PERGAMON

Journal of Structural Geology 24 (2002) 1619–1625

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jstrugeo

Tectonic controls on kimberlite location, southern Africa

Susan Vearncombe*, Julian R. Vearncombe

Vearncombe & Associates Pty Ltd, 14A Barnett Street, Fremantle 6160, Australia

Received 7 August 2001; revised 5 October 2001; accepted 10 October 2001

Abstract

The relationship between kimberlite (the host to diamonds) ascent paths from mantle depths >150 km to surface and major structures is controversial. We use a geometric method of spatial analysis (SpaDiS™), which requires neither statistics nor algebraic models to show that crustal architecture is critical in the localisation of kimberlites. Distinct corridors of kimberlites are parallel to, but not within, prominent shear zones and crustal faults. Instead the kimberlites occur in relatively homogeneous, strong crust capable of maintaining the very high CO_2 pressures necessary for rapid emplacement. Archaean directional trends in kimberlite distribution are recognised on craton, whereas Proterozoic and Carboniferous–Permian (Karoo) age trends are recognised both on and off the Archaean craton. © 2002 Published by Elsevier Science Ltd.

Keywords: Kimberlite; Tectonic controls; Crustal architecture

1. Introduction

There is a well-known correlation between diamondiferous kimberlites and Archaean cratons. Isotopic data indicate that diamonds formed early in lithosphere development and survived in mantle roots beneath cratons, to be entrained and rapidly transported to the earths surface as xenocrysts in kimberlite at any time from mid-Proterozoic to the Tertiary (Anderson, 1979; Helmstaedt and Gurney, 1995; Morgan, 1995). Although some authors have claimed little association between kimberlite location and tectonic structures (Skinner et al., 1992) it is now widely suggested that kimberlites occur in structural corridors (Dawson, 1970; White et al., 1995). Corridors of kimberlite and related intrusions are petrologically zoned along strike, commonly with carbonatites and non-diamondiferous kimberlites off-craton and diamondiferous kimberlites on Archaean cratons. However, despite assertions in the literature that kimberlite location is controlled by crustal-scale fracture zones, there are no maps (or other critical data) showing kimberlites systematically located in such zones, and no mechanistic relationship between deep faults or shears and kimberlite emplacement has been demonstrated. Similarly, there is little emphasis in the literature on Archaean tectonic lineaments as a control on kimberlite location despite evidence that the diamonds in kimberlite formed in the Archaean (Richardson et al., 1993). Here, we evaluate critically the link between kimberlite location and structure, thus contributing to exploration targeting (Fig. 1).

2. Spatial analysis

The spatial distribution of kimberlites can be analysed, maintaining a consistent north, by placing every kimberlite in turn at a common origin and plotting all other kimberlites relative to this origin (called a translations diagram). The analytical method was first used to determine interatomic distances in crystals, and in geology to determine strain from the distribution of objects in a rock (Patterson, 1934, 1935; Perutz, 1942; Fry, 1979). This unbiased geometric method of spatial analysis is made viable for large data sets by modern computers using SpaDiS™ software (Vearncombe and Vearncombe, 1999, 2000). The method analyses every spatial relationship without using statistics or algebraic models. For n kimberlites there are $n^2 - n$ spatial relationships and, because of the square function, the analysis yields interpretable results with small as well as large data sets. The resulting relationships diagram is further analysed by construction of a rose diagram recording the relationships in each radial sector (Vearncombe and Vearncombe, 1999, 2000). Directions of spatial continuity can be easily determined at different scales by selecting distance ranges (Fig. 2). The rose diagram shows the preferred directions of spatial continuity that may correspond to geological lineaments. Detailed analysis of the relationships

---

* Corresponding author. Tel.: +61-8-9335-3316; fax: +61-8-9335-1845.
E-mail address: vearncom@iinet.net.au (S. Vearncombe and J. R. Vearncombe).

0191-8141/02/$ - see front matter © 2002 Published by Elsevier Science Ltd.
PII: S0191-8141(01)00152-3

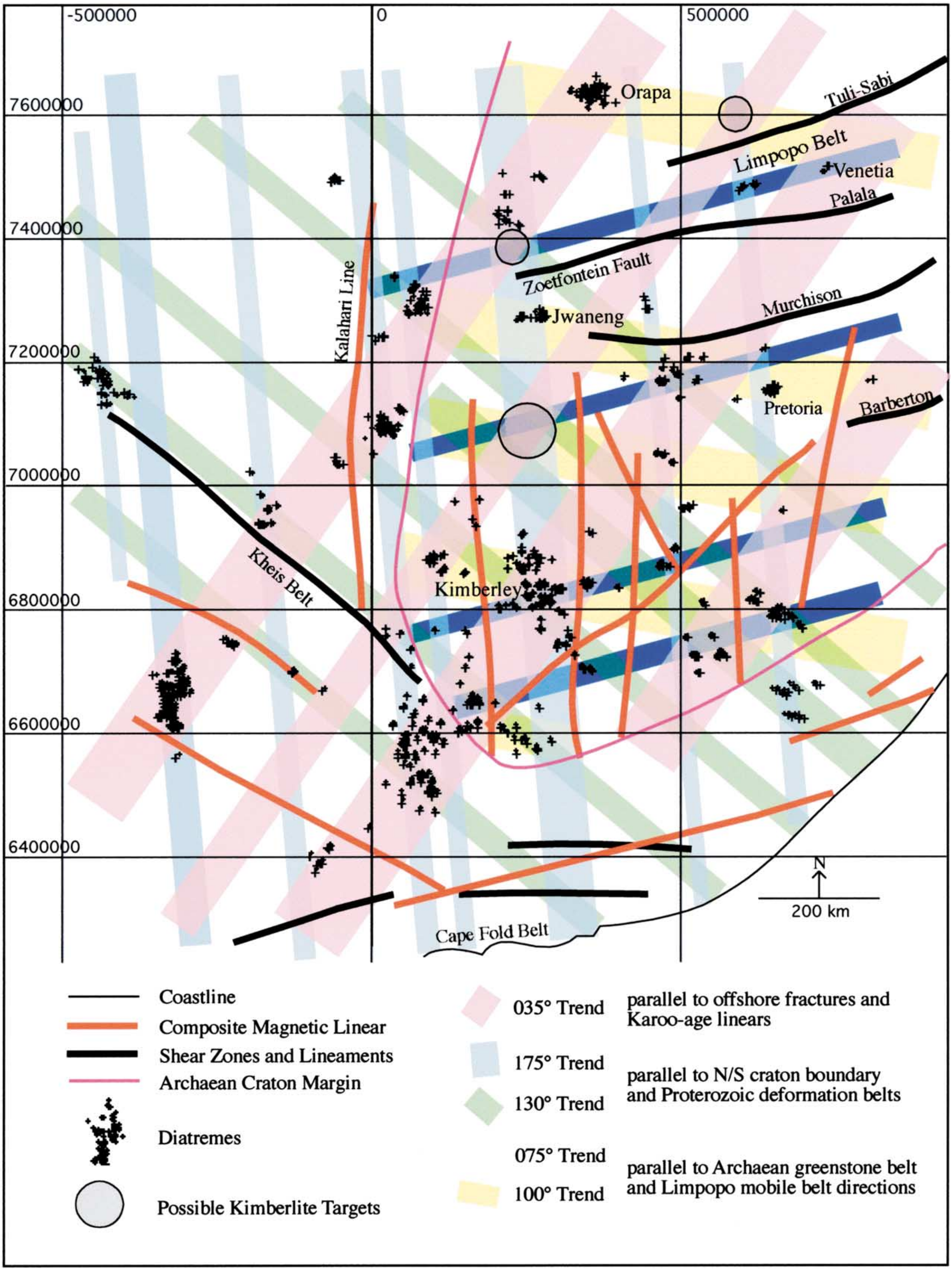
-500000
0
500000
7600000
7400000
7200000
7000000
6800000
6600000
6400000
Orapa
Tuli-Sabi
Limpopo Belt
Venetia
Palala
Zoetfontein Fault
Kalahari Line
Jwaneng
Murchison
Pretoria
Barberton
Kheis Belt
Kimberley
Cape Fold Belt
N
200 km
Coastline
Composite Magnetic Linear
Shear Zones and Lineaments
Archaean Craton Margin
Diatremes
Possible Kimberlite Targets
035° Trend
parallel to offshore fractures and Karoo-age linears
175° Trend
130° Trend
parallel to N/S craton boundary and Proterozoic deformation belts
075° Trend
100° Trend
parallel to Archaean greenstone belt and Limpopo mobile belt directions

diagram yields information on lineament width, length, spacing and repetitions.

For this study we use data on kimberlite location from Key and Ayers (2000) for Botswana, and data supplied by Ashton Mining Ltd for the rest of southern Africa. Data on 780 kimberlite locations from Botswana, Lesotho, South Africa, Swaziland and Namibia (Fig. 1), yielding a total 607,620 spatial relationships (not shown here) have been analysed. Also the distribution off-craton is compared with that on-craton, to determine possible variations in tectonic controls on kimberlite location (Fig. 2). There are 365 off-craton and 415 on-craton kimberlites yielding, respectively, 132,860 and 171,810 spatial relationships. Rose diagrams quantify the directions of spatial continuity for distance ranges of all, <500, <200 and <50 km. From the translation diagram, the width, spacing and integrity of spatial directions can be assessed.

The analysis reveals several robust directions of spatial continuity as shown in Table 1 and Figs. 1 and 2. Important directions are 035°, 175°, 130°, 075° and 100°. All these structural directions can be recognised on regional geology maps of southern Africa (summary Table 1). However, the corridors of kimberlite diatremes are not coincident with the prominent linear structural features interpreted from aeromagnetic data. To the contrary, kimberlites are located parallel to and between the major multiply re-activated deformation lineaments (Fig. 1).

The spatial analysis for both on- and off-craton kimberlite data shows prominent 035° (estimated variation ±5°) oriented corridors of Carboniferous to Tertiary age. This trend has a kimberlite definition ratio of 2.1. (The kimberlite definition ratio is defined as the percentage of kimberlites within the corridor divided by the percentage of ground occupied by the corridor.) The 035°-trend has no significant Archaean representation and few major aeromagnetic linears either on or off the craton. The 035°-trending kimberlite corridors are sub-parallel to the south east coastline of South Africa and oceanic fracture zones, suggesting an association of on-land extensions and off-shore fracture zones (Marsh, 1973).

Narrow well-defined corridors trending 175° (±15°) are prominent off-craton but less well-defined on-craton. The 175°-trend (kimberlite definition ratio 2.5) is sub-parallel to the greenstone belts of the western Kaapvaal Craton and the Kalahari Line (Hutchins and Reeves, 1980). Similarly, prominent magnetic linears along zones of multiple reactivation and complex geology are evident both on- and off-craton in this orientation. The kimberlite corridors lie between these prominent magnetic linears. Another linear alignment developed both on- and off-craton comprises kimberlites in narrow corridors oriented 130° (±10°). These corridors are parallel to the Mid-Proterozoic deformation of the Kheis belt.

The 075° (±5°) oriented corridors (on-craton kimberlite definition ratio 2.8) are restricted to on-craton kimberlites and parallel a dominant Archaean structural trend. This direction includes most greenstone belts in the north and eastern parts of the Kaapvaal Craton, the Archaean and Proterozoic trends of the metamorphic Limpopo Belt and the southern craton margin. Other structures including the prominent Zoetfontein Fault in Botswana have a 070° to 080° direction that affect younger strata and they may represent reactivated fundamental Archaean structures.

The rose diagrams for off- and on-craton kimberlites show an orientation along 100° (±10°) but this is not a prominent linear in the off-craton relationships plot. Off-craton clusters of relationships are positioned along the 100°-trend, but relationships are not aligned to 100°, being mostly aligned to 035°, 175° and 130°. On-craton trends oriented to 100° (on craton kimberlite definition ratio 1.5) correlate with post-Karoo dyke swarms through Botswana and represents a second order direction in some Archaean greenstone belts. The 100°-trend is the orientation of many kimberlite dykes in Lesotho and Kimberley (Dawson, 1970).

The sum of intersections of any two corridors contain 83% of all the kimberlites and occupy 32% of the study area. This represents a kimberlite definition ratio of 2.6. The intersections of any three corridors contain 33% of all the kimberlites and occupy 14% of the study area, equating to a kimberlite definition ratio of 2.3.

Although the kimberlite corridors appear across most of the craton, their importance varies from region to region and as a function of distance as illustrated by the rose diagrams for different distance ranges (Fig. 2). This implies critical differences in the direction(s) to be followed if looking for the next kimberlite field or the next kimberlite pipe within a field.

3. Discussion

Major pre-existing zones of weakness oriented subparallel to the directions of relative continental separation appear

Fig. 1. Map of location of on- and off-craton kimberlites and related intrusions in southern Africa, showing the craton boundary, prominent shear zones and lineaments, prominent composite magnetic linears and corridors identified by this study along which the kimberlites occur. The composite magnetic linears are discrete alignments of multiple magnetic features comprising elements of more than one age, and commonly multiple re-activation events. They have been identified on regional aeromagnetic data of southern Africa by us, but are rarely represented on traditional geological maps because they are buried beneath a regolith cover, Tertiary to Recent sands or beneath Karoo Sequences. The prominent shear zones and lineaments are similar except that they are well exposed and documented structures comprising mylonite zones. The kimberlite corridors are of Archaean, Carboniferous–Permian (Karoo and Mesozoic) age, orientations are determined from the rose diagrams and their spacing from the translations diagram (Fig. 2). One corridor is positioned to maximise the number of kimberlites along it, using Kimberley as the origin. All other corridors and trends are constrained by the width, spacing and repetition measured directly from the relationships diagrams (Fig. 2). The circles represent areas in which this study predicts new kimberlite fields.

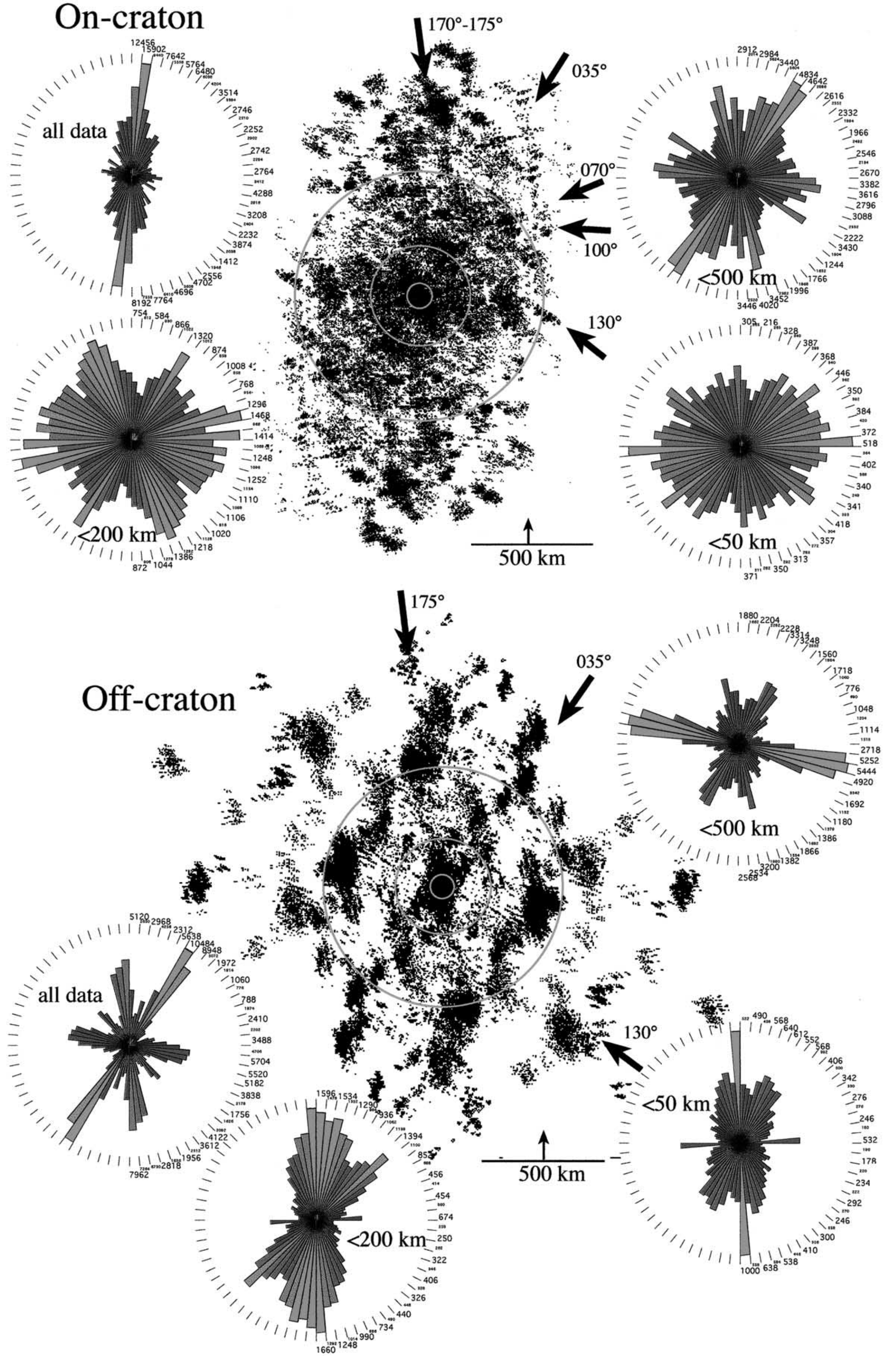
On-craton
170°-175°
035°
070°
100°
130°
all data
<500 km
<200 km
<50 km
500 km
Off-craton
175°
035°
130°
<500 km
all data
<200 km
<50 km
500 km

Table 1
Linear trends of southern Africa kimberlite distribution

Direction	% study area occupied by interpreted linear (Fig. 1)	Kimberlites within interpreted corridor	Character of trends	Approx. spacing	Age structural grain	Structures parallel to controlling grain
035 ± 5°	36%	78%	Broad corridors with internal narrow linears	~ 400, ~200 and <80 km	Karoo to Tertiary, on- and off-craton	Agulhas and Falkland Fracture Zones; KwaZulu coastline; Upper and Lower Beaufort and Ecca stratigraphic boundaries in Orange Free State; some ?Karoo dykes
175 ± 15°	26%	65%	Narrow corridors	~ 160 km but highly variable	Archaean on-craton and off-craton Proterozoic or Karoo	Kalahari Line and prominent parallel mixed element magnetic linears in Orange Free State and Transvaal; Lebombo Range; Amalia Greenstone Belt;
130 ± 10°	18%	38%	Narrow corridors	~ 100 km	Middle Proterozoic and possibly Karoo, on- and off-craton	Kheis Belt; Western Limpopo Belt in Botswana; Mixed element magnetic linears; NE margin of Drakensburg mountains; some Proterozoic and Karoo stratigraphic contacts
075 ± 5°	11% on-craton	31% on-craton	Narrow corridors	~ 200 km	Archaean, on-craton	Mixed element magnetic linears, Northern Province greenstone belts; Limpopo shear zones including Palala and Triangle shear zones; Zoetfontein Fault; magnetic linears in Transvaal and Orange Free state; some ?Proterozoic dykes
100 ± 10°	38% on-craton	59% on-craton	Broad corridors	?120–280 km	Archaean, Proterozoic and Karoo, mostly on-craton	Post-Karoo dyke swarm Botswana, Johannesburg greenstone belt; parts of Barberton and Giyani belts; parts of Limpopo belt; long axis of Transvaal basin and Bushveld Complex

to control the locations of offshore fracture zones that develop in new oceans (Sykes, 1978). We have shown that corridors parallel to the fracture zones are a control on kimberlite emplacement. The craton-wide evidence for Archaean, Proterozoic and Karoo age spatial controls emphasises multiple crustal reactivation with corridors that originated from the Archaean to the time of continental rifting in the Karoo. As an example of multiple reactivation, the crust of the metamorphic Limpopo Belt underwent major tectono–thermal events at 3150, 2650 and 2000 Ma. Post-kinematic dykes were emplaced at 2200, 1900 and 1770 Ma, extension and sedimentation occurred at 1700 and 250 Ma, and major igneous activity at about 177 Ma (Barton, 1979; Barton et al., 1983; Harris et al., 1987; Kamber et al., 1995; Manton, 1968). Thus, reactivation, including Proterozoic structural reworking, basin rifting and magma generation at recurrent intervals appears to be a factor in controlling kimberlite location. The Yilgarn Craton of Western Australia, for instance, lacks significant structural reactivation, basin rifting and repeated magma intrusions except around its margins, a factor possibly related to the paucity of kimberlite intrusion, and an absence of known diamondiferous kimberlite.

Time constraints on the transport of xenoliths in kimberlite are severe, because the diamonds must rapidly lose heat until a temperature is reached where the reaction to graphite is metastable. One estimate is that kimberlites travelled the ~200 km from deep mantle to surface in about 5 h, or at 7 m/s, and only an over-pressured fluid within a crack can achieve emplacement at these velocities (Anderson, 1979).

Fig. 2. Translations diagram of all spatial relationships for on- and off-craton kimberlites, and rose diagrams with 5° radial sector angles showing preferred linear directions of continuity for distances ranges: all, <500, <200 and <50 km. Note that the spatial relationships and the kimberlite corridors appear across most of the craton, but their importance varies from region to region and as a function of distance, as illustrated by the rose diagrams for different distance ranges. This implies critical differences in the direction(s) to be followed if looking for the next kimberlite field or the next kimberlite pipe within a field.

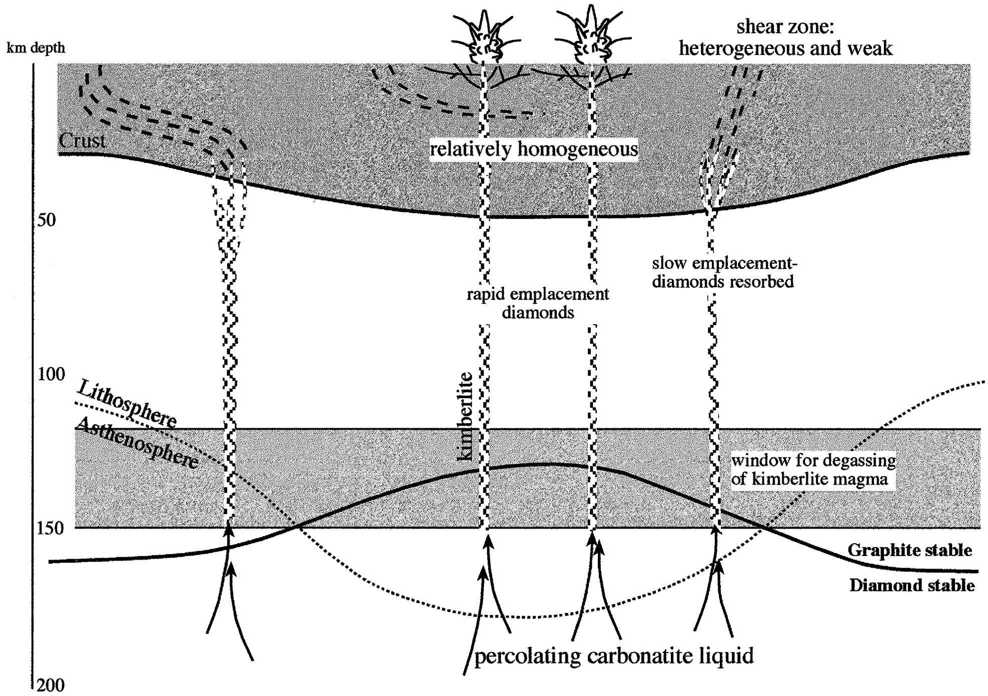

Fig. 3. Schematic model for kimberlite emplacement involving three emplacement phases. First, up-rising carbonatite magma from the asthenosphere forms kimberlite and crystallises diamond in the lithosphere (or entrains pre-formed diamond). At depths of 150–120 km the second phase is CO_2 degassing and rapid upward motion through the lithosphere. Third, in the crust there are relatively slow emplacement events into deformation belts, which fail to penetrate the whole crust, and rare violent events, which emplace kimberlite into rheologically strong crusts and to the surface.

The crack cannot accelerate faster than the fluid can flow in the crack. A volatile phase such as CO_2 at the crack tip allows the crack to accelerate, and exsolution reactions would be too slow for rapid kimberlite emplacement. This raises the possibility, to be tested in future research, that the kimberlite, despite its velocity of emplacement, is sensitive to crustal architecture. Carbonatite magmas rise from the asthenosphere to the lower lithosphere where they percolate through host peridotite or ecolgite, form kimberlite magma and crystallise diamonds or entrain diamond formed in a pre-kimberlite event (Daniels et al., 1996; Cartigny et al., 1998). Here the CO_2 solubility in kimberlite melt drops dramatically. Decreasing pressure in the range 50–40 GPa, results in degassing of ascending kimberlite magmas in the depth range 150–120 km (Brey et al., 1991). The very high pressures are maintained only in strong, relatively homogeneous, crust limiting emplacement to rare events. In weaker, heterogeneously deformed or deforming crust, high CO_2 pressures are less easily maintained and hence fluid dissipates over a period of time (Fig. 3). This predicts deformed and metamorphosed non-diamondiferous kimberlite in deformation zones of the lower and middle crust. We are unaware of kimberlites of this type in the southern Africa study area, but deformed and metamorphosed kimberlites at Naberru (Western Australia) may be examples of this.

Spatial analysis clearly demonstrates that kimberlite location is structurally controlled, and these controls involve fundamental crustal features including Archaean and Proterozoic directions and offshore Phanerozoic fracture zones. However, the kimberlites are not in deformation zones or deep-seated fundamental fracture systems. Stronger crust requiring higher fluid pressures to fracture, is more likely to host forcefully emplaced kimberlite. Thus kimberlites are located in corridors along linears of strong, less deformed zones and parallel to, rather than along, known faults and shear zones. The target areas defined in Fig. 1 are lacking known kimberlite pipes; they are areas in which more than three kimberlite-bearing corridors intersect and areas of relatively homogenous crust, between, rather than along, major crustal lineaments.

The analysis presented here is for all kimberlites of southern Africa, without subsetting or analysis according to age of kimberlite, diamond content, kimberlite type or with other alkaline intrusions included. The majority of the southern Africa kimberlites are Cretaceous to Tertiary in age, but older kimberlites such as those at Premier (Pretoria), Venetia, The Oaks, and Lerala are included, and should be analysed separately in subsequent studies. This would reveal variations in the distribution with time and under widely disparate stress fields. However, public domain databases of age, diamond content, and kimberlite type are at best incomplete. Globally, spatial analysis of kimberlites according to age, type and diamond-content in the context of regional geology will elucidate the detailed mechanisms of tectonic control on kimberlite location.

Acknowledgements

We gratefully acknowledge Keith Jones (Ashton Mining Ltd) and Roger Key (British Geological Survey) for location data and discussions. Incisive comments by Tom Blenkinsop, Rob Kerrich, Patrick Orr and two Journal–selected referees have improved greatly the manuscript.

References

Anderson, O.L., 1979. The role of fracture dynamics in kimberlite pipe formation. In: Boyd, F.R., Meyer, H.O.A. (Eds.). Kimberlites, Diatremes and Diamonds. American Geophysical Union, pp. 344–353.

Barton, J.M., 1979. The chemical compositions, Rb–Sr isotopic systematics and tectonic setting of certain post-kinematic mafic igneous rocks, Limpopo Mobile belt, Southern Africa. Precambrian Research 9, 57–80.

Barton, J.M., Du Toit, M.C., Van Reenen, D.D., Ryan, B., 1983. Geochronologic studies in the southern marginal zone of the Limpopo Mobile Belt, southern Africa. Special Publication Geological Society South Africa 8, 55–64.

Brey, G.P., Kogarko, L.N., Ryabchikov, I.D., 1991. Carbon dioxide in kimberlitic melts. N. Jb. Miner. Mh. 4, 159–168.

Cartigny, P., Harris, J.W., Javoy, M., 1998. Eclogitic diamond formation at Jwaneng. No room for a recycled component. Science 280, 1421–1424.

Daniels, L.R.M., Gurney, J.J., Harte, B., 1996. A crustal mineral in a mantle diamond. Nature 376, 153–156.

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

Fry, N., 1979. Random point distributions and strain measurement in rocks. Tectonophysics 60, 89–105.

Harris, N.B.W., Hawkesworth, C.J., Van Calsteren, P., McDermott, F., 1987. Evolution of continental crust in southern Africa. Earth Planet Science Letters 83, 85–93.

Helmstaedt, H.H., Gurney, J.J., 1995. Geotectonic controls of primary diamond deposits: implications for area selection. Journal of Geochemical Exploration 53, 125–144.

Hutchins, D.G., Reeves, C.V., 1980. Regional geophysical exploration of the Kalahari in Botswana. Tectonophysics 69, 201–220.

Kamber, B.S., Kramers, J.D., Napier, R., Cliff, R.A., Rollinson, H.R., 1995. The Triangle Shear zone, Zimbabwe revisited: new data document a important event at 2.0 Ga in the Limpopo Belt. Precambrian Research 70, 191–213.

Key, R., Ayers, N.P., 2000. The 1998 edition of the National Geological Map of Botswana. Journal of African Earth Science 30, 427–451.

Manton, W.I., 1968. The origin of associated basic and acid rocks in the Lebombo–Nuanetsi igneous province, southern Africa, as implied by strontium isotopes. Journal of Petrology 9, 23–39.

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

Morgan, P., 1995. Diamond exploration from the bottom up: regional geophysical signatures of lithosphere conditions favourable for diamond exploration. Journal Geochemical Exploration 53, 145–165.

Patterson, A.L., 1934. A Fourier series method for the determination of the component of intra-atomic distances in crystals. Physics Review 46, 372–376.

Patterson, A.L., 1935. A direct method for the determination of the components of inter-atomic distances in crystals. Ziet. fur Kristallographie 90, 517–554.

Perutz, M.F., 1942. X-ray analysis of Haemoglobin. Nature 149, 491–494.

Richardson, S.H., Harris, J.W., Gurney, J.J., 1993. Three generations of diamonds from old continental mantle. Nature 366, 256–258.

Skinner, E.M.W., Clement, C.R., Gurney, J.J., Apter, D.B., Hatton, C.J., 1992. The distribution and tectonic setting of South African kimberlites. Russian Geology and Geophysics 33, 26–31.

Sykes, L.R., 1978. Intra-plate seismicity, reactivation of preexisting zones of weakness, alkaline magmatism and other tectonism postdating continental fragmentation. Reviews Geophysics Space Physics, 621–988.

Vearncombe, J.R., Vearncombe, S., 1999. The spatial distribution of mineralization: applications of Fry Analysis. Economic Geology 94, 475–486.

Vearncombe, J.R., Vearncombe, S., 2000. The spatial distribution of grade. In: Fourth International Mining Geology Conference, Mine Geology 2000, Australasian Institute of Mining and Metallurgy, pp. 87–93.

White, S.H., Boorder, H. de, Smith, C.B., 1995. Structural controls of kimberlite and lamproite emplacement. Journal Geochemical Exploration 53, 245–264.