

magmas have intruded along folded strata that form basins in the floor, as at Noril'sk-Talnakh. Higher in the sequence, the sulphides occur in the ultramafic bases of rhythmically cyclic units. Where the magmas have intruded the pyritic Virginia formation as sills, massive and massive breccia-filled or vein ores are developed, but although some assimilation of sulphur has been inferred (Mainwaring and Naldrett, 1977), now there is evidence of significant ingestion of sediments. However, the majority of ores are either net-textured or disseminated types.

Work by the Minnesota Department of Natural Resources (MDNR, 1977), based on 324 boreholes over a limited area, and some limited bulk sampling at INCO's Spruce pit, recognized only 2359 Mt of ore with a grade of 0.66 per cent copper and 0.20 per cent nickel. All the data from the bulk sampling suggest an average grade of 0.124 g/t PGE, which agrees well with the ores of the related Great Lakes nickel deposit in Canada (Vermaak, 1985a). The average distribution of the individual PGE is platinum 20.52 per cent, palladium 76.43 per cent, ruthenium, 1.18 per cent, rhodium 1.42 per cent, iridium 0.17 per cent, and osmium 0.28 per cent. These data include the preliminary results of flotation tests undertaken by Inco, which yielded a concentrate of 4.49 g/t PGE. The identified resources (provisional) of the Duluth Complex are shown in Table 2.21. The term provisional is used, since it is clearly risky to apply the PGE grade in a small area to the entire 11 000 Mt of reserves.

2. The Crillion-La Perouse Complex in the southern

Fairweather Range of Alaska contains the Brady Glacier deposit near the base of a 10 000 m thick synformal layered intrusion (US National Materials Advisory Board, 1980). The massive and disseminated copper-nickel ores occur in peridotite and gabbro, and reserves reportedly total more than 90,7 Mt of ore containing 0.5 per cent nickel and 0.3 per cent copper. The disseminated ore contains 0.19 g/t, and the massive ore 1.31 g/t, of Pt+Pd in the ratio 1:1.125. The limits of the orebody have not been determined, since it extends under moving glacial ice.

3. The New Rambler mine occurs in the Centennial mining district, near the crest of the Medicine Bow Mountains in Albany county, southeastern Wyoming, with the Independence, Kentucky Derby, and Mother Lode mines in the close vicinity. Shear zones of intense cataclastic deformation have hydrothermally and metasomatically altered the rocks of the Mullen Creek and Elkhorn layered ultramafic to mafic complexes (Loukes, 1989; Loukes and Glasscock, 1989), which are related to the undeformed and unaltered Lake Owen complex of the same age (c. 1775 My). Originally, the mineralization in this area was considered to be hydrothermal in origin (McCallum *et al.*, 1976; Naldrett, 1989) but later authors have queried this contention.

Loukes (1989) has described the Mullen Creek complex, which was emplaced in supracrustal gneisses subjected to an almandine-amphibolite metamorphic grade, as having a strike length of about 41 km, a thickness of about 8500 m, and an outcrop area of 200 km<sup>2</sup>. The northwestern margin

of the complex was tectonically juxtaposed against Archaean gneisses of the Wyoming craton, while shearing along the mylonite suture dragfolded the sill-like Mullen Creek layered intrusion into a closed, U-shaped isoclinal syncline with near-vertical dips. Some 12 cyclic units have been recognized in the ultramafic to mafic sequences. The lower layers contain the cumulus sulphide mineralization in chromite-harzburgerite and harzburgerite layers at the base of several cyclic units. Loukes (*op. cit.*) suggests that they have a magmatic origin in an island-arc tectonic setting. He unfortunately provides virtually no data on the grade and reserves of the sulphides.

The New Rambler mine closed as a result of a fire in 1918. Three podlike lenses of massive ore were mined in a shear zone, giving rise to a 50 000 t waste dump consisting mainly of material from the alteration envelope which surrounded the ore. The dump was sampled by Theobald and Thompson (1968), and assayed 3 per cent copper and 1 g/t PGE. They quote older 'representative ore' as containing 5 per cent copper, 12.44 g/t platinum, and 18.66 g/t palladium, but seven ore samples from the district yielded only 1.24 g/t platinum and 1.55 g/t palladium. Naldrett (1989) quotes 21 samples of ore as containing an average of 2.9 g/t platinum, 71 g/t palladium, and 0.2 g/t rhodium, with virtually no other PGE. McCallum *et al.* (1976) suggest an even higher grade of 4.4 g/t platinum, 76.0 g/t palladium, and 0.21 g/t other PGE (5.46 per cent platinum, 94.28 per cent palladium, 0.26 per cent other PGE). In spite of Loukes' postulate that the sulphides are magmatic, it would appear that the sulphides and the PGE were concentrated into shear zones, particularly as the PGE concentrations in the related but undisturbed Lake Owen complex rarely exceed 1 g/t. As neither the basic details of the deposits nor overall grade estimates are available, it was not possible to calculate the PGE resources.

## 2.6. Canada

Canada has been a major PGE producer for many years. Although a large number of orebodies contain PGE (Vermaak, 1985a), only two will be considered in this report, namely the Sudbury and Lac des Isles deposits, which are currently the only major PGE producers in that country.

### 2.6.1. The Sudbury Basin

The Sudbury nickel-copper deposits were discovered in 1883. Production started in 1887, and Sudbury is still a major source of nickel, copper, and other elements. The PGE are one of the by-products of that mining. A large volume of geological literature concerning the Sudbury basin is available. Much of it is contradictory and contentious, but Naldrett and his co-workers have recently undertaken excellent fresh research in the area.

The Sudbury basin is spoon- or oyster-shaped with a 60 km long major axis striking N65°E, and a minor axis of 27 km. The surrounding rocks are Archaean (Pre-

Huronian) Keewatin metasediments and metavolcanics, while the sequentially following early Huronian (2500 to 2150 My; Early Proterozoic) sedimentary Timiskaming, Bruce, and unconformable Cobalt formations were intruded by granite, alkaline rocks and gabbros (the Nippasing 'diabase') during the Mid-Huronian (2150 to 2000 My). Some authors link these intrusives to the Sudbury Irruptive, which was intruded some 1850 My ago in the middle to late Huronian. The 1200 to 1850 m thick Onaping tuffs, breccias, ignimbrites, and cataclastics, the 300 m thick Onwatin (carbonaceous slaty argillites, limestone, and cherts) and the 850 m thick Chelmsford sedimentary formation of the Whitewater Group followed the Irruptive. These rocks are apparently confined to the Sudbury basin.

The edges of the Sudbury basin have been divided into a North Range (centripetal dips 30° to 50° S) and a South Range (dips mostly 40° to 70° N), but the Irruptive body probably has more gentle centripetal dips. Disregarding the marginal and footwall ore-bearing units for the present, the average stratigraphic thickness of the Sudbury rocks consist of 704 m of quartz norite at the base, 961 m of the main gabbro-norite, 394 m of upper gabbro, 1552 m of granophyre, and a highly variable thickness of roof gabbro. About 30 per cent of the gabbroic rocks contain a pervasive micropegmatic mesostasis, but an upward cryptic variation is nevertheless discernible in this stratigraphy. The existence of an ultramafic component is evidenced by the ultramafic xenoliths in the basal part of the Irruptive. The contaminated basal norite cannot represent the original liquid of the Irruptive (including the ultramafic pole), but the granophyre could represent a late-magmatic intrusion, as in the Bushveld Complex.

Apart from the Vermillion-type orebodies, which may be later in age (although the compositions of their ores are very much like those of the Sudbury basin), the main marginal and offset deposits and their associated deuterically altered gabbro-norite (the 'sublayer units') of the South Range are compositionally distinct from the Irruptive rocks, and the magmatic members show distinct fractionation patterns. The rocks of the North and East Ranges exhibit a crude stratigraphy: massive-sulphide stringers, the footwall comminution breccia with massive to disseminated footwall ore, the hangingwall breccia with massive to disseminated hangingwall ore, the xenolithic (30 per cent) norite, and the mafic norite (the latter probably the oldest in the sequence) at the top. In the South Range, the marginal deposits occur as massive ore along the footwall, which is not as brecciated as in the North Range. The offset deposits are dyke-like offshoots of sublayer gabbro-norites that extend for several kilometres from the Irruptive and transgress the regional geological grain of the surrounding footwall rocks. Conformable offsets (Frood Stobie orebody) also exist. Studies by Naldrett *et al.* (1982) and Li *et al.* (1992) of the Strathcona deposit, have shown that the PGE are zoned in the nickel-copper sulphides, with platinum, palladium,

Table 2.21  
Known and inferred mineralization of the Duluth Complex (after Martineau, 1988)

Intrusion	Ore type	Approx. dimensions, m	Cu + Ni, %	Resources Mt
Thunder Bay	B	6 000 × 25 × 50		
Nathan's Series	A	20 000 × 2 000 × 40	0.5	180
Tuscarora	A	10 000 × 3 000 × 15	0.25	4 000
	A	10 000 × 3 000 × 5	0.3	1 000
Kawishiwi	A	12 000 × 3 000 × 50	1.0	300
Birch Lake	C	Intermittent	0.67	4 500
	C	300 × 150 × 20	0.3	15
Babbitt	A	12 000 × 700 × 60	1.7	4
	B	4 500 × 500 × 40	0.3	1 000
	C + D	600 × 300 × 20	0.98	250
Other	B + C	-	4.1	10
Total	-	-	0.7	250
			<b>0.46</b>	<b>11 259</b>

Ore types

- A Uniform stratiform sheets
- B Enriched stratiform sheets or lenses in basins
- C Contact envelopes or rims at contacts of intrusion with sulphur-rich sediments
- D Remobilized veins as inclusion veins or at intrusive gabbro-gabbro contacts