

## Diamonds from Myanmar and Thailand: Characteristics and Possible Origins

W. L. GRIFFIN,<sup>†</sup>

GEMOC ARC National Key Centre, Macquarie University, New South Wales 2109, Australia, and CSIRO Exploration and Mining,  
North Ryde, New South Wales 2113, Australia

T. T. WIN,

CSIRO Exploration and Mining, North Ryde, New South Wales 2113, Australia

R. DAVIES,

GEMOC ARC National Key Centre, Macquarie University, New South Wales 2109, Australia

P. WATHANAKUL,

Faculty of Science, Kasetsart University, Bangkok, Thailand, and GEMOC ARC National Key Centre, Macquarie University,  
New South Wales 2109, Australia

A. ANDREW,

CSIRO Division of Petroleum Exploration, North Ryde, New South Wales 2113, Australia

I. METCALFE,

Asia Centre, University of New England, Armidale, New South Wales 2351, Australia, and GEMOC ARC National Key Centre,  
Macquarie University, New South Wales 2109, Australia

AND P. CARTIGNY

Geochemisches Institut, University of Gottingen, 37083 Gottingen, Germany

### Abstract

Diamonds occur in modern alluvial deposits at several localities in Myanmar, Thailand, and Sumatra; the deposits do not contain typical diamond indicator minerals, and no obvious primary sources have been found in the surrounding terrane, which is characterized by Phanerozoic tectonic and magmatic activity. Detailed studies of diamonds from Theindaw and Momeik in Myanmar and Phuket in Thailand have been undertaken to clarify their origin. Syngenetic mineral inclusions in the diamonds are largely of the peridotitic paragenesis, with a smaller eclogitic component. Carbon and nitrogen isotope compositions are typical of kimberlitic and lamproitic diamond suites worldwide. Nitrogen aggregation states indicate a long residence and/or significant deformation at mantle temperatures; many stones show plastic deformation features. The rounded and polished surfaces of most of the diamonds reflect resorption in a corrosive magma. These features do not support an exotic or unusual origin for the diamonds, for example, by subduction-exhumation. Extensive abrasion and abundant brown radiation damage spots suggest long surface transport. Their distribution within the Sibumasu terrane, and their close association with Carbo-Permian glacial-marine sediments, suggest that these diamonds were derived from primary sources in northwestern Australia or within the terrane itself, prior to the Early Permian separation of the Sibumasu terrane from the Gondwanaland margin. The isotopic data and the dominantly peridotitic nature of syngenetic inclusions rule out the Argyle lamproite as a possible source and also distinguish the Myanmar- Thailand diamonds from morphologically similar stones from eastern Australia.

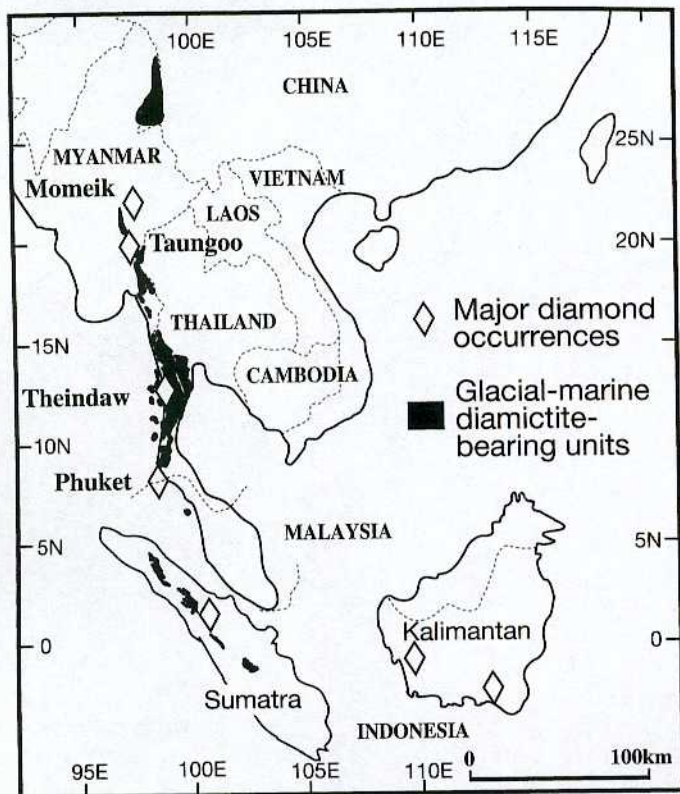


FIG. 1. Map of mainland Southeast Asia, showing the distribution of major alluvial diamond deposits and Carboniferous-Early Permian glacial-marine sediments.

and several exploration companies, and our own investigations. Furthermore, no obvious intrusive or extrusive rocks of types that might serve as diamond sources have been identified despite detailed mapping in these areas. The Southeast Asian diamonds thus are classic headless placers. Their setting in an area characterized by widespread Mesozoic subduction processes, as has been suggested by several authors for the alluvial diamonds of eastern Australia (O'Reilly, 1989; Barron et al., 1996; Griffin et al., 2000).

To understand the origin of these enigmatic diamonds and to provide an improved exploration model, we carried out detailed studies of the morphology, mineral inclusions, growth history, nitrogen concentration and aggregation state, and isotopic composition of diamonds from Myanmar and Thailand. We have examined 125 stones from Phuket, 111 from Theindaw, and 26 from Momeik; these range in size from <0.02 to 3.5 ct, averaging ca 0.2 ct. Isotopic data and nitrogen aggregation data are presented here for 99 of these diamonds. Although there are differences among the samples from different areas, the small sample size means these may not be representative, and the similarities among the samples are striking. They are therefore described together here. More detailed data on the distribution and physical characteristics of the diamonds from Myanmar and the geology of individual deposits are given by Win et al. (2000).

## Geologic Setting

The East and Southeast Asian region comprises an assembly of Gondwanaland-derived allochthonous continental terranes (Fig. 2) that formed the India-northwestern Australian Gondwanaland margin in the Early Paleozoic (Fig. 3). These terranes were rifted and separated from Gondwanaland as three successive continental slivers in the Devonian, late Early Permian, and Late Triassic-Late Jurassic. Reassembly of the terranes to make up Southeast Asia occurred progressively between the early Carboniferous and the Cenozoic (Metcalf, 1996a, b, 1998). The terranes that make up mainland Southeast Asia include South China, Indochina, Sibumasu, West Burma, and southwestern Borneo (Fig. 2). South China and Indochina (including southwestern Borneo, which is believed to be derived from the margin of these) separated from the northeastern margin of Gondwanaland in the Devonian, along with the North China and Tarim blocks. The Sibumasu terrane separated from northwestern Australia, as part of the elongate Cimmerian continental sliver, in the late Early Permian (Fig. 3), while the West Burma terrane, along with the Lhasa block and other small continental fragments now located in southwestern Sumatra, Borneo, and Sulawesi, separated from northwestern Australia in the Triassic-Jurassic. The known occurrences of diamonds in Southeast Asia, except for those in Borneo, all lie on the Sibumasu terrane, and the headless diamond placers of Burma, Thailand, and Sumatra are all associated with Carbo-Permian glacial-marine diamictites that occur in this terrane (Fig. 1).

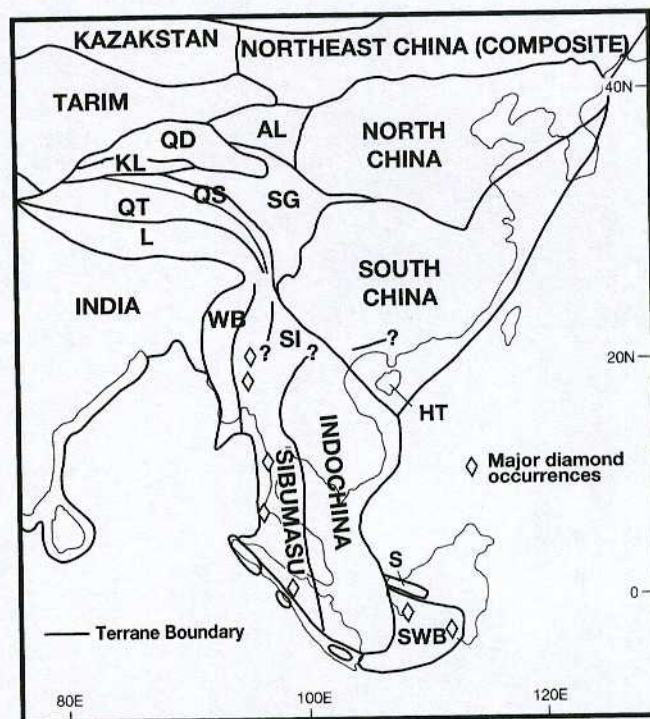


FIG. 2. Terrane map of Asia, showing locations of known alluvial diamond deposits, after Metcalfe (1996b). AL = Ala Shan terrane, HT = Hainan Island terranes, KL = Kunlun terrane, L = Lhasa terrane, QD = Qaidam terrane, QS = Qamdo-Simao terrane, QT = Qiangtang terrane, S = Semitau terrane, SG = Songpan Ganzi accretionary complex, SI = Simao terrane, SWB = southwest Borneo, WB = West Burma.



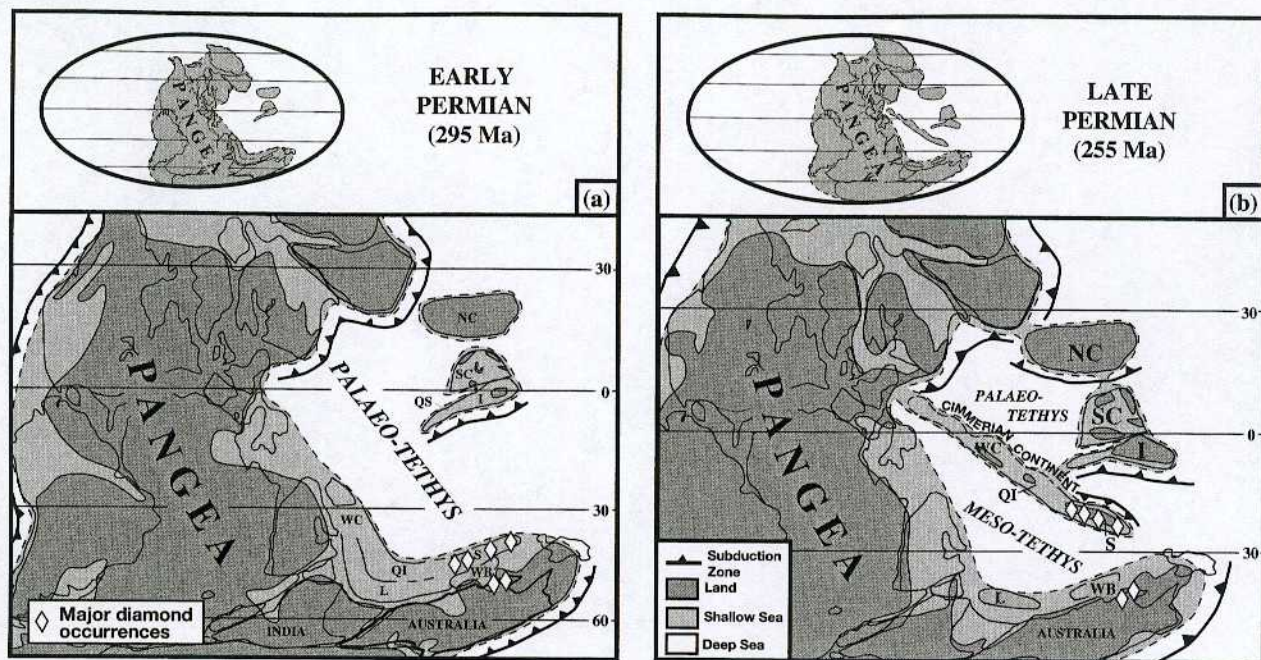


FIG. 3. Permian reconstructions of the Gondwanaland margin, showing location of major diamond deposits within the Sibumasu terrane relative to those in northwestern Australia, and the derivation of the Sibumasu and West Borneo terranes from the continental margin west of Australia, after Metcalfe (1998). I = Indochina, L = Lhasa, QI = Qiangtang, NC = North China, S = Sibumasu, SC = South China, WB = West Burma, WC = Western Cimmerian continent.

Details of the individual occurrences are given by Win et al. (2000). The Momeik diamonds are derived from gem gravels in alluvial systems draining an area of high-grade metamorphic rocks of presumed Archean age, intruded by Miocene granites (Win et al., 2000). In the Taungoo area, the basement rocks are Mergui Group metasediments of probable Carboniferous age, intruded by Mesozoic granites; the diamonds are found in Quaternary gravels mined for gold. The Mergui Group also crops out in the Theindaw area, within a Tertiary sedimentary basin. In the Phuket area, the Carboniferous-Permian metasedimentary rocks of the Kaeng Krachan Group have been intruded by Cretaceous granitic rocks, which are the primary sources for the alluvial tin deposits, from which the diamonds are recovered. In the Phuket area, Garson et al. (1975) suggested that the diamonds could be derived from the pebbly mudstones (glacial-marine diamictites) of the Kaeng Krachan Group, although testing of these rocks did not recover any diamonds.

Small bodies of ultrabasic rocks are found in the Momeik and Taungoo areas, and dikes of minette and basaltic rocks have been found in the Theindaw and Phuket areas (Win et al., 2000; Wathanakul, unpub. data), but no kimberlitic or lamproitic rocks have been identified. The lack of any of the typical mantle-derived indicator minerals (pyrope garnet, chrome diopside, chromite, magnesian ilmenite) associated with the diamonds suggests that kimberlitic or lamproitic rocks are not being eroded in these areas at the present time, and thus are not likely to be the immediate sources of the placer diamonds.

#### Methods

Initial examination of the diamonds was done using Nikon fibre optic zoom binocular microscopes with both transmitted

and incident light. More detailed examination of surface features and morphology was carried out with a Cambridge S240 scanning electron microscope (SEM) at the CSIRO Division of Coal and Energy Technology, North Ryde. Internal structures were studied using polarized transmitted light (birefringence), ultraviolet (UV) photoluminescence, and electron cathodoluminescence (CL). A Cambridge Instruments CCL8200 cathodoluminescence stage mounted on a Nikon petrographic microscope was used for CL studies. The mineral inclusions in the diamonds were analyzed on a CAMEBAX SX50 electron microprobe at Macquarie University, using a range of natural and synthetic mineral standards and full matrix corrections. Ultraviolet fluorescence was observed in the stereoscopic microscope using short-wavelength UV, transmitted by fluid-optic light guides.

Nitrogen contents and nitrogen aggregation states were measured from Fourier transform infrared (FTIR) spectra obtained using a Digilab BIO-RAD FTS-60A with a UMA-300A microscope attachment and liquid nitrogen reservoir at the CSIRO Division of Coal and Energy Technology, North Ryde. Absorption spectra were measured between wave numbers of 4,000 and 400  $\text{cm}^{-1}$  at a resolution of 8  $\text{cm}^{-1}$ , with an aperture of 60  $\mu$ . Spectra were collected after 64 scans. The data were processed at GEMOC, Macquarie University, using Bruker OPUS 2.2 software and the spreadsheet program of Mendelssohn and Milledge (1995). The resorption morphology classification scheme of McCallum et al. (1994) and Otter and Gurney (1989), and the surface feature nomenclature of Robinson et al. (1989) are used in Tables 1 and 2 and in the text.

Most carbon isotope analyses were done at the CSIRO Division of Petroleum Research (North Ryde). Single or multiple



TABLE 1. Comparison of Diamond Populations

	Momeik	Theindaw	Phuket
No. observed	26	111	125
Weight (ct)			
Range	0.11–3.00	0.002–0.664	0.041–2.09
Median	0.257	0.074	0.198
Average	0.528	0.164	0.281
Color (%)			
Colorless		2	4
Yellow	54	31	38
Brown	46	66	53
Other		1	5
Form (%)			
Octahedron	4	10	2
Dodecahedron	76	72	71
Macle	12	10	11
Aggregate	8	5	8
Irregular-fragmented		3	8
Resorption class (%)			
5	4	2	
4		2	
3	4	12	4
2	12	16	3
1	80	68	93
Surface features (%)			
Lamination lines	50	59	85
Glossy surface	35	44	56
Shield-shaped laminated	0	7	59
Hillocks	27	52	38
Trigons	8	14	19
Corrosion pits, ruts	54	45	60
Abrasion-percussion	58	59	70
Network surface	35	29	25
Radiation spots	50	31	62
Cathodoluminescence			
Blue	67	41	38
Yellow	8	29	16
Blue and yellow patches		6	11
Blue-yellow oscillatory		8	23
Blue core, yellow rim	8	8	12
Yellow core, blue rim	17	8	
UV luminescence			
Blue	50	36	53
Yellow		30	17
Blue-yellow	8	13	4
White			3
Inert	42	21	23
Nitrogen			
(%) type II	4	10	2
Range (ppm) N, type I	10–1,350	5–1,100	45–1,025
Average (ppm) N, type I	585	565	460
Average (%) B aggregate	30	27	28

fragments of diamond weighing in total between 0.2 and 2 mg were placed into a previously cleaned 6-mm (od) quartz glass tube (>20 cm long), together with 10 to 20 mg of conditioned CuO. Tubes were evacuated, sealed, and reacted in a furnace at 1,000°C for 5 h. CO<sub>2</sub> produced by oxidation of the diamond was separated cryogenically from other gases and collected in a gas sample tube for mass spectrometric analysis on a Finnigan 252 mass spectrometer using dual inlet mode. An internal anthracite standard ( $\delta^{13}\text{C} = -23.1$  PDB) was run with each batch and the international graphite standard NBS21 ( $\delta^{13}\text{C} = -28.1$  PDB) was analyzed at regular intervals. Reproducibility on different fragments of single stones was typically  $\pm 0.1$  per mil, but some stones were clearly heterogeneous.

A smaller number of carbon isotope analyses, along with analyses of nitrogen content and the isotopic composition of nitrogen, were carried out at the Laboratoire de Géochimie des Isotopes Stables, Institut de Physique du Globe, University of Paris 7, using methods described by Cartigny et al. (1998). Values of  $\delta^{13}\text{C}$  measured on the same stones in the two laboratories are generally in good agreement, though there is a tendency for the Paris values to be slightly lighter than the Sydney values (mean difference 0.3‰).

### Physical Features

The proportions of stones from each area showing different physical features are summarized in Table 1. More detailed data for the stones from Myanmar are given by Win et al. (2000). Data on individual stones for which isotopic data have been obtained are given in Table 2.

### Color

Some stones are colorless but most range from yellow through brown (the dominant color) to deep reddish-brown (cognac); rare pink stones are known, especially from the Phuket area. The brown colors, in particular, are associated with plastic deformation, seen as lamination lines on resorbed surfaces (see below). The proportion of yellow stones may be higher at Momeik than in the other two areas, but the small sample size does not allow detailed comparison.

### Morphology

Most of the diamonds from both Myanmar and Thailand have rounded forms and smooth, often glossy surfaces; octahedral stones with planar faces are rare. Approximately 90 percent of the stones from all three areas fall in resorption categories 1 or 2 (dodecahedral or tetrahahedroidal) of McCullum et al. (1994). The Phuket sample appears to have a significantly higher proportion of highly resorbed stones (category 1), especially compared to the Theindaw sample. Fewer than 10 percent of the stones retain traces of octahedral form (categories 3 to 4); 10 to 25 percent of the sample consists of twinned crystals, including flattened macles which are heavily resorbed. This resorption has removed 25 to 60 percent of the original mass of most stones and produced a wide range of surface microstructures visible in SEM images.

### Surface features

Lamination lines, reflecting plastic deformation, occur on 50 to 60 percent of the Myanmar stones and 85 percent of the Phuket stones examined; more than one direction is commonly present. Aside from lamination lines, the most common surface features are shield-shaped laminae, followed by hillocks, etch pits, and rare trigons. Shield-shaped laminae are especially common in the Phuket sample but relatively rare in the other samples. More than 50 percent of the stones have strikingly glossy surfaces, which appear smooth even at high magnification in the SEM; the proportion of such stones is highest in the Phuket sample. Features reflecting corrosion in near-surface environments include corrosion pits and ruts, which are found on ca. 60 percent of the stones. Abrasion during alluvial transport is reflected in a high proportion of broken stones, abundant percussion scars and frosted edges, and rhombic cracking.



TABLE 2. Physical and Chemical Characteristics of Selected Diamonds from Myanmar and Thailand

Sample no.	Carats	Col	Form	Res. cat.	PD	CL color	UV color	N (ppm)	(%) B agg.	$\delta^{13}\text{C}$ Sydney	$\delta^{13}\text{C}$ Paris	$\delta^{15}\text{N}$ Paris	Inclusions
<b>Momeik</b>													
MMK3	0.237	Br	D	1	x	Y-C/B-R	B-C/Y-R	526	70	-4.84			
MMK5	0.17	Br	D,c	3	x	B	I	522	12				Chromite
MMK7	0.505	Br	D	1		Y-C/B-R	Y-C/B-R	Type II					Olivine
MMK8	0.561	Br	D	1	x	B,d-C/B,p-R	I	634	28	-2.62			
MMK9	0.498	Br	D	1	x	B,p	B	336	22				Olivine
<b>Theindaw</b>													
TD 1	0.0525	Br	D,f	3		B	B,d	525	n/a	-4.41	-4.87	-3.90	
TD 2	0.014	Br	O,d	3		B,d-C/B,p-R	B	n/a	n/a	-10.45			
TD 4	0.0215	Br,p	D	1		B-C/Y-R	Y	n/a	n/a	-21.19			
TD 5	0.028	Br	D/M,f	2	x	??	Y	n/a	n/a	-3.37			
TD 6	0.038	Br	D,b	3	x	Y-C/B-R	Y,p	Type II			-5.05		
TD 8	0.055	Br	O,f	4	x	n/a	B-C/Y-R	Type II			-19.37	-19.63	
TD 10	0.038	Br	D,b	2	x			546	25	-4.71			
TD 12	0.0355	Br	D,f	2	x	B,d-C/B,p-R	B-C/Y-R	903	35	-8.46			
TD 13	0.0345	Br,p	O	5	x	Y	B-C/Y-R	442	22	-5.19			
TD 16	0.052	Br	D,b	3		Y	Y	Type II		-17.74	-17.08		
TD 17	0.04	Br	M,f,b	3	x	Y	Y	147	11	-5.77	-6.20	-0.10	
TD 18	0.028	Br	D	1		B,L	B	1014	20	-6.04	-4.81		
TD 19	0.016	Br	O	5		Y	B	820	20	-3.33			
TD 20	0.0023	Br	D	1	x	Y-C/B-R	B	1247	63	-4.20	-4.66	-8.60	
TD 26	0.431	Br	D,b	1	x	Y	Y	51	5	-4.49			Olivine
TD 30	0.294	Br	D,e	1	x	B/Y OX	B	40	5	-5.39			Olivine
TD 34	0.45	Y,p	D	1		Y	Y	580	38	-6.13			
TD 35	0.399	Br	D/T	1	x	B/Y-PAT	B/Y	420	28	-5.82			Olivine
TD 46	0.09	Y	D,b	1	x	B	Y	450	15	-5.76			Omphacite
TD 50	0.076	Br,p	D	2	x	B-C/Y-R	B/Y	522	48	-4.79			
TD 52	0.08	Br	D	1	x	Y/G	Y	n/a	n/a	-4.69			
TD 54	0.74	Br	D,e	1	x	B/Y-PAT	B	831	32	-3.78			Olivine
TD 55	0.081	Cr	D	?		B/Y OX	B	n/a	n/a	-12.33			
TD 56	0.079	Y	D,e	1	x	B/Y OX	Y	n/a	n/a	-5.77			
TD 57	0.084	Y,p	D,b	1		Y	Y	n/a	n/a	-15.85			
TD 60	0.051	Br	D	1	x	Y	I	392	8	-4.60			
TD 62	0.053	Br,p	D,b	1	x	Y	Y	Type II		-5.20			
TD 63	0.051	Br,p	O	3		B/Y-C	B/Y	351	25	-4.06			
TD 69	0.058	Y-Br	D	3		B,d-C/B,p-R	I	524	10	-6.28			
TD 72	0.044	Br,p	D/M	2	x	B	B	696	12	-10.48			
TD 75	0.04	Br,p	D,b	1	x	Y-C/B-R	Y	50	5	-7.36			
TD 76	0.054	Br	D/M	1	x	Y-C/B-R	B	837	80	-6.74			
TD 77	0.047	Br	D	1	x	B,d-C/B,p-R	B	340	30	-4.39			
TD 78	0.054	Br	D/M	1	x	Y-C/B-R	B	877	80	-5.47			
TD 79	0.047	Br,p	D	1	x	B	B	992	25	-5.06			
TD 82	0.026	Br,p	D,e	1	x	B,d-C/B,p-R	I	696	12	-4.26			
TD 84	0.047	Br,p	D,b	?		B	B	876	22	-5.68			
TD 85	0.024	Br,p	D	1	x	B/Y OX	Y	Type II		-6.01			
TD 86	0.029	Y	D	1	x	P	Y	n/a	n/a	-5.21			Coesite
TD 87	0.037	Y	D	1		Y,d-C/Y,p-R	Y	609	9	-4.65			
TD 88	0.045	Y	D/M	1	x	B	B	696	12	-8.44			
TD 90	0.038	Y,p	D	1	x	G-C/Y-R	Y/G	Type II		-4.99			
TD 91	0.015	Br,p	D	2	x	B	I	1000	38	-4.88			
<b>Phuket</b>													
TDA 3 (QD3)	0.203	Br,P	M,f	1	x	B-Y OX		318	20	-3.31			
TDA 4 (QD4)	0.271	Br,P	M,f	1	x	B-Y OX		705	35	-5.55			
TDA 5 (PD5)	0.179	G	a	1	x	Y OX		64	10	-3.41			
TDA 6 (PD6)	0.318	Br	D/M	1	x	Y OX		151	65	-4.81			
TDA 9 (PD9)	0.462	Br	a	1	x	Y-G		92	48	-5.31			
TDA 10 (PD10)	0.088	Br	D,e	1	x	B-W		752	40	-3.95	-4.26	-1.70	
TDA 11 (PD11)	0.250	Br	c	1	x	Y		293	30	-4.80			
TDA 12 (PD12)	0.198	Br	D	1	x	d.B, Y band		478	15	-5.00	-4.93	-8.90	
<b>Duplicate analysis</b>													
TDA 14 (QD14)	0.322	Br,p	c	1	x	i		409	20	-11.00			
TDA 16 (PD16)	0.491	Br	M,c?	1	x	Y OX		440	33	-5.22			
TDA 18 (PD18)	0.018	Y,p	D,f	2		B		458	10	-4.15	-4.55		
TDB 26 (RD3)	0.581	Br	D,f	1	x	B-Y OX	Y	271	14	-4.93			
TDB 28 (RD5)	0.323	Y,p	D	1	x	B-Y OX		832	80	-4.18			
TDB 29 (RD6)	0.177	B	D,f	1	x	Y,Bc		461	15	-5.07	-5.53		



TABLE 2. (Cont.)

Sample no.	Carats	Col	Form	Res. cat.	PD	CL color	UV color	N (ppm)	(%) B agg.	$\delta^{13}\text{C}$ Sydney	$\delta^{13}\text{C}$ Paris	$\delta^{15}\text{N}$ Paris	Inclusions
TDB 30 (RD7)	0.172	B	D,f	2	x	Y		626	17	-5.69			
TDB 31 (RD8)	0.156	B,p	D,t	1	x	B		46	15	-4.94	-5.38	-5.60	
TDB 32 (RD9)	0.152	B	D,t	1	x	B		604	40	-5.31	-5.32	2.20	
TDB 33 (RD10)	0.118	Y,p	D	1		B		497	25	-4.99			
TDC 34 (SD1)	0.274	Br	D,t	1	x	Y-G		580	50	-5.43	-5.72	-12.80	
TDC 35 (SD2)	0.231	Br	D	1	x	B		857	48	-6.17	-6.37	-4.80	
TDC 36 (SD3)	0.198	Y	D	1	x	Y		856	12	-6.91	-7.03	2.20	
TDC 37 (SD4)	0.157	Y	c	1		Y		496	12	-3.98	-4.47	2.60	
TDC 38 (SD5)	0.124	Y	D	3 to 4		B-Y PAT		811	18	-7.02			
TDC 39 (SD6)	0.127	Y	D	1		Y-G		450	30	-6.51	-7.02	6.00	
TDC 40 (SD7)	0.106	Y,p	f	1	x	B,p		408	68	-4.04			
TDC 43 (SD10)	0.287	Y	f		x	Y-C				-5.34			
TDC 44 (SD11)	0.220	Y	f		x	B-Y OX				-5.21			
TDC 45 (SD12)	0.158	Y,p	f			i				-4.25			
TDD 50	0.983	Y,p	T	1	x	B-Y	W			-4.64			Olivine
TDD 52	0.590	Y,p	irr.	1	x	Y-G	i	264	12	-5.07			Olivine Olivine Chromite
TDD 54													
TDD 58	0.073	Y,p	cut			B	n/a					-7.11	
TDE 68	0.112	Br	T	1	x		Y			-4.78			Olivine
TDE 69	0.107	Br	D	1						-5.44			Olivine
TDF 80	0.330	Br,p	D	1	x	B-Y PAT	B	980	35	-5.04			
TDF 81	0.325	Br	T	1	x	B	i	424	20	-4.78			
TDF 82	0.314	Br,p	D	1	x	B-C,Y-R	i	246	10	-3.80			Olivine
TDF 83	0.301	Y,p	T	1	x	B-Y OX	i	200	10	-3.80			
TDF 86	0.265	Y,p	T	1	x	B-C,Y-R	B	536	25	-11.9			E-gnt, magn.
TDF 87	0.263	Br,p	D	1	x	B	Y,p	256	70	-4.18			Olivine
TDF 89	0.255	Br,d	T	1	x	Bc,Yr	i	352	22	-3.89			
TDF 90	0.254	Y,p	T	2	x	B-Y OX	Y,p	70	28	-4.57			Sanidine, coes.
TDF 94	0.220	Br	T	1		Y	Y-G			-4.41			
TDF 95	0.214	Br,p	irr	1	x	B-C,Y-R	B	338	10	-5.53			
TDF 97	0.204	Br,p	D	1	x	Y	Y			-3.59			Olivine
TDF 98	0.204	Br,d	T	1	x	B	i	943	35	-4.78			
TDF 101	0.156	Br,p	T,f	1	x	B-C,Y-R	B	385	18	-5.18			
TDF 102	0.118	Br	T,e	1	x	B-Y PAT	B-Y	320	25	-4.21			
TDG 116	0.126	Y	cut			B	i			-4.34			
TDG 118	0.104	Gr	cut			B-Y OX	B						Olivine
TDG 123	0.067	N/C	cut			B	B			-5.42			Olivine

## Abbreviations:

Col = color: B = blue, Br = brown, C = cognac, d = dark, G = green, Gr = gray, N/C = colorless. P = pale, Y = yellow

Res. Cat. = Resorption category, after Robinson et al. (1989)

Form: a = aggregate, b = broken, c = composite, D = dodecahedron, d = distorted, e = elongate, f = flattened, M = macle, O = octahedron, t = trigons, T = tetrahexahedroid

CL color: B = blue, -C = core, d = dark, G = green, OX = oscillatory, p = pale, -PAT = patches, -R = rim, Y = yellow

UV color: B = blue; -C = core, d = dark, G = green, I = inert, p = pale, -R = rim, y = yellow

PD = plastic deformation (lamination lines)

Brown (rarely green) spots occur on many of the stones examined. These spots, and others not seen in ordinary light microscopy, appear on CL images as black spots fringed with yellow; ca. 40 percent of the stones from the Myanmar deposits and 60 percent of the stones from Phuket show this feature. Green radiation spots are caused by radiation from nearby U, Th-rich minerals, and become brown through heating or prolonged surface exposure; brown spots are thus common on alluvial diamonds (Vance et al., 1973).

## Internal structure

Many diamonds luminesce in the visible range when bombarded by electrons. This CL comes only from the outer few microns of the surface, and CL is typically used to study internal structures of diamonds by observing a polished section (Bulanova, 1995). However, the strongly resorbed surface of

many of the present stones cuts across growth zones, allowing us to image the internal structure even of whole stones. A blue CL color is characteristic of most diamonds from kimberlites (Bulanova, 1995), and about half of the stones studied here show luminescence in shades of blue to white. However, a high proportion show strong yellow CL colors, which may be uniform or display oscillatory zoning in color intensity (see plates in Win et al., 2000). This yellow color also is seen along deformation planes, and deformation appears to be responsible for the yellow CL color of nitrogen-poor zones within the diamonds (Davies et al., 1999). Many stones show a characteristic oscillatory blue-yellow CL pattern, which is related to the appearance of shield-shaped laminae on the resorbed surfaces and outlines octahedral growth zoning. Still others show isolated patches of yellow CL, often oscillatory zoned, against a blue background.



TABLE 3. Representative Analyses of Mineral Inclusions in Diamonds

Locality Sample	Olivine							
	Myanmar BTD-35	Myanmar BTD-26	Myanmar BTD-26	Myanmar BTD-54	Thailand PD-8	Thailand TD-68	Thailand TD-69	Thailand TD-52
SiO <sub>2</sub>	40.92	41.21	41.89	41.31	40.41	41.27	41.07	41.77
Al <sub>2</sub> O <sub>3</sub>	0.02	0.02	0.00	0.00	0.03	0.00	0.01	0.03
Cr <sub>2</sub> O <sub>3</sub>	0.03	0.05	0.03	0.04	0.14	0.06	0.05	0.07
FeO	9.76	8.39	7.96	7.13	8.85	7.38	6.75	5.67
MnO	0.08	0.09	0.15	0.10	0.11	0.10	0.09	0.09
MgO	48.59	50.08	50.42	50.96	50.06	50.99	51.68	52.29
CaO	0.09	0.06	0.05	0.04	0.06	0.06	0.03	0.07
NiO	0.45	0.36	0.37	0.35	0.31	0.37	0.40	0.38
Total	99.93	100.25	100.88	99.93	99.98	100.24	100.07	100.38
Mg no.	89.9	91.4	91.9	92.7	91.0	92.5	93.2	94.3

Locality Sample Mineral	Other peridotitic phases				Eclogitic phases			
	Thailand TD-64 Chr-Py	Myanmar MMK-5 Chr (w/Fe alloy)	Thailand TDD-54 Chr	Myanmar BTD-26 Opx	Myanmar BTD-46 Omph.	Thailand TDF-86 Gt	Thailand TDF-86 carbonate	Thailand TDE-90 Sanidine
SiO <sub>2</sub>	42.17	0.51	0.31	57.01	54.75	40.71	0.02	65.14
TiO <sub>2</sub>	0.06	0.46	0.02	0.07	0.54	0.37	0.00	0.00
Al <sub>2</sub> O <sub>3</sub>	14.54	7.36	6.00	2.54	10.38	22.10	0.02	17.79
Cr <sub>2</sub> O <sub>3</sub>	11.18	64.08	65.16	0.30	0.03	0.06	0.00	0.00
FeO	5.94	16.73	11.61	5.74	6.00	14.92	0.14	0.04
MnO	0.18	1.18	0.00	0.14	0.08	0.27	2.19	0.00
MgO	21.15	9.42	14.48	34.04	8.14	12.50	6.80	0.01
CaO	4.67	0.01	0.01	0.43	14.13	8.37	48.07	0.00
Na <sub>2</sub> O	0.01	na	na	0.02	4.92	0.14	0.02	0.43
K <sub>2</sub> O	na	na	na	na	0.42	na	na	16.45
NiO	0.00	0.13	0.13	0.08	0.01	0.02	0.00	0.04
Total	99.90	99.88	97.71	100.37	99.39	99.46	57.25	99.90
Mg no.	86.4	50.1	69.0	91.4	70.7	59.9	98.8	

The highest proportion of stones with blue CL occurs in the Momeik sample, and the highest proportion of pure yellow CL stones in the Theindaw sample. The proportion of stones with blue-yellow oscillatory zoning is distinctly higher in the Phuket population. Most diamonds show blue or yellow luminescence under UV light and several show blue cores and yellow rims. This latter feature, and the yellow or yellow-blue oscillatory CL pattern, is uncommon in kimberlitic diamonds but has been observed in stones from the Argyle lamproite in northwestern Australia (J.W. Harris, pers. commun.). Many of the diamonds prepared as polished plates show birefringence under crossed polars. In some cases this birefringence outlines octahedral growth zoning; in most it is irregular and appears to be related to strain.

### Chemical Features

#### Syngenetic mineral inclusions

Syngenetic mineral inclusions identified in this study are mainly of the peridotitic paragenesis and include olivine, enstatite, chromite, Cr pyrope garnet, and native iron. A smaller number of inclusions is of the eclogitic paragenesis. Compositions of representative phases are given in Table 3.

Twenty-four olivine inclusions have been recovered from 16 diamonds and range in composition from Fo<sub>89</sub> to Fo<sub>94.7</sub>;

the covariation in Fo and CaO contents (Fig. 4) suggests that both the lherzolitic and the harzburgitic subparageneses are represented. Whereas the latter predominates in most suites of peridotitic diamonds worldwide, more than one-third of the Myanmar and Thailand diamonds appear to be from the lherzolitic subparagenesis. A single enstatite inclusion has high Al and Ca contents and probably is lherzolitic. A Cr pyrope inclusion is subcalcic, indicating a harzburgitic paragenesis. Win et al. (2000) describe an unusual composite inclusion consisting of chromite, native Fe, and a silica phase; the chromite is more iron rich than most other diamond inclusion chromites (Table 3).

Inclusions of the eclogite paragenesis comprise one omphacite, one garnet-magnesian calcite pair, and a sanidine-coesite pair. These inclusions all fall within the ranges described from suites of diamonds in kimberlites and lamproites worldwide (Meyer, 1987).

#### Nitrogen contents and aggregation

Nitrogen is the most important impurity in natural diamonds; type I diamonds have measurable N contents, whereas type II diamonds are defined as containing only traces of N. Nitrogen is taken into the diamond lattice initially as single-atom substitutions (N centers) but aggregates through time



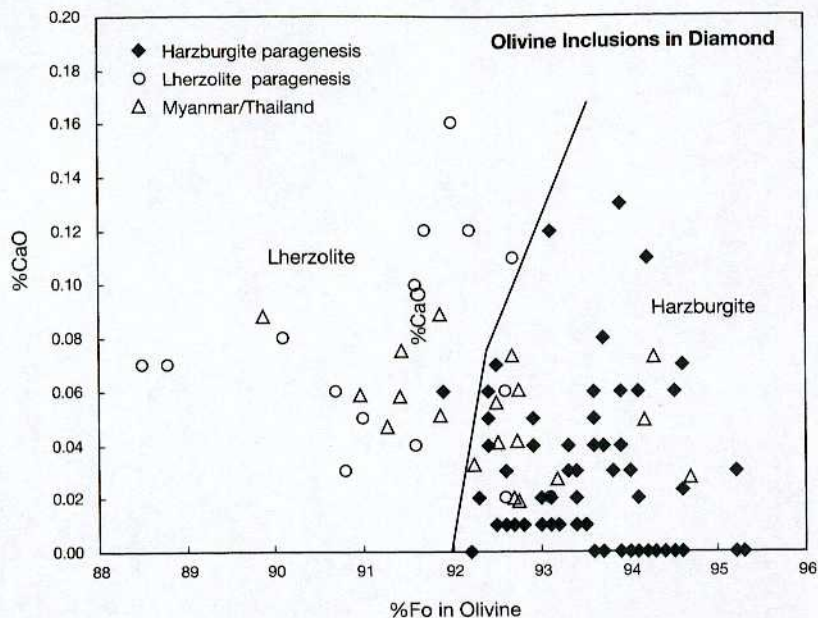


FIG. 4. CaO vs. Fo (%) in olivine inclusions from diamonds, classified by paragenesis on the basis of associated phases: Lherzolitic paragenesis is defined by the coexistence of olivine and Cr diopside, harzburgitic paragenesis by coexistence of olivine and subcalcic Cr pyrope, chromite or low Ca enstatite (compilation of pub. data; Davies, 1998). The solid line separates the two parageneses at >90 percent confidence.

into pairs (type IaA) and then into more complex groupings (type IaB; Allan and Evans, 1981). This diffusion-controlled process is dependent on temperature, time, and the density of defects caused by deformation (Evans and Harris, 1989; Evans, 1992). Nitrogen contents and aggregation state are routinely determined by FTIR microscopy (Mendelsohn and Milledge, 1995) and provide constraints on the history of the diamonds. In this work we have acquired FTIR spectra on 185 diamonds.

The Fourier transform infrared studies show that ca. 10 percent of the Theindaw diamonds have very low N contents (type II diamonds); one type II diamond has been found in the Phuket sample and one from Momeik. In the other stones, N content ranges up to >1,300 ppm, and average ca. 500 ppm. The degree to which nitrogen is aggregated to type IaB ranges between 10 and 80 percent and averages ca. 30 percent. There are only small differences among the three localities in terms of N content; the range is slightly smaller in the Thai stones, and the average N content is slightly lower. In view of the small sample sizes, these differences are not considered to be significant. The type I diamonds from all three areas can be divided into two groups based on their nitrogen content and nitrogen aggregation characteristics (Fig. 5). The main group contains low to moderate amounts of nitrogen (10–1,350 ppm, avg ca. 600 ppm). Their nitrogen aggregation states range from <5 to 65 percent IaB (avg about 20% IaB) and the degree of aggregation is roughly correlated with N content. There is no obvious correlation between N content and color.

The second group of type I diamonds (ca. 15%) has much higher nitrogen aggregation states (45–85% IaB; avg 65% IaB) relative to their nitrogen contents (100–850 ppm; avg about 335 ppm). This indicates that these diamonds either share a longer mantle residence time, have been stored at

higher average mantle temperatures, or have a higher proportion of lattice defects than the main Theindaw group (Evans and Harris, 1989; Mendelsohn and Milledge, 1995). All of these diamonds show brown colors and good development of lamination lines, implying strong plastic deformation with accompanying development of defects. We therefore interpret their high aggregation states as the result of strong deformation, rather than as evidence of greater age or higher temperature origin (cf. Taylor et al., 1990). This mechanism may also have enhanced the rate of aggregation in many of the other plastically deformed diamonds and makes any attempt to estimate mantle residence ages (time-temperature isotherms) from nitrogen aggregation subject to unacceptable errors (Evans and Harris, 1989; Evans 1992).

#### Carbon and nitrogen isotopes

Carbon isotope compositions of Myanmar and Thailand diamonds show a distribution similar to other diamonds worldwide, but there are some differences between the sample groups. All but two values of  $\delta^{13}\text{C}$  from Phuket fall between  $-3$  and  $-8$  per mil, corresponding to the distribution of values in nearly all diamonds of the peridotitic paragenesis (Fig. 6). This observation is consistent with the peridotitic nature of most syngenetic inclusions thus far found in the Thai diamonds. Two Phuket stones have  $\delta^{13}\text{C}$  values between  $-11$  and  $-12$  per mil, and one of these (sample TDF86) contains inclusions of eclogitic garnet and magnesian calcite (Table 3). Most of the data from Myanmar also fall in the main peridotitic peak, but nine values spread from  $-8$  to  $-22$  per mil. None of the stones with low  $\delta^{13}\text{C}$  contained syngenetic inclusions, and the two eclogitic inclusions identified from the Myanmar suite occur in diamonds with  $\delta^{13}\text{C}$  values ( $-5.2$ ,  $-5.8\text{‰}$ ) that fall in the main peak. However,  $\delta^{13}\text{C}$  values  $<-8$



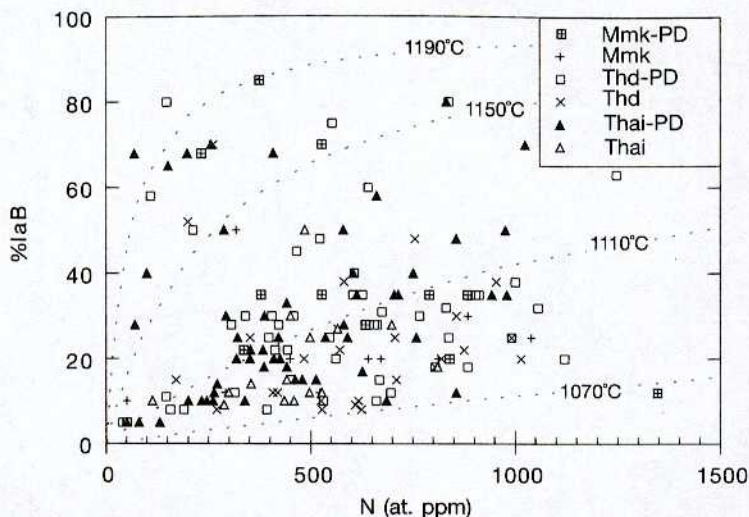


FIG. 5. Nitrogen contents and aggregation states (%IaB) for diamonds from Myanmar and Thailand, showing the anomalously high aggregation states of many diamonds with plastic deformation (PD). MmK = Momeik, Thai = Phuket, Thd = Theindaw. Isotherms are calculated for a mantle storage time of 2 Ga, following Mendelsohn and Milledge (1995), and are intended for reference only.

per mil typically are found in diamonds of the eclogitic paragenesis worldwide and are rare in the peridotitic paragenesis (Sobolev et al., 1979; Gurney, 1989; Kirkley et al., 1991; cf. sample TDF86), and such diamonds in the Myanmar sample, therefore, are interpreted as probably belonging to the eclogitic paragenesis. The relative abundance of low  $\delta^{13}\text{C}$  values in the two suites, therefore, suggests that the proportion of diamonds of the eclogitic paragenesis is higher in the Myanmar diamond population.

The diamonds from Myanmar and Thailand are similar to other diamonds of peridotitic paragenesis (and most diamonds of eclogitic paragenesis) in terms of the relationship between  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  (Fig. 7; Cartigny et al., 1998). They are isotopically distinct from the largely eclogitic diamonds from the Argyle lamproite (NW Australia), which show a major peak between  $-8$  and  $-13$  per mil  $\delta^{13}\text{C}$ , and from morphologically similar diamonds from eastern Australia, which have generally heavier carbon. The isotopic data rule out a genetic relationship to either of these populations but emphasize the similarity of the Thai and Burmese diamonds to other kimberlitic and lamproitic diamonds worldwide.

#### Discussion: Possible Origin(s) of Diamonds from Myanmar and Thailand

The compositions of syngenetic inclusions show that the diamonds from Myanmar and Thailand formed in environments that were dominantly peridotitic, with a minor eclogitic component. The inclusions of peridotitic paragenesis reflect both lherzolitic and harzburgitic mineral assemblages, typical of those observed in diamonds from kimberlites and lamproites worldwide. The isotopic compositions of carbon and nitrogen in these diamonds also are similar to those observed in most diamond suites derived from kimberlitic and lamproitic sources (Figs. 6, 7). Our data thus indicate that the diamonds from Myanmar and Thailand are derived from normal mantle sources. None of these diamonds shows the isotopically heavy carbon found in most of the diamonds from

eastern Australia, which could plausibly be regarded as related to subduction processes (O'Reilly, 1989; Barron et al., 1996; Davies et al., 1999; Griffin et al., 2000).

The nitrogen contents and nitrogen aggregation states of the Myanmar and Thailand diamonds also are similar to many diamond suites from known sources. Although nitrogen aggregation state is an unreliable guide to the details of diamond history (Evans and Harris, 1989; Evans 1992), it offers some constraints, particularly by comparison to diamonds of known history. The microdiamonds found in metamorphic rocks such as those of Kazakhstan, which are believed to have formed during deep subduction of continental crust (Sobolev and Shatsky, 1990), show high N content and very low degrees of IaB aggregation (Finnie et al., 1994; De Corte et al., 1999), consistent with a short, low-temperature history. In contrast, the nitrogen aggregation states of the diamonds from Myanmar and Thailand suggest both a longer and higher temperature history. There is thus no evidence that these diamonds are related to subduction processes.

Our studies of internal structure by UV photoluminescence, cathodoluminescence, and birefringence reveal octahedral growth zoning in many of these diamonds. Octahedral growth also is demonstrated by the presence of shield-shaped laminae on the resorbed surfaces. This growth zoning is truncated by the present strongly rounded forms, which clearly demonstrates that those forms are secondary and reflect resorption of the diamonds at high temperature. By analogy with similar features on diamonds from kimberlites and lamproites, this is strong evidence that these diamonds were transported to the surface in magmas (Robinson et al., 1989).

The high proportion of diamonds with extremely glossy, low-relief surfaces may indicate that this magma was highly alkaline; similar surfaces have been produced experimentally by dissolution of diamond in sodium carbonate at  $800^\circ\text{C}$  (Mahlzan, 1997). These highly polished surfaces are cited by Hall and Smith (1984) as a significant feature of diamonds from lamproitic sources, as contrasted to kimberlitic diamond



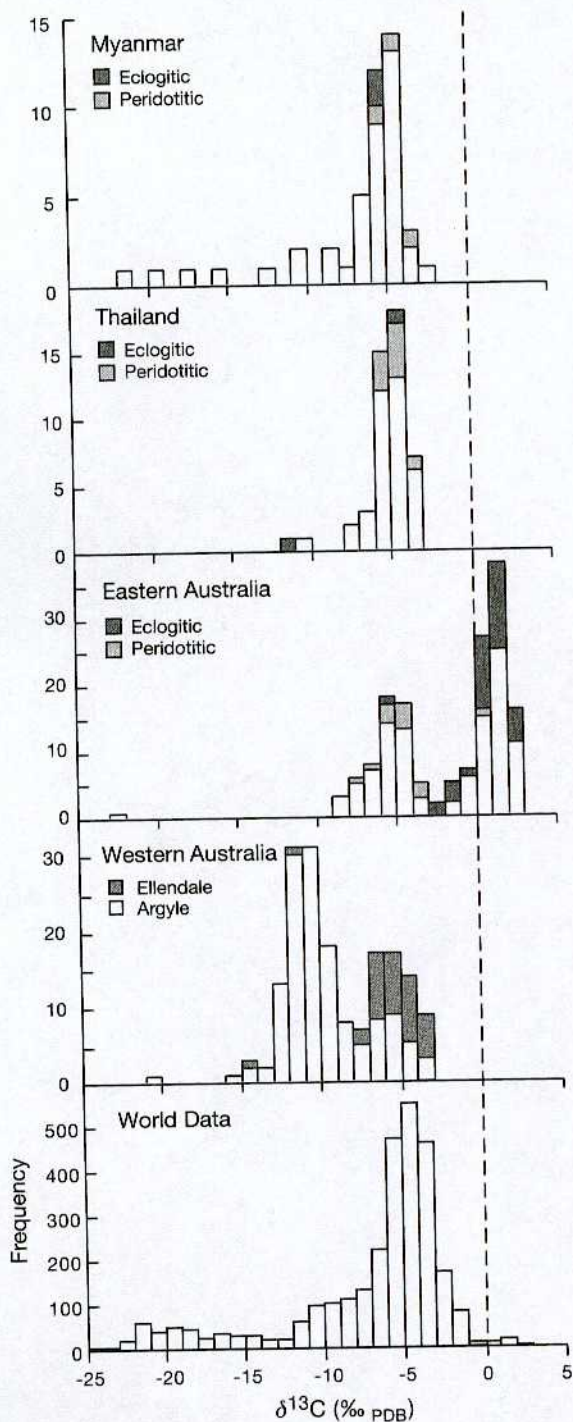


FIG. 6. Histograms of  $\delta^{13}\text{C}$  for diamonds from Myanmar and Thailand, compared to data from eastern Australia (Davies et al., 1999, and in prep.), Western Australia (Jaques et al., 1989), and worldwide (van Heerden et al., 1995a, b).

populations. The high incidence of plastic deformation, yellow-blue oscillatory CL and reversed UV zonation may not be diagnostic but appear to be more characteristic of diamonds from lamproitic sources, rather than kimberlitic ones (G. Bulanova, pers. commun.; J.W. Harris, pers. commun.).

The common occurrence of breakage and surface wear, and especially the abundance of brown radiation damage spots, attest to long periods of residence in surface environments and alluvial systems and suggest that these diamonds may be far removed from their primary sources.

The Myanmar-Thailand-Sumatra alluvial diamond localities lie within the Sibumasu terrane (Metcalf, 1996a) and are all associated with Carbo-Permian glacial-marine diamictites that occur within this terrane (Fig. 1). Paleogeographic reconstructions (Fig. 3) suggest that the Sibumasu terrane was detached from northwestern Australia in the Permian and drifted northward to initially amalgamate with South China-Indochina and then eventually became part of Southeast Asia. Its original location lay west of the Kimberley region of northwestern Australia, which contains many known diamond deposits of Proterozoic age. These include not only the Argyle lamproite (ca. 1.2 Ga) but many smaller kimberlites of Late Proterozoic age (Jaques et al., 1989).

The isotopic data presented here exclude the Argyle lamproite as a possible source for the Myanmar-Thailand diamonds but do not further constrain the source. There are few data on the diamonds of the Upper Proterozoic kimberlites of the Kimberley region, which might be an alternative source. The diamondiferous lamproites of the Lennart shelf of Western Australia are better known, but their Miocene age (Jaques et al., 1989) excludes them as a source for diamonds in the Sibumasu terrane, which had separated from Western Australia long before then (Fig. 3).

Northwestern Australia was glaciated in the Late Carboniferous-Early Permian, and Carbo-Permian glacial-marine sediments derived from the western Australian continent were deposited on the continental margin of Gondwanaland, now recognized as the Sibumasu terrane in Southeast Asia. The glacial-marine sediments are found from Sumatra through Peninsular Malaysia and western Thailand to northern Myanmar (Fig. 1) and extend northwestward into Tibet. The Phuket and Theindaw diamond occurrences are especially closely associated with these glacial-marine deposits. We therefore suggest that the Myanmar-Thailand diamonds were derived from primary sources on the Australian continent or in the West Burma terrane while it was still a part of that continent, and subsequently deposited in the Carbo-Permian glacial sediments, which represent the immediate sources of the placer diamonds.

We cannot exclude the possibility that the diamonds are derived from primary (lamproitic?) sources within the Proterozoic basement of the western Australian-derived Sibumasu and West Burma terranes. However, the Paleozoic sequence of the Sibumasu terrane appears to have formed the passive continental margin of northwestern Australian Gondwanaland and there is no evidence to suggest the presence of nearby kimberlitic or lamproitic primary sources for the diamonds. It is possible that such sources may lie buried beneath younger sedimentary rocks or that they are yet to be discovered, but the lack of minerals indicative of such sources in the placer deposits suggests that their presence is unlikely.

The Kalimantan diamonds lie in the southwestern Borneo terrane, which had its origin on the South China-Indochina margin (Metcalf, 1996b, 1998); like the alluvial diamonds from eastern Australia, they may be directly or indirectly



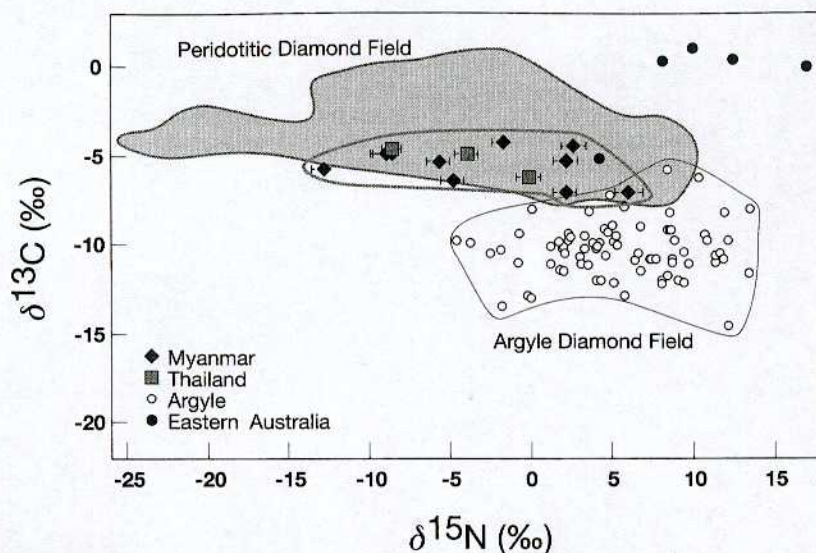


FIG. 7.  $\delta^{13}\text{C}$ - $\delta^{15}\text{N}$  relationships in diamonds from Myanmar and Thailand, compared to the worldwide distribution and diamonds from the Argyle (Australia) lamproite and alluvial deposits in eastern Australia. Data for worldwide peridotitic diamonds from Cartigny et al. (1998), data for Argyle from Boyd et al. (1994) and Van Heerden et al. (1995a, b).

related to subduction processes (Griffin et al., 2000). Alternatively, they may have been derived from the Sibumasu terrane before the rotation of the southwestern Borneo terrane away from Indochina (Metcalf, 1996b, 1998). More detailed studies of the Kalimantan diamonds will be required to evaluate their origin(s); the data presented here and by Davies (1998) and Davies et al. (1999) provide the comparative database necessary for such evaluation.

### Conclusions

1. The alluvial diamonds of the Sibumasu terrane are derived from a largely peridotitic (harzburgitic) mantle with a minor eclogitic component; the latter type is more abundant in the Myanmar samples. The nitrogen aggregation states of the diamonds indicate a long high-temperature history, and their carbon and nitrogen isotope compositions distinguish them from the diamonds of eastern Australia, which are of probable subduction origin.

2. The rounded forms and polished surfaces of most of these diamonds are the result of resorption in a corrosive magma. Some features of the diamonds, including the polishing, oscillatory blue-yellow CL patterns, and the abundance of plastic deformation, are more common in diamonds carried to the surface by lamproitic, rather than kimberlitic, magmas.

3. Surface features including abrasion, breakage, and abundant brown radiation damage spots, and the lack of associated mantle-derived indicator minerals, suggest that the diamonds have spent considerable time in high-energy surface environments and may have travelled far from their primary sources.

4. The distribution of the diamonds within the Sibumasu terrane, and their close geographic association with Carboniferous glacial-marine sediments, suggest that the diamonds were derived from primary sources in northwestern Australia, or within the terrane itself, prior to the Early Permian separation of the Sibumasu terrane from the Gondwanaland

margin. The isotopic composition of carbon and nitrogen in the Sibumasu diamonds, and their dominantly peridotitic paragenesis, rule out the Argyle lamproite of northwestern Australia as a possible source but do not further constrain the source.

### Acknowledgments

We are especially indebted to the Myanmar Ministry of Mines for providing some of the diamonds used in this study. John Cochran of CSIRO Division of Coal and Energy Technology (DCET) provided extensive assistance with the SEM studies. Tony Vasallo, also of DCET, kindly provided access to his FTIR equipment and much help with the data acquisition. Judith Milledge provided the FTIR software and training in its use during an extended visit by RMD to her laboratory. Norm Pearson and Carol Lawson helped greatly with the electron microprobe analyses. We also thank Jeff Harris, Bruce Wyatt, and Simon Shee for many useful discussions on aspects of diamond mineralogy. This work was supported by CSIRO-DEM a GEMOC seeding grant and Kasetsart University funds. This is contribution 226 from the ARC National Key Centre for the Geochemical Evolution and Metallogeny of Continents ([www.es.mq.edu.au/GEMOC/](http://www.es.mq.edu.au/GEMOC/)).

February 29, September 14, 2000

### REFERENCES

- Allen, B.P., and Evans, T., 1981, Aggregation of nitrogen in diamond, including platelet formation: Royal Society of London Proceedings, v. A375, p. 93-104.
- Barron, L.M., Lishmund, S.R., Oakes, G.M., Barron, B.J., and Sutherland, F.L., 1996, Subduction model for the origin of some diamonds in the Phanerozoic of eastern New South Wales: Australian Journal of Earth Sciences, v. 43, p. 257-267.
- Boyd, S.R., and Pillinger, C.T., 1994, A preliminary study of  $^{15}\text{N}/^{14}\text{N}$  in octahedral growth form diamonds: Chemical Geology, v. 116, p. 43-59.
- Bulanova, G.P., 1995, The formation of diamond: Journal of Geochemical Exploration, v. 53, p. 1-23.



- Cartigny, P., Harris, J.W., Phillips, D., Girard, M., and Javoy, M., 1998, Subduction-related diamonds? The evidence for a mantle derived origin from coupled  $\delta^{13}\text{C}$ - $\delta^{15}\text{N}$  determinations: *Chemical Geology*, v. 147, p. 147-159.
- Davies, R.M., 1998, Alluvial diamonds from eastern Australia: Unpublished Ph.D. thesis, North Ryde, NSW, Australia, Macquarie University, 275 p.
- Davies R.M., O'Reilly S.Y., and Griffin W.L. 1999, Diamonds from Wellington, NSW: New insights into the origin of eastern Australian diamonds: *Mineralogical Magazine*, v. 47, p. 447-471.
- De Corte, K., Cartigny, P., Shatsky, V.S., Sobolev, N.V., and Javoy, M., 1999, Characteristics of microdiamonds from UHPM rocks of the Kokchetav massif (Kazakhstan): International Kimberlite Conference, Cape Town, 7th, Proceedings, v. 2, p. 174-182.
- Evans, T., 1992, Aggregation of nitrogen in diamonds, in Field, J.E., ed., *The properties of synthetic and natural diamonds*: Carlton, Victoria, Blackwell, Academic Press, p. 259-290.
- Evans, T., and Harris, J.W., 1989, Nitrogen aggregation, inclusion equilibration temperatures and the age of diamonds: Geological Society of Australia Special Publication 14, p. 1002-1006.
- Finnie, K.S., Fisher, D., Griffin, W.L., Harris, J.W., and Sobolev, N.V., 1994, Nitrogen aggregation in metamorphic diamonds from Kazakhstan: *Geochimica et Cosmochimica Acta*, v. 58, p. 5173-5177.
- Garson M.S., Mitchell A.H.G., Young W., and Tait N., 1975, Tin-tungsten exploration on the Thai peninsula: London, Institute of Geoscience Memoir 1, 112 p.
- Griffin, W.L., O'Reilly, S.Y., and Davies, R.M., 2000, Subduction-related diamond deposits? Constraints and possibilities: *Reviews in Economic Geology*, v. 11, p. 291-310.
- Gurney, J.J., 1989, Diamonds: Geological Society of Australia Special Publication 14, p. 935-965.
- Hall, A.E., and Smith, C.B., 1984, Lamproite diamonds—are they different? University of Western Australia, Department of Geology Publication 8, p. 167-212
- Jaques, A.L., Hall, A.E., Sheraton, J.W., Smith, C.B., Sun, S.S., Drew, R.M., Foudoulis, C., and Ellingsen, K., 1989, Composition of crystalline inclusions and C-isotopic composition of Argyle and Ellendale diamonds: Geological Society of Australia Special Publication 14, p. 966-989.
- Kirkley, M.B., Gurney, J.J., Otter, M.L., Hill, S.J., and Daniels, L.R., 1991, The application of C isotope measurements to the identification of the sources of C in diamonds: A review: *Applied Geochemistry*, v. 6, p. 477-494.
- Mahlzan, H., 1997, Diamonds, in *Gem News, Gems and Gemology* (Spring ed.), p. 60-61.
- McCallum, M.E., Huntley, P.M., Falk, R.W., and Otter, M.L., 1994, Morphological, resorption and etch feature trends of the diamonds from kimberlite populations within the Colorado-Wyoming state line district, USA: Brasilia, Companhia de Pesquisa de Recursos Special Publication 1B, v. 2, p. 32-50.
- Mendelssohn, M.J., and Milledge, H.J., 1995, Geologically significant information from routine analysis of the mid-infrared spectra of diamonds: *International Geology Review*, v. 37, p. 95-110.
- Metcalf, I., 1996a, Pre-Cretaceous evolution of SE Asian terranes: Geological Society Special Publication 106, p. 97-122.
- 1996b, Gondwanaland dispersion, Asian accretion and evolution of eastern Tethys: *Australian Journal of Earth Sciences*, v. 43, p. 605-623.
- 1998, Palaeozoic and Mesozoic geological evolution of the SE Asian region: Multidisciplinary constraints and implications for biogeography, in Hall, R., and Holloway, J.D., eds., *Biogeography and geological evolution of SE Asia*: Amsterdam, Netherlands, Backhuys, p. 25-41.
- Meyer, H.O.A., 1987, Inclusions in diamond, in Nixon, P.H., ed., *Mantle xenoliths*: New York, NY, John Wiley and Sons, p. 501-522.
- O'Reilly, S.Y., 1989, Nature of the east-Australian lithosphere, in Johnson, R.W., ed., *Intraplate volcanism in eastern Australia and New Zealand*: Cambridge University Press, p. 290-297.
- Otter, M.L., and Gurney, J.J., 1989, Mineral inclusions in diamond from the Sloan diatremes, Colorado-Wyoming state line kimberlite district, N. America: Geological Society of Australia Special Publication 14, p. 1042-1053.
- Robinson, D.N., Scott, J.A., van Niekerk, A., and Anderson, V.G., 1989, The sequence of events reflected in the diamonds of some southern African kimberlites: Geological Society of Australia Special Publication 14, p. 990-1000.
- Sobolev, N.V., and Shatsky, V.S., 1990, Diamond inclusions in garnets from metamorphic rocks: A new environment for diamond formation: *Nature*, v. 343, p. 742-746.
- Sobolev, N.V., Galimov, E.M., Ivanovskaya, I.N., and Yefimova, E.S., 1979, Isotopic composition of carbon from diamonds containing inclusions: *Akademiya Nauk SSR Doklady*, v. 249, p. 1217-1220 (in Russian).
- Taylor, W.R., Jaques, A.L., and Ridd, M., 1990, Nitrogen-defect aggregation characteristics of Australasian diamonds: Time-temperature constraints on the source regions of pipe and alluvial diamonds: *American Mineralogist*, v. 75, p. 1290-1310.
- van Heerden, L.A., Gurney, J.J., and Deines, P., 1995a, The carbon isotopic composition of harzburgitic, lherzolitic, websteritic and eclogitic diamonds from southern Africa: A comparison of genetic models: *South African Journal of Geology*, v. 98, p. 119-125.
- van Heerden, L.A., Boyd, S.R., Milledge, J.H., and Pillinger, C.T., 1995b, The carbon- and nitrogen-isotopes characteristics of the Argyle and Ellendale diamonds, Western Australia: *International Geology Review*, v. 37, p. 39-50.
- Win, T.T., Davies, R., and Griffin, W.L., 2000, Distribution and characteristics of diamonds from Myanmar: *Journal of Asian Earth Science*, in press.