

# 1 Introduction

Magmatic Nickel-Copper-Platinum-group element sulfide deposits form as the result of the segregation and concentration of droplets of liquid sulfide from mafic or ultramafic magma, and the partitioning of chalcophile elements into these from the silicate magma.

The size of the deposits, their grades and ratios of economic metals are very variable. This is illustrated in Table 1.1, which summarizes data on tonnes of resources + production, grades of Ni, Cu, Co and PGE, tonnes of contained metal, and value of the ore and of the individual metals. It is also illustrated in Fig. 1.1, which shows the percentages that Ni+Co, Cu and the PGE contribute to the value of many magmatic sulfide deposits/camps.

## 1.1 Classification of Magmatic Sulfide Deposits

The deposits fall naturally into two major groupings, those that are of value primarily because of their Ni and Cu, and which tend to be rich in sulfide with the ore containing 20 to 90 percent sulfide, and those of value primarily because of their PGE, which tend to be sulfide poor with the ore containing 0.5 to 5 percent sulfide (see Fig. 1.1). With certain exceptions, sulfide-rich types cluster at the nickel apex of the diagram; many of the smaller deposits and camps, which are not included in this compilation, also fall in this area. Sulfide-poor PGE-rich deposits cluster near the PGE apex. Exceptions to this grouping are the Platreef, which consists of a cloud of stratigraphically controlled, weakly disseminated sulfides, and the deposits of the Noril'sk and Duluth regions. The Cu-rich footwall ores at Sudbury also plot in the intervening area, but these have been derived from the contact ores (see Chap. 8) and do not constitute a separate camp, merely a sub-type of mineralization that occurs within the Sudbury camp.

In this book, the primary division of magmatic sulfide deposits is between the sulfide-poor type that cluster close to the PGE apex of Fig. 1.1 and those much richer in sulfide for which Ni and Cu together constitute the metals of major economic interest. Because of their origin, magmatic

**Table 1.1.** Estimated resources (including that already mined) and values of main deposits of Ni-Cu and PGE sulfide ores1. Ore resources (including that already mined) and average metal concentrations in the ores<sup>1</sup>

Deposit/camp	Ore resource [10 <sup>6</sup> t]	Ni wt%	Cu wt%	Co wt%	Pt g/t	Pd g/t	Rh g/t	Ru g/t	Ir g/t	Os g/t	Total PGE g/t
Noril'sk region <sup>2</sup>	1309.3	1.77	3.57	0.061	1.84	7.31	0.191	0.093	0.026	0.036	9.50
Sudbury <sup>3</sup>	1648.0	1.20	1.08	0.038	0.46	0.58	0.056	0.044	0.019	0.008	1.17
Duluth <sup>4</sup>	4000.0	0.20	0.60	0.019	0.15	0.49	0.007	0.007	0.003	0.003	0.66
Jinchuan <sup>5</sup>	515.0	1.06	0.75	0.019	0.13	0.10	0.005	0.010	0.010	0.011	0.26
Pechenga <sup>6</sup>	339.0	1.18	0.63	0.045	0.12	0.17	0.005	0.007	0.004	0.006	0.32
Thompson <sup>7</sup>	150.3	2.32	0.16	0.046	0.10	0.54	0.046	0.072	0.033	0.041	0.83
Mt Keith <sup>8</sup>	478.0	0.60	0.01	0.014	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Voisey's Bay <sup>9</sup>	136.7	1.59	0.85	0.090	0.07	0.10	0.005	0.007	0.002	0.002	0.19
Kambalda <sup>10</sup>	67.0	2.90	0.21	0.207	0.30	0.42	0.065	0.197	0.047	0.097	1.13
Perseverance (Agnew) <sup>11</sup>	52.0	1.90	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Raglan <sup>12</sup>	24.7	2.72	0.70	0.054	0.82	2.27	0.150	0.374	0.065	0.080	3.76
Total Bushveld	11549.9	0.13	0.06	0.00	2.87	1.80	0.307	0.539	0.100	0.054	5.67
- UG-2 <sup>13</sup>	5742.6	0.04	0.02	0.00	2.66	1.71	0.428	0.710	0.131	0.062	5.70
- Merensky <sup>13</sup>	4210.0	0.15	0.06	0.00	3.57	1.85	0.216	0.449	0.082	0.051	6.21
- Platreef <sup>14</sup>	1597.3	0.41	0.20	0.00	1.77	2.01	0.114	0.165	0.038	0.033	4.12
Great Dyke <sup>15</sup>	2574.0	0.21	0.14	0.00	2.77	2.13	0.130	0.289	0.052	0.047	5.42
Stillwater <sup>16</sup>	32.3	0.05	0.02	0.00	5.30	19.11	0.270	0.100	0.096	0.043	24.91
Portimo Area <sup>17</sup>	218.6	0.08	0.18	0.00	0.38	1.54	0.00	0.00	0.00	0.00	1.92
Lac des Iles <sup>18</sup>	94.1	0.05	0.06	0.00	0.18	1.66	0.008	0.00	0.00	0.00	1.85

**Table 1.1** (cont.)

## 2. Metal resources (including that already mined out)

Deposit/camp	Ni [10 <sup>3</sup> t]	Cu [10 <sup>3</sup> t]	Co [10 <sup>3</sup> t]	Pt [t]	Pd [t]	Rh [t]	Ru [t]	Ir [t]	Os [t]	Total PGE, [t]
Noril'sk region <sup>2</sup>	23201	46728	801	2412	9573	250	122	34	47	12438
Sudbury <sup>3</sup>	19776	17798	621	763	961	92	73	31	13	1933
Duluth <sup>4</sup>	8000	24000	757	585	1959	27	27	11	12	2621
Jinchuan <sup>5</sup>	5459	3888	99	65	51	3	5	5	6	135
Pechenga <sup>6</sup>	4000	2150	152	41	59	2	2	1	2	107
Thompson <sup>7</sup>	3486	243	69	15	80	7	11	5	6	124
Mt Keith <sup>8</sup>	2868	57	67							
Voisey's Bay <sup>9</sup>	2174	1162	123	10	13	1	1	0	0	26
Kambalda <sup>10</sup>	1943	144	139	20	28	4	13	3	7	75
Perseverance (Agnew) <sup>11</sup>	988	49								
Raglan <sup>12</sup>	672	173	13	20	56	4	9	2	2	93
Total Bushveld	15276	6881		33111	20803	3548	6231	1157	623	65473
– UG-2 <sup>13</sup>	2412	1034		15279	9809	2457	4077	752	356	32730
– Merensky <sup>13</sup>	6315	2652		15012	7790	909	1891	345	214	26161
– Platreef <sup>14</sup>	6549	3195		2820	3204	182	263	60	53	6582
Great Dyke <sup>15</sup>	5405	3604		7130	5483	335	744	135	120	13946
Stillwater <sup>16</sup>	15	7		171	616	9	3	3	1	804
Portimo Area <sup>17</sup>	175	393		83	337					420
Lac des Iles <sup>18</sup>	50	58		17	156	1				174

**Table 1.1** (cont.)

3. Value of ore resources (millions US\$), value of ore (US\$ per tonne) and proportion (%) that PGE contribute to total value<sup>19</sup>

Deposit/camp	Ni	Cu	Co	Pt	Pd	Rh	Ru	Ir	Os	Total	Ore (US\$/t)	PGE (%)
Noril'sk region <sup>2</sup>	191870	77101	18029	49864	59734	4591	352	98	135	401774	307	29
Sudbury <sup>3</sup>	163548	29367	13972	15765	5998	1682	210	91	38	230670	140	10
Duluth <sup>4</sup>	66160	39600	17033	12093	12224	500	78	31	34	147753	37	17
Jinchuan <sup>5</sup>	45146	6415	2238	1354	316	46	15	15	17	55562	108	3
Pechenga <sup>6</sup>	33080	3548	3420	847	366	34	7	4	6	41312	122	3
Thompson <sup>7</sup>	28828	402	1555	310	502	126	31	14	18	31786	212	3
Mt. Keith <sup>8</sup>	23718	95	1506							25319	53	
Voisey's Bay <sup>9</sup>	17975	1917	2768	212	82	12	3	1	1	22971	168	1
Kambalda <sup>10</sup>	16069	237	3123	417	175	79	38	9	19	20166	301	4
Perseverance (Agnew) <sup>11</sup>	8171	82								8252	159	0
Raglan <sup>12</sup>	5556	286	298	421	349	68	27	5	6	7015	284	12
Total Bushveld	126332	11353		684404	129811	65035	18008	3344	1800	1040086	90	87
- UG-2 <sup>13</sup>	19946	1706		315817	61208	45037	11783	2173	1029	458698	80	95
- Merensky <sup>13</sup>	52225	4376		310298	48610	16662	5465	997	618	439251	104	87
- Platreef <sup>14</sup>	54161	5271		58289	19993	3336	760	173	153	142137	89	58
Great Dyke <sup>15</sup>	44703	5946		147377	34212	6146	2149	390	346	241269	94	79
Stillwater <sup>16</sup>	124	12		3533	3846	160	9	9	4	7698	239	98
Portimo Area <sup>17</sup>	1446	649		1717	2101					5913	27	65
Lac des Iles <sup>18</sup>	412	96		350	975	14				1848	20	72

**Table 1.1** (cont.)

<sup>1</sup>Metal contents are in situ, with no allowances made for dilution or loss on beneficiation.

<sup>2</sup>estimate, Naldrett and Searcy (unpublished data), based on analytical data of Naldrett et al. (1996), Distler and Kunilov (1994).

<sup>3</sup>reserves and Ni grade after Naldrett et al. (1989); Cu/Ni, Co/Ni and PGE/Ni ratios after data of Naldrett et al. (1999) (~350 analyses Co, and ~1500 analyses PGE in typical Sudbury ores).

<sup>4</sup>tonnage, Ni and Cu grade from Listerud and Meinecke (1977); Co/Ni and PGE/Ni ratios from Naldrett (1989).

<sup>5</sup>tonnage and Ni grade from Chai and Naldrett (1992); Cu/Ni, Co/Ni, PGE/Ni ratios from Tang (1993), his Table IV.

<sup>6</sup>Ni data from Green (personal communication 1999); Cu/Ni and PGE/Ni ratios from Brugmann et al. (2000).

<sup>7</sup>reserves of Ni from INCO Ltd, Cu/Ni ratio from Theyer (1980), Co/Ni and PGE/Ni ratios from data of Bleeker (1990).

<sup>8</sup>Ni data from poster at AGSO meeting, Canberra, 1996.

<sup>9</sup>tonnage and Ni, Cu and Co grades, Lightfoot and Naldrett (1999); PGE data obtained from PGE/Ni ratios of 190 samples with >20% sulfide from Naldrett et al. (2000a).

<sup>10</sup>tonnage and Ni grade from Stone and Masterton (1998); Cu/Ni and PGE/Ni ratios from Naldrett (1989); Co/Ni ratio is an average value from Leshar (1989), his Table 5.1.

<sup>11</sup>Ni data from poster at AGSO meeting, Canberra, 1996; Ni/Cu from Keays and Davidson (1976).

<sup>12</sup>Data from Leshar, ed (1999).

<sup>13</sup>tonnes of PGE from Vermaak (1995), his Table 2.7; grade of total PGE from Vermaak (1995) his Table 2.1; Ni and Cu grades using Ni/(Pt+Pd) and Cu/Ni ratios of Naldrett (1989).

<sup>14</sup>tonnes of PGE from Vermaak (1995), his Table 2.7; grade of total PGE from Vermaak (1995, p. 17); Ni and Cu grades from Naldrett (1989).

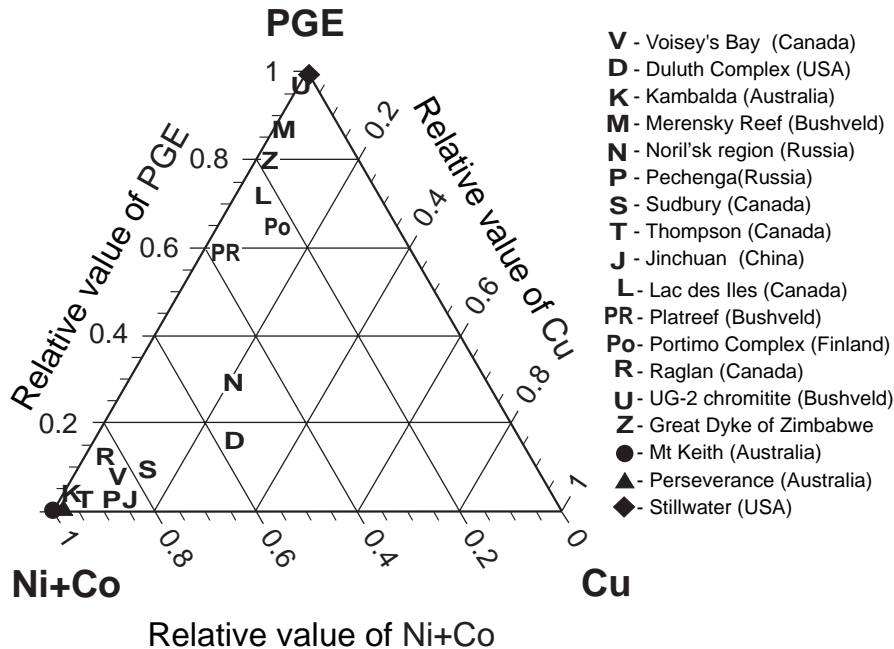
<sup>15</sup>PGE data from Vermaak (1995); Ni/(Pt+Pd) and Cu/(Pt+Pd) ratios from study of Naldrett and Wilson (1990).

<sup>16</sup>tonnes and grade of (Pt+Pd) of proven and probable reserves for Stillwater and East Boulder mines from Zientek et al. (2002); Pt/Pd ratio from Vermaak (1995); Ni and Cu calculated using Zientek et al.'s Pt and Pd data and Naldrett's (1989) ratios for Ni/(Pt+Pd) and Cu/(Pt+Pd).

<sup>17</sup>information from release on Internet by Arctic Platinum Partnership (Goldfields and Outokompu), July 2002.

<sup>18</sup>data for tonnage and Pt and Pd grades as given at Cordilleran Round-up, Vancouver, January 2000; metal:Pd ratios from Naldrett (private data).

<sup>19</sup>Prices used for April 2003: Ni = 8.27 US\$/kg (3.75 US\$/lb); Cu = 1.65 US\$/kg (0.75 US\$/lb); Co = 22.05 US\$/kg (10.00 US\$/lb); Pt = 20.67 US\$/g (643 US\$/troy oz); Pd = 6.24 US\$/g (194 US\$/troy oz); Rh = 18.33 US\$/g (570 US\$/troy oz); Ru = 2.89 US\$/g (90 US\$/troy oz); Ir = 2.89 US\$/g (90 US\$/troy oz); Os = 2.89 US\$/g (90 US\$/troy oz).



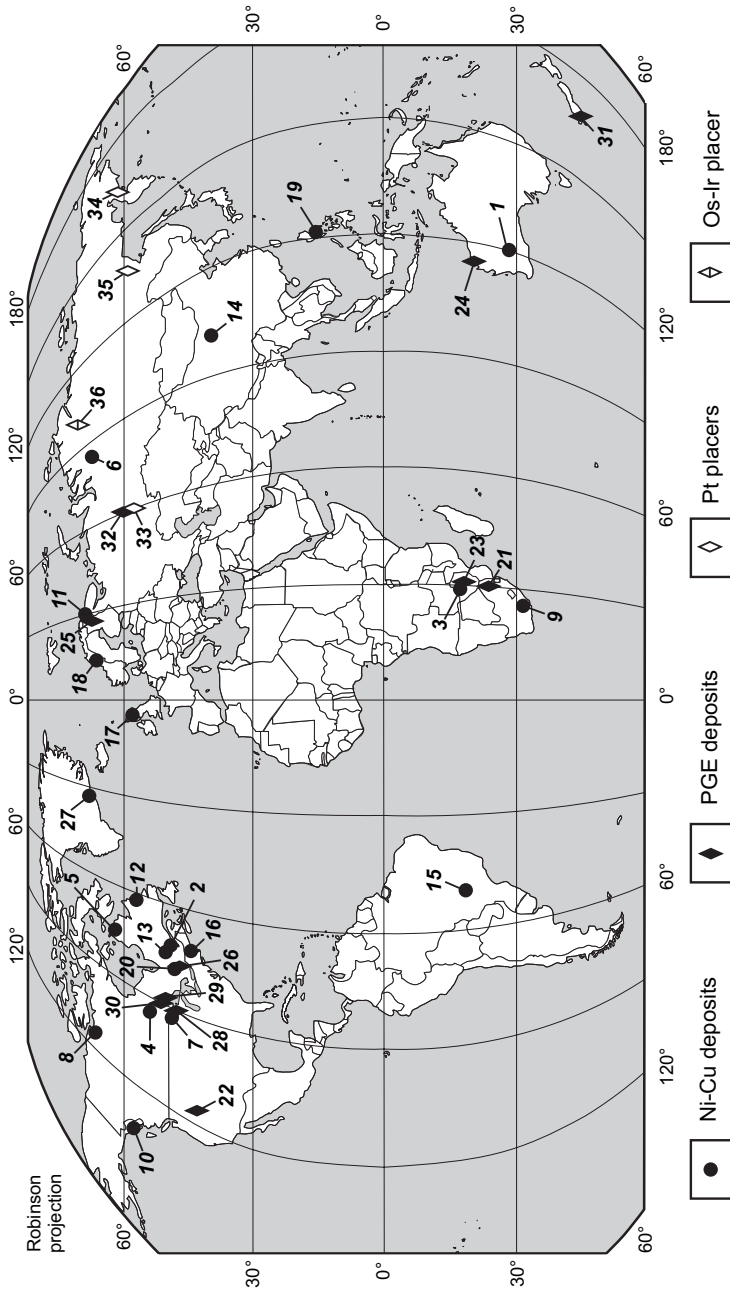
**Fig. 1.1.** Relative value of the contributions of Ni+Co, Cu and PGE to the magmatic sulfide deposits listed in Table 1.1

sulfide deposits are closely related to bodies of mafic or ultramafic rock, and the most convenient way in which to consider them is in terms of the type of magma responsible for the rocks with which they are associated. Typically the type of magma involved bears a close relationship to the tectonic setting within which it was emplaced.

The locations of important deposits, both Ni-Cu dominant and PGE dominant, are shown in Fig.1.2.

Considering first Ni-Cu deposits, these are further divided into six classes (Table 1.2) on the basis of their associated magma type. Class NC-1 (Chap. 3) comprises those related to komatiitic magmatism. Currently known deposits fall into two sub-classes, those related to Archean komatiites (e.g. the deposits of Western Australia, Zimbabwe and the Abitibi belt of Canada) and those related to Proterozoic komatiites (e.g. those of the Raglan and Thompson belts which are both in Canada)<sup>1</sup>. The

<sup>1</sup> References for the literature related to individual deposits or camps are given in this section only in cases in which the deposits are not mentioned in subsequent chapters of this book.



**Fig. 1.2.** Geographic distribution of the world's most important magmatic sulfide Ni-Cu and PGE deposits. Numbers of the deposits correspond to those used in Tables 1.2 and 1.3

**Table 1.2.** Classification of sulfide nickel-copper deposits based on “petro-tectonic setting”

Class	Related Magmatism	Camps and deposits (No on Figure 1.2, name and age)	Tectonic Setting of magmatism
NC-1	Komatiite	1 = Wiluna-Norseman greenstone belt (Kambalda, Mt Keith, Perseverance and others) (A) 2 = Abitibi (A) 3 = Zimbabwe (A)	Greenstone belts (rift?)
		4 = Thompson (PPR) 5 = Raglan (PPR)	Rifted Continental Margin
NC-2	Flood Basalt	6 = Noril'sk (Ph) 7 = Duluth (NPR) 8 = Muskox (NPR)	Rift (Triple junction)
		9 = Insizwa (Ph)	Rifted Continental Margin
		10 = Wrangelia (Ph)	Rifted Island Arc
NC-3	Ferropicrite	11 = Pechenga (MPR)	Rifted Continental Margin
NC-4	Anorthosite-Granite-Troctolite	12 = Voisey's Bay (NPR)	Rift
NC-5	Miscellaneous Picrite-Tholeiite	13 = Montcalm (A)	Greenstone belts (rift?)
		14 = Jinchuan (MPR)	Rifted Continental Margin
		15 = Niquelandia (MPR)	Continental rift
		16 = Moxie (Ph) 17 = Aberdeenshire Gabbros (Ph) 18 = Rona (Ph)	Orogenic (Compressive)
		19 = Acoje (Ph)	Ophiolite Belt (ocean)
NC-6	Impact Melt	20 = Sudbury (MPR)	Meteorite Impact

Age: A = Archean (>2500 MA); PPR = Paleoproterozoic (2500-2000 MA); MPR = Mesoproterozoic (2000-1400 MA); NPR = Neoproterozoic (1400-600 MA); Ph = Phanerozoic (<600 MA)

tectonic setting of Archean komatiites is debatable, but certainly is related to rifting, while the Proterozoic examples are the result of magmatism that developed at rifted continental margins. With certain exceptions, komatiitic magmatism has become less magnesian and lower in temperature on progressing from the Archean to the Proterozoic, and this accounts for some of the differences between the two sub-classes.



Class NC-2 (Chap. 4) comprises deposits that have developed within the feeders to Flood basaltic magmatism. They can be further subdivided in terms of their tectonic setting: i.e. those related to an intra-continental rift or triple junction (e.g. Noril'sk, Duluth and Muskox); those related to a rifted continental margin (e.g. Insizwa) and those related to flood basalts that have developed in an oceanic environment (e.g. Wrangelia see Chap. 10). The most important deposits belong to the first sub-class, and there are insufficient examples of the other sub-classes to allow one to determine whether there are significant differences within these sub-classes.

Class NC-3 comprises a relatively uncommon magmatic association, that of ferropicrites, for which the only significant example is the Pechenga camp of the Kola peninsular. The tectonic setting is debated (see Chap. 5), but is most likely that of a rifted continental margin.

Class NC-4 covers those deposits that are related to Anorthosite-Granite-Troctolite complexes such as the Nain Plutonic Complex of Labrador, Canada. For many years this association was not thought to be important as a source of magmatic sulfide deposits, but the 1995 discovery of Voisey's Bay deposit (Chap. 6) changed this prevailing viewpoint. Thus far Voisey's Bay is the only significant deposit of this association, although the uneconomic mineralization at Pants Lake (80 km south of Voisey's Bay and also associated with the Nain Plutonic Suite) constitutes another example of sulfides that have developed with this association. As discussed in Chap. 10, the Voisey's Bay deposit appears to be closely related to faulting that may be incipient rifting.

Class NC-5 comprises a miscellaneous grouping of deposits that are all associated with magmas ranging from picritic to tholeiitic in composition. Their tectonic settings are very varied. Montcalm (Barrie and Naldrett 1988) occurs in an Archean greenstone belt and the tectonic setting is undetermined at present. Jinchuan, described in Chap. 7, is associated with a fault system that is interpreted as a rifted continental margin (see Chap. 10). The Niquelandia deposit occurs in one of a series of mafic/ultramafic intrusions which form a belt in the central part of Brazil. The intrusions occur in a mixed psammitic-pelitic sequence of sediments with interlayered volcanic horizons, and are thought to have been intruded into a Mesoproterozoic continental rift that became metamorphosed during Neoproterozoic continental collision (Ferreira-Filho et al. 1995). The Moxie intrusion of Northern Main (Thompson and Naldrett 1984), the Caledonian intrusions of north-eastern Scotland (Fletcher 1987), and the Rona intrusion near Narvik, Norway (Boyd and Mathiesen 1979) were emplaced in a compressive orogenic environment. The Acoje Ni sulfide deposit in the Zambales ophiolite of the Phillipines (Bacuta et al. 1987,

**Table 1.3.** Classification of PGE deposits based on “petro-tectonic setting”

Class	Related Magmas	Intrusive Complex (No on Figure 1.2, name and age)	Tectonic condition of magmatism	Example of deposits (name and type)
PGE-1	High Proportion of U- type magma*, Lesser amount of Tholeiite	21 – Bushveld (PPR)	Intra-Cratonic	Merensky Reef (1); UG-2 Chromitite (3); Platreef (5); Dumite Pipes (8)
		22 – Stillwater (A)	Not determined	J-M Reef (1)
		23 – Great Dyke (A)	Intra-Cratonic Rift	Main Sulfide Zone (2)
PGE-2	U-type and Tholeiite	24 – Munni-Munni i (A)	Intra-Cratonic?	Layer of Porphyritic Websterite (2)
		25 – Penikat (PPR)		SJ Reef (1)
		25 – Portimo (PPR)		SK and RK Reefs (1); Marginal Ore (5)
		26 – East Bull Lake (PPR)	Rifted Continental Margin	Marginal Ore (5)
		26 – River Valley (PPR)		Marginal Ore (5)
27 – Skaergaard (Ph)	Platinova (2)			
PGE-3	Tholeiite	27 – Cap Edvard Holm (Ph)	Rift (Triple junction)	Willow Ridge Reef (1)
		28 – Sonju Lake (NPR)		Sonju Lake "Reef" (2)
		29 – Coldwell (NPR)	Marathon (5); Bermuda (4)	
		30 – Lac des Iles (A)	Robie Zone (7)	
		31 – Longwoods (Ph)	Not determined	Longwoods area (10)
PGE-4	Calc-alkaline mafic	32 – Volkovsky (Ph)		Volkovsky (6); Baron (?)
PGE-5	Ural-Alaskan Ultramafic/Mafic of Alkaline Affinity	33 – Nizhny Tagil and others of Urals Platinum Belt (Ph)	Orogenic (Island Arc)	Soloviev Hills (9); Urals placers (10)
		34 – Koryakia Region (Ph)		Seynav-Galmoznav (10)
PGE-6	Alkaline Mafic/Ultramafic	35 – Kondyor (Ph)	Craton, at boundary with VPB**	Kondyor (10)
		36 – Guli (Ph)	Rift	Ingarinda (10)

Table 1.3. (cont.)

\*U-type magma is high-magnesian basaltic andesite with approx. 52-55wt% SiO<sub>2</sub>, 12-14 wt% Al<sub>2</sub>O<sub>3</sub>, 1000-2000 ppm Cr (Irvine and Sharpe, 1986). \*\*VPB = Volcano-plutonic Belt.

Deposit types: 1-4 = Stratiform deposits: 1 = Sulfide-bearing reef; 2 = Sulfide association, no reef; 3 = Chromitite association; 4 = Magnetite association; 5-6 = Stratabound deposits: 5 = Sulfide association; 6 = Magnetite association; 7-9 = Discordant deposits: 7 = Sulfide association; 8 = Dunite pipes; 9 = Chromitite veinlets and schlieren; 10 = Placers.

Age symbols are explained in Table 1.2

Rossman et al. 1989) is the only known example of a deposit occurring within an ophiolite complex. Sudbury (NC-6) is unique (Chap. 8) and comprises a class on its own, i.e. mineralization that has developed from the melt produced by extra-terrestrial impact (see recent summary by Naldrett 2003).

Considering now sulfide-poor, PGE-rich deposits, the initial division of these deposits is on the basis of petro-tectonic setting, as has been done above for Ni-Cu deposits (Table 1.3). In Chap. 9, where these deposits are discussed in detail, they are further sub-divided on the basis of morphology and predominant mineralogical association of the ore bodies, including whether they are stratiform, stratabound or discordant; and whether the PGE show a sulfide, chromite or magnetite association. As discussed in Chap. 9, it has become apparent (Iligna 1994; Miller and Andersen 2002; Alapieti and Lahtinen 2002), that the largest PGE deposits of the world occur in intrusions (Bushveld Igneous; Stillwater Igneous Complex; Great Dyke of Zimbabwe) that are characterized by a high proportion of an early magma with a distinctive Al<sub>2</sub>O<sub>3</sub>-poor and MgO-, Cr- and yet SiO<sub>2</sub>-rich (U-type) composition, which was followed in the same intrusion by one with a more typical tholeiitic composition. Many of the PGE concentrations occur at levels in the intrusions at which there is trace element evidence of variable degrees of mixing of these two magma types. This association is grouped as a distinctive class, PGE-1, in Fig. 1.2.

Deposits in intrusions that also show evidence of U-type and tholeiitic magmas, but in which the tholeiitic component is dominant are grouped as class PGE-2. These deposits include the Pennikat and Portimo complexes in Finland, and the Munni Munni intrusion in the Pilbarra Archean block of Western Australia.

Class PGE-3 comprises intrusions for which there is no evidence of an early U-type magma, but for which the magma is clearly tholeiitic. Examples include the East Bull Lake and River Valley intrusions respectively west and east of Sudbury, Keweenaw intrusions of the Lake

Superior area including the Sonju Lake intrusion within the Duluth Complex and the Coldwell intrusion (Barrie et al. 2002), the Kap Edvard Holm and Skaergaard intrusions of East Greenland, and the Lac des Iles deposit in Canada.

Calc-alkaline magmatism (Class PGE-4) is known to host PGE concentrations, although none of these have proved to be economic. Examples include intrusions of the Platinum Belt in the Ural mountains of Russia, where at both the Volkovsky deposit and the Baron prospect PGE are concentrated in zones rich in titaniferous magnetite, apatite and Cu sulfides (see Chap. 9 for details). The Longwoods Intrusive Complex (Cowden et al. 1990) is clearly calc-alkaline and forms part of an accreted volcanic terrain at the southern tip of the southern end of the South Island of New Zealand. PGE-bearing gold placers have been derived from the intrusion, but the nature and origin of the primary PGE mineralization is not understood at the present time.

Class PGE-5 deposits are associated with a distinctive style of dominantly ultramafic intrusion that is commonly referred to as the Ural-Alaskan type (Johan 2002). The nature of the magma to which they are related is still not clearly defined, but the primary melt had an alkaline affinity (see Chap. 9). These intrusions are the source of the most important of the world's Pt placers: Soleviev Hills, Urals; Kondyor massif, Eastern Siberia (Malich 1999); and the Seynav-Galmoznav massif, Koryakia, Russia (Batanova and Astrakhantzev 1992; Vidik et al. 1999). Bedrock platinum is associated primarily with veinlets and segregations of remobilized chromite in recrystallised dunite in the Nizhniy Tagil massif of the Urals Platinum Belt (Soloviev Hills deposit) where some mining has taken place. Van Treeck and Newberry (in press) reported hydrothermal remobilized Pt associated with magnetite in the Union bay intrusion of SE Alaska.

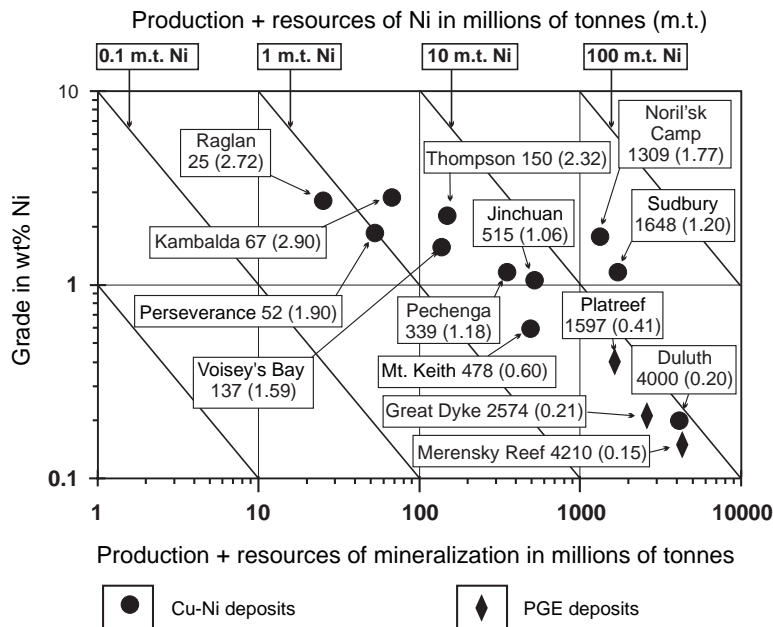
Class PGE-6 covers mineralization associated with carbonatite-bearing mafic/ultramafic intrusions that are clearly alkaline in composition. An example is the Early Triassic Guli intrusion in the northern part of the Siberian platform that is the source of Os-Ir placers (Malich 1999). The placers are not economic, but they are important because they constitute the only significant concentration of Os-Ir minerals in placers, and are exploited on a small scale by local prospectors.

It should be noted that the foregoing classification of deposits that is based primarily on the petrology and to a lesser extent on the tectonic setting of the host magmatic formations is not the only way in which to consider the deposits. A somewhat different scheme for grouping deposits, which is more useful when the objective is exploring for them, is discussed in Chap. 10. Here they are viewed in terms of how they fit into a very

simple scheme of rifting. Discussion of this different scheme has been confined to the end of this book, and it has not been used to guide its layout, because our understanding of the environments of ore formation are constantly changing, and it was thought unwise to use a framework for the book which might itself require modification in a few years. It has been decided, therefore, to use the more firmly established petrogenetic framework that has been outlined above.

## 1.2 Size and Composition of Deposits

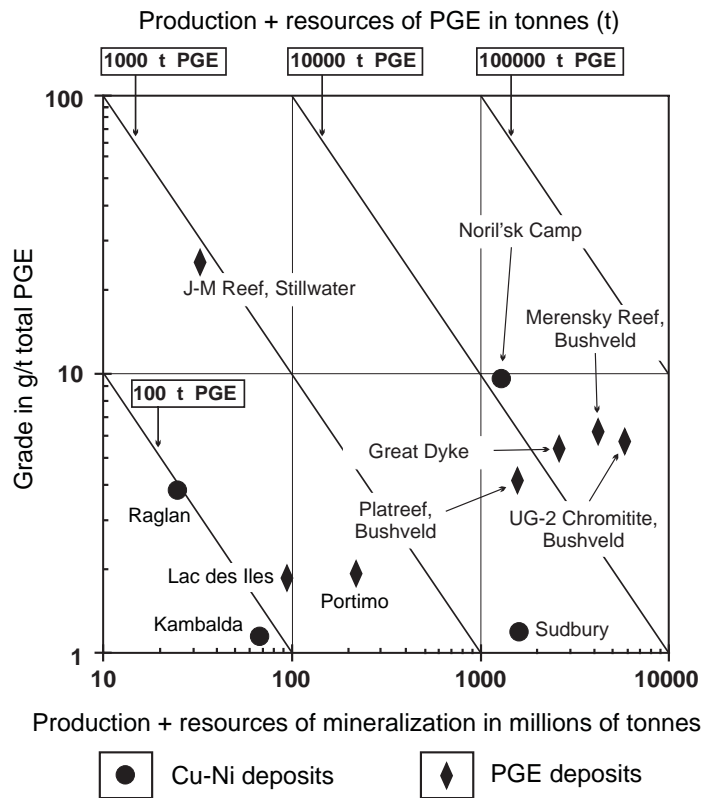
The relative importance of a selected group of the world's largest deposits/camps as a source of Ni is illustrated in Fig. 1.3. The Noril'sk and Sudbury camps dominate in terms of contained Ni, although the Ni/Cu ratio at Noril'sk is approximately 0.5 while at Sudbury it is about 1.1. Duluth represents a major Ni resource, but the low grade (0.2 wt% Ni, 0.66wt% Cu), coupled with environmental constraints on operating large, low grade deposits means that as yet it has not been mined. Excluding Duluth, Jinchuan



**Fig. 1.3.** Plot of grade in wt% Ni versus production + resources of mineralization in millions of tonnes for major Ni and PGE sulfide deposits of the world. Data are from Table 1.1

ranks third in the world in terms of contained Ni, with Pechenga, Thompson, Mt Keith, Voisey's Bay, Kambalda, Perseverance and Raglan in 4th to 10th places respectively. Important reserves of Ni are associated with some PGE deposits (in the reefs of the Bushveld Complex and sulfide zones of the Great Dyke Zimbabwe) but Ni grades are very low (0.04 to 0.41 wt% – Table 1.1) and Ni only constitutes a byproduct.

The importance of deposits in terms of their PGE is illustrated in Fig. 1.4. The sources of these data are explained in Table 1.1. The deposits of the Bushveld complex (Merensky Reef, UG-2 chromitite and Platreef) dominate, although the Noril'sk ores and the Main Sulfide zone in the Great Dyke constitute important resources. It should be noted that despite their near equivalence with regard to total contained Ni, the data indicate that the deposits at Noril'sk contain 6 to 7 times as much PGE as those at Sudbury.



**Fig.1.4.** Plot of grade in g/t total PGE versus production + resources of mineralization in millions of tonnes for major PGE-containing deposits. Data are from Table 1.1

Some important compositional differences exist between Ni-Cu deposits that have formed in association with different magma types. These are illustrated in Table 1.4 and in the Appendix. Most Archean Komatiite-related deposits are characterized by high Ni tenors (=Ni content in 100% sulfide)<sup>2</sup> and high Ni/Cu ratios, which reflect the compositions of their source magmas. The Mt Keith (50) and Epoch (58) deposits have particularly high Ni/Cu ratios, but these deposits have been affected strongly by talc-carbonate alteration, and their compositions have likely been changed by the transfer of Ni from silicates to sulfides during this alteration (Eckstrand 1975).

The Pd/Ir ratio is a measure of the steepness of the PGE profile on a chondrite- or mantle-normalized PGE plot. As pointed out by Naldrett and Duke (1980), Archean komatiite-related deposits have relatively low ratios, while those related to progressively less mafic magmas have progressively higher ratios. This is shown in Table 1.4 in the progressive increase of this ratio from Archean komatiite deposits (typical MgO contents of magma = 30wt%), through Proterozoic komatiite deposits (typical MgO contents = 20wt%), the ferro-picrite related deposits of Pechenga (typical MgO contents = 15wt%), the magnesian basalt-related deposit at Jinchuan (MgO content of magma = 12 wt%) to the deposits at Sudbury and Voisey's Bay. The flood basalt-related deposits, with the exception of In-sizwa, have the highest Pd/Ir ratios of all deposits. The Alexo deposit is exceptional with regard to other Archean komatiite-related deposits in terms of its high Pd/Ir and Pd/Pt ratios and low Ni content in 100% sulfides – in many respects it resembles those deposits that are associated with much less mafic magmas, although the environment at Alexo is one of typical Archean komatiitic lavas.

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<sup>2</sup> In calculating the metal content in 100% sulfide, the whole-rock Ni content is assumed to be all in sulfide, and is then calculated as though it were all in pentlandite containing 36 wt% Ni (a typical value for Sudbury pentlandite). The sulfur required for the pentlandite is then subtracted from the whole rock sulfur content. The same calculation is made for Cu, assuming that it is all present as chalcopyrite, and the sulfur subtracted as was done for Ni. The remaining sulfur is then calculated as though it were present in monoclinic pyrrhotite. The percentages of pentlandite, chalcopyrite and pyrrhotite are combined to give a total percent sulfide in the sample. This gives a conversion factor to recalculate the metals as though they were present in 100% sulfide. Errors will occur in this recalculation if the sulfide content is low, and significant Ni is present in olivine (a correction for this effect is discussed in Chap. 6), or if other minerals, such as pyrite, bornite or chalcocite are present in significant amounts. The errors introduced by assuming fixed compositions for pentlandite and pyrrhotite (both solid solutions) are minor in comparison with other potential errors.

**Table 1.4.** Average Sulfide Compositions of Different Classes of Nickel Deposits (based on data presented in Table 1.1 and in the Appendix)

	Wt% Ni in 100% Sulfide		Ni/Cu	Ni/Co	Pd/Pt	Pd/Ir
	Range	Average				
<b>Archean komatiite-related deposits</b>						
<b>Western Australia</b>						
Kambalda	9–19	14.20	13.50	0.07	1.39	8.87
<b>Zimbabwe (massive ore)</b>						
Trojan		10.80	7.71		0.49	7.14
Epoch		23.60	58.00		0.49	0.95
Shangani		13.33	13.50		0.30	8.58
<b>Canada</b>						
Langmuir		12.33	25.08		1.88	5.88
Alexo		6.42	15.07		2.62	77.27
<b>Proterozoic komatiite-related deposits</b>						
<b>Cape Smith Belt</b>						
Raglan	10.4–15.3	12.8	3.88	0.02	2.84	38.06
<b>Thompson Nickel Belt</b>						
Pipe-2		3.95	24.68	22.00	2.26	2.15
Thompson		8.46	14.32	50.00	4.46	13.40
Bucko Lake		20.85	3.88		2.87	21.19
<b>Flood basalt-related deposits</b>						
Noril'sk		6.25	0.58	58.00	3.43	217.34
Duluth		4.09	0.33	10.50	3.35	184.17
Great Lakes Nickel		5.19	0.52		4.02	303.56
Insizwa		5.88	0.91		2.40	18.12
<b>Anorthosite-related deposits</b>						
Voisey's Bay	3.64–4.61	4.07	1.87	18.00	1.29	59.98
<b>Other deposits</b>						
Pechenga	2.7–13.7	10.49	1.86	26.00	1.33	9.74
Jinchuan	9.4–11.0	10.69	1.76	56.00	1.00	14.37
Sudbury	2.5–8.0	5.5	1.11	32.00	1.26	30.65

A more detailed break-down of these deposits appears in the Appendix

It can be seen from the Appendix that different classes of deposit have characteristic proportions of the PGE, expressed in terms of the ratio of (Pt+Pd)/(Ni+Cu) with PGE expressed in g/t and Ni and Cu expressed in wt%. Essentially all of the komatiite deposits have ratios between 0.1 and 0.5, with the exception of the Raglan deposits, which have ratios of about 0.7 to 0.9. The Sudbury deposits show a variation, depending on location. Typical ore from those on the South Range (see Chap. 8) have ratios from 0.3 to 1, while those on the North and East Ranges have ratios between 0.05 and 0.3. Marked exceptions to this generalization are the Cu-rich



footwall ores of the North and East Ranges which have ratios from 0.5 to 1. The ores at Voisey's Bay, Pechenga and Jinchuan have similar ratios to those at Sudbury, respectively ranging from 0.05 to 0.1, 0.05 to 0.3 and 0.04 to 0.5. Deposits related to Flood basalts are generally characterized by higher proportions of PGE to other metals, with ratios between 0.5 and 5.

As would be expected, deposits that are mined primarily for PGE have  $(\text{Pt}+\text{Pd})/(\text{Ni}+\text{Cu})$  (PGE in g/t, Ni and Cu in wt%) that are much higher than in Ni- and Cu-rich ores. PGE-enriched horizons such as the Merensky and UG-2 Reefs of the Bushveld, the J-M Reef of the Stillwater, the SK Reef of the Portimo area, Finland and the Main Sulfide Zone of the Great Dyke vary between 9 and 350. PGE-rich mineralization in the marginal zones of the East Bull Lake and River Valley intrusions near Sudbury and the Portimo intrusion(s) in Finland is also characterized by high ratios from 11 to 18.

In summary, one can say that most sulfide-rich Ni-Cu deposits have  $(\text{Pt}+\text{Pd})/(\text{Ni}+\text{Cu})$  (PGE in g/t, Ni and Cu in wt%) ratios of less than 0.5, except those related to flood basalts, which have ratios between 0.5 and 5. Most sulfide-poor, PGE-rich deposits have ratios of 10–30, with some exceptional deposits with ratios >100.

The compositional characteristics discussed above are the consequence of the genesis of the sulfides constituting the mineralization, and are unlikely to vary widely within mineralization of the same style within a given area. It is thus important to establish these characteristics at an early stage of exploration, because it will provide a guide as to the kind of deposit that one should be exploring for.

### **1.3 General Considerations for the Genesis of the Deposits**

Key aspects in the genesis of a magmatic sulfide ore deposit are (i) that the host magma becomes saturated in sulfide and segregates immiscible sulfide, (ii) that the sulfides are themselves concentrated in a restricted locality where their abundance is sufficient to constitute ore, and (iii) that these sulfides react with a sufficient amount of magma to concentrate chalcophile elements to an economic level. It is the objective of this section to examine some of the world's major magmatic sulfide camps with a view to determining how these aspects have been fulfilled.

Early segregation of liquid sulfide is not part of the normal cooling and crystallization of mafic magma. The world's important deposits of Ni-Cu sulfides (as opposed to sulfide deposits of interest primarily because of

their PGE content) occur almost exclusively at the base of their associated igneous bodies, which implies that the magmas involved were saturated in sulfide, and carrying excess sulfide at the time of their final emplacement. The high PGE content (1–10 ppb Pt, Pd) of most basaltic magma other than MORB implies that these magmas are not sulfide saturated as they leave the mantle, or during their ascent into the crust. Something has to happen to specific batches of magma prior to emplacement to cause sulfide saturation, if a significant magmatic deposit is to form.

The principal factors controlling the solubility of iron sulfide in a silicate melt are discussed in Chap. 2, in which it is concluded that these are: 1) Pressure; 2) Temperature; 3) FeO+TiO<sub>2</sub> content of the melt; 4) Oxidation state of the melt; 5) Mafic versus felsic components in the melt.

With regard to factor 1, Mavrogenes and O'Neill (1999) have shown that pressure has a negative effect on the ability of a silicate melt to dissolve sulfide, that is, as a melt ascends in the crust, its ability to dissolve iron sulfide increases. Since most melts leave the mantle unsaturated in sulfide, they will not achieve saturation as they ascend to shallower depths (lower pressures). This effect can be offset to some extent by decrease in temperature, which has a negative effect on sulfur solubility (Buchanan and Nolan 1979). Most melts are intruded or extruded close to their liquidus temperatures, indicating that they have cooled during ascent, however the data of Mavrogenes and O'Neill (1999) indicate that the effect of cooling is likely to be less than the effect of decreasing pressure, so that, apart from the influence of changing composition, melts are likely to reach the surface unsaturated in sulfide. Silicates will start crystallizing before sulfides segregate, and any sulfides that develop subsequently will therefore be intermixed with cumulus silicates. Ni-Cu-dominant (as opposed to PGE-dominant) magmatic sulfide deposits need to be much richer in sulfide than will be produced by the co-precipitation of solid silicate and sulfide liquid under cotectic conditions. What is required is for some external factor to bring about the segregation of considerable sulfide in a magma without causing significant silicate crystallization.

Variation in the FeO or TiO<sub>2</sub> content (factor 3), while occurring as a magma crystallizes and fractionates, is also not something which is readily imposed on a magma externally, and, in general, these elements either remain constant (FeO), or increase (TiO<sub>2</sub>) during the early stages of fractional crystallization, thus adding to the ability of the melt to dissolve sulfide. Oxidation (factor 4) is capable of causing sulfide precipitation without necessarily causing silicates to form; to this author's knowledge, the only situation where this might have played a role is that of the Platreef of the Bushveld Complex, where the Bushveld magma has ingested a large amount of limestone from adjacent country rocks (Buchanan and Rouse

1984). This is however a deposit of rather weakly disseminated sulfide, important primarily for its PGE content. As will be seen in Chap. 2, felsification of a mafic magma, and the addition of sulfur from an external source, are the most important causes of sulfide segregation. PGE deposits in layered intrusions, such as the Merensky Reef of the Bushveld Complex and the J-M Reef of the Stillwater Complex have different characteristics, and are the result of different genetic processes, as is brought out in Chap. 9.

The composition of the sulfide liquid responsible for a deposit of magmatic sulfide depends on (a) the composition of the silicate magma with which the sulfide liquid reacted, (b) the value of the coefficients governing the partitioning of elements between silicate magma and sulfide liquid, (c) the ratio of silicate magma to sulfide liquid involved in the reaction. The effect of magma composition on the resulting magmatic sulfide deposit is considered for individual deposit types in many of the following chapters. Factors (b) and (c) are discussed in Chap. 2.

As with silicate liquids, sulfide liquids do not normally freeze in situ, but cool slowly, depositing cumulates of early forming nickeliferous pyrrhotite (monosulfide solid solution or mss) with the remaining liquid becoming steadily depleted in Fe and enriched in Cu. Commonly, this liquid escapes from early-forming cumulates, so that some parts of a deposit are enriched in cumulates, and others are enriched in the crystallization products of the fractionated liquid (Ebel and Naldrett 1997; Naldrett et al. 1997). This is also discussed below. Sulfide systems react much more rapidly at a given temperature than silicate systems, so that the mineralogy of a magmatic sulfide deposit is the result of the equilibration of the initially-formed minerals over a range of subsolidus temperatures, down to below 150°C. Sulfide phase equilibria governing these reactions are also discussed in Chap. 2.

The order of chapters subsequent to Chap. 2 requires some comment. In general it follows the classification scheme proposed above. Class NC-1, komatiite-related deposits, are discussed first in Chap. 3. Class NC-2, deposits related to flood basalt magmatism are the focus of Chap. 4. Class NC-3, deposits related to ferropicritic magmatism form the focus of chapter 5, while Class NC-4 (anorthosite-granite-troctolite-related deposits) is discussed in Chap. 6. Jinchuan is by far the most important deposit belonging to Class NC-5 and this is described in Chap. 7. Sudbury (Class NC-6) is the oldest of the major magmatic sulfide districts, and, from a historical perspective, has received the greatest amount of attention from researchers over the longest time and is the subject of Chap. 8. As discussed above, PGE deposits occur associated with many different magma types. Descriptions of many of these, and a discussion of the genesis of the different

styles of mineralization involved are found in Chap. 9. This book concludes with a chapter (Chap. 10) summarizing key factors that have arisen from consideration of individual districts, and outlining guidelines for using these factors in exploration.