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CAMBIOS POST-DEPOSICIONALES DEL YACIMIENTO SALOBO, PROVINCIA MINERAL DE CARAJAS, NORTE DE BRASIL

POST-DEPOSITIONAL CHANGES OF THE SALOBO ORE DEPOSIT, CARAJÁS MINERAL PROVINCE, NORTHERN BRAZIL

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INTRODUCTION

The Salobo polymetallic ore deposit (Cu-Au-Ag-Mo), located in the mining district of Carajás, Amazonian Region, is known as the largest copper deposit in Brazil, with a measured reserve of 157 Mt grading 1.21% Cu and 0.57g/t Au (Vieira et al.,1988). The primary mineralization is hosted by a late Archean iron formation which is part of the Salobo-Pojuca volcanic-sedimentary sequence (Farias & Saueressig, 1982). In the Salobo area, this volcanic-sedimentary sequence consists of metamorphosed basaltic rocks, iron formations, greywakes and arkosic arenites which are thought to have been deposited in an extensional continental rift basin, developed on the gneissic basement of the Xingu Complex (Docegeo, 1988). The ore forms concordant lens-like bodies which extend for more than 10 km along a strike of N70°W dipping 84°SW (Fig. 1A and B).

Docegeo (1988) included the rocks of the Salobo-Pojuca sequence in the Itacaiúnas Supergroup together with other volcanic-sedimentary sequence of the Carajás area which differ from the underlying granite-greenstone supracrustals. In general, the Itacaiúnas Su-

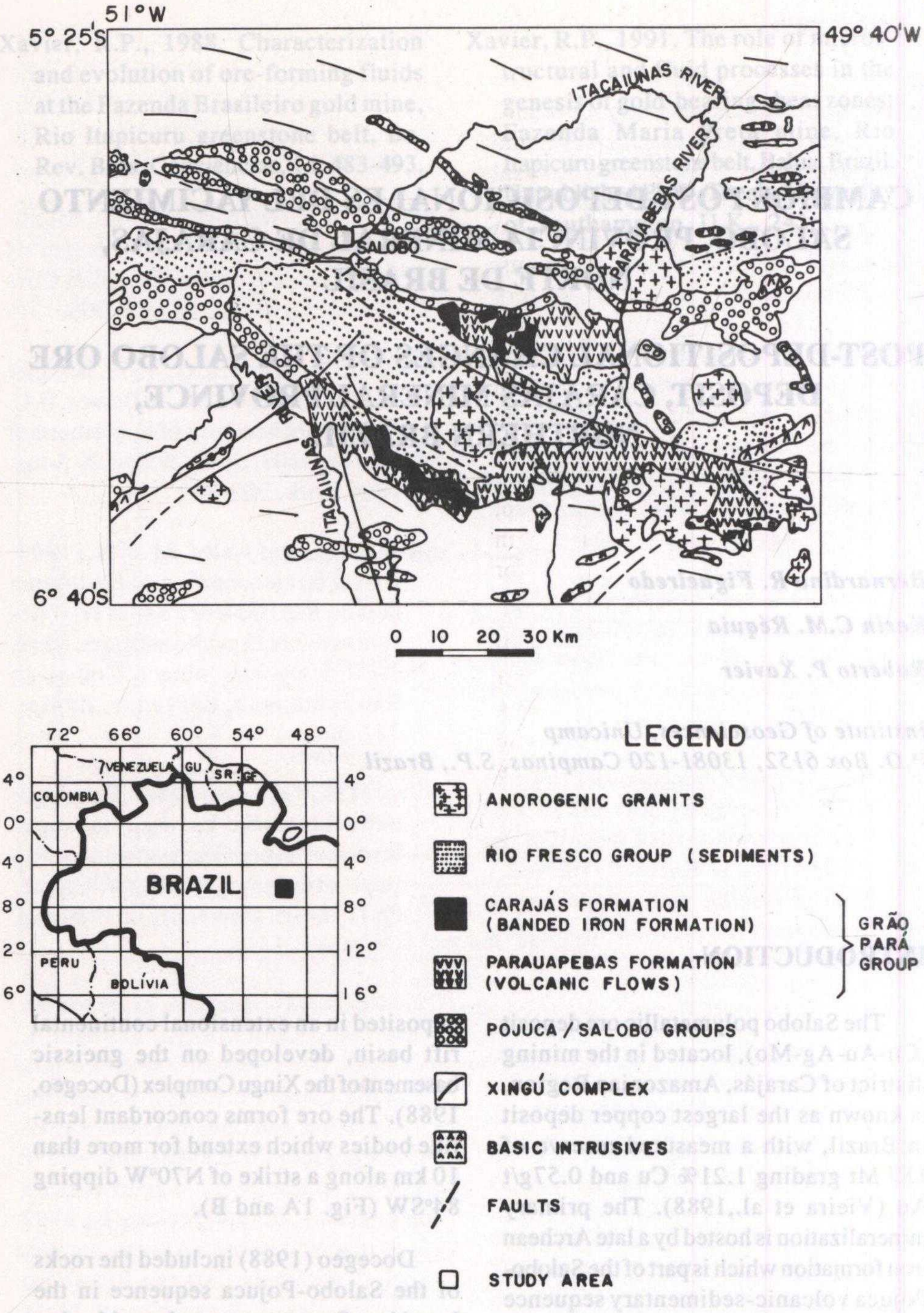

Fig. 1A: Carajás geological map (after Docegeo, 1988).

pergroup comprise basic and felsic volcanic rocks and chemical-terrigineous sedimentary rocks in its lower portion, and a thick clastic-sedimentary sequence on he top. This rock association and the bimodal character of the basal volcanism resemble, at a great extent, the stratigraphy of other Archean transtensional basins in other continents, e.g., the Hamersley Basin in Western Australia (Trendal, 1983). However, the scarcity of isotope data and the ambiguous interpretations of major and trace element geochemistry of volcanic rocks led to the present controversy between those who suggest a within plate rifting (Gibbs at al., 1986; Docegeo, 1988) or a convergent plate margin evolution (Dardenne et al.,1988) for the Itacaiúnas Supergroup.

Machado et al. (1991) obtained U/Pb zircon ages around 2859 M.a. for the migmatization of the Xingu Complex and 2851 M.a. for the amphibolites in the lower portion of the Salobo-Pojuca sequence and concluded that the latter is part of the Xingu basement complex, hence, older than the rocks of the Itacaiúnas Supergroup. On the other hand, in accordance with the tectonic model postulated by Araújo et al. (1988), the Salobo deposit, located at the northern portion of the Itacaiúnas shear belt, is part of a positive flower structure linked to a sinistral strike-slip system in which the tectonic transport occurred from SW to NE.

The high-grade metamorphosed iron formations of the Salobo deposit were classified by Lindenmayer (1990) in Type 1 (fayalite-magnetite or grunerite-magnetite with minor hastingsite, biotite, almandine, greenalite and fluorite) and Type 2 (magnetite-almandine-grunerite-biotite, with minor fayalite, hastingsite, tourmaline, chlorite, fluorite, greenalite and quartz). Lindenmayer (1990) also demonstrated that these iron formations underwent a progressive high temperature and low pressure metamorphism at conditions of a thermal gradient of 85°C/km, $P_{CO2}>P_{H2O}$ and low fO_2 at 2761 M.a. (Machado et al., 1991) or 2700 M.a. (Tassinari et al., 1982).

Still according to Lindenmayer (1990), these rocks were subsequently affected by two metamorphic-hydrothermal alteration episodes. The first episode occurred at 650-550°C and 2.5 kbar and was marked by intense shearing, emplacement of the Old Salobo Granite (2573 M.a. according to Machado et al., 1991), breakdown of fayalite and hastingsite into grunerite, magnetite and quartz, and the presence of slightly oxidizing, acidic and highly saline fluids. The second episode occurred at 370°C and was accompanied by the reactivation of shear zones and the chloritization of Fe-Mg minerals in the presence of slightly oxidizing, acidic and moderate saline fluids. These two metamorphic-hydrothermal events are suggested to have taken place before the uplift of the basement, which was dated in the interval 2581-2551 M.a. (Machado et al., 1991).

The Salobo sequence underwent reheating during the emplacement of post-tectonic granitoid intrusions like the Young Salobo Granite (1880 M.a. according to Cordani, 1981) but the influence of this anorogenic plutonism on the Salobo deposit is still uncertain.

This study attempts to relate the mineralogical and textural changes observed in the ores, as well as the types and evolution of the fluids, with the metamorphic-hydrothermal events postulated by Lindenmayer (1990), with the purpose of contributing to further assessment of alternative genetic models for the Salobo ore deposit.

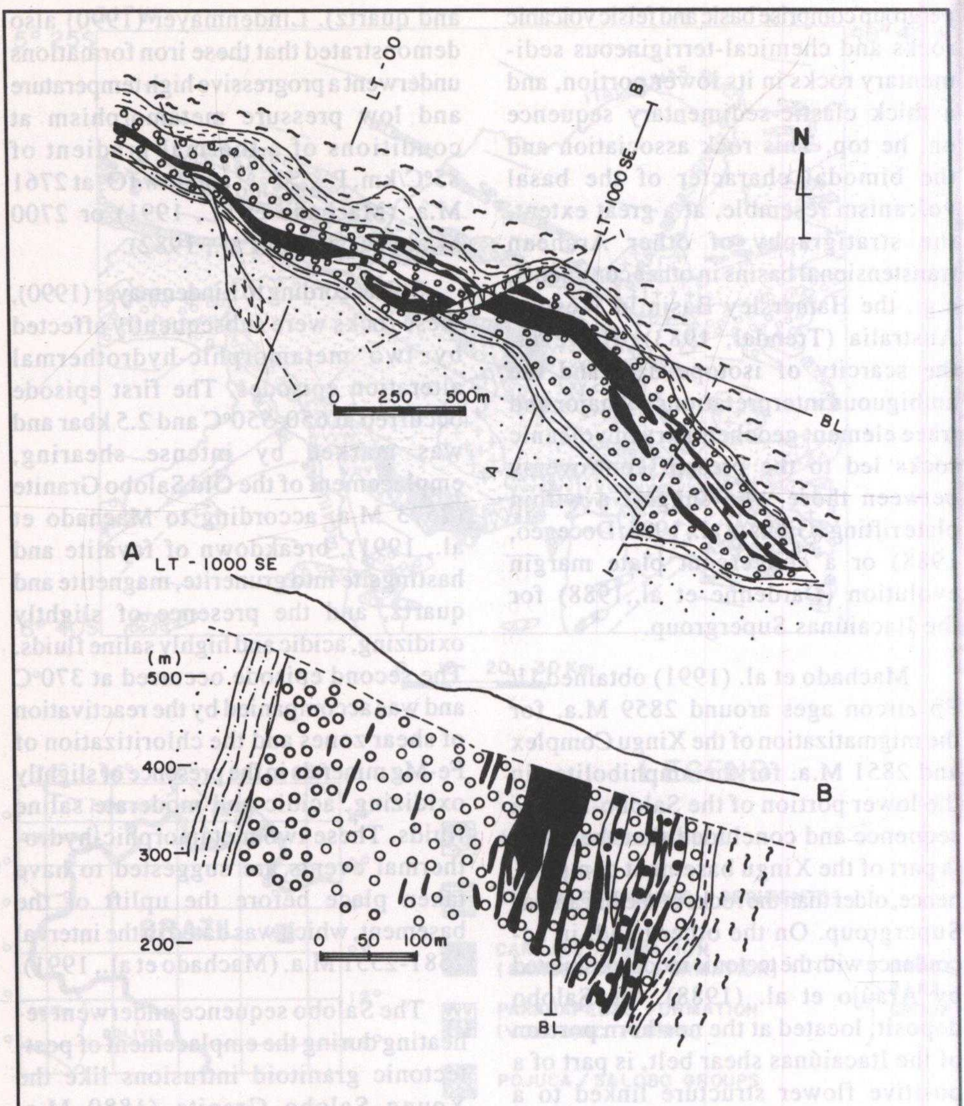

Fig. 1B: Salobo deposit geological map (Lindernmayer, 1990 modified after Docegeo, 1988).

MINERALOGICAL STUDIES

The mineralization at Salobo is formed by magnetite, chalcopyrite, bornite and chalcosite. Minor amounts of ilmenite, hematite, digenite, molybdenite, uraninite, graphite, saflorite, cobaltite and gold also occur in the ores, but the iron sulfides are rare. The mineralization occurs mainly disseminated in Types 1 and 2 silicate iron formations. Other non-opaque phases include tourmaline, fluorite, allanite, epidote, apatite, plagioclase, stilpnomelane and actinolite.

The magnetite-bornite-chalcosite assemblage is dominant and occurs in all host rock types. However, the occurrence of chalcopyrite seems to be restricted to the Type 1 iron formation or in veins found in metasomatic actinolite-rich rocks. These sulfides experienced mechanic-flow and recrystallization during metamorphism and occur either interstitially in the rocks or interlayered with micas and amphiboles. Bornite and chalcosite display mirmekitic intergrowths due to exsolution at lower temperatures. Euhedral magnetite grains with characteristic sharp contacts with sulfides and reaction contacts with silicates clearly experienced annealing during metamorphism. Examination under electron microscopy showed that small inclusions of uraninite, molybdenite, ilmenite, fluorite, apatite and allanite occur in these granoblastic magnetite. Another type of magnetite, derived from the decomposition of fayalite, co-exists with grunerite and quartz and displays a characteristic lamellar texture. No significant differences in chemical composition were observed among lamellar and granoblastic magnetites.

Native gold was observed in association with magnetite, chalcopyrite and sulfosalts. In two samples, the gold grains were observed as inclusions in Ni-rich saflorite, rimmed by cobaltite. Microprobe determinations indicate that the gold is rich in Cu (10 wt%) and contains minor amounts of Fe, As and Ag. Molybdenite contains traces of Fe and occurs both disseminated and in veins, associated with Cu-sulfides. Uraninite occurs as 8-20 m inclusions in magnetite and as small black inclusions surrounded by its radioactive haloes in biotite and hastingsite.

GEOCHEMISTRY OF THE SALOBO HOST ROCKS

Major and trace element contents were determined in a total of 19 mineralized rock samples from the Salobo ore deposit including mostly the two iron formation types (Table 1). The chemical compositions of the Types 1 and 2 iron formations differ mainly in the enrichment of Fe, Ca, Ce, As and B in the former and of Si, Ti, Al, Mg, K, V, Cr and Ni in the later. The Mn, Na, P, Co and Zn contents do not display any noticeable variation between these rock types. Due to the occurrence of mineralized veins, which are responsible for the extraordinary high contents of Cu, S, Mo and Ag in some samples, no conclusive remarks can be drawn from their content variations among the different lithologic types.

This chemical data-base, comprising 19 samples and 23 variables (element contents), was processed by a number of statistical sub-routines included in the Arthur computer program for pattern recognition analysis (Scarminio and Bruns, 1989). The application of the principal component analysis to these data is depicted in the diagram of Figure 2A, in which the relative proximity of one

TABLA 1

wt%	SIF1	SIF2	HA	AA	MA
SiO2	13.75	31.01	18.40	25.40	47.70
TiO2	0.20	1.06	0.42	0.05	1.70
A12O3	2.33	8.45	4.05	1.30	8.70
FeO	65.81	39.82	35.38	46.48	15.00
MnO	0.53	0.56	0.20	0.22	0.23
MgO	1.08	2.80	2.60	2.10	6.80
CaO	2.26	0.67	4.16	1.56	3.20
Na20	0.05	0.08	0.38	0.17	1.76
K20	0.40	1.17	0.50	0.13	1.90
P20s	0.31	0.31	1.40	0.08	0.48
CuO	3.58	4.18	22.82	7.26	2.75
5°2	3.13	2.04	14.00	6.56	1.16
TOTAL	93.43	92.15	104.31	91.31	91.98
ppm					
Ce	1613	965	935	<50	850
V	110	158	148	98	250
Co	133	130	97	1375	59
As	4	<1	2	6	<1
B	394	84	55	115	44
Cr	55	206	44	27	50
Zn	43	55	44	78	28
Ni	81	136	129	451	82
Mo	256	976	49	49	85
Y	192	135	490	159	192
Ag	8	16	49	16	7

Table 1: Average chemical compositions of silicate iron formations of type 1 (SIFl; 6 samples) and type 2 (SIF2; 8 samples), metasomatic hastingite rock (HA; 2 samples), actinolite metasomatic rock (AA; 2 amples) and meta-arkose (MA; 1 sample).

sample to each other indicates the degree of similarity between them. In this principal component 1 versus principal component 2 diagram, 79% of total variance was preserved. The rock samples cluster in two main fields corresponding to the Types 1 and 2 iron formations. Exceptions are samples 4 and 11 (hastingsite-rich rocks), 15 and 18 (actinolite metasomatic rocks) and 16 (meta-arkose). The examination of the chemistry of these lithological groups leads to the consideration that the principal component 1 may represent, from right to left, an increase in Si, Al, Ti, Cr, Co and K and a decrease in Fe and As contents. The principal component 2 may represent an increase in Cu, S, Ag and Ca contents, from bottom to top.

The element concentrations have also been processed by a multi-elemental correlation method in which the covariance and the correlation matrix are calculated for the variables. In a bi-dimensional projection depicted in Figure 2B, the relative proximity of one element to each other indicates the degree of positive correlation between them. The highest positive correlation values were obtained for the pairs Ni and Co, Ti and Al and Ag and Cu, whereas the highest negative correlation values were obtained for the pairs Fe and Si, Mg and Fe, V and Fe and Ti and Fe.

The application of this multi-elemental statistical approach lead to a clear distinction between Types 1 and 2 iron formations in accordance with previous classification (Lindenmayer, 1990). Additionally, the association of Ce, As and B with Type 1 iron formation and of Ti, V, Cr and Ni (and hence Co) with Type 2 iron formation have become evident. The very high positive correlation between Cu and Ag also suggests that a similar correlation may exist between Cu and Au, due to the fact that silver occurs as an alloy with gold in the Salobo ores.

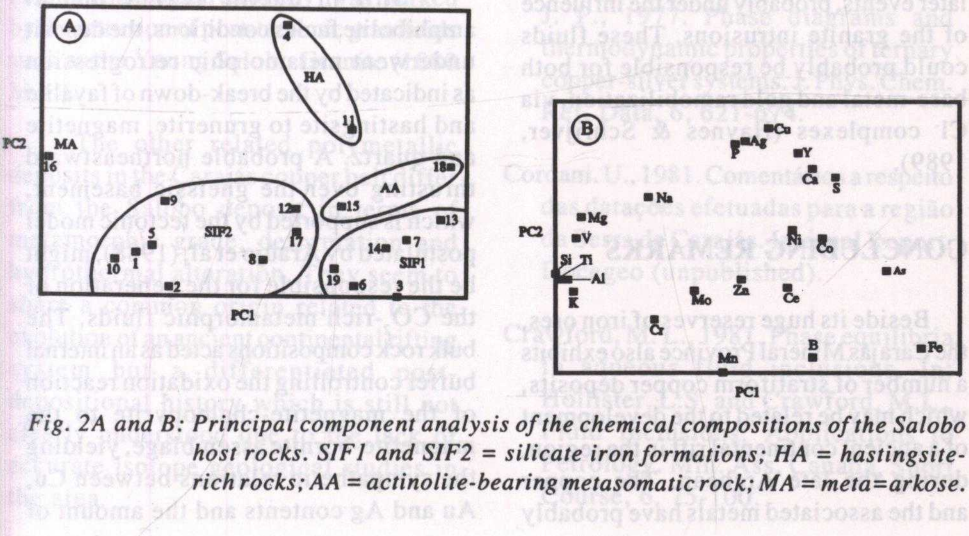

Fig. 2A and B: Principal component analysis of the chemical compositions of the Salobo host rocks. SIF1 and SIF2 = silicate iron formations; HA = hastingsite-rich rocks; AA = actinolite-bearing metasomatic rock; MA = meta=arkose.

CHEMISTRY OF FLUIDS

Two types of fluid inclusions have been found in quartz of the Type 2 iron formation:

(i) Monophase carbonic inclusions, along intragranular healed fractures, composed of nearly pure CO_2 (Tm CO_2 -56.5/-57.0°C) and with CO_2 densities in the range of 0.83-0.67 g/cm^3 (Th CO_2 12.9-27.3°C);

(ii) Aqueous inclusions, often containing one or more solid halides, along sets of crosscutting trails or groups within the limits of the quartz grains. These fluid inclusions represent complex brine solutions with minimum salinities in the range of 1.7 to 17.6 eq.wt% NaCl (Tm of ice -25.4/-0.6°C). Trails of these aqueous inclusions crosscutting trails with the monophase carbonic inclusions were only locally observed, suggesting the late nature of the former.

A preliminary interpretation of these data points towards a model in which the carbonic fluids were generated during the high-temperature metamorphic-hydrothermal event and shearing whereas aqueous fluids were generated during later events, probably under the influence of the granite intrusions. These fluids could probably be responsible for both base-metal and gold remobilization, via Cl^- complexes (Haynes & Schrijver, 1989).

CONCLUDING REMARKS

Beside its huge reserves of iron ores, the Carajás Mineral Province also exhibits a number of stratiform copper deposits, which may be related to the development of a ancient continental rift in the region, during the late Archean. The copper and the associated metals have probably been scavenged from the basalts of the basal volcanic pile by recycled seawater, during the subsidence of the basin, and deposited in the overlying sedimentary rocks.

In the case of the Salobo ore deposit, the amount of magnetite in the silicate iron formations controls the Cu-Au-Ag-Mo mineralization which may suggest that mineralization pre-dated metamorphism and deformation. Nevertheless, the mineralogical, geochemical and textural features of the ores indicate that the Salobo deposit underwent significant post-depositional transformations.

The deposit was submitted to progressive high amphibolite facies metamorphism as indicated by the presence of the mineral-paragenesis formed by fayalite, hastingsite, almandine and magnetite. The prevailing reducing conditions during this metamorphic event are consistent with the occurrence of uraninite as small inclusions in magnetite porphyroblasts and of graphite disseminated in the host rocks. Apatite, fluorite, allanite and molybdenite were already present in the rock during the recrystallisation of magnetite.

Still in ductile regime and at amphibolite facies conditions, the deposit underwent metamorphic retrogression as indicated by the break-down of fayalite and hastingsite to grunerite, magnetite and quartz. A probable northeastward thrusting over the gneissic basement, which is supported by the tectonic model postulated by Araújo et al. (1988), might be the responsible for the generation of the CO_2-rich metamorphic fluids. The bulk rock compositions acted as an internal buffer controlling the oxidation reaction of the magnetite-chalcopyrite to the magnetite-bornite assemblage, yielding the sympathetic relations between Cu, Au and Ag contents and the amount of magnetite in the rock. During the late stages of this retrogression event, at low amphibolite facies conditions, the sulfides were still suitable to mechanic-flow in the presence of Cl-bearing aqueous-saline fluids. This event was accompanied by plutonism and shearing.

Subsequently, as the uplift of the Salobo sequence continued, the ore deposit was submitted to locally important metamorphic changes at greenschist facies conditions within a more brittle regime. In this event, the ore-bearing rocks underwent partial chloritization and the magnetite was locally oxidized to hematite. The deposition of the copper-rich gold may have occurred at temperatures less than 400ºC (Chang et al.,1977). The close association of native gold with sulfo-arsenides suggests that the participation of thiocomplexes-bearing fluids during the remobilization of gold must be regarded as locally important. All these low-temperatures features of the Salobo ores must be related to the latest thermal event recorded in the region by previous studies (K/Ar ages of 1903 M.a. and 2022 M.a. according to Tassinari et al., 1982). The end of this major tectonic event in the Early Proterozoic (Trans-Amazonian Orogeny) was marked by the intrusion of post-tectonic granitoids such as the Young Salobo Granite (1880 M.a.).

The other related polymetallic deposits in the Carajás copper belt differ from the Salobo deposit in terms of metamorphic grade, deformation and hydrothermal alteration. They seem to share a common origin related to the evolution of an ancient continental rifting system but a differentiated post-depositional history which is still not clearly understood due to the lack of accurate isotope geological studies in the area.

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