Spatial distribution of bauxitic duricrusted laterites on the Bamiléké plateau (West Cameroon): constrained GIS mapping and geochemistry

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Abstract

Estimation of the mineral resources potential is an important issue for most of developing countries. The spatial distribution of lateritic landsurfaces and bauxite on the Bamiléké plateau (West Cameroon) has been investigated with a Boolean modeling process into a GIS environment on the basis of geological constraints namely elevation, rock types, landscape morphology and soil types. Field observation and SRTM (Shuttle Radar Topographic Mission) data allowed the differentiation of two lateritic surfaces separated by a minimum altitude difference of about 60 m. These surfaces constrained by favorable rock types, slope steepness and soil types provided a potential lateritic bauxitic area of 381 km² (17.2% of the total study site), which matches the current bauxitic areas and evidences a large non-explored area in the north of the study site. Field validation and the integration of legacy spatial data resulted in an area of 60.1 km² for potential bauxitic ores, i.e. obviously duricrusted landsurfaces (with 47.8 km² in the upper surface and 12.3 km² in the lower surface). Geochemical data (mostly Al_2O_3 wt.%) obtained from duricrust samples were treated by geostatistical methods and classical kriging interpolation to discriminate between bauxitic and ferruginous laterites. This highlighted a geochemical trend from higher alumina values on the upper surface (40-66 wt.%) to lower values on the lower surface (13-44 wt.%). Finally, our study documents two indurated lateritic surfaces arranged in a staircase manner and having different geochemical characteristics. The total bauxitic-rich surface is distributed in five different spots throughout the study area and covers 56.2 km², while ferruginous laterites occupy a spot of 3.9 km². GIS mapping approach of lateritic landsurfaces, accounting for reliable constraints, might be promising for larger scale investigations of mineral resources in developing Countries.

Keywords: Bauxite; Boolean modeling; Kriging; Bamiléké plateau; Cameroon

1. Introduction

Many Third World Countries rely mainly on their natural resources to sustain their economic development. In Cameroon, the exploitation of mineral resources has traditionally been a significant component of the economy (Ntép Gweth, 2009). However, knowledge on the real potential of these resources is generally limited by a lack of geo-exploration tool required for their reliable and comprehensive assessment and classification at the national-wide level. In this country, the most widespread ore deposits are lateritic bauxites, representing the 6^{th} reserve in the world. Bauxites occur in the Adamaoua and Western regions, and have been previously studied by many authors (Eno Belinga, 1968; Eno Belinga, 1972; Hiéronymus, 1973; Momo Nouazi et al., 2012; Morin, 1985; Nicolas and Eno Belinga, 1969; Nyobe, 1987) using classical approaches of field survey and laboratory analyses. Nowadays, GIS and remote sensing tools permit more accurate mapping of such resources by integrating favorable geological constraints in a GIS-based model.

Our study aimed at satisfying the practical need for supporting bauxite exploration in Cameroon with up-to-date maps, by defining the relation between bauxitic deposits and their geological environment. For this purpose, we used a GIS-modeling approach, based on a well-established procedure previously tested in several studies on mineral potential assessment (Bonham-Carter, 1994; Boroushaki and Malczewski, 2008; Carranza, 2002; Carranza, 2009; Carranza et al., 1999; Carranza et al., 2008; Cheng and Agterberg, 1999; Guha et al., 2013; Harris et al., 2008; Harris et al., 2001; Robinove, 1989; Thiart and De Wit, 2000; Thole et al., 1979; Varnes, 1974; Zadeh, 1965). The approach deals with GIS-based geologically constrained mineral potential mapping, a multistage strategy for delineating mineralized zones (Reeves et al., 1990). Multivariate and multisource geo-exploration datasets were combined to enhance favorable geologic features indicative of mineral deposit (Bonham-Carter, 1994; Hodgson, 1990). Our interest was thus to know via the Boolean model of Varnes (1974) and Robinove (1989), whether the spatial criteria linked to the genetic environment and landscape distribution of bauxites can be used to define predictive map of bauxite occurrence for further field exploration and geochemical survey.

2. Physiography of the study area

The study site lies between longitudes 09°56'-10°20'E, and latitudes 05°18'-5°45'N and covers an area of 2209 km^2 within the Bamiléké plateau extending between 09°44'-10°33'E, and 04°10'-05°56'N in West Cameroon (Figs. 1A and B). The main morphological features of this area is the Mount Bambouto, culminating at the altitude of 2725 m (Fig. 1B), which is the third most important and highest volcano of the Cameroon Volcanic Line (Déruelle et al., 1991). It covers the southern part of the West Cameroon highland between the Bamoun plateau in the east, the Grassfields in the north and the Mbô plain in the south and west.

The climate of the Bamiléké plateau is sub-equatorial, influenced by high altitudes, with 1600-2000 mm mean annual rainfall and 18°C-20°C for the mean annual temperature.

The Cameroon Volcanic Line consists of a wide Cenozoic volcanic complex extruded on the Neoproterozoic Panafrican granito-gneissic basement, which is also intruded by mafic and felsic plutons (Kwekam et al., 2010). The volcanic complex is known to be the parent material for the plateau Bamiléké bauxites. The new ^{40}K-^{40}Ar geochronological data showed three main periods of volcanic activity extending from the Miocene (Burdigalian) (Marzoli et al., 1999) to the Pliocene (Nkouathio, 2006), and uncommon lava spots extending up to ~0.5 My (Kagou Dongmo et al., 2010). Lavas geochemistry shows a trend extending from basanites to trachytes or phonolytes.

3. Methods

3.1. Conceptual model of bauxite occurrence

A conceptual and exploration model for evaluating the bauxite potential of the Bamiléké Plateau was built based on geological criteria (Carranza, 2002; De Araújo and Macedo, 2002; Hodgson, 1990;

Reeves et al., 1990). Amongst the operators used for examining the spatial association of geological features is the Boolean model, which is based on a reclassification of the input maps into only two classes (Bonham-Carter, 1994; Carranza et al., 2008; Harris et al., 2001; Robinove, 1989; Thiart and De Wit, 2000; Varnes, 1974), i.e., the maximum and minimum evidential score classes (0 or 1). Reclassified maps are combined logically according to a set of steps so-called inference network (Fig. 2), which reflects the inter-relationships of processes controlling the occurrence of a geo-object and the spatial features indicating the presence of this geo-object (Carranza, 2002; Carranza, 2009). Finally, the output of combined evidential maps via Boolean logic modeling is a two class map; the first class represents locations where all of the prospective recognition criteria are satisfied, whilst the second class represents locations where at least one is unsatisfied (Carranza, 2009).

The study was carried out with ILWIS GIS software (ITC ILWIS Unit, 2001) using a three step methodology including: (1) gathering spatial data into a GIS, (2) extracting spatial evidential data and creating derivative maps to be used as spatial evidence of bauxite mineralization, (3) integrating the spatial evidence map to create bauxitic potential map and validating the predictive map (Bonham-Carter, 1994).

3.2. Analysis of constraints

In our study, the criteria or constraints from the rock types, landscape morphology (elevation ranges and slopes), and soil types were defined and linked to delineate favorable zones on the Bamiléké Plateau. These zones are potentially duricrusted landsurfaces areas with alumina-rich surface materials, which are characterized by deep and extremely leached soils (Hiéronymus, 1973; Momo Nouazi et al., 2012; Nyobe, 1987).

Lateritic bauxites are known to form mainly by chemical weathering of rocks in which low silica content favors crystallization of gibbsite instead of kaolinite (Tardy, 1993). However, many other studies have also described bauxite formation from a variety of parent materials including basic and acid rocks

(Bildgen, 1973; Boulangé, 1984; Boulangé et al., 1997; Boulangé et al., 1996; Boulangé and Colin, 1994; Chardon et al., 2006; Eno Belinga, 1972; Momo Nouazi et al., 2012; Soler and Lasaga, 2000). Meanwhile, the geological substratum is an important factor contributing to the preservation of lateritic bauxites from surface stripping (Boulangé, 1984). On the Bamiléké plateau, a variety of rocks derived from complex magmatic and metamorphic events exist (Dumort, 1968; Kagou Dongmo et al., 2010; Kwekam et al., 2010; Nkouathio et al., 2008), but the bauxites are formed exclusively upon volcanic rocks (Momo Nouazi et al., 2012; Morin, 1985; Nyobe, 1987).

Bauxitic laterites generally occur on high elevation, low relief planation landsurface remnants lying on flat or gently sloped surfaces (Grandin and Thiry, 1983; Chardon et al., 2006; Beauvais and Chardon, 2013). These morphological characteristics allow localizing bauxitic laterites from altitudinal levels and slope distribution (Riis and Fjeldskaar, 1992).

Bauxitic laterites are developed under a tropical climate that favors deep rock weathering and the development in soils of a thick B-horizon resulting from lixiviation process (Boulangé and Colin, 1994; Grandin and Thiry, 1983; Maignien, 1966; Pedro, 1968; Tardy, 1993). Commonly, bauxites described on well-preserved landsurfaces show thickness extending up to 20 and 30 m (Grandin and Thiry, 1983; Segalen, 1967). The presence or absence of the B-horizon in soils was used to determine potential areas of bauxite development in the study area.

4. Results

4.1. Favorable constraints

4.1.1. Favorable rock types

Within the study site, volcanic rocks cover 64% of the total surface (Fig. 3A), comprising mainly basalts (64%), trachytes (28%) and ignimbrites (6%), which have been formed since 19 My covering an area of 1406 km² (Marzoli et al., 1999; Nkouathio et al., 2008). All these volcanic rocks currently show evidence of deep weathering process (Tematio et al., 2004). Phonolites and volcanic ashes cover limited areas (~1%) on the study site. These recent volcanic rocks range from 4 My for phonolites (Nkouathio et al., 2008) to 0.48 My for volcanic ashes (Kagou Dongmo et al., 2010). The phonolites are found on elevated dykes with no evidence of weathering. Volcanic ashes are very little altered exhibiting a very thin non-differentiated profile (Tsopjio Jiomeneck et al., 2011). Taking into account all these data, basalts, trachytes and ignimbrites are rock types with potential to control bauxite occurrences in the study area.

4.1.2. Favorable morphological features: elevation and slope

On the Bamiléké plateau, legacy data and field observations have contributed to differentiate two lateritic surfaces with minimum elevation of 1520 and 1580 m for the lower and the upper surface, respectively (Fig. 3B). The 60 m height difference (Dh; Fig. 4) is a lithologically controlled feature marked by flow scarps separating two types of volcanic materials. These are reported on the central and the western part of the study site (Fig. 4) as a limit between the Mount Bambouto lava and the surrounding shield (Nkouathio et al., 2008); and on the southeastern part by the Bangam flow scarp. The lower surface is an undulated low relief landscape with few interfluves culmunating up to about 1580 m, corresponding mainly to the Doumbouo-Fokoué area (Fig. 3B; Fig. 4) between large remnants of the upper surface (Fig. 3B). The upper surface includes the so called Fongo-Tongo deposit, the Loung deposit and the Bangam deposit (Fig. 3B; Fig. 4) and a large unexplored area in the northern part of the study site (Fig. 3B), whose the maximum altitude is not actually well defined although laterites have been described up to about 1900 m.

Remnants of bauxitic surfaces on the Bamiléké plateau are most often highly dissected due to the combined effects of tectonic uplift, climate and drainage pattern (Morin, 1985), and are incised by steep valleys. Landscape dissection results in two morphological features related to different incision stages. The first one corresponds to isolated gently sloping interfluves (0 to 5°; Fig. 3C), which are covered by continuous duricrusted laterites (Fig. 5A) and limited by steep slopes up to 76° (Fig. 5B). The second feature corresponds to widespread elongated interfluves with convex summits showing slope classes ranging from 0 and 15° (Fig. 3C). Well-preserved duricrusts occur on the lowest slopes, but are stripped on increasing slopes steepness. This is obvious on a sequence at Doumbouo-Fokoué showing continuous duricrust on the top, discontinuous duricrust on summit shoulder, and gravelly horizon on 15° slopes marking the lower topographic limit of the lateritic surface (Fig. 5C). Landform units and slope classes derived from SRTM (Shuttle Radar Topographic Mission) data were thus potential morphological features for mapping bauxitic deposits. The favorable elevation ranges delineate a surface of 685 km^2 and 223 km^2 on the upper surface and lower surface, respectively (Fig. 3B). Favorable sloping land surface covers a total surface of 1702 km^2 with slopes ranging between 5-15° over a surface of 1176 km^2 (Fig. 3C).

4.1.3. Favorable soil classes

Three major soil classes are recorded in the area: andosols, andic-ferralitic soils and ferralitic soils (Tematio, 2005; Tematio et al., 2009; Tematio et al., 2004) corresponding respectively to andosols, acrisols and ferralsols of the World Reference Base for soil classification (FAO-ISRIC, 2006; Jones et al., 2013). These soils form a toposequence extending from andosols at the upper part of the Bambouto volcano, to acrisols at the middle, and to ferralsols in lower part (Fig. 3D). The B-horizon is well developed except in the andosols of high altitudes where cool climate prevents clay formation and instead favors organo-metal complexes embedding Al and Fe (Tematio, 2005). This results in the development of a thick organic horizon lying in most cases directly on the bedrock. These andosols are associated on either side of the Mont Bambouto caldera edge with lithosols, which were strongly eroded and reworked out by numerous landslides occurring from the top of the volcano to about 600 m altitudes westward. Accordingly, only ferralsols and acrisols, which cover 1645 and 131 km^2, respectively, are considered for the modeling process.

4.2. Mapping the bauxitic potential

Spatial evidences of bauxitic potential were constrained successively from different geological features as described in section 3. First, the maps constrained by elevation and lithology displayed two main areas of bauxite potential, i.e., the northern area made up mainly of the upper surface and the southern area made up mainly of the lower surface (Fig. 6A). The total potential surface at this stage covers 682 km² (538 km² and 144 km² for the upper and the lower surface, respectively). This surface was further constrained with the favorable soil classes, and the resulting surface showed 422 km² with 291 km² for the upper surface and 131 km² for the lower surface. The spatial distribution pattern remains the same as the first potential map, except that the upper surface was reduced in the northern part of the study site (Fig. 6B).

Finally, the map derived from the altitudes, lithology, and soils was further constrained by the slope map that resulted in a predictive bauxitic map characterized by large blank areas with dissected pattern (Fig. 6C) corresponding to slopes ranging from 15 to 76°. The total potential surface is 381 km², i.e. 17.2% of the total studied zone. The slopes of 5-15° is the most represented (76%), showing that the dominant morphological features for bauxite occurrence are the convex shaped summit of elongated interfluves.

4.3. Validation of the predictive bauxitic laterites map

As shown in the inference network of Fig. 2, the map of the predictive bauxitic areas was an intermediate step of the modeling process. Comparing this map with data from previous studies and field campaigns was the final step to validate the efficiency of the model for evaluating the accuracy of bauxite mapping. The validation consisted in (i) gathering data from different sources to precisely delineate lateritic duricrusts, and (ii) integrating geochemical data interpolated by kriging to differentiate between ferruginous and bauxitic laterites. The first step in validating the output map was carried out by a rough comparison between the predictive map and the areas with previously studied bauxites deposits such as Fongo-Tongo, Djeu and Loung-Ndoh (Morin, 1985; Nyobe, 1987), Doumbouo-Fokoué (Hiéronymus, 1973; Momo Nouazi et al., 2012; Morin, 1985), and Bangam (Hiéronymus, 1973; Morin, 1985). The predictive map perfectly matches these areas and highlights a large northern site for which legacy data are still lacking as shown on the figure 6C. Upon validation process, the predictive map delineate a surface of 60.1 km² of lateritic duricrusts on the Bamiléké plateau with 47.8 km² for the upper surface and 12.3 km² for the lower surface (Fig. 6D).

The second step aimed at differentiating between bauxitic laterites and ferruginous laterites. For this purpose, a total of 65 samples randomly distributed in the study area were collected, analyzed for geochemical data (Table. 1) and used for geostatistical analyses. The process of interpolation carried out in this step consisted in determining the distribution of alumina weight percentage on regularly distributed points (pixels) from randomly distributed analytical point values. The output of point interpolation is a raster map, whose pixel values are calculated by interpolation from input point values. The kriging method with a minimum mean interpolation error is currently used (Theodossiou and Latinopoulos, 2006). In this study, the kriging process established a spatial correlation between the spatial input values at an optimal lag distance of 1 km. A spherical model fitted to the semi-variogram from this correlation was used as interpolation function. The figure 7 shows the kriging map differentiating three main geochemical areas. The first area is characterized by highest alumina values, confined on the upper surface (comprising localities of Fongo-Tongo, Djeu, Loung-Ndoh and Bangam). The geochemical trends are represented with alumina values decreasing from Fongo-Tongo to Djeu on the western part of the lateritic map, and on the eastern part with a slight increasing trend toward the SE (Bangam). These areas display interpolated alumina values extending from 44 up to 66 wt.% Al_2O_3. The second area is delineated in the southern part of the lower surface at Fokoué and Sa, where alumina values extend from 40 to 44 wt.% Al_2O_3 with a slight decrease northward (Fig. 7). The third area is confined to the Doumbouo region where ferruginous laterites are characterized by alumina content less than 40 wt.%, varying from 39 to 13 wt.% Al_2O_3. The total bauxitic-rich surface of the Bamiléké plateau is then of 56.2 km², while ferruginous laterites cover a surface of 3.9 km².

5. Discussion

5.1. Spatial features evidence and predictive map of bauxite potential

The Boolean model applied in this study has resulted in an 82.8% reduction in the potential bauxite area to be considered. The predictive map has indicated that the bauxite potential covers 17.2% of the total study area, that perfectly matches known areas of bauxite deposits as derived from previous studies on the Bamiléké plateau (Hiéronymus, 1973; Momo Nouazi et al., 2012; Morin, 1985; Nyobe, 1987). Out of the 17.2% bauxite potential from the predictive map, the total confirmed bauxitic area of the Bamiléké plateau derived from validation steps only covers about 3% of the total investigated area (56.1 km²). This reduced bauxitic surface can be explained by (i) the advanced stage of bauxitic landsurface dismantling (Momo Nouazi et al., 2012), which induces the total stripping of duricrust on interfluves with favorable genetic characteristics (rock and soil) and favorable morphological criteria; and (ii) the flat and gently sloped areas in the northern part of the predictive map covered by unaltered basaltic and trachytic flows. This methodology allows a regional scale evaluation of lateritic bauxites by highlighting the low preservation and increasing dismantling of these lateritic surfaces, which had already been noticed all over the remnants of the planation surfaces (see Momo-Nouazi et al., 2012). The criteria used in this study are quite similar to those used by Carranza (2002) for determining the predictive map of nickeliferous-laterites of the Isabela area in Philippines. The resulting map demonstrated the reliability of the method in large areas with a limited number of mineral prospects. It is thus a relatively effective, rapid, and cheap approach, which can be applied to assess a large number of mineral potential as described by Bonham-Carter (1994). It can then be considered as a promising approach applicable to other bauxitic regions of Cameroon such as the Adamaoua bauxitic landsurfaces with wide duricrusted and gently sloped plateaus ($\leq 2°$) developed on volcanic rocks (Eno Belinga, 1966; Vicat and Bilong, 1998) for a larger scale spatial regionalization.

5.2. Bauxites of the Bamileké plateau and its economic potential

Bauxites of the Bamiléké plateau are distributed in five main spots named Bangam, Doumbouo-Fokoué, Fongo-Tongo, Loung-Ndoh and Djeu with respectively 39.87 km^2, 8.44 km^2, 4.52 km^2, 1.78 km^2 and 1.59 km^2. They contain essentially 40-66 wt.% of alumina that is less than those of Minim-Martap (45–75wt%) but more than those of Ngaoundal-Ngaoundourou (46-48 wt.%) in the Adamaoua region (Eno Belinga, 1966; Vicat and Bilong, 1998). The total bauxite reserve of the Bamiléké plateau is still not quantified. However, some attempts based on (i) thickness data from limited number of pits and (ii) surface evaluation by contouring have been performed on the Fongo-Tongo and the Doumbouo-Fokoué spots with 46 million tons (Hiéronymus, 1973) and 9 million tons (Momo Nouazi et al., 2012), respectively. These values are lower than those of the Adamaoua region of Cameroun. The Bangam spot revealed by this study with the largest (39.9 km^2) and richest bauxitic ore (45-66 wt.% alumina) has unfortunately not been evaluated so far. Further researches on vertical extent of bauxite in this spot are thus highly recommended here.

6. Summary and conclusion

This study has suitably combined spatial multisource data to define potential bauxitic laterites distribution on the Bamiléké plateau, and evaluate the usefulness of including field observations, and geochemical data processed by statistical method for improving the mineral mapping process. Genetic criteria and a regolith landform model were successfully used to predict and precisely delineate areas of bauxite occurrence, thereby highlighting a total bauxitic-rich surface of 56.2 km^2. The alumina content of these duricrusts is quite high, but the large spatial distribution into five spots may render their bauxitic exploitation quite expensive. However, results of this study can be considered as an important input into the assessment and classification of lateritic ores in Cameroon.

At the national-wide level, the bauxitic laterites potential has not yet been fully assessed. Using the approach developed in this study, the bauxite potential for the entire country could be achieved much more cheaply than the traditional methods. The whole Cameroon volcanic line with deep weathered and elevated volcanic shields provides most of the useful genetic and geomorphic criteria applicable for such study.

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References

Ballentine, C.J., Lee, D.C., Halliday, A.N., 1997. Hafnium isotopic studies of the Cameroon Line and new HIMU paradoxes. Chemical Geology 139, 111-124.

Beauvais, A., Chardon, D., 2013. Modes, tempo, and spatial variability of Cenozoic cratonic denudation: The West African example. Geochemistry, Geophysics, Geosystems 14(5), 1590-1608. doi:10.1002/ggge.20093.

Bildgen, P., 1973. Contribution à l'étude de la genèse et de l'évolution des bauxites karstiques de Provence: géologie, minéralogie, géochimie des formations bauxitiques des Alpilles. Doctorat 3ème cycle, Paris, 134 pp.

Bonham-Carter, G.F., 1994. Geographic Information Systems for Geoscientists. Modeling with GIS. First ed. Pergamon, New York.

Boroushaki, S., Malczewski, J., 2008. Implementing an extension of the analytical hierarchy process using ordered weighted averaging operators with fuzzy quantifiers in ArcGIS. Computers & Geosciences 34(4), 399-410.

Boulangé, B., 1984. Les formations bauxitiques latéritiques de Côte d'Ivoire. Les faciès, leur transformation, leur distribution et l'évolution du modelé. Thèse et Mémoire ORSTOM, 363 pp.

Boulangé, B., Ambrosi, J.-P., Nahon, D., 1997. Laterites and Bauxites. In: H. Paquet and N. Clauer (Editors), Soils and Sediments : mineralogy and geochemistry. Springer Berlin Heidelberg, pp. 49-65

Boulangé, B., Bouzat, G., Pouliquen, M., 1996. Mineralogical and geochemical characteristics of two bauxite profiles, Fria, Guinea Republic. Mineral Deposita 31, 432-438.

Boulangé, B., Colin, F., 1994. Rare earth element mobility during conversion of nepheline syenite into lateritic bauxite at Passa Quatro, Minais Gerais, Brazil. Applied geochemistry 9, 701-711.

Carranza, E.J.M., 2002. Geologically-Constrained Mineral Potential Mapping (Examples from the Philippines). Ph.D. Thesis Thesis, International Institute for Geo-Information Science and Earth Observation, Enschede, 480 pp.

Carranza, E.J.M., 2009. Geochemical anomalies and mineral prospectivity mapping in GIS., Hanbook of exploration and environmental geochemistry pp. 351.

Carranza, E.J.M., Mangaoang, J.C., Hale, M., 1999. Application of mineral exploration models and GIS to generate mineral potential maps as input for optimum land-use planning in the Philippines. Natural Resources Research 8(2), 165-173.

Carranza, E.J.M., van Ruitenbeek, F.J.A., Hecker, C., van der Meijde, M., van der Meer, F.D., 2008. Knowledge-guided data-driven evidential belief modeling of mineral prospectivity in Cabo de Gata, SE Spain. International Journal of Applied Earth Observation and Geoinformation 10(3), 374-387.

Chardon, D., Chevillotte, V., Beauvais, A., Grandin, G., Boulangé, B., 2006. Planation, bauxites and epeirogeny: One or two paleosurfaces on the West African margin? Geomorphology 82, 273-282. doi:210.1016/j.geomorph.2006.1005.1008.

Cheng, Q., Agterberg, F.P., 1999. Fuzzy weights of evidence and its application in mineral potential mapping. Natural Resources Research 8 (1), 27-35.

De Araújo, C.C., Macedo, A.B., 2002. Multicriteria Geologic Data Analysis for Mineral Favorability Mapping: Application to a Metal Sulphide Mineralized Area, Ribeira Valley Metallogenic Province, Brazil. Natural Resources Research 11(1), 29-43.

Déruelle, B., Moreau, C., Nkoumbou, C., Kambou, R., Lissom, J., Njonfang, E., Ghogomu, R.T., Nono, A., 1991. The Cameroon Line: a review. In: A.B. Kampunzu, R.T. Lubala (Eds.), Magmatism in extensional structural settings. The Phanerozoic African Plate. Springer, Berlin, pp. 274-327.

Dumort, J.C., 1968. Carte géologique de reconnaissance au 1/500.000. . imprimerie Nationale, D.M.G. Yaoundé, .

Eno Belinga, S.M., 1966. Contribution à l’étude géologique, minéralogique et géochimique des formations bauxitiques de l’Adamaoua (Cameroun) Doctorat de Troisième Cycle, Université de Paris, Paris 155 pp.

Eno Belinga, S.M., 1968. Etude pétrographique des bauxites de Ngaoundal et de Minim-Martap dans l’Adamaoua (Cameroun). Annales de la Faculté des Sciences 1, 55-68.

Eno Belinga, S.M., 1972. L’altération des roches basaltiques et le processus de bauxitisation dans l’Adamaoua (Cameroun). Doctorat d’Etat, Université Paris, Paris, 571 pp.

FAO-ISRIC, 2006. World Reference Base for Soil Resources FAO, Rome.

Grandin, G., Thiry, M., 1983. Les grandes surfaces continentales tertiaires des régions chaudes. Succession des types d'altération. Cahier ORSTOM, série Géologie 13(1), 3-18.

Guha, A., Singh, V.K., Parveen, R., Vinod Kumar, K., Jeyaseelan, A.T., Dhanamjaya Rao, E.N., 2013. Analysis of ASTER data for mapping bauxite rich pockets within high altitude lateritic bauxite, Jharkhand, India. International Journal of Applied Earth Observation and Geoinformation 21, 184-194.

Harris, J.R., Lemkow, D., Jefferson, C., Wright, D., Falck, H., 2008. Mineral Potential Modelling for the Greater Nahanni Ecosystem Using GIS Based Analytical Methods. Natural Resources Research 17(2), 51-78.

Harris, J.R., Wilkinson, L., Heather, K., Fumerton, S., Bernier, M.A., Ayer, J., Dahn, R., 2001. Application of GIS processing techniques for producing mineral prospectivity maps - a case study: mesothermal Au in the Swayze Greenstone Belt, Ontario, Canada. Natural Resources Research 10(2), 91-124.

Hiéronymus, B., 1973. Etude minéralogique et géochimique des formations bauxitiques de l'ouest Cameroun. Doctorat 3e Cycle, Univ. Paris VI, Paris, 98 pp.

Hodgson, C.J., 1990. Uses (and abuses) of ore deposit models in mineral exploration. Geoscience Canada 17(2), 79-89.

ITC ILWIS Unit, 2001. ILWIS 3.0 Academic user's guide. ITC, Enschede, NL, pp. 520.

Jones, A., Breuning-Madsen, H., Brossard, M., Dampha, A., Deckers, J., Dewitte, O., Gallali, T., Hallett, S., Jones, R., Kilasara, M., Le Roux, P., Micheli, E., Montanarella, L., Spaargaren, O., Thiombiano, L., Van Ranst, E., Yemefack, M. , Zougmor. R., (eds.), 2013. Soil Atlas of Africa. European Commission, Publications Office of the European Union, Luxembourg. 176 pp.

Kagou Dongmo, A., Nkouathio, D., Pouclet, A., Bardintzeff, J.-M., Wandji, P., Nono, A., Guillou, H., 2010. The discovery of Late Quaternary basalt on Mount Bambouto: implications for recent widespread volcanic activity in the southern Cameroon Line. Journal of African Earth Sciences 57, 96-108.

Kwekam, M., Liégeois, J.P., Njonfang, E., Affaton, P., Hartmann, G., 2010. Nature, Origin and Significance of the Fomopéa Pan-African High-K Calc-alkaline Plutonic Complex in the Central African Fold Belt (Cameroon) Journal of African Earth Sciences 57, 79-95.

Maignien, R., 1966. Compte rendu de recherche sur les laterites. Col. Rech. Rers. Nat. UNESCO, Paris 4.

Marzoli, A., Renne, P.R., Piccirillo, E.M., Francesca, C., Bellieni, G., Melfi, A.J., Nyobe, J.B., N'ni, J., 1999. Silicic magmas from the continental Cameroon volcanic line (Bambouto and Ngaoundéré): 40Ar/39Ar dates, petrology, Sr-Nd-O isotopes and theirpetrogenetic significance. Contrib. Mineral. Petrol. 135, 133-150.

Momo Nouazi, M., Tematio, P., Yemefack, M., 2012. Multiscale organization of the Doumbouo-Fokoué Bauxites Ore Deposits (West Cameroun): Implication to the Landscape Lowering. Open Journal of Geology 2, 14-24.

Morin, S., 1985. Cuirasses et reliefs de l'ouest Cameroun, Laboratoire de géomorphologie du CEGET/CNRS, 33405 Talence, France.

Nicolas, J., Eno Belinga, S.M., 1969. Contribution à l'étude de l'origine et de l'évolution des bauxites de l'Adamaoua (Cameroun). C. R. Ac. SC. Paris, série D, 268, 1157-1160.

Nkouathio, D.G., 2006. Evolution tectono-magmatique et volcanologique de la Ligne du Cameroun: comparaison d'un volcanisme de graben (plaine de Tombel) et d'un volcanisme de horst (monts Bambouto). Thèse Doctorat Thesis, Université Yaoundé-1, Yaounde, Cameroun, 231 pp.

Nkouathio, D.G., Kagou, D.A., Bardintzeff, J.M., Wandji, P., Bellon, H., Pouclet, A., 2008. Evolution of volcanism in graben and horst structures along the Cenozoic Cameroon Line (Africa): implications for tectonic evolution and mantle source composition. Min. Pet. 94, 287-303.

Ntép Gweth, P., 2009. Ressources minérales des arrondissements de la région de l'Ouest. Extrait de la carte thématique de ressources minérales du Cameroun sur un fond géologique (2001).

Nyobe, J.B., 1987. A geological and geochemical study of the Fongo-Tongo and areally related bauxites deposits, Wersten Highlands, Republic of Cameroun. PhD thesis, 352 pp.

Pedro, C., 1968. Distribution des principaux types d'altérations à la surface du globe. Présentation d'une esquisse géographique. Revue Géogr. Phys. Géol. Dyn. 10(5), 457-470.

Reeves, C.V., Westerhof, A.B., Botman, L.G., Dessauvagie, T.F.J., Dijkstra, S., 1990. Systematic mineral resource development in the '90s and the next century: new techniques, old challenges. ITC Journal 2, 92-101.

Riis, F., Fjeldskaar, W., 1992. On the magnitude of the late Tertiary and Quaternary erosion and its significance for the uplift of Scandinavia and the Barents sea. In: R.M. Larsen, H. Brekke, B.T. Larsen, E. Talleras (Eds.), Structural and tectonic modeling and its application to petroleum geology. NPF Special Publications 1, Elsevier Amsterdam, pp. 163-185.

Robinove, C.J., 1989. Principles of logic and the use of digital geographic information systems. In: W.J. Ripple (Ed.), Fundamentals of Geographic Information Systems, a Compendium. American Society for Photogrammetry and Remote Sensing, pp. 112-124.

Segalen, D., 1967. Les sols et la géomorphologie du Cameroun Cahier ORSTOM, Sér. Pédologie 5(2), 137-187.

Soler, J.M., Lasaga, A.C., 2000. The Los Pijiguaos bauxite deposit (Venezuela): A compilation of field data and implications for the bauxitization process Journal of South American Earth Sciences 13, 47-65.

Tardy, Y., 1993. Pétrologie des latérites et des sols tropicaux. Masson, Paris.

Tematio, P., 2005. Etude cartographique et pétrographique des sols à caractères ferralitiques et andosoliques dans lesmonts Bambouto (Ouest Cameroun): influence de la nature lithologique et des facteurs du milieu sur la nature et la distribution des sols en regions de montagne tropicale humide. Doctorat d'Etat Thesis, Univ. Yaoundé I, Yaounde, 251 pp.

Tematio, P., Fritsch, E., Hodson, M.E., Lucas, Y., Bitom, D., Bilong, P., 2009. Mineral and geochemical characterization of a leptic-aluandic soil and athapto-aluandic-ferralsol developed on trachytes in Mount Bambouto (Cameroon volcanic line). Geoderma 152, 314-323.

Tematio, P., Kengni, L., Bitom, D., Hodson, M., Fopoussi, J.C., Leumbe, O., Mpakam, H.G., Tsozué, D., 2004. Soils and their distribution on Bambouto volcanic mountain, West Cameroon highland, Central Africa. Journal of African Earth Sciences. 39, 447-457.

Theodossiou, N., Latinopoulos, P., 2006. Evaluation and optimization of ground water observation network using the Kriging methodology. Environmental modeling and software 21, 991-1000.

Thiart, C., De Wit, M., 2000. Linking spatial statistics to GIS: exploring potential gold and tin models of Africa. South African Journal of Geology 103(3-4), 215-230.

Thole, U., Zimmermann, H.-J., Zysno, P., 1979. On the suitability of minimum and product operators for intersection of fuzzy sets. Fuzzy Sets and Systems 2(3), 167-180.

Tsopjio Jiomeneck, S.P., Tematio, P., Wilson, A., Yemefack, M., 2011. Andosolization of Soils on a Strombolian Cone at Mount Bambouto, Cameroon. Open Journal of Soil Science 1, 97-105.

Varnes, D.J., 1974. The logic of geological maps, with reference to their interpretation and use for engineering purposes. United States Geological Survey Professional Paper 837.

Vicat, J.-P., Bilong, P., 1998. Géosciences au Cameroun. Presses Universitaires de Yaoundé.

Zadeh, L.A., 1965. Fuzzy sets. IEEE Information and Control 8 (3), 338-353.

Table 1. Alumina (wt.%) of diricrusted laterites on the Bamiléké Plateau

Lower surface		**Upper surface**							
Doumbouo-Fokoué		Fongo-Tongo		Bangam		Loung		Djeu	
Sample	**Al_2O_3 (wt%)**	**Sample**	**Al_2O_3 (wt%)**	**Sample**	**Al_2O_3 (wt%)**	**Sample**	**Al_2O_3 (wt%)**	**Sample**	**Al_2O_3 (wt%)**
DF1	31.3	FO1	50.8	BA1	51.1	LO1	57.3	DJ1	22.3
DF2	35.1	FO2	59.7	BA2	47.1	LO2	39.1	DJ2	27.2
DF3	52.6	FO3	34.0	BA3	48.4	LO3	54.7	DJ3	28.9
DF4	38.7	FO4	43.1	BA4	38.4	LO4	44.3	DJ4	47.3
DF5	37.6	FO5	44.4	BA5	38.3	LO5	53.7	DJ5	40.0
DF6	42.0	FO6	47.2	BA6	60.3	LO6	46.9	DJ6	35.2
DF7	44.5	FO7	49.4	BA7	60.4	LO7	54.9	DJ7	38.4
DF8	28.7	FO8	51.6	BA8	59.7				
DF9	35.9	FO9	48.2	BA9	46.8				
DF10	36.0	FO10	37.4	BA10	43.5				
DF11	35.0	FO11	44.0	BA11	42.8				
DF12	47.5	FO12	49.8	BA12	40.0				
DF13	49.5	FO13	57.5	BA13	47.3				
DF14	36.0	FO14	44.9						
DF15	33.3	FO15	50.1						
DF16	37.7	FO16	49.9						
DF17	13.8	FO17	39.3						

Figure 1

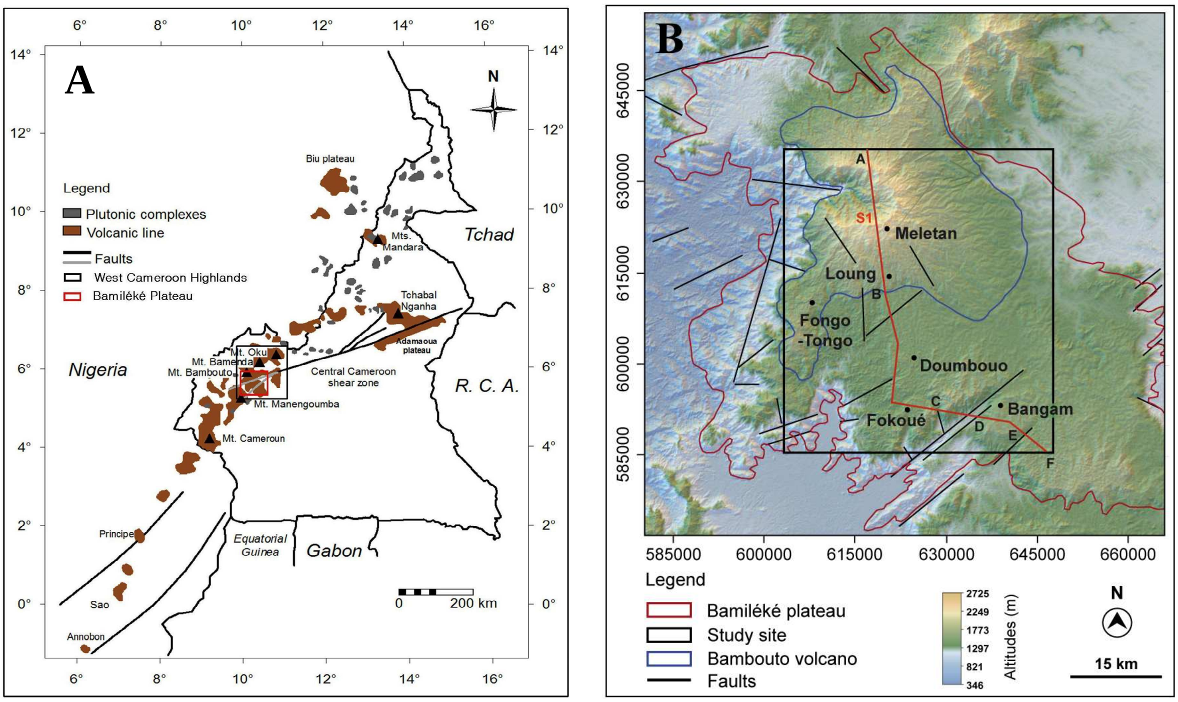

Figure 1. A: Localization and structure of the Cameroon volcanic line (from Ballentine et al., 1997; and Ngako et al., 2006); B: morphology of the Bamiléké plateau. Letters A to F mark the major morphological changes along the cross section in figure 4.

Figure 2

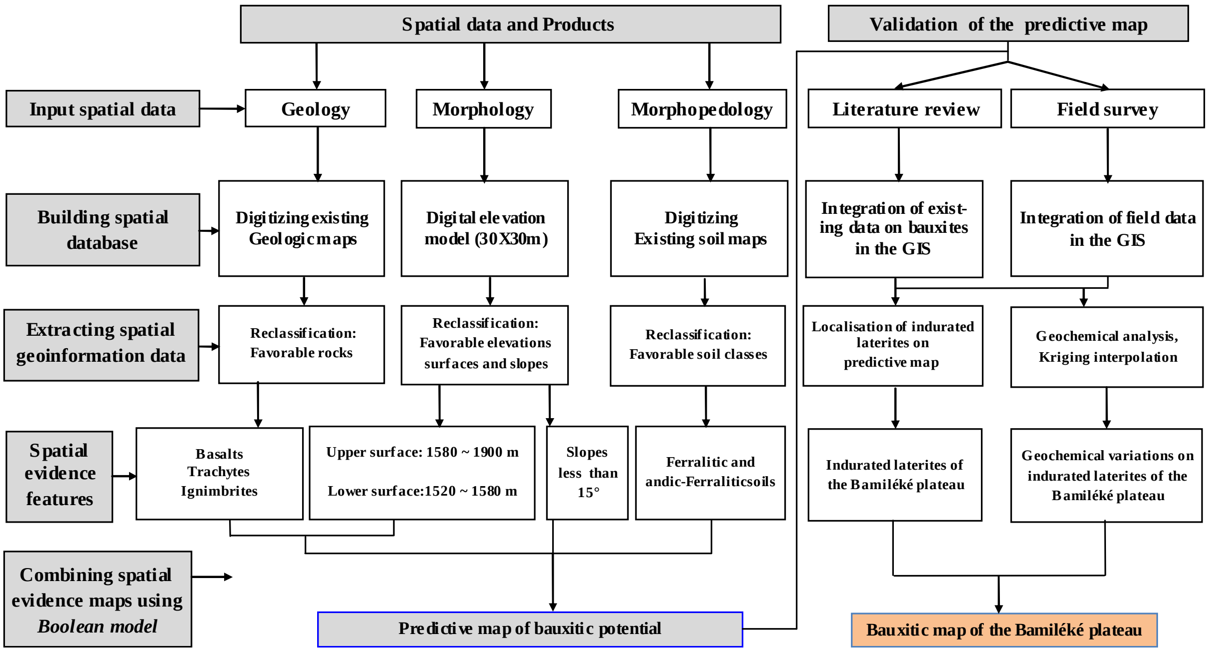

Figure 2. Methodology applied to undertake geologically constrained mapping of the Bamiléké plateau bauxites

Figure 3

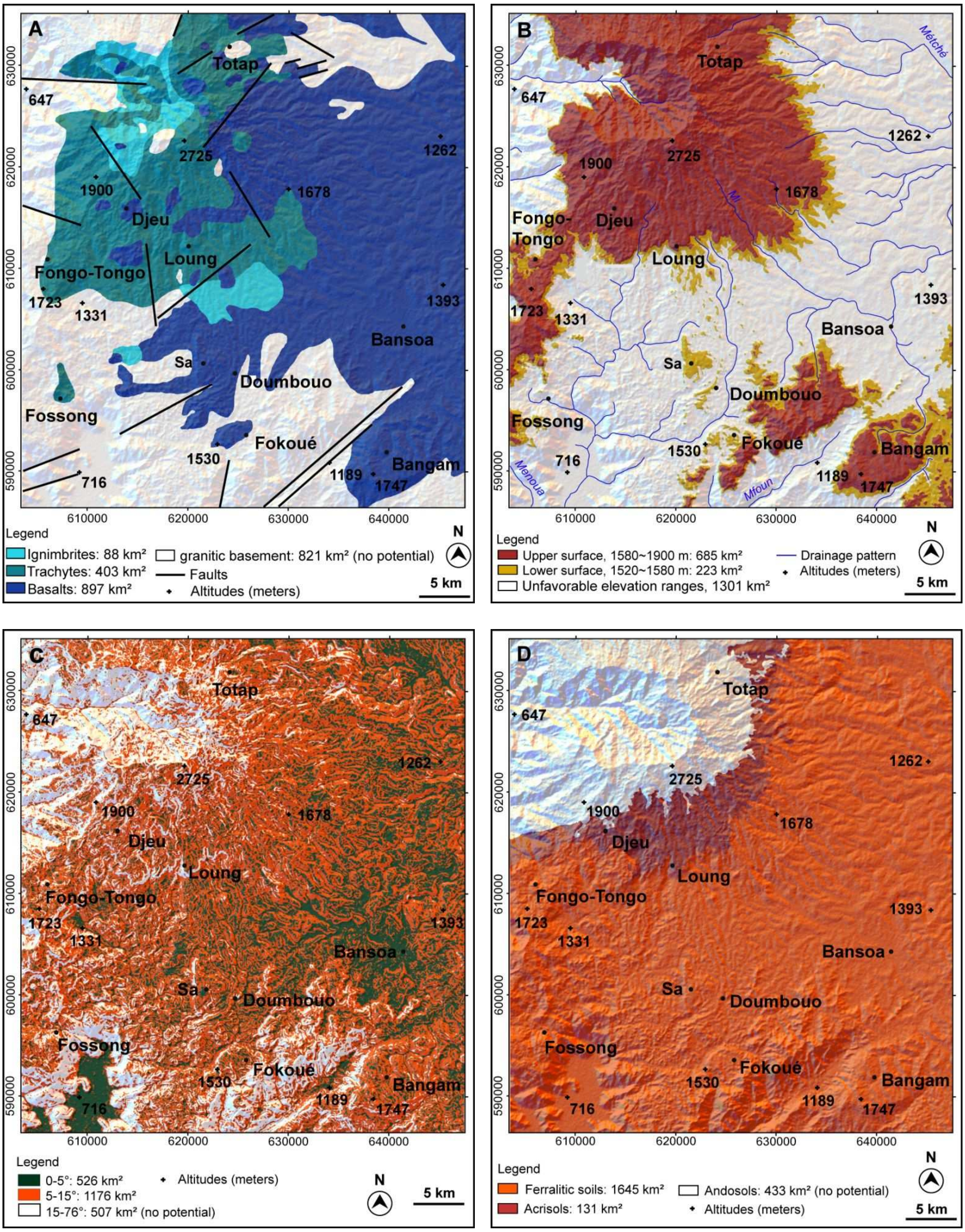

Figure 3. Favorable constraints maps. A: rocks; B: elevation ranges; C: slopes; D: soil

Figure 4

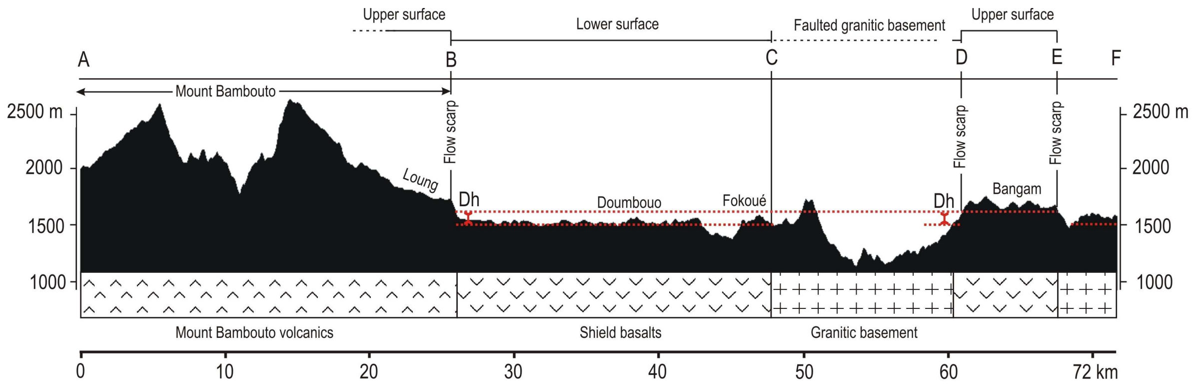

Figure 4. Cross section showing the vertical and lateral distribution of lateritic surfaces. Section S1 on figure 1B

Figure 5

Figure 5. Morphological distribution of duricrust on the Bamiléké plateau. A: continuous duricrust on flat interfluves; B: steep slope limiting flat duricrust on the top; C: convex slope showing evidence of duricrust dismantling

Figure 6

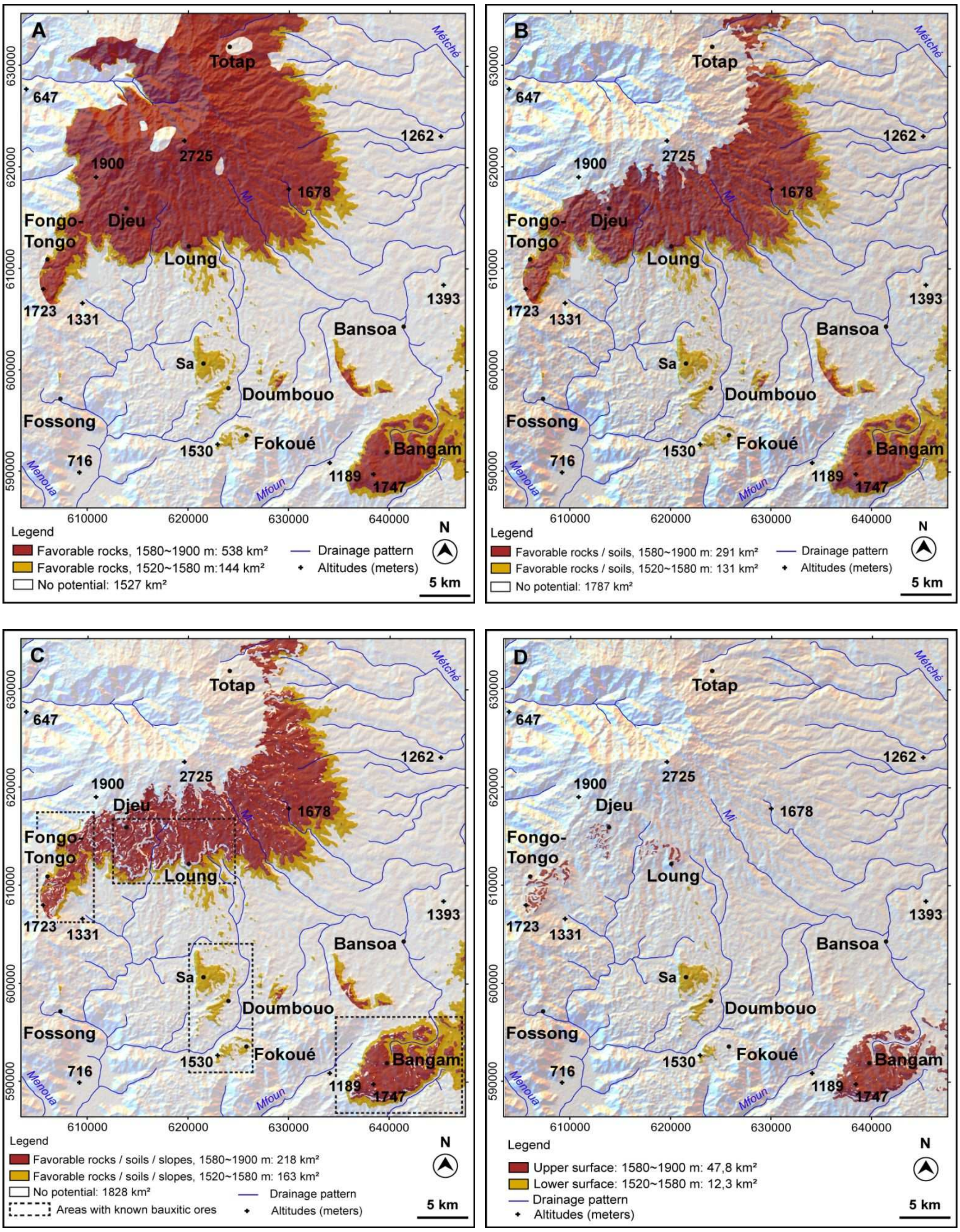

Figure 6. Potential maps and field validation results. A: favorable elevation ranges constrained with favorable rock types; B: A constrained with favorable soil classes; C: B constrained with favorable slopes; D: map of indurated laterites of the Bamiléké plateau.

Figure 7

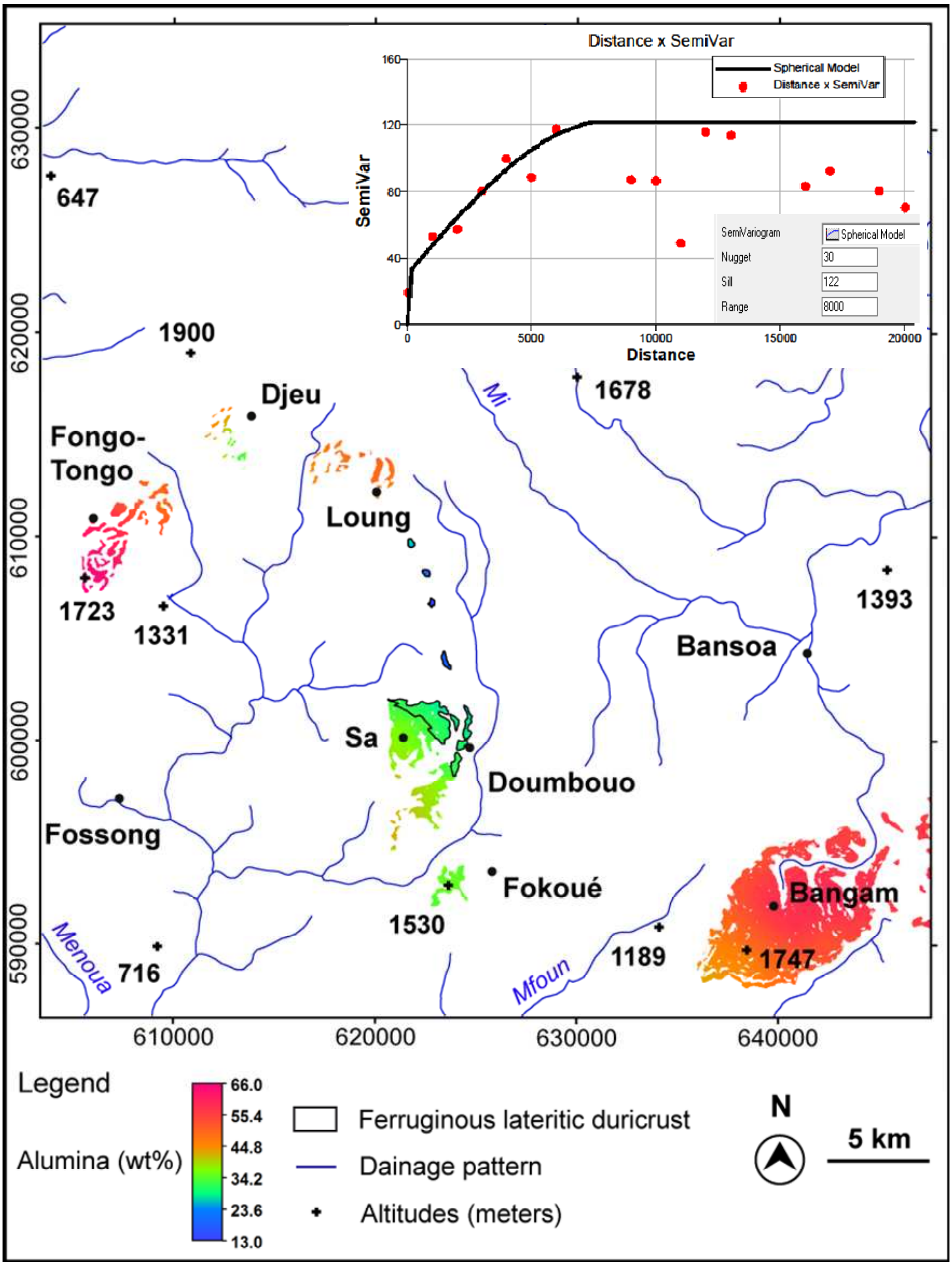

Figure 7. A: Semi-variogram model; B: map showing the distribution of alumina percentages on indurated laterites of the Bamiléké plateau