO8	AO9	AO10	AO11	AO12	AO13	AO14	AO15	AO16	AO17	AO18	AO19	AO20
Weight (mg)	113	108	95	122	479	479	500	111	110	111	133	106	110	521	108	101	116	118	106	98
Control	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Counts	22	29	31	289	66	107	463	208	102	589	144	216	678	954	1015	78	123	146	1803	294
Calculation for 100%	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Gas level (%)	10	10	10	100	10	10	100	100	10	10	100	100	10	100	100	100	100	100	100	100
C %	0.04	0.05	0.07	0.05	0.03	0.04	0.02	0.04	0.19	1.06	0.02	0.04	1.23	0.04	0.19	0.02	0.02	0.02	0.34	0.06
CO2%	0.14	0.20	0.24	0.17	0.10	0.16	0.07	0.14	0.68	0.39	0.08	0.15	0.45	0.13	0.69	0.06	0.08	0.09	1.25	0.22
CaCO3%	0.32	0.45	0.54	0.39	0.23	0.37	0.15	0.31	1.55	8.84	0.18	0.34	10.27	0.31	1.57	0.13	0.18	0.21	2.83	0.50
	DO1	DO2																		
Weight (mg)	105	107																		
Control	0	25																		
Counts	101	570																		
Calculation for 100%	0.02	0.02																		
Gas level (%)	100	100																		
C %	0.02	0.10	Min D	0.02	0.10	0.06	0.06													
CO2%	0.07	0.37	0.07	0.37	0.22	0.21														
CaCO3%	0.16	0.85	0.16	0.85	0.50	0.49														
	EO1	EO2	EO3	EO4	EO5	EO7	EO8	EO9	E11	E12										
Weight (mg)	110	127	117	96	102	181	179	154	105	101										
Control	25	25	25	25	25	25	25	25	25	25										
Counts	156	147	266	188	304	177	226	123	155	109										
Calculation for 100%	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02										
Gas level (%)	100	100	100	100	100	100	100	100	100	100										
C %	0.02	0.02	0.04	0.03	0.05	0.02	0.02	0.01	0.02	0.02	Min E	0.01	Max E	0.05	Mean E	0.03	SD E	0.01		
CO2%	0.09	0.07	0.15	0.12	0.20	0.06	0.08	0.05	0.09	0.06	0.05	0.20	0.10	0.05						
CaCO3%	0.20	0.16	0.34	0.28	0.46	0.14	0.19	0.11	0.21	0.14	0.11	0.46	0.22	0.11						

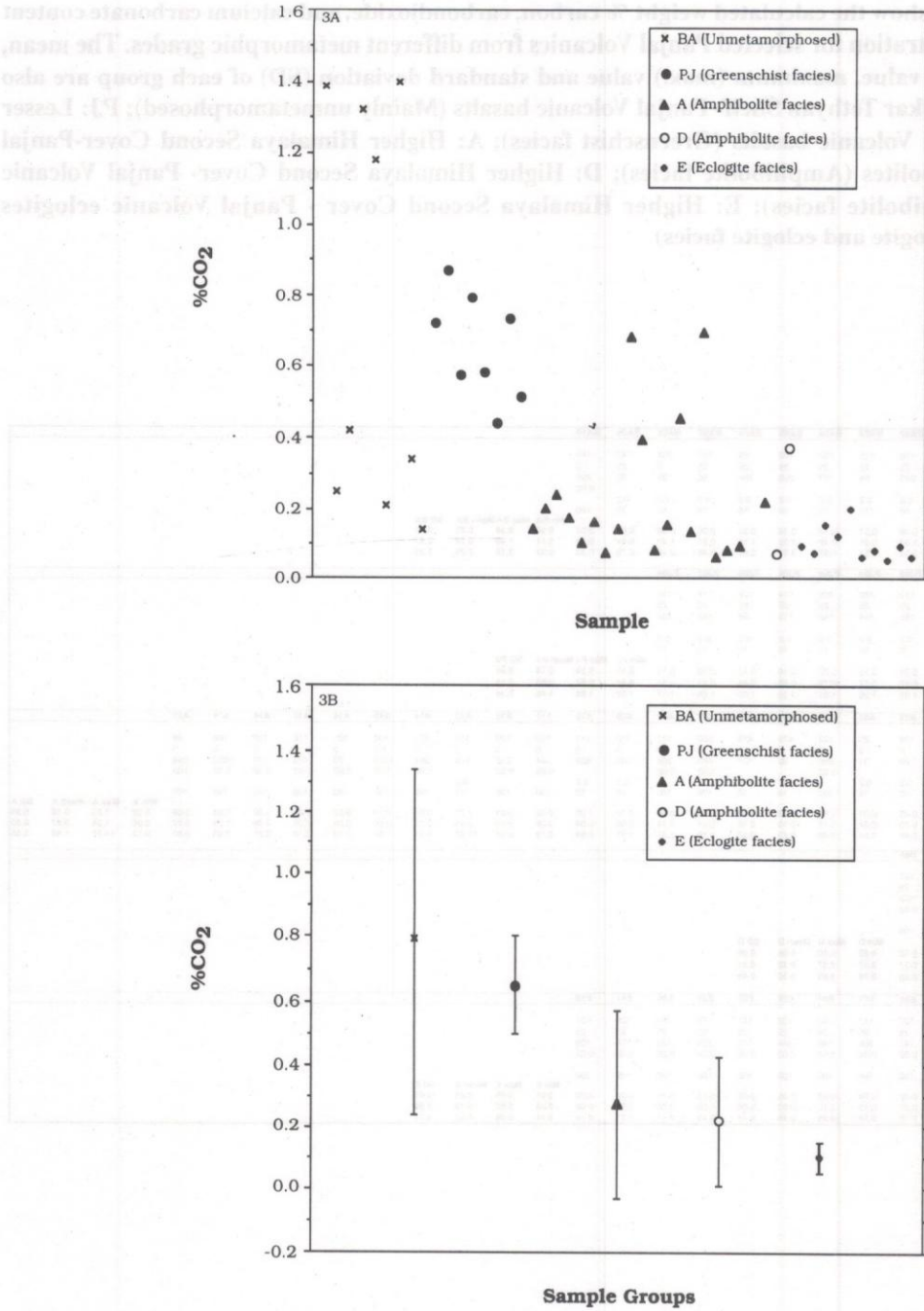


Fig. 3 A. Carbon dioxide content of samples from the Panjal Volcanics groups of the Northwest Himalaya
 B. Mean carbon dioxide group content, with standard deviation, for the Panjal Volcanics groups of the Northwest Himalaya

Therefore, the loss on ignition data can only be used as a general indication of the volatile element component of a sample. Essentially, the main drawback of the loss on ignition therefore, is that it does not provide information about specific volatiles unless further analysis is done. A more accurate estimation of H₂O content can be made according to the equation:

$$\text{H}_2\text{O} = \text{Loss On Ignition} + 0.111 \text{ FeO} - \text{CO}_2 \quad (\text{Equation 6})$$

However, this requires two additional separation techniques to be used on the sample analysis. In this study, coulometric titration only was used for determining the amount of CO₂ in a sample. Whilst no absolute indication of H₂O content can be determined, a closer approximation can be made by:

$$\text{H}_2\text{O} (+ 0.111 \text{ FeO}) = \text{Loss On Ignition} - \text{CO}_2 \quad (\text{Equation 7})$$

METHOD

The sample powder (grain size, after grinding, was less than 200 mesh (< 0.01 mm)) was dried for 24 hours in an oven at 105°C - 110°C. A cubicle is then weighed and 1.2 g of the sample powder added. This is then reweighed. The samples are then dried for 2 hours in an oven at 1050°C and left to cool for 10 minutes in an exsiccator with Potassium Permanganate which keeps the moisture from the air out and stops the sample from re-hydrating. They are then reweighed. CO₂ determination have been previously described.

OBJECTIVES AND SAMPLES

The aim of the work with the volatile and water content analysis in the Northwest Himalaya is to compare the Panjal Volcanics basaltic volatile variation with metamorphic grade. The objectives and samples are the same as above.

RESULTS

Fifty samples were analysed and the results are shown in Table 2. All calculations, including the maximum, minimum and mean values with their standard deviation of each group, are also shown. A

Volatile Alteration and Metamorphic Facies

summary diagram with L.O.I. variation, from left to right with increasing metamorphic grade, is shown in Fig. 4A. Group means with their standard deviation variation in L.O.I., with increasing metamorphic grade from left to right is shown in Fig. 4B.

By calculation from equation 7., an estimation of the H₂O (+ FeO) content can be made (Table 3) and the results are again shown on a summary diagram with H₂O (+ FeO) variation (Fig. 5A). Group means with their standard deviation variation in H₂O (+ FeO), with increasing metamorphic grade from left to right is shown in Fig. 5B.

INTERPRETATION AND SUMMARY

The main observations for both the loss on ignition and the H₂O (+ FeO) in the Panjal Volcanics is that, similar to the CO₂ determination, it can be seen that with an increase in metamorphic grade there is a decrease in the L.O.I. and H₂O (+ FeO) content (Fig. 5). This therefore suggests that with increasing metamorphism, volatiles are being driven off by dehydration reactions. Again, it is noted that in the amphibolite / eclogite facies, the H₂O content is very low and that the major loss of H₂O seems to have occurred in the unmetamorphosed and greenschist facies.

GENERAL DISCUSSION

It is interesting to note than in five amphibolite samples and five eclogite samples, the H₂O (+ FeO) value is negative. This can be interpreted as either not all of the volatiles were extracted by the L.O.I. as the % CO₂ content was higher; or that the L.O.I. amount was negative due to the oxidation of the iron (e.g., sample E01); or of possible overestimations in the CO₂ content. Clearly, it is not possible to have negative H₂O amounts. If these values are removed from the mean calculations, the average for group A rises to 0.27 % H₂O (+ FeO) and for Group E to 0.41 % H₂O (+ FeO). These differences can be regarded as very small and in effect argue that the loss of volatiles for the eclogites and the amphibolites were the same. This does agree well with the temperature

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calculations on the amphibolites and eclogites which argue that the temperature of formation are the same ($650^{\circ}\text{C} \pm 50^{\circ}\text{C}$).

Moreover, it is also interesting to compare the results of this work with the results of some theoretical calculations made for the wt. % H_2O of a subducting, and therefore dehydrating, oceanic crust or tholeiitic basalt (Peacock, 1993). Predictions are made by combining calculated pressure temperature paths with a model of metabasalt phase equilibria, where a progression (for the upper parts of the oceanic crust) pass through greenschist to amphibolite to granulite to eclogite facies. The facies concept employed by Peacock (1993) shows that the hydrous minerals breakdown by a complex series of metamorphic reactions. It is important to note that the wt. % H_2O calculations are metamorphic mineral norms. Calculated weight % H_2O content for specific facies are (Fig. 6) shown below:

Metamorphic facies	Wt. % H_2O
Zeolite (\approx unmetamorphosed)	8.5 %
Greenschist	3.4 %
Amphibolite (low temperature)	2.1 %
Amphibolite (high temperature)	1.3 %
Eclogite (high pressure and temperature)	0.8 %

The agreement between the results obtained from the Panjal Volcanics (Table 3) and the data above, albeit from completely different directions, is clearly apparent.

There are two further points that need to be addressed: what are the actual minerals involved in the devolatilisation reactions and by what mechanism did the devolatilisation take place. Clearly, from the above methods which utilise whole rock analysis of basaltic to eclogitic samples, it is impossible to ascertain this with any degree of certainty. However, the most probable sources of the CO_2 in the Panjal Volcanics are fluid / gaseous inclusions and minor interstitial carbonates. The H_2O source is probably from the

breakdown of hydrous minerals (amphiboles, micas, clays) and fluid inclusions.

Finally, it is also necessary to question whether the volatiles which are found in the unmetamorphosed basalt were primary in the magma, or were subsequently introduced at a later stage by sea water circulation and/or sea floor alteration. In this paper, it is inferred that both the CO_2 and the H_2O components were present before the onset of the Himalayan metamorphism, but are not necessarily representative of the original volatile composition of the primary magma. Therefore, they could have been introduced at any time between magma extrusion (Upper Carboniferous - ?Lower Triassic) until the Himalayan collision (Late Cretaceous - Paleocene) and it is likely that they were. The above analysis only shows what the effect of the Himalayan metamorphism had on the unmetamorphosed basalts.

SUMMARY OF CO_2 , VOLATILE (AND WATER) CONTENT

There is a decrease in volatile and water (with FeO) content with an increase in metamorphic grade, with similar results obtained for the amphibolite and eclogite facies metamorphism. This implies that they are being extracted with increasing metamorphic grade, presumably by dehydration, devolatilisation and decarbonation reactions. The Panjal Volcanics may offer numerous other opportunities to test the effects of metamorphism on samples that have been progressively metamorphosed upto eclogite facies.

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	BA01	BA02	BA03	BA04	BA05	BA06	BA07	BA08	BA09	BA10	Min BA	Max BA	Mean BA	SD BA
LOI%	11.44	7.59	3.19	2.23	5.90	11.03	3.02	9.96	4.51	2.36	2.23	11.44	6.12	3.64
	PJ01	PJ02	PJ03	PJ04	PJ05	PJ06	PJ07	PJ08	Min PJ	Max PJ	Mean PJ	SD PJ		
LOI%	1.42	2.13	1.86	2.69	2.86	4.02	3.82	2.54	1.42	4.02	2.67	0.90		
	A01	A02	A03	A04	A05	A06	A07	A08	A09	A10	A11	A12	A13	A14
LOI%	0.35	0.08	0.90	0.56	0.31	0.15	0.43	0.76	0.76	0.16	0.61	0.40	0.26	0.34
	A15	A16	A17	A18	A19	A20	Min A	Max A	Mean A	SD A				
	0.71	0.17	0.23	0.17	0.83	0.50	0.08	0.90	0.43	0.26				
	D01	D02	Min D	Max D	Mean D	SD D								
LOI%	0.14	1.06	0.14	1.06	0.60	0.65								
	E01	E02	E03	E04	E05	E07	E08	E09	E11	E12	Min E	Max E	Mean E	SD E
LOI%	-0.23	0.01	0.39	0.65	0.97	0.04	0.49	0.16	0.08	0.05	-0.23	0.97	0.26	0.36

Table 2 The calculated loss on ignition (LOI) for selected Panjal Volcanics from different metamorphic grades. The mean, minimum (min.) value, maximum (max.) value and standard deviation (SD) of each group is also shown. Sample grouping abbreviations same as in Table 1.

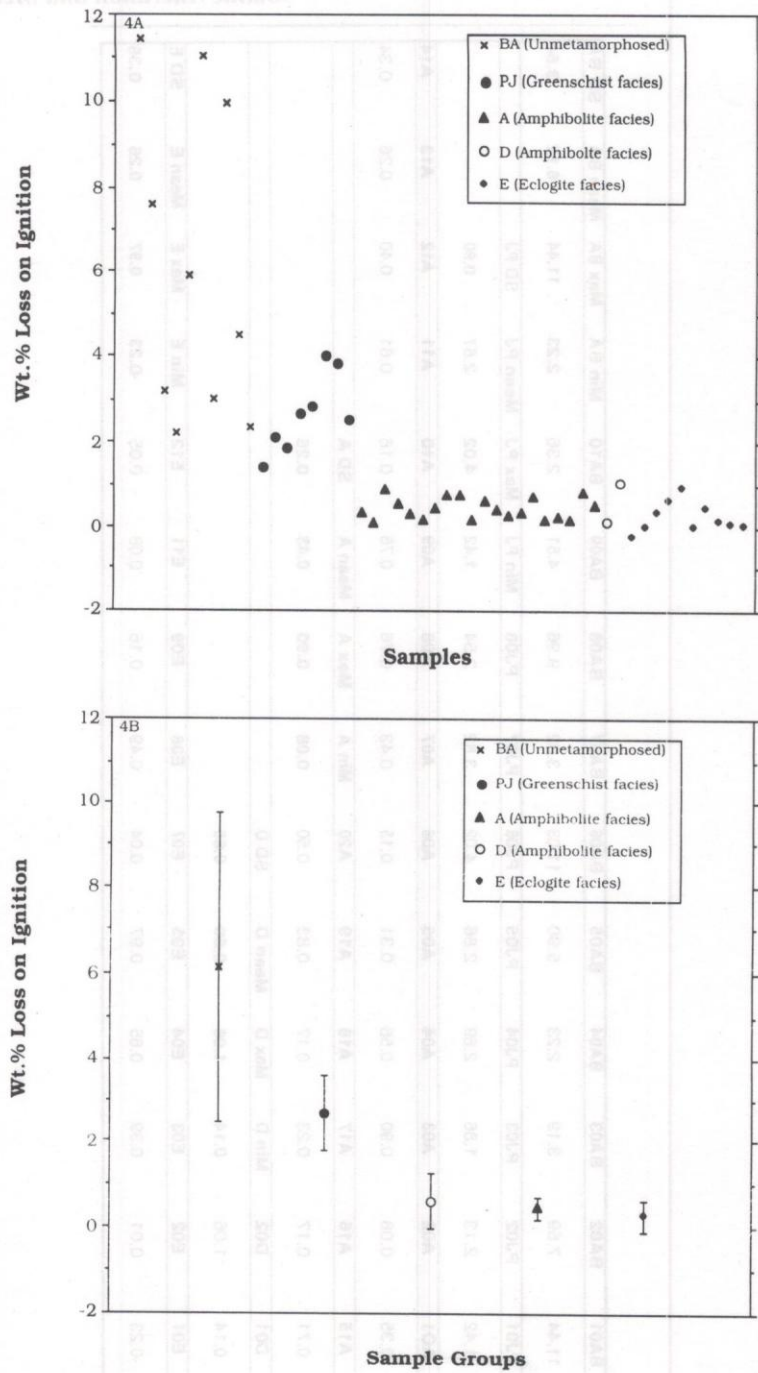


Fig. 4 A. Loss on ignition content of samples from the Panjal Volcanics groups of the Northwest Himalaya
 B. Mean loss on ignition group content, with standard deviation, for the Panjal Volcanics groups of the Northwest Himalaya

Volatile Alteration and Metamorphic Facies

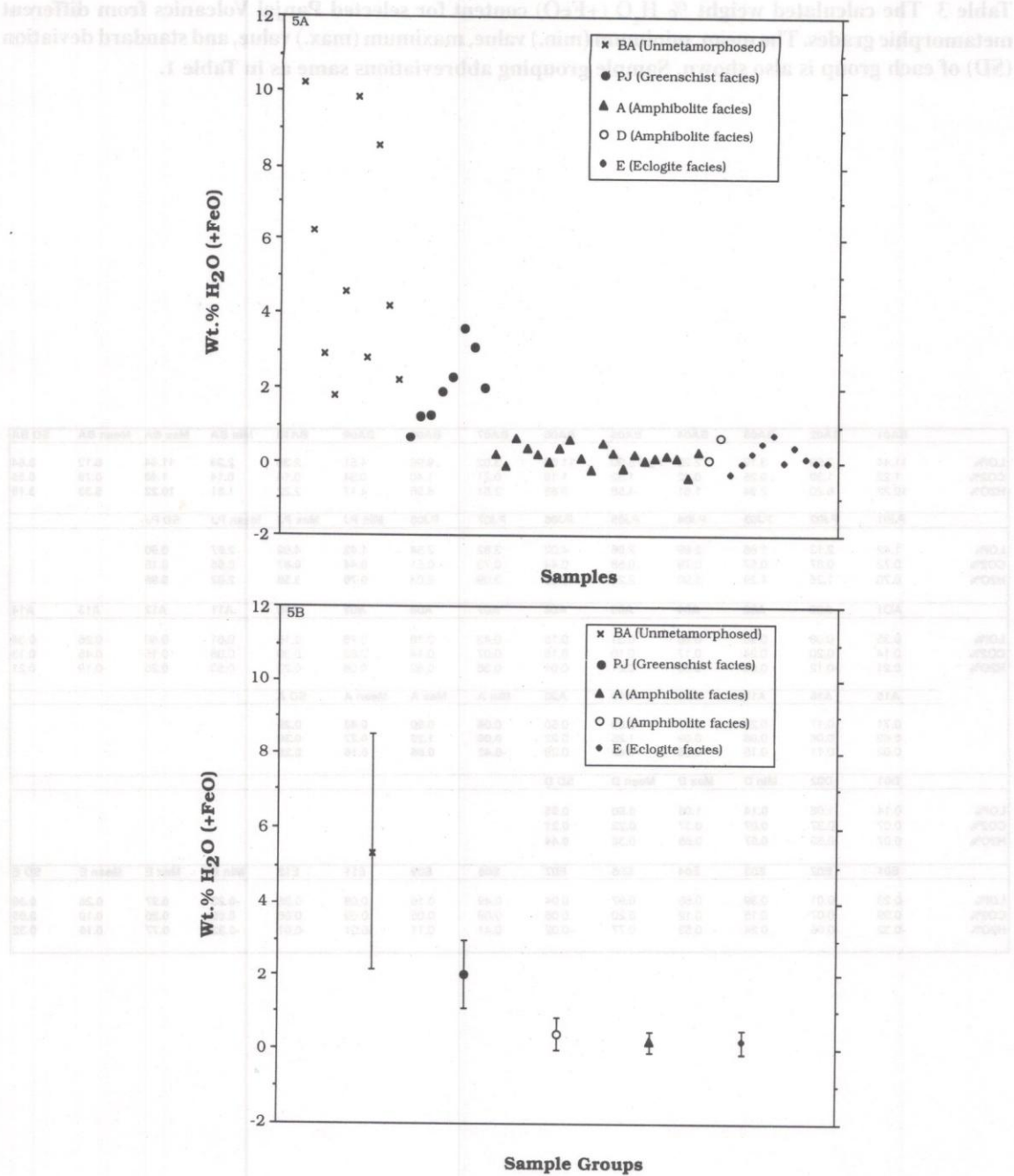


Fig. 5 A. H₂O (+ FeO) content of samples from the Panjal Volcanics groups of the Northwest Himalaya
 B. Mean H₂O (+ FeO) group content, with standard deviation, for the Panjal Volcanics groups of the Northwest Himalaya

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Table 3 The calculated weight % H₂O (+FeO) content for selected Panjal Volcanics from different metamorphic grades. The mean, minimum (min.) value, maximum (max.) value, and standard deviation (SD) of each group is also shown. Sample grouping abbreviations same as in Table 1.

	BA01	BA02	BA03	BA04	BA05	BA06	BA07	BA08	BA09	BA10	Min BA	Max BA	Mean BA	SD BA
LOI%	11.44	7.59	3.19	2.23	5.90	11.03	3.02	9.96	4.51	2.36	2.23	11.44	6.12	3.64
CO ₂ %	1.22	1.39	0.25	0.42	1.32	1.18	0.21	1.40	0.34	0.14	0.14	1.40	0.79	0.55
H ₂ O%	10.22	6.20	2.94	1.81	4.58	9.85	2.81	8.56	4.17	2.22	1.81	10.22	5.33	3.19
	PJ01	PJ02	PJ03	PJ04	PJ05	PJ06	PJ07	PJ08	Min PJ	Max PJ	Mean PJ	SD PJ		
LOI%	1.42	2.13	1.86	2.69	2.86	4.02	3.82	2.54	1.42	4.02	2.67	0.90		
CO ₂ %	0.72	0.87	0.57	0.79	0.58	0.44	0.73	0.51	0.44	0.87	0.65	0.15		
H ₂ O%	0.70	1.26	1.29	1.90	2.28	3.58	3.09	2.03	0.70	3.58	2.02	0.96		
	A01	A02	A03	A04	A05	A06	A07	A08	A09	A10	A11	A12	A13	A14
LOI%	0.35	0.08	0.90	0.56	0.31	0.15	0.43	0.76	0.76	0.16	0.61	0.40	0.26	0.34
CO ₂ %	0.14	0.20	0.24	0.17	0.10	0.16	0.07	0.14	0.68	0.39	0.08	0.15	0.45	0.13
H ₂ O%	0.21	-0.12	0.66	0.39	0.21	-0.01	0.36	0.62	0.08	-0.23	0.53	0.25	-0.19	0.21
	A15	A16	A17	A18	A19	A20	Min A	Max A	Mean A	SD A				
	0.71	0.17	0.23	0.17	0.83	0.50	0.08	0.90	0.43	0.26				
	0.69	0.06	0.08	0.09	1.25	0.22	0.06	1.25	0.27	0.30				
	0.02	0.11	0.15	0.08	-0.42	0.28	-0.42	0.66	0.16	0.28				
	D01	D02	Min D	Max D	Mean D	SD D								
LOI%	0.14	1.06	0.14	1.06	0.60	0.65								
CO ₂ %	0.07	0.37	0.07	0.37	0.22	0.21								
H ₂ O%	0.07	0.69	0.07	0.69	0.38	0.44								
	E01	E02	E03	E04	E05	E07	E08	E09	E11	E12	Min E	Max E	Mean E	SD E
LOI%	-0.23	0.01	0.39	0.65	0.97	0.04	0.49	0.16	0.08	0.05	-0.23	0.97	0.26	0.36
CO ₂ %	0.09	0.07	0.15	0.12	0.20	0.06	0.08	0.05	0.09	0.06	0.05	0.20	0.10	0.05
H ₂ O%	-0.32	-0.06	0.24	0.53	0.77	-0.02	0.41	0.11	-0.01	-0.01	-0.32	0.77	0.16	0.32

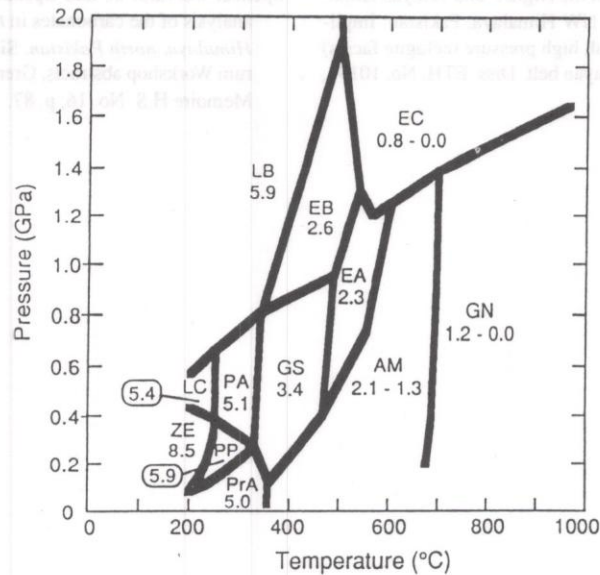


Fig. 6 Pressure-temperature diagram of metamorphic facies with calculated maximum H₂O content for a basaltic bulk composition (from Peacock, 1993). AM: Amphibolite facies; EA: Epidote-amphibolite facies; EB: epidote blueschist facies; EC: Eclogite facies; GN: Granulite facies; GS: Greenschist facies; LB: Lawsonite-blueschist facies; LC: Lawsonite-chlorite facies; PP: Prehnite -pumpellyite facies; PrA: Prehnite-actinolite facies; PA: Pumpellyite-actinolite facies; ZE: Zeolite facies

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