Sci

**Borrower:**

$

WEB ~~SITE~~ ~~LIB. HAS~~ ~~Current~~ 12 months only

**140.211.112.16**

Record 44 of 47

ILL pe

Record 7 of 47

7/12

CAN YOU SUPPLY ? YES NO COND FUTUREDATE

:ILL: 6961902 :Borrower: WOS :ReqDate: 20040706 :NeedBefore: 20040715

:Status: IN PROCESS 20040707 :RecDate: :RenewalReq:

:OCLC: 1767232 :Source: FS5ILL :DueDate: N/A :NewDueDate:

:Lender: CWU,*ORU,HTM,WEA,ORE

:CALLNO: *Lender's OCLC LDR: v.1-v.51,v.53-v.241,v.251-v.255,v.257- 1964-

:TITLE: Tectonophysics.

:IMPRINT: Amsterdam, Elsevier Scientific Pub. Co.

:ARTICLE: Zhang, Dazheng; Lutz, Timothy M. "Structural control of igneous complexes and kimberlites; a new statistical method"

:VOL: 159 :NO: 1-2 :DATE: 19890220 :PAGES: 137-148

:VERIFIED: GeoRefS NO: 1989026656 CODEN: TCTOAM Type: illus., analytic level, Serial ISSN: 0040-1951 [FORMAT: Serial]

:PATRON: Keene, Rob / 04-2617

:SHIP TO:

ILLWestern Oregon University
Hamersly Library
345 N Monmouth Ave
Monmouth, OR 97361-1396
**ARIEL IP**: 140.211.112.16

:BILL TO: same **** Please include your TIN FEIN on invoice

:SHIP VIA: Ariel/1st Class Mail :MAXCOST: postage :COPYRT COMPLIANCE: CCG

:FAX: ARIEL IP: 140.211.112.16 fax(503 838-8645)

:E-MAIL: ilibloan@wou.edu

:BILLING NOTES: WOU TIN 93-6001786-A3

:AFFILIATION: **Member of LVIS, ORBIS**

:LOCATIONS: XFF,ORZ,OIP,ONB,IOD,TXO,RIU,IBS,BDR,FXG,XFM,YPM,TXJ,FGM,ISU,MDY,BBH,UMR,IAD,TFW

**OCLC Number:**

**ILLWestern Oregon University**
**Hamersly Library**
**345 N Monmouth Ave**
**Monmouth, OR 97361-1396**
****ARIEL IP**: 140.211.112.16**

earth movements in the Nankai
Inst., 4: 1–14.
lement modeling of a preseismic
term anomalous surface deforma-
55–76.
marks on the characteristics of
ivities. In: Proceedings of Earth-
ch Symposium, pp. 97–105 (in
and Sato, H., 1976. The crustal
associated with the Nankaido
Geod. Soc. Jpn., 45: 77–78 (in
981. Structure of the uppermost
inferred from travel times of S
in Japanese).
rmation due to dislocation in a
Phys. Earth, 19: 31–46.
nations in an obliquely layered
slip fault. J. Phys. Earth, 22:
1975. Static deformations in an
. Part II. Dip-slip fault. J. Phys.
1973. Static deformations due to
several layers in a multi-layered
nent. J. Phys. Earth, 21: 227–249.
sis of relatively deep earthquakes
ecial reference to the underthrust-
Plate. J. Geosci. Osaka City Univ.,
hanisms of major earthquakes in
ir tectonic significance. J. Phys.
pendent strain accumulation and
plications for the 1946 Nankaido
is, M.I.T., Cambridge, Mass., 292
1985. Configuration of subducted
eath the Chubu district, central
(in Japanese).
crustal deformation and its rela-
ic movement on the Pacific coast
Res. 7: 157–170.
g, Y.K., 1967. The Finite Element
and Continuum Mechanics.

*Tectonophysics*, 159 (1989) 137–148
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands



# Structural control of igneous complexes and kimberlites: a new statistical method

DAZHENG ZHANG and TIMOTHY LUTZ

*Department of Geology, University of Pennsylvania, Philadelphia, PA 19104-6316 (U.S.A.)*

(Received January 8, 1988; revised version accepted June 24, 1988)

## Abstract

Dazheng Zhang and Lutz, T., 1989. Structural control of igneous complexes and kimberlites: a new statistical method. *Tectonophysics*, 159: 137–148.

The spatial distribution of magmatic activity may provide important information about magma formation, magma transport through the lithosphere, and the mechanical properties of the lithosphere. Zones of weakness in the crust, tentatively associated with deep crustal fractures, have been hypothesized to control the locations of magmatic centers. A connection between some lineaments and large-scale crustal structures suggests that magma emplacement could be controlled by sets of fractures with linear outcrop patterns. In this case, the locations of magmatic centers would not be distributed randomly but would have an anisotropic component. Thus, identification and characterization of such anisotropic control is a valuable exercise.

Previous attempts to derive information about anisotropies from the locations of magmatic centers have been flawed or have provided only an estimate of the directions of anisotropy. In this paper we extend concepts presented previously (Lutz, 1986) to derive estimates of the locations, as well as the trends, of the features that could control magmatism. Monte Carlo simulations of random point patterns are used to provide a null model relative to which the characteristics of actual patterns can be evaluated on a statistical basis. Tests on simulated anisotropic patterns show that the method can successfully reveal underlying anisotropies even if a substantial proportion of the magmatic centers are located randomly.

Applications to central magmatic complexes in Nigeria and to kimberlites in South Africa reveal control by anisotropies in both areas. However, the trends and locations are not apparently related to prominent geologic features previously suggested to have played a role. Thus, the anisotropies are imposed either by structures at depth or by structures that appear at the surface as minor fractures and joints.

Shallow igneous complexes are often associated with potentially valuable economic deposits. Therefore, this method provides a means to predict the locations of resources. However, the method can be applied to the analysis of anisotropy in any features that can be approximated by points lying within a plane. Thus, earthquake epicenters might be analyzed to determine locations to be avoided to reduce seismic risk.

## Introduction

Some geologic features such as earthquake epicenters, kimberlites, and igneous complexes are pointlike, i.e. their locations relative to one another can be approximated by points in a plane. The spatial distribution of these features may be random or may be controlled by regional geologic structures such as major fractures. In the case of magma transport, the fractures might develop either along pre-existing zones of weakness in the crust or they might form in response to stress fields at the time the magma is ascending. The role of epeirogenic faults and transform fault exten-

0040-1951/89/$03.50 

sions in controlling the locations of igneous activity has recently been reviewed with special regard to kimberlites (Mitchell, 1986).

When fractures do play a role, the pointlike features may be distributed anisotropically along the trend of the structures. Thus, the spatial distribution of points, in turn, may be useful to reveal large-scale structures. Chapman (1968) suggested that alkaline igneous complexes were located at nodal points of a lattice formed by intersecting sets of crustal fractures. He proposed that grid lines could be constructed so that the complexes were located at nodal positions, but he did not propose an objective way to determine the lattice orientations. Thompson and Hager (1979), in a study of magnetic anomalies, required that lattice lines should fall close to a certain minimum number of points. However, they did not explain how this number could be found. Furthermore, both Chapman (1968) and Thompson and Hager (1979) perceived a lattice line as one passing close to a large number of pointlike features relative to other choices of orientation. However, if the points lie in an elongated region then lines parallel or subparallel to the elongation direction may pass close to a relatively large number of points regardless of any lattice pattern (Lutz, 1986). Therefore, these methods rely heavily on intuitive perceptions that in application might lead to subjective conclusions about the importance of tectonic control and the orientations and locations of lattice lines.

Lutz (1986) showed that spatial anisotropy could be quantified by using the distribution of azimuths of lines connecting all pairs of points. Monte Carlo simulations of random points were used to eliminate effects related to the shape of the region and to provide a reference distribution from which confidence levels could be determined. This method, termed the line azimuth method, provides a means to find the trends of anisotropies but not the locations of the lattice lines. It is the purpose of this paper to present a new method that can provide information about both the orientations and the locations of lattice lines.

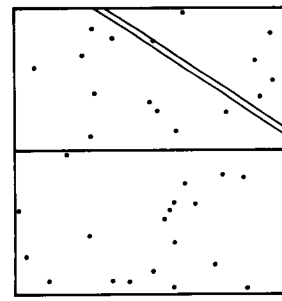
## Results

To develop our model we adopt the concept of a probabilistic structural lattice as proposed by Lutz (1986, p. 422). That is, crustal structures are considered to be narrow zones in which the probability of an event, such as magma emplacement, is high relative to their surroundings. The traces of the structures on the earth's surface describe a lattice that controls the locations of pointlike features and creates a lattice distribution of points. Thus, the areal distribution of lattice points is anisotropic. A lattice of order 1 consists of a set of traces with a single orientation; two intersecting sets with different orientations define a lattice of order 2; and so on.

Because we are interested in finding the locations of lattice lines as well as their orientations we need to resolve spatial and directional information. Imagine viewing a map of lattice points through a filter that consists of a set of parallel, equally-spaced lines that form narrow windows. For some arbitrary orientation of the filter the points could be roughly evenly distributed among the windows. However, rotating the filter until the lines are parallel to a lattice direction causes the points to be distributed heterogeneously. Windows over lattice lines contain all of the points while the others are empty. We propose to implement such a filtering method.

## Methods

In general, the pointlike features to be studied will occupy a region within an irregular, and possibly elongated, shape. For a given set of points we can define the region using a convex bounding polygon as described by Lutz (1986, p. 427) and can divide it into parallel strips as suggested above. We choose an equal number of strips to span the region regardless of orientation. This means that the average number of points per strip is constant throughout the analysis. A disadvantage is that the width of the strips, and therefore the spatial resolution, may vary somewhat as a function of orientation. The width of all strips in a single orientation is kept constant so that resolution does not vary across the region. However, since the longer strips thus have larger areas than the shorter strips the number of points per strip will vary even in the absence of an anisotropy (Fig. 1). To



hat is, crustal structures are
ow zones in which the prob-
ch as magma emplacement,
surroundings. The traces of
earth's surface describe a
e locations of pointlike fea-
ttice distribution of points.
bution of lattice points is
of order 1 consists of a set of
rientation; two intersecting
entations define a lattice of

erested in finding the loca-
is well as their orientations
tial and directional informa-
g a map of lattice points
onsists of a set of parallel,
hat form narrow windows.
rientation of the filter the
ly evenly distributed among
, rotating the filter until the
lattice direction causes the
d heterogeneously. Windows
in all of the points while the
propose to implement such

tlike features to be studied
vithin an irregular, and pos-
. For a given set of points
on using a convex bounding
by Lutz (1986, p. 427) and
el strips as suggested above.
umber of strips to span the
ientation. This means that
points per strip is constant
is. A disadvantage is that
s, and therefore the spatial
somewhat as a function of
n of all strips in a single
stant so that resolution does
egion. However, since the
larger areas than the shorter
oints per strip will vary even
n anisotropy (Fig. 1). To



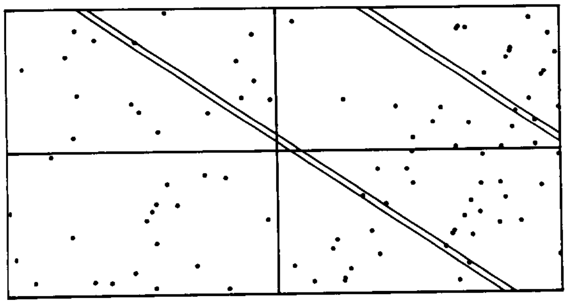


Fig. 1. Two hypothetical strips with the same orientation within a defined region containing points. Longer strips within such a region have larger areas and thus a higher probability of containing points.

eliminate this effect, the areal point density, $d$, is defined as:

$$d = n/(l \cdot w)$$

where $n$ is the number of points within a strip, and $l$ and $w$ are the length and the width of the strip, respectively. For random points, the expected point density would be constant for all strips in a single orientation.

Ideally, we would like to vary the orientation of the strips continuously while keeping track of the density in each strip. The locations of strips with anomalously high densities could indicate zones of structural control, and orientations for which many anomalous strips occur could indicate a lattice direction. In practice, the orientation of the strips is changed incrementally. For example, if the increment is 5°, then 36 different orientations are required to cover the full 180° range in azimuth.

In the actual situation, a single strip might not entirely cover the points associated with a lattice line. For example, the strip direction might not exactly parallel a lattice line, or, if points deviate slightly from a lattice line, the points might straddle two strips. To reduce the possibility of missing lattice lines in this way we use strips that overlap by half; i.e., the region is covered by twice as many strips as required by their width.

Some variation in density from strip to strip will occur even for random points. Following Lutz (1986) we use Monte Carlo methods to generate many sets of random points within the region to develop an empirical distribution of density for each strip in each orientation. The same number of random points are generated in each set as actually occur within the region. The density distribution of each strip expected from random points provides us with a density standard against which the observed density can be compared.

*An example*

To simplify the exposition of our method we use an elongated rectangle that has a length/width ratio of 2/1 and contains 100 points: 50 points controlled by lattice lines trending N30°E and 50 other points located at random (Fig. 2). Fig. 3A shows the region in Fig. 2 rotated so that the N30°E lattice lines are vertical. Figure 3B is a graph of density vs. distance measured from the left to the right in Fig. 3A. The average density and its variation derived from 200 sets of random points are shown by the thinner lines. Note that while the average density of random points is nearly constant from strip to strip the variation in density becomes larger close to the edges of the region as the strips become shorter.

We normalize the observed densities by taking into account the density distribution of the random points. The relative density, $D$, of a strip is defined as:

$$D = (d - M)/S$$

where $d$ is the actual point density, and $M$ and $S$ are the average density and the standard deviation (s.d.) for random points, respectively. The relative

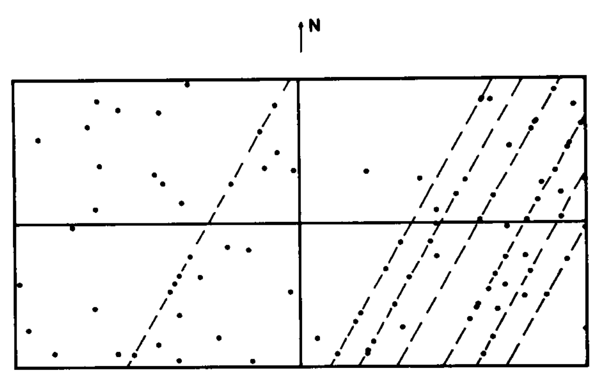



Fig. 2. One hundred points within a region distributed by two different processes. Fifty points are located along lattice lines with a common orientation (N30°E) but with a random spatial location. The other fifty points are located at random.

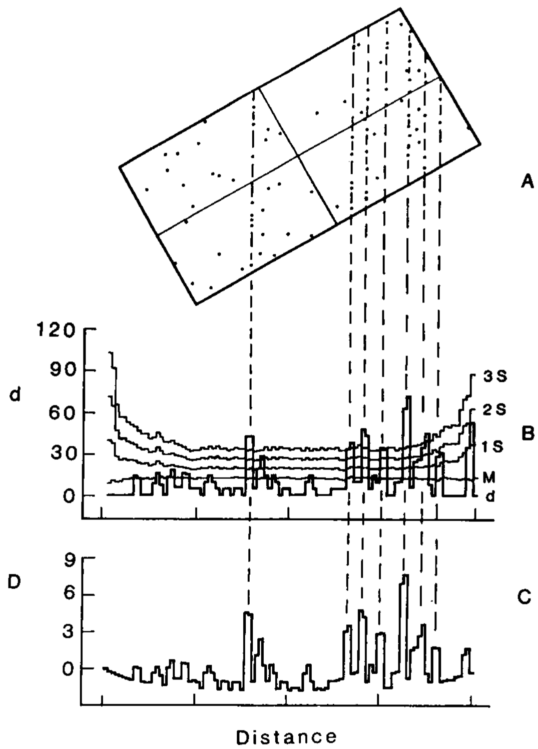



Fig. 3. A. The region in Fig. 2 is rotated so that the lattice lines are vertical on the page. B. Density vs. distance histogram perpendicular to the lattice lines for the points in 3A shows that peaks occur at the locations of the lines. The average density for random points ($M$) is nearly constant. The variability in the density ($1S = 1$ standard deviation, etc.) for random points is larger near the edges of the region where the strips are short. C. Relative density vs. distance showing the pattern after normalization to the Monte Carlo simulations.

density measures the deviation of the observed strip densities from the average density in terms of the magnitude of the variation expected from random points. The high peaks in the graph of relative density vs. distance (Fig. 3C) correspond with the locations of most of the built-in lattice lines.

To place the analysis on a rigorous statistical basis we should use the empirical distributions of relative density to define a critical value that would be exceeded with some small probability, such as 0.05. However, as Lutz (1986, p. 428) has pointed out, placing too much faith in precise critical values is probably unjustified. Instead, we use a limiting value, $L$, for each case we consider such that 2 s.d. $\leq L \leq$ 3 s.d. Choosing a value lower than this range will enhance the likelihood of accepting a line as a lattice line when it in fact results from random points. Choosing a higher value will tend to reduce the probability of finding any but the most densely populated lattice lines. In all of the cases we have studied the results are relatively insensitive to the exact value of $L$.

A relative density greater than $L$ (e.g., $L > 2$ s.d. above the mean) should be unlikely for any single strip. However, in practice the analysis requires that we examine the relative densities of all strips for each direction. Several thousands of strips may be involved. Thus, there is a good chance that some strips with relative densities exceeding $L$ will occur even for random points. To avoid having such "rogue" strips play an undue role in estimating the lattice directions we accumulate densities greater than $L$ for each direction and plot them against strip direction to obtain an azimuth diagram. The ordinate depends both on the extent to which the densities of individual strips deviate from the average density and the number of strips that have anomalous densities. Thus, the peaks on an azimuth diagram should indicate the directions in which there is the greatest consistent tendency for an anisotropy that is penetrative at the scale of the analysis.

For our example in Fig. 3 we use $L = 3$. The azimuth diagram (Fig. 4) has a high peak at N30°E that clearly corresponds with the built-in anisotropy orientation.

In practice, the region is divided into constant-width, half-overlapping strips and the density for each strip is calculated in each orientation. Then

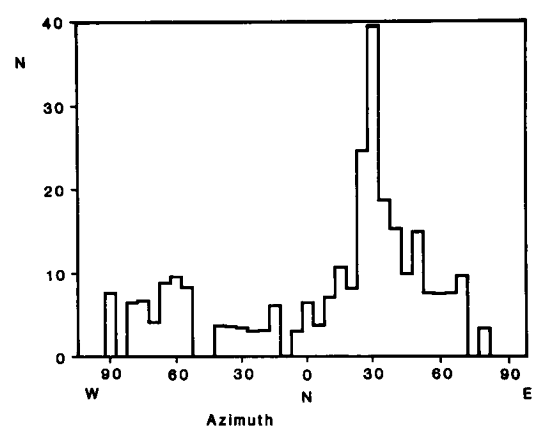



Fig. 4. Frequency of cells exceeding $L = 3$ vs. azimuth for the N30°E direction. Same data as in Figs. 2 and 3.

the identical procedure
random points generat
the empirical density
mulated. The azimuth d
to find the direction(s)
density vs. distance diag
tion is used to find th
lines.

*Random points*

The fact that the lat
the built-in lattice line
covered shows that the
though 50% of the poin
random points mimics
same type of feature mi
some might be contro
might actually occur ra
of the method more sy
consider the effect of
points to total points.
proportions of lattice p
90%) we generated 20 s
case there were 10 bui
90% of the points are o
lines (> 7/10) can be
when only 25% of the
only about half of th

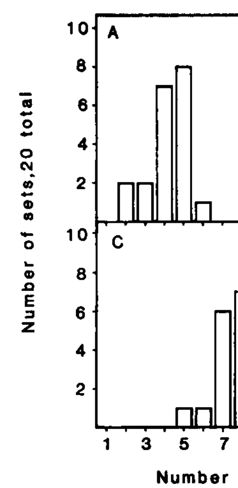
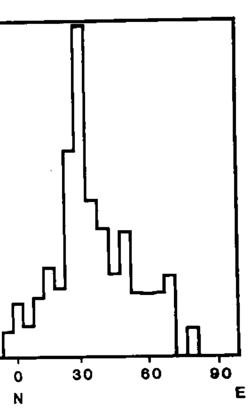



Fig. 5. Number of sets of 10
trials for 4 different propor
points. A. 25/100 points. B. 5
D. 90/100 points. For examp
out of 10 were foun

its. Choosing a higher e probability of finding populated lattice lines. studied the results are exact value of $L$. er than $L$ (e.g., $L>2$ ld be unlikely for any ractice the analysis re- relative densities of all Several thousands of Thus, there is a good with relative densities en for random points. gue" strips play an un- e lattice directions we er than $L$ for each di- ainst strip direction to . The ordinate depends h the densities of indi- the average density and have anomalous densi- azimuth diagram should which there is the grea- or an anisotropy that is the analysis.

g. 3 we use $L=3$. The is a high peak at N30°E with the built-in ani-

s divided into constant- rips and the density for each orientation. Then




ling $L=3$ vs. azimuth for the lata as in Figs. 2 and 3.



the identical procedure is followed for each set of random points generated within the region, and the empirical density distributions are accumulated. The azimuth diagram is constructed first to find the direction(s) of lattice lines. Then the density vs. distance diagram for each lattice direction is used to find the locations of the lattice lines.

*Random points*

The fact that the lattice direction and most of the built-in lattice lines in the example are recovered shows that the method worked well even though 50% of the points were random. Including random points mimics the fact that in nature the same type of feature might originate in two ways: some might be controlled by structures, others might actually occur randomly. To test the power of the method more systematically we explicitly consider the effect of the proportion of lattice points to total points. For each of four different proportions of lattice points (25%, 50%, 75% and 90%) we generated 20 sets of 100 points. In each case there were 10 built-in lines. When 75% or 90% of the points are on lattice lines, most lattice lines ($>7/10$) can be found (Fig. 5). However, when only 25% of the points are on lattice lines, only about half of them ($4/10$–$5/10$) can be found. In all cases, the chances of finding a lattice line where none exists is small.

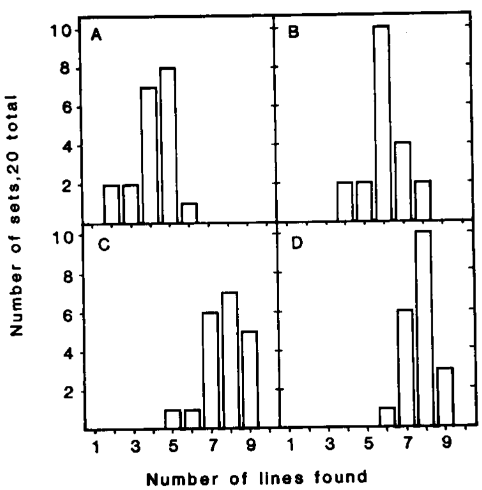



Fig. 5. Number of sets of 10 lattice lines detected out of 20 trials for 4 different proportions of lattice points to total points. A. 25/100 points. B. 50/100 points. C. 75/100 points. D. 90/100 points. For example, for 75/100 points (C) 8 lines out of 10 were found in 7 out of 20 trials.

*Strip width*

Within two extreme limits there is some latitude in selecting the number, or width, of the strips. If too few strips are taken, then the strips will not be highly elongated enough to resolve directional variations in density. If too many strips are taken, then the average density will be so small that the probability of finding more than a single point per strip becomes very small as well and the statistics become highly erratic. The number of strips ideally should be related to the scale on which the anisotropy is expressed.

Another consideration is that structural lattices are not likely to be perfect. Real features are not perfectly pointlike, and they are not located exactly on structures with perfectly linear traces having an absolutely constant orientation. Even if a lattice exerts strong control, deviations of real features from ideal lattice lines are expected to be common rather than exceptional. Thus, the example given above is somewhat unrealistic because the points were generated precisely on lattice lines. To assess the effect of points that deviate from ideal lattice lines we generated some sets of points on lattice lines and then perturbed them by a small, random distance in a random direction. Three sets of 100 points were generated in a rectangle two units long and one unit wide, as in Fig. 1. Fifty points are distributed along, but deviate from, 10 built-in, N30°E lattice lines and the other 50 points are random. The locations of the points in each case are the same except for differences in the amplitudes of perturbation (0.005, 0.04, and 0.075). Thus, the differences between the results should be interpreted to result from the differences in the size of the perturbation and the strip width.

The relative density vs. distance diagrams (for N30°E) constructed using 150 strips, each with a width of about 0.03, (Fig. 6A–C) show that when the deviations of the points from the lattice lines are smaller than the strip width the peaks are usually only a few strips wide, often two because of the 50% overlap (Fig. 6A). When the deviations are significantly larger than the strip width, the

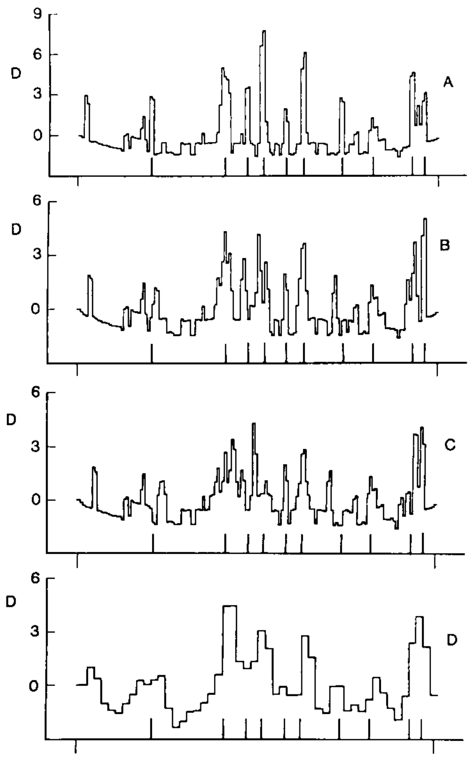



Fig. 6. Relative density vs. distance perpendicular to N30° E lattice lines; the locations of the lines are indicated by vertical lines above the distance scale. The magnitude of the random noise that perturbs the locations of the points is taken relative to unity for the width of the rectangle. A. Noise = 0.005; 150 strips. B. Noise = 0.04; 150 strips. C. Noise = 0.075; 150 strips. D. Noise = 0.04; 50 strips.

peaks are broader, relatively smaller, and harder to separate (Fig. 6B, C).

The corresponding azimuth diagrams (Fig. 7A–C) show that the height and width of the orientation peak are also strongly affected. The maximum peak for the smallest deviation (Fig. 7A) is more than twice as high as for the other two cases. For the largest deviation, about two and a half times the strip width, the peak is broad (25° ) and the mode is not exactly at N30° E (Fig. 7C). Selecting a strip much narrower than the average amount by which the points deviate from a lattice line reduces the signal to noise ratio in terms of determining the locations and the directions of lattice lines.

On the other hand, choosing a wider strip is not necessarily better because the relationship between strip width and the distances between lattice lines must also be considered. Figure 6D is constructed from the same set of points as Fig. 6B, but with strips three times as wide (0.09). No improvement is apparent since the width of the strips is now becoming comparable to the distance between some lattice lines, and some pairs of lines that were resolved in Fig. 6B cannot be resolved in Fig. 6D. The azimuth diagrams (Figs. 7B and 7D) show little difference in the relative peak heights, but the absolute sum of densities is lower when there are fewer strips.

*Summary*

The most remarkable aspect of the foregoing section is that good estimates of the lattice direction and the locations of some of the lattice lines can be obtained even when 50% of the points are random and all of the lattice points can deviate from lattice lines by up to two and a half times the strip width. These results indicate that the method is fairly robust to departures from the ideal lattice model on which it was based. However, the statistical nature of the method is also brought out: you may be able to find some of the lines under most conditions, and most of the lines under some conditions, but you cannot be sure of finding all of the lines under any conditions.

Intuitively, it would be expected that the line azimuth method (Lutz, 1986) and the method presented in this paper, when applied to the same set of points, should yield the same directions of

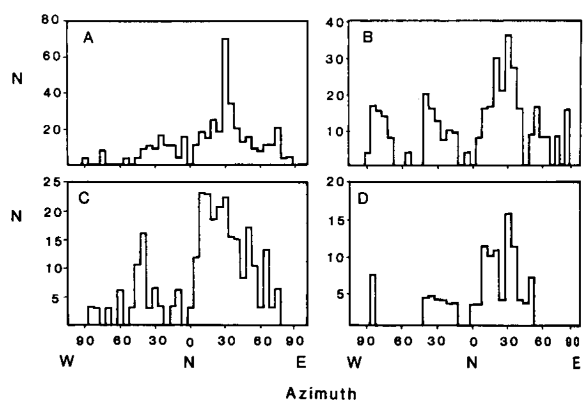



Fig. 7. Azimuth diagrams corresponding to the amount of noise and number of strips in each section of Fig. 6.

anisotropies. As one of o
this is not invariably so.
because the methods u
spatial organization. Th
the line azimuth method
of line segments within a
tion that can be found o
total number of line seg
tional to the square of t
method uses point dens
fined direction, and de
tional to the number of

A further difference
plicitly assumes that th
tirely across the region
line azimuth method d
assumption and as a c
sensitive to short-range
not be detected by our
objective of the analysis
can be used for predictiv
the entire region our
appropriate.

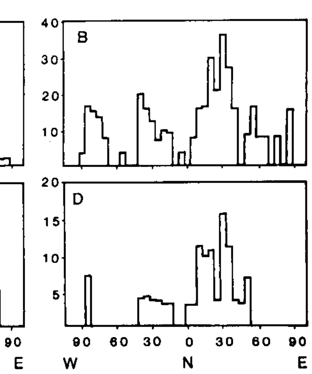
Thus, differences in
these two methods do
both, are invalid. Rat
phasize the difficulties a
with the analysis of an
provide some measure o
a group of points; the
interpreted keeping in
tween them.

## Applications

Hypotheses for the o
features, such as ring c
have been proposed to e
acteristics of their di
arguments have been u
distribution of some ig
and space. For exampl
suggested that age tre
Niger and Nigeria could
tion of the African co
spheric heat source fr
Silurian to the end of
when Africa moved slo

ie distances between lattice
sidered. Figure 6D is con-
set of points as Fig. 6B,
times as wide (0.09). No
nt since the width of the
comparable to the distance
es, and some pairs of lines
g. 6B cannot be resolved in
iagrams (Figs. 7B and 7D)
the relative peak heights,
of densities is lower when

e aspect of the foregoing
imates of the lattice direc-
of some of the lattice lines
hen 50% of the points are
lattice points can deviate
to two and a half times the
ts indicate that the method
tures from the ideal lattice
based. However, the statis-
od is also brought out: you
ne of the lines under most
of the lines under some
nnot be sure of finding all
conditions.
be expected that the line
., 1986) and the method
when applied to the same
eld the same directions of




corresponding to the amount of
ips in each section of Fig. 6.

anisotropies. As one of our applications will show, this is not invariably so. Discrepancies can result because the methods use different measures of spatial organization. The estimate of direction in the line azimuth method is based on the number of line segments within a defined range of orientation that can be found over the entire region. The total number of line segments is roughly proportional to the square of the number of points. Our method uses point density within strips of a defined direction, and density is directly proportional to the number of points.

A further difference is that our method explicitly assumes that the lattice lines extend entirely across the region without interruption. The line azimuth method does not incorporate this assumption and as a consequence may be more sensitive to short-range anisotropies that would not be detected by our method. However, if the objective of the analysis is to find lattice lines that can be used for predictive purposes on the scale of the entire region our method should be more appropriate.

Thus, differences in the results obtained by these two methods do not imply that either, or both, are invalid. Rather, the differences emphasize the difficulties and complexities associated with the analysis of anisotropies. Both methods provide some measure of the spatial anisotropy of a group of points; the results of each must be interpreted keeping in mind the differences between them.

## Applications

Hypotheses for the origin of point-like igneous features, such as ring complexes and kimberlites, have been proposed to explain two different characteristics of their distribution. Plate-tectonic arguments have been used to explain the overall distribution of some igneous complexes in time and space. For example, Bowden et al. (1976), suggested that age trends of ring complexes in Niger and Nigeria could be explained by the motion of the African continent over a sub-lithospheric heat source from the beginning of the Silurian to the end of Jurassic. During intervals when Africa moved slowly magma would be generated and ascend; but times of rapid movement would inhibit magmatism. Such hypotheses may explain the large-scale geography of some igneous rocks, particularly why they sometimes occur diachronously within elongated regions. However, they do not explicitly address the formation of lattice patterns.

Marsh (1973) proposed that alignments of alkaline complexes on the east coast of South America and the southwest coast of Africa are the continental expressions of transform faults that developed during the initial opening of the South Atlantic about 130–140 m.y. ago. He suggested that the complexes lie along small circles centered on the pole of rotation of the two plates. This hypothesis suggests that magmas either form, or are able to rise, along deep continental fractures. A structural lattice of order 1 oriented parallel to the transform fault trend might be expected under this hypothesis.

Chapman's (1968) model for the evolution of granite magma chambers proposed that magmas ascend at the nodal position of two sets of fractures and crystallize to form granite complexes. An order-2 lattice controlled by crustal fractures is expected from this model.

Turner (1976) also proposed that fractures could guide the locations of volcanic eruptions and that ring complexes developed as high level magma chambers beneath them. He suggested that basement fractures which are now evident only as insignificant joints may have controlled the locations of large intrusive complexes. In this case, correlations between some joint directions and lattice directions might be expected.

To test the idea that structural lattices control the locations of igneous complexes we apply our method to ring complexes in Nigeria and to kimberlites in South Africa. In each case we compare our results to the forms of control predicted by the various hypotheses given above.

### *Nigerian ring complexes*

Nearly 50 granite ring complexes have been recognized in the area of the Jos Plateau of Nigeria. These ring complexes are circular or elliptical in outline, and range in size from 1500 $km^2$ to $< 2$

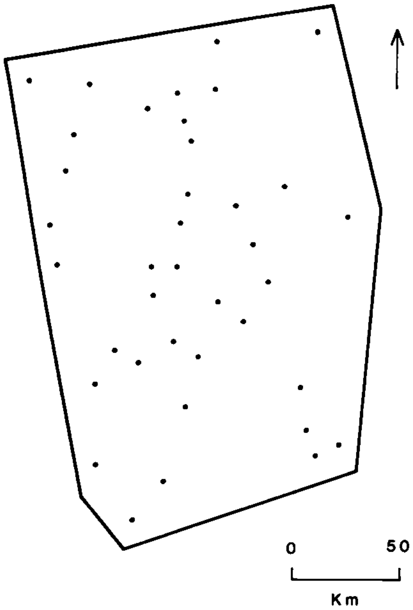



Fig. 8. Schematic map of 38 Nigerian ring complexes used in this study from Kinnaird (1981) and Turner (1977).

km². As described previously, they are part of a more extensive chain that extends from the Benue River Valley in the south through the Jos Plateau to the Air highlands of northern Niger. In addition, the similar, but younger, Cameroun granites to the south of the Nigerian ring complexes follow a northeasterly alignment but without a strong time transgressive pattern (Cahen et al., 1984).

Turner (1976) proposed that the N–S trend of the basement rocks might have influenced the N–S trend of the granite belt in Nigeria. He suggested that migration of igneous activity within some ring complexes occurred along several different trends with no single dominant direction. He found that the NNW and NNE alignments were parallel to zones of shearing in the basement. However, he did not attempt to show that the alignments were part of a regionally consistent structural lattice.

We apply the method developed in this paper to 38 ring complexes in Nigeria (Fig. 8); several outlying complexes are not used. The azimuth diagram ($L = 2.5$ s.d.) has a single high peak at N15°E that is interpreted to represent the direction of an order-1 lattice (Fig. 9). Analysis of the same group of points using the method of Lutz (1986) also suggests that N15°–20°E is the most likely lattice direction. The lattice orientation is significantly different from both the azimuth expected for a transform fault extension into Nigeria (N72°E) suggested by Marsh (1973) and the N–S trends of basement structures suggested by Turner (1976). There is no suggestion of an order-2 lattice such as would be expected from Chapman's model.

The lattice direction coincides with the NNE alignment proposed by Turner (1976), a result that suggests that the NNE-trending shear zones are the most likely known geologic structures to have controlled the distribution of the complexes.

The relative density vs. distance plot for the N15°E direction (Fig. 10) suggests that relatively few lattice lines can be located well. A peak with a height of almost 2.5 near the right margin of the region is associated with a single point that falls within a very short strip. This situation shows that peaks near the edges of the region that depend on only one or two points, and that represent strips that probably have a very low elongation, should not be assumed to have geologic validity. Although only four lattice lines are indicated (Fig. 11) about 50% of the points are associated with them.

### *Bushmanland kimberlites of South Africa*

The Bushmanland plateau is situated about 100 km inland from the southwest coast of South

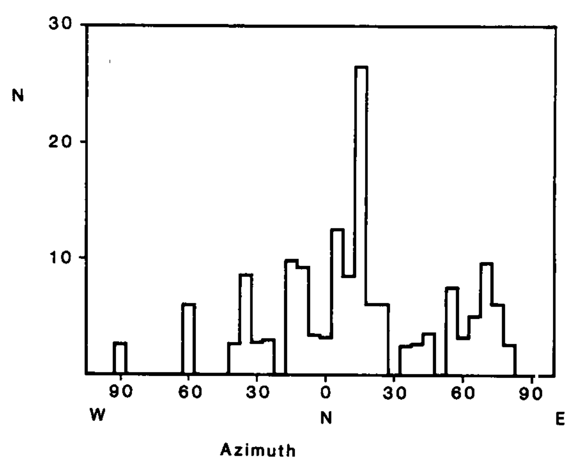
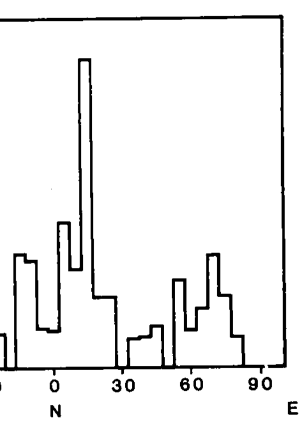



Fig. 9. Azimuth diagram for the Nigerian complexes ($L = 2.5$ s.d.).

N15°–20°E is the most
The lattice orientation is
om both the azimuth ex-
ult extension into Nigeria
Aarsh (1973) and the N–S
tures suggested by Turner
estion of an order-2 lattice
ed from Chapman's model.
coincides with the NNE
Turner (1976), a result that
-trending shear zones are
geologic structures to have
on of the complexes.
vs. distance plot for the
10) suggests that relatively
ocated well. A peak with a
ar the right margin of the
h a single point that falls
. This situation shows that
the region that depend on
, and that represent strips
ery low elongation, should
ave geologic validity. Al-
e lines are indicated (Fig.
points are associated with

*s of South Africa*

lateau is situated about 100
southwest coast of South




the Nigerian complexes ($L = 2.5$
s.d.).



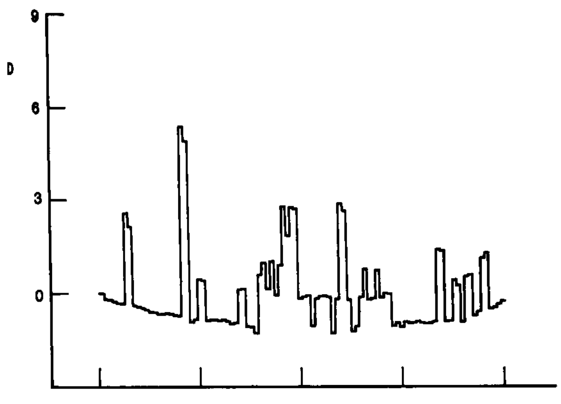



Fig. 10. Relative density vs. distance diagram for the Nigerian complexes for the N15° E direction (Fig. 9).

Africa. The faults in this region run northwesterly (Dawson, 1970; Cornelissen and Verwoerd, 1975). It was proposed that the emplacement of kimberlite pipes was controlled by joints which trend N25°E and N47°E in the Riembreek–Kap Kap area of Bushmanland (Cornelissen and Verwoerd, 1975). This proposal was based on the orientations of 328 joints and 18 kimberlite "pipe lineaments" (visually appealing alignments of nearby kimberlite pipes). However, both the joint and lineament diagrams have multiple modes and correlations between them are not straightforward (cf. Cornelissen and Verwoerd, 1975, fig. 4). It is also difficult to imagine that superficial features such as minor joints could control the appearance of kimberlites, which are formed from deep (over 100 km) magma sources (Mitchell, 1986).

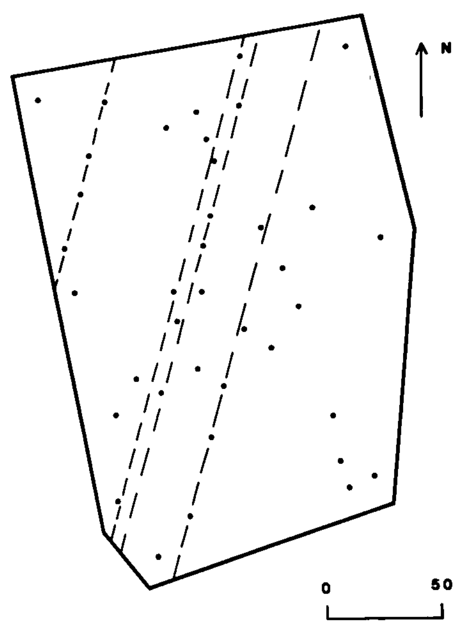



Fig. 11. Map showing the locations and orientations of lattice lines for the Nigerian complexes. Lines located based on peaks in Fig. 10.

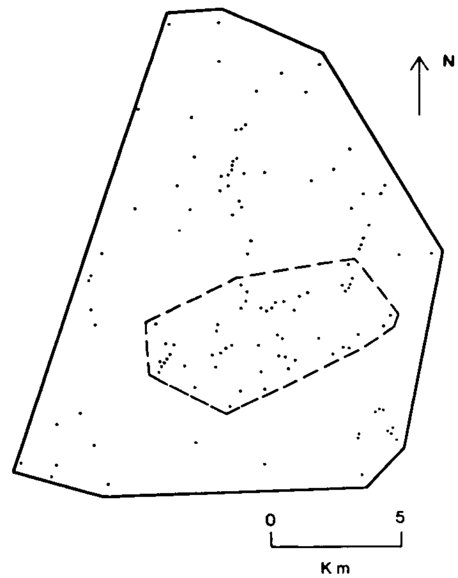



Fig. 12. Schematic map of 124 kimberlites in South Africa from Cornelissen and Verwoerd (1975), Fig. 3. The dashed line defines a subarea containing 54 points.

There are a total of 124 kimberlite pipes in the Riembreek–Kap Kap area (Fig. 12). We apply our method to the entire group of kimberlites as well as to those in a subarea in which there is an obvious concentration of 54 pipes. Following Lutz (1986) we suggest application of the method to subareas as a means to verify results or to detect differences in anisotropic patterns from one area to another.

The azimuth diagrams for both sets of points (Fig. 13A, B) yield a high peak around N20°E, which is close to one of the minor joint directions proposed by Cornelissen and Verwoerd. The distance diagrams for N20°E for both areas (Fig. 14) show that there is a good correspondence between the locations of the peaks derived from each set of points. The lattice lines estimated from each distance diagram (Fig. 15) match up well, suggesting

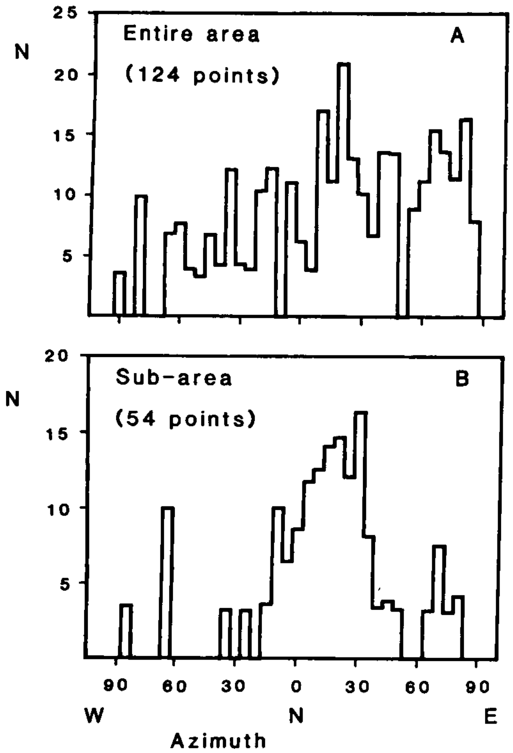



Fig. 13. Azimuth diagrams for kimberlites. A. Entire area. B. Subarea.

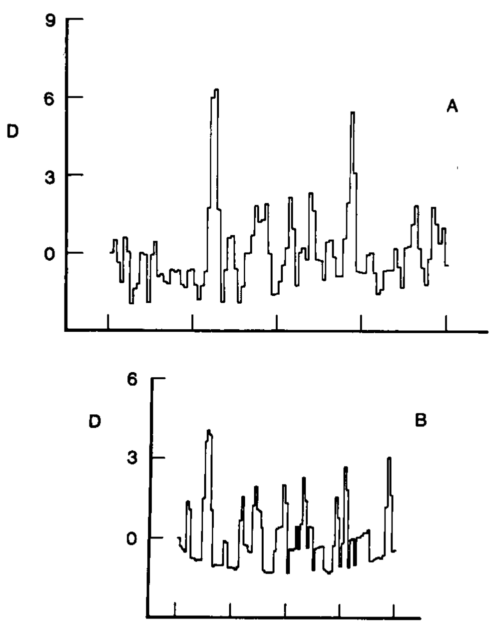



Fig. 14. Distance diagrams for the kimberlites for the N20 ° E direction. A. Entire area. B. Subarea. The diagrams are arranged so that the distance scales are the same and are in the proper relative locations.

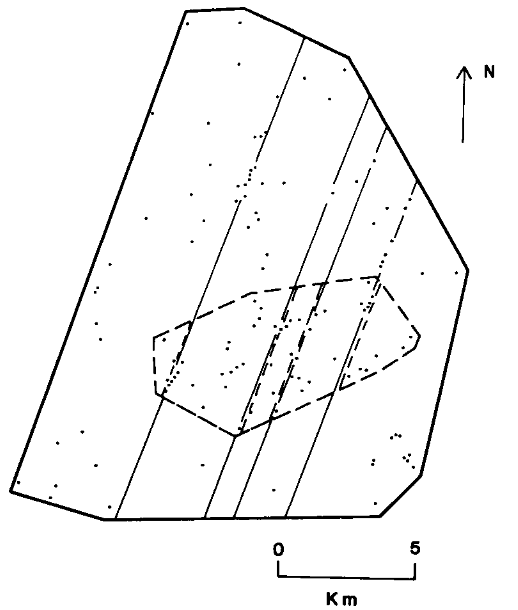



Fig. 15. Map showing the lattice lines determined for the entire area (solid) and for the subarea (dashed).

that the analysis is recovering information that is not strongly dependent on the specific set of points selected.

When the line azimuth method is applied to the same sets of points the preferred direction in both cases is N60 °–65 ° E, and in each case the azimuth peaks far exceed the 95% critical value. There is no evidence for a N20 ° E direction of anisotropy. The difference between the results most likely originates because the methods make different assumptions, as outlined previously. The interpretation for the Riembreek–Kap Kap area might be that two sets of linear structures affected the locations of the kimberlites. A schematic diagram (Fig. 16) illustrates the possible difference. A set of lattice lines trending N20°E and extending continuously across a region would be an interpretation suggested by the results of our method alone (Fig. 16A). To synthesize our results with those of the line azimuth method, we propose an en echelon arrangement (Fig. 16B). The lattice lines trend N60 ° E and have the same total length as those in Fig. 16A, but do not form a continuous set. These would not be detected by our method but might be by the line azimuth method. The en echelon pattern (trending N20 ° E) is continuous

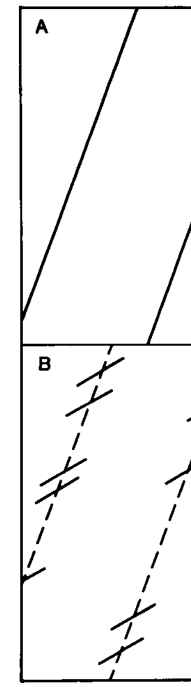


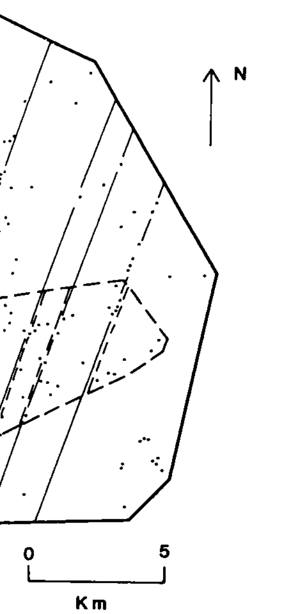

Fig. 16. Schematic diagram illu
lattice lines that might explain
A. Regionally coherent lines tre
ing N60 ° E arranged in en ech
(N20 ° E) indicate

across the region and c
analysis. We suggest suc
explanation for the kimb

## Conclusions

The results of the stu
gested that the central c
the kimberlites in South
isotropically. Rather, th
parently controlled by li
respond to structures in
neither case can a convin
between the directions o
the analysis and the tr
structures. The indicate
from the directions of t
suggested by Marsh (197
cause the anisotropy are
and have no known surf

Chapman's hypothesi
igneous complexes are




e lines determined for the entire
the subarea (dashed).

vering information that is
n the specific set of points

n method is applied to the
referred direction in both
d in each case the azimuth
% critical value. There is
E direction of anisotropy.
the results most likely
methods make different
previously. The interpre-
–Kap Kap area might be
structures affected the
tes. A schematic diagram
possible difference. A set
N20°E and extending
gion would be an interpre-
results of our method
nthesize our results with
h method, we propose an
t (Fig. 16B). The lattice
have the same total length
do not form a continuous
detected by our method
azimuth method. The en
g N20°E) is continuous

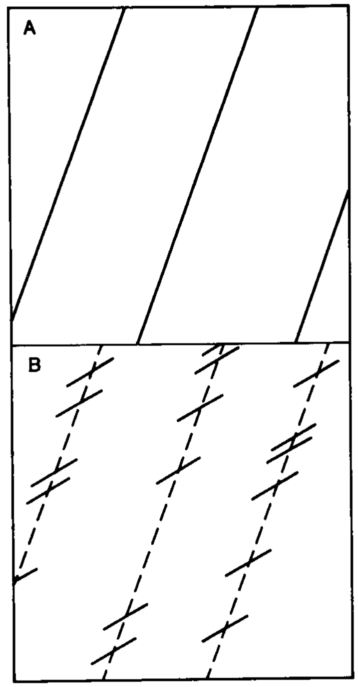



Fig. 16. Schematic diagram illustrating two configurations of lattice lines that might explain the results for the kimberlites. A. Regionally coherent lines trending N20°E. B. Lines trending N60°E arranged in en echelon pattern. En echelon trend (N20°E) indicated by dashed lines.

across the region and could be detected by our analysis. We suggest such a pattern as a possible explanation for the kimberlite results.

## Conclusions

The results of the studies presented above suggested that the central complexes in Nigeria and the kimberlites in South Africa are not distributed isotropically. Rather, their emplacement was apparently controlled by linear zones that may correspond to structures in the crust. However, in neither case can a convincing connection be shown between the directions of the trends indicated by the analysis and the trends of known geologic structures. The indicated trends deviate sharply from the directions of transform fault extensions suggested by Marsh (1973). Thus, the features that cause the anisotropy are evidently located at depth and have no known surface expression.

Chapman's hypothesis is that the locations of igneous complexes are controlled by two sets of continuous, regional scale structures that intersect. This hypothesis is not supported by data from Nigeria and South Africa. Only one set of lattice lines is found in Nigeria. There is some evidence for two directions of structural control in South Africa but only one set of continuous lines was found.

The method developed in this paper is an advance over previous methods of analyzing the distributions of pointlike features because it is designed to find the locations of lattice lines as well as their orientations. It incorporates the use of Monte Carlo distributions to quantify departures from randomness in terms of empirical statistical distributions. A valuable aspect of the method is that it provides a basis for predicting the locations of undiscovered or future events. The potential of this method to selectively develop or avoid locations (e.g. in applications to economic deposits and earthquakes, respectively) is the most promising application to be developed in the future.

## Acknowledgements

The authors thank R.I. Harker, J. Nevius, H.W. Pfefferkorn, and E.L. Srogi for helping to improve an earlier version of the manuscript. Phil Molzer assisted with figure preparation. The computer facilities used in this study were provided through a grant from the IBM Advanced Education Project.

## References

Bowden, P., Van Breemen, O., Hubchinson, J. and Turner, D.C., 1976. Palaeozoic and Mesozoic age trends for some ring complexes in Niger and Nigeria. Nature, 259: 297–299.

Cahen, L., Snelling, N.J., Delhal, J. and Vail, J.R., 1984. The Geochronology and Evolution of Africa. Clarendon Press, Oxford, 512 pp.

Chapman, C.A., 1968. A comparison of the Maine coastal plutons and the magmatic central complexes of New Hampshire. In: E. Zen et al. (Editors), Studies of Appalachian Geology, Northern and Maritime. Wiley, New York, pp. 385–396.

Cornelissen, A.K. and Verwoerd, W.J., 1975. The Bushmanland kimberlites and related rocks. Phys. Chem. Earth, 9: 71–80.

Dawson, J.B., 1970, The structural setting of African kimberlite magmatism. In: T.N. Clifford and I.G. Gass (Editors), African Magmatism and Tectonics. Hafner, New York, pp. 321–335.

Kinnaird, J.A. (chief compiler), 1981. Geology of the Nigerian anorogenic ring complexes, 1 : 500,000. Bartholomew, Edinburgh.

Lutz, T.M., 1986. An Analysis of the orientations of large-scale crustal structures: a statistical approach based on areal distributions of pointlike features. J. Geophys. Res. 91(B1): 421–434.

Marsh, J.S., 1973. Relationships between transform directions and alkaline igneous rock lineaments in Africa and South America. Earth Planet. Sci. Lett., 18: 317–323.

Mitchell, R.H., 1986. Kimberlites: Mineralogy, Geochemistry, and Petrology. Plenum, New York.

Thompson, A.M. and Hager, G.M., 1979. Lineament studies in structural interpretation of a stabilized orogenic region: Appalachian Piedmont, Delaware and adjacent Pennsylvania. In: M.H. Podwysocki and J.L. Earle (Editors), Proceedings of the Second International Conference on Basement Tectonics. Basement Tectonics Committee, Denver, Colo., pp. 74–85.

Turner, D.C., 1976. Structure and petrology of the Younger Granite ring complexes. In: C.A. Kogbe (Editor), Geology of Nigeria. Elizabethan Publ. Co., Lagos, pp. 143–158.

Turner, D.C. (compiler), 1977. Nigeria: the northern ring complexes, 1 : 250,000. Bartholomew, Edinburgh.

*Tectonophysics,* 159 (1989) 149–
Elsevier Science Publishers B.V.

# Anal
# and cha
# by a non-d

SUZANNE RAY

[1] *Laboratoire de G*
[2] *Laboratoire de Géologie*
[3] *Laboratoir*

## Abstract

Raynaud, S., Fabre, D.,
and characterizatio
*Tectonophysics*, 159:

Tomodensitometry is
X-ray images without a
gravimetric density and
between radiological de
core specimens that are
volumetric deformation.

## Introduction

In rocks subjected t
stress-field, little is kno
genesis, structure, and g
faulting. Laboratory ex
may give deformation n
check the stress field an
strain gauges stuck on t
failure phenomena are d
a non-destructive metho
tion of cracks leading to
experiment. The X-ray
propriate method. This
assessment of tomodensi
to the study of the inter

0040-1951/89/$03.50 