

CHAPTER 8: CONSTRAINING THE EFFECT OF HYDROTHERMAL ALTERATION

In order to understand the effect that the alteration events had on the ultramafic to mafic rocks of the Uitkomst Complex, a geochemical approach was followed. Due to the fact that certain elements are mobilized more readily than others, and mobilization of some elements occurred in pairs, the composition of the altered rock differs from that of the original rock type. The aim of this chapter is to determine the extent of alteration in each of the units and determine if there is any detectable preferential distribution of elements during alteration. The degree of hydrothermal alteration is demonstrated with the use of the isocon diagram discussed in the next paragraph. Pseudo-sections were also modeled in an effort to constrain the fluid composition in terms of X_{CO_2} and X_{H_2O} with temperature (T).

8.1 Isocon Diagram

The isocon diagram was developed by Grant (1986) to provide a simple graphical solution to Gresens' (1967) equations. The isocon method rearranges Gresens' equations into a linear relationship between the concentrations of components in the altered rock, relative to the concentration of components in the original rock. A simultaneous solution of these equations for all components, that show no relative gain or loss of mass, is defined as an "isocon". An isocon is represented by the straight line through the origin on a plot of concentrations in the altered rock against the concentrations in the original rock. The position of different elements plotted relative to the isocon gives an indication of the mobility of the elements. The slope of the isocon defines the mass change in the altered rock, whereas the deviation of a data point from the isocon defines the concentration change for that component.

In this study, the sample used as the "original" rock in the isocon for each mineralogical unit was the sample from the specific lithological unit exhibiting the most primitive mineral assemblages and displaying the least visible petrographic alteration. The samples with the least amount of alteration for the different units are the following: for the BGAB Unit, sample UK32N, for the LHZBG Unit, sample UK12J, for the xenoliths from the LHZBG

Unit, sample SH176, for the PCR Unit, sample UK12D and for the LrPRD Sub-unit, sample UK48C.

The x-axis marked " C_o " indicates the elemental concentration in the "original" rock and " C_a " on the y-axis indicates the concentration of elements in the "altered" rock.

One diagram for each of the lithological units is given (figures 8.1 to 8.3), along with a table indicating the immobile elements and the increase or decrease in elements relative to the isocon line. The least mobilized elements (< 10 %) are highlighted in the table in an effort to determine sympathetic variation of elements with Zr. Zr was selected as the isocon line of choice as Zr has been shown to be common and very stable in metamorphosed siliceous dolomite (Ferry, 2000). Zr is also not expected to be irregularly concentrated in mafic rocks, in contrast to felsic rocks in which a greater variance in the abundance of Zr may be possible, owing to the presence of zircon (Ferry, 2000).

The tables in which the isocon results are reported have been divided according to the mobility of the elements (Brownlow, 1979; Levinson, 1974). The mobile elements (section A of given table) are given as: Cl and S. The elements of high mobility (section B of given table) are given as: Mg, Ca, Na, Mo, Sr, U, Zn, F and V. The elements considered to be of medium mobility (section C of given table) are: As, Cu, Ni and Co. Elements considered having a low mobility (section D of given table) are: Si, K, P, Pb, Rb, Cs and Ba. Finally, the immobile elements (section E of given table) are: Ti, Al, Fe, Mn, Ga, Nb, Th, W, Y, Cr, Sc, La and Ce. The term "variable" in these tables refers to random enrichment and depletion of the samples relative to the "original" sample composition assumed.

8.2 Isocon analyses of the Lower Harzburgite Unit

Sample UK12J, a peridotite, is used as the original composition as it showed the least amount of alteration products. Sample UK12J contains, according to XRD analyses, 51 % diopside, which under the petrographic microscope appears unaltered and, after EMP analysis, was found to be diopside typical of the LHZBG Unit. Sample UK12J also contains chromite grains and minor olivine. Sample UK12J also contain very little sulphides. The diopside grains were replaced by some actinolite grains and contain pockets of chlorite. However, sample UK12J to appear to be the least altered of the sections encountered in the Uitkomst section. Some serpentine after olivine is also found in sample UK12J.

Most of the samples from the LHZBG Unit in this study show the effect of assimilation of dolomitic country rock and late stage hydrothermal alteration. Both may affect the composition or mobilization effects represented by the delta values obtained from the isocon analyses from this unit.

An example of an isocon from the LHZBG Unit is shown by Figure 9.2 and a summary of the increase and decrease in certain elements (delta value) relative to the Zr-isocon line is presented in Table 8.1.A to E. The elements that suffered less than 10% increase or decrease has been highlighted in the table.

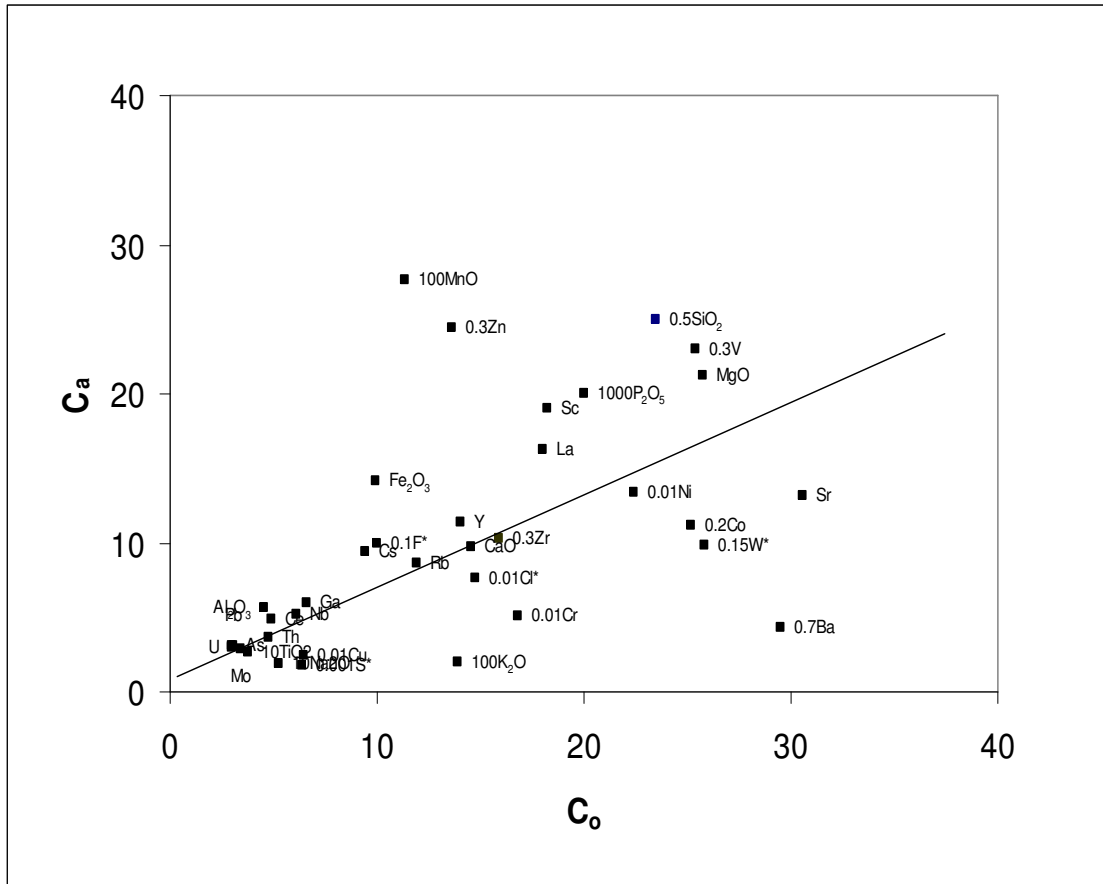


Figure 8.1. Isocon diagram for the LHZBG Unit using sample UK68G as C_a and based on sample UK12J, as unaltered composition C_o . The solid line indicates the Zr-isocon line. All elements marked with an asterisk are to be considered semi-quantitative.

The elements in the area above the isocon line (Figure 8.1) indicate that those elements suffered a significant addition (positive delta values) in the sample and the elements in the area below the isocon suffered a significant loss (negative delta values) in the sample.

Table 8.1.A. The increase and decrease of mobile elements, relative to the Zr-isocon (expressed as delta values) for the LHZBG Unit. Sample UK12J is used as C₀ (the least mobilized elements are highlighted).

Element	UK12H	UK12L	UK20G	UK20I	UK32G	UK32J	UK32L	UK44D	UK44G	UK44I	UK48L
Cl*	-48.38	90.03	15.75	-58.49	3.93	-80.33	-79.66	-49.10	-76.75	-68.34	-78.06
S*	-79.44	134.02	-71.55	68.98	229.89	-92.75	-93.76	-83.86	348.90	80.79	689.06
Element	UK48N	UK48O	UK48Q	UK57I	UK57K	UK61E	UK61F	UK68C	UK68E	UK68G	UK68I
Cl*	-72.46	-98.94	-96.45	-46.27	-82.13	-84.88	-77.77	-60.75	-87.27	-19.78	-97.29
S*	509.46	818.17	232.69	-16.23	717.57	583.46	475.34	16.11	416.69	-58.26	552.29

Element	Trend
Cl	Variably depleted in all samples, enriched in 12L, 20G and 32G.
S	Enriched in most samples, massively in UK48, 57, 61 and 68, but depleted in UK12H, 20G, 32J and L, 44D and 68G

Table 8.1.B. The increase and decrease of elements with high mobility, relative to the Zr-isocon (expressed as delta values) for the LHZBG Unit. Sample UK12J is used as C₀ (the least mobilized elements are highlighted).

Element	UK12H	UK12L	UK20G	UK20I	UK32G	UK32J	UK32L	UK44D	UK44G	UK44I	UK48L
MgO	49.09	-45.10	93.17	154.65	158.22	-17.10	-9.58	76.06	52.18	-5.81	39.30
CaO	-38.98	-0.54	-70.02	-16.15	-19.40	-79.06	-50.88	-41.89	-42.97	-24.71	-55.11
Na ₂ O	-46.28	-21.50	-7.26	-39.19	24.15	-75.83	-72.22	-15.57	-71.41	-77.14	-41.08
Mo	-65.73	65.84	-64.53	26.46	17.70	-71.42	-41.99	-64.72	87.01	22.19	389.10
Sr	-64.24	197.78	-37.16	6.67	333.38	-65.77	-31.60	24.36	0.20	126.79	14.81
U	16.50	246.49	20.58	94.61	88.58	-33.61	-5.60	19.92	245.87	158.47	832.93
Zn	139.56	2.22	-31.50	65.46	109.54	-8.79	49.49	-16.36	25.49	70.23	63.58
F*	16.50	250.65	20.58	94.61	88.58	-33.61	-5.60	19.92	650.72	-7.83	467.43
V	72.11	38.48	-29.51	-18.17	23.98	-32.84	-7.44	-5.11	-76.43	-45.38	-45.33
Element	UK48N	UK48O	UK48Q	UK57I	UK57K	UK61E	UK61F	UK68C	UK68E	UK68G	UK68I
MgO	-21.97	166.44	47.57	69.27	-55.54	21.38	174.62	-6.74	24.39	27.23	-2.43
CaO	-22.91	-60.48	-65.01	14.49	87.63	57.37	64.02	-37.86	-42.23	3.94	-71.71
Na ₂ O	-27.99	-52.57	-82.86	-51.13	-75.55	-35.24	-53.92	-52.36	-88.14	-45.69	-72.49
Mo	343.81	316.07	97.27	-26.38	529.13	408.07	282.96	30.48	213.46	28.77	320.17
Sr	48.04	-9.12	-33.29	-51.71	1108.19	517.50	927.00	-56.40	8.92	-33.63	67.50
U	836.65	670.98	197.88	59.94	1520.63	1092.99	906.92	1.57	764.92	54.48	847.25
Zn	91.07	163.16	255.67	51.20	75.68	161.52	417.06	23.85	132.29	176.71	224.98
F*	24.13	105.56	18.73	59.94	913.44	632.15	151.50	1.57	23.90	54.48	214.16
V	75.90	-29.68	5.58	37.14	149.34	93.49	40.03	66.60	62.93	40.10	-7.65

Table 8.1.B. Continued.

Element	Trend
MgO	Variably enriched , but depleted in some samples
CaO	Variably depleted in all samples, excluding UK57 and 61 and 68G that is enriched. This may again be due the presence of micro-xenoliths or greater assimilation products in these samples
Na ₂ O	Variably depleted in all samples, but slightly enriched in UK32G.
Mo	Variably enriched in all samples, massively in UK48, 57 and 61, but depleted in UK12H, 20G, 32J and L, 44D and 57I.
Sr	Variably depleted and enriched in all samples. Most enriched in UK57 and 61
U	Variably enriched in all samples, but massively in UK48, 57, 61 and 68.
Zn	Variably enriched in all samples, increased enrichment with increase in depth in UK48 and 68. Depleted in UK20G, 32J and 44D.
F	Variably enriched in all samples, but depleted in UK32J and L and 44I.
V	Variably depleted and enriched, notably enriched in UK57, 61 and 68 depletingly enriched with depth.

Table 8.1.C. The increase and decrease of elements with medium mobility, relative to the Zr-isocon, (expressed as delta values) for the LHZBG Unit. Sample UK12J is used as C₀ (the least mobilized elements are highlighted).

Element	UK12H	UK12L	UK20G	UK20I	UK32G	UK32J	UK32L	UK44D	UK44G	UK44I	UK48L
As	16.50	252.94	389.42	94.61	128.82	-33.61	-5.60	176.01	176.62	-7.83	23.56
Cu	-93.38	100.50	-42.73	77.03	-64.76	-69.87	-97.01	-25.45	364.88	119.15	343.60
Ni	-67.80	95.70	-44.84	116.45	170.05	-54.52	-62.22	-78.22	232.02	42.31	812.77
Co	-55.60	58.91	-22.84	108.45	356.13	-50.34	-24.41	-75.97	99.77	38.75	449.65
Element	UK48N	UK48O	UK48Q	UK57I	UK57K	UK61E	UK61F	UK68C	UK68E	UK68G	UK68I
As	24.13	307.85	34.19	111.49	29593.02	65.12	204.10	1.57	733.79	60.27	-9.69
Cu	456.60	135.08	1185.98	-63.53	918.94	398.49	47.06	9.05	1479.50	-42.26	1582.98
Ni	891.17	1283.23	92.24	66.83	699.46	740.90	643.68	7.14	148.27	-7.98	595.09
Co	52.72	186.12	45.53	31.43	399.21	449.50	358.50	6.48	602.48	-31.38	249.54

Table 8.1.C. Continued.

Element	Trend
As	Variably enriched in all samples, but massively enriched UK57K.
Cu	Variably enriched in all samples, massively in UK48, 57 and 68, but depleted in UK12H, 32, 57I and 68G.
Ni	Variably enriched in all samples, massively in UK48, 57 and 61 but depleted in UK12H, 20G, 32J and L and 44D
Co	Variably enriched in all samples, but depleted in UK12H, 20G, 32J and L, 44D and 68G.

Table 8.1.D. The increase and decrease of elements with low mobility, relative to the Zr-isocon, (expressed as delta values) for the LHZBG Unit. Sample UK12J is used as C₀ (the least mobilized elements are highlighted).

Element	UK12 H	UK12L	UK20 G	UK20I	UK32 G	UK32J	UK32L	UK44 D	UK44G	UK44I	UK48 L
SiO ₂	29.70	-16.84	17.33	132.54	92.68	-20.59	-5.77	16.36	5.66	-5.22	-14.85
K ₂ O	-83.24	-86.79	-82.65	45.79	4.16	-90.45	-86.42	-82.74	-82.93	-86.74	-82.22
P ₂ O ₅	16.50	23.54	20.58	94.61	88.58	114.62	-5.60	19.92	18.63	-7.83	23.56
Pb	266.41	171.16	81.00	481.60	266.24	179.55	151.00	390.89	16.24	11.63	524.75
Rb	-18.97	-15.83	-20.44	87.79	93.64	-49.15	-53.73	-44.26	42.19	-39.82	51.19
Cs	16.50	-8.18	20.58	94.61	88.58	-33.61	-5.60	19.92	18.63	-7.83	23.56
Ba	-34.34	-40.09	-76.13	-34.98	58.78	-66.36	-61.72	-76.51	-41.84	-78.98	-82.16
Element	UK48 N	UK48 O	UK48 Q	UK57I	UK57 K	UK61E	UK61F	UK68 C	UK68E	UK68 G	UK68I
SiO ₂	4.93	81.22	22.44	82.22	-0.44	28.79	145.26	5.10	11.64	64.22	-29.32
K ₂ O	-82.14	-70.42	-82.92	-76.99	-76.68	-76.24	-63.81	-85.39	-82.17	-77.77	-87.00
P ₂ O ₅	24.13	105.56	18.73	59.94	62.08	65.12	151.50	1.57	23.90	54.48	-9.69
Pb	193.84	955.40	225.03	56.72	58.82	1033.80	1071.90	132.13	79.17	56.41	514.38
Rb	48.47	93.17	-1.46	-44.57	86.59	74.14	193.38	-53.19	10.31	11.01	68.48
Cs	24.13	105.56	18.73	59.94	62.08	65.12	151.50	1.57	23.90	54.48	-9.69
Ba	-86.80	-78.14	-79.97	-46.59	-80.60	-67.62	-69.44	-77.75	-86.82	-77.57	-86.48

Table 8.1.D. Continued.

Element	Trend
SiO ₂	Variably enriched and depleted. No vertical or lateral distribution pattern discernable.
K ₂ O	Variably depleted in all samples, but slightly enriched in UK20I and 32G.
P ₂ O ₅	Variably enriched in all samples, but depleted in UK32L, 44I and 68I.
Pb	Variably enriched in all samples, mostly in UK48 and 61.
Rb	Variably depleted and enriched in all samples.
Cs	Variably enriched in most samples, but depleted in UK12L, 32J and L, 44I and 68I.

Ba	Variably depleted in all samples, notably UK48 and 68, but enriched in UK32G.
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Table 8.1.E. The increase and decrease of immobile elements, relative to the Zr-isocon, (expressed as delta values) for the LHZBG Unit. Sample UK12J is used as C₀ (the least mobilized elements are highlighted).

Element	UK12H	UK12L	UK20G	UK20I	UK32G	UK32J	UK32L	UK44D	UK44G	UK44I	UK48L
TiO ₂	1.49	32.37	-36.43	-16.40	13.03	-4.36	2.74	2.75	-77.52	-45.85	-40.15
Al ₂ O ₃	-19.46	-29.77	-77.93	-83.05	7.80	-24.68	91.33	-32.08	-99.74	-55.50	-99.73
Fe ₂ O ₃	-15.73	12.52	57.14	131.06	132.08	-15.88	25.94	49.52	66.07	32.13	210.83
MnO	14.82	39.50	47.96	112.93	155.54	-40.48	57.33	78.89	52.78	52.37	48.97
Ga	16.52	0.33	-21.66	63.02	30.47	-11.69	16.61	6.83	-8.52	-33.20	-52.15
Nb	-34.74	32.17	-20.89	15.17	47.56	-24.81	-3.23	8.72	61.36	6.16	154.51
Th	-26.52	150.48	-23.94	22.76	18.96	-58.12	-40.45	-24.36	255.40	8.11	603.90
W*	-63.76	-31.38	-77.87	-60.69	-58.38	-97.68	-89.06	-74.96	-79.56	-90.71	-95.69
Y	-20.24	34.31	25.72	29.70	34.56	-27.34	-25.88	-16.93	14.48	-6.07	44.38
Cr	873.97	-46.70	-50.48	-66.27	-35.23	-91.97	-80.50	-85.38	-94.04	-91.87	-73.24
Sc	51.91	56.18	-27.81	26.58	83.17	-51.25	-16.85	17.27	-95.76	-77.46	-47.47
La	-8.14	6.39	11.21	55.15	78.42	-46.33	-1.35	6.22	35.48	-9.71	12.27
Ce	16.50	-8.18	20.58	94.61	88.58	120.23	131.53	45.34	18.63	-7.83	23.56
Element	UK48N	UK48O	UK48Q	UK57I	UK57K	UK61E	UK61F	UK68C	UK68E	UK68G	UK68I
TiO ₂	15.24	-43.11	24.11	18.25	93.76	13.50	7.34	-5.99	-4.06	9.35	1.95
Al ₂ O ₃	-67.82	-80.92	11.33	-13.31	-5.33	-99.64	75.56	23.27	52.80	92.38	-99.80
Fe ₂ O ₃	193.48	271.52	94.09	19.04	283.25	217.58	350.55	44.10	100.95	119.81	146.88
MnO	87.76	67.50	33.18	113.98	237.21	169.38	335.94	57.46	72.28	276.98	-30.06
Ga	12.95	34.82	58.91	37.63	-8.65	-29.03	132.23	31.43	24.56	40.27	-23.67
Nb	137.62	192.76	59.99	-7.29	289.86	209.58	240.59	24.98	113.49	31.12	129.07
Th	590.31	607.01	165.03	0.89	839.71	754.92	542.88	8.65	337.52	20.21	552.65
W*	-95.67	-92.83	-95.86	-33.67	-69.15	-30.25	-91.23	-80.72	-69.83	-41.28	-96.85
Y	85.15	58.53	12.72	4.66	114.84	102.41	83.90	18.35	70.96	24.97	26.15
Cr	4.32	-85.39	-73.53	-15.10	-24.11	-11.62	-57.89	37.64	-16.75	-53.70	-92.29
Sc	106.92	-26.47	-14.68	38.87	128.82	59.74	68.94	78.06	114.62	60.93	-68.25
La	20.02	76.20	-14.93	49.62	87.13	88.35	121.83	-7.49	-2.57	39.44	-33.90
Ce	24.13	105.56	18.73	59.94	62.08	65.12	151.50	1.57	23.90	54.48	-9.69

Table 8.1.E. Continued.

Element	Trend
TiO ₂	Variably enriched and depleted , UK57K notably enriched and 44G depleted.
Al ₂ O ₃	Variable but mostly depleted . Enriched in UK32L, 48Q, 61F, 68C 68E and 68G. This may be due to the presence of micro-xenoliths or greater assimilation products in these samples.
Fe ₂ O ₃	Enriched in most samples. Enriched with depth in UK68. Depleted in UK12H and 32J.
MnO	Enriched in all samples and increasingly with depth in UK12 and 20, except UK32G and 68I that is depleted
Ga	Variably enriched and depleted. Enriching with depth in UK48 and depleting in UK44.
Nb	Variably enriched in all samples, massively in UK48, 57 and 61 but depleted in UK12H, 20G, 32J and L and 57I.
Th	Variably depleted in samples UK12, 20, 32 and 44, but enriched in UK48, 57,61 and 68
W	Variably depleted in all samples and notably UK48.
Y	Variably enriched in all samples, but depleted in UK12H, 32J and L, 44D and I.
Cr	Variably depleted in all samples, notably UK32 and 44, but highly enriched in UK12H
Sc	Variably depleted and enriched, notably enriched in UK57, 61 and 68.
La	Variably enriched in all samples, but depleted in UK32J and L, 44I, 48Q, 68 C, E and I.
Ce	Variably enriched in all samples, but depleted in UK12L, 44I and 68I

No element appears to vary sympathetically with Zr. UK32L, UK44I and UK68C suffered the most mobilization of elements. UK32 and UK44 are samples that differ most often from the trend of enrichment or depletion relative to the other samples. UK32 and 44 are located in the NW central part of the broad part of the intrusion in the study area. The samples fall in the “talc rich zone” of the study area. UK48, 57 and 61, in the SE part of the broad part

of the complex, appear to have gained the most elements. Mo, Nb, Ni, Y, Th, U, Y, Zn, S, and V seem to increase from the NW to the SE in the study area (Figure 10.0). The massive enrichment in especially U and Th towards the SE may be due to the fact that U, and for that matter Th if a U-Th coherence is assumed, forms highly mobile carbonate complexes (Dawood et al., 2004), which would precipitate once the hydrothermal fluid had cooled.

8.3 Isocon analyses of the calc-silicate xenoliths from the Lower Harzburgite Unit

Sample SH176 is used as the original composition as it showed the least amount of alteration products. The mineralogical composition of Sample SH176 has been found, by means of XRD analyses to be composed of 60 % diopside. EMP analyses revealed these diopside grains to be of fassaite composition. This sample also contains some epidote and grossular. Sample SH176 was chosen as representative of the original composition as it contains no visible sulphides and it was indicated by Hulley (2005) that the sulphides intruded the xenoliths as a late stage fluid, which may have affected the original composition. Dolomite values are not used as C_o value as it would demonstrate the recrystallization and formation of skarn minerals rather than the effects of alteration due to late stage fluids, the aspect this investigation is interested in.

An example of an isocon from the xenoliths from the LHZBG Unit is shown by Figure 8.2 and a summary of the increase and decrease in certain elements (delta value) relative to the Zr-isocon line is presented in Table 9.3.A to E. The elements that suffered less than 10% increase or decrease has been highlighted in the table.

Table 8.2.A to E. has been arranged in such a manner that the isocon results are listed, from right to left, according to a decrease in the total amount of alteration minerals, as determined by XRD analyses.

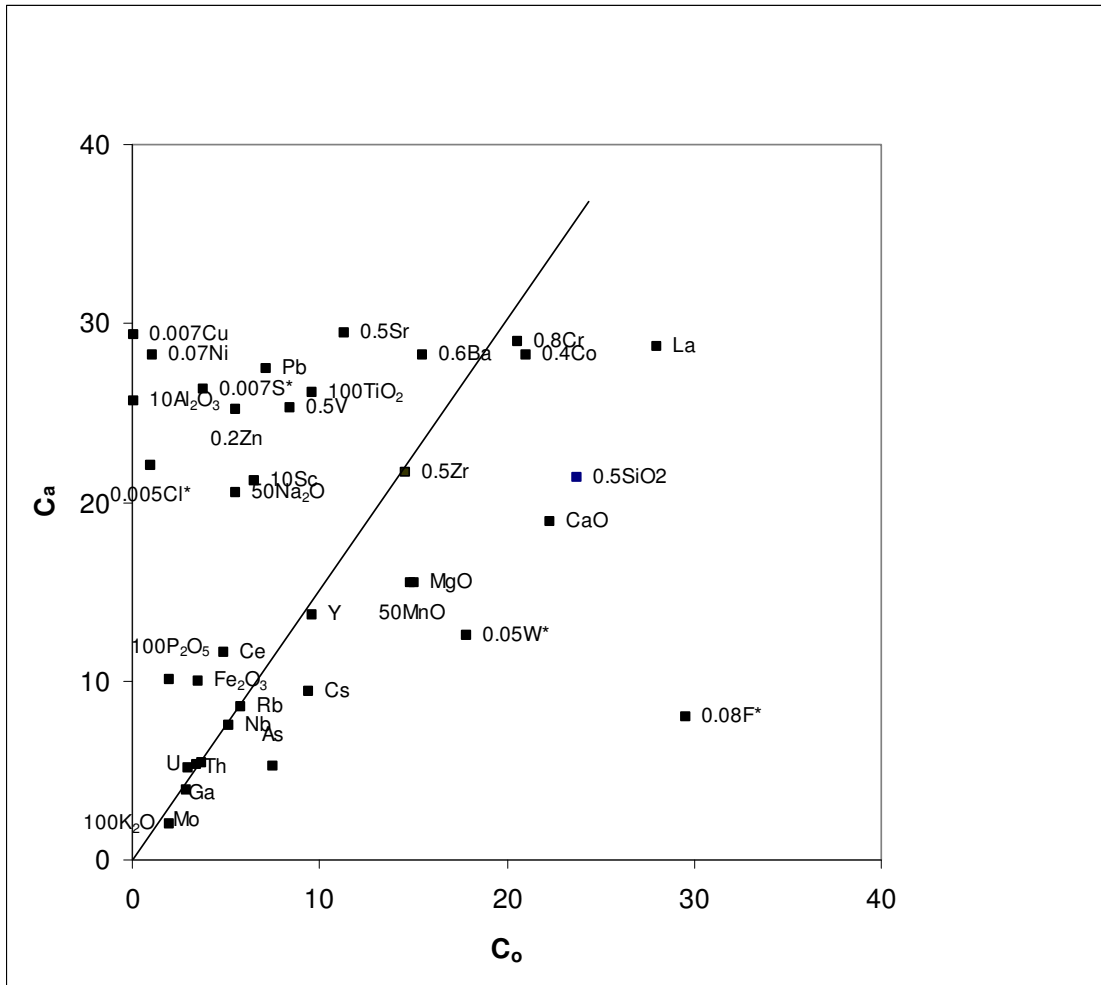


Figure 8.2. Isocon diagram for the xenoliths from the LHZBG Unit using sample UK30 as C_a and based on sample SH176, as unaltered composition C_o . The solid line indicates the Zr-isocon line. All elements marked with an asterisk are to be considered semi-quantitative.

The elements in the area above the isocon line (Figure 8.2) indicate that those elements suffered a significant addition (positive delta values) in the sample and the elements in the area below the isocon suffered a significant loss (negative delta values) in the sample.

Table 8.2.A. The increase and decrease of mobile elements, relative to the Zr-isocon (expressed as delta values) for the xenoliths in the LHZBG Unit. Sample SH176 is used as C_0 (the least mobilized elements are highlighted).

Element	UK12I	UK3O	UK48G	UK3U	UK3N	Trend
Cl*	-11.54	-93.17	132.27	-17.31	-91.76	Variable depleted , enriched in UK48G
S*	158.12	-78.55	-74.69	-82.92	-95.50	Variable depleted , enriched in UK12I

Table 8.2.B. The increase and decrease of elements with high mobility, relative to the Zr-isocon (expressed as delta values) for the xenoliths LHZBG Unit. Sample SH176 is used as C_0 (the least mobilized elements are highlighted).

Element	UK12I	UK3O	UK48G	UK3U	UK3N	Trend
MgO	2037.11	44.51	450.62	44.97	25.63	Enriched , highly in UK12I
CaO	2001.68	75.65	548.83	37.78	-21.94	Variable enriched , highly in UK12I
Na ₂ O	-83.51	-59.84	251.04	-26.03	-42.14	Variable depleted , but enriched in UK48G
Mo	2097.80	11.06	121.16	-12.56	-60.16	Variable
Sr	-68.56	-42.62	-83.15	-70.21	-94.89	Depleted
U	767.82	-4.46	36.12	-29.30	-75.82	Variable enriched with alteration
Zn	676.18	-67.17	111.58	-38.48	-67.26	Variable
F*	425.00	449.72	1644.87	330.18	-24.52	Variable enriched , depleted in UK3N
V	43.46	-50.59	372.38	-6.91	-28.49	Variable , highly enriched in UK48G

Table 8.2.C. The increase and decrease of elements with medium mobility, relative to the Zr-isocon, (expressed as delta values) for the xenoliths from the LHZBG Unit. Sample SH176 is used as C_0 (the least mobilized elements are highlighted).

Element	UK12I	UK3O	UK48G	UK3U	UK3N	Trend
As	1792.90	113.99	233.83	220.31	110.76	Enriched , highly in UK12I
Cu	-76.66	-99.56	-97.40	-99.51	-99.86	Depleted
Ni	-79.22	-94.36	-97.91	-95.44	-99.22	Depleted
Co	507.53	11.38	157.27	-4.07	-62.88	Variable

Table 8.2.D. The increase and decrease of elements with low mobility, relative to the Zr-isocon, (expressed as delta values) for the xenoliths from the LHZBG Unit. Sample SH176 is used as C_0 (the least mobilized elements are highlighted).

Element	UK12I	UK3O	UK48G	UK3U	UK3N	Trend
SiO ₂	505.65	65.61	386.50	34.57	17.34	Enriched
K ₂ O	-94.59	48.82	-78.07	28.29	-15.59	Variable
P ₂ O ₅	-64.84	-70.48	372.38	28.29	-59.32	Variable , highly enriched in UK48G
Pb	407.54	-60.97	130.34	207.90	102.59	Variable enriched , depleted in UK3O
Rb	-14.59	-0.29	-17.69	7.64	-43.07	Variable depleted
Cs	658.14	48.82	372.38	28.29	-15.59	Variable enriched , depleted in UK3N
Ba	-87.41	-18.41	360.00	57.34	9.39	Variable , highly enriched in UK48G

Table 8.2.E. The increase and decrease of immobile elements, relative to the Zr-isocon, (expressed as delta values) for the xenoliths from the LHZBG Unit. Sample SH176 is used as C₀ (the least mobilized elements are highlighted).

Element	UK12I	UK3O	UK48G	UK3U	UK3N	Trend
TiO ₂	-7.41	-45.02	87.66	-14.37	3.72	Variable depleted , highly enriched in UK3O
Al ₂ O ₃	-99.60	-99.42	-99.21	28.29	-15.59	Variable mostly depleted
Fe ₂ O ₃	553.77	-47.57	45.89	-38.83	-68.21	Variable , highly enriched in UK12I
MnO	2525.31	43.55	407.81	51.98	-32.54	Variable enriched , highly in UK12I
Ga	73.95	0.68	46.87	106.04	6.24	Variable enriched
Nb	221.14	2.38	151.50	-15.36	-47.69	Variable
Th	289.59	-12.74	-9.39	-33.88	-75.23	Variable depleted with alteration
W*	897.76	112.03	418.59	66.06	55.18	Variable enriched
Y	272.42	4.91	82.24	8.56	-50.91	Variable enriched , depleted in UK3N
Cr	-55.94	5.95	-37.60	41.81	84.49	Variable depleted with alteration
Sc	-42.68	-54.21	372.38	28.29	-15.59	Variable , highly enriched in UK48G
La	820.09	45.42	410.71	26.26	-28.65	Variable enriched , depleted in UK3N
Ce	-22.71	-37.09	61.83	28.29	-15.59	Variable

No element appears to vary sympathetically with Zr. UK3 O and U appear to have suffered the least mobilization of elements.

8.4 Isocon analyses of the Chromitiferous Harzburgite Unit

Sample UK12D is used as the original composition as it showed the least amount of alteration products and is located outside of the talc-rich area. Investigation under a petrographic microscope revealed sample UK12D to be composed of mainly fairly unaltered precursor mafic minerals. XRD analyses indicated that sample UK12D is composed of 12 % olivine, 21 % diopside, 20 % hornblende as well as 8 % chromite. EMP analyses revealed the olivine to be magmatic fosterite and the diopside as also being derived from a magmatic source. The main alteration minerals present is talc (10 %) and chlorite (14 %) after diopside.

Most of the samples from the PCR in this study show the effect of late stage deuteric hydrothermal alteration. All of the samples taken from the talc-rich area have been almost completely replaced by secondary minerals.

An example of an isocon from the PCR is shown by figure 8.3 and a summary of the increase and decrease in certain elements (delta value) relative to the Zr-isocon line is presented in Table 8.3.A to E. The elements that suffered less than 10% increase or decrease has been highlighted in the table.

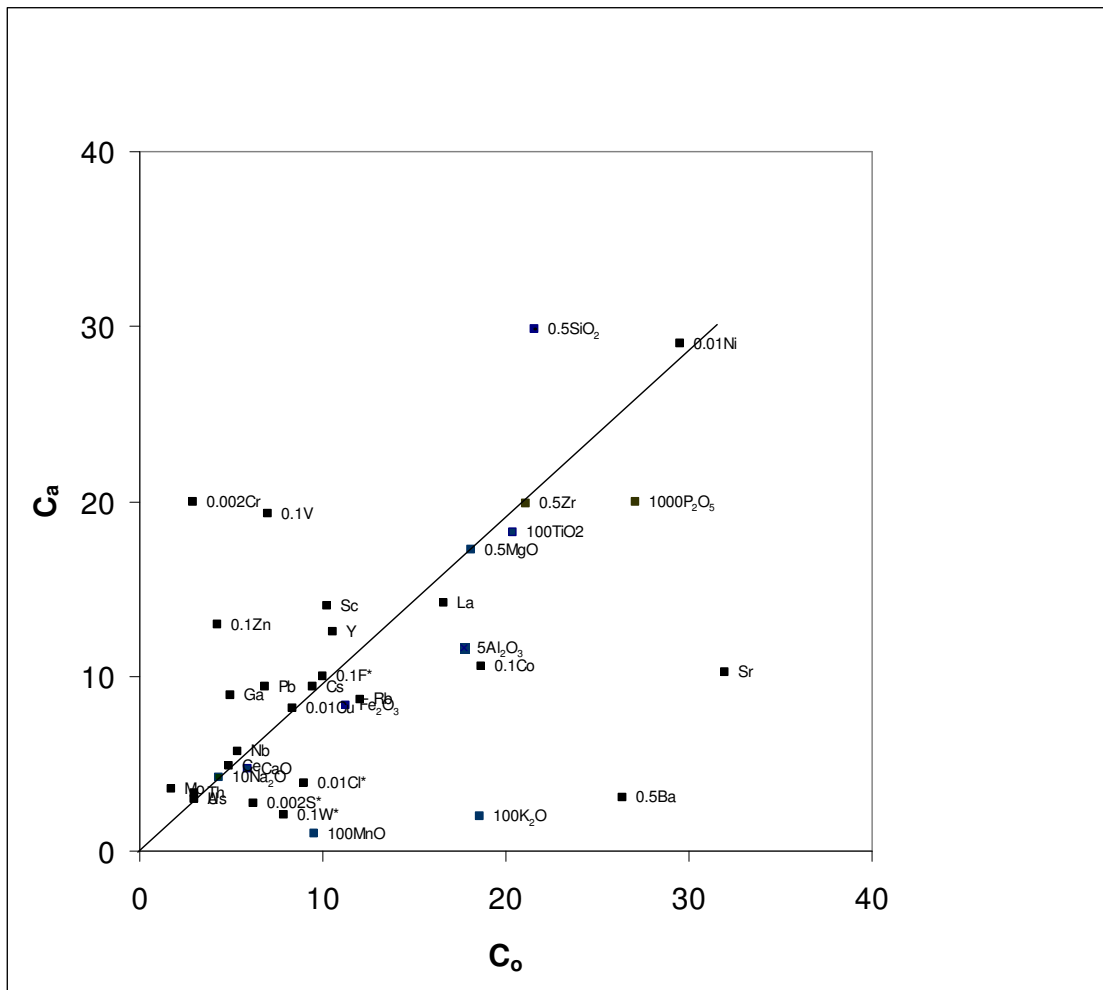


Figure 8.3. Isocon diagram for the PCR using sample UK32B as C_a and based on sample UK12D, as unaltered composition C_o . The solid line indicates the Zr-isocon line. All elements marked with an asterisk are to be considered semi-quantitative.

The elements in the area above the isocon line (Figure 8.3) indicate that those elements suffered a significant addition (positive delta values) in the sample and the elements in the area below the isocon suffered a significant loss (negative delta values) in the sample.

Table 8.3.A. The increase and decrease of mobile elements, relative to the Zr-isocon (expressed as delta values) for the PCR Unit. Sample UK12D is used as C₀ (the least mobilized elements are highlighted).

Element	UK12A	UK12G	UK20B	UK20D	UK32B	UK32D	UK44A	UK44C	UK48E	UK48G
Cl*	-6.37	18.81	-40.13	31.54	-26.78	-0.52	118.65	-6.52	-68.61	-10.08
S*	194.43	221.11	38.32	369.29	105.55	214.90	370.63	329.56	309.89	133.92
Element	UK48J	UK57A	UK57D	UK57F	UK57H	UK61A	UK61B	UK61C	UK61D	UK68A
Cl*	3.03	15.74	-15.59	-7.96	-21.75	3.70	9.88	2.06	-3.78	20.91
S*	706.57	136.73	-3.89	60.01	1150.24	423.31	94.08	46.80	7.29	873.18

Element	Trend
Cl	Variably depleted and enriched, notably enriched in UK48E.
S	Variably enriched in all samples.

Table 8.3.B. The increase and decrease of elements with high mobility, relative to the Zr-isocon (expressed as delta values) for the PCR Unit. Sample UK12D is used as C₀ (the least mobilized elements are highlighted).

Element	UK12A	UK12G	UK20B	UK20D	UK32B	UK32D	UK44A	UK44C	UK48E	UK48G
MgO	-1.15	11.07	-0.37	63.77	0.65	-58.48	91.45	8.00	-8.66	12.74
CaO	-84.68	-43.84	-76.87	10.97	-15.84	38.04	-17.37	-10.41	-78.40	-66.44
Na ₂ O	-73.27	-10.46	-28.44	11.95	1.47	-39.66	-42.60	23.17	-56.81	-35.09
Mo	280.36	241.53	390.63	-9.43	114.88	15.38	2.09	-5.86	-53.24	24.91
Sr	-67.53	-38.48	-57.49	-31.36	-66.24	-34.64	-27.67	13.31	-84.70	-55.27
U	230.59	136.30	339.48	57.03	5.84	-25.21	77.01	4.93	-18.93	-1.18
Zn	-6.39	317.96	274.02	57.03	28.42	-25.21	77.01	141.52	-18.93	-1.18
F*	-74.12	131.75	-57.85	74.65	51.57	-48.77	-29.15	-80.94	498.86	689.07
V	-71.26	252.63	-51.98	-13.93	143.23	-61.44	28.25	8.83	-24.68	17.86
Element	UK48J	UK57A	UK57D	UK57F	UK57H	UK61A	UK61B	UK61C	UK61D	UK68A
MgO	51.40	-14.93	-0.22	38.48	74.97	14.69	-32.86	-7.60	-1.18	38.30
CaO	-7.43	-49.49	-93.34	73.60	80.18	-58.45	7.60	23.69	69.68	-71.94
Na ₂ O	-24.77	-36.31	-63.29	-42.94	-15.92	-49.12	-38.96	-79.71	-67.97	-70.35
Mo	-9.39	173.14	-43.43	-5.82	71.16	365.65	109.92	-41.45	-38.88	767.02
Sr	-56.18	-70.44	-87.89	-52.78	-55.62	-48.36	-59.49	153.12	209.51	-19.26
U	57.09	146.90	-1.91	63.29	82.08	336.51	37.38	1.52	5.97	849.90
Zn	211.69	-2.27	29.70	29815.89	82.08	35.80	-15.09	583.16	9.94	43.06
F*	957.10	40.02	2.31	705.46	827.26	232.09	-10.42	103.42	-36.88	1001.02
V	-30.54	-51.42	-70.38	1117.25	580.92	358.61	-63.55	-10.75	-54.48	165.32

Table 8.3.B. Continued.

Elements	Trend
MgO	Depleted in UK32D, 48E, 57A and enriching with increasing depth in UK12, 20, 57 and 61.
CaO	Decreasingly depleted with increasing depth in UK12, 20, 32, 48 and significantly depleted in UK57D.
Na ₂ O	Decreasingly depleted with increasing depth in UK 12, 20, 32, 44 and 48. UK61C significantly depleted.
Mo	Variably enriched and depleted.
Sr	Variably depleted in all samples, but enriched in UK44C and 61C and D.
U	Variably enriched in all samples, but depleted in UK32D, 48E and G and 57D.
Zn	Variably enriched in most samples. Massively in UK57H
F	Variably enriched and depleted. Most notably in the central part.
V	Variably enriched and depleted. UK57 massively enriched.

Table 8.3.C. The increase and decrease of elements with low mobility, relative to the Zr-isocon, (expressed as delta values) for the PCR Unit. Sample UK12D is used as C₀ (the least mobilized elements are highlighted).

Element	UK12A	UK12G	UK20B	UK20D	UK32B	UK32D	UK44A	UK44C	UK48E	UK48G
As	403.39	54.09	-7.85	167.78	5.84	-25.21	77.01	195.10	-11.96	180.87
Cu	11.60	219.42	-40.38	-32.62	-40.28	-85.79	-59.56	-44.76	-12.83	5.84
Ni	-3.60	25.27	21.35	82.35	44.81	181.34	129.20	16.49	-24.25	-18.80
Co	-72.46	96.39	-72.89	2.04	-33.94	-67.81	8.77	-69.13	220.89	253.32
Element	UK48J	UK57A	UK57D	UK57F	UK57H	UK61A	UK61B	UK61C	UK61D	UK68A
As	84.39	-13.52	10.08	63.29	96.66	461.56	-15.09	202.47	669.91	618.36
Cu	-37.75	-52.94	-40.17	-25.25	58.19	-38.86	-44.22	-77.76	-49.08	450.07
Ni	199.96	39.95	-4.59	107.40	117.76	116.04	73.51	32.56	-9.82	-55.35
Co	217.97	43.68	-54.85	533.86	460.25	71.01	9.08	156.83	-11.67	565.54

Table 8.3.C. Continued.

Element	Trend
As	Enriched in most samples.
Cu	Depleted in most samples, but decreasing depletion with depth in UK12, 20, 44, 57. Significantly enriched in UK68A.
Ni	Enriched in most samples. Depleting with depth in UK61
Co	Variably enriched and depleted. More enriched towards the SE.

Table 8.3.D. The increase and decrease of elements with low mobility, relative to the Zr-isocon, (expressed as delta values) for the PCR Unit. Sample UK12D is used as C₀ (the least mobilized elements are highlighted).

Element	UK12A	UK12G	UK20B	UK20D	UK32B	UK32D	UK44A	UK44C	UK48E	UK48G
SiO ₂	23.86	-4.10	-8.67	75.74	46.46	-12.06	94.84	20.16	-18.92	7.13
K ₂ O	-89.91	-88.28	-16.16	-83.07	-88.59	691.62	-47.38	13.02	-9.78	62.80
P ₂ O ₅	-30.94	-19.79	-28.49	15.85	-21.92	-44.83	30.58	-3.74	-40.19	-27.10
Pb	51.94	8.67	-19.18	-31.40	44.71	0.74	-14.56	66.36	14.52	-43.12
Rb	-33.08	-8.77	36.64	-52.04	-23.73	432.45	21.40	27.43	1.39	60.75
Cs	-6.39	8.73	-7.85	57.03	5.84	-25.21	77.01	4.93	-18.93	-1.18
Ba	-92.04	-78.92	-77.25	-43.68	-87.76	-39.68	-19.86	-51.45	-65.19	-37.72
Element	UK48J	UK57A	UK57D	UK57F	UK57H	UK61A	UK61B	UK61C	UK61D	UK68A
SiO ₂	107.64	16.16	45.94	116.49	113.58	4.40	-2.50	25.29	22.69	8.55
K ₂ O	-45.87	-90.68	-89.42	-82.39	-80.37	102.94	-90.84	-89.05	-88.58	-84.58
P ₂ O ₅	15.89	-36.20	-27.64	20.47	34.33	-17.15	-37.36	-25.11	-21.82	5.54
Pb	86.99	11.92	-57.15	-28.67	-20.46	9.58	-62.91	-30.34	-53.71	440.50
Rb	40.53	-27.64	-81.31	-65.80	-31.09	83.22	-39.61	-76.94	-46.44	51.53
Cs	57.09	-13.52	-1.91	63.29	82.08	12.31	-15.09	1.52	5.97	43.06
Ba	-29.89	-92.65	-87.47	-71.78	-62.16	-26.35	-82.27	-76.30	-75.59	-87.84

Table 8.3.D. Continued.

Element	Trends
SiO ₂	Variably enriched in most samples, but depleted in UK12G, 20B, 32D, 48E and 61B
K ₂ O	Depleted in most samples, but largely enriched in UK32D.
P ₂ O ₅	Depleted in most samples, but with decreasing depletion with increasing depth in UK12, 20, 48, 57 and part of 61.
Pb	Variably enriched and depleted. Massively enriched in UK68A.
Rb	Variably enriched and depleted.
Cs	Variable. Enriching with depth in UK12, 20, 48, 57 and lower 61. Depleting with depth in UK32, 44 and top 61.
Ba	Depleted in all samples, but decreasingly depleted with depth in UK12, 20, 32 and 57.

Table 8.3.E. The increase and decrease of immobile elements, relative to the Zr-isocon, (expressed as delta values) for the PCR Unit. Sample UK12D is used as C₀ (the least mobilized elements are highlighted).

Element	UK12A	UK12G	UK20B	UK20D	UK32B	UK32D	UK44A	UK44C	UK48E	UK48G
TiO ₂	-17.66	-28.51	52.87	-8.67	-5.56	34.89	50.60	3.66	-25.43	-7.63
Al ₂ O ₃	-42.97	-8.90	37.01	-73.37	-30.49	22.28	117.82	-4.25	-37.55	-76.71
Fe ₂ O ₃	-12.48	59.62	7.60	13.44	-21.83	-17.29	34.54	14.89	-17.05	-7.82
MnO	-90.18	11.06	-90.33	64.71	-88.90	98.08	123.51	28.57	-58.99	-89.63
Ga	156.62	-18.14	255.80	-1.93	91.49	7.24	147.64	16.68	0.95	13.33
Nb	50.06	49.39	75.78	-41.67	12.49	-24.53	-34.25	0.05	-47.22	7.36
Th	274.51	304.90	377.23	57.03	17.24	-25.21	77.01	4.93	-18.93	-1.18
W*	128.72	-91.71	53.53	-47.37	-72.47	-65.35	-67.46	-63.97	-93.82	-38.36
Y	-2.31	35.47	21.09	-15.71	26.01	-31.14	24.11	-2.96	-18.49	-26.18
Cr	-47.56	56.51	-39.54	-7.07	-17.18	-15.31	81.44	-4.86	66.98	89.17
Sc	-3.60	25.27	21.35	82.35	44.81	181.34	129.20	16.49	-24.25	-18.80
La	-36.50	-0.60	-20.19	62.11	-9.59	3.31	137.52	3.58	-17.88	-12.20
Ce	-6.39	8.73	-7.85	57.03	5.84	36.87	291.45	4.93	-18.93	-1.18
Element	UK48J	UK57A	UK57D	UK57F	UK57H	UK61A	UK61B	UK61C	UK61D	UK68A
TiO ₂	45.89	-17.31	-36.64	8.96	49.82	132.91	52.78	-3.45	54.57	-57.97
Al ₂ O ₃	-0.81	-25.87	-99.72	0.12	9.28	342.87	65.35	-49.75	-94.86	-99.60
Fe ₂ O ₃	43.66	-33.93	-42.80	20.14	84.90	29.12	-12.72	-24.40	-15.18	166.13
MnO	107.63	-90.93	-71.60	152.51	206.94	-88.22	-38.13	61.41	121.35	-25.00
Ga	98.68	91.47	-26.76	88.45	44.32	490.38	82.83	-20.19	0.99	-42.06
Nb	-9.26	32.73	-48.41	-6.51	26.05	92.31	-2.89	-52.70	-45.50	186.05
Th	57.09	215.20	-1.91	63.29	82.08	380.24	37.91	1.52	5.97	978.62
W*	-32.26	-26.50	-92.53	-25.89	99.92	29.36	83.06	-79.45	-81.94	-89.10
Y	17.37	15.09	-59.53	20.14	33.56	21.39	8.14	-12.97	-13.76	70.19
Cr	123.73	16.52	-43.14	292.79	241.38	52.09	4.49	74.92	-10.06	262.84
Sc	199.96	39.95	-4.59	107.40	117.76	116.04	73.51	32.56	-9.82	-55.35
La	35.03	-23.66	-1.44	73.12	94.24	-10.53	-3.55	10.43	20.92	36.10

Ce	57.09	-13.52	212.90	63.29	82.08	12.31	-10.50	8.01	19.76	43.06
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Table 8.3.E. Continued.

TiO ₂	Variably depleted and enriched , notably enriched UK61A.
Al ₂ O ₃	Variably depleted and enriched, notably enriched 61A.
Fe ₂ O ₃	Variably enriched and depleted.
MnO	Most samples variably highly enriched and slightly depleted.
Ga	Enriched in most samples, but depleted with depth in UK12, 20 and 32. Enriching with depth in UK48.
Nb	Variably enriched and depleted.
Th	Variably enriched in all samples, but depleted in UK32D, 48E, G and 57D. Massively in UK68A
W	Variably depleted in most samples. Less depleted with depth in UK48, 57.
Y	Variably enriched and depleted. Depleted with depth in UK20, 32, 44 and 61
Cr	Variably depleted and enriched. Most notably in the central part.
Sc	Variably enriched in all samples, but depleted in UK12A, 48E and G, 57D, 61D and 68A. Enriched with depth in UK12, 20, 32 and depleted with depth in UK44 and 61.
La	Variable . Enriching with depth in UK12, 20, 32, 48, 57 and 61.
Ce	Enriched . Enriching with depth in UK12, 20, 32, 48 and lower 61.

No element appears to vary sympathetically with Zr. It would appear that UK44C, UK48G and UK57D suffered the least mobilization of elements. It would appear that a significant number of elements are either depleted or enriched with depth. This may indicate mobilization of elements by a deuteritic system.

8.5 Discussion of isocon results for the units

It was suggested by van Zyl (1996) that the Uitkomst Complex was affected by a deuteritic late-stage fluid. The isocon method was employed to test this hypothesis and determine the

amount of elemental mobilization in such a system. It is conceivable that flow regimes may have developed in the fluid-enriched environment of the Uitkomst Complex's basal units, which would have contributed to redistribution of the compatible and incompatible trace elements.

The LHZBG Unit shows some spatial variation in element enrichment or depletion that may be related to a difference in conditions in the narrow relative to the broad part of the intrusion in the study area. It has been indicated that Mo, Nb, Ni, Y, Th, U, Y, Zn, S, and V increase in content from the NW to the SE. This may indicate mobilization of some elements that was then transported in the direction of indicated magma flow, and deposited in the broadening area of the intrusion. It has been shown that the massive increase in the U content towards the SE may be due to the formation of a carbonate complex which would be able to transport it away from the source area to where it could precipitate due to cooling of the fluid (Dawood et al., 2004). With the exception of Fe₂O₃, MnO and Zn, no other major or trace elements show a spatial variation either increasing or decreasing with height. This may indicate that the final distribution of major and trace elements may be a function of the degree of assimilation of country rock by the intruding ultramafic magma or slight variations in the composition of the intruding magma. Here the selection of the C₀ sample was again problematic, due to the high alteration mineral content in most samples from this unit. In this unit the most pristine sample was again selected with the same assumption as noted previously.

The xenoliths located in the LHZBG Unit was also variably enriched and depleted in both major and trace elements. This may be due to the compositional variation in the fluids that was expelled by the xenolith during the period it was subjected to partial assimilation or the composition of the fluid that infiltrated the xenolith at a late stage. As with the previous units, the selection of the C₀ sample was problematic due to the presence of alteration minerals in all samples, again the most pristine samples was selected and assumed to represent the composition most akin to the original, unaltered composition.

The PCR Unit show a weakly defined spatial distribution of some major and trace elements that indicate a vertically moving thermo-chemical agent may be responsible for the final distribution of the elements with height. Most of the elements show a vertical variation that changed with depth. This variation may indicate that the thermochemical agent suffered a loss in ability to transport the mobilized elements as it migrated upwards. However not all of the major and trace elements where mobilized in all of the sampled boreholes show the same variation. The irregular variation may indicate that the thermochemical conditions varied with position in the intrusion. The major and trace elements do not indicate a spatial variation in the horizontal distribution of elements. It should be noted again that the selection of the C_o sample was problematic, but was selected using the same criteria as noted before.

8.6 Compositional pseudo-sections

In order to constrain the temperature and CO₂-partial pressure that prevailed in the LHZBG and PCR units, during formation of the observed mineral assemblages, pseudo-sections were generated. The pseudo-sections were generated by means of the *Perple_X* (Connelly, 2005) modelling software version 7. The dataset used was the 2004 unpublished version of the Holland and Powell (1998) thermo dataset.

Two samples were selected for the LZHBG and PCR each. The bulk chemistry of the sample, as determined by XRF analyses, were used to generate the pseudo-sections. The T-XCO₂ for these samples are calculated and reported for the specific bulk composition, with a-x models that are appropriately complex to be representative of the observed mineralogy. The T-MH₂O pseudo-sections represent adding progressively higher amounts of water to an anhydrous bulk composition. All the pseudo-sections are constructed at 3 Kbar

8.7 Limitations of pseudo-sections

The modelling of alteration processes performed using *Perple_X* is limited to low temperature environments, such as the observed talc-bearing assemblages. Higher temperature alteration processes resulting in e.g. pure fassaitic-diopside is not amenable to

such modelling as too few associated minerals developed to constrain the T-X conditions. Cr-bearing minerals cannot be modelled and a Cr-free system involving a spinel solid solution is assumed. Particular protolith rock types are assumed for the LHZBG and PCR. The LHZBG is assumed to be a harzburgite, but is skewed to favour diopside. The PCR is assumed to be a harzburgite-peridotite. The precursor mineralogy is used to check the corresponding alteration assemblages observed and calculated. The absence of K-bearing primary minerals precludes considering mica minerals in the retrograde assemblages, owing to the retrograde assemblages not having isochemical equivalents of the magmatic rocks. This particular approach does not allow discrimination between areas that were subject to the metasomatic effects of near similar fluids. This would require additional data on fluid fluxes that is not supported by the current spatial information available.

8.8 Modelling Results

The abbreviations used in the pseudo-sections are given in Table 8.4.

Table 8.4. Definitions of abbreviations used in pseudo-section models.

Abbreviation	Definition
Feldspar	Na-Ca plagioclase
OI(HP)	Olivine solid solution
Opx (HP)	Orthopyroxene solid solution
Cpx (HP)	Clinopyroxene solid solution
cAmph(DP)	Ca-Na-Fe-Mg amphibole solid solution, which will be either hornblende or tremolite-actinolite depending on grade
Atg	Antigorite solid solution
T	Talc solid solution
Dol(HP)	Dolomite-magnesite solids solution
oCcM(HP)	Calcite-magnesite solid solution
Chl	Chlorite solid solution
q	Quartz
sid	Siderite
ky	Kyanite
ab	Pure albite

(Abbreviations after: http://www.perplex.ethz.ch/PerpleX_solution_model_glossary.html)

8.8.1 Lower Harzburgite Unit

Two samples were selected and modelled to be representative of the LHZBG unit, namely UK20G and UK48Q. The preserved primary magmatic mineral in these samples is olivine. Calcite has been texturally interpreted to represent relict country rock or xenolith inclusion, but may also represent secondary mineralogy. The secondary minerals for both samples are: amphibole (actinolite-tremolite), chlorite, dolomite, serpentine and talc. Based on the petrography, the formation of chlorite and serpentine is indicated to have formed last owing to the pocketed occurrence of these two minerals.

In Figure 8.4 (UK20G) and Figure 8.6 (UK48Q) it is indicated that the T-X(CO₂) conditions that satisfy the mineral assemblages observed in both these samples are not present in the range of calculated conditions. The presence of either feldspar, albite or orthoproxene excludes these assemblages of being representative of the conditions that prevailed in the LHZBG at the time of formation.

The assemblages observed in the samples from UK20G are reflected by assemblage numbers 35, 39, 40, 49 and 51 in Figure 8.5. This would indicate the T-X(CO₂) conditions to in the in this part of the LHZBG to have been between 300 and 480 °C (573 and > 753 K) and the CO₂-content of the fluid to have been < 0.3^{E-1} bar.

In UK48Q the mineral assemblages observed in the samples (Figure 8.7) are represented by assemblages number 4, 10, 11, 16, 22, 24, 25, 32, 35 and 36. This would suggest that a broad range of T-X(CO₂) conditions prevailed in the LHZBG unit during the formation of the observed mineral assemblages. The upper range is 660 °C (> 933 K) and the X(CO₂) range is up to 0.1. This would indicate a cooling and buffering towards progressively lower X(CO₂) conditions with decreasing temperature (T).

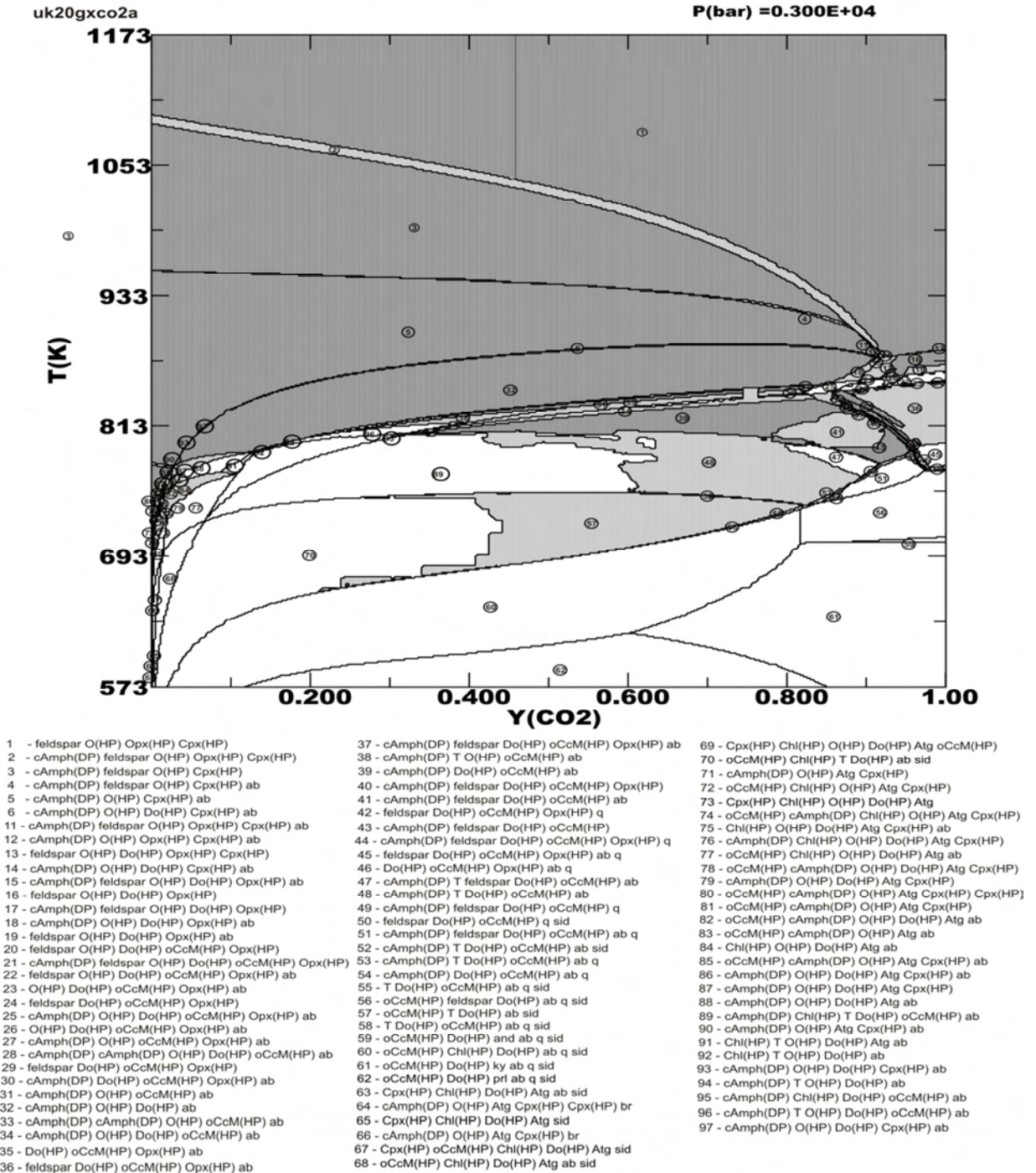


Figure 8.4: Pseudo-section for UK20G T-X(CO₂).

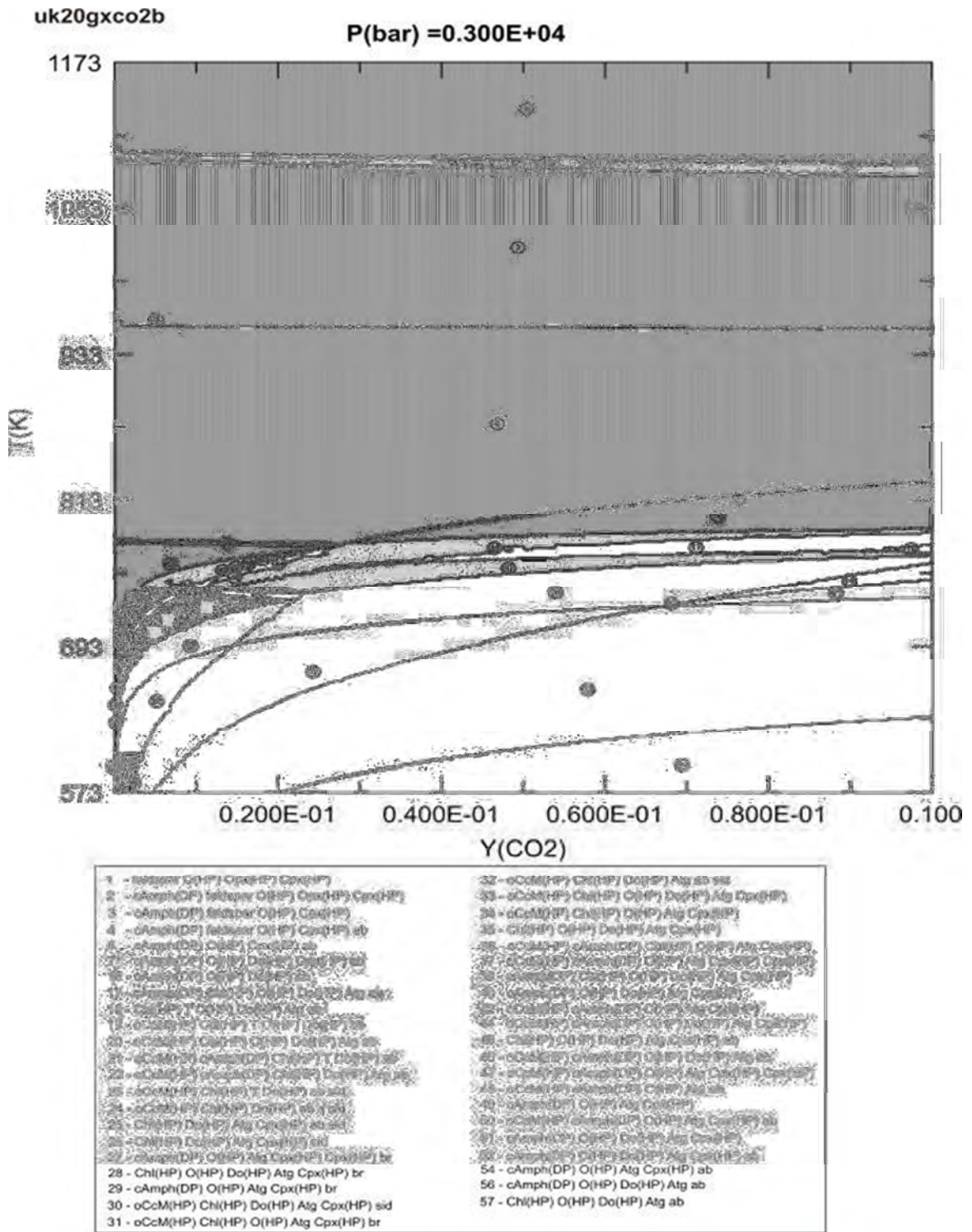


Figure 8.5: Pseudo-section for UK20G T-X(CO₂).

uk48q no1

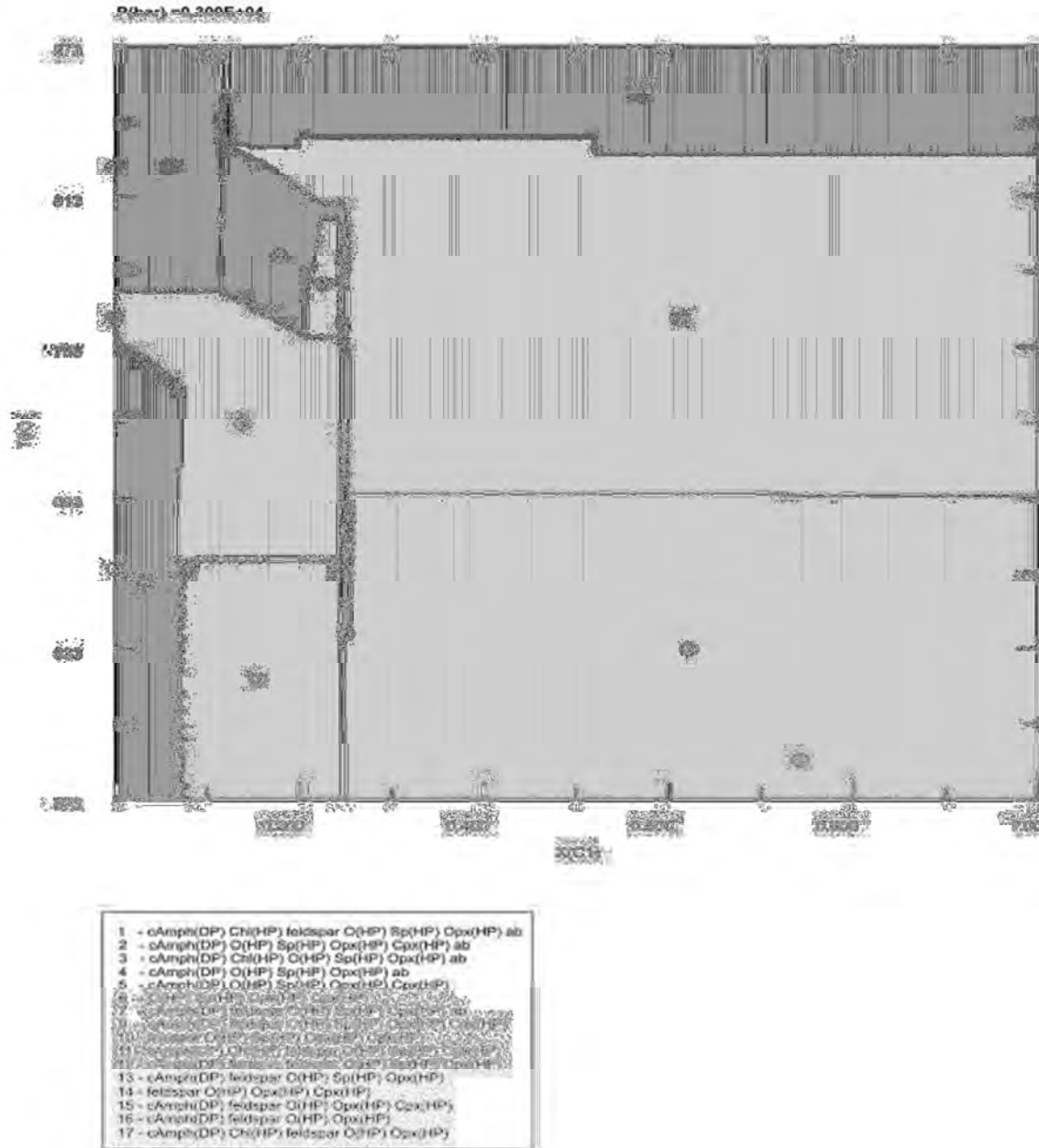


Figure 8.6: Pseudo-section for UK48Q T-M(H₂O).

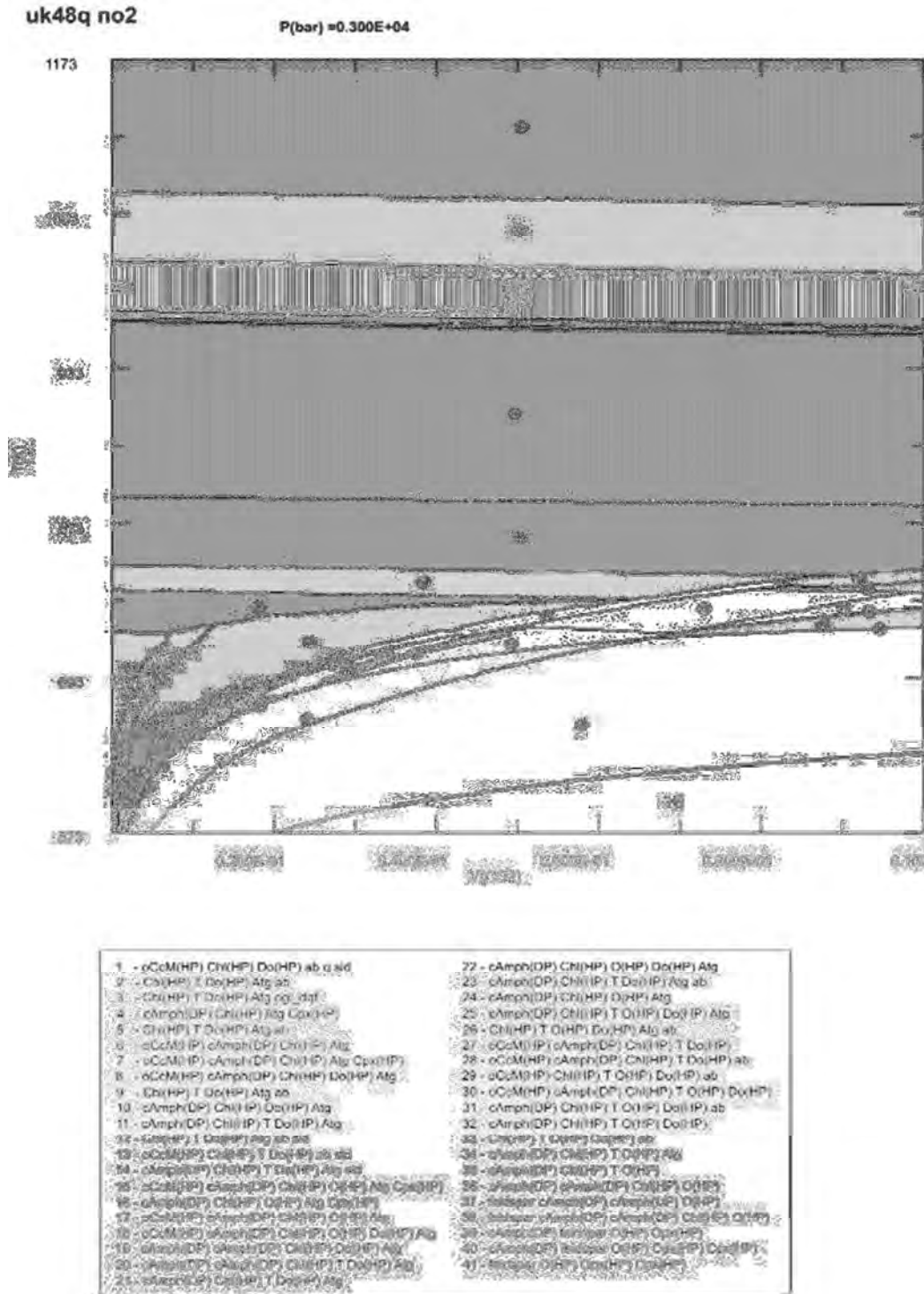


Figure 8.7:Pseudo-section for UK48Q T-X(CO₂).

8.8.2. Chromitiferous Harzburgite Unit

Two samples were selected and modelled to be representative of the PCR unit, namely UK44C and UK61B. XRD analyses indicated the preserved primary magmatic mineral in these samples are olivine in UK44C and diopside in UK61B. The secondary minerals in both are: calcite, amphibole (actinolite-tremolite), chlorite, dolomite, serpentine and talc. Based on the petrography, the formation of chlorite and serpentine is indicated to have formed during the last preserved alteration event, owing to the pocketed occurrence of these two minerals.

In the full water environment (Figure 8.8) no observed assemblages are present as all the reactions contain either feldspar or albite or orthopyroxene.

In UK44C the T-X(CO₂) conditions that are required for the mineral assemblages observed, numbers 87,88 and 89 (Figure 8.9) give a broad range of conditions. The temperature is above 540 up to 660 °C (> 813 to > 933 K) with the X(CO₂) condition range up to 0.8. In Figure 12.7 the range of observed assemblages occurs over a broad range of conditions. The observed assemblages are numbers 17, 20, 26, 28, 29, 30, 34, 35 and 36. This constrains the formation conditions to a temperature up to 660 °C (993 K). The range of the assemblages and conditions would suggest a decrease in X(CO₂) with a decrease in T.

In the broadest part of the intrusion, where sample UK61 B was collected, no observed assemblage is present in the full water condition diagram (Figure 8.11). All the assemblage present in this diagram either contains feldspar, albite or orthopyroxene that is not observed in the sample.

The T-X(CO₂) conditions are again over a very broad range. The observed assemblages, present in Figure 12.9, are present in numbers 7, 15, 17, 18, 20, 24, 25, 27, 28, 29, 53, 54, 62, 67, 73, 77, 78 and 81. This places the X(CO₂) conditions up to 1.0. The temperature is constrained up to around 600 °C (> 873 K). The conditions represented in Figure 8.13 have the observed assemblages over the entire range of X(CO₂) conditions. The assemblages are

given by numbers 6 to 10, 34, 41 and 44. This constrains the upper temperature to 660 °C (< 993 K).

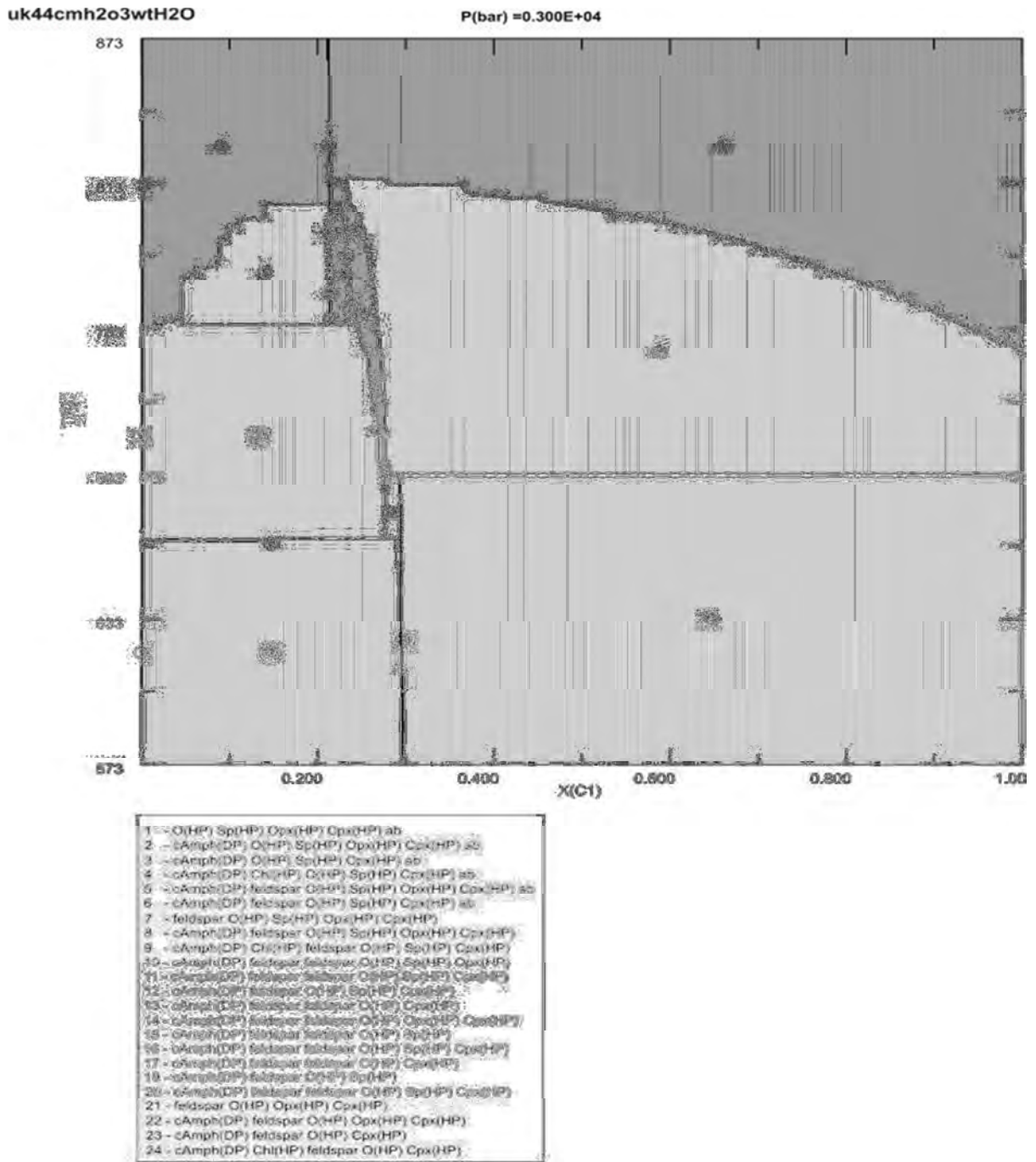


Figure 8.8: Pseudo-section for UK44C T-M(H₂O).

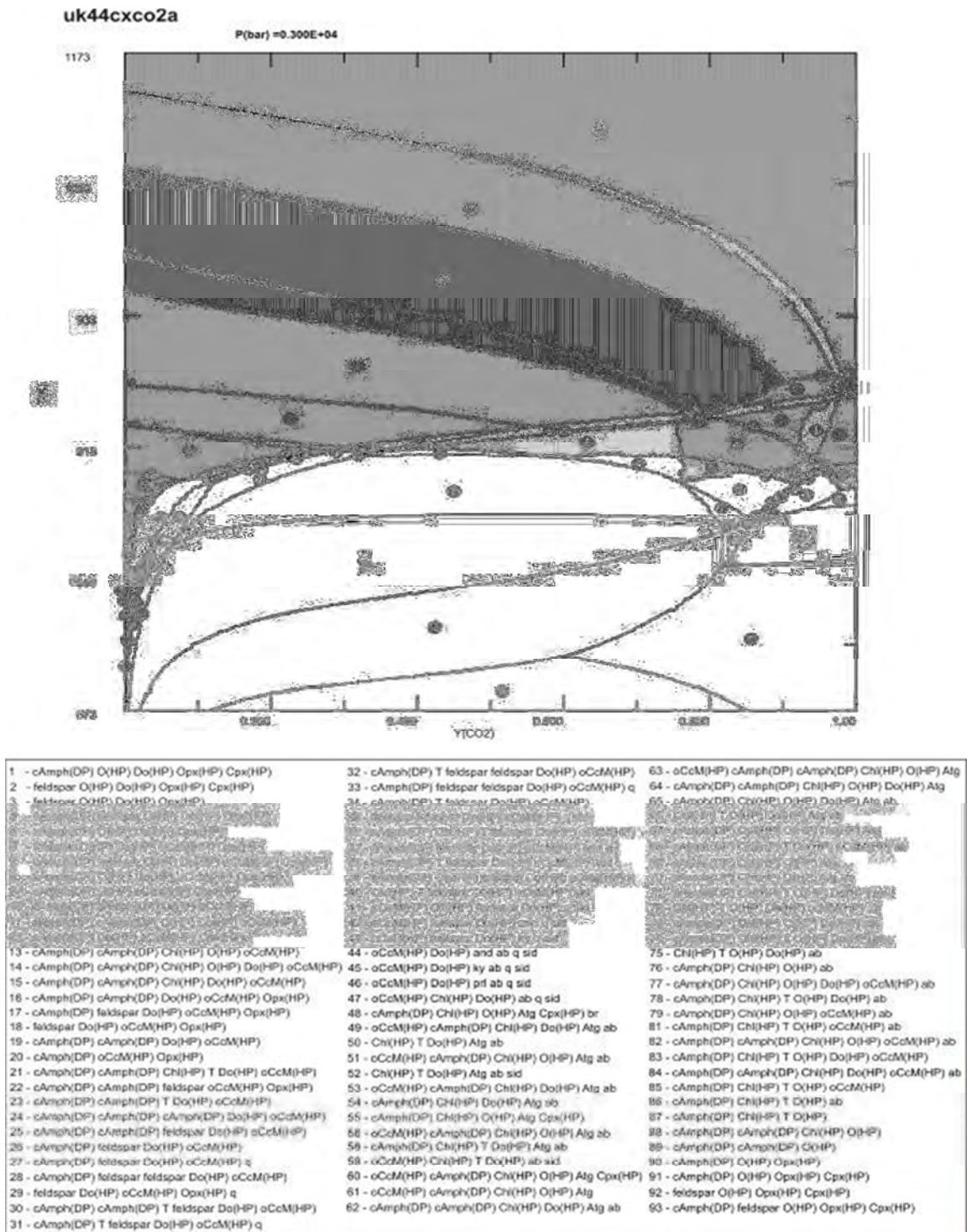
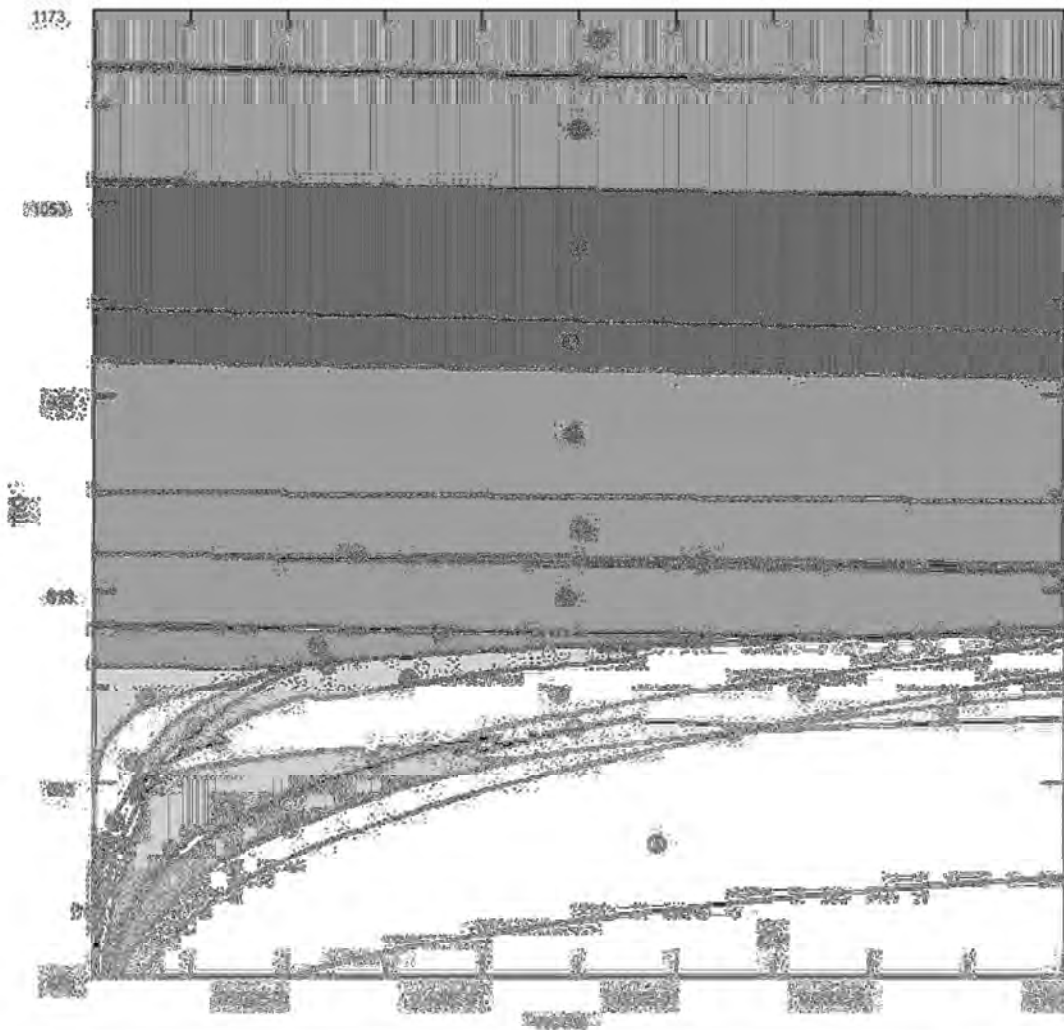


Figure 8.9: Pseudo-section for UK44C T-X(CO₂).

uk44cxco2b

P(bar) = 0.300E+04



1 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	20 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg Cpx(HP)
2 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	21 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
3 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	22 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
4 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	23 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
5 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	24 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
6 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	25 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
7 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	26 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
8 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	27 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
9 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	28 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
10 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	29 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
11 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	30 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
12 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	31 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
13 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	32 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
14 - Ch(HP) T Do(HP) Alg ab	33 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
15 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	34 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
16 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	35 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
17 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	36 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
18 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	37 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
19 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab	38 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
	39 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab
	40 - cAmph(DP) Ch(HP) O(HP) Do(HP) Alg ab

Figure 8.10: Pseudo-section for UK44C T-X(CO₂)

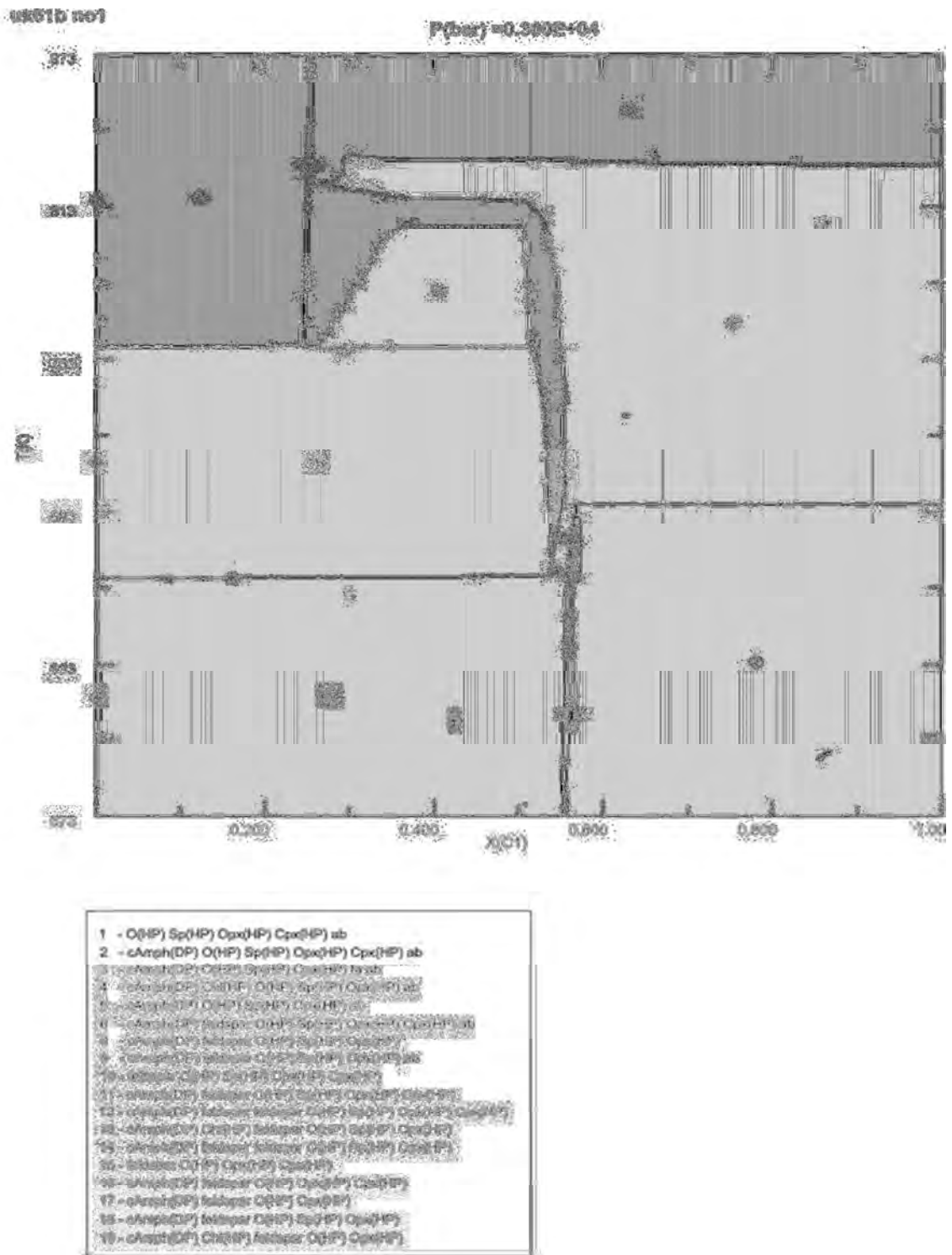


Figure 8.11: Pseudo-section for UK61B T-M(H₂O).

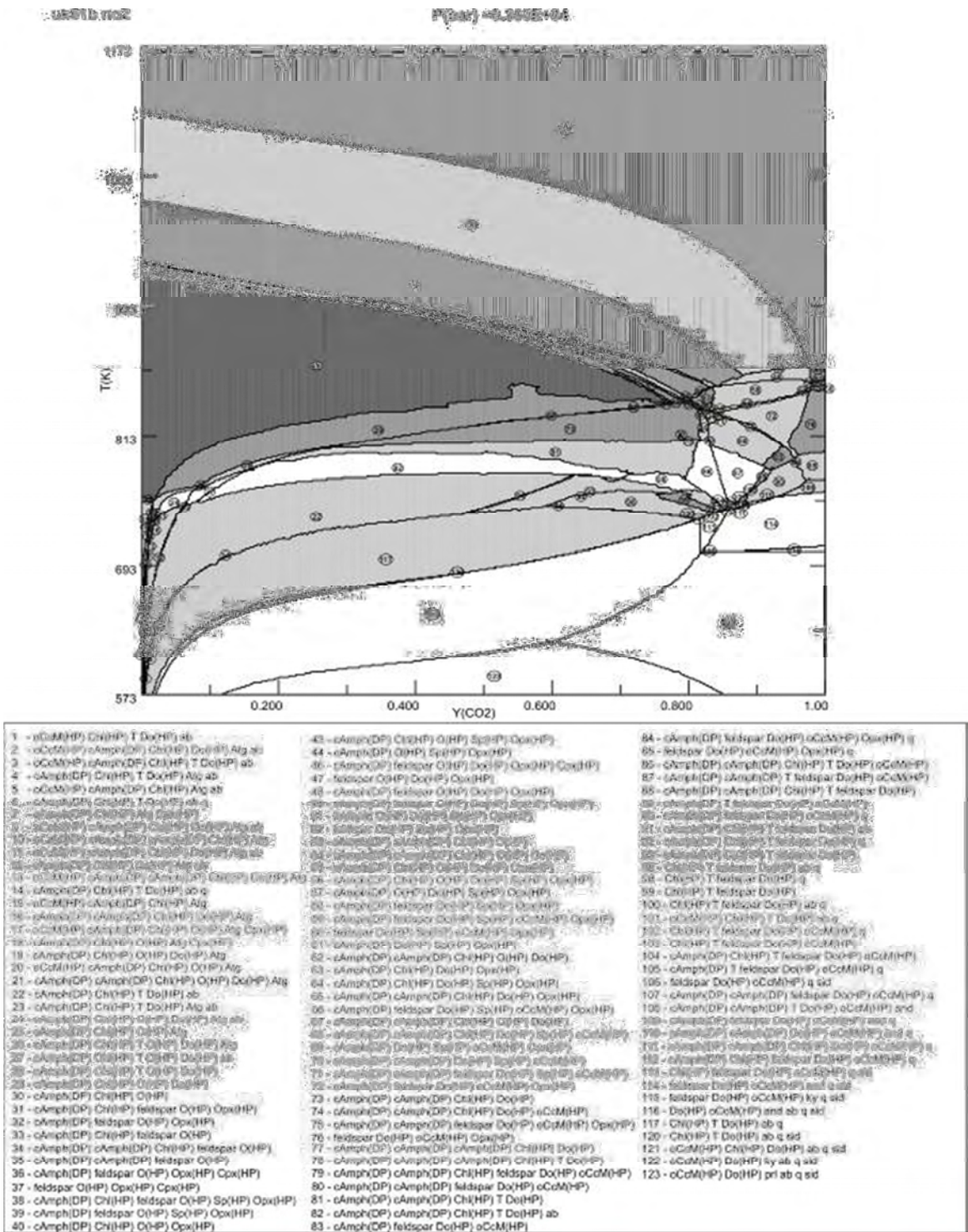
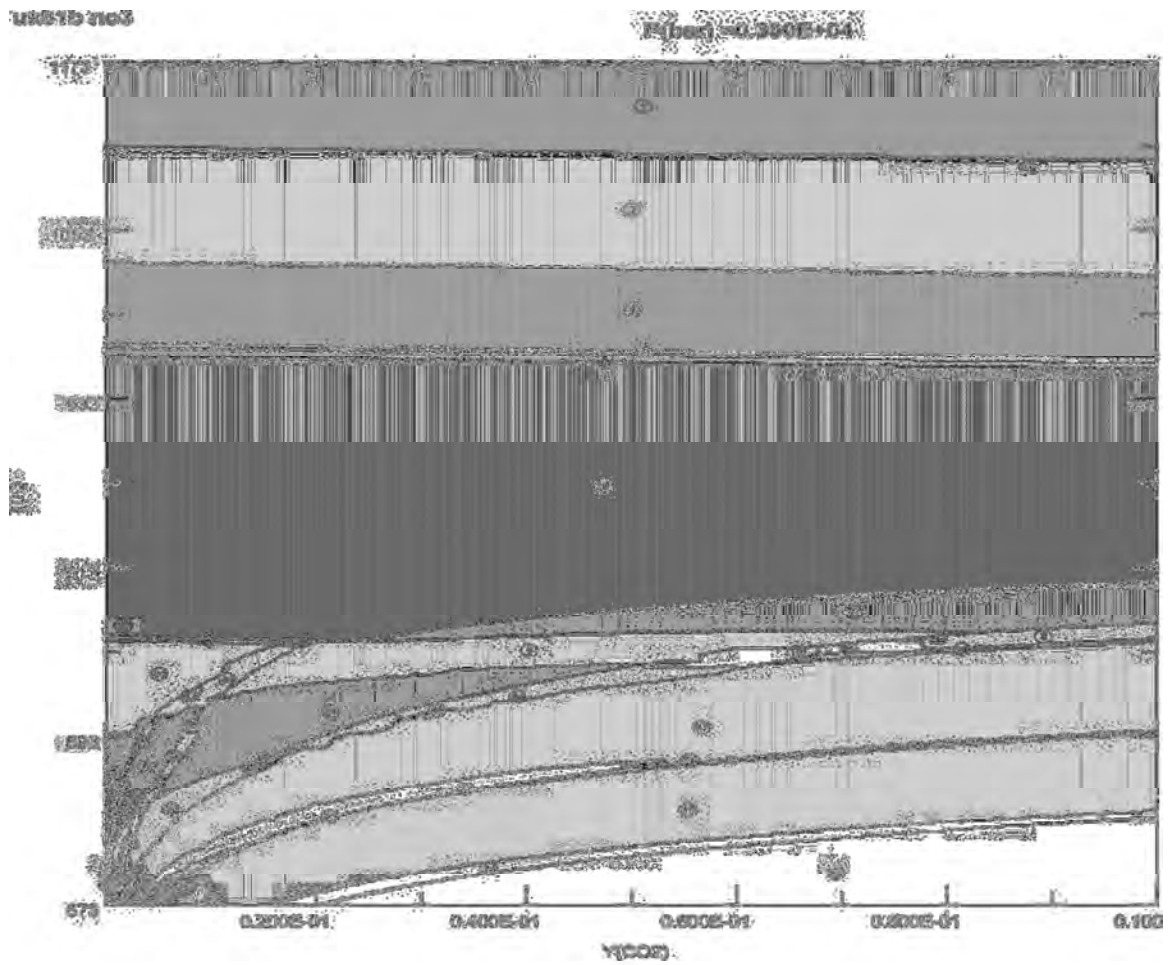


Figure 8.12: Pseudo-section for UK61B T-X(CO₂).



1 - feldspar Qtz(Hp) Cpx(Hp) Cls(Hp)	20 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
2 - feldspar(DP) feldspar Qtz(Hp) Qtz(Hp) Cpx(Hp)	21 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
3 - feldspar(DP) Chl(Hp) feldspar Qtz(Hp) Cpx(Hp)	22 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
4 - feldspar(DP) Chl(Hp) feldspar Qtz(Hp) Cpx(Hp)	23 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
5 - feldspar(DP) Chl(Hp) T Do(Hp) Ab q	24 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
6 - cAmph(DP) Chl(Hp) O(Hp) Do(Hp)	25 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
7 - cAmph(DP) Chl(Hp) T O(Hp) Do(Hp)	26 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
8 - cAmph(DP) Chl(Hp) T O(Hp) Do(Hp)	27 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
9 - cAmph(DP) Chl(Hp) O(Hp) Do(Hp) Alq	28 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
10 - cAmph(DP) Chl(Hp) T O(Hp) Do(Hp) Alq	29 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
11 - feldspar cAmph(DP) Chl(Hp) T O(Hp) Do(Hp)	30 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
12 - cAmph(DP) Chl(Hp) T O(Hp) Do(Hp) Ab	31 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
13 - cAmph(DP) Chl(Hp) T Do(Hp) Ab	32 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
14 - cAmph(DP) Chl(Hp) T Do(Hp) Ab	33 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
15 - Chl(Hp) T Do(Hp) Ab q	34 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
16 - cAmph(DP) Chl(Hp) Do(Hp) Ab q sid	35 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
17 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q	36 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
18 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q	37 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
19 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q	38 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
20 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q	39 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
21 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q	40 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
22 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q	41 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
23 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q	42 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
24 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q	43 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
	44 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
	45 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
	46 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
	47 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q
	48 - cAmph(DP) Chl(Hp) T Do(Hp) Ab q

Figure 8.13: Pseudo-section for UK61B T-X(CO₂).

8.9 Deuteric Fluid Compositions

The lateral distribution of elements, due to the effect of the hydrothermal alteration, based on borehole averages, does not seem to indicate a discernable distribution over the entire complex, for the boreholes analysed. There is little to no consistency in the hydrothermal alteration signature, as determined by the isocon method, both within and between units. This would suggest that the hydrothermal fluid responsible for the alteration was not derived from a magmatically generated fluid. A late-stage magmatic fluid would concentrate incompatible elements and it is expected that such an enrichment trend would be obvious in the isocon diagrams.

In the light of both the inconsistent enrichment and depletion trends shown by the isocon method and the apparent mobilization of Th and U it is suggested that the fluid was mixture of magmatic and meteoric fluids. The mobilization of Th and U in a carbonate-rich fluid environment was indicated earlier. Assimilation of dolomite country rock is the most obvious source of such a carbonate-rich fluid, releasing meteoric water into the system. The isotope study of Sakar et al. (2005) supports this hypothesis of assimilation of a crustal component. However, in a later study by Sakar et al., (2008) assimilation of country rock is indicated not to have taken place in the Uitkomst Complex, but field evidence to the contrary, in especially the LHZBG, is neglected.

The CO₂-rich fluids are capable of transporting certain elements more effectively e.g. Th and U (Dawood et al., 2004) and Ti and Al (Hynes, 1980) relative to an H₂O-rich fluid. It is suggested here that the deuteric fluid was very variable in composition and possibly pH and Eh (no work was done to establish this proposition). The mineralogy suggest variable X_{CO2} conditions such as high X_{CO2} conditions for the formation of talc and low X_{CO2} conditions for the formation of serpentine. This non-homogeneous fluid composition led the variable enrichment and depletion of elements observed in this study.

It is not possible to constrain the exact T-X(CO₂) conditions that prevailed in the two units investigated. It is however evident that a broad range of CO₂-partial pressures and temperature ranges would be able to achieve the assemblages observed in these units. It is suggested that only the effect, of the last set of conditions that prevailed in the system is reflected by the observed mineral assemblages. Earlier assemblages that were amenable to later over-printing would not be preserved in the current samples.

It is suggested that the X(CO₂) conditions in the LHZBG were more hydrous with a lower CO₂ content during the final retrograde event that affected this unit. In contrast the last retrograde event that affected the PCR had a higher X(CO₂), resulting in the stabilization of a larger amount of talc-carbonate-chlorite assemblage. It is suggested that the assemblages indicate cooling and buffering towards progressively lower X(CO₂) conditions in the system.

The lack of correlating assemblages in the M(H₂O) pseudo-section, due to the presence of albite, feldspar and orthopyroxene, would suggest that either: a) the system was disrupted not to produce the expected assemblages or b) that the system was not hydrated by the addition of external water to the system during formation. The presence of retrograde metamorphic assemblages eliminates the last option.