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MINERALOGY AND GEOCHEMISTRY OF CALCRETES OVERLYING SOME KIMBERLITES IN INDIA AND SOUTH AFRICA

B. Singh and M. Cornelius

CRC LEME OPEN FILE REPORT 187

March 2005

(CRC LEME Report 134R / CSIRO Exploration and Mining Report 710R,
2nd Impression 2005.)

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CRC LEME is an unincorporated joint venture between CSIRO-Exploration & Mining, and Land & Water, The Australian National University, Curtin University of Technology, University of Adelaide, Geoscience Australia, Primary Industries and Resources SA, NSW Department of Mineral Resources and Minerals Council of Australia.

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MINERALOGY AND GEOCHEMISTRY OF CALCRTES OVERLYING SOME KIMBERLITES IN INDIA AND SOUTH AFRICA

Balbir Singh

CRC LEME Restricted Report 134 / E&M Report 710R

April 2000

ASTRO YILGARN REGOLITH PROJECT
Diamond Exploration in Regolith-Dominated Terrain, Yilgarn Craton, Western Australia

CRC LEME is an unincorporated joint venture between the Australian National University, University of Canberra, Australian Geological Survey Organisation and CSIRO Exploration and Mining. Headquarters:- CRC LEME c/o CSIRO Exploration and Mining, Private Mail Bag 5, Wembley 6913, Western Australia.

PREFACE

The Astro Yilgarn Regolith Project - Diamond exploration in regolith-dominated terrain, Yilgarn Craton, Western Australia - was sponsored solely by Astro Mining N.L- and was completed in January 2000. The principal objective of the project was to develop concepts, methods and technologies for locating diamond-bearing pipes (and associated regolith deposits) in the Yilgarn Craton, with the approach emphasizing regolith-landscape evolution. The specific objectives were (i) to establish a regional overview and framework of the geomorphic history and landform evolution of the Yilgarn Craton relevant to the project objectives, (ii) to establish district-scale frameworks of regolith relationship (mapping, stratigraphy and characteristics) for key tenements of Astro Mining, (iii) to establish through orientation, modeling and deduction, geochemical and mineralogical exploration methods optimized to the chosen regolith-landform regimes, and (iv) to translate research findings into practical exploration techniques to be applied by the Astro Mining exploration team.

During the project, Astro Mining collected calcretes overlying a number of kimberlites in India and South Africa. These were made available to CRC LEME for a detailed study. The principal objectives of the study were to characterise these calcretes, understand mechanism of their formation, and identify any characteristics that can be attributed to the parent kimberlitic material. This report summarises characteristics of the kimberlitic calcretes and discusses relevance of calcretes in general for kimberlite exploration.

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1.0 INTRODUCTION

1.1 Relevance of calcrete to diamond exploration

Calcretes occur extensively in the arid parts of the Yilgarn craton of Western Australia and in other parts of the world with similar climatic conditions (Milnes and Hutton, 1983). Two general types of calcretes have been recognised in the Yilgarn: groundwater and pedogenic calcretes (Mann and Horwitz, 1979; Anand et al., 1997). The groundwater calcretes are massive, tabular carbonate bodies that form in arid areas with periodic recharge of the groundwater system (Mann and Horwitz, 1979). Consequently, they are generally associated with present drainages and paleodrainages, and are common in the Yilgarn, particularly about 30° north of the Menzies line (Butt et al., 1977). Geomorphic setting and climatic conditions, rather than bedrock geology, appear to play a dominant role in the development of groundwater calcretes.

In contrast, pedogenic calcretes are carbonate accumulations that form in soil profiles as nodules, cobbles, pods and sheets. They occur in a variety of geomorphic settings, including relict, erosional and depositional areas on various bedrock types. However, they are generally more abundant in erosional regimes on mafic and ultramafic rocks (Anand et al., 1997), indicating that pedogenic calcretes receive a significant proportion of cations, and possibly anions, from weathering of underlying bedrock. It is, therefore, likely that pedogenic calcretes, developed from a weathered alkaline ultramafic, may have unique mineralogical and/or geochemical characteristics inherited from the parent body.

Calcretes also have the capacity to indurate and trap components of the soil matrix, fresh rock fragments and/or discrete minerals, and protect them from weathering. Bulk geochemistry and petrographic characteristics of inclusions can readily indicate the bedrock type. Thus, calcretes may serve as a potential sampling medium for kimberlite exploration.

1.2 Objectives of the study

The objectives of this study were to (i) investigate the geochemistry, mineralogy and fabric of calcretes developed on weathered kimberlites in India and South Africa, (ii) understand the mechanism of their formation and (iii) identify any characteristics that can be attributed to the kimberlitic nature of their parent material.

2.0 SAMPLE LOCATIONS AND PREPARATION

2.1 Sample locations

Astro Mining sampled calcretes from the surface of several kimberlitic bodies in India and Africa. Hand specimens, varying in size from 50 to 100 mm, were made available to CRC LEME for a detailed study. Sample locations, as received from Astro Mining, are given in Table 1.

A representative set of calcretes from the Merredin region in the Yilgarn, developed mainly on granitic and mafic lithologies, was also included to provide comparative petrographic data. For geochemical comparison, summary statistics of 250 calcrete samples from the Merredin region was used.

2.2 Sample preparation

Samples were split into three parts. One part was retained for reference, another used for preparation of petrographic thin sections and polished blocks, and the remaining portion was pulverised to <75 μm in a case hardened carbon steel ring mill (Robertson et al., 1996) for geochemical and mineralogical analyses.

Polished blocks and thin sections on glass slides were prepared for petrographic analysis in transmitted and reflected light to obtain information on fabric and mineralogy. The blocks and thin sections were polished to a sub-micron finish.

Table 1. Location of calcrete and rock samples received from Astro Mining.

CSIRO No.	Original No.	Field ID/ Pipe	Date	Longitude	Latitude	Country
121323	IARG 80000	MK-1	12/2/98	77.06406	16.82418	
121324	IARG 80001	MK-2A	12/2/98	77.63987	16.83508	
121325	IARG 80002	MK-2B	12/2/98	77.63987	16.83508	
121326	IARG 80003	MK-3	12/2/98	77.64132	16.83602	
121327	IARG 80004	MK-5	12/2/98	77.59496	16.84056	
121328	IARG 80005	NK-1A	12/2/98	77.49637	16.77182	
121329	IARG 80006	NK-1B	12/2/98	77.49637	16.77182	
121330	IARG 80007	CC-1A	13/2/98	77.69825	14.52681	
121331	IARG 80008	CC-1B	13/2/98	77.69825	14.52681	
121332	IARG 80009	CC-2A	13/2/98	77.6808	14.52565	
121333	IARG 80010	CC-2B	13/2/98	77.6808	14.52656	India
121334	IARG 80011	CC-5A	13/2/98	77.63639	14.51912	
121335	IARG 80012	CC-5B	13/2/98	77.6393	14.51912	
121336	IARG 80013	Granite	13/2/98	77.68613	14.51898	
121337	IARG 80014	Pipe-2	13/2/98	77.40802	15.02509	
121338	IARG 80015	Pipe-10A	13/2/98	77.50567	14.99029	
121339	IARG 80016	Pipe-10B	13/2/98	77.50567	14.99029	
121240	IARG 80017	Pipe-10C	13/2/98	77.50567	14.99029	
121341	IARG 80018	Pipe-10D	13/2/98	77.57967	14.99029	
121342	IARG 80019	MK-8	13/2/98	77.57967	16.87124	
121343	IARG 80020	CC-5C	13/2/98	77.63639	14.51912	
121344	IARG 80021	Bahradih	17/2/98	82.2012	20.2153	
121302	NAR-72000	H-2-A	8/3/1998	-25.25103	17.69493	
121303	NAR-72001	H-2-B	8/3/1998	-25.25103	17.69493	
121304	NAR-72002	H-2-C	8/3/1998	-25.25103	17.69493	
121305	NAR-72003	H-1-A	8/3/1998	-25.24068	17.707	
121306	NAR-72004	H-1-B	8/3/1998	-25.24068	17.707	
121307	NAR-72005	H-1-C	8/3/1998	-25.24068	17.707	
121308	NAR-72006	B-H-1	9/3/1998	-25.93329	17.79308	
121309	NAR-72007	B-H-2	9/3/1998	-25.93329	17.79308	
121310	NAR-72008	B-H-3	9/3/1998	-25.93329	17.79308	
121311	NAR-72009	B-H-4	9/3/1998	-25.93329	17.79308	
121312	NAR-72010	B-H-5	9/3/1998	-25.93065	17.79536	Namibia
121313	NAR-72011	B-H-6	9/3/1998	-25.93061	17.79457	
121314	NAR-72012	B-H-7	9/3/1998	-25.93061	17.79457	
121315	NAR-72013	Garub-29	10/3/1998	-27.46272	18.9818	
121316	NAR-72014	Garub-29b	10/3/1998	-27.4647	18.98229	
121317	NAR-72015	Garub-14	10/3/1998	-27.46673	18.97725	
121318	NAR-72016	Garub-14/23	10/3/1998	-27.46635	18.97523	
121319	NAR-72017	Garub-14/23	10/3/1998	-27.46635	18.97523	
121320	NAR-72018	Stinkdorm	10/3/1998	-27.61655	19.0592	
121321	NAR-72019	Ondermatje-1	10/3/1998	-28.36532	19.43452	
121322	NAR-72020	Ondermatje-1	10/3/1998	-28.36532	19.43452	

3.0 ANALYTICAL PROCEDURES

3.1 Multi-element geochemical analysis

X-ray fluorescence (XRF) analysis was conducted on fused powders in the CSIRO laboratories, Floreat Park for the following elements. Detection limits, in percent for oxides and parts per million for trace elements, are given below in brackets.

Al_2O_3 (0.01),	CaO (0.001),	K_2O (0.01),	MgO (0.01),	MnO (0.002),
Na_2O (0.01),	P_2O_5 (0.002),	SiO_2 (0.01),	TiO_2 (0.003),	Ba (20),
Cl (20),	Ce (15),	Cr (10),	Cu (10),	Ga (3),
La (10),	Ni (10),	Nb (4),	Pb (5),	Rb (5),
S (10),	Sr (5),	V (5),	Y (5),	Zn (5),
Zr (5).				

3.2 X-ray diffraction

XRD patterns of the powdered samples were obtained using Cu Kα radiation on a Philips PW1050 vertical diffractometer, fitted with a graphite diffracted beam monochromator. Samples were scanned over a 2θ range of 3-65° at a scan speed of 1°/min, and diffraction intensities were recorded at 0.02° intervals. The relative proportions of constituent minerals were estimated from the intensities of their major diffraction peaks and the chemical composition of the sample.

3.3 Petrography and scanning electron microscopy

Polished blocks and thin sections were examined in reflected and transmitted light to obtain information on mineralogy and internal fabrics. Selected samples were further investigated using a JEOL Geo SEM-2 scanning electron microscope for qualitative chemical analysis of discrete minerals and for investigating morphological features identified in the polished blocks and thin sections.

4.0 RESULTS AND DISCUSSION

4.1 Indian calcretes

4.1.1 Overall mineralogy

Calcretes over Indian kimberlites consist mainly of calcite and dolomite with small amounts of serpentine and smectite (Table 2). Quartz, a common constituent of calcretes on the Yilgarn, is almost absent in the Indian kimberlitic calcretes.

4.1.2 Petrography

Hand specimens of Indian calcretes show a variety of morphologies including nodular, massive and friable, and contain abundant large inclusions of saprolite and rock fragments (Figure 1). The wide range of morphology is due partly to random sampling from the surface and the different geomorphic setting of each location. Inclusions of rock and saprolite fragments indicate that some of the calcretes have developed in the saprolite of shallow weathered profiles.
High magnification images of polished blocks and thin sections show that most Indian kimberlitic calcretes contain abundant grains of primary minerals (Figure 2, 3). In some, smectite pseudomorphs after olivines are present.

Back-scattered scanning electron microscopy and qualitative chemical analysis of the resistant mineral grains reveal that grains encapsulated within the calcretes include chromite, ilmenite, perovskite and apatite (Figure 4). Size of the primary mineral grains varies from 2 to 200 μm.

In general, the samples with high concentrations of Ti, P, Nb and Cr (Table 3) contain abundant grains of perovskite, apatite, ilmenite and chromite, whereas samples poor in these elements (Samples 80016, 80017) have fewer and smaller grains of these minerals. In contrast to kimberlitic calcretes, the calcretes developed from granitic parent materials are free of primary heavy minerals. Precipitates of secondary barite, however, are present in some (Figure 5).

In some kimberlitic calcretes, dolomite appears to have replaced smectite pseudomorphs and ground mass smectite, whereas calcite occurs as an invading phase precipitated in existing pores and voids (Figure 4).

Table 2. Semi quantitative bulk mineralogical analysis of calcrete samples from India.

Sample No.	Calcite	Dolomite	Smectite	Serpentine
80001	major	traces	minor	traces
80002	major	traces	minor	traces
80003	major	minor	minor	traces
80005	major	major	minor	traces
80007	major	minor	Traces	traces
80009	major	minor	Traces	traces
80011	major	minor	minor	traces
80013	major	major	traces	nil
80015	major	minor	nil	nil
80016	major	minor	traces	traces
80017	major	traces	nil	nil
80018	traces	major	minor	nil
80020	traces	major	minor	nil

4.1.3 Major elements

The chemical analyses of Indian kimberlitic calcretes, along with summary statistics of the Merredin granitic calcretes for comparison, are given in Table 3. Silica contents in Indian calcretes vary from 4 to 18%, depending on the abundance of smectite and serpentine minerals since quartz is almost absent. The mean SiO_2 content in Merredin calcretes is about 20%, mainly contributed by quartz present in the calcrete nodules.

The Al content is low, compared to granitic calcretes, mainly due to the absence of kaolinite and Al-bearing smectite which are common accsessory phases in the granitic calcretes. The Fe_2O_3 content varies from 0.6 to 6.5% and appears to be assocated with the Fe-smectite, nontronite.

The Ca and Mg contents of the Indian calcretes vary from 25 to 49% CaO and from 2 to 20% MgO. Calcium and Mg are present in both carbonate and non-carbonates forms. Thus, Ca and Mg contents do not directly the reflect abundance of calcite and dolomite in the calcretes. The Ca content of kimberlitic calcretes is significantly greater than that of granitic calcretes due to absence of quartz.

4.1.4 Alkaline ultramafic indicator elements

Trace elements are discussed in two groups: The first group of elements are strong indicators of ultramafic rocks and include Cr, Cu, Ni, Co, and Zn. The second group of elements reliably distinguishes alkaline from non-alkaline ultramafic rock and includes Nb, P, Ti, Zr and REEs.

Table 3. Chemical composition of Indian kimberlitic calcretes and summary statistics of Merredin calcretes.

		Indian kimberlitic calcretes													*Merredin calcrete statistics; n=250*			
Sample	**Units**	**80001**	**80002**	**80003**	**80005**	**80007**	**80009**	**800011**	**800013***	**800015**	**800016**	**800017**	**800018**	**800020**	**Mean**	Median	90th percentile	99th percentile
SiO_2		7.59	4.77	6.63	18.43	5.37	10.32	8.42	11.93	4.34	4.04	6.38	10.15	11.51	19.89	19.30	27.69	38.65
Al_2O_3		1.38	0.95	1.28	3.22	0.88	2.32	1.25	2.51	0.72	1.08	1.54	1.36	1.42	6.66	6.63	8.95	11.25
Fe_2O_3		5.91	2.44	3.66	6.58	1.54	3.18	3.16	1	0.7	0.6	0.77	1.47	4.45	1.41	1.28	1.95	3.69
MnO		0.11	0.04	0.09	0.06	0.03	0.06	0.05	0.04	0.01	0.01	0.01	0.05	0.04	0.02	0.01	0.03	0.06
MgO		3.52	2.46	5.34	10.42	6.39	9.51	6.25	10.22	3.76	3.18	3.98	19.66	16.24	9.29	10.19	14.82	16.78
CaO	**%**	43.99	48.35	43.52	25.88	43.76	37.73	40.5	33.93	48.14	48.88	46.57	26.35	25.14	26.43	25.55	32.47	36.89
Na_2O		<0.01	<0.01	<0.01	0.25	0.06	0.1	0.11	0.71	0.12	<0.01	0.08	0.09	0.12	0.18	0.16	0.28	0.53
K_2O		0.03	0.07	0.08	0.2	0.1	0.11	0.15	0.31	0.11	0.22	0.39	0.06	0.08	0.50	0.44	0.85	1.27
TiO_2		2.46	1.09	1.43	2.48	0.33	0.42	0.67	0.09	0.05	0.06	0.07	0.19	0.91	0.10	0.10	0.14	0.26
P_2O_5		0.17	0.1	0.13	0.2	0.1	0.12	0.31	0.02	0.11	0.08	0.08	0.3	0.45	0.01	0.01	0.01	0.03
Ba		118	97	171	528	504	338	255	275	778	1000	756	197	228	663	394	1682	3258
Ce		84	39	51	109	30	49	91	36	65	60	56	106	127	13	18	52	75
Cr		370	144	195	457	153	170	335	15	86	57	62	242	450	65	60	101	146
Co		51	20	39	26	14	21	21	<10	<10	<10	<10	16	15	<10	<10	<10	13
Cu		54	24	38	58	16	28	26	<10	<10	<10	<10	10	44	<10	<10	<10	29
La		49	25	30	63	25	27	62	32	56	60	52	82	116	136	104	264	511
Ni		304	158	208	316	174	256	232	24	116	68	74	206	274	<10	<10	15	45
Nb	**ppm**	60	29	35	68	17	17	52	<4	34	21	21	71	78	5	5	8	11
Pb		<5	<5	<5	<5	<5	<5	5	<5	6	7	6	5	5	19	15	37	56
Rb		<5	<5	7	14	10	15	9	16	6	11	16	<5	<5	28	23	50	89
Sr		283	251	392	762	575	480	710	1387	270	318	384	710	1418	916	905	1282	1526
V		72	48	66	82	20	66	38	28	12	12	14	22	34	26	23	38	64
Y		7	<5	5	9	<5	7	9	11	<5	<5	5	7	21	65	51	129	284
Zn		35	21	23	32	<5	22	28	11	<5	<5	<5	18	43	6	5	10	28
Zr		105	61	89	145	39	76	95	17	21	21	29	49	135	63	58	99	214
Total		65.2	60.2	62.2	67.7	58.6	63.9	60.9	60.8	58.1	58.1	59.9	59.7	60.4	65	64	70	74

* Granitic calcrete from the same general area as Indian kimberlitic calcrete.

In comparison to the granitic calcretes from Merredin, the Indian kimberlitic calcretes consistently contain greater concentrations of the first group of elements (Cr, Cu, Ni, Co and Zn) (Table 3). Chromite and smectite, indentified in most samples, appear to host these elements.

Compared to granitic calcretes, the kimberlitic calcretes also contain greater concentrations of most of the second group elements, including P, Nb, Ce and Zr. Concentrations of P and Nb in kimberlitic calcretes are several times greater than those in granitic calcretes. Phosphorus is hosted by apatite, and Nb, Ce and Zr probably by perovskite and ilmenite. Sample 8001, 8002, 8003 and 8020 are particularly rich in Ti, Cr and P. These samples contain abundant grains of perovskite, ilmenite, chromite and apatite.

Concentrations of La, Ba and Sr show erratic patterns and are generally less than those in Merredin calcretes.

The samples containing dolomite and smectite are generally rich in Cr and Ni, probably due to association of these elements with smectite.

Sample No. 8013 is a granitic calcrete from the same general area as the Indian kimberlitc calcretes. It has significantly lower concentrations of both groups of elements. Lanthanum concentrations are, however, comparable with those of some kimberlitic calcretes.

4.1.4 Other elements

Concentrations of Ga and Pb are generally lower than those of granitic calcretes, possibly due to greater abundance of these elements in the granitic source rocks and their weathering products. The concentrations of all other trace elements in Table 3 either show no consistent pattern or are below detection limit for both populations.

4.2 African calcretes

4.2.1 Bulk mineralogy

Calcite is also the dominant carbonate in most African kimberlitic calcretes (Table 4). A few consist of only dolomite with no or minor calcite. In contrast to the Indian calcretes, quartz is present in most as a minor component and traces of smectite and mica occur in some. Calcretes dominated by dolomite also contain significant amounts of smectite, similar to Indian kimberlitic calcretes.

4.2.2 Petrography

Photographs of hand specimens and polished sections of a representative set of African kimberlitic calcretes are shown in Figure 6. Similar to Indian calcretes, the African kimberlitic calcretes display a variety of morphologies, including nodular and massive, and contain abundant large inclusions of

Table 4 Mineralogical composition of the African kimberlitic calcretes.

Sample no.	Quartz	Calcite	Dolomite	Smectite	Mica
121303	minor	minor	major	traces	traces
121304	minor	-	major	traces	traces
121306	-	-	major	minor	-
121307	minor	-	major	minor	traces
121308	minor	major	-	-	traces
121312	minor	major	-	-	traces
121314	minor	major	-	-	traces
121316	minor	major	-	-	traces
121317*	-	minor	major	-	-
121319	minor	major	-	-	traces
121320	major	minor	-	-	-
121321	mnor	major	-	-	traces

*The sample also contains primary minerals not listed here.

saprolite and primary rock fragments.

SEM images of all calcretes show some evidence of their kimberlitic source materials, including primary minerals such as chromite, ilmenite, perovskite, apatite, and pseudomorphs of large mica grains (Figure 7, 8). The primary minerals are particularly abundant in samples 12306, 12307, 12308, 121314 and 121320.

4.2.3 Major elements

Chemical analyses of African kimberlitic calcretes, and summary statistics of the Merredin granitic calcretes, are given in Table 5. The Si content in the African calcretes varies from about 8 to 55% SiO_2, a major portion of which is contributed by quartz and a small portion by smectite and mica.

As in the Indian calcretes, the Al content of African calcretes is low compared to Merredin granitic calcretes. The Fe_2O_3 content is also low in most African calcretes and appears to be assocated with Fe-smectite and/or mica. Calcium and Mg contents of the African calcretes vary from 15 to 45% CaO and from 2 to 17% MgO, generally in the same range as Indian calcretes.

4.2.4 Alkaline and ultramafic indicator elements

In comparison to the granitic calcretes, the African kimberlitic calcretes contain, with few exceptions, more Cr, Cu, Ni, P, Ce, Nb and Zr, and less Ga, La and Pb. Barium and Sr concentrations show an inconsistent pattern but are of the same order as the Merredin granitic calcretes.

Exceptionally high concentrations of indicator elements in sample 121317 are due to fresh rock material in the calcrete. Sample 121316 contains the lowest concentrations of Ni, Cu, and Cr. However, it can still be distinguished from the granitic calcretes on the basis of high P and Nb, and low Al, Ga, La and Pb concentrations.

Samples 121306 and 12307 contain more Cr, Ni, and Cu, which appears to be due to a higher smectite content in these samples. The samples with abundant primary minerals (sample number given above) are rich in Ti, Nb, Cr and P. A qualitative assessment suggests that the bulk of the trace element content, particularly in samples free of smectites, is hosted by discrete mineral grains rather than carbonates.

5.0 DISCUSSION

Calcretes investigated in this study were collected from soils and saprolite overlying kimberlites. In most cases, the kimberlitic rocks were exposed at the surface as rubble, suggesting that the kimberlites were located in an erosional area, with only a shallow weathered profile.

Field morphology and mineralogy of kimberlitic calcretes from both India and Africa are largely similar to granitic calcretes of the Merredin region (Figure 9) and are indistinguishable from that of granitic calcretes unless large inclusions of fresh material are present.

Calcite and dolomite are the only carbonate minerals in the kimberlitic calcretes from both India and Africa. These minerals are common in calcretes derived from a variety of lithologies under different physiographic settings (Anand et al., 1997). Thus, these carbonate minerals, or their ratios, do not provide any indication of their kimberlitic origin. Some kimberlitic calcretes contain serpentine, which suggests that they developed from saprolite of a mafic/ultramafic parent.

Chromium, Cu, Ni, Zn, P, Nb, Ce and Zr in the kimberlitic calcrete are significantly more abundant than in granitic calcretes. Concentrations of these elements, or their ratios, can readily distinguish kimberlitic from non-kimberlitic calcretes. The Nb and P of kimberlitic calcretes are particularly useful as their concentrations are greater than the 99^{th} percentile of the Merredin calcretes. Niobium correlates well with TiO_2 (Figure 10), confirming that it is hosted by Ti-bearing mineral(s) such as perovskite and ilmenite.

Lanthanum concentrations in the kimberlitic calcretes are generally less than in the Merredin calcretes, while Ba and Sr concentrations vary erratically. These elements are unsuitable for distinguishing kimberlitic calcretes from granitic calcretes.

Table 5 Chemical composition of African kimberlitic calcretes and summary statistics of Merredin calcretes.

	South African kimberlitic calcretes												**Merredin calcrete statistics; n=250**			
Ident	**121303**	**121304**	**121306**	**121307**	**121308**	**121312**	**121314**	**121316**	**121317**	**121319**	**121320**	**121321**	**Mean**	Median	90th percentile	99th percentile
SiO_2	19.35	16.43	15.28	15.740	20.52	16.40	17.15	10.33	27.11	23.6	55.7	8.19	19.89	19.30	27.69	38.65
Al_2O_3	2.0	1.9	2.5	2.0	2.2	2.2	2.4	1.7	7.1	3.2	5.5	1.4	6.66	6.63	8.95	11.25
Fe_2O_3	1.7	1.7	2.9	1.9	2.6	2.2	2.7	1.1	7.1	2.1	3.2	1.9	1.41	1.28	1.95	3.69
MnO	0.03	0.02	0.10	0.14	0.03	0.03	0.04	0.02	0.22	0.03	0.09	0.03	0.02	0.01	0.03	0.06
MgO	14.8	16.3	17.5	17.2	3.0	2.1	2.3	2.4	6.8	1.8	0.8	2.7	9.29	10.19	14.82	16.78
CaO	24.9	24.9	24.0	24.0	36.7	40.3	39.1	44.3	19.7	36.0	15.8	45.3	26.43	25.55	32.47	36.89
Na_2O	0.14	0.19	0.22	0.25	0.13	0.19	0.14	0.02	3.61	0.30	1.46	0.19	0.18	0.16	0.28	0.53
K_2O	0.48	0.52	0.36	0.34	0.51	0.49	0.52	0.30	0.26	0.65	1.44	0.58	0.50	0.44	0.85	1.27
TiO_2	0.16	0.15	0.26	0.17	0.26	0.19	0.23	0.10	1.28	0.19	0.68	0.21	0.10	0.10	0.14	0.26
P_2O_5	0.08	0.06	0.08	0.02	0.15	0.11	0.19	0.12	0.71	0.16	0.27	0.27	0.01	0.01	0.01	0.03
Ba	765	116	240	128	226	1193	151	208	308	629	464	1177	663	394	1682	3258
Ce	36	33	22	23	44	50	49	39	145	54	84	44	13	18	52	75
Cl	<20	<20	<20	80	<20	<20	<20	<20	<20	<20	100	<20	167	50	400	1287
Cr	175	203	259	481	108	66	83	24	107	41	19	72	65	60	101	146
Co	11	12	24	27	15	11	15	<10	23	<10	10	18	6	6	9	13
Cu	13	10	59	11	80	65	14	<10	236	16	46	23	0	-2	6	29
Ga	3	4	4	<3	<3	3	<3	<3	5	3	4	<3	8	8	11	15
La	<10	21	14	<10	18	16	32	12	64	15	48	17	136	104	264	511
Ni	159	108	271	340	109	60	22	<10	23	15	10	41	4	1	15	45
Nb	21	18	24	22	31	26	35	18	90	17	35	24	5	5	8	11
Pb	<5	<5	<5	<5	<5	7	<5	<5	22	5	19	<5	19	15	37	56
Rb	20	19	11	11	21	16	21	13	<5	24	44	41	28	23	50	89
S	320	100	220	540	260	590	170	170	180	480	160	610	546	480	860	1415
Sr	1073	1041	832	919	488	569	280	268	368	342	203	1042	916	905	1282	1526
V	55	28	56	79	49	39	50	28	122	50	106	46	26	23	38	64
Y	9	15	10	10	15	17	14	9	34	17	19	12	65	51	129	284
Zn	15	15	20	17	22	16	25	12	117	24	26		6	5	10	28
Zr	123	114	86	90	145	151	140	80	266	155	295	153	63	58	99	214
Sum of oxides	63.6	62.3	63.2	61.8	66.1	64.2	64.9	60.4	74.0	68.0	84.8	60.8	65	64	70	74

Both Indian and African kimberlitic calcretes contain varying amounts of smectite and primary minerals including ilmenite, chromite, perovskite and appatite. Samples with high concentrations of indicator elements contain abundant grains of primary minerals; those with low concentrations contain smaller and fewer grains of primary minerals. The primary minerals and smectite appear to account for most of the anomalous trace element content of the kimberlitic calcretes.

The trace element content of calcretes with least primary minerals is similar to or only marginally greater than the median values for the granitic calcretes. It seems that trace elements in kimberlitic calcretes are hosted by enclosed primary minerals rather than by carbonate minerals. The fine-grained nature of primary mineral grains encapsulated in the kimberlitic calcretes precludes separation of pure carbonates for trace element analysis.

6.0 CONCLUSIONS

- The morphology and carbonate mineralogy of kimberlitic calcretes from India and Africa is indistinguishable from those of granitic calcretes in the Yilgarn.
- The kimberlitic calcretes, contain significant amounts of indicator minerals, and therefore are anomalous in Cr, Cu, Ni, Zn, P, Nb, Ce and Zr compared to granitic calcretes in the Yilgarn. There is no evidence of chemical enrichment of anomalous elements in the carbonate phases.
- Inclusion of indicator minerals in kimberlitic calcretes is attributed to development of these calcretes in shallow weathered profiles.
- In the Yilgarn, kimberlitic calcretes containing resistant primary grains may be expected only in erosional areas. In the residual areas, primary minerals are unlikely to survive due to extreme weathering. However, fine-grained weathering products of indicator minerals may be present in calcretes of the residual areas.
- Calcretes formed in transported overburden overlying a weathering kimberlite may not contain anomalous geochemistry even if the bulk of the Ca and Mg is received from the underlying kimberlite.

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8.0 REFERENCES

Anand, R.R., Phang, C., Wildman, J.E. and Lintern, M.J., 1997. Genesis of some calcretes in the southern Yilgarn Craton, Western Australia: implications for mineral exploration. Australian Journal of Earth Sciences 44, 87-103.

Butt, C.R.M., Horwitz, R.C.H. and Mann A.W., 1977. Uranium occurrences in calcretes and associated sediments in Western Australia. CSIRO Australia, Division of Mineralogy, Perth, Report FP16.

Mann, A.W., and Horwitz, R.C., 1979. Groundwater calcrete deposits in Australia: some observations from Western Australia. Journal of Geological Society of Australia, 26: 293-303.

Milnes, A.R. and Hutton, J.T., 1983. Calcretes in Australia. In: Soils: An Australian Viewpoint., 119-162. CSIRO, Melbourne/Academic Press, London.

Robertson, I.D.M., Dyson, M., Hudson, E.G., Crabb, J.F., Willing, M.J. and Hart, M.K.W., 1996. A case-hardened, low contamination ring mill for multi-element geochemistry. Journal of Geochemical Exploration, 57: 153-158.

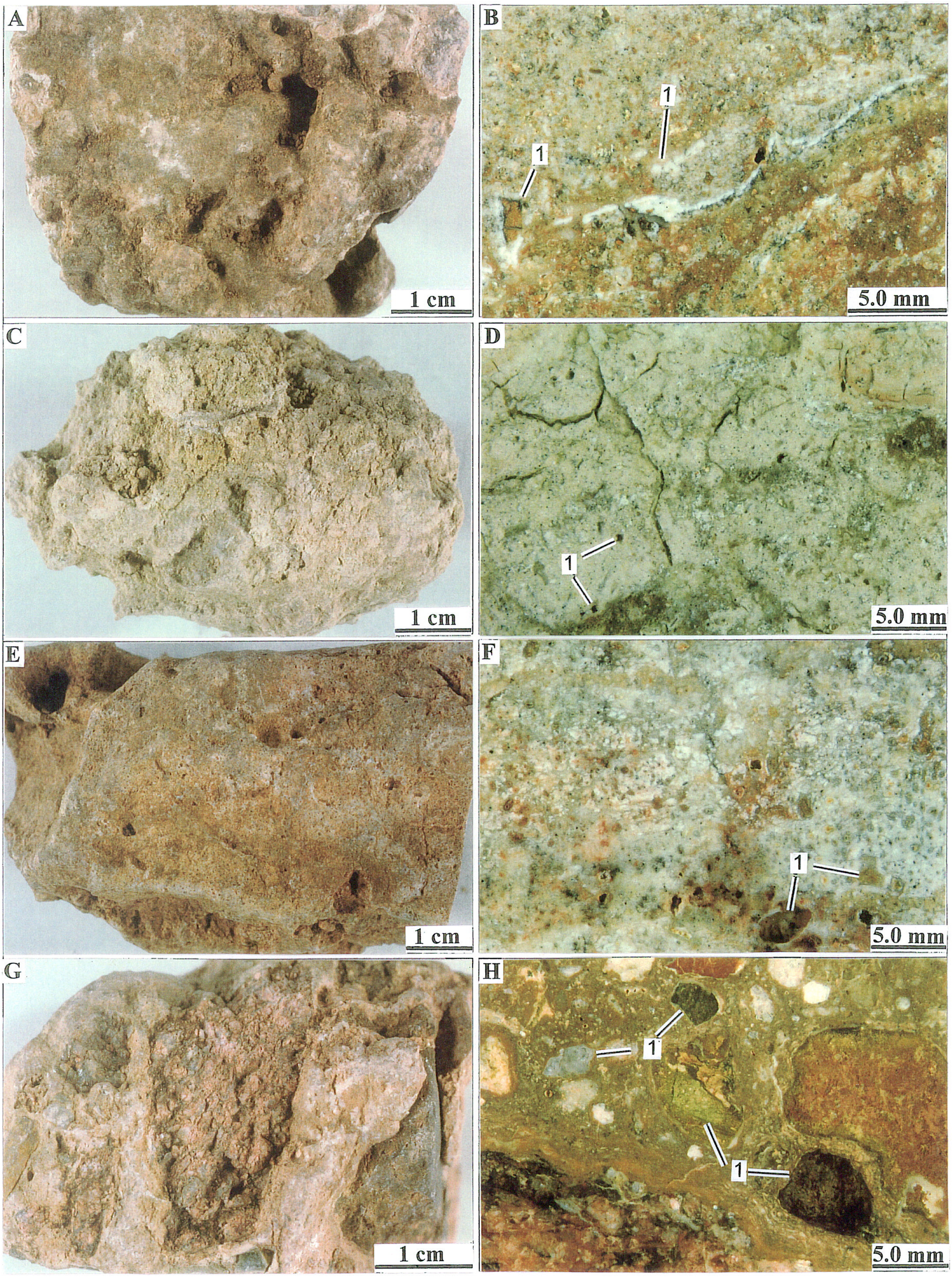


Figure 1. Handspecimens and cross-sections of a representative set of Indian kimberlitic calcretes, showing a variety of morphologies including nodular (A), friable (B) and massive (C). The right hand side column shows cross sections of the calcretes on the left. The cross-sections show a variety of inclusions (1), and their colour ranges from light green to brown.

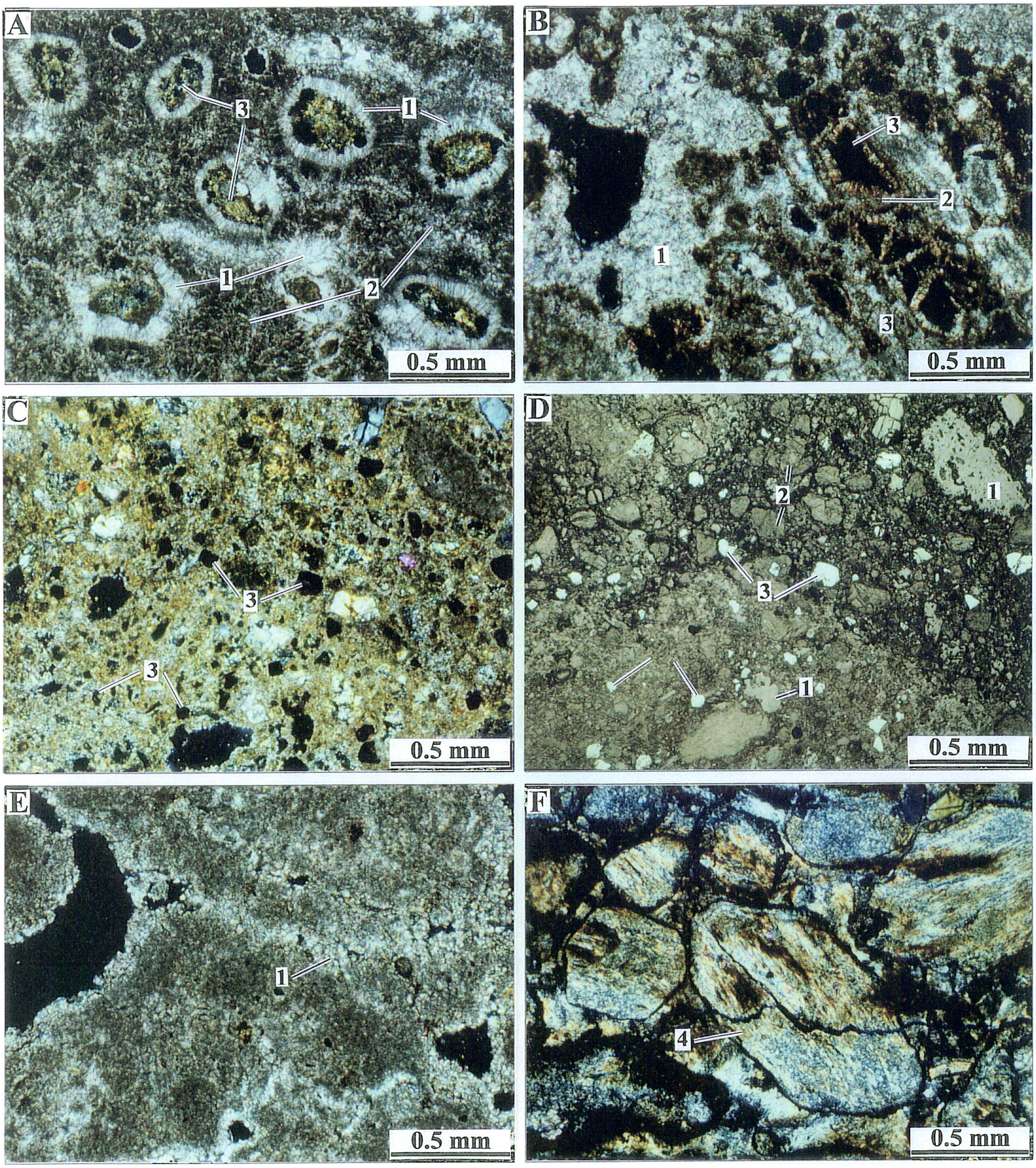


Figure 2. Transmitted and reflected light (D) photomicrographs of the representative Indian calcretes. The micrographs show calcite (1) precipitated in voids and pores in a matrix of dolomite (2). Primary kimberlitic minerals (3) are present in all calcretes overlying kimberlites. The granitic calcrete (E) is massive and lacks resistant primary minerals and pseudomorphs after weatherable minerals. The micrograph (F) shows smectite pseudomorphs (4) after olivine in kimberlitic saprolite.

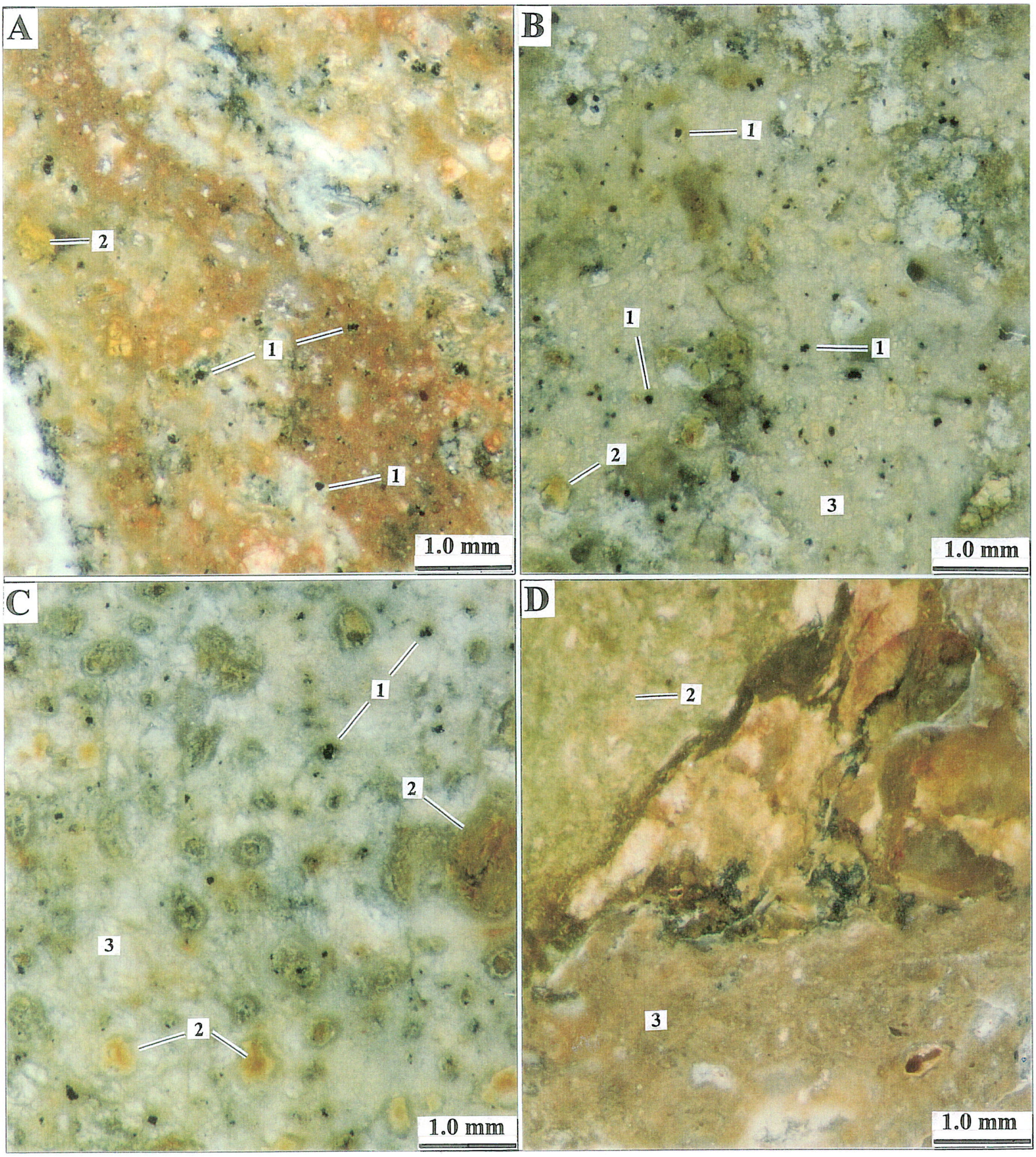


Figure 3. Reflected light photomicrographs of the polished blocks of some Indian calcretes. Abundant primary grains (1) and smectite (2) are present within carbonate matrix (3).

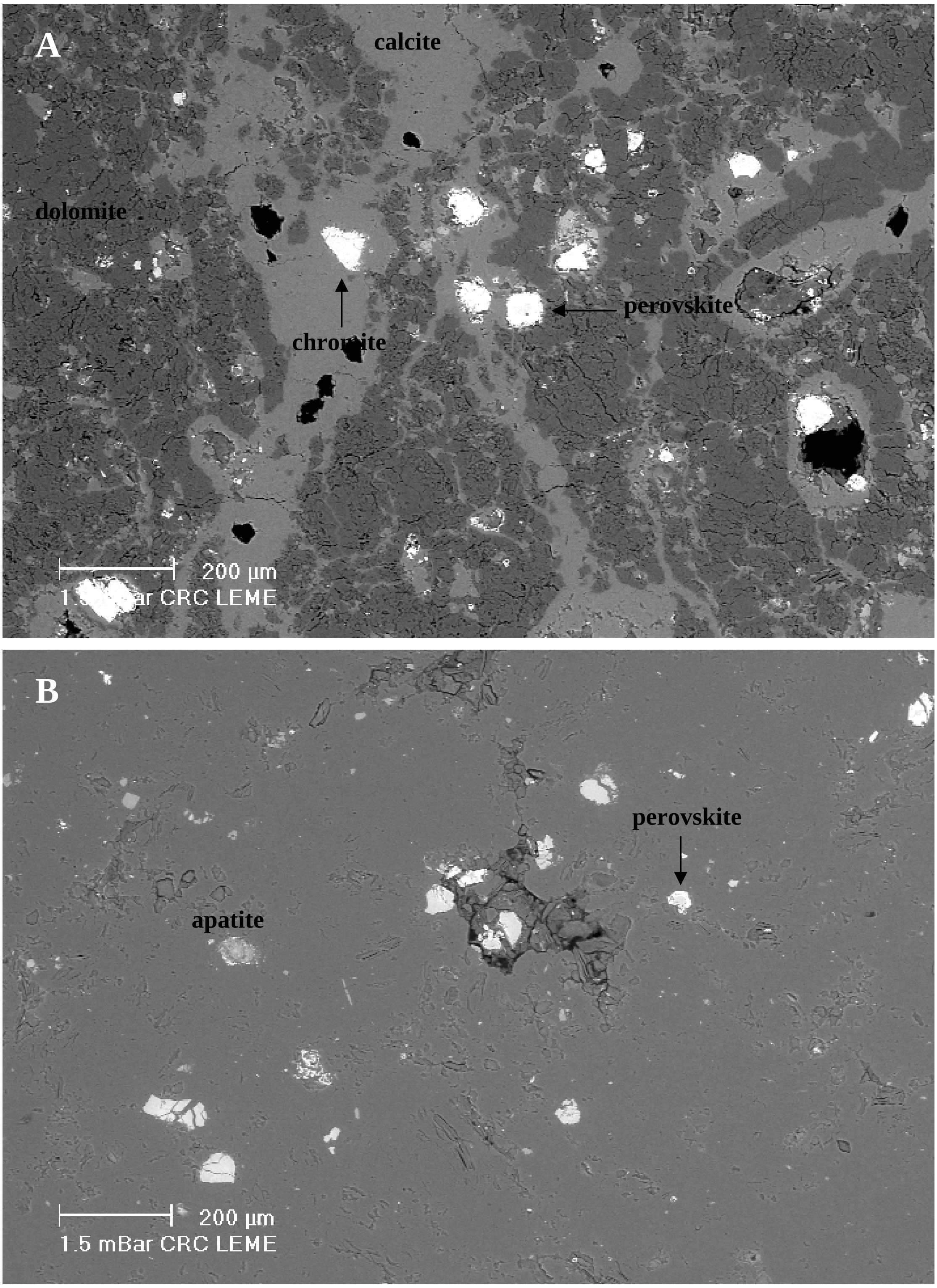
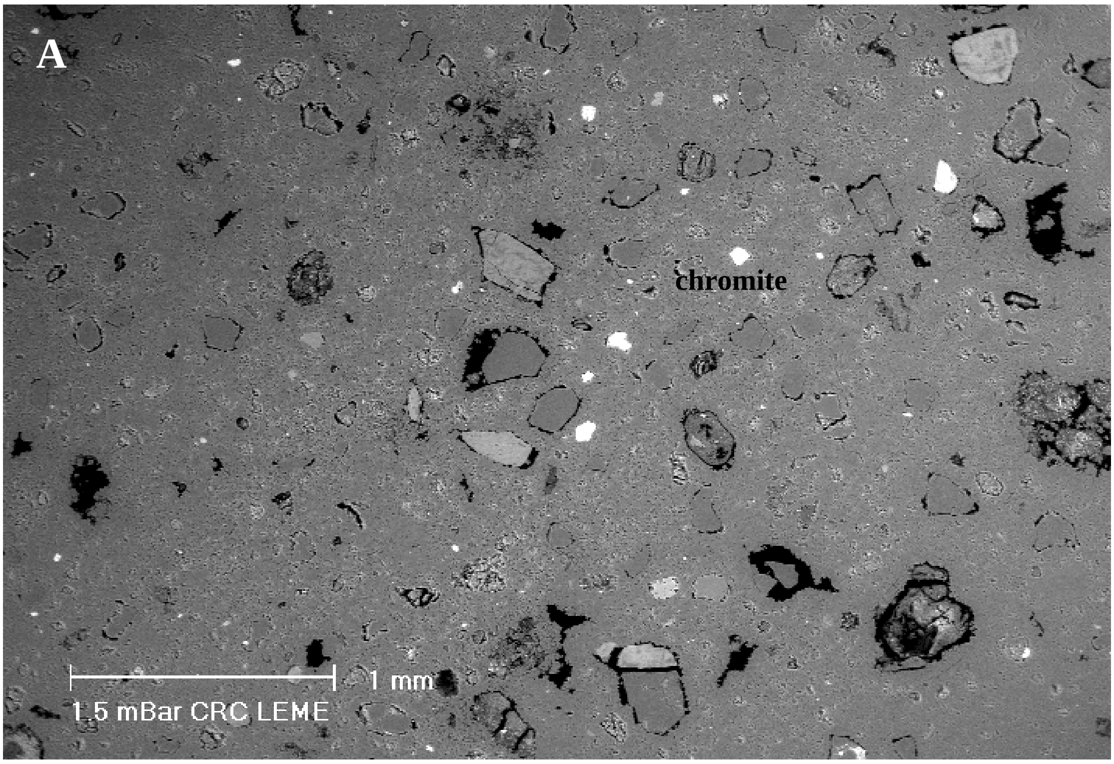


Figure 4. Back scattered electron image of polished sections of sample 80011 and 80020 from India. The micrographs show primary kimberlitic minerals in a matrix of calcite and dolomite.



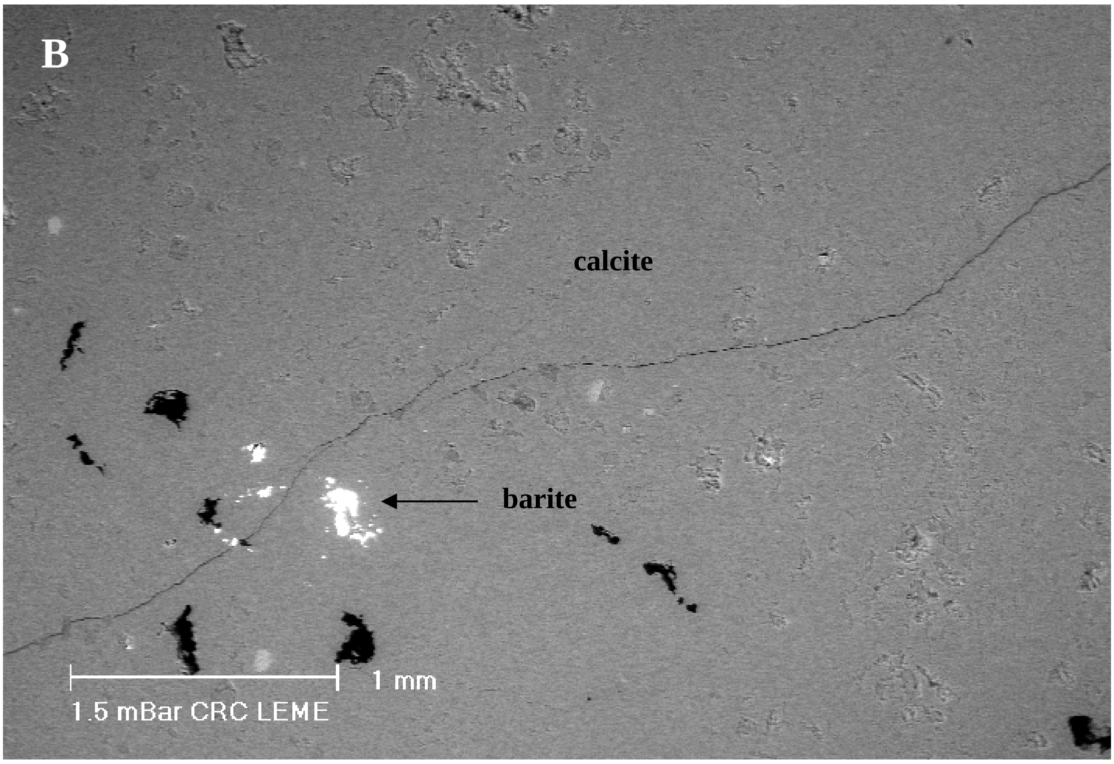


Figure 5. Back scattered electron image of polished sections of a African kimberlitic calcrete (Sample 121303) and a Merredin granitic calcrete.

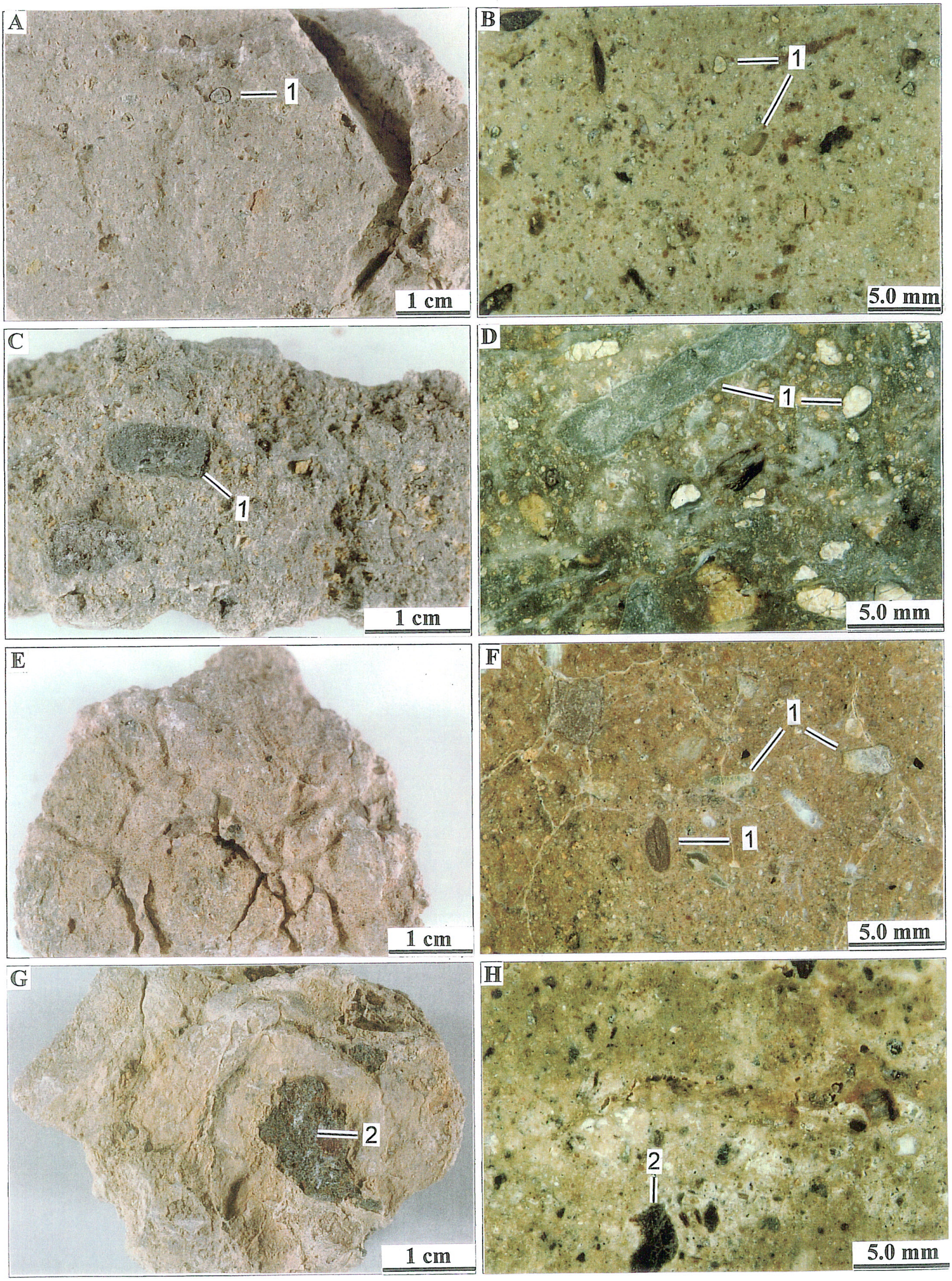


Figure 6. Hand specimens and cross-sections of a representative set of African kimberlitic calcretes. The right hand side column shows cross sections of the calcretes on the left. The cross-sections show abundant inclusions of saprolite (1) and rock fragments (2), and their colour ranges from light green to brown.

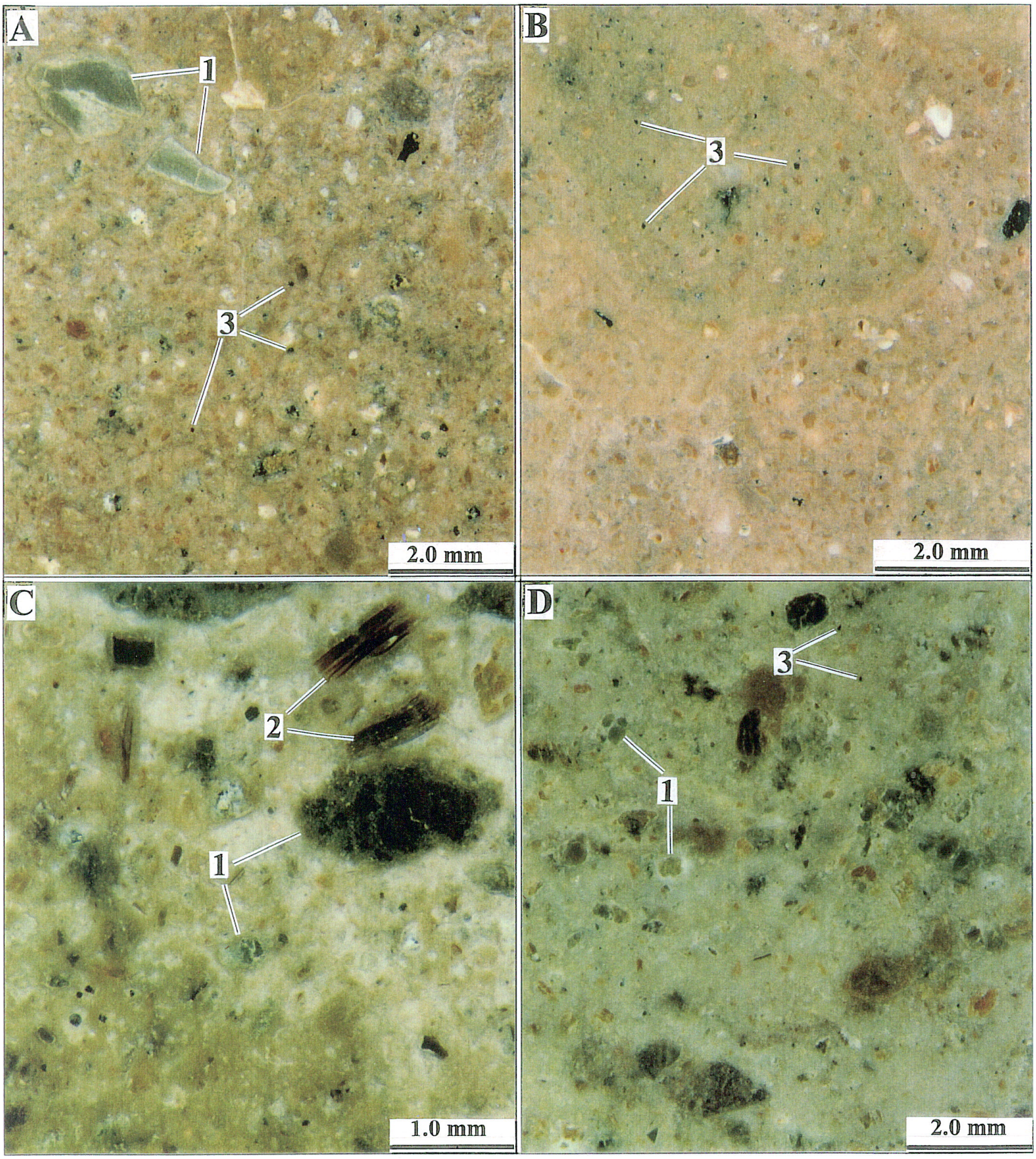


Figure 7. High magnification optical micrographs of polished cross-sections of some African calcretes. The calcretes show inclusions of smectitic saprolite (1), mica pseudomorphs (2) and resistant mineral grains (3).

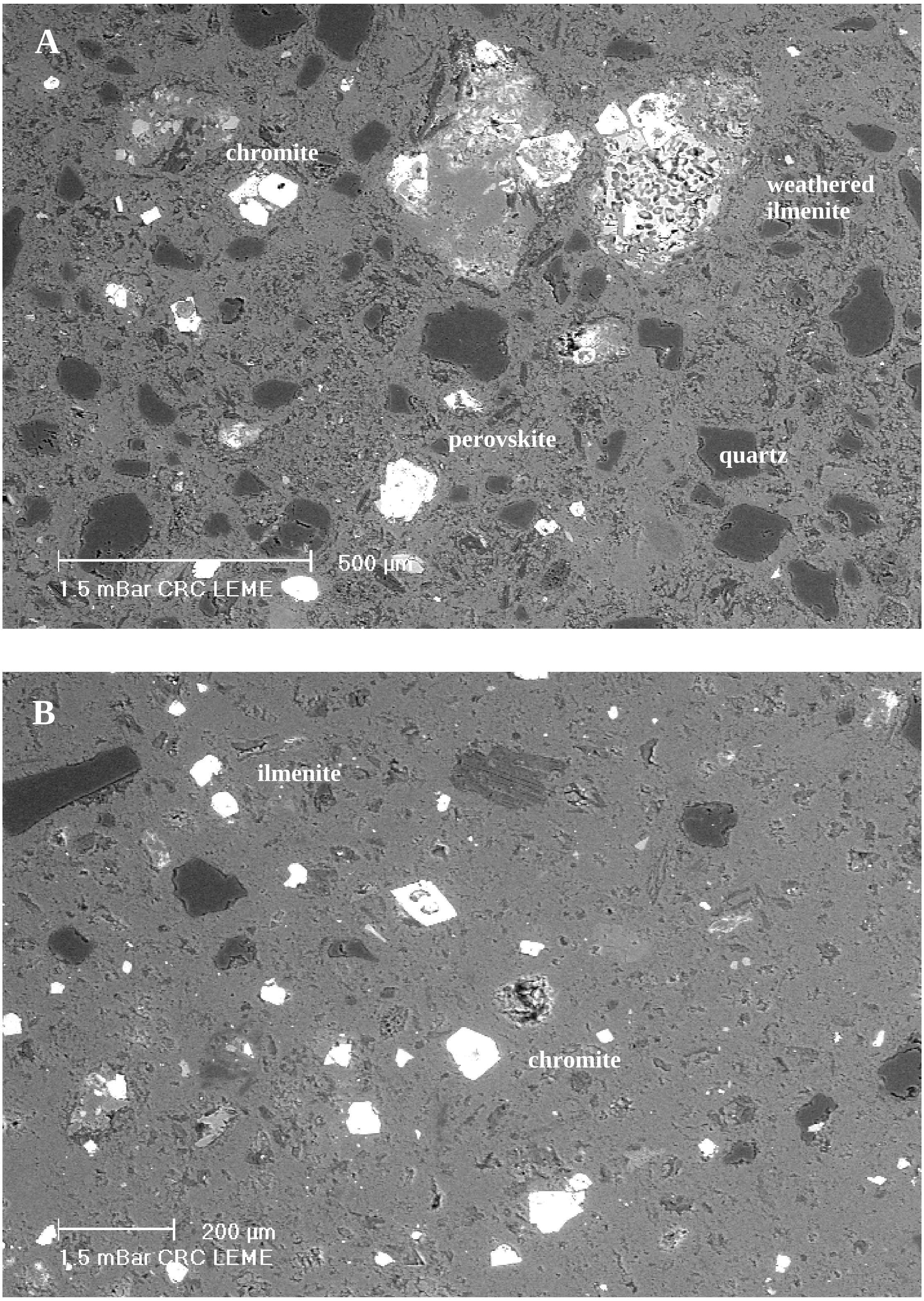


Figure 8. Back scattered electron image of polished sections of sample 121314 and 12308 from South Africa. The micrographs show primary kimberlitic minerals in a matrix of calcite and dolomite. Quartz grains are also present.

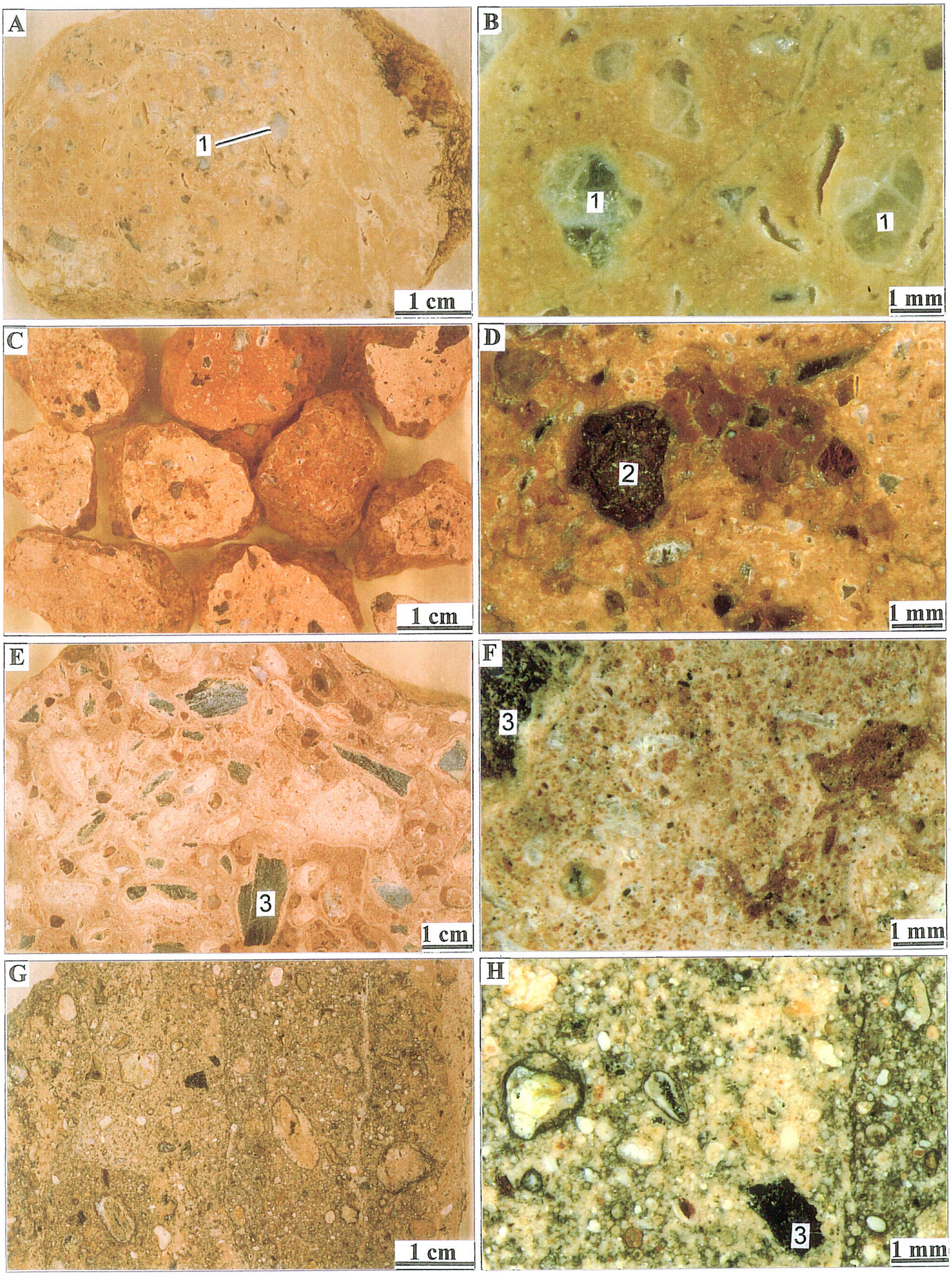


Figure 9. Cross-sections of a representative set of Merredin granitic calcretes. The right hand column is a magnified view of the figures on the left. Quartz grains (1), Fe oxide (2) and rock fragments (3) are present in a calcite matrix. The calcretes shown in (E) and (F) contain abundant primary rock fragments (3), giving a general appearance similar to that of kimberlitic calcretes.

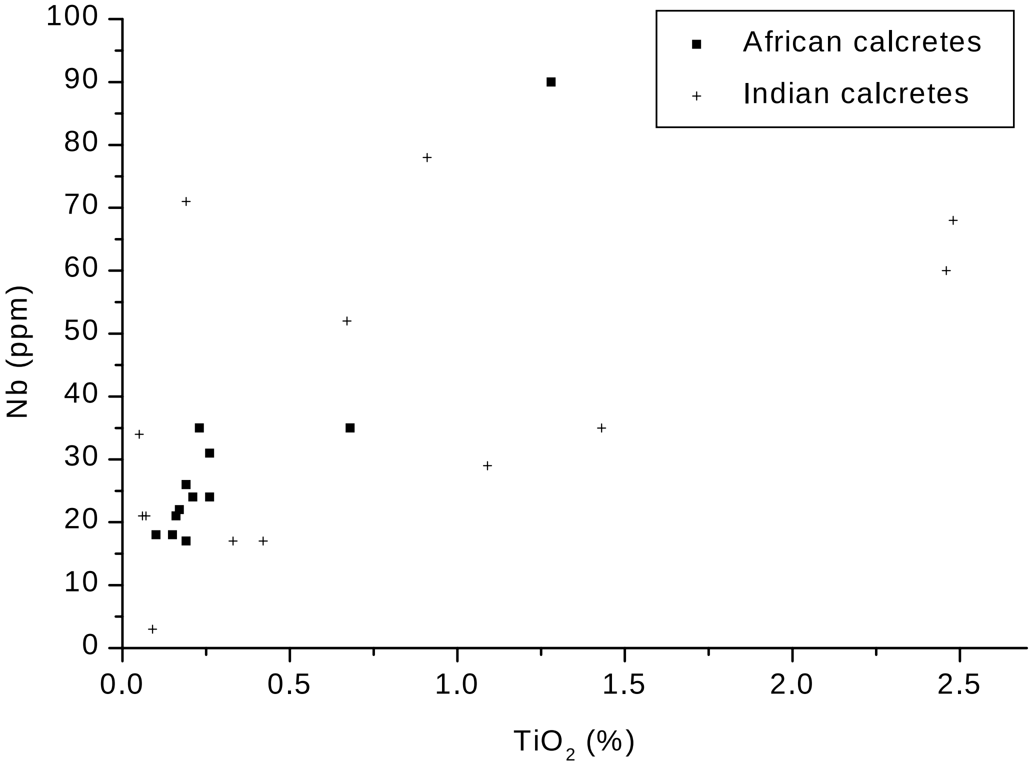


Figure 10. A plot of TiO_2 content against Nb concentration in kimberlitic calcretes.