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Proceedings of 10th International Kimberlite Conference

Volume 2

Dedicated to Barbara Scott Smith

GEOLOGICAL SOCIETY OF INDIA
1958

Springer

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Special Issue of the Journal of the Geological Society of India

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ISBN 978-81-322-1172-3 ISBN 978-81-322-1173-0 (eBook)
DOI 10.1007/978-81-322-1173-0
Springer New Delhi Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013942130

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

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The 10th International Kimberlite Conference

International Kimberlite Conferences (IKCs) are special events that are held across the world once in 4–5 years. IKC is the confluence platform for academicians, scientists and industrial personnel concerned with diamond exploration and exploitation, petrology, geochemistry, geochronology, geophysics and origin of the primary diamond host rocks and their entrained xenoliths and xenocrysts (including diamond) to get together and deliberate on new advances in research made in the intervening years. Ever since the organization of first IKC in 1973 and its tremendous success, the entire geological world eagerly look forward to subsequent such conferences with great enthusiasm and excitement. The scientific emanations from IKCs continue to make significant impact on our understanding of the composition, nature and evolution of the planet we live on. The previous conferences were held at Cape Town (1973), Santa Fe, New Mexico (1977), Clermont-Ferrand, France (1982), Perth, Western Australia (1987), Araxa, Brazil (1991), Novosibirsk, Russia (1995), Cape Town (1998), Victoria, Canada (2003) and Frankfurt, Germany (2008).

The tenth IKC was held at Bangalore, India between 6 and 11th February 2012. The conference was organized by the Geological Society of India in association with the government organizations, academic institutions and Indian diamond mining companies. About 300 delegates from 36 countries attended the conference and 224 papers were presented. The papers include 78 oral presentations and 146 poster presentations on following topics: Kimberlite geology, origin, evolution and emplacement of kimberlites and related rocks, petrology and geochemistry of metasomatised lithospheric mantle magmas, diamond exploration, cratonic roots, diamonds, diamond mining and sustainable developments and policies and governance of diamond exploration. Pre- and post-conference field trips were organized to (i) the diamond bearing kimberlites of Dharwar Craton in South India, (ii) lamproites of Bundelkhand Craton in northern India and (iii) diamond cutting and polishing industry of Surat, Gujarat in western India. A series of social and cultural programmes depicting cultural diversity of India were organized during the conference. The Kimberlite fraternity enjoyed yet another socially and scientifically successful conference.

Cultural programmes organized during 10th IKC

About the Editors

Dr. D. Graham Pearson is Canada Excellence Research Chair—Arctic Resources in the Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Canada. Dr. Pearson obtained his B.Sc. from the Royal School of Mines, Imperial College, London and his Ph.D. from Leeds University. He taught at Durham University for 15 years, becoming Professor of Geochemistry and now holds a CERC research chair in Arctic Resources specialising in diamonds, kimberlites and cratonic roots. Pearson has been a member of the International Kimberlite Conference Advisory Committee since 2007.

Dr. Herman S. Grütter is currently associated with the Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Canada. Dr. Grütter has over 20 years' senior-mining, junior-mining and consulting experience in kimberlite targeting, exploration and early stage resource definition on projects spanning the globe. He obtained a B.Sc. (Hons) from the University of Cape Town in 1986 and a Ph.D. in metamorphic petrology from the University of Cambridge in 1993. He maintains applied research interests in mantle mineralogy and petrology, and in craton evolution.

Dr. Jeff W. Harris retired in 2006 after a distinguished academic career at the University of Glasgow. Since retirement he has held an Honorary Research Fellowship at Glasgow. For over 30 years, he was a consultant to De Beers Consolidated Mines, managing their worldwide outside diamond research programmes conducted at Universities and equivalent institutions; a research endeavour which played a major part in furthering our understanding of geochemical processes operating in the mantle.

Dr. Bruce A. Kjarsgaard is a Senior Research Scientist in Geological Survey of Canada, Ottawa, Canada. Dr. Kjarsgaard received his Ph.D. in Geology (experimental petrology) from the University of Manchester, England in 1990. He has been with the Geological Survey of Canada (GSC) in Ottawa since 1990, working as an economic geologist. His research involves broad-based petrological studies (including mineralogy, geochemistry and volcanology) of mantle-derived volatile-rich ultramafic magmas (kimberlite, lamprophyre, nephelinite–carbonatite) and their attendant economic mineralization (diamonds, and niobium and REE, respectively).

Dr. Hugh O'Brien is a Senior Research Scientist in Finland Isotope Geosciences Laboratory (SIGL), Geological Survey of Finland (GTK), Espoo, Finland. Dr. O'Brien received his B.S. in 1982 from University of Minneapolis and his Ph.D. from UW in Seattle in 1988. After a short stint (88–91) with the Geological Survey of Finland (GTK), he returned to Seattle for post-doctoral studies. Since 1997, he has been a senior research scientist at GTK, covering diamond exploration and mantle and ore research using isotopic and electron beam methods.

Dr. N. V. Chalapathi Rao is currently an Associate Professor of Geology at Banaras Hindu University, Varanasi, India. Dr. Rao holds Ph.D. degrees from Osmania University, Hyderabad (India) and University of Cambridge (UK). His research specialisation concerns petrology, geochemistry and genesis of kimberlites, lamproites, lamprophyres and their entrained crustal and mantle xenoliths with focus on lithospheric evolution and diamond prospectivity.

Dr. Steven Sparks is Professor of Geology in the School of Earth Sciences at Bristol University, Bristol, UK. His research concerns volcanic and igneous processes and he has made contributions in petrology, many physical volcanology, fundamental fluid mechanics, sedimentology, and in hazard and risk assessment methods. He has been past-President of the Geological Society of London and IAVCEI President of the Volcanology, Geochemistry and Petrology section of the American Geophysical Union 2008–2012.

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The Rio Tinto's diamond sponsorship has been utilized for the publication of the Proceeding Volume. BHP Billiton and De Beers supported the conference with platinum sponsorship. Australian Scientific Instruments, Ministry of Earth Sciences, Government of India, National Geophysical Research Institute (NGRI) and National Mineral Development Corporation (NMDC) supported the conference with silver sponsorship. The generous financial contributions made by the 7, 8 and 9th IKC organizing committees helped in providing the financial assistance to the students and other senior scientists. The Geological Survey of India has provided logistic support during field trip to the South Indian Kimberlites. The National Mineral Development Corporation permitted the field trip delegates to visit their properties at Majhgawan. The Rio Tinto India Exploration Ltd. has permitted the delegates to visit their property, study the core samples and offered traditional camp-site hospitality at Bunder.

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Dedication

Currently the principal of her own consulting company (Scott Smith Petrology Inc.) Barbara Scott Smith has extensive experience in kimberlite and related rock geology and is widely recognized as an expert in her field.

Barbara studied geology at the University of Edinburgh and was awarded a B.Sc.Hons degree in 1972. In 1977 she was awarded a Ph.D. degree from the same university for a thesis entitled "Petrogenesis of kimberlites and associated potassic lamprophyres from Central West Greenland". This study involved the use of a variety of analytical techniques including electron microprobe analysis, X-ray diffraction, X-ray fluorescence, wet chemistry, flame photometry, spectrophotometry and atomic absorption methodologies.

Following her postgraduate studies (during which she lectured to civil engineering students) Barbara was employed as a Reseach Mineralogist at the Anglo American Research Laboratories in Johannesburg. She remained at the AARL until 1981, rising rapidly to the rank of Principal ResearchMineralogist. It was at the AARL and the subsequently formed Kimberley Petrology Unit that her early interest in kimberlites and, later, lamproites was enhanced.

At the AARL and the KPU Barbara was involved in petrographic, mineralogical and geochemical investigations of rock and mineral samples derived from the worldwide exploration activities of the De Beers Group of Companies. In addition she also examined rocks and minerals obtained from operating and worked out or dormant mines in southern Africa and elsewhere. During thisperiod of her career Barbara travelled widely to carry out mine mapping operations and to log diamond drill cores derived from diamond mines and exploration drilling.

Scott Smith Petrology Inc. was opened in 1982 and offers a range of specialised services in applied kimberlite geology of direct use in diamond exploration, prospect evaluation and mining operations. These services include interpretation of the internal geology of kimberlite and relatedrock intrusions, evaluation of the matrix mineralogy of these rocks, an assessment of the near-surface modes of emplacement of the intrusions and evaluation of their potential to contain economically significant quantities of diamonds.

Initially most of Barbara's work was on behalf of De Beers and between 2001 and 2003 she founded the De Beers Canada Petrology Unit. In 2004 Barbara established a professional school of kimberlite petrology for the development and training of diamond industry professionals and academics wishing to advance their knowledge of kimberlites and lamproites.

Barbara has travelled widely during her career. In addition to her extensive field experience in Canada her work has taken her to the USA, Greenland, Australia. South Africa, Lesotho, Zambia, Namibia, Botswana, ZImbabwe, Ivory Coast, Tanzania, China, India and various countries in Europe, including the important diamond areas of Yukatia and Arkhangelsk in Russia.

As a consequence of her visits to kimberlite and lamproite provinces around the world Barbara has accumulated an extensive and unique collection of rock and mineral samples which will provide material for much future research.

Between 1990 and 1996 Barbara was a member of the working group on the nomenclature and definitions of “lamprophyric, lamproitic and kimberlitic rocks” of the International Union of Geological Sciences Sub-Commission on the “Systematic of Igneous Rocks” Woolley et al. 1996). Barbara has been a member of the International Kimberlite Conference Advisory Committee since 1990. Between 2001 and 2004 she was an Honorary Research Associate at the Department of Earth and Ocean Sciences and Mineral Deposits Research Unit at the University of British Columbia and she has been an adjunct Professor in the same Unit since 2004.

Barbara has attended more than 60 conferences and has been an invited or keynote speaker at more than a dozen of these scientific meetings. She has undertaken more than 100 publication reviews for technical journals and published books and has been a guest editor for the Proceedings of the 8thInternational Kimberlite Conference and for the Proceedings of the 2006 Workshop on Kimberlite Emplacement in the Journal of Volcanology and Geothermal Research (Vol. 174, 2008).

In 2009 Barbara was presented with the Hugo Dummett Award for excellence in diamond exploration and development by the Association for Mineral Exploration, British Columbia. She is honored here for her outstanding long-service to the kimberlite community.

Kimberlite Terminology and Classification

B. H. Scott Smith, T. E. Nowicki, J. K. Russell, K. J. Webb, R. H. Mitchell, C. M. Hetman, M. Harder, E. M. W. Skinner, and Jv. A. Robey

Abstract

Description, classification and interpretation of kimberlites and related rocks, and communication of that information, underpin the development of three-dimensional geological models used in generating reliable diamond resource estimates. A rationalisation of kimberlite terminology and classification is presented in a practical, systematic framework or scheme. The scheme has five stages and is based on progressively increasing levels of interpretation building upon a series of descriptors that are applied independently of, and prior to, genetic classifications. Stage 1 of the scheme is rock description (alteration, structure, texture, components) and involves only limited genetic interpretation. The components are ascribed to three classes: compound clasts (kimberlitic, mantle, crustal), crystals, in particular olivine, and interstitial matrix (groundmass, interclast cement or clastic matrix). Kimberlitic compound clasts include magmaclasts (e.g. solidified melt-bearing pyroclasts), lithic clasts (e.g. autoliths) and accretionary clasts. Where possible, subsequent stages involve classification and higher levels of interpretation, based on increasing degrees of genetic inference. Stage 2 is the petrogenetic

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D. G. Pearson et al. (eds.), *Proceedings of 10th International Kimberlite Conference*,
Volume 2, Special Issue of the Journal of the Geological Society of India,
DOI: 10.1007/978-81-322-1173-0_1,

classification into parental magma type and mineralogical type. Stage 3a is the broad textural-genetic classification into coherent kimberlite and volcaniclastic kimberlite. In Stage 3b, coherent kimberlite is further subdivided into intrusive kimberlite or extrusive kimberlite, and volcaniclastic kimberlite into pyroclastic kimberlite, resedimented volcaniclastic kimberlite and epiclastic volcanic kimberlite. Pyroclastic kimberlites can be assigned into two main classes: Kimberley type (formerly tuffisitic kimberlite) and Fort à la Corne-type (formerly pyroclastic kimberlite). Stage 4 incorporates an assessment of the spatial relationship to and the morphology of the kimberlite body from which the rocks under investigation derive. Stage 5 involves more detailed genetic interpretation with more specific classification based on the mode of formation.

Keywords
Kimberlite • Terminology • Classification • Nomenclature • Diamond • Exploration • Evaluation • Mining

Introduction

Reliable evaluation and mining of primary diamond deposits is founded on a good understanding of the geology of kimberlites and related rocks. Description, classification and interpretation of these rocks, and communication of that information, underpin the development of three-dimensional (3D) geological models. Such models are essential in generating accurate diamond resource estimates. Current kimberlite terminology has evolved over more than four decades (Dawson 1971, 1980; Hawthorne 1975; Clement and Skinner 1985; Mitchell 1986, 1995; Field and Scott Smith 1998; Cas et al. 2008, 2009). Problematic aspects of terminology result from: (i) kimberlites and related rocks having attributes not adequately addressed by standard igneous petrological or volcanological terminology; and (ii) the inconsistent use and misuse of some terms. Here we present an improved, rationalised and staged approach to kimberlite terminology and classification. The practical and systematic framework, or scheme, is intended to assist in the description, recognition and understanding of the complex and unusual rocks encountered during diamond exploration and mining. One goal of our approach is, as far as possible, to align kimberlite terms with those of mainstream geology, while maintaining terminology that is applicable to the economics of primary diamond deposits. The terminology is based on a 300-term Glossary (Scott Smith et al. in press) which is intended to be used as a companion document during the application of this scheme.

Key Principles and Objectives

The five-stage scheme (Table 1; after Scott Smith et al. 2008a, b, 2012) involves progressive investigation and interpretation. Stage 1, the descriptive stage, is based mainly on observations and requires only limited genetic interpretation, whereas Stages 2–5, when possible, involve classification into specific rock types based on increasing degrees of genetic inference. Stage 1 is considered to be the most critical part of the nomenclature scheme because it provides the evidence, or foundation, for the interpretations undertaken in Stages 2–5. Importantly, Stage 1 also provides the basic information required for the definition and internal subdivision of potential primary diamond deposits into different lithological units and phases that can be used in the development of economically relevant geological models (Fig. 1). Lithological units are subdivisions of rocks which have unifying characteristics that are distinct from adjacent rocks. A phase of kimberlite, or other parental magma type (e.g. lamproite), comprises the near surface emplacement products derived from a single batch of magma. Different magma batches typically have different diamond contents, and internal variability within emplacement products of single magma batches can result from contrasting intrusive, volcanic and post-emplacement processes. One phase of kimberlite may comprise one or more lithological units, lithofacies, facies and/or facies associations, thus the terms are not synonymous. Stages 2–5 permit a greater understanding of any potential primary diamond deposit and higher degrees of confidence in geological models based on Stage 1, resulting in improved predictions of diamond distribution.

The concept encompassed in Table 1 is partly inspired by the approach of McPhie et al. (1993) and has some similarities to Cas et al. (2008, 2009). However, there are key differences between our scheme for kimberlite nomenclature and these approaches. Most critically, McPhie et al. (1993) and Cas et al. (2008, 2009) begin with an initial textural subdivision into coherent or volcaniclastic facies (or "fragmental" in the case of Cas et al. 2008, 2009) and the descriptive terminology used for each of these facies is

Table 1 A systematic framework (scheme) for the description, classification and interpretation of kimberlites

Stage 1	Stage 2	Stage 3a	Stage 3b	Stage 4	Stage 5
PROGRESSIVE INTERPRETATION					
Rock Description	**Petrogenetic Classification**	**Textural-Genetic Classification**		**Intrusive / Volcanic Spatial Context**	**Genetic / Process Interpretation**
Alteration: intensity; distribution; mineralogy; imposed textures; preservation; timing; xenolith reaction **Structure:** e.g. massive; inhomogeneous; layered; flow zoned; laminated; cross-bedded; jointed **Texture:** component distribution; shape; size distribution (e.g. well sorted; inequigranular); packing; support (e.g. clast or matrix supported) **Components:** compound clasts (e.g. xenoliths, magmaclasts, autoliths, accretionary clasts); crystals (e.g. olivine macrocrysts, crustal xenocrysts); interstitial matrix	**Parental Magma Type:** e.g. kimberlite; lamproite; melnoite; alnoite; olivine melilitite **Mineralogical Classification:** e.g. monticellite; phlogopite; carbonate	**Coherent:** *[descriptors]* coherent *kimberlite* (CK)	**Intrusive:** *[descriptors]* intrusive coherent *kimberlite* (ICK) or hypabyssal *kimberlite* (HK)	e.g. intra-crater ICK sheet; non-volcanic HK plug; sub-volcanic root zone-fill	e.g. composite flow-differentiated hypabyssal sheet; intrusive plug
			Extrusive: *[descriptors]* extrusive coherent *kimberlite* (ECK)	e.g. intra-crater ECK; extra-crater ECK	e.g. fountain-fed clastogenic lava lake; effusive lava flow
		Volcaniclastic: *[descriptors]* volcaniclastic *kimberlite* (VK)	**Pyroclastic:** *[descriptors]* pyroclastic *kimberlite* (PK) or *[descriptors] kimberlitic* [standard pyroclastic rock name] **Kimberley-type:** *[descriptors]* Kimberley-type pyroclastic *kimberlite* (KPK)	e.g. pipe-fill KPK; subsurface diatreme-fill KPK; crater-fill KPK	e.g. fluidised; column collapse
			Fort à la Corne-type: *[descriptors]* Fort à la Corne-type pyroclastic *kimberlite* (FPK)	e.g. vent-proximal FPK, intra-crater FPK; crater rim FPK; distal extra-crater FPK	e.g. spatter; fallout; base surge; pyroclastic flow
			Resedimented Volcaniclastic: *[descriptors]* resedimented volcaniclastic *kimberlite* (RVK) or *[descriptors]* resedimented *kimberlitic* [standard sedimentary rock name]	e.g. pipe-fill RVK; intra-crater *kimberlitic* sediments; distal extra-crater RVK	e.g. grain flow; debris flow; mass flow; lacustrine; reworked crater rim; alluvial fan; turbidite
			Epiclastic Volcanic: *[descriptors]* epiclastic volcanic *kimberlite* (EVK) or *[descriptors]* epiclastic *kimberlitic* [standard sedimentary rock name]	e.g. pipe-proximal EVK; epiclastic volcanic *kimberlitic* sediment	e.g. lithified crater rim scarp slope mass wasting
Example names: uniform, xenolith-poor, medium-grained, olivine macrocryst-rich rock; massive, xenolith-rich, fine to medium-grained, olivine-poor rock; cross-bedded microcrystic rock	**Example names:** olivine macrocryst-rich carbonate phlogopite monticellite kimberlite; leucite lamproite; olivine macrocryst-poor phlogopite orangeite	**Example names:** xenolith-poor, flow zoned, variably macrocrystic CK; xenolith-rich, well bedded VK	**Example names:** macrocryst-poor ICK; uniform macrocrystic HK; flow banded crystal-poor ECK; thickly bedded PK; massive unsorted very macroxenolith-rich KPK; graded xenolith-poor olivine pyrocryst-rich FPK; cross-bedded very fine-grained crystal-dominated RVK; well sorted resedimented *kimberlitic* sandstone; poorly sorted EVK; bedded *kimberlitic* lapilli tuff	**Example names:** steep discordant HK sheet; diatreme-fill massive xenolith-rich KPK; crater-fill mega-graded olivine pyrocryst-dominated FPK	**Example names:** graded, olivine pyrocryst-rich FPK fallout deposit; *kimberlitic* lacustrine mudstone; clast supported, very xenolith-rich RVK mass flow deposit

Dashed and *dotted lines* indicate potential for gradations between rock types. In Stages 3–5, the scheme focuses on kimberlites (shown in *red* from Stage 2) but the term can be replaced by another parental magma type such as lamproite. The descriptors shown in *green* can vary according to the stage or purpose of the investigation or the rock name

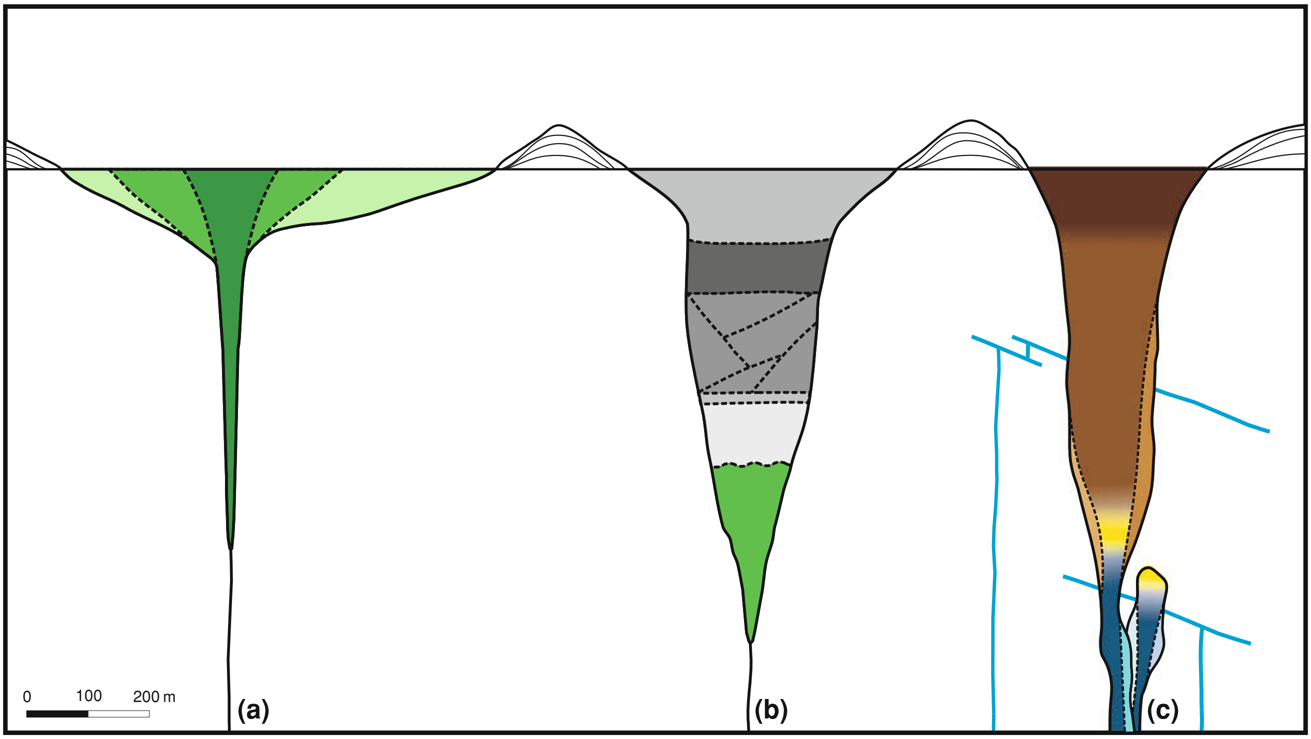


Fig. 1 Schematic representation of the internal geology of different types of kimberlite pipes (from Scott Smith 2008a; based on three-dimensional geological models developed for Canadian diamond resource estimations reconstructed to the time of emplacement). Such geological models are the maps used to predict the volume and diamond content of a body. Based on the textural-genetic classifications of Stage 3 in Table 1: *green* = Fort à la Corne-type pyroclastic kimberlite; *brown* = Kimberley-type pyroclastic kimberlite; *blue* = coherent kimberlite; *yellow* = transitional textures from Kimberley-type pyroclastic kimberlite to coherent kimberlite; *grey* = resedimented volcaniclastic kimberlite. Illustrations of type examples of some of these rock types are shown in Fig. 2 (in which summary terms are coloured to match this figure). The geometry of different internal kimberlite units within each pipe type is distinct (shown by *variable colours* or *shades of colour* separated by *dashed lines* for internal contacts). **a** Concentric funnel-shaped nested craters with one feeder. Internal contacts have dips of ~30–60° and are either gradational or sharp. **b** Horizontal layers or wedge-shaped units. Internal contacts have dips of ~0–45° and may be sharp or gradational. **c** Asymmetric units have internal contacts which are sharp and steep with dips of ~60–90°. Single units can be vertically extensive. Coherent kimberlite also occurs in associated intrusive sheets. Extra-crater deposits as shown are seldom preserved

different. Further description of the body or rock depends upon this initial facies assignment (e.g. coherent vs. volcaniclastic) and if this is changed after additional investigation, the original descriptors need to be replaced. Our experience is that the subdivision of kimberlite into either coherent or volcaniclastic commonly requires detailed investigation and, in some instances, may not be possible with any acceptable degree of confidence. On this basis, the textural-genetic classification in our scheme is considered at a later stage in the rock naming process (Table 1). The scheme presented here builds upon a series of descriptors (Stage 1) that are applied independently of, and prior to, textural-genetic classifications (Stage 3). This order is aimed at reducing incorrect textural-genetic assignments that can be very misleading, especially with respect to predictions of internal geology (Fig. 1) and diamond distribution.

Coherent and volcaniclastic are the standard textural subdivisions of volcanic rocks (e.g. McPhie et al. 1993) and are assigned in Stage 3a as part of the textural-genetic classification. The term "coherent" was originally coined for volcanic–subvolcanic settings and includes both intrusive and extrusive rocks, which can be difficult to differentiate. Conventionally, the term "coherent" is applied to a rock until further subdivision into intrusive (in the case of kimberlite usually hypabyssal) and extrusive (lava) can be made. This designation is particularly relevant to kimberlites where most pipes encompass volcanic–subvolcanic settings. Historically, however, the term "coherent" has not been widely applied to kimberlites, because most occurrences have been interpreted as intrusive, and therefore described as hypabyssal. Most hypabyssal rocks (e.g. diabase) are coherent and the term "coherent" is implicit in previous, and current, usage of hypabyssal kimberlite. The term "coherent" includes but, importantly, is not synonymous with hypabyssal. Documented examples of extrusive kimberlite lavas are not common, either because of lack of formation or lack of preservation or both.

The Scheme

The scheme (Table 1) is applied to rock bodies, lithological units and samples derived from them. Typically, the scheme is applied progressively, with an overall broadening of the scale of observation (i.e. incorporation of smaller and larger scale observations), increased sample density, greater integration of other data and higher levels of interpretation as investigations proceed from Stages 1 to 5. Stages 1–3 are typically applied to a sample or unit but Stages 4 and 5 commonly rely on much larger scale information and context. The scheme focuses on the most common primary source of diamonds, kimberlites, but it is applicable to rocks generated from other parental magma types (e.g. lamproites or orangeites). Examples illustrating the application of the scheme shown in Table 1 are presented in Fig. 2. There are, however, some rock types associated with kimberlite pipes and sheets which contain little or no kimberlitic constituents (e.g. country rock breccias, sedimentary rocks including non-volcanic epiclastic rocks) that are not covered by this scheme.

Stage 1: Rock Description

Stage 1 of the scheme is rock description (alteration, structure, texture, components; Table 1) and involves mainly observation with only limited genetic interpretation. The sequence in which the descriptions are considered broadly reflects a progressive decrease in the scale of observation from megascopic through macroscopic to microscopic. For example, alteration is discussed first because it is commonly a readily recognisable megascopic and macroscopic feature. The interstitial matrix is presented last, because it is difficult to discern and microscopic examination is usually required to determine its character.

Although Stage 1 is primarily descriptive, it does require a broad understanding of these rock types, particularly in terms of identifying the primary components and their replacement products. The observations are summarised as a descriptive rock name which highlights the significant and characteristic features of that rock (see example names in Stage 1 in Table 1 and Fig. 2). The descriptors used in the name can be selected according to the objectives of the task at hand and could vary for different parts of the same investigation. For many economic investigations, the features that distinguish different phases of kimberlite within a single body (Fig. 1) are useful characteristics to include in the descriptive rock name. Importantly, for investigations aimed at the economic assessment of kimberlites, regardless of whether the textural-genetic classification of the host rock is understood, Stage 1 should emphasise the components that are relevant in the prediction of diamond distributions, in particular olivine, other mantle-derived xenocrysts and all types of xenoliths. The descriptors can be changed and/or carried forward into rock names assigned during subsequent stages as appropriate to the investigation (shown in green in Table 1 and Fig. 2).

Although the Stage 1 descriptors overlap with those of Cas et al. (2008, 2009), there are some key distinctions which are listed below.

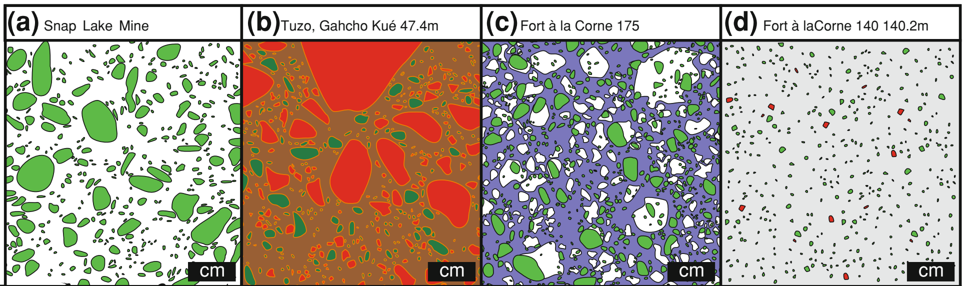
(i) The size and abundance descriptors for crystals and magmaclasts as well as xenoliths (and autoliths) given in Tables 2, 3, 4 and 5 are kimberlite specific and thus more relevant to the economics of diamond deposits.

(ii) A single set of non-genetic size descriptors for crystals is presented (Table 4) that can be applied irrespective of the textural-genetic classification, in particular prior to classification as either coherent or volcaniclastic. This is an essential requirement for an applied nomenclature scheme designed to be practical. Standard size classes are generally different for igneous versus volcanic rocks and volcaniclastic versus coherent rocks.

(iii) The term "magmaclast" is retained (Fig. 3, Tables 4 and 5) to prevent the premature misinterpretation of certain components (melt segregations vs. pyroclasts). The original suggested use of "magmaclast" (Field and Scott Smith 1998) is now modified; magmaclasts must contain solidified melt thus excluding crystals which are devoid of magmatic selvages (see pyrocryst in Fig. 3e and crystals below).

(iv) A 25 % cut-off for crystal abundance subdivisions (Table 5) is avoided, because this value is the average mode for olivine macrocryst abundance in typical hypabyssal kimberlites (see crystals below and Fig. 4a, c (ii)); thus different abundance descriptors are not assigned to rocks with very similar olivine contents on either side of the mode.

(v) The previous use of the term "breccia" to describe kimberlites with >15 % xenoliths (Clement and Skinner 1985) is discontinued and replaced with descriptors based on specific xenolith sizes and abundances (Tables 2, 3). The term breccia can be used as a general term to describe certain rock types associated with kimberlite bodies which are not included in this scheme. The most widespread types are country rock breccias which are dominated by angular fragments of country rock that occur in situ or close to in situ. The breccias form by kimberlite-related volcanic, subvolcanic and/or intrusive processes. Kimberlitic constituents are typically a minor component or not detectable. The interclast areas can be composed of a mineral



		(a) Snap Lake Mine	(b) Tuzo, Gahcho Kué 47.4m	(c) Fort à la Corne 175	(d) Fort à laCorne 140 140.2m
Stage 1	Rock Description	very xenolith-poor very fine to very coarse olivine-rich uniform rock	micro to small macroxenolith-rich very fine to coarse olivine-poor massive rock	very xenolith-poor very fine to coarse olivine-rich fine to ultra coarse magmaclast-rich massive rock	very xenolith-poor super fine to fine olivine-rich graded rock
Stage 2	Petrogenetic Classification	very xenolith-poor very fine to very coarse olivine-rich monticellite kimberlite	micro to small macroxenolith-rich very fine to coarse olivine-poor kimberlite	very xenolith-poor very fine to coarse olivine-rich fine to ultra coarse magmaclast-rich monticellite kimberlite	very xenolith-poor super fine to fine olivine-rich kimberlite
Stage 3a	Textural-Genetic Classification	very xenolith-poor very fine to very coarse olivine-rich coherent monticellite kimberlite	micro to small macroxenolith-rich very fine to coarse olivine-poor volcaniclastic kimberlite	very xenolith-poor very fine to coarse olivine-rich fine to ultra coarse magmaclast-rich volcaniclastic monticellite kimberlite	very xenolith-poor super fine to fine olivine-rich volcaniclastic kimberlite
Stage 3b		v-x-poor vf-vc ol-rich intrusive coherent monticellite kimberlite	mix-smax-rich vf-c ol-poor Kimberley-type pyroclastic kimberlite	v-x-poor vf-c ol-rich f-uc melt-bearing pyroclast-rich Fort à la Corne-type pyroclastic monticellite kimberlite	v-x-poor sf-f ol-pyrocryst-rich Fort à la Corne-type pyroclastic kimberlite
Stage 4	Intrusive / Volcanic Spatial Context	v-x-poor vf-vc ol-rich ICK *inclined intrusive sheet*	mix-smax-rich vf-c ol-poor KPK *diatreme-fill*	v-x-poor vf-c ol-rich f-uc melt-bearing pyroclast-rich FPK *vent-proximal crater-fill*	v-x-poor sf-f ol-pyrocryst-rich FPK *crater-fill*
Stage 5	Genetic / Process Interpretation	v-x-poor vf-vc ol-rich HK *uniform hypabyssal sheet*	mix-smax-rich vf-c ol-poor KPK *massive fluidised deposit*	v-x-poor vf-c ol-rich f-uc melt-bearing pyroclast-rich FPK *massive spatter deposit*	v-x-poor sf-f ol-pyrocryst-rich FPK *graded fallout deposit*
	Summary	**uniform olivine macrocrystic HK inclined sheet**	**massive olivine macrocryst-poor KPKx diatreme-fill**	**massive olivine macrocrystic FPK crater-fill**	**graded olivine microcrystic FPK crater-fill**

Fig. 2 Examples illustrating application of the scheme shown in Table 1, focusing on the components that are economically relevant in the prediction of diamond distributions (i.e. olivine and xenoliths). The figure shows the macroscopic constituents traced in polished slabs of four rock samples from Scott Smith and Smith (2009). These rocks display minimal alteration resulting from weathering; the textures are well preserved and the original mineralogy is evident. Different component types are represented by different colours. *Green* = olivine crystals or their pseudomorphs (31, 11, 21 and 6 modal % in **a**, **b**, **c** and **d**, respectively); *white* (**a**, **c**) = solidified former melt (crystalline groundmass in **a** shown in Fig. 5 of Mogg et al. 2003; cryptocrystalline/glassy groundmass in **c** similar to Fig. 5 of Scott Smith 2008a); *red* = country rock xenoliths and xenocrysts (30 and <1 modal % in **b** and **d**, respectively); *brown* (**b**) = interclast matrix (Fig. 7b of Hetman et al. 2004); *purple* (**c**) and *grey* (**d**) = microscopic components not traced (for **c** cf. Fig. 3 of Scott Smith 2008a; for **d** see Figs. 7b, 8a of Berryman et al. 2004) and later interclast cement (carbonate cement in **c** shown in Fig. 3b of Scott Smith 2008a; serpentine-like cement in **d** shown in Fig. 8c of Berryman et al. 2004). Thin orange borders on all constituents in **b** schematically show the thin selvages observed in thin section (as shown in Fig. 7b of Hetman et al. 2004). Rock names are only applied to a sample when the evidence allows and the naming format is flexible. Here the staged approach to the terminology reflects an overall increasing level of investigation. The observations were made on the illustrated polished slabs and augmented with drillcore and thin section examination. **Stage 1** observations are summarised in a descriptive rock name (*green* text; cf. example names of Stage 1 in Table 1). Xenoliths are listed first because they are typically larger and more easily discerned. The descriptors can be retained or modified as appropriate to subsequent stages of the investigation (as shown in *green* in Stages 3a and b in Table 1). In **Stage 2**, the petrogenetic rock name (*red* text) replaces "rock" from Stage 1, combining the petrogenetic classification and, when possible, the mineralogical classification (usually requiring petrographic observations in thin section). A mineralogical classification for samples **b** and **d** is not possible because of the lack of resolvable crystalline groundmass and is omitted. In **Stage 3a**, initial broad textural subdivisions are added (*black* text). In **Stage 3b**, the descriptor terms are retained but abbreviated to make the rock name much more manageable (from Tables 2, 3, 4 and 5; ol = olivine). More detailed observations and interpretations result in the following changes: replacement of the term magmaclast by melt-bearing pyroclast (after Fig. 3d) in sample **c**; and the more specific textural-genetic rock name (*black* text) for all samples. In **Stage 4**, terms describing the spatial context of the rock (*black italicised* text) are applied to the abbreviated textural-genetic rock name from Stage 3 (*black and red upper case* letters, from Table 1). In **Stage 5**, data from previous Stages are integrated to propose a high-level genetic interpretation (*black italicised* text). This stage typically requires incorporation of information from a broader context than the specific sample or portion of the body being classified (e.g. for **a** McBean et al. 2003; for **b** Hetman et al. 2004; for **d** Scott Smith and Smith 2009). The pertinent information for each sample is summarised in the *bottom* row and *coloured* to match Fig. 1 to illustrate how the scheme is applicable to the development of three-dimensional geological models required for evaluation and diamond resource estimation

cement (e.g. carbonate), a fine-grained clastic matrix (e.g. pulverised country rock), minor volcaniclastic or coherent kimberlite or can remain void. There can be a gradational change in rock type from fractured country rock to country rock breccias to xenolith-dominated kimberlite. Xenoliths are displaced from their source and incorporated into kimberlites mainly during ascent and emplacement.

Table 2 Size descriptors for lithic compound clasts, in particular xenoliths; for autoliths substitute [autolith] for [xenolith] (similarly for autoclasts, epiclasts; for crystal, magmaclast and accretionary clast size descriptors see Table 4)

Size range	Modifier	Descriptor	Abbreviation
<16 mm	–	micro [xenolith]	mix
16–64 mm	small	macro [xenolith]	smax
>64–256 mm	medium		mmax
>256–1024 mm	large		lmax
>1.0–4.1 m	small	mega [xenolith]	smex
>4.1–16.4 m	medium		mmex
> 16.4 m	large		lmex

Table 3 Abundance descriptors for lithic compound clasts, in particular xenoliths; for autoliths substitute [autolith] for [xenolith] (similarly for autoclasts, epiclasts; for crystal, magmaclast and accretionary clast abundance descriptors see Table 5)

Percentage range	Descriptor	Abbreviation
0	[xenolith]-free	x-free
>0–5	very [xenolith]-poor	v-x-poor
>5–15	[xenolith]-poor	x-poor
>15–50	[xenolith]-rich	x-rich (or Kx)
>50–75	very [xenolith]-rich	v-x-rich (or Kxx)
>75	[xenolith]-dominated	x-dominated (or Kxxx)

Table 4 Size descriptors for crystals and magmaclasts (similarly for accretionary clasts; for lithic clast size descriptors see Table 2). See also Fig. 4b

Size range (mm)	Descriptor	Abbreviation
<0.125	ultra fine	uf
0.125–0.25	super fine	sf
>0.25–0.5	very very fine	vvf
>0.5–1	very fine	vf
>1–2	fine	f
>2–4	medium	m
>4–8	coarse	c
>8–16	very coarse	vc
>16	ultra coarse	uc

Table 5 Abundance descriptors for crystals; for magmaclasts substitute [magmaclast] for [crystal] (similarly for accretionary clasts; for lithic clast abundance descriptors see Table 3). See also Fig. 4a

Percentage range	Descriptor
0	[crystal]-free
>0–5	very [crystal]-poor
>5–15	[crystal]-poor
>15–50	[crystal]-rich
>50–75	very [crystal]-rich
>75	[crystal]-dominated

Given the importance of Stage 1, this stage is discussed below in more detail than the subsequent stages.

Alteration. Unlike many other mineral deposits, the description of alteration products is not the primary objective of most investigations of kimberlites and related rocks. The overriding intention, especially during the evaluation of primary diamond deposits, is to determine the original nature of the rocks as reflected by the "Example names" in Table 1. Alteration affects the ability to determine the original structure, texture and components (Table 1, Stage 1). Thus, some description and understanding of rock components resulting from alteration is necessary to establish the degree of confidence in the description, classification and interpretation of the original nature of the kimberlite rock, and in turn the confidence level of the geological model. Where relevant, the descriptive rock names can be modified by adding alteration terms that convey, for example, intensity (e.g. subtle, complete), distribution (e.g. pervasive, local vein-like) and mineralogy (e.g. carbonatised). Mineral replacement in kimberlites occurs mainly by: (i) pre- or syn-emplacement deuteric alteration processes involving internal magmatic fluids (e.g. deuteric replacement of olivine by serpentine and/or carbonate which is widespread because, at the time of emplacement, kimberlite magmas are extremely rich in juvenile volatiles, in particular CO_2 and H_2O); (ii) post-emplacement or post-depositional hydrothermal processes associated with external fluids from later degassing magmas or meteoric water heated by magmatic activity; and (iii) weathering in response to surface processes and external fluids such as groundwater (e.g. clay mineralisation of previously deuterically serpentinised olivine), the severity of which depends on the climate. In this scheme, alteration also includes departures from the usual primary groundmass mineralogy of kimberlites (e.g. introduction of clinopyroxene) that result from interactions between the hot host magma and country rock whether as xenoliths or in situ at a kimberlite to country rock contact.

Structure and texture. Structure and texture pertain to the physical characteristics or appearance of a rock and can be summarised using standard descriptors in most instances (see examples in Stage 1 of Table 1). Structure encompasses the megascopic features or internal organisation of the rock. Texture summarises the small-scale arrangement of, and relationships among, the components of a rock or part thereof. Structure and texture are important observations used in Stages 2–4 (Table 1).

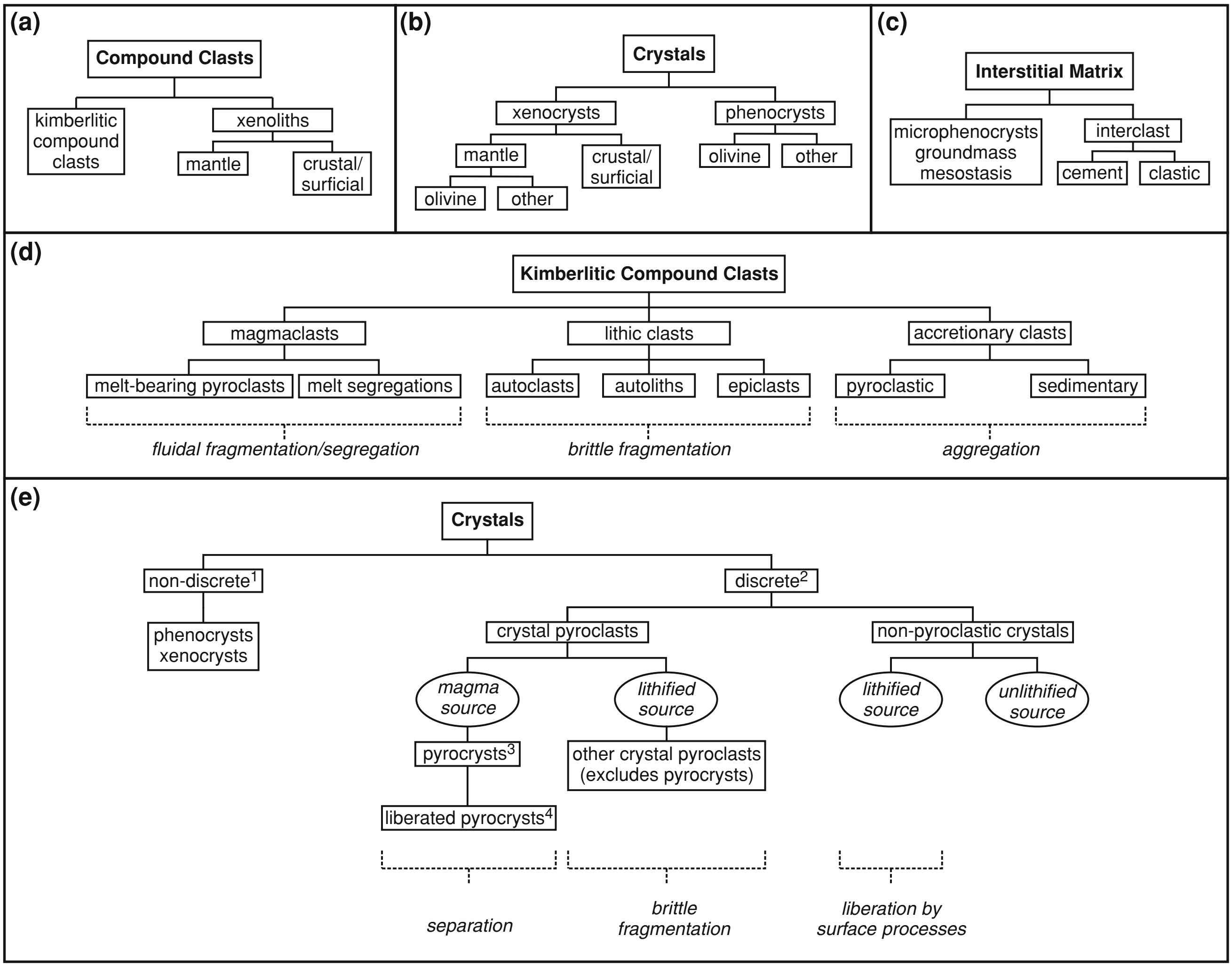


Fig. 3 Conceptual framework for the description of kimberlite components. The components are ascribed to three main classes **a** compound clasts, **b** crystals, and **c** interstitial matrix (listed in order of decreasing size). Further subdivision is based on composition and origin (**d** and **e**). Notes for **e**: (*1*) occur within solidification products of original host melt (includes crystals in magmaclasts); (*2*) kimberlitic and non-kimberlitic crystals separated from a former host melt, a former lithified source or derived from a former unlithified source; (*3*) crystals separated by pyroclastic emplacement processes from the original host kimberlite melt but not necessarily from exsolved magmatic fluids; (*4*) pyrocryst that has been completely separated from the original host kimberlite magma including both melt and exsolved magmatic fluids

Components (Fig. 3). The components of a rock or unit are the most critical part of any rock description (Stage 1 in Table 1 and Fig. 2). They can be ascribed to three classes or groups: (a) compound clasts, (b) crystals and (c) interstitial matrix (listed in order of decreasing size), each of which is further subdivided as shown in Fig. 3. Although many standard descriptors can be used there are some kimberlite-specific aspects to describing components.

Compound clasts (Fig. 3a, d). Compound clasts are components of a rock or unit that comprise assemblages of crystals. They are subdivided into two main types (Fig. 3a) based on composition: xenoliths (accidental non-kimberlitic inclusions) and kimberlitic compound clasts (composed entirely or partly of kimberlitic constituents; which include magmaclasts, lithic kimberlitic clasts and accretionary clasts, Fig. 3d). The term "clast" is used in the broadest sense to include the products of different processes of formation: brittle fragmentation or failure of country rocks or consolidated kimberlite (e.g. crustal xenoliths in Fig. 3a; lithic kimberlitic clasts in Fig. 3d); fluidal fragmentation/segregation (e.g. magmaclasts in Fig. 3d) and particle aggregation (e.g. accretionary clasts in Fig. 3d).

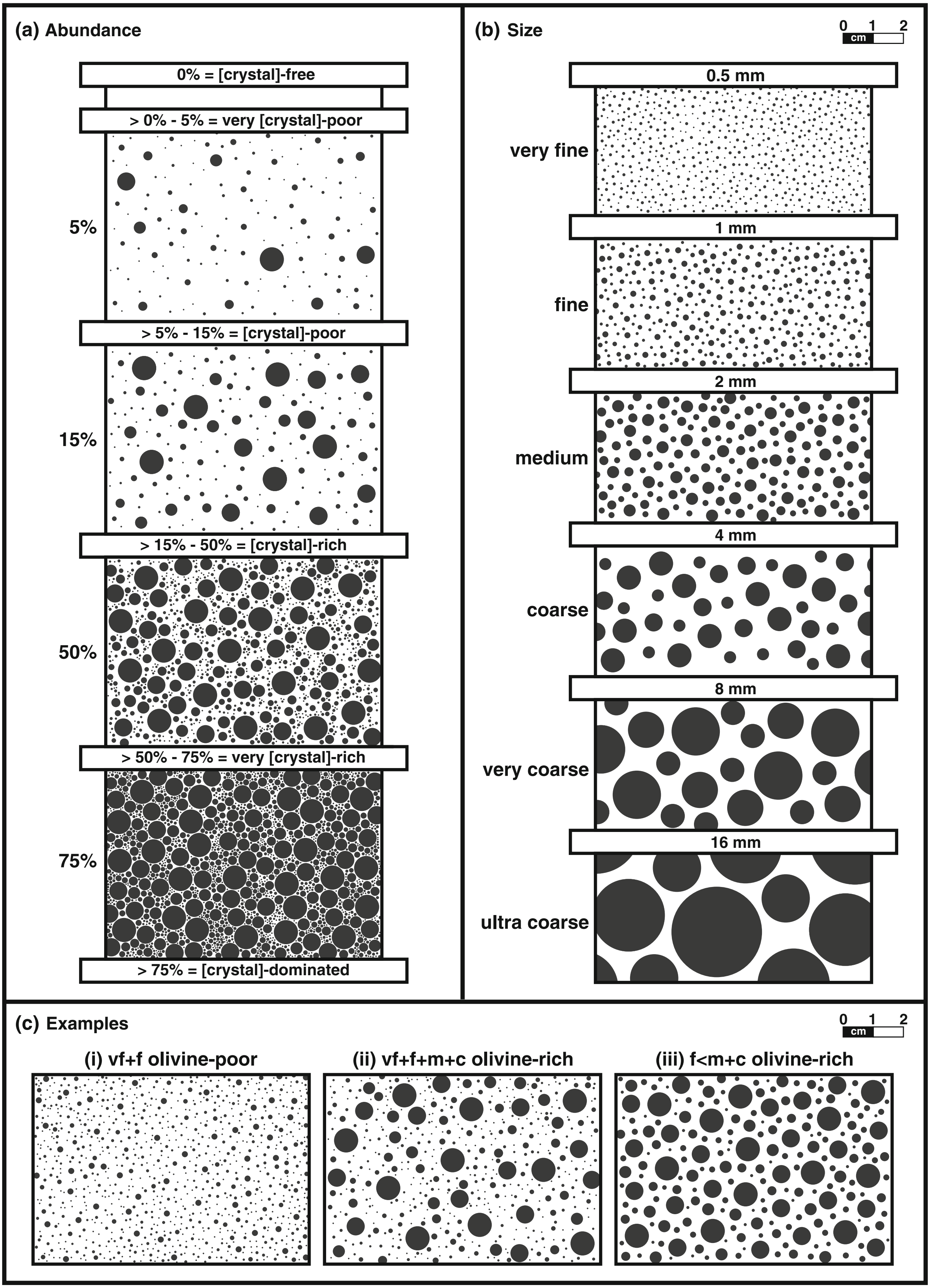
Xenoliths are fragments of pre-existing genetically unrelated wall rock incorporated during ascent or emplacement of kimberlite magma and its volcanic products. Xenoliths are subdivided according to their origin: mantle (e.g. peridotite, eclogite) and crustal/surficial (Fig. 3a). The total and relative abundance, distribution, character and degree of alteration or metamorphism of xenoliths can be extremely useful in distinguishing different phases of kimberlite. Broad size and abundance descriptors for xenoliths are provided in Tables 2 and 3, respectively, and can be applied based on simple visual estimates. Crustal xenoliths (e.g. granitoid or gneissic basement, sediments, non-kimberlitic volcanics) are most common and their incorporation into, and 'dilution' of, kimberlite is an important aspect of the economic assessment of primary diamond deposits, generally requiring detailed studies and acquisition of quantitative abundance data (e.g. Fig. 2b). Importantly, the xenolith size and abundance of a relatively small sample may be different from that of the larger scale intersection or unit from which it derives; the selection of petrographic samples to examine the nature of the host kimberlite typically avoids xenoliths. Such larger scale data are commonly integrated in the higher levels of interpretation such as in Stages 4 and 5. When relevant, the internal nature of compound clasts can be described using the descriptors suggested for alteration, structure and texture discussed above and for crystals and interstitial matrix discussed below.

Magmaclasts are the most widespread and common type of kimberlitic compound clast (Fig. 3d). "Magmaclast" is a general descriptive term for a physically distinct, fluidal-shaped clast of solidified kimberlite magma formed prior to and during final emplacement by any process (e.g. Fig. 2c). Magmaclasts form by fluidal fragmentation/segregation processes typically during near-surface emplacement events prior to solidification. The general term "magmaclast" is replaced by more specific terms if more detailed interpretation allows for further classification (Figs. 3d, 2c). They include: (i) solidified melt-bearing pyroclasts formed by fragmentation and subsequent rapid cooling of fluidal kimberlite magma; and (ii) solidified melt segregations which are discrete bodies of melt formed by segregationary processes within coherent kimberlite magmas. Melt segregations are widespread, in some instances common, and are a reflection of the particular properties of kimberlite magmas (low viscosity, high volatiles). Segregations of melt in melt are one variety of melt segregation comprising discrete segregationary patches within a coherent melt. Segregations of melt in fluid are the specific variety of melt segregation comprising bodies of segregated or immiscible melt set in a matrix representing the crystallisation products of a volatile-rich fluid host. Confusion of melt segregations with pyroclasts is misleading, sometimes with economic consequences. Magmaclasts can range widely in abundance and might be the dominant constituent of a rock. Size and abundance descriptors are the same as for crystals, as presented in Tables 4 and 5.

Lithic kimberlitic compound clasts are formed by the brittle fragmentation of lithified kimberlitic rocks and include autoclasts, autoliths and epiclasts (Fig. 3d). Volcanic autoclasts are fragments formed non-explosively by the movement of the cooled and solidified portions of the emplacing kimberlite magma (commonly lava) and occurring within the same magma. Autoclasts have not been documented in kimberlites, either because of lack of formation of lava or lack of preservation or both. Autoliths are accidental inclusions of pre-existing lithified kimberlite of any type (i.e. clasts of an earlier phase of kimberlite). They typically differ texturally and/or mineralogically from the enclosing host kimberlite (e.g. an autolith of coherent kimberlite in a volcaniclastic kimberlite or vice versa). Autoliths are seldom abundant but can be useful in understanding the geological history of a kimberlite body and in distinguishing phases of kimberlite. Kimberlitic epiclasts are fragments created from any type of pre-existing kimberlitic rocks exposed to surface processes such as chemical and/or physical weathering. Lithic kimberlitic compound clasts are described using the same size and abundance descriptors as for xenoliths given in Tables 2 and 3.

Accretionary clasts are aggregates of fine-grained particles including volcanic kimberlitic and non-volcanic constituents formed by any process. The recognition of accretionary clasts can provide important evidence towards interpreting a rock as extrusive, and in determining the environment and process of formation. They typically form in subaerial environments and are spherical to subspherical in shape, but they could also form subsurface. There are two main types of accretionary clasts found in volcaniclastic rocks: pyroclastic and sedimentary, which form by volcanic eruption or by non-volcanic resedimentation processes, respectively. The abundance, size and shape of accretionary clasts are most similar to those of crystals and magmaclasts, and thus the descriptors in Tables 4 and 5 can be applied. The term "accretionary clast" is more general than "accretionary lapilli" (which have a restricted size range) and can be applied regardless of clast size or interpreted pyroclastic versus sedimentary origin. An accretionary clast with a relatively large crystal/lithic kernel can be described as an "armoured clast".

Crystals (Fig. 3b, e). For practical purposes, descriptors for crystals apply primarily to those that are observable with the unaided eye or under the binocular microscope; characterisation of the very fine-grained minerals occurring in the interstitial matrix (discussed below; Fig. 3c) usually requires microscopic examination and may be incorporated into rock descriptions (e.g. Fig. 2d). Descriptors for crystals are applied to any crystals within kimberlites regardless of their context, including crystals occurring within magmaclasts and pyroclastic accretionary clasts. Those occurring within lithic clasts (xenoliths and autoliths) and within sedimentary accretionary clasts should be considered and described separately.


(a) Abundance
0% = [crystal]-free
> 0% - 5% = very [crystal]-poor
5%
> 5% - 15% = [crystal]-poor
15%
> 15% - 50% = [crystal]-rich
50%
> 50% - 75% = very [crystal]-rich
75%
> 75% = [crystal]-dominated
(b) Size
0 1 2
cm
0.5 mm
very fine
1 mm
fine
2 mm
medium
4 mm
coarse
8 mm
very coarse
16 mm
ultra coarse
(c) Examples
0 1 2
cm
(i) vf+f olivine-poor
(ii) vf+f+m+c olivine-rich
(iii) f<m+c olivine-rich

◀ **Fig. 4** Diagrammatic guide to the abundance and size descriptors for crystals in kimberlite (Fig. 3b); for magmaclasts, substitute [magmaclast] for [crystal] (similarly for accretionary clasts). The *black circles* mimic the characteristic round shape of olivine macrocrysts and many magmaclasts. Only crystals that are observable with the naked eye (>∼0.5 mm, i.e. macrocrysts and relatively coarse-grained microcrysts) are depicted. **a** Crystal abundance classes are shown inside the *white bars* (from Table 5). Between the *white bars*, each figure illustrates the cut-offs between the abundance classes using a range of crystal sizes. **b** Figures illustrate the crystal size classes from very fine to ultra coarse from Table 4. Each figure includes a range of crystal sizes within each class. The finer size classes given in Table 4 not illustrated here are usually interstitial matrix (Fig. 3c). For reference, the abundances of crystals within each of these figures are: very fine = 11 %; fine = 18 %; medium = 32 %; coarse = 31 %; very coarse = 54 %; ultra coarse = 69 %. **c** Schematic example rocks are illustrated with abbreviated olivine size and abundance descriptors (from Tables 4 and 5). It is implicit in the use of any size terms >1 mm (f upwards) for olivine that they are macrocrysts. These observations provide key lines of evidence to understanding mantle, ascent and near surface magmatic and volcanic emplacement processes. The abundances of the depicted olivines are: (*i*) 7 %; (*ii*) 25 %; (*iii*) 39 % where (*ii*) is a diagrammatic representation of a typical macrocrystic hypabyssal kimberlite which has the potential to be of economic interest (cf. Fig. 2a). This schematic hypabyssal kimberlite represents a typical pre-eruption kimberlite magma which can be used as a benchmark to assess the degree of modification to the olivine size and abundances during the emplacement of such magmas. For example, rocks (*i*) and (*iii*) could be different emplacement products of such a magma which have undergone flow differentiation within a hypabyssal sheet, sorting during deposition from a pyroclastic eruption column (cf. Fig. 2d) or sorting during resedimentation. The very brief rock descriptors usefully summarise the differences in macroscopically observable olivine crystal content between these samples and can be used to predict diamond distributions within, and between, phases of kimberlite. The degree of economic interest increases from (*i*) to (*ii*) to (*iii*) reflected in the increased abundance and size of the olivine macrocrysts (fine-medium and coarse-grained olivine), assuming that they are predominantly mantle derived

Olivine is the dominant and essential crystal type in kimberlites forming ∼50 modal % of a typical hypabyssal kimberlite and is the critical component in the interpretation of the geology, diamond prospectivity and economic potential of kimberlites and related rocks.

Olivine crystals can be subdivided using two approaches: (i) non-genetically and descriptively based only on the crystal size; and (ii) paragenetically based on interpretations of the origin of the crystals. Olivine crystals can be described based on their size as macrocrysts (>1 mm) and microcrysts (<1 mm) (e.g. Summary in Fig. 2). "Macrocryst" is a non-genetic term used to describe large (>1 mm; no upper size cut-off), generally anhedral crystals that commonly can be seen with the unaided eye (e.g. Fig. 2a–c). The term "macrocryst" is widely used as proposed by Clement et al. (1984) with a lower size cut-off of 0.5 mm. Here the cut-off is adjusted to 1 mm for the following practical reasons: (i) crystals less than 1 mm are less visible to the unaided eye and are thus difficult to identify and quantify; (ii) increasing the lower cut-off size enhances the economic relevance of crystals termed macrocrysts (e.g. a rock dominated by very fine-grained olivine ranging from 0.5 to 1 mm would, based on the previous use of the term "macrocryst", be described as very olivine macrocryst-rich, and yet would have a very low potential for hosting significant concentrations of commercially relevant diamonds); and (iii) increasing the cut-off size significantly reduces the extent to which relatively coarse-grained (>0.5 mm) phenocrystic olivine (i.e. predominantly crystallised from the kimberlite melt) would be classified as macrocrystic, thereby further enhancing the relevance of macrocrysts to the economic assessment of kimberlites (see below). The term "microcryst" is a non-genetic term used to describe small (<1 mm) crystals that are not clearly recognisable with the unaided eye and reliably discernible only under the microscope (e.g. Fig. 2d). Mitchell (1995, p. 5) proposed the term "microcryst" with a cut-off of 0.5 mm which is here modified to 1 mm as discussed above for macrocrysts.

Further interpretation of crystals includes their paragenesis and origin (e.g. phenocrysts versus xenocrysts; and for the latter, mantle or crustal origin, Fig. 3b), and it is important to distinguish between them where possible. Two main olivine parageneses are recognised in kimberlite: (i) that which has crystallised from the kimberlite melt and therefore can be termed phenocrystic (or microphenocrystic); and (ii) that which is derived by disaggregation of mantle-derived peridotite and therefore of xenocrystic origin. Olivine xenocrysts are typically anhedral and range from 0.5 mm to in excess of 10 mm. They are commonly characterised by internal deformation and the presence of inclusions of other mantle-derived minerals, and can have overgrowths of olivine that crystallised from the kimberlite melt (Brett et al. 2009). Xenocrystic olivine is of primary importance for economic assessment of kimberlites as it provides an indication of the amount of mantle material incorporated in the magma and hence the potential quantity of associated diamond (when the sampled mantle contains diamond). Olivine crystals formed primarily by crystallisation from the kimberlite melt (i.e. phenocrystic) are typically finer grained (<∼0.5–1 mm) than the dominant xenocryst population and commonly show euhedral grain shapes. They can contain cores of xenocrystic olivine (Brett et al. 2009). Because these crystals are primarily formed from the kimberlite magma, they are not directly relevant to diamond content. The chosen size cut-off between macrocrysts and microcrysts usefully distinguishes between olivine crystals that are predominantly of xenocrystic origin and those that are predominantly phenocrystic. However, there are overlaps in the size distributions of these olivine types and size cut-offs should not be used as the primary means of distinguishing between different olivine parageneses. Similarly, to avoid inappropriate genetic implications, we recommend that the term "megacryst" not be used as a size descriptor (even though they are typically very large, and originally defined as >10 mm). Application of the term to kimberlites should be restricted to its petrogenetic sense (e.g. Mitchell 1995, p. 6). For descriptive purposes, prior to detailed investigations showing that any crystal forms part of the megacryst suite, it is recommended that they are termed "macrocrysts" with appropriate size descriptor modifiers (Table 4; e.g. ultra coarse ilmenite macrocryst).

In addition to olivine, many kimberlites contain other less common but distinctive macrocrysts which are xenocrysts of mantle-derived minerals (e.g. pyrope garnet, magnesian ilmenite, chrome spinel, chrome diopside). The macrocryst suite includes the crystals commonly referred to as "kimberlite indicator minerals" by diamond explorationists. These minerals provide important data regarding the nature of the mantle through which the kimberlite magma passed which is relevant to the assessment of the diamond potential of kimberlites. Features such as the type, total and relative proportions, colour, size, replacement and reaction of macrocrysts can be useful in distinguishing phases of kimberlite.

A wide variety of crustal/surficial xenocrysts can be present in kimberlite commonly reflecting the mineralogy of the country rock or surficial materials (e.g. feldspar and mica from granite, quartz sand grains which were unconsolidated at the time of incorporation).

Non-genetic descriptors for the size and abundance of crystals in kimberlites are provided in Tables 4 and 5 (illustrated in Fig. 4), respectively, and can be applied regardless of the nature or origin of the rock (e.g. Stage 1 in Table 1 and Fig. 2). The size subdivisions (Table 4) have been modified from those of Field and Scott Smith (1998) to be more consistent with the widely used grain size scale of Wentworth (1922). Thus, the size ranges are largely consistent with those of Cas et al. (2008, 2009). Where appropriate and useful, size descriptors can be applied to multiple components in the same rock (e.g. very fine-grained quartz-bearing, medium-grained olivine-rich rock).

The key ranges of crystal abundance and associated descriptors presented in Table 5 have been defined such that: (i) the categories are sufficiently broad to be appropriate and meaningful even for simple visual estimates (Fig. 4); (ii) the average mode for olivine macrocryst abundance (20–25 %) in coherent kimberlites lies in the middle of an abundance category thereby avoiding the use of different abundance descriptors for rocks having similar olivine contents on either side of the mode; and (iii) they are useful from an economic perspective (e.g. Fig. 4c). Thus, the abundance ranges are different from those suggested by Cas et al. (2008, 2009). The abundance descriptors in Table 5 can be applied to the general crystal content in cases where crystal mineralogy has not been determined, but it is preferable to apply them to specific crystal types, in which case the term "crystal" (in parentheses in Table 5) is replaced by the crystal type in question (e.g. olivine-rich or olivine macrocryst-rich; but it is implicit in the use of any size terms >1 mm for olivine that they are macrocrysts). The term "olivine macrocrystic" can be used to describe kimberlite with 15–50 % olivine macrocrysts (i.e. it is synonymous with "olivine macrocryst-rich") as per Clement et al. (1984) and Field and Scott Smith (1998), but with an upper abundant limit added (e.g. Summary in Fig. 2a, c). Similarly, the term "olivine microcrystic" can be used to describe kimberlite with 15–50 % olivine microcrysts (e.g. Summary in Fig. 2d). The term "bearing" is useful to indicate the presence of a component without any specific abundance connotation (e.g. ilmenite macrocryst-bearing).

Crystals can be further subdivided into two broad groups: non-discrete and discrete (Fig. 3e). This is an important distinction in determining the textural-genetic classification and genetic processes. Non-discrete crystals (phenocrysts, xenocrysts) are those partially or completely enclosed within the solidification products of the original host kimberlite melt, usually groundmass (includes magmaclasts). "Discrete crystal" is a term used to describe a separate crystal. The term can be used without knowledge of the process leading to its separation. Discrete crystals include crystal pyroclasts and non-pyroclastic crystals separated from a former host melt, a former lithified source or derived from a former unlithified source (Fig. 3e). Discrete crystal pyroclasts include: (i) crystals separated from the host kimberlite melt during emplacement before solidification; and (ii) crystals separated from pre-existing lithified sources such as earlier phases of kimberlite or from unrelated sources such as xenoliths or country rock. The new term "pyrocryst" (Fig. 3e) describes a crystal pyroclast completely separated during pyroclastic emplacement processes from the original host kimberlite melt before solidification. Pyrocrysts, dominantly olivine, can be common in certain pyroclastic kimberlites (e.g. Fig. 2d) because the abundant olivine crystals carried in the magmas are readily separated from the volatile-rich, low-viscosity melt. Pyrocrysts may be generated subsurface and occur within exsolved magmatic fluids. A liberated pyrocryst (Fig. 3e) is one which is completely separated (generally above the vent at the Earth's surface) from its host kimberlite magma (including both melt and exsolved magmatic fluids) before solidification. Other crystal pyroclasts form predominantly from lithified sources including country rock and kimberlitic rocks by brittle fragmentation or disaggregation during explosive volcanic eruptions.

Non-pyroclastic crystals (Fig. 3e) are crystals liberated from pre-existing rocks or unlithified deposits by surface processes (including resedimentation, weathering and erosion).

Interstitial matrix (Fig. 3c). Interstitial matrix is the material occurring between crystals (Fig. 3b) and/or compound clasts (Fig. 3a), the nature of which is important in determining textural-genetic classifications (Stage 3) and genetic processes (Stage 5). Groundmass describes the melt solidification products (microphenocrysts, microcrystalline or cryptocrystalline or amorphous/glassy groundmass and/or mesostasis) which form relatively rapidly from the late-stage melt between any pre-existing phenocrysts and other entrained solids, typically during or immediately after final emplacement. The mesostasis is the final fraction of melt to crystallise or solidify between existing crystals or the last-formed interstitial mineral or minerals. Groundmass and mesostasis occur in coherent kimberlite and within magmaclasts, the nature of which, where crystalline, is important in establishing the parental magma type and mineralogical classification (Stage 2).

The term "interclast matrix" is used here to describe any material, clastic or crystalline, that occurs between magmaclasts, crystals or other clast types. There are two main types of interclast matrix: clastic material and crystalline cement. Cement in volcaniclastic rocks comprises chemically precipitated infill minerals (from magmatic or non-magmatic fluids) and is distinct from a clastic matrix. Clastic interclast matrix can be composed of fine volcanic and/or extraneous components, including finely comminuted country rock or surficial sediments. It can also include fine particles produced by post-eruption processes such as abrasion during reworking. Where relevant, the size and abundance of microscopic crystals and coarser cement-forming grains within the interstitial matrix can be described using Tables 4 and 5.

Stage 2: Petrogenetic Classification

Stage 2 is the petrogenetic classification of parental magma type and the further subdivision into mineralogical types. The parental magma type and mineralogical subdivision are of prime economic significance: (i) to confirm that the rock is kimberlite or other related rock (e.g. lamproite) with potential to contain diamonds; and (ii) to identify different phases of kimberlite intrusion or eruption within a particular body (Fig. 1). Parental magma type is based on typomorphic and characteristic primary magmatic mineral assemblages (minerals whose occurrence, crystal structure and composition are a direct consequence of crystallisation from a particular magma type) summarised in petrographic-based definitions (Woolley et al. 1996; Scott Smith et al. in press). This stage requires identification of the primary minerals (phenocrysts, groundmass), for which microscope-based petrography is usually necessary to reach an acceptable degree of confidence. Where primary minerals have been replaced, regardless of the process, the original mineralogy can in many cases be determined petrographically based on features such as relict grain shapes. Where the parental magma type can be determined, the term "rock" from Stage 1 is replaced, for example, with kimberlite (as shown in red in Stage 2 of Table 1 and Fig. 2). The scheme focuses on kimberlites but the term "kimberlite" can be replaced by another parental magma type such as lamproite. The mineralogical classification subdivides rocks of one parental magma type. Rocks are given compound names using the original main constituent minerals listed in increasing order of modal abundance (after Skinner and Clement 1979; Mitchell 1995). For the purposes of mineralogical classification of kimberlites, olivine is ignored because its presence is implicit in classification of a rock as kimberlite. The addition of a modifier describing the olivine abundance (e.g. olivine-poor from Table 5; Fig. 2) provides information on the olivine content. The resulting terms are combined into a petrogenetic rock name (see example names for Stage 2 in Table 1 and Fig. 2).

Stage 3: Textural-Genetic Classification

Stage 3, the textural-genetic classification, is the second subdivision of a parental magma type, the other being the mineralogical classification discussed above. Stage 3 consists of two sub-stages that require increasing information and interpretation (Table 1). If Stage 3 is not possible based on available information, the scheme should not be applied further than Stages 1 and/or 2. Textural-genetic rock names summarise the results of Stage 3, or of Stage 3a if 3b cannot be achieved and if useful, a series of descriptive prefixes can be added from Stages 1 and/or 2 (see example names in Table 1 and Fig. 2). If more appropriate, standard volcanological and sedimentological rock names can be used.

Stage 3a. This stage is the broad textural-genetic classification into coherent and volcaniclastic. The term "coherent" is applied to rocks formed entirely by the direct solidification of a significant volume of magma. The term "coherent kimberlite" should be used instead of "magmatic kimberlite" (latter suggested by Field and Scott Smith 1998). This is consistent with standard volcanological terminology and avoids confusion with other usages of the term magmatic (e.g. magmatic volatile). Coherent kimberlites are characterised by an interstitial matrix that comprises a continuous crystalline or quenched groundmass, representing the solidification products of former kimberlite melt. The groundmass of these rocks can contain variable

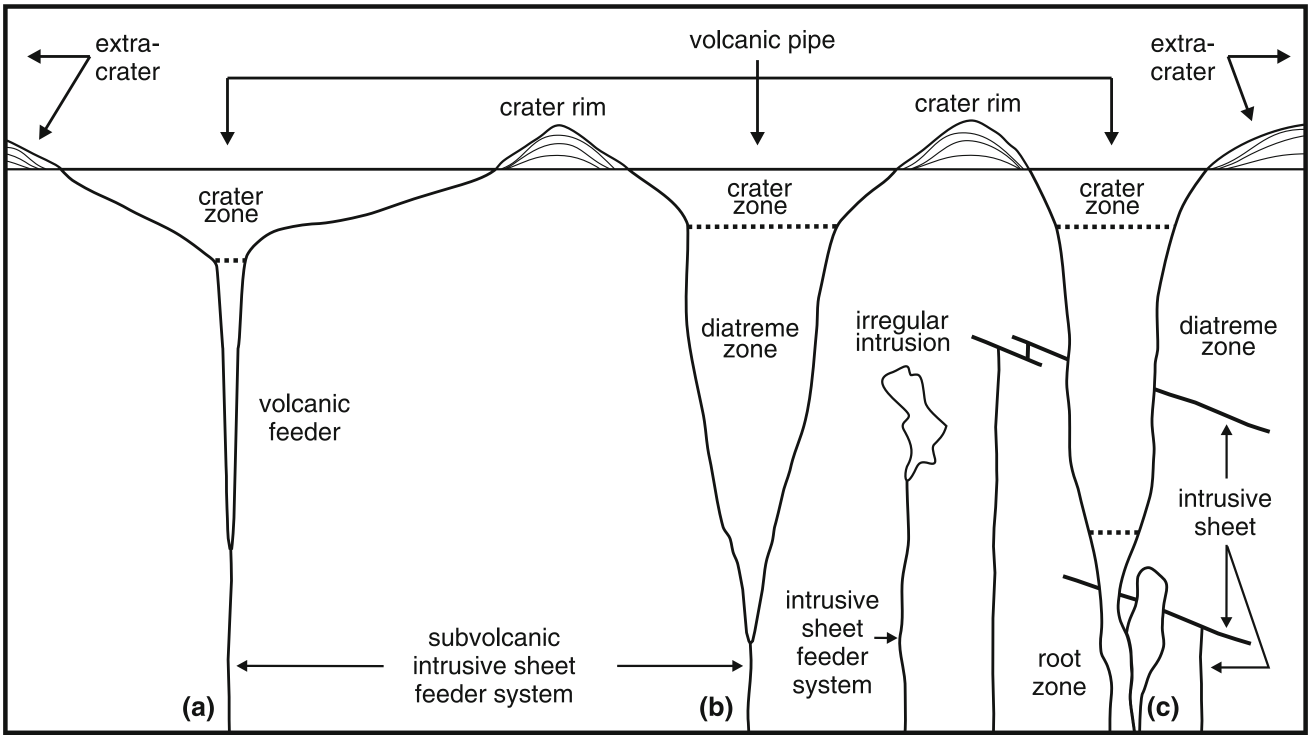


Fig. 5 Diagrammatic guide to terminology for kimberlite body morphology and pipe zones. Body outlines **a**, **b** and **c** are after Fig. 1 (from Scott Smith 2008b). In particular note that the term diatreme zone is used irrespective of the nature of the infill (compare both diatreme zones in this figure with contrasting types of infill shown in Fig. 1)

proportions of magmatic fluid segregations (late-stage patches of the final minerals to crystallise from pockets of residual volatile-rich fluids). Coherent kimberlite includes rocks composed of the crystallisation products of abundant discrete segregations of melt in a continuous volatile-rich fluid host. Although not widespread, this textural type reflects the volatile-rich properties of kimberlite magmas and the close to in-situ separation of those volatiles from the melt during emplacement. This textural type of kimberlite forms without the magma undergoing fragmentation.

Coherent kimberlites that display residual evidence for a pyroclastic origin are termed "clastogenic". These can result from processes such as welding, agglutination and coalescence of spatter. An interpreted original pyroclastic origin of such rocks could be accounted for at the genetic stage (Stage 5) of the scheme (e.g. clastogenic lava lake). Incorrect application of the term "coherent kimberlite" to rocks can result from the lack of recognition of pyroclastic or volcaniclastic features, in some instances as a consequence of alteration.

The term "volcaniclastic" is applied to rocks composed of a substantial proportion of volcanic particles with no implied clast-forming, transport and depositional process or environment. The term "volcaniclastic" is preferred to "fragmental" as used synonymously by Cas et al. (2008, 2009). The term "fragmental" as applied to a rock or texture has many meanings and thus can be confusing. Primary volcanic and sedimentary processes combine to generate diverse volcaniclastic deposits and rocks. Volcaniclastic kimberlites commonly contain melt-bearing pyroclasts and/or pyrocrysts (±xenoliths and crystals from wall rocks and surficial deposits) set in an interclast cement (e.g. Fig. 2c, d) or clastic matrix of fine-grained particles. Less commonly observed diagnostic constituents of volcaniclastic kimberlites include epiclasts and both pyroclastic and sedimentary accretionary clasts. Incorrect application of the term volcaniclastic kimberlite can result from misinterpretation of patchy or domainal textures resulting from alteration of coherent rocks.

Stage 3*b*. This stage involves more detailed classification of the type of coherent or volcaniclastic rock, where there is sufficient evidence to do so.

Coherent kimberlite. Coherent kimberlite can be subdivided into intrusive or extrusive types (Table 1). In most cases, this designation requires knowledge of the context and contact relationships. Most extrusive coherent rocks are lavas. "Hypabyssal" refers to an intrusive body formed at a shallow, but undefined, depth below the Earth's surface and is commonly applied to rocks forming volumetrically minor intrusions (e.g. plugs, sheets; Fig. 5); this usage is consistent with that of igneous petrological nomenclature. The term "coherent" is implicit in usage of "hypabyssal".

Intrusive coherent rocks also occur as higher level late-stage intrusions of kimberlite into broadly coeval volcaniclastic deposits. In this case the term "hypabyssal" might not apply.

Volcaniclastic kimberlite. As shown in Table 1, volcaniclastic kimberlite is subdivided into pyroclastic kimberlite (formed from explosive volcanic eruptions, deposited or emplaced by primary pyroclastic processes and displaying no evidence for resedimentation), resedimented volcaniclastic kimberlite (formed by sedimentary re-deposition of unconsolidated pyroclastic and other surface materials) and epiclastic volcanic kimberlite (consolidation of detritus containing epiclasts derived from exposed lithified volcanic kimberlite by surface processes). Pyroclastic kimberlite can be subdivided into two classes with newly recommended names based on their type areas: Kimberley-type pyroclastic kimberlite (formerly tuffisitic kimberlite) and Fort à la Corne-type pyroclastic kimberlite (formerly pyroclastic kimberlite, e.g. Scott Smith 2008a, b). Each class encompasses a variety of textural rock types characterised by a set of unifying textural and component features. Fort à la Corne-type pyroclastic kimberlites (e.g. Fig. 2c, d) are in many aspects comparable to certain basaltic pyroclastic rocks but many display kimberlite-specific characteristics. One example is the common occurrence of discrete crystals interpreted to be liberated olivine pyrocrysts (Fig. 3e). The Kimberley-type pyroclastic kimberlites are distinctive and have been well described in many kimberlite bodies (e.g. Fig. 2b; Table 1 of Hetman 2008; Mitchell et al. 2009). Their occurrence has been repeated in time and space and in different settings, They are typically spatially separate from Fort à la Corne-type pyroclastic kimberlites and have no counterparts formed from other, more common magma types. The differences between the two classes of pyroclastic kimberlite are very relevant to the economic evaluation of kimberlites (e.g. Fig. 1a, c). Resedimented volcaniclastic kimberlites contain pyroclastic components and typically comprise an admixture of non-kimberlitic extraneous material in addition to fine particles produced by abrasion. The interclast matrix of resedimented volcaniclastic kimberlites is commonly clastic but cement can also occur. Epiclastic volcanic kimberlites are not commonly found. If no volcanic constituents are present or recognised among the kimberlitic constituents (e.g. the kimberlitic epiclasts could be derived from exposed hypabyssal kimberlite), then the rock is termed an epiclastic kimberlite.

Stage 4: Intrusive/Volcanic Spatial Context

Stage 4 incorporates an assessment of the spatial relationship to, and the morphology of, the kimberlite body from which the rocks under investigation derive (Fig. 5). This requires larger scale observations and is typically based on drilling and/or mapping information. Kimberlite bodies include volcanic pipes and sheet-like or tabular bodies. Most tabular kimberlite bodies are intrusive sheets (Fig. 5c) which can be described as vertical, horizontal or inclined and referred to as dykes and sills when determined to be discordant or concordant, respectively. Other sheet-like bodies could occur and include extrusive coherent kimberlite sheets or lavas (possible examples are poorly documented) as well as tabular extra-crater deposits of volcaniclastic kimberlite. For pipe-like bodies, simple descriptors such as steep-sided, flared, inclined or irregular can be added. General descriptors (e.g. upper, middle, lower zones) can be used to describe different parts of pipes. Where relevant, pipes can also be subdivided into different more specific pipe zones: crater, diatreme and root (Fig. 5). Diatreme zone describes the steep-sided portion of a pipe that can occur below a crater (Fig. 5b) and, where present, above a root zone (Fig. 5c). These terms should only be used in a strictly descriptive sense to designate the morphology and relative vertical location of the portion of the body being described. Pipe zone terms should not be used to denote a specific process of formation or type of infill material. Thus, in contrast to previous usage (e.g. diatreme-facies of Clement and Skinner 1985), the term diatreme is not restricted to Kimberley-type pipes or their infill. The term diatreme can be applied to any steep-sided pipe zone irrespective of the nature of the infill. Example terms describing both the pipe zone and nature of the infill include diatreme-fill resedimented volcaniclastic kimberlite and diatreme-fill Kimberley-type pyroclastic kimberlite (which describe parts of Fig. 1b and c, respectively; see also example names in Stage 4 of Table 1 and Fig. 2).

Stage 5: Genetic/Process Interpretation

Stage 5 involves advanced interpretation of the rock formation process by integrating the information obtained in Stages 1–4 and, in most cases, relies on increased sample density and level of investigation. The results are combined into a genetic rock name (e.g. Stage 5 in Table 1 and Fig. 2). Interpretations are based on well-established intrusive and volcanic processes and products described in various standard texts, many of which also apply to kimberlite bodies. The unusual characteristics of kimberlite magmas, however, result in certain apparently unique kimberlite-specific rock types. Also, most kimberlite studies focus on subsurface rocks which can be expected to involve processes and products that are not well known. In many cases, the interpretations made in Stage 5 are subjective, considered to be lower confidence than those made in previous stages or can reveal more than one potentially valid