

Alteration Typology and Geochemical Signatures of the Napélépéra Gold-Bearing Granodiorite in South-West Burkina Faso (West Africa)

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Abstract

The characterization of the relationships between mineralization and hydrothermal alteration is an essential element in understanding gold deposits. In south-west Burkina Faso, the Napélépéra mineralisation, the mobility of chemical elements and alteration-mineralization relationships were studied by means of selected core drilling and geochemical analyses using ICP-MS (Inductively Coupled Plasma Mass Spectrometry) and ICP-AES (Inductively coupled plasma atomic emission spectroscopy). The mineralised granodiorite is grey porphyroid with quartz, plagioclase, biotite and amphibole. It is meta-luminous and located in the tholeiitic series. The $\text{Na}_2\text{O} + \text{CaO}$ versus $\text{Fe}_2\text{O}_3 + \text{MgO}$ alteration diagram divides the samples according to alteration dominance. Chloritisation and carbonation are the main alterations. There is a relationship between gold mineralisation at Napélépéra and alteration, and the paragenesis of gold + pyrite ± carbonate ± silica ± sericite is the main characteristic. Carbonation is the result of fluid input in the shear corridor of the mineralised zone. The mass balance of comparative metals in the proximal and distal zones of the mineralisation shows the absence of metals, while As, Hg, Ag and Bi are strongly enriched from the distal zone to the mineralised zone. The oxides associated with the mineralisation are mainly NaO, SrO and CaO.

Keywords

Gold Mineralization, Alteration, Mass Balance Granodiorite

1. Introduction

Hydrothermal ore deposits are formed by concentrating large volumes of hydro-

thermal fluids in confined environments in the earth's crust to give economic mineral concentrations [1] [2]. These economic concentrations of metals occur in environments with imbalances in parameters such as pH, pressure, temperature and oxygen content [3]. The mobility of chemical elements characterises the imbalance in parameters and creates a geochemical dispersion that is characteristic of deposits. On the one hand, the circulation of these fluids at different levels of the crust is very often attributable to plutonism, which favours mineral remobilisation in the surrounding rocks [4] [5] [6]; on the other hand, the orogenic phenomena responsible for the major geological structures create favourable conditions for the circulation of fluids and hydrothermal alteration [7]. In all likelihood, irrespective of the composition of the initial fluid, interaction with the host rock causes a mineralogical transformation reflected by gains or losses in chemical elements, which characterises a given mineralisation: this is its signature. Once identified, this signature provides a reference point for investigation and a practical guide for exploration. In the Napélépéra gold-bearing granodiorite, the circulation of mineralising fluids occurred in a ductile-breaking shear context marked by brecciation of the host rock and emplacement of mineralised micro veins [8]. As a result, the only work carried out in this zone of interest consisted of a structural study, but no tangible data on the nature and contribution of the fluids is available to better characterise the mineralisation. Clearly, the scenario fills this gap as part of a drive to improve petrographic and geochemical knowledge of the Napélépéra pluton and give it a metallogenic identity at this scale of investigation. This study will show the existing link between alteration and mineralization due to the mobility of metals in the process of establishment of the Napélépéra deposit.

2. Geological Context

The Napélépéra mineralisation is located in south-west Burkina Faso (**Figure 1**), in the Gaoua-Batié belt, which is the southern extension of the Boromo belt [7] [9]. The geological environment is made up of basic, intermediate and acid volcano-plutonic meta-formations (basalt, gabbros, granite) and volcano-sedimentary metaformations (chert, silt, sandstone) forming the prolific Gaoua-Batié belt. The meta-volcanics are in the form of mafic aphyric and porphyric lavas \pm foliated and topped by cherty levels sometimes heavily impregnated with iron oxide, giving BIFs (Banded Iron Formation). Intermediate terms of \pm magnetic andesites are intercalated in basalts and sediments. The lithofacies as a whole is cut by polycyclic, structured granitic masses of the Tonalite-Trondhjemite-Granodiorite series [10] [11]. The elliptical, NW-SE-trending Napélépéra granodiorite, approximately 24 km long and 10 km wide, occupies a central position and its cartographic representation suggests a late emplacement on the aforementioned units. In short, it is embedded in the TTGs and its NE edge is in contact with the basalt-Gabbro units of the Gaoua-Batié belt [12] [13].

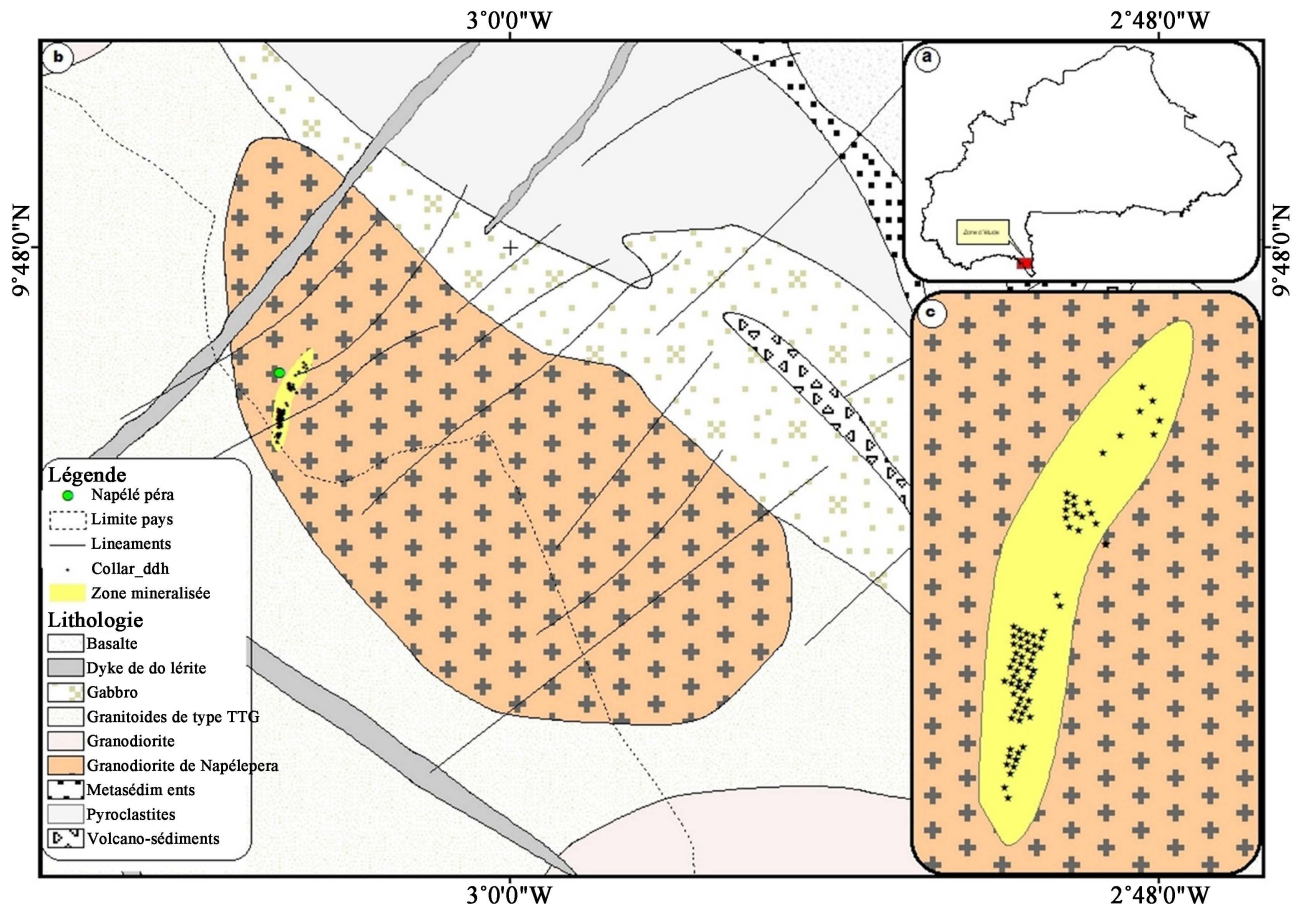


Figure 1. Geological map of the study area (Modified from [14]). (a) Location of the study area on the map of Burkina Faso; (b) Local geology; (c) Mineralised zone in the granodiorite.

3. Materials and Methods

Geoscientific literature on gold mineralisation associated with birimian granitoids and their geodynamic context preceded the field investigations. This work consisted of a selection of seventeen (17) benchmark core holes with well-known mineralised intersections, for detailed descriptions using acid-supported magnifying glasses and magnetic pencils, backed up by microscopic details.

To better constrain the spatial evolution of alteration associated with mineralisation, eight (08) samples were taken based on the degree of alteration in three (03) of the drill holes selected for geochemical analysis using ICP-MS (Inductively Coupled Plasma Mass Spectrometry) and ICP-AES (Inductively coupled plasma atomic emission spectroscopy). The results of these multi-element analyses are presented in **Table 1** below. The mobility of the chemical elements and their relationship with the types of alteration and mineralisation were interpreted using nomenclature and chemical affinity diagrams.

4. Results and Discussions

In the almost total absence of outcrops, core drilling provides a better overview of the Napélépéra pluton at depth. The pluton has undergone extensive weathering up

Table 1. Multi-element analyses (major and trace elements) of the Napélépéra granodiorite.

Element (wt %)	N20	N21	N46	N47	N49	N50	N51	N53
SiO ₂	62.9	60.4	56.4	52.2	55.5	60.7	49	56
Al ₂ O ₃	15.5	13.45	14.6	11.5	14.55	16	15.6	14.85
Fe ₂ O ₃	5.81	3.97	6.25	7.77	6.33	7.35	6.88	6.68
CaO	5.59	5.24	6.34	6.81	5.65	6.29	6.96	6.31
MgO	2.76	1.82	3.53	2.78	2.78	3.74	3.32	3.11
Na ₂ O	4	7.73	3.14	5.25	2.8	4.23	2.86	3.6
K ₂ O	0.58	0.14	1.28	0.81	2.16	0.72	2.22	0.96
Cr ₂ O ₃	0.011	0.007	0.013	0.011	0.011	0.014	0.013	0.013
TiO ₂	0.53	0.36	0.6	0.53	0.61	0.63	0.61	0.62
MnO	0.08	0.06	0.09	0.09	0.07	0.09	0.09	0.06
P ₂ O ₅	0.18	0.03	0.22	0.27	0.21	0.22	0.21	0.22
SrO	0.06	0.06	0.05	0.09	0.04	0.06	0.04	0.03
BaO	0.03	<0.01	0.03	0.02	0.06	0.03	0.04	0.03
LAW	2.17	7.03	8.34	8.05	9.12	1.89	11.15	7.4
Total	100.2	100.3	100.88	96.18	99.89	101.96	98.99	99.88
C	0.17	2.1	1.69	2.72	2.09	0.07	2.76	1.24
S	0.01	0.63	<0.01	3.46	0.04	0.02	<0.01	<0.01
Ba (ppm)	281	39.2	273	199.5	548	268	311	275
This	37.4	21.6	34.1	38.7	29.3	37.6	36.7	32.1
Cr	70	50	80	70	80	110	100	100
Cs	0.16	0.08	0.6	0.26	0.68	0.27	0.67	0.36
Dy	1.91	0.89	2.14	2.88	1.93	2.72	2.2	1.69
Er	1.04	0.5	1.12	1.3	1.04	1.33	1.06	0.82
Eu	1.08	0.53	1.26	1.24	1.1	1.42	1.12	0.85
Ga	17.2	27.5	17.2	19	22.4	23.7	22.6	20.1
Gd	2.56	1.28	2.91	4.08	2.84	4.18	3.01	2.22
Ge	<5	<5	<5	<5	<5	<5	<5	<5
Hf	4.2	2.1	2	6.6	4.4	3.7	3.1	2.6
Ho	0.37	0.17	0.39	0.46	0.36	0.5	0.41	0.31
La	16.6	9.6	14.6	14.6	12	14.3	15.8	15
Lu	0.13	0.07	0.12	0.16	0.13	0.16	0.15	0.12
Nb	5.1	5.2	4.1	3.5	4.7	4.2	4.5	4.7
Nd	17.6	9.9	17.9	23.2	16.7	23.4	19.6	15.7
Pr	4.37	2.44	4.19	5.27	4.03	5.46	4.89	4.02

Continued

Rb	12.8	3.3	28.4	17.6	48.9	12.2	51.9	22.5
Sm	3.09	1.73	3.48	4.7	3.46	4.69	3.84	2.71
Sn	1	1	1	1	2	2	1	1
Sr	508	553	419	834	394	527	385	302
Your	0.3	0.3	0.1	0.1	0.3	0.2	0.3	0.4
Tb	0.34	0.16	0.36	0.51	0.35	0.52	0.41	0.27
Th	0.96	1.46	0.54	0.87	0.48	0.34	0.62	0.85
Tm	0.16	0.09	0.16	0.17	0.15	0.22	0.18	0.12
U	0.23	0.6	0.22	0.64	0.39	0.12	0.22	0.46
V	99	31	114	79	112	116	126	110
W	<1	14	1	15	16	1	9	2
Y	9.8	4.1	10.2	12.4	9.8	13.8	11	8
Yb	0.9	0.52	0.98	1.08	0.89	1.12	0.96	0.75
Zr	173	79	90	298	207	154	125	113
As	0.4	1	<0.1	27.5	0.1	0.2	<0.1	<0.1
Bi	0.01	0.03	0.01	0.09	0.01	<0.01	0.01	0.02
Hg	0.008	0.007	<0.005	0.021	<0.005	<0.005	<0.005	<0.005
In	0.01	0.02	0.025	0.021	0.019	0.012	0.02	0.026
Re	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001
Sb	<0.05	<0.05	<0.05	0.12	<0.05	<0.05	<0.05	<0.05
Visit	<0.2	0.3	<0.2	1.2	<0.2	<0.2	<0.2	<0.2
Te	0.01	1.62	0.02	7.07	0.06	0.01	0.01	0.12
Tl	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Ag	<0.5	0.5	<0.5	2.5	<0.5	<0.5	<0.5	<0.5
Cd	<0.5	<0.5	<0.5	0.5	<0.5	<0.5	<0.5	<0.5
Co	17	15	24	24	21	23	25	23
Cu	25	12	103	33	46	52	68	24
Li	10	<10	40	<10	20	10	20	40
Mo	<1	17	<1	<1	<1	<1	<1	<1
Ni	57	37	77	66	68	68	70	78
Pb	2	7	6	9	5	2	<2	3
Sc	10	8	13	12	12	15	15	12
Zn	59	55	84	86	144	92	92	87

to sixty (60) metres thick, with limonite predominating over haematite and kaolinite. In the fresh zone, this results in a variation in petrographic appearance that can be observed macroscopically from the distal zone to the mineralised

zone. This appearance reflects a kind of alteration zonation on a macro scale and the substitution of pink and pink grey colour for the grey colour characteristic of the pluton depending on the degree of hydrothermal alteration.

4.1. Petrography and Geochemistry of Granodiorite

The Napélépéra pluton contains basic xenoliths and is cut by dolerite dykes (**Figure 2(a)**). Overall, the structure of the pluton is slightly foliated (**Figure 2(b)**) to massive. The texture is gritty porphyroid in a mineralogical matrix of the order of a millimetre. The main minerals are quartz (20% - 25%), plagioclase (15% - 20%), biotite (30% - 35%) and amphibole (10% - 15%) (**Figure 2(c)** & **Figure 2(d)**). Alkali feldspars account for a small proportion (1% - 5%). In general, plagioclase alters to sericite, quartz occurs either in xenomorphic form with rolling extinction characteristic of primary quartz or in recrystallised or cracked form under the pressure-temperature effect of deformation. Biotite is abundant with a slight mineral orientation and amphibole alters to chlorite.

The Napélépéra pluton shows high levels of Al_2O_3 while the sum of alkalis $\text{Na}_2\text{O} + \text{K}_2\text{O}$ (4.42% - 5.08%) is low except in the mineralised zone where it is \approx 6% - 7%. The TAS diagram shows a dioritic composition (**Figure 3(a)**) for the granodiorite. It is located in the tholeiitic and calc-alkaline series (**Figure 3(b)**) of the SiO_2 - K_2O diagram except for highly altered samples. It is metaluminous (**Figure 3(c)**) according to the $\text{Fe} + \text{Mg} + \text{Ti}$ vs. $\text{Al} - (\text{K} + \text{Na} + 2\text{Ca})$ diagram. The

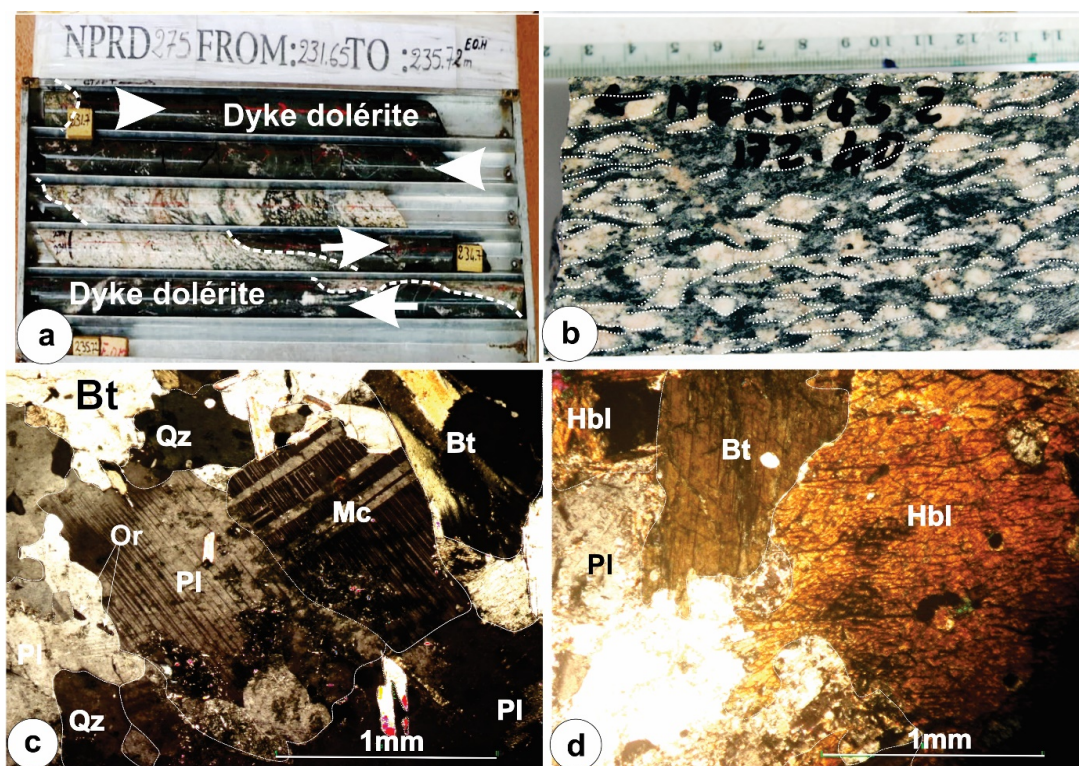


Figure 2. Macroscopic and microscopic photographs of the Napélépéra granodiorite. (a) dolerite dyke intersecting the granodiorite; (b) slight foliation of the granodiorite; ((c), (d)) microscopy of the granodiorite, Pl = Plagioclase, Or = Orthoclase, Qz = Quartz, Bt = Biotite, Mc = Microcline, Hbl = Hornblende, Py = Pyrite.

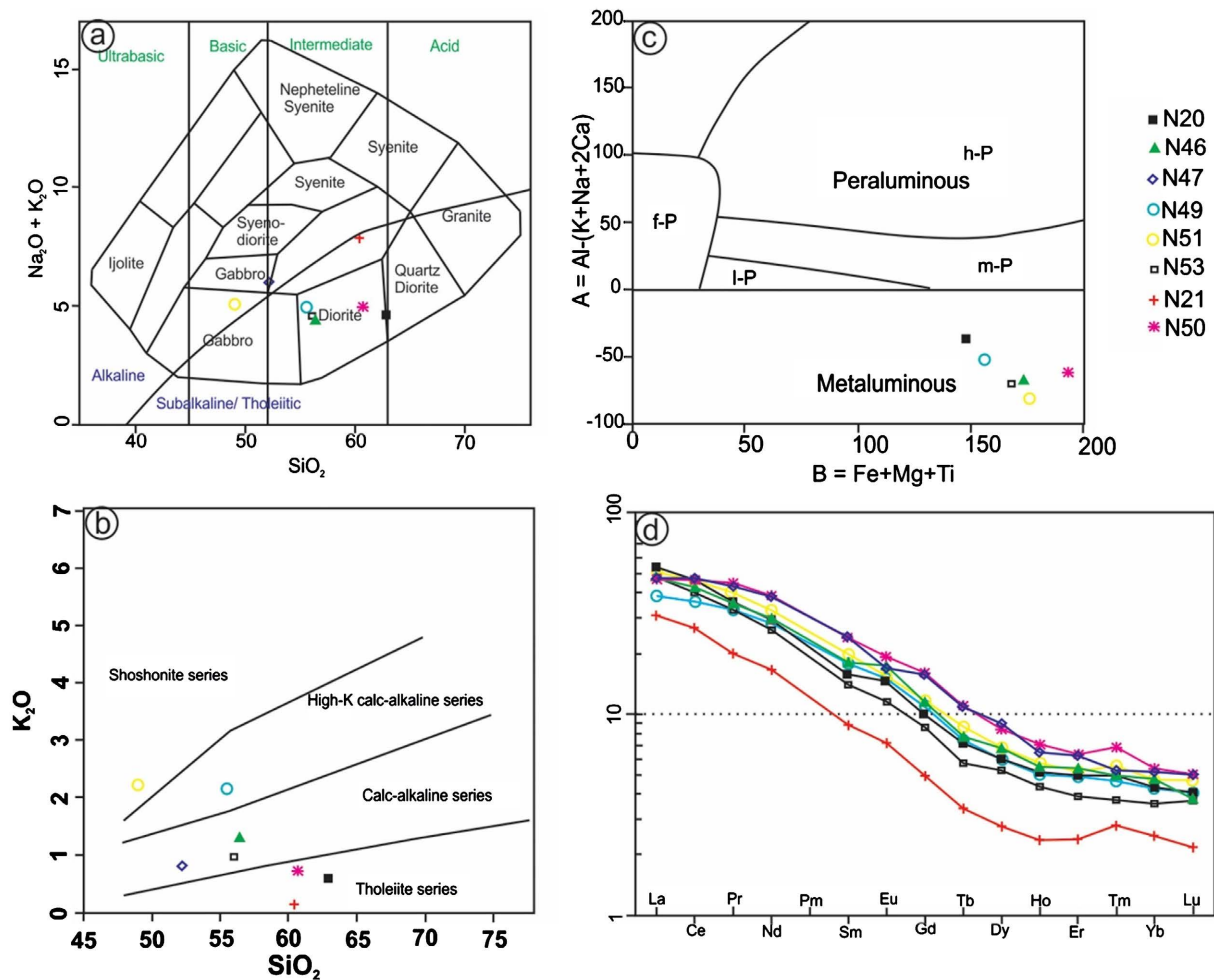


Figure 3. Classification diagram for the Napélépéra granitoid (a) Nomenclature diagram [15]; (b) magmatic affinity diagram [16]; (c) granitoid discrimination diagram [17]; (d) rare earth profile.

REE pattern (**Figure 3(d)**) shows a parallelism of spectra that could suggest a cogenetic link between the samples. Microscopic precision reveals that, apart from the variable nature of the alteration, the samples come from the same rock.

4.2. Characteristics of Alterations

The alterations deduced from the multi-scale observations define zones, each with a predominant type of alteration. They form paragenetic associations based mainly on chlorite, carbonate sericite and quartz.

Chloritisation: Chlorite replaces the ferromagnesian phases of granodiorite. It is developed on biotite and amphibole minerals. It occurs as a free mineral around grains of quartz or pyrite (**Figure 4(a)**) when the alteration is intense and as veinlets associated with sericite (**Figure 4(b)**).

Chlorite is found in varying proportions throughout the rock, with a predominance in the distal zone, where in places it is the only alteration mineral. The paragenesis chlorite + sericite \pm silica is formed in these zones.

Sericitisation: Sericite is the second most common alteration mineral found

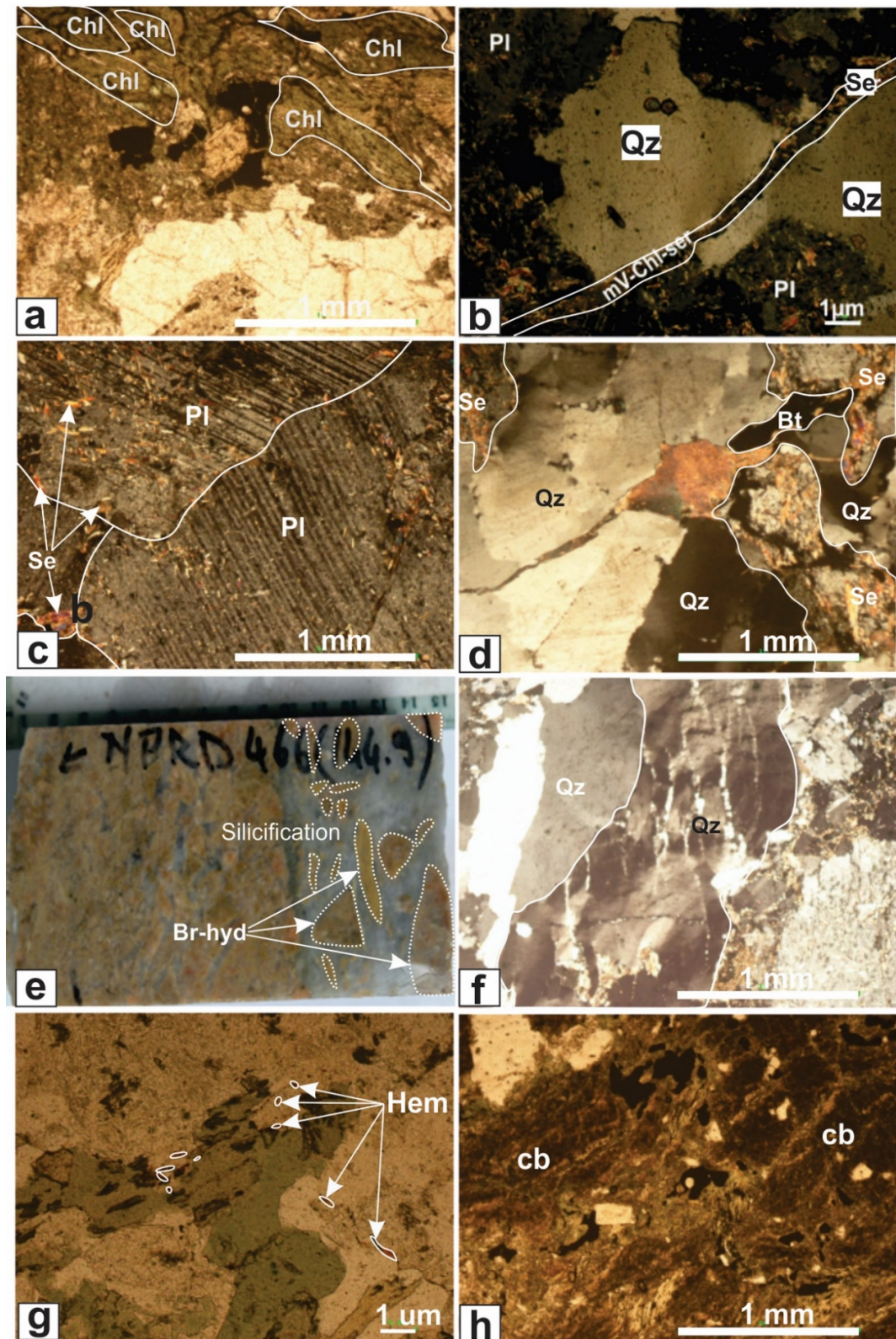


Figure 4. Alteration typologies. (a) photograph of chlorite minerals; (b) chlorite-sericite microvein; (c) plagioclase sericitisation; (d) sericite microvein; (e) silica brecciation; (f) quartz recrystallisation; (g) photograph of hematite minerals; (h) carbonate circulation. Qz = Quartz or recrystallised quartz; Cb = carbonate; Hem = Hematite; Se = sericite; Br-hyd = hydraulic breccia; Pl = Plagioclase; Chl = chlorite.

in rock. Macroscopically, it appears as fine flakes with a silky sheen. Microscopically, it forms a matrix of small needles overprinting the shapes of the feldspar relics from which it is derived (Figure 4(c)). It is also present in the form of veinlets, associated with chlorite or calcite (Figure 4(d)). Sericite is intense in the proximal mineralised zone where it is associated with carbonate. Where sericite predominates, it is mainly associated with carbonate and secondarily with silica and chlorite. In these zones, the paragenesis sericite + carbonate \pm silica \pm chlorite is formed.

Silicification: This is associated with quartz or quartz-carbonate veins, invasive silicification breccias (Figure 4(e)), or in pervasive form as very fine or re-crystallised quartz grains (Figure 4(f)). Silicification is observed in all the cores described.

Carbonation: Carbonates appear in the form of 1) free grains, 2) veinlets and 3) fine micrometric matrix carbonate grains, 4) intense circulation accompanied by haematisation (Figure 4(g)). Carbonation is frequently only observed in the proximal, mineralised zone. In the mineralised zone, the rock is almost completely replaced by carbonates (Figure 4(h)). Carbonation is often associated with oxidation. The association of carbonate + silica \pm sericite is characteristic of these zones.

From the diagram of alterations $\text{Na}_2\text{O} + \text{CaO}$ versus $\text{Fe}_2\text{O}_3 + \text{MgO}$ [18], the distribution of samples confirms chloritisation and carbonation as the main alterations (Figure 5). Samples N20 and N46 are healthy to slightly chloritised

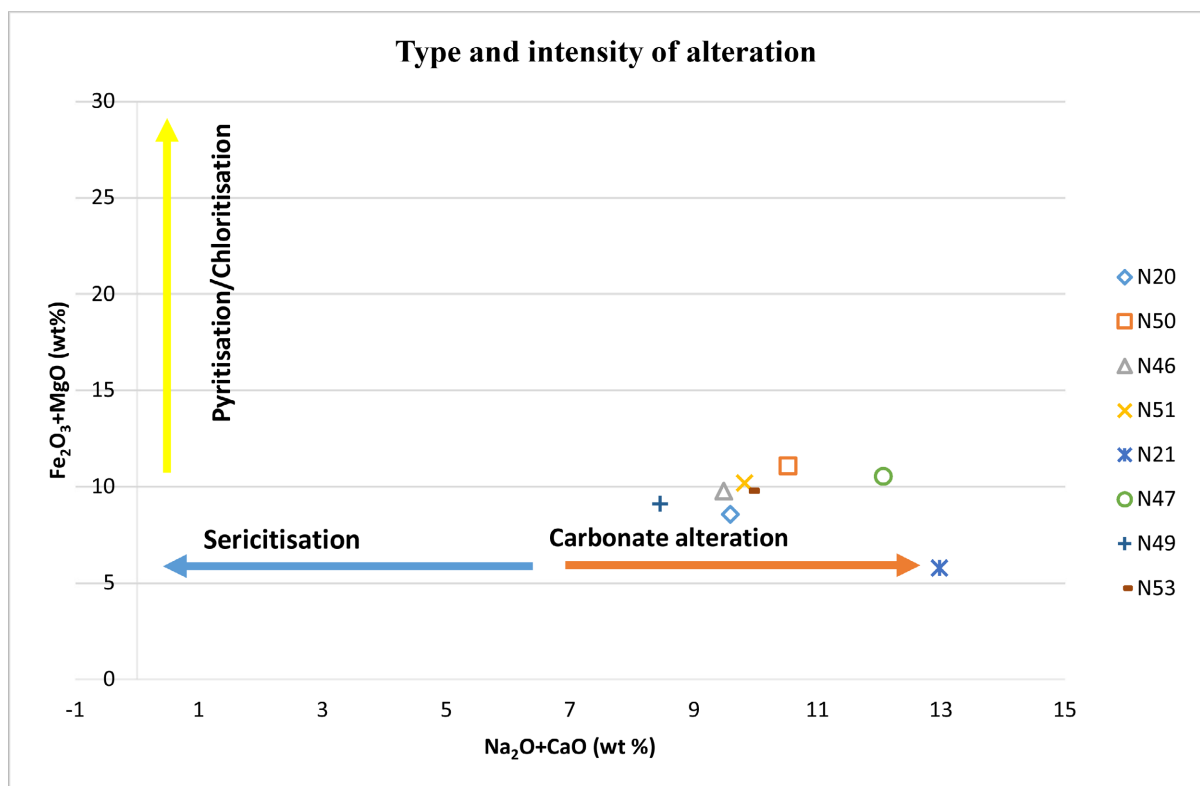


Figure 5. Diagram from [18] showing the types and intensity of alteration in the Napélépéra deposit.

samples. Sample N49 in the proximal zone is sericitised. Samples N21 and N47 from the mineralised zone have strong carbonate alteration with a high pyrite concentration for N47. The intensity of carbonation increases from the distal zone (N20, N46) to the proximal zone (N51) to the heart of the mineralisation (N21, N47).

4.3. Relationship between Alteration and Mineralisation

Although several types of alteration have been described in the Napélépéra gold-bearing granodiorite, carbonation is the alteration associated with mineralisation. The paragenesis gold + pyrite ± carbonate ± silica ± sericite characterises the gold mineralisation at Napélépéra (**Figure 6**). This carbonation is the result of fluid input in the shear corridor of the mineralised zone. This alteration is characteristic of intrusive-related gold mineralisation described by [19] and [20]. These alterations have the same characteristics as those described in NW Ghana in the Julie gold deposit [21] [22] and in the Chirano district [23].

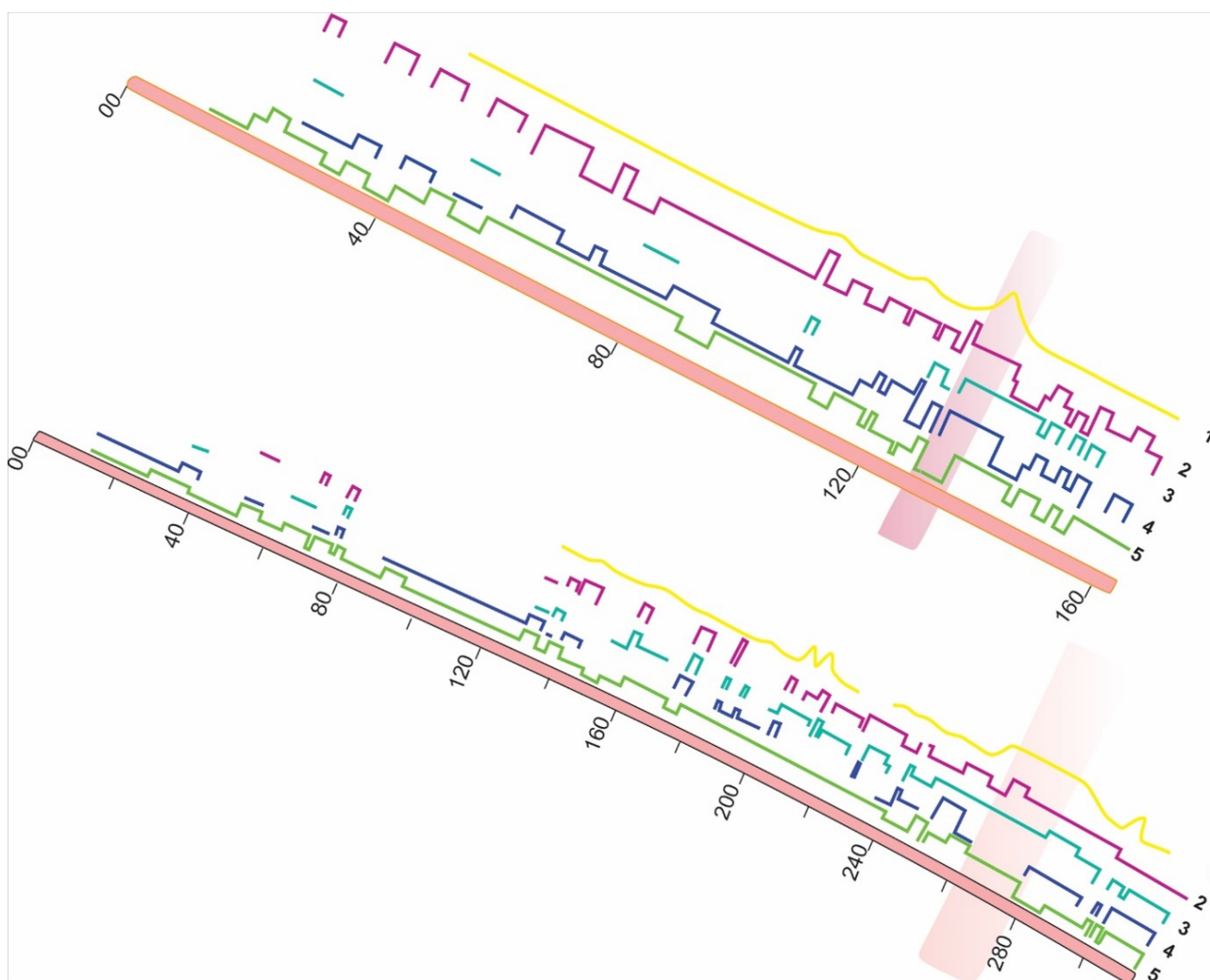


Figure 6. Relationships between alteration and mineralisation. 1) percentage change in pyrite; 2) intensity of silicification; 3) intensity of carbonation; 4) intensity of sericitisation; 5) intensity of chloritisation.

4.4. Geochemical Signature

The geochemical balance of the major elements and metals in the mineralised zones (ZM), compared with that in the proximal (ZP) and distal (ZD) non-mineralised zones, shows that the mineralising fluids have induced leaching of chemical elements characterised by ratios of less than 1 and input when these ratios are greater than 1 (**Figure 7**). The SiO_2 shows a mass balance that is justified by the forms in which the silica is observed, either in the form of invasive silicification that brecciated the granodiorite or in the form of recrystallisation.

The concentrations of Al_2O_3 are similar in samples taken from all levels. Feldspars are the main minerals containing this oxide and, as they weather to form sericite, the Al_2O_3 content did not vary significantly during the weathering process, which was marked by relatively little leaching.

Fe_2O_3 remains balanced between the proximal and distal facies due to the relatively low intensity of hydrothermal alteration. Its mass balance compared with the mineralised zone shows an enrichment due to the oxidation of pyrite and the formation of haematite minerals.

CaO is depleted in the proximal zone due to the alteration of the plagioclase to sericite. The contribution of mineralising fluid has favoured the carbonation process characteristic of mineralisation and is shown by a contribution in the mass balance compared between ZM and ZP.

MgO is depleted in both the proximal and mineralised zones. This depletion is due to the leaching of Mg^{2+} ions during the alteration of ferromagnesian minerals (biotite and amphibole).

Na_2O : sodium oxide is the opposite of the other oxides analysed in all the samples. It is characterised by a slightly constant content in the healthy rock, with depletion in the proximal zones due to alteration of the orthoclase and microcline. An enrichment in the mineralised zone is characteristic of the contribution of mineralising fluids.

K_2O : the ZP/ZD ratio shows enrichment in potassium oxides due to the sericitisation of orthoclase and microcline and later leached by mineralising fluids through concentration.

Cr_2O_3 and TiO_2 remain virtually immobile during the hydrothermal alteration process.

MnO and SrO are enriched by carbonation.

The mass balance of comparative metals in the proximal and distal zones shows the absence of metals associated with sericitisation and chloritisation. Metal enrichment is the result of the circulation of mineralising fluid. As, Hg, Ag and Bi were enriched 8 to 650 times, depending on the metal, from the distal zone to the mineralised zone (**Figure 7**). The high content of Na_2O and SrO in the Napélépéra mineralisation could be explained by an influx of fluid rich in these metals. It forms a peak in the mineralised zone, as do metals and non-metals such as arsenic (As), tellurium (Te), silver (Ag), mercury (Hg), bismuth (Bi) and selenium (Se). This phenomenon would justify these elements having

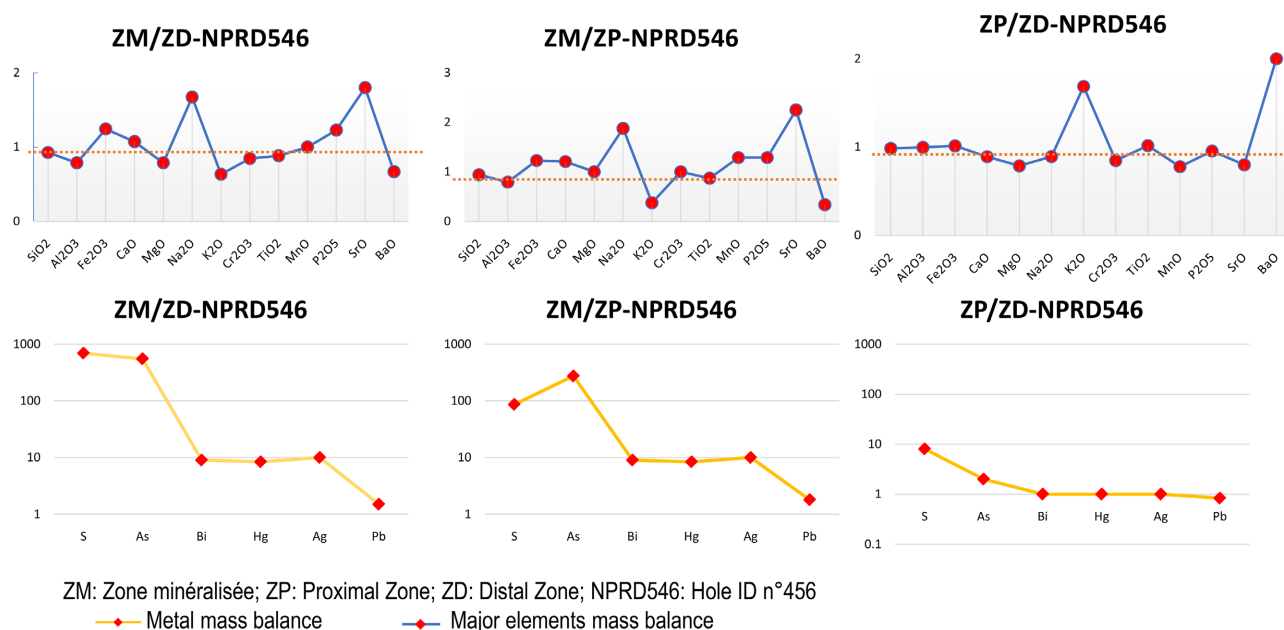


Figure 7. Mass balance of major elements and metals.

the same source of enrichment.

5. Conclusion

The Napélépéra mineralisation in southwest Burkina Faso is characterised by quartz-carbonate-sulphide microveinlets and sheared quartz veins. It is characterised by intense hydrothermal alteration in the proximal and mineralised zones. This study has characterised mineral alteration and geochemical dispersion in order to deduce the relationship between mineralisation and hydrothermal alteration. The association of gold, pyrite, carbonate and quartz is characteristic of the mineralisation. The mass balance of metals shows a correlation with a high concentration of metals accompanying gold, such as arsenic, silver and mercury in the mineralised part. The oxides associated with mineralisation are mainly NaO, SrO and CaO, showing that the mineralising fluid is enriched in these elements.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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