Geodynamic framework of large volcanic fields highlighted by SRTM DEMs: Method evaluation and perspectives exampled on three areas from the Cameroon Volcanic Line

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A B S T R A C T

This study is a part of a wider investigation to evaluate how much can be learnt by using low-cost methods such as systematic moderate-resolution remote sensing to map and quantify geological structures at the regional scale on very large volcanic provinces only partly studied in the field. Volcanic-centre and cinder-cone distribution, faults and structural lineaments are mapped combining Shuttle Radar Topography Mission (SRTM), Digital Elevation Models (DEMs) and Landsat satellite images. As an example of the method, we present the interpretation of structural data and morphological features of three contrasted areas from the Cameroon Volcanic Line (Tombel graben, Upper Benue valley, and Ngaoundéré area) for which local field studies are available for comparison. At a local scale, this remote-sensing method of mapping displays good to excellent correlations with previously published data and, by itself, it allows one to constrain the structural setting of each area. Numerical treatment of vent and cinder-cone localisation can be related to tension fractures (T direction), whereas numerical treatment of the lineaments constrains the associated fault system to a single transtensional (strike-slip + extension) Riedel type fracture network. The first results on the Cameroon Volcanic Line are promising and could be used at a larger scale on numerous volcanic provinces for which field data are not yet available.

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1. Introduction

Recognition of the close spatial association of faults, lineaments and volcanic centres has led to the construction of models explaining the pattern of regional deformation in different geodynamic environments. Volcanoes can be associated with regional tectonic structures resulting from extensional (e.g. Smith et al., 1995), strike-slip (e.g. Aydin et al., 1990) or compressional strain (Tobisch and Cruden, 1995; Galland et al., 2007). At a local scale, vents can be related to tension fractures, e.g. in Iceland (Opheim and Gudmundsson, 1989; Chorowicz et al., 1997) or Ethiopia (Korme, 1997), or to active faults (e.g. Cello et al., 1985). Regional tectonic structures have been shown to strongly influence the growth of volcanic edifices in preferential directions (e.g. Adiyaman et al., 1998), as evidenced by the non-random localization of main eruptive centres and secondary eruptive vents (e.g. Nakamura, 1969; Connor et al., 1992). Nakamura (1977) inferred principal stress orientations in the Aleutian arc from the systematic pattern of volcanic vent alignments whereas Opheim and Gudmundsson (1989) and Chorowicz et al. (1997) showed that the distribution and shape of small vent buildings and the orientation of tension fractures were directly related to the tectonic regime. While the linear distribution of volcanoes related to tension fractures can thus be used as indicators of the tectonic stress regime, a key problem in the study of very large volcanic provinces is that numerous areas have not yet been studied in the field and that, consequently, structural and volcanologic maps are not available for such an approach. However, in modern volcanic fields, topography datasets at a kilometer scale may usually compensate the lack of such data. Volcanic centres, cinder-cones, faults and structural lineaments can be mapped combining Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEMs) and Landsat satellite images. SRTM DEMs yield a homogeneous ~90 m spatial-resolution topographic dataset with near global coverage (from 60°N to 56°S) and display the best resolution available for numerous poorly known areas.

A suitable geodynamic environment to examine such key issues is the Cameroon Volcanic Line (CVL) now called Cameroon Hot Line (CHL; Déruelle et al., 1998; Moreau et al., 1998; Déruelle et al., 2007), which covers several thousands square kilometers. The relationship between volcanism and compressional, strike-slip and extensional deformations is not well established, especially in the central part of the CVL, due to the lack of detailed fieldwork, of volcanic-activity monitoring, or of research on the structure of the large active volcanic fields. Documenting the distribution of volcanic vents and volcanotectonic structures can help identify the factors that key-control the
spatial distribution of volcanic activity, and the influence of regional tectonics on the structure and evolution of the shields. Conversely, detailed understanding of shield structures can help unravel tectonic processes at work within the CVL. This approach is tested here through a morphostructural study and the numerical treatment of structural features of three sites from the CVL: the Tombel graben area, the Upper Benue valley (Yola branch), and the Ngaoundéré area (Adamawa plateau). These areas have been selected on the basis of the available geological maps, which allow discussion of our remote-sensing methodology. After a comparison between off-field mapping and published maps, we propose new interpretations of the structural framework related to the geodynamic environment of the studied zones.

2. Geological setting of the three selected areas from the CVL

2.1. The Cameroon Volcanic Line (CVL)

The NNW-trending Cameroon Volcanic Line (CVL) extends for more than 2000 km across the Gulf of Guinea and Africa, mainly in Cameroon (Fig. 1). It crosses both the ocean and the continental domains from Pagalu Island in the Gulf of Guinea (Atlantic Ocean) to Lake Chad. Some authors even extend the line to Tibesti and Southern Libya (Vincent, 1970; Tempier and Lasserre, 1980). The CVL comprises many Cainozoic (60 Ma to recent) volcanic centres and anorogenic plutonic ring-complexes. It is divided into two branches at its northern end, the first one westward across the Benue Valley, and the other to the east throughout the Ngaoundéré plateau. The central part of the CVL is crossed by NE–SW major faults (Moreau et al., 1987), while its oceanic part is mainly composed of volcanic islands forming a N30° linear array. Numerous hypotheses have been proposed to explain its structure and formation (see Déruelle et al., 1991 and 2007 for a review). It has been considered to result (i) from the movement of the African plate over a hotspot (Morgan, 1983). The similarities in size and shape between the CHL and the nearby Benue Trough to the NW led Fitton (1980) to postulate that the CHL resulted from an anti-clockwise rotation of the African lithosphere over a hotspot at about 80–65 Ma, thus locating the hotspot beneath Mount Cameroon instead of beneath the Benue Trough. (ii) From membrane stresses generated by movement of the African plate away from the equator (Freeth, 1978). (iii) From reactivation of ancient postpanafrican basement fractures (Moreau et al., 1987).
et al., 1987). Lack of a consistent space–time migration (see the chronological syntheses in Fitton and Dunlop, 1985 and Déruelle et al., 1991, 2007) and the fact that Mount Cameroon (MC) and Bioko island are currently the only active volcanoes, are in conflict with a conventional hotspot model. So far, the most widely accepted structural explanation is that the CHL would be a succession of “en-échelon” mega-tension gashes resulting from reactivation during Aptian–Albian times of the N70E shear zone-associated faults at the onset of opening of the Central Atlantic Ocean (e.g. Moreau et al., 1987). Following Déruelle et al. (1998) and Moreau et al. (1998), a recent review of the petrological, geochemical and isotopic data (Déruelle et al., 2007) re-interprets the CVL as a mantle “Hot Line” (the “Cameroon Hot Line”: CHL) instead of a hotspot trail.

### 2.2. Selected areas

The geodynamic settings of the three studied areas (Tombel graben, Upper Benue valley, and Ngaoundéré area) have been described previously in detail (i.e. Derruelle and Regnoult, 1983; Moreau et al., 1987; Ngounouo, 1993; Nkouathio et al., 2002; Tchameni et al., 2006) and are only shortly summarized below.

- The Tombel area (Fig. 1) is a trough (or graben) located between the Mt Cameroon and Mt Manengouba stratovolcanoes in SW Cameroon. Its N30° elongation axis is parallel to the general orientation of the CVL. It has a rectangular shape (44 km × 10–20 km) and covers an area of ~800 km²; its altitude increases gradually from 100 m to the south to more than 500 m to the north (Tchoua, 1974). The Cainozoic volcanic formations rest unconformably over Precambrian metamorphic formations intruded by late Proterozoic granitoids (Dumort, 1968; Lamilen, 1989; Tagne Kamga, 1994).

- The Yola branch of the Garoua rift is the northeastern branch of the Upper Benue valley; it is a wide flat basin of Cretaceous age covering an area of 4500 km², at an average altitude of 300 m. Available seismic profiles (PoudjomDjomani et al., 1997) indicate that the Garoua-rift E-W trending basins are in fact a mosaic of half-grabens and horsts covered with various sedimentary units separated by unconformities and intensively hatched by listric faults (Moreau et al., 1987, and Ngounouo et al., 2003).

- The Ngaoundéré area (Adamawa plateau) is located in central Cameroon, at the northeastern end of the CVL (Fig. 1). It is an asymmetrical horst of Precambrian basement rocks bounded by N70E faults (Moreau et al., 1987) and cut by the Foumbian Shear Zone which is part of the ENE–WSW-trending Pan-African Central African Shear Zone which extends over 2000 km from Cameroon to Sudan (Corna and Dars, 1983). The Adamawa plateau has been uplifted during the Cainozoic, up to 1 km relative to the surrounding area. This uplift is characterised by altitudes ranging from 800 m in its northern part to 1200 m in its southern part. A gravity study shows positive Bouguer anomalies beneath the Adamawa uplift (PoudjomDjomani et al., 1992). These anomalies are interpreted as resulting from both lithospheric thinning (40 km) and crustal thinning (10 km), which could be related to the early stage of continental rifting along pre-existing basement weakness zones (PoudjomDjomani et al., 1997).

Those three studied areas were selected for their differences in terms of surface areas, of geological environment, of observable volcanological features, and the availability of geological maps used to constrain this approach and validate our results.

### 3. Methodology

There are many ways to form linear and/or circular features in a geological environment. Linear features can be faults, joints, dykes, steep to vertical strata or even anthropic features such as roads. Circular features can be cinder-cones in volcanic areas, or topographic domes. It is also possible to define lines as limits between areas either anthropic (different agricultural uses) or natural (surfaces of different tones), or by linking discrete objects of similar nature such as meanders in a series of streams, notches in ridges, etc. In some cases, these lines may be purely coincidental (with a random distribution) but, in other cases, they have genetic relationships to subtle or deep buried faults. Hence, all potential lines need to be viewed with caution and subdivided into categories with different degrees of confidence. The choice of a kilometer scale of investigation and the combination of DEMs and Landsat images allow one to constrain linear and circular features of geomorphological origin. Landsat images have been used to control and infer the DEMs interpretation concerning the nature of rocks and human-related linear features. Here, the linear features referred to as lineaments will only be those of geological (lithological and/or structural) origin. As for circular features with high slopes, they may also have various origins, such as being either domes or cinder-cones in volcanic areas. However, on the topographic map of the volcanic area, cinder-cones are marked by a protuberance causing the change of slope and topography while, on the slope map which is simply the derivative of the topographic map, the cinder-cone is marked by a point or a circle. The difference between the cinder-cones and other types of volcanoes is simple as the latter often have cinder-cones but are often surrounded by deformed halos (which in some cases represent the limits of lava flow) around their summit. This is perfectly illustrated on the slope maps.

#### 3.1. Remote sensing mapping

Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEMs) are a homogeneous 3-arc-second (~90 m) spatial-resolution topographic dataset with near global coverage (from 60°N to 56°S). SRTM data were acquired by the radar system onboard the Space Shuttle Endeavour, during an 11-day mission in February 2000. Topographic data were obtained from single-pass synthetic aperture radar (SAR) interferometry (Rabus et al., 2003). SRTM DEMs are freely available on the Internet and can be visualized with standard map viewer softwares. Gaps in the SRTM data occur for steep terrains due to shadows in the radar sight angles; nevertheless SRTM data do represent the best readily available topographic data (Rodriguez et al., 2006) to study volcano morphology and structures in regions lacking accurate topographic maps (Kervyn et al., 2007).

The main morphological features of the studied areas (lineaments and cinder-cones) were processed by using Surfer® 8.02 (Golden Software) and controlled against the Landsat images. This software was used to get the shaded relief model showing the terrain under an artificial illumination, with bright sides and shadows (shaded relief maps are raster maps based on grid files [xyz coordinates, e.g. DEM]). These maps use colours to indicate the local orientation of the surface relative to a user-defined light source direction (the orientation of each grid cell), which is inferred from the calculated reflectance of a point light source on the grid surface. Many types of maps used in this work can be extracted from the original altimetry database, such as, for example:

#### 3.1.1. A three-dimensional view

It is a perspective view of the terrain from a user-defined position above the terrain. This view is a digital elevation model displayed as a raster ‘blanket’ in three dimensions. The user can specify the sighting parameters to define the perspective of the observer in relation to the 3D model (Fig. 2a, b, and c). The light source can be thought of as the sun shining on a topographic surface. Portions of the surface that face away from the light source reflect less light towards the viewer and thus appear darker, displaying it with light position angles at 45° vertically and 135° horizontally. The rotation angle is 0° and the projection is orthographic.
3.1.2. A slope model (Fig. 2 d, e, and f)

It shows the slope angle of each grid node on the surface, with slope values varying from zero (horizontal) to 90° (vertical). A sudden slope change can be associated with a lineament, a topographic object (lava flow, cinder-cone, pluton, dyke, ...) or a lithological change. The slope model is associated to a three-dimensional perspective view of the slope variation.
3.2. Softwares used

The image analysis by the moments-of-inertia method had its beginnings in the late 1970s (Rink, 1976) and has been revisited in the early 1990s (Jahn, 1991) and 2000s (Launeau, 2004). The method is especially appropriate for 2D section analysis. It was developed and illustrated through the study of a rock image, which resulted in the SPO2003 and INTERCEPTS2003 softwares by Launeau and Robin (2003). They digitized their image while differentiating the individual phases, each one being given a specific numerical code. The image was then processed by a search algorithm of all neighboring pixels with the same code. The tensor representing the moment of inertia then results from the exploration of the pixel coordinates by rows and columns. The resulting moment of inertia is independent of shapes. Here, we will only use the « center-to-center method » part of the program which allows one to analyze the spatial distribution of the objects. The principle of the distribution analysis of a population of objects by the center-to-center method can be summarized as follows.

In a way similar to phase identification by Launeau and Robin (2003), the individual objects are given a specific code, based on their nature. The feature image is then analyzed through an algorithm to compare neighboring pixels according to the codes, and to define the shape of each object in detail. This information is reported next at the center of each object and the resulting dataset is analyzed by another algorithm to search for the nearest neighbor with similar characteristics. This provides distribution maps of the similar objects, the maps being finally converted into a covariogramme (for further explanations and the complete mathematical development, see Jahn, 1991; Launeau and Robin, 1996; Launeau and Cruden, 1998).

The SPO2003 software principle above follows that of the optical method of Robertson (1943), later computerized by Leistel et al., 1984. The method has been used in geology mainly to establish correlations between positional properties of ore deposits and some of their inherent properties (Leymarie, 1968; Marconnet et al., 1981; Cottard, 1982) as an alternative to analogical calculation methods such as autocorrelation used to show the statistical significance of spatial distribution of geological assemblages (Wartenberg, 1985) or to analyse the surface distribution of subvolcanic or volcanic complexes (Moreau et al., 1987).

As for the INTERCEPTS2003 software (Launeau and Robin, 1996, 2003), it calls upon a method which belongs to stereology, a branch of geometry whose aim is to infer information in 0, 1, and 2D from 1, 2, or 3D data. Here, one considers the number of item boundaries intercepted on a 2-dimensional image by a set of parallel scan lines along a number of directions: these directions range between 0 and 180° and their number is a function of the pitch angle chosen. Roses obtained from this method of interception can be decomposed into a Fourier series, which may itself be used to extract a direction rose (for more details about the method, see Launeau and Robin, 1996). The limit on this software is that one must first isolate each item and give each one a distinctive color before analysis.

3.3. Structural treatment

The observed lineaments and other topographic objects on the shaded relief models were manually digitised and plotted on the screen by using graphic softwares. This yielded different maps for the linear structures, ridge cut-offs and uniformly dipping bedding surfaces, topographic changes and circular objects. These features can be related to tectonic characteristics. The maps resulting from slope and curvature analysis are based on the presence of sudden slope-angle changes (or slope breaks), which can be due to lithological differences, topographic differences, or to the presence of thrusts or faults (Fig. 3). To constrain this approach and validate our results, we then compared the feature maps drawn here to the published geological maps (Figs. 4, 5 and 6) and found that the degree of consistency only depends on the accessibility of the area. After such a validation, the maps were exported as Bitmap files which are accepted by the SPO2003 and INTERCEPTS2003 softwares (Launeau and Robin, 1996; Launeau and Cruden, 1998; Launeau, 2004). The
present approach was first developed by and Nkono (2008) who analyzed images of volcanic cones and lineaments over an area of 110 km aside.

The SPO2003 software was used to analyze the distribution, the mean orientation, and the arrangement of the geological circular features (cinder-cones) by the analogical centre-to-centre method.
(Fig. 7). It was also used to obtain the length of the lineaments and their orientation in terms of azimuth, with the lengths finally converted into a synthetic rose diagram (Fig. 7) or into a radar-type diagram of lineament cumulative lengths (Fig. 7). The limits on regional maps are simple: the SPO2003 software does not analyze objects the size of which is less than 5 pixels.

The results obtained through the above method of identification are then compared to the geological maps of the studied areas, that is, to maps based on field work. The match is very close to 100% (validation process and results) within the limits imposed by the SRTM image resolution that is 270 m (3 × 90 m). The difficulty of observation of identified areas of high altitudes also arises for the regions of low altitudes. This problem is solved simply by selecting appropriate color-scale representations for the topographic maps and slopes maps. Practically, this is done by reprocessing the SRTM images through the Surfer® software which allows an optimum mode of representation through a free choice of scale, colors, lighting, etc...

The geological maps of the regions studied show that the size of the cinder-cones varies from 500 m to 1 km in diameter, which is significantly greater than the size of the smallest observable items (270 m).

All the structural lineaments were also systematically mapped. Maps of the slope gradient and of the slope orientations were particularly helpful to highlight breaks in slope, ideal to detect tectonic features such as faults characterized by a linear topographic step. Attention was focused on recent lineaments directly related to volcanoes. Faults are identified by: (1) fault scarps; (2) displacements of volcanic boundaries, structural surfaces or erosion surfaces; (3) occurrences of straight lines, which are several kilometres in length; and (4) typical patterns such as horsetail or tail-crack structures (Adiyaman et al., 1998). To analyse the principal orientations, lineaments were mapped precisely at the scale of each area. The lineaments were analyzed through the INTERCEPTS2003 software developed by Patrick Launeau and Robin (1996, 2003) to obtain the main lineament orientations (in terms of azimuth), these data being presented in rose diagrams (Fig. 7).

4. Results

4.1. Raw maps of lineament and cinder-cone distribution

The three studied sites have some differences in terms of surface areas, of geological environment and of observable volcanological features. The area of the graben of Tombel (~1900 km²; Fig. 4) contains 106 observed cinder-cones (26% of 401 from the complete degree square) and 74 observed lineaments (37% of 200 from the complete degree square). The Upper Benue valley (Fig. 5) extends on a comparable 2000 km² area and contains 100 observable cinder-cones (32% of 303 from the complete degree square) and only 20 lineaments (30% of 66 from the complete degree square). By contrast, the Ngaoundéré area (~4800 km²; Fig. 6) located on the Adamawa plateau contains only 44 observed cinder-cones (37% of 119 from the complete degree square), and 98 lineaments (54% of 198 from the complete degree square).

Results from the Tombel graben area display the best correspondence (~94% of the total number of features) between the features...
mapped from SRTM-Landsat-derived images and the published geological map. Indeed, 106 cinder-cones have been identified by the method proposed in this work against 113 mapped by Nkouathio et al. (2002), among which 84 are unquestionably the same objects as for their location. In the Upper Benue valley, 102 cinder-cones have been identified on the SRTM-Landsat-derived images against only 31 identified and mapped by Ngounouno (1993). Nevertheless, among these 31 cones, 23 are indeed observed in remote-sensing images. In the Ngaoundere area (Adamawa plateau), the correspondence between cinder-cone distribution maps cannot be assessed because the geological map of Tchameni et al. (2006) mainly is a lithological map that does not include morphological features to compare to the SRTM-Landsat-derived map; however, there is a good correspondence for the northern limit of the volcanic field and for the major lineament/fault locations.

4.2. Structural results

Cinder-cones, as circular objects, have been considered as punctual features and analyzed through the centre-to-centre method using the SPO2003 software. The results are illustrated by a covariogram image (Fig. 7a) on which the contrast and colors indicate the general

Fig. 6. Ngaoundere area (Adamawa plateau). Comparison between the map of structural features (lineaments and cinder-cones) obtained from the SRTM images (slope, topography) and the published geological map (Tchameni et al., 2006). The structural features are represented on a simplified geological background. The continuous lines represent the lineaments, the stars represent cinder-cones. (a) Slope map from SRTM images, (b) geological map (Tchameni et al., 2006), and (c) structural features identified on SRTM images. 1 biotite±hornblende porphyroid granitoids, 2 hornblende biotite granitoids, 3 amphibole and garnet gneisses, 4 biotite±muscovite granitoids, 5 basalts.
The direction of distribution of the cinder-cones (colour variations from green to orange to white correspond to a decreasing cinder-cone density associated to a given direction). In some cases, the directions used for establishing the covariograms can be subdivided into primary and secondary, as illustrated on Fig. 7b (principal direction) and Fig. 7c (secondary directions). In the Tombel graben area, cinder-cones are

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<th>Tombel graben</th>
<th>Upper Benue valley</th>
<th>Ngaoundéré area</th>
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Fig. 7. Analysis of the various structural features (lineaments and cinder-cones) identified on SRTM images for the 3 studied areas: the Tombel graben, the Ngaoundéré area (Adamawa plateau), and the Upper Benue valley (Yola branch of the Benue trough). a) Mean direction under which cinder-cones are distributed. These directions were obtained by the centre-to-centre method using SP02003 software (Launeau and Robin, 2003). The green color corresponds to the highest concentration of cinder-cones, the white zone marks the absence of cinder-cones; yellow and orange correspond to the intermediate concentration. b) Representation of the principal direction (given here by the number near each black ellipse) under which cinder-cones are distributed. c) Representation of the secondary directions under which cinder-cones are distributed; the mean directions are indicated by the numbers near each small black ellipse. d) Rose diagrams obtained by the analysis of lineaments (analysis was made every 5°); directions are indicated by the numbers. e) Directions of lineaments in terms of cumulative length (analysis was made every 10°); numbers give the mean orientations. f) Rose diagrams of lineaments by the INTERCEPTS2003 software (Launeau and Cruden, 1998), analyses were made every 10°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
mainly distributed along a N25 general direction with two secondary directions (N50 and N154). In the Upper Benue valley, the covariogram is more complex: the cinder-cone distributions can be decomposed into two main directions (N54 and N132) and several secondary directions associated to each primary direction (N115 and N160 relative to N54, and N32 and N72 to N132). In the Ngaoundere area (Adamawa Plateau), there are two primary directions (N65 and N110) and three secondary directions close to N28, N65 and N115.

Lineaments, as linear objects, were individually analyzed and counted by orientation sectors of 5° (using the SPO2003 software) in terms of numbers (Fig. 7d) and cumulative lengths (Fig. 7e). They were also globally analyzed as a network through the intercept method (INTERCEPTS2003 software; Fig. 7f). Rose diagrams for lineament numbers, cumulative-length radar-type diagrams, and direction roses obtained with the intercept method roughly display comparable results.

For the Tombel graben area, the rose diagram (Fig. 7d) shows two principal directions (around N63 and N170), and two secondary ones (N40 and N110). The cumulative-length-type radar diagram (Fig. 7e) shows three principal directions of fracturing (N32, N65, N173) and two minor directions (N110 and N120). The analysis of the orientation of the lineaments through the INTERCEPTS2003 software (Fig. 7f) yields a principal N63 direction, two secondary directions (N156 and N25) and one subsidiary N115 direction.

For the Upper Benue valley, lineament orientations display four main (N29, N62, N112 and N172) and two secondary (N10 and N48) directions. Cumulate lengths of lineaments show that the fracturation is largely controlled by two main directions only (N58 and N170) highlighting a drawing artefact and/or a change in the fracture network (the main length of a lineament changes with orientation sector). The direction rose diagram (INTERCEPTS2003) has a principal (N168), two secondary (N53, N111) and two minor (N22 and N80) directions.

In Ngaoundere area, the rose diagram displays two main directions near N65 and N167 with three secondary directions at N15, N35 and N110. The cumulative lengths show a complex fracturation pattern, with main N51, N71 and N163 directions and a second level of fracturation near N10, N35, and N105. The direction rose diagram (INTERCEPTS2003) shows two/three principal (N18, N66 and 109) and one/two secondary (N109 and N156) directions.

5. Discussion

5.1. SRTM DEMs tectono-volcanological mapping and treatment

The difference in terms of percentage of correspondence between the map of the structural features (lineaments and cinder-cones) identified on remote-sensing images and the geological maps drawn from fieldwork varies from area to area, which illustrates the differences between the geological and geographical environments in the three studied areas: among these differences, the field accessibility and the quality of exposures and outcrops have a direct and significant influence on the details reported on the geological maps.

For the easily accessible Tombel graben area, the correspondence is excellent (94%) between the volcanological features deduced from the maps derived from remote sensing and those of the published geological map. By contrast, for the Upper Benue valley area which is difficult to access according to its position in the central swampy part of the valley, the geological map is much less precise and the remote-sensing method appears to be promising. In fact, this area is covered by recent alluvial sediments that might even prevent direct proper observation of the lineaments.

Tectono-volcanological features mapped using SRTM-Landsat-derived images have been analysed to constrain their main orientations that can further be used at a global scale for geodynamic interpretations. The directions of cinder-cones alignments are investigated by the centre-to-centre method to constrain tension fractures related to the tectonic regime, whereas lineament orientation could highlight the fracture network associated to the main active faults in such a recent volcanic field. Automatic counting process of length and direction for each lineament or for the complete population of lineaments interpreted as a network (intercept method) yields comparable results. The rather good concordance between the results of lineament analysis through various methods allows the subjective part inherent to the operator to be severely limited. This study shows that the very fast intercept method (Laureau and Robin, 1996) yields results comparable to those obtained from more complex and time-consuming methods such as the cumulative-length counting, and that it may easily and usefully replace this classical method.

5.2. Tectonic and geodynamic interpretations

The different orientations and geometrical relations obtained through analysis of the structural features with the various methods were examined altogether in terms of the Riedel system for the geodynamic interpretation of each volcanic field (e.g. Moreau et al., 1987; van Wyk de Vries and Merle, 1998). Riedel shear fractures were first recognised as an important feature of brittle to semi-brittle shear zones by Riedel (1929), who produced these structures in analogue experiments with clay. The subject has since been the focus of extensive research in many domains: field studies (e.g. Moore, 1979; Davis et al., 1999; Ahlgren, 2001; Katz et al., 2004), analogue modelling with clay (e.g. Cloos, 1955; Schalenko, 1968; Wilcox et al., 1973 Smith and Durney, 1992; Marques, 2001) and sand (e.g. Naylor et al., 1986), direct shear experiments (e.g. Bartlett et al., 1981; Moore and Byerlee, 1992; Schreus, 1994) and numerical modelling (e.g. Dresen, 1991; Braun, 1994; McKinnon and Garrido de la Barra, 1998). These works resulted in a widely accepted model of shear fracture orientation in non-coaxial deformation illustrated in Fig. 8a. The most conspicuous element of this idealised geometry is the Riedel conjugate set, comprising synthetic Riedel fractures (R) and conjugate antithetical Riedel fractures (R'), oriented at 45° ± θ, where θ is the internal angle of friction of the rock. Also important are synthetical P-shear fractures (at −45° + θ/2) and the purely tensional T fractures (at 45° in simple shear). The precise angular relationships of the different sets of fractures and the shear plane are dependent on the internal angle of friction, as well as on the strain rate and stress state (Ahlgren, 2001) and vorticity (Smith and Durney, 1992). This framework is generally interpreted as a precursor to faults in a synthetically driven model (e.g. Ahlgren, 2001) where R fractures are the first to develop, followed by P fractures.

In the Tombel graben area (Fig. 8b), the vents and cinder-cones can be related to tension fractures (T direction–map projection of α1) oriented N25; while the lineaments are principally related to synthetic and antithetic fractures, R at N40, and R' at N172, respectively. Some other faults are related to the P direction oriented N103, with the E direction at N115 (Extensional direction–map α3 projection). The relation between the orientations of lineaments and cinder-cones can be explained as the result of a transtensional [strike-slip + extension] stress field. This model is comparable to the one deduced from the structural data of the nearby Mt Cameroon. The Tombel area, which lies at the southern tip of CVL is subjected to a diachronous N65 strike-slip regime.

In the Upper Benue valley area (Fig. 8c.), the structural features have been related to a local extensional regime, in view of the Riedel model. The covariogram of cinder-cones analysis by the centre-to-centre method shows that the cinder-cones are distributed along two parallel tension crack (T) systems. In the first one, the T direction is close to 132° (tension crack), P’−20°, E−49°, R’−167°, and R’−111°. The second system is characterized by T−54° (tension crack), P’−168°, E−152° and R’−47°. The combination of the two systems displays
shared directions: for example, the major lineament orientation corresponds to the $R'$ parameter in the first system and to $P$ in the second system. The average principal N54 orientation of the cinder-cone alignments corresponds to the general orientation of the main Benue basin and to the Cainozoic trend for the fault network, whereas the second N132 direction is parallel to the Adamawa volcanic plateau and to the general Mesozoic-trend fault system in central Africa (Kampunzu and Popoff, 1991). The relation between the orientation of the lineaments and the cinder-cone distribution in this area as a whole can be interpreted as resulting either from a transtensional (strike-slip + extension) regime with $\sigma_1$ in the EW direction, $\sigma_2$ oriented NS and a vertical lower stress direction $\sigma_3$, or from a local extensional regime with $\sigma_1$ vertical and $\sigma_3$ in the EW direction and $\sigma_2$ oriented NS. It presents the characteristics of an early step of development in a Riedel system with a blocking of the extension marked by the development of $R$ and $R'$ faults and a great development of the $T$ fractures (Antoine et al., 1985).

In the Ngoundéré area (Fig. 8d), the principal N65 cinder-cone alignment corresponds to the general orientation of the intracontinental basins, such as the Mbere-Djerem basin and also to the orientation of the southeastern boundary of the Adamawa plateau. This direction also corresponds to Cainozoic faults which control the emplacement of the Adamawa Plateau. The N135 alignment of the cinder-cones corresponds to the opening direction of the central part of Benue basin. This orientation also represents the long axis of Yola branch basin (Benue through). In the area, two superimposed Riedel systems could explain this complex direction fan. The first one would be related to the Mesozoic fault trend: vents with cinder-cones are distributed along N105 stress fractures ($T$) while lineaments are principally related to $R$ at N126, $R'$ at N63 and $P$ at N162, with an extension direction $E$ at N15. The second system would be related to the Cainozoic volcanic trend: vents and cinder-cones, oriented at N128, can also be related to $T$. Lineaments are principally related to $R$ at N52, $R'$ at N162 with $E$ at N121. In a two-stage volcanic emplacement, the two systems could describe a shared direction fan with two successive stress fields. The second one (Cainozoic) having used the pre-existing Mesozoic fault system (Kampunzu and Popoff, 1991).

6. Conclusions

Volcanic centres and cinder-cone distribution, faults and structural lineaments have been mapped combining Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEMs) and Landsat satellite images. The method, quite simple and not expensive, provides an excellent complement to conventional geological mapping. It can be carried out upstream or downstream of any classical geological study.

The method has been used to study the distribution of lineaments and cinder-cones in three areas of the large volcanic province called the Cameroon Volcanic Line (CVL): the Tombel graben, the Upper Benue valley (Yola branch), and the Ngoundere area (Adamawa plateau). These areas were selected because classical geological maps derived from fieldwork are available. The main advantage of the remote-sensing method is the possibility to study areas that are not easily reachable for field work. The correspondence between the maps obtained through the remote-sensing method and those based on geological fieldwork is generally very good. The use of several tools, taken one by one, for the structural analysis of the lineament and cinder-cones distribution, avoids, or at least much reduces, the subjective part in interpreting the SRTM images. However, one of the
References

Despite the differences in terms of the geological mapping available, numerous other large volcanic objects with sizes used in this paper at a regional scale (low resolution is not yet a constraint) will lead to a regional framework that could enhance the geodynamic interpretation of the Cameroon Volcanic Line and of other large volcanic fields around the world.

The main purpose of this article was to develop and test a method of SRTM image analysis which could help build geodynamics model. Despite the differences in terms of the geological mapping available, three areas selected here validate this method which may thus be confidently applied to areas for which there are no geological maps. The geological data extracted from the SRTM images do correspond to the reality of the field.

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References


