1. PLACER URANIUM, GOLD

INTRODUCTION

Placer deposits represent concentrations of heavy minerals of certain elements, particularly of gold, uranium, and platinum, by sedimentary processes. Depending on the age and the state of their consolidation, the deposits are empirically classified as paleoplacers if they formed in ancient coarse siliciclastic rocks, or as modern placers if they are a part of Pliocene to Recent unconsolidated clastic sediments. According to the main commodities and the host environments the placers are subdivided into 1.1 Paleoplacer uranium, gold, and 1.2 Placer gold, platinum. Paleoplacer deposits are further subdivided into uraniferous and auriferous pyritic quartz pebble conglomerates and sandstones (subtype 1.1.1) which contain detrital pyrite and are older than 2.4 Ga; and auriferous hematitic conglomerates and sandstones (subtype 1.1.2) which are younger, and contain hematite in place of pyrite. The transition from pyrite to hematite with time marks the increase in oxygen in the Earth's atmosphere.

Contents

1.1 PALEOPLACER URANIUM, GOLD

S.M. Roscoe

INTRODUCTION

Paleoplacer concentrations of detrital heavy minerals containing elements such as Au, PGEs, Sn, W, REEs, Ti, Zr, Cr, Th, U, and Fe are common in indurated and metamorphosed fluvial to littoral clastic sedimentary rocks of all ages. There are, however, some remarkable differences between heavy mineral suites in Archean and very early Aphebian rocks and those in rocks younger than about 2.4 to 2.2 Ga. In the younger rocks, ferric oxide is present as an important, if not dominant, constituent of minerals in the allogenic suite and also as an ubiquitous authigenic constituent of the host rocks. These younger paleoplacers (subtype 1.1.2) are similar to unconsolidated recent placers except for easily decipherable and expectable modifications incurred during diagenesis and metamorphism. The ancient pyritic paleoplacers (subtype 1.1.1), on the other hand, contain allogenic and authigenic pyrite in lieu of magnetite and hematite. They occur in conglomerates containing clasts of quartz or resistant rocks, or in associated quartz-rich arenite beds, unlike the ferric oxide-bearing paleoplacers which occur in chemically immature as well as in mature clastic sedimentary rocks.

Paleoplacers, like placers, were formed wherever vigorous water or air currents have sorted heavy and light, large and small, mineral and rock clasts, and thus produced lenses or layers containing heavy minerals (and, commonly, relatively large clasts of lighter minerals and rocks) in greater abundance than elsewhere in a clastic sedimentary formation. The term is generally applied only to those heavy mineral accumulations that are notably enriched in particular commodities (e.g., gold paleoplacers) and implies a provenance containing special primary sources of these commodities in addition to sources of the more common heavy minerals. The question of whether gold, uranium minerals, and pyrite in subtype 1.1.1 deposits, pyritic quartz pebble conglomerates, were originally transported and deposited as detrital grains has long been a subject of debate. The empirical classification of the ancient pyritic deposits as paleoplacers is useful, however, because the ore minerals are concentrated – in association with undoubted heavy detrital minerals – in coarse, quartz-rich clastic metasedimentary rocks deposited under high energy conditions especially favourable for development of placer deposits.

Uraniferous pyritic quartz pebble conglomerates (subtype 1.1.1 deposits) in the Huronian Supergroup at Elliot Lake, north of Lake Huron in Canada (Fig. 1.1-1), have been a major source of uranium since 1956. This is the only district in which this class of paleoplacer contains very little gold and has nevertheless been mined. Auriferous pyritic quartz pebble conglomerates (subtype 1.1.1 deposits), in the Witwatersrand Supergroup and Dominion Group in South Africa (Fig. 1.1-2), have produced far more gold than any other type of gold-bearing mineral deposit. They have also produced very important amounts of byproduct and coproduct uranium. Witwatersrand-type deposits are also mined in Brazil. In contrast to the very limited number of pyritic paleoplacer mining districts, pyritic paleoplacers containing only low concentrations of uranium and gold are common in formations of quartzose arenites more than 2.4 billion years old.

Deposits of subtype 1.1.2 have been mined on a small scale in many places and significant amounts of gold have been produced from hematitic quartz pebble beds in Ghana. In general, however, this most abundant type of paleoplacer is of little importance compared to either the much richer ancient pyritic Witwatersrand gold paleoplacers or unconsolidated placers containing relatively low concentrations of cheaply recoverable particulate gold.

Roscoe, S.M.
1996: Paleoplacer uranium, gold; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 10-23 (also Geological Society of America, The Geology of North America, v. P-1).

IMPORTANCE

Subtype 1.1.1

Uraniferous pyritic quartz pebble conglomerate (Huronian Supergroup)

From initial production in 1957 until the end of 1992, the Elliot Lake district (also known as the Blind River area) has produced about 140 500 t[1] of uranium from ores grading about 0.09% U. This is 13.8% of total uranium production in the 'Western World' during the same period and 59.9% of total Canadian production. At peak annual production in 1959, 11 mines, with combined total mill capacity of 30 800 t per day, produced 9400 t – at that time 28% of 'Western World' production (Fig. 1.1-3). Elliot Lake ores and tailings contain major potential thorium, yttrium, and rare-earth element resources, and small quantities of these have been produced in the past. Remaining uranium resources in the Elliot Lake district are lower grade than past production. In 1993 only one mine (Stanleigh) was producing uranium.

[1] Production data have been derived from various sources, most importantly: Mining Annual Review; Minerals Yearbook, United States Department of Interior; Mineral Information Bulletin, Mineral Resources Division, Department of Energy, Mines and Resources, Canada (and predecessor Department of Mines and Technical Surveys, Canada); Consolidated Goldfields, P.L.C., annual report on gold; annual reports of Rio Algom Ltd. and Denison Mines Ltd.

Contents

Auriferous pyritic quartz pebble conglomerates and quartzites (Witwatersrand Supergroup)

About 40 000 t of gold have been produced (to the end of 1987) from about 4 billion tonnes of pyritic quartz pebble conglomerate ores mined since 1886 when deposits of this type were discovered in the Transvaal, South Africa. Peak annual production of 1000 t reached in 1970, represented 79% of 'Western World' production. For a 38 year period, 1949 to 1987, these deposits yielded 75% of 'Western World' gold production. Annual production has decreased in recent years to about 600 t in 1987. This decrease and, more importantly, increasing production elsewhere in the world, notably Nevada, U.S.A., reduced South Africa's share of 'Western World' production to 44% in 1987.

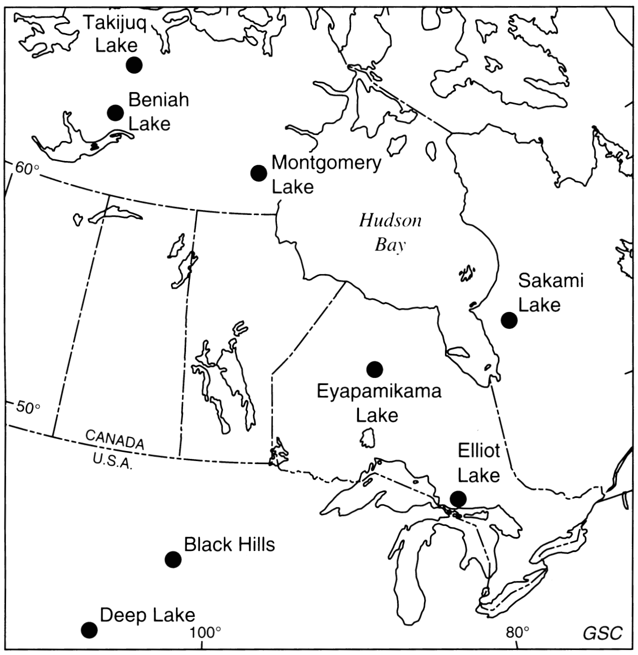

Figure 1.1-1 Occurrences of pyritic uraniferous quartz pebble conglomerates in North America (after Roscoe, 1981, 1990).

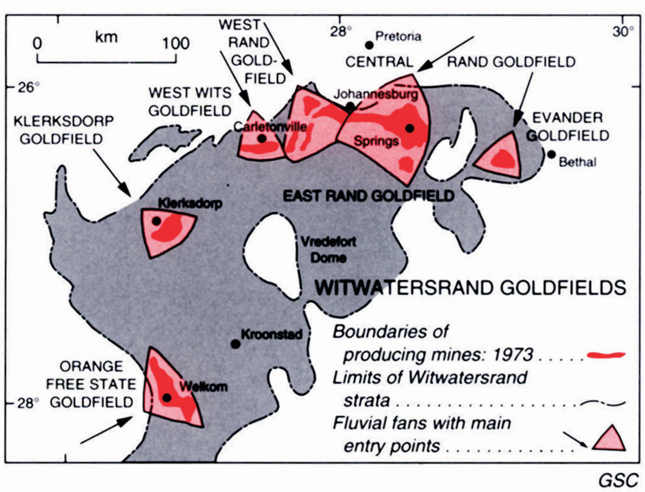

Figure 1.1-2. Areas of gold- and uranium-bearing conglomerates in the Witwatersrand goldfields, South Africa (after Tankard et al., 1982).

Extraction of uranium from South African gold ores began in 1952 and between 1952 and 1987 has totalled approximately 125 600 t U, about 14% of the uranium produced in this period in the 'Western World'. Most Witwatersrand gold ores and resources contain more than 15 times more uranium than gold (Bourret, 1981) and some, as at Vaal Reefs, as much as 33 times more (Minter, 1981). Clearly, these resources and some 4 billion tonnes of tailings represent a major potential uranium resource. In addition to byproduct uranium, pyrite is recovered from some ores and used to produce sulphuric acid required by uranium extraction plants, and small amounts of osmium, iridium, and diamonds are recovered from South African conglomerate ores.

Subtype 1.1.2

Ghana gold production from hematitic paleoplacers

Production to date of at least 227 t (250 tons) of gold from hematitic conglomerates in Proterozoic quartzites of the Tarkwaian System in Ghana (Vogel, 1987) is substantial, but much smaller than that from vein-type deposits in metamorphic rocks of the underlying Birimian System, an outstanding gold-producing Proterozoic greenstone belt. Uranium is not significantly concentrated in the Tarkwaian conglomerates or in any other hematitic conglomerates.

SIZE AND GRADE OF DEPOSITS

Subtype 1.1.1

Huronian deposits

The main mining areas in the Elliot Lake district are about 10 km apart and extend down dip to depths of about 1200 m below surface on the north and south flanks of a syncline (Fig. 1.1-3). The largest, at Quirke Lake, extends 10 km in an east-southeast direction and is as much as 3.5 km wide. Conglomeratic zones are mined at several stratigraphic levels through a formational thickness of 100 m. The lowermost, and by far the most productive of these, was estimated to contain some 200 million tonnes of drill-indicated ore grading 0.10% U when mining began in 1956 (Roscoe, 1957). The Nordic zone, trending northwest, is 6 km long and as much as 2 km wide. The main zone in this area is overlain by a more extensive, lower grade conglomeratic section. Pronto and Agnew Lake mines, respectively 20 and 75 km south and east of Elliot Lake, mined relatively small remnants of once more extensive conglomerate zones.

Witwatersrand deposits

The Witwatersrand goldfields resemble huge fans containing thin sheets of pebble beds. Mine workings are centered on 'paystreaks' that radiate out from fan apices. Some paystreaks can be followed for more than 10 km. The East Rand fan, the largest of the six goldfields, according to

Pretorius (1974), "extends for 40 km down the central section from the apex of the fan to the base of the fan where it merges with the main lacustrian environment. The mid-fan portion is 50 km wide and the fanbase 90 km wide. The western lobe is 45 km long and the eastern lobe 20 km." Drill exploration has been extended in places to depths of nearly 5 km and mining to nearly 4 km. Some mines exploit two or more reefs (stratiform ore zones) that are widely separated stratigraphically. The uppermost sections of some of these, truncated at unconformities, are at depths as great as 3 km. Pretorius (1974) cited average ore grades for all Witwatersrand production to 1972 as 9.2 g/t Au, with the especially rich Carletonville Goldfield averaging 19.4 g/t and the most uraniferous Krugersdorp (West Rand) Goldfield, 6.3 g/t Au. Ore processed in uranium extraction plants in the period 1953-1972 contained an average of 213 g/t (0.021%) U for the Witwatersrand as a whole, 188 g/t for Carletonville ores, and 477 g/t for Krugersdorp ores.

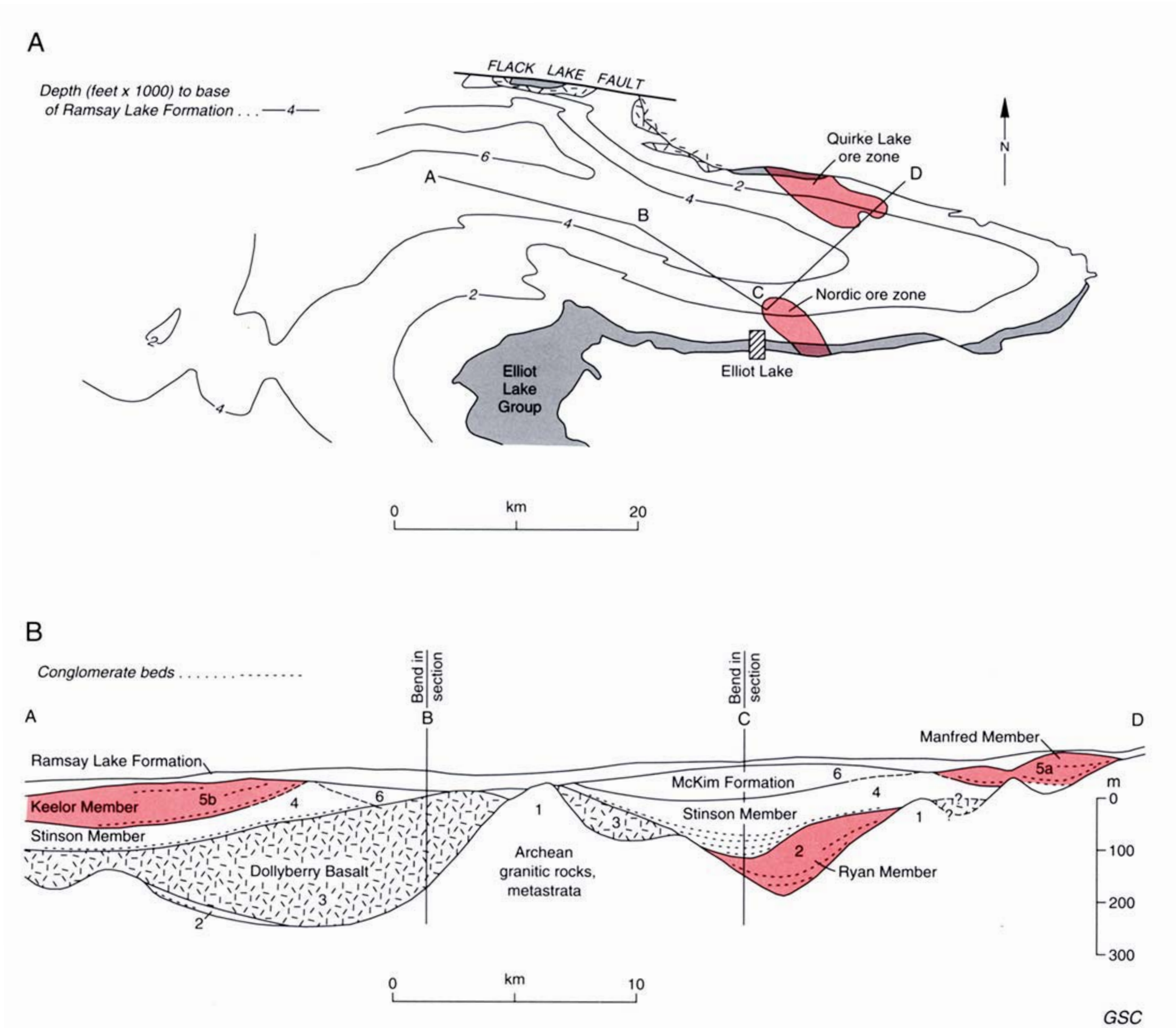

Figure 1.1-3. Stratigraphic relations in the Huronian Supergroup near Elliot Lake. **A)** Map showing outcrop of Elliot Lake Group (grey shading), depth to the base of the overlying Matinenda Formation, and the Quirke Lake and Nordic ore zones (red). **B)** Schematic cross-section showing relations among Ramsay Lake and McKim Formations and arenaceous members of the Matinenda Formation. Uraniferous members are shown in red, conglomerate beds are represented by dashed lines. Designation of units by numbers and patterns correspond to those shown in Figure 1.1-6. * For lithostratigraphy only see Table 1.1-1. (from Roscoe, 1981).

Subtype 1.1.2

Tarkwaian hematitic paleoplacers, Ghana

Mining operations have been carried out through areas as much as 3 km long and 1 km wide along a 12 km distance. Mining thicknesses have been between 1.2 and 7 m and ore grades between 3.5 and 14 g/t Au (Vogel, 1987).

GEOLOGICAL FEATURES

Pyritic paleoplacers (subtype 1.1.1) and many hematitic paleoplacers (subtype 1.1.2) occur in thick successions of clastic sedimentary rocks dominated by thick quartz arenite units that are chemically, mineralogically, and texturally submature to supermature. Major portions of these variably micaceous and feldspathic quartzite units, including very coarse grained members containing pyritic (or hematitic) quartz pebble beds, consist of channel-type crossbeds that show unimodal dip directions. They are interpreted as having been deposited under fluvial conditions, primarily in braided stream systems within broad valleys and, most importantly, on huge alluvial fans (Minter, 1978; Roscoe, 1981). In addition to such terrestrial deposits, the Huronian Supergroup and the South African host assemblage, which includes the Dominion Group, Witwatersrand Supergroup, and Ventersdorp Supergroup, contain volcanic rocks, quartz arenites with bimodal (herringbone) crossbedding that likely reflects deposition in the intertidal zone, siltstones and argillites deposited in standing water, carbonate rocks, glaciogenic sediments, and iron-formation (in Witwatersrand).

Conglomeratic zones in the Matinenda Formation in the lower part of the Huronian Supergroup have been mined for uranium in two extensive areas near the town of Elliot Lake, north of Lake Huron midway between Sudbury and Sault Ste. Marie, and at two outlying areas south and east of Elliot Lake. Uneconomic occurrences of uraniferous pyritic paleoplacers have been found elsewhere in Canada (Roscoe and Donaldson, 1988; Roscoe et al., 1989; Roscoe, 1990; Fig. 1.1-1): Sakami Lake in Quebec; Eyapamikama Lake in northwestern Ontario; Beniah Lake 130 km northeast, and Takijuq Lake 400 km north, of Yellowknife, Northwest Territories, and in the Montgomery Lake Group near Henik Lakes, Northwest Territories (Roscoe, 1981). Sub-ore grade occurrences have also been discovered at Deep Lake in the United States in the Deep Lake Group and Phantom Lake rocks in the Medicine Bow and Sierra Madre mountains of Wyoming and at Nemo in the Black Hills of South Dakota (Houston and Karlstrom, 1987).

In South Africa, auriferous pyritic quartz pebble conglomerates, with U/Au ratios less than 50, occur in the Witwatersrand Supergroup thoughout its 350 by 200 km extent (Fig. 1.1-2). Six gold mining areas, termed 'goldfields' are distributed along an arc 420 km long, concave to the southeast, the direction of sediment transport (Fig. 1.1-2). Mining has also been carried out in much less extensive older strata of the Dominion Reef Group, which contain conglomerate beds with U/Au ratios very much higher (Von Backström, 1981) than Witwatersrand ores, but distinctly lower than the approximate 10 000 U/Au ratios of Elliot Lake ores. Radioactive auriferous pyritic conglomerates are also present in the older Pongola Supergroup (Saager et al., 1987) 400 km southwest of, and the Pietersburg greenstone belt 280 km northeast of, the Witwatersrand goldfields (Meyer et al., 1987). A pyritic gold paleoplacer is mined near Jacobina, Bahia, Brazil (Gama, 1982), and other pyritic quartz pebble beds near Belo Horizonte, 975 km south of Jacobina, have been explored for uranium (Villaca and Moura, 1981). Similar beds are present at several localities in the Pilbara Block in Western Australia (Carter and Gee, 1987) within the lower Fortesque Group (about 2.7 Ga) and within the Gorge Creek Group (about 3.0 Ga). Small amounts of gold were mined from Fortesque beds early in the century. Auriferous radioactive pyritic quartz pebble beds have also been found in Karnataka State in southern India (Srinivasan and Ojakangas, 1986) and in the Singhbhum craton near Calcutta (Rao et al., 1988).

Occurrences of pyritiferous conglomerates have been reported in Karelia and Ukraine (Salop, 1977), but of these, some in Finland are epigenetic deposits, more akin to sandstone-type or unconformity-type deposits, in conglomerate beds that elsewhere in the vicinity and regionally are hematitic rather than pyritic (Aikas and Sarikkola, 1987). Others are not well enough documented to establish that they are stratiform and pyritic throughout entire formations, as are the Huronian and Witwatersrand deposits.

The most noteworthy auriferous hematitic paleoplacers (subtype 1.1.2) are in the Tarkwaian "System" in Ghana (Vogel, 1987), which was deposited after about 2135 Ma (Davis et al., 1994). Monazite-, zircon-, and rutile-bearing hematitic quartz pebble beds in the Lorrain Formation in the upper part of the Huronian Supergroup, Ontario, although not economically significant, are of special interest because they are the oldest known concentrations of subtype 1.1.2 hematitic, nonpyritic heavy minerals. Their general association with minor redbeds has been considered evidence that the atmosphere changed during deposition of the Huronian sequence to one that, for the first time, was capable of oxidizing iron minerals (Roscoe, 1969).

The Huronian succession (Canada)

The *Huronian Supergroup* comprises 4 groups of formations that form southerly thickening wedges with aggregate maximum thicknesses totalling as much as 15 km according to Roscoe and Card (1992). In ascending order (Table 1.1-1) these are: the *Elliot Lake Group*, up to 4000 m thick; *Hough Lake Group,* up to 3700 m thick; *Quirke Lake Group*, up to 2400 m thick; and *Cobalt Group*, up to 5000 m thick. The Elliot Lake Group contains the only volcanic formations in the Huronian succession and relatively fine grained pelitic sediments, as well as arenaceous units and pyritic quartz pebble conglomerate beds. The basal unit of the Hough Lake Group, the *Ramsay Lake Formation*, consists of polymictic paraconglomerate that disconformably overlies the eroded surface of Elliot Lake Group rocks or, in many northern areas, Archean basement rocks. Similar conglomeratic units, the *Bruce* and *Gowganda formations*, respectively, form the bases of the Quirke Lake and Cobalt groups, and in each of the three upper groups, paraconglomerate is succeeded by fine grained sediments, the *Pecors, Espanola,* and *Firstbrook formations,* which in turn are overlain by great thicknesses of quartz arenites, the *Mississagi, Serpent,* and *Lorrain formations.* At some places west of Elliot Lake, an unconformity at the base of the Gowganda Formation cuts out almost all of the Quirke

Table 1.1-1. Stratigraphy of the Huronian Supergroup at Elliot Lake, Canada (from Roscoe, 1969).

Group	Formation	Composite lithological sequence
Cobalt	Bar River	quartzite, red siltstone quartzite
	Gordon Lake	varicoloured siltstone
	Lorrain	quartzite arkose
	Gowganda	reddish argillite, argillite conglomeratic greywacke, grey and pink arkose
Quirke Lake	Serpent	arkose-subgreywacke
	Espanola	dolomite, siltstone siltstone, greywacke limestone
	Bruce	conglomeratic greywacke
Hough Lake	Mississagi	coarse subarkose
	Pecors	argillite, siltstone
	Ramsay Lake	conglomeratic greywacke
Elliot Lake	McKim	subgreywacke, argillite
	Matinenda	gritty subarkose
	Copper Cliff	acid volcanics
	Thessalon Pater Stobie	basic volcanics
	Livingstone Creek	subarkose

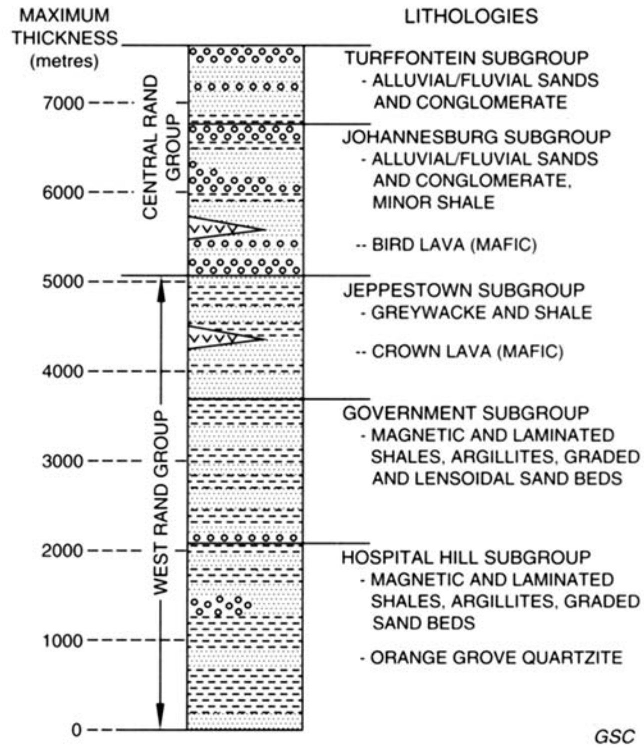

Figure 1.1-4. Generalized stratigraphic column of the Witwatersrand Supergroup, South Africa. Circles = conglomerate; dots = sands, greywacke, quartzite; dashes = shale, argillite; vees = volcanics (after Tankard et al., 1982).

Lake Group. The cyclicity of formations has been interpreted as related to glaciations accompanied by depression, followed by deglaciations resulting in rapid isostatic uplift and resumption of fluvial sand deposition (Frarey and Roscoe, 1970).

South African paleoplacer hosts

The following outline of the major South African paleoplacer host succession (Fig. 1.1-4 and 1.1-5) is taken largely from Pretorius (1976) and Tankard et al. (1982). The major host units include, in ascending order, the 3.07 Ga volcanic *Dominion Group* (2710 m thick), *Witwatersrand Supergroup* (Fig. 1.1-4), including the West Rand Group (4670 m) which contains marine sediments, and the Central Rand Group (2420 m) of dominantly fluvial clastic sediments; and the dominantly volcanic *Ventersdorp Supergroup* (7860 m; Fig. 1.1-5) which has yielded a zircon U-Pb age of 2.71 Ga (Armstrong et al., 1990).

Paleoplacers in the Dominion Group are restricted to a basal unit of submature arenite, as much as 60 m thick, in the *Renosterhoek Formation.* This unit, deposited in southwesterly flowing streams within paleovalleys on granitic basement rocks, is overlain by 1100 m of subaerial mafic to intermediate volcanic rocks containing paleosol zones. The uppermost 1550 m of the group consist of quartz and feldspar phyric lavas that have given a zircon U-Pb age of 3.07 Ga (Armstrong et al., 1990).

The West Rand Group consists mainly of shale and sandstone deposited in both fluvial and marginal marine environments. The lowermost part, the *Hospital Hill Subgroup,* contains a contorted iron-formation unit near its base, and some minor subeconomic paleoplacer beds and tilloidal conglomerate near its top. The overlying *Government Subgroup* contains paleoplacers in the base of upward-fining sequences interpreted as fans that prograded southwest and southeast over tidal deposits. Ten of these deposits produced more than 35 t of gold near the turn of the century. The Coronation Formation, near the middle of the subgroup, contains tillite overlain by magnetic shale. The *Jeppestown Subgroup* at the top of the West Rand Group contains a 250 m sequence of thin amygdaloidal basalt lava flows, *Crown lava,* that extends throughout the preserved part of the West Rand depository. Some minor gold production was obtained from paleoplacers in this subgroup in the early part of the century. The dominantly shaly Roodepoort Formation, as thick as 600 m, caps the subgroup.

The Central Rand Group contains most of the productive gold paleoplacers. The Booysens Formation and equivalent shaly beds mark the top of a lower division, the *Johannesburg Subgroup,* as much as 1500 m thick, which is overlain by an upper division, the *Turffontein Subgroup,* as much as 1800 m thick. Placers at or near the base of the Johannesburg Subgroup, including the *Carbon Leader, Middelvlei, Main,* and *Main Leader placers,* have been

Contents

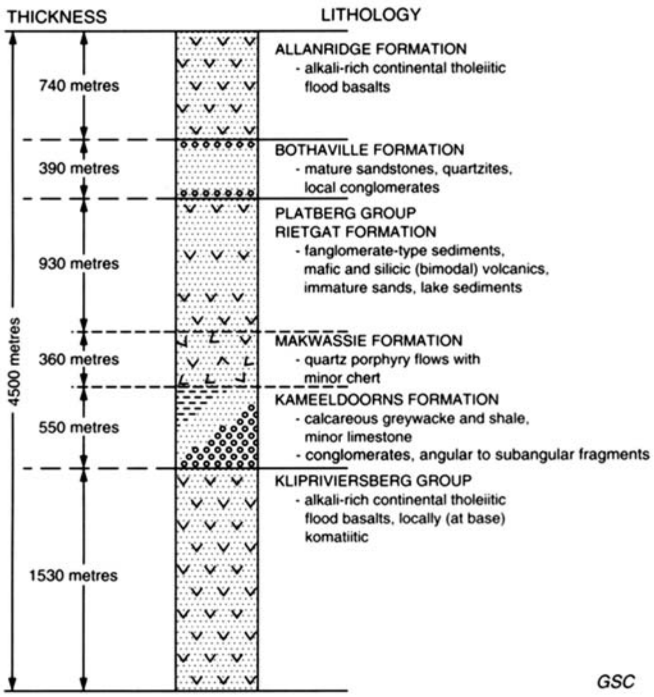

Figure 1.1-5. Generalized stratigraphic column of the Ventersdorp Supergroup, South Africa (after Winter, 1976, and SACS, 1980).

particularly important producers in the northern goldfields. Broad channels filled with diamictite are also present at the base of the subgroup. In the upper part of the subgroup the *Steyn, Basal,* and *Vaal placers* are most important in the Welkom and Klerksdorp goldfields, the *Bird* in the East Rand Goldfield. Four especially uraniferous placers are mined in the upper part of the subgroup in the Krugersdorp Goldfield. Lavas (*Bird amygdaloid)* are present in the central part of the subgroup south and east of Johannesburg. These are about 200 m thick near Johannesburg and thicken easterly to about 1200 m in the Evander area, where an intrusive sill is also present. Sedimentary rocks, on the other hand, thin easterly. The Turffontein Subgroup contains conglomeratic zones and individual massive conglomerate beds which are thicker and contain much larger pebbles than are present lower in the succession, yet numerous placers in this upper subgroup have been less productive than thin placers in the underlying Johannesburg Subgroup. Extensive conglomeratic sections are barren, low grade, or contain patchy gold concentrations. Important Turffontein placers have been mined in the Welkom, Klerksdorp (*Cristalkop, Gold Estates,* and *Orkney),* and Krugersdorp (*Kimberley placers)* goldfields. The only placer mined in the Evander Goldfield is in the Turffontein Subgroup.

Volcanic and sedimentary rocks of the Ventersdorp Supergroup concordantly to unconformably overlie the Witwatersrand Supergroup and overlap its eroded margins onto Dominion Group and older rocks to extend, mainly in the subsurface, over an area 800 km long and as much as 300 km wide. Two unconformities separate three groups of formations collectively comprising as much as 5775 m of strata. The lower one, the *Klipriviersberg Group,* consists of up to 1830 m of continental tholeiitic basalts with a basal veneer of fluvial sediments, including the very important *Venterpost placer* (formerly called Ventersdorp contact reef or VCR). Overlying formations include fault controlled alluvial fan sediments, andesitic volcanic rocks, and quartz phyric flows as much as 2100 m thick (*Makwassie Formation*) that have given a zircon U-Pb age of 2714 ± 8 Ma (Armstrong et al., 1990).

The youngest auriferous pyritic conglomeratic beds in southern Africa are in the *Black Reef Formation* at the base of the Chuniespoort Group of the Transvaal Supergroup. This group, which consists mainly of dolomite and iron-formation, unconformably overlies Ventersdorp and older rocks and is unconformably overlain by the Pretoria Group. A Rb-Sr whole rock age of 2.2 Ga (Burger and Coertze, 1975) has been obtained for volcanic rocks (*Hekpoort Formation*) in the latter group. Paleosol above the volcanic rocks (Retallack, 1986) shows evidence of development of an oxygen-bearing atmosphere believed by many to be unfavourable for the formation of pyritic placers.

The oldest gold paleoplacers are in the Pongola Supergroup. These lie stratigraphically above volcanic rocks that gave a zircon U-Pb age of 3.09 Ga, and rhyolite within the Pongola Supergroup has yielded a zircon U-Pb age of 2940 ± 22 Ma (Hegner et al., 1984).

Geological setting of Elliot Lake paleoplacers

Pyritic quartz pebble conglomerate uranium ores of the Elliot Lake district occur in the Matinenda Formation of the Elliot Lake Group, which is the lowest Group of the Huronian Supergroup succession (Table 1.1-1). East and south of the main ore zones in the Elliot Lake area, feldspathic, micaceous quartzite, grit, and quartz pebble beds of the Matinenda Formation nonconformably overlie paleosol-mantled Archean basement rocks. The latter are highly deformed metavolcanic rocks, likely about 2.7 Ga in age, that have been intruded by granite believed to be more than 2.65 Ga on the basis of the youngest zircon U-Pb ages obtained for comparable rocks in the region (Krogh et al., 1984). West of the ore zones, Matinenda beds were deposited atop the eroded, weathered surface of the Dollyberry Formation, a succession of subaerial tholeiitic basalt flows that is locally as much as 300 m thick. It too overlies paleosol-mantled Archean basement rocks and, locally in outcrop and drill core 20 km west of Quirke Lake, is separated from basement by a cushion of coarse Huronian clastic sediments including radioactive pyritic conglomerate. This unit, termed Crazy Lake Formation, is poorly sorted but otherwise is not unlike gritty facies of the Matinenda Formation.

Elliot Lake ore zones

The *Nordic* and *Quirke* ore zones and the *Keelor* conglomerate zone (Fig. 1.1-3) are in lenses of Matinenda subarkose termed, respectively, *Ryan, Manfred,* and *Keelor* members. These are characterized by quartz grains that are generally very coarse, but highly varied in grain size and variably sorted, as reflected by greenish colours imparted to the rocks by matrix sericite. Subarkose in the *Stinson Member,* which overlies the Ryan Member and underlies the Manfred and Keelor members, is better sorted, more homogeneous, finer grained, and paler coloured. A distinctive nonpyritic, nonradioactive conglomerate characterized by rounded, well sorted, tightly packed clasts of basalt and subordinate to dominant quartz clasts marks the base of the member. Throughout much of the area, the Stinson conglomerate is merely a layer of single small pebbles, mainly of quartz, but where it occurs above the Nordic ore zone and above Dollyberry Basalt, it contains massive layers of large basalt cobbles.

The Ryan Member is as much as 170 m thick along a northwesterly trending axis that is close to the centreline of the Nordic ore zone (see Pienaar, 1963, Fig. 8). It overlies Archean metavolcanic and metasedimentary rocks and also Huronian basalt and patches of basal conglomerate. The main ore body, *Nordic reef*, the underlying productive *Lacnor reef*, and the overlying less productive *Pardee reef*, occupy a 30 m stratigraphic interval 0 to 30 m above the base of the member. Other pyritic quartz pebble beds and lenses occur throughout overlying coarse Ryan subarkose, but upwards through the pile they become sparser and thinner, contain smaller pebbles, and are less uraniferous. The southeasterly elongated Nordic zone parallels paleocurrent flow as indicated by foreset dips and is bordered on the northeast by a basement ridge of iron-formation against which the Lacnor and Nordic reefs abut. The Pardee reef and overlying Ryan strata, however, cross this ridge and the overall form of the Ryan 'bulge' resembles a fan with a convex upper surface and an apex near the north end of the Nordic ore zone. Deposition may have involved valley filling with upstream (northwesterly) migration of the fall line to a notch in a steeper slope from which alluvial braided distributaries built a broad fan. The original morphology and even the original depositional limits of the member, however, are masked by erosion preceding and accompanying deposition of the Stinson Member and the Ramsay Lake Formation. Thick zones in the Stinson Member mimic those in the underlying Ryan Member and may represent superposed fans (Pienaar, 1963, Fig. 16). Particularly thick sections, as much as 130 m, overlie flanks of the Nordic ore zone and are complementary to thinned sections in the Ryan Member, corresponding to conglomerate-filled channels that cut deeply into the lower member, locally even removing sections of ore zones. The basalt clasts were derived from the Dollyberry Formation, which became a prolific source of such clasts only after the Ryan Member was deposited. This led Roscoe (1981) to suggest that the Dollyberry Formation was erupted and built into a high-standing edifice after deposition of the Ryan Member as well as after deposition of the Crazy Horse Formation. If others, notably Bennett (1979), are correct in believing that only one episode of volcanism occurred in the western part of the Huronian belt and that this preceded deposition of the entire Matinenda Formation, then a structural block containing the Dollyberry Formation must have been uplifted abruptly following deposition of the Ryan Member.

The Manfred Member, hosting the Quirke Lake ore zones, nonconformably overlies Archean basement rocks to the north, and Dollyberry Basalt flows to the west, and to the south it conformably overlies a grey subarkose unit that Robertson and Steenland (1960) and Roscoe (1969) considered correlative with the Stinson Member. The Denison reef zone (C reef in Rio Algom Mines), by far the most important in the district, is at or near the base of the Manfred Member. It is a section of pyritic conglomerate, conglomeratic subarkose, and subarkose lenses and is as much as 10 m thick to the north, but thins and contains reduced proportions of conglomerate towards the south and southeast down the paleoslope. A medial part up to 2.5 m thick, nearly devoid of pebble layers, is traceable thoughout the entire mining area and divides the reef into upper and lower sections comparable to the closely spaced Nordic and Lacnor reefs of the Nordic ore zone. In many areas the upper and lower parts have been mined separately or only one has been mined. The Manfred Member, as much as 100 m thick (Pienaar, 1963) in the northwestern part of the Quirke Lake mining zone at the boundary between the Quirke mine and Denison mine properties, contains abundant conglomeratic layers in addition to the Denison reef. Of these, the Quirke reef (also known as A reef and at Denison as E reef), located 30 m above the Denison reef, has been extensively mined. Other sections with abundant pyritic quartz pebble layers, both below and above the Quirke reef, can be followed considerable distances. The upper surface of the Manfred Member was extensively eroded prior to deposition of the Ramsay Lake Formation, a glacial mixtite unit (Fralick and Miall, 1987) at the base of the Hough Lake Group. This unconformity cuts down through the entire member in some areas in both the northern and southern parts of the Quirke Lake mining zone and the basal part of the Ramsay Lake Formation has become enriched in quartz grains and pebbles, pyrite, and radioactive minerals derived from unconsolidated Matinenda sands and gravels (see Fralick and Miall, 1987).

The Keelor Member, and a contained subeconomic conglomeratic zone, 15 to 30 km west of Quirke Lake, overlies Dollyberry Basalt in its proximal northern part and, like the Manfred Member (Fig. 1.1-6), overlies Stinson subarkose in more distal portions to the south (Roscoe, 1981). The most northerly, deepest, most proximal part of the Keelor Member has not yet been delimited by drilling, but it too is truncated by the Ramsay Lake Formation, and lower conglomerate beds abut against rises in the surface of underlying volcanic rocks. Southerly parts of the most conglomeratic section, however, have not been affected by sub-Ramsay Lake erosion and its original fan-like form is apparent in sections and isopachal plans drawn from drill core data (Roscoe, 1957). Deposition of the coarse detritus of the Keelor and Manfred members can be considered to have been initiated at points where streams debouched off Huronian lava fields and Archean uplands onto more gently sloping surfaces of Huronian sands (*Stinson bajadas*). Gravel and coarse sand deposits were built up, evidently both headward and downslope, as alluvial fans and coalescent fans, by distributary braided streams (Roscoe, 1981).

Early investigators of the Elliot Lake deposits noted that the conglomerate orebodies are largely within or overlie depressions in the pre-Huronian surface (e.g., Hart et al., 1955; Roscoe, 1957; Derry, 1960; Robertson and Steenland, 1960; Pienaar, 1963). Most considered this consistent with subaerial deposition of the conglomeratic zones as gravel beds in river valleys. Robertson and Steenland (1960), however, considered that the conglomerates and other Matinenda strata were deposited on marine deltas. This would explain thickness variations of Matinenda units that far exceed sub-Matinenda paleotopographic relief as indicated by variations in thickness of basal units. Construction of alluvial fans from fan heads that migrated

Contents

headward up valleys (Roscoe, 1969) is a more likely explanation, in the absence of changes in lithologies and sedimentary structures that would suggest transitions from high energy fluvial environments to marginal marine environments.

Uranium concentrations in Huronian strata other than the Matinenda Formation

Beds of uraniferous pyritic quartz pebble conglomerate as much as 1 or 2 m thick are interlayered with thin amygdaloidal basalt flows near the base of the Thessalon Formation, 60 to 115 km west of Elliot Lake, and also in the uppermost quartzite beds of the Livingstone Creek Formation that underlies the volcanic rocks. Correlations of these formations with Matinenda units and volcanic rocks at Elliot Lake are uncertain, but Bennett (1979) considered the Livingstone Creek Formation to predate the latter strata, with the exception of the Crazy Lake Formation. The Mississagi Formation of the Hough Lake Group contains geographically and stratigraphically widespread lenses of small quartz and black chert pebbles with associated pyrite, zircon, and monazite. Some proximal facies of the formation in northern parts of the belt consist of coarse subarkose, grit, and substantial radioactive conglomerate beds lithologically similar to major components of the Matinenda Formation at Elliot Lake.

In the Wanapitei Lake-Temagami Lake area, 25 to 70 km north and northeast of Sudbury, the Mississagi Formation, along with some basal lenses of fine grained clastics, polymictic conglomerate, and quartz pebble conglomerate, nonconformably overlies Archean basement rocks (Long, 1987). Several radioactive conglomerates have been found to contain erratic concentrations of gold much higher than any found in Elliot Lake ores. This is interesting as the Temagami occurrences are only 15 km to 35 km from several gold deposits in basement greenstone rocks, whereas the Elliot Lake area is 140 km south and southeast of greenstone belts that contain known deposits that could have been sources of detrital gold. Several uranium occurrences north of Sudbury, in and near Roberts Township, are noteworthy as they occur in fine grained quartzite and siltstone, rather than conglomerate, and contain abundant ilmenite, as well as pyrite, rutile, and zircon. The heavy minerals, which appear to be detrital grains in hydraulic equilibrium (H.R. Steacy, pers. comm., 1976; Goodwin, 1980 in Long, 1987), occur in graded laminae.

Minerals and mineral zonations

Pyrite occurs as several types of grains in matrices of Elliot Lake and Witwatersrand pyritic conglomerates along with quartz, feldspar, and muscovite. It is the most abundant heavy mineral, averaging about 3% in Witwatersrand ores, and more than this in Elliot Lake ores. Other heavy minerals concentrated in South African and/or Huronian pyritic quartz pebble conglomerates include garnet, chromite, sphene, rutile, monazite, xenotime, apatite, tourmaline, ilmenite, columbite, corundum, cassiterite, osmiridium, and diamond. Modes of occurrence and shapes and sizes of uraninite grains (Liebenberg, 1958; Ramdohr, 1958; Roscoe, 1969) and of some of the gold (Hallbauer, 1981) and pyrite are consistent also with a placer origin, although some pyrite, gold, uraninite (or pitchblende), and other uranium minerals are authigenic or have been remobilized. Feather and Koen (1975) have identified 70 minerals in

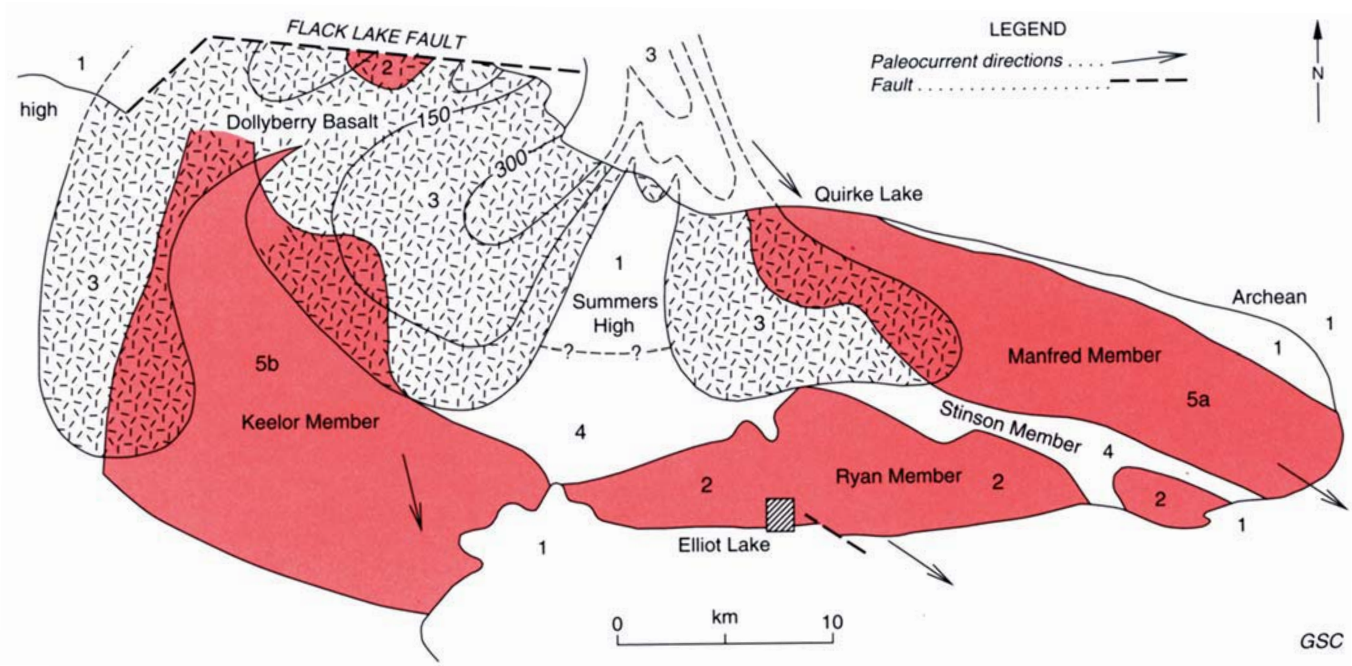

Figure 1.1-6. Subsurface distribution of conglomeratic and volcanic strata in the Elliot Lake Group at Elliot Lake. Designations of units by numbers and patterns are as shown in Figure 1.1-3; red indicates uranium-bearing units; contour lines indicate approximate thickness (m) of unit 3 (from Roscoe, 1981).

Contents

Witwatersrand ores. These include common sulphides and sulpharsenides. Kerogen, also referred to as carbon, hydrocarbon, and thucholite, is abundant in some, but not all, South African ores. It occurs as granules and as concordant seams associated with and incorporating heavy minerals. The seams commonly have columnar structure and some are in layers that apparently represent distal pebble-free extensions of thin conglomerate ore beds. They are commonly uranium-rich and may be phenomenally rich in gold.

Origin of kerogen

The character and origin of kerogen in the ancient paleoplacers has been intensely studied and debated (Liebenberg, 1955, 1958; Hallbauer, 1981; Schidlowski, 1981; Zumberge et al., 1981; Ruzicka, 1981; Mossman and Dyer, 1985). Liebenberg considered that the "hydrocarbon" was introduced as a fluid, fixed as a solid by the polymerizing effect of radiation, and that this process was accompanied by dissolution of detrital uraninite and dispersal of uranium and thorium through the resultant 'thucholite'. Others have thought that the kerogen represents algal mats that grew in situ, and that these organic mats trapped uranium and gold both mechanically and chemically. Hallbauer (1975) found extremely delicate, branching cellular uraniferous filaments in organic seams. He considered these to represent microfossils of fungal hyphae, the columnar forms to have been lichen, and spheroidal particles to have possibly been spores. Development of such relatively advanced organisms in Archean time and the preservation of extremely delicate structures in rocks of greenschist facies is difficult to accept. According to Schidlowski (1981), the 'thucolite' might have formed relatively late where fluidal hydrocarbon came in contact with radioactive minerals. Relationships between the character of kerogen and proximity to uraninite grains (Landais et al., 1990) lend support to this hypothesis. It is noteworthy that methane is abundant enough in some South African mines to be a problem. Underlying strata of the West Rand Group offer a credible source.

In the Elliot Lake mines, concentrations of kerogen nodules with fibrous sepiolite, and crystals of calcite, pyrrhotite, pyrite, pale sphalerite, and galena are common in open fissures that are not confined to ore zones. The hydrocarbon is only very weakly radioactive. The galena contains 'future' lead so rich in ^{206}Pb that it must have had a radon parent. Kerogen in these occurrences is only very weakly radioactive. It is noteworthy that gas may be observed bubbling out of water-filled fractures in Denison mine and that methane, radon, and helium have been identified in the gas. Concordant seams of kerogen, such as those described by Ruzicka and Steacy (1976) and Ruzicka (1981), are rare. They appear to be limited to small thin lenses in which they are associated with laminae composed almost entirely of uraninite grains. Kerogen (identified by its volatility under the X-ray beam of a microprobe) also occurs as irregular random replacements within some, but not all, uraninite grains in ores other than uraninite-rich layers, according to Ruzicka (1981). Ruzicka (1981) considered that the concordant kerogen seams were formed in situ during sedimentation by organisms, but it seems reasonable to suppose that both types of kerogen occurrences could be postore, formed from transient methane.

Mineral and grain size zonations in conglomerates

The Denison reef and other conglomeratic sheets in the Quirke Lake mining area show pronounced decreases in pebble size southerly and easterly down the paleoslope, and reduction in U/Th ratios concomitant with reductions in uraninite contents and increases in monazite contents (Robertson and Steenland, 1960). Titanium mineral abundance also increases downstream from the richest uraninite concentrations, and zircon is enriched in the most distal small pebble conglomerate and grit (Roscoe, 1969). Changes in abundance and size of quartz clasts, pyrite, uraninite and other mineral grains have been documented quantitatively by Theis (1979). The zonations can only be interpreted as the results of hydraulic sorting of detrital grains including uraninite. Hydraulic equivalence of ore minerals has also been noted in South Africa (Koen, 1961; Coetzee, 1965; Hiemstra, 1968). Minter (1976) has documented uraninite-gold zonations in Witwatersrand ores. Gold is concentrated with detrital uraninite, but the highest uranium/gold ratios are downstream from the highest gold contents, suggesting that some gold was originally deposited as particles with average equivalent hydraulic sizes larger than those of most of the uraninite grains carried by the streams.

Tectonic settings of pyritic conglomerate-bearing successions

A variety of tectonic settings have been proposed for the major tectonostratigraphic blocks that contain pyritic paleoplacers. Bickle and Eriksson (1982) considered the Witwatersrand Supergroup to have been deposited in a tensional regime. Burke et al. (1985, 1986) proposed that the Dominion Group may be part of an Andean-type volcanic arc, that the Witwatersrand Supergroup filled a foreland basin developed when the Kaapvaal and Zimbabwe cratons collided at 2.7 Ga, and that deposition of the Ventersdorp Supergroup was a result of rifting caused by this collision. Clendenin et al. (1987) have proposed that the Dominion-Witwatersrand, Ventersdorp, and Chuniespoort depositional systems were developed in a series of successor basins formed through a 3.1 to 2.2 Ga interval in response to changes in stresses generated first by subduction of oceanic crust and finally by collision of the Zimbabwe Craton with the Kaapvaal Craton. One wonders whether this time interval is not excessive, and thus whether it might not be more reasonable to consider (a) the Ventersdorp eruptions (Van Niekerk and Burger, 1978) as a prelude to opening of an ocean at ca. 2.6 Ga and deposition of Chuniespoort dolomites and iron-formation as passive margin deposits, and (b) the disconformably overlying fine grained clastic sediments of the Pretoria Group as the fill of post-collision (2.6-2.2 Ga) foreland basins. Models invoking ocean closing and continental collision a few hundred kilometres north of the present erosional edge of the Witwatersand Supergroup perhaps unnecessarily constrain its possible provenance area, as evidence for such a collision during the period postulated is not compelling.

Various models have also been proposed for the tectonic setting for deposition of the Huronian Supergroup. Young (1983) proposed deposition in an aulacogen that opened southeastward into the region that is now the Grenville

Province. Card (1978) considered the Huronian depository to have developed as an elongate intracratonic graben. Zolnai et al. (1984) regarded the Huronian Supergroup as a passive margin sequence deposited along the southern margin of the Superior Province Archean craton and deformed ca. 1.9 Ga when its southern part was overridden by an allochthonous terrane. Fahrig (1987) postulated that deposition began with rifting that was accompanied by intrusion of the Matachewan mafic dyke swarm and extrusion of the early Huronian lavas, then continued on the passive south margin of the Archean craton. A U-Pb zircon age of 2454 ± 2 Ma has been reported (Heaman, 1988) for a dyke of the Hearst-Matachewan swarm. This compares with a U-Pb age of 2450 +25/-10 Ma for felsic volcanic rock (Coppercliff Formation) near the base of the Huronian Supergroup.

A south-facing passive margin model has also been proposed for the Snowy Pass Supergroup in Wyoming (Karlstrom et al., 1983), which contains a succession that is comparable unit for unit with the succession in the western part of the Huronian Supergroup. These similarities are so remarkable that it is inconceivable that accumulation of the two occurred in separate depositories. A reconstruction permitting their deposition as one and the same succession, and their subsequent rifting apart is possible. This reconstruction, with the Snowy Pass belt and the Wyoming craton rotated about 140° (Roscoe and Card, 1993), matches and extends the centripetal pattern of fluvial paleocurrents exhibited in the Huronian belt. It also adds subjacent strata (Phantom Lake suite) to Elliot Lake Group rocks deposited south of Sault Ste. Marie. The reconstructed depository, with effluent direction constrained towards the south or southeast, is not unlike the Witwatersrand depository with its semicircular centripetal inflow. Parts of the Baltic Shield, which contain glaciogenic, hematitic paleoplacers and other strata similar to the Cobalt Group, as well as rocks similar in character and age to those in the Superior Province, may have formed the eastern part of the proposed combined Huronian-Snowy Pass depository. According to this scenario, the early Aphebian deposition of dominantly fluvial 2.45 Ga sediments seems likely to have occurred in a tensionally strained zone that had a northerly trend, like the 2.45 Ga Matachewan dyke swarm, within a large, newly assembled (2.7 Ga) continent that was being uplifted due to trapped heat, including radiogenic heat generated relatively rapidly in the ancient rocks. It can be further postulated that the large continent began to break up at 2.2 Ga when large volumes of gabbro were intruded in the Huronian area, the Lake Superior area, the Wyoming cratonic segment, and the Baltic segment. Strata containing iron-formation and carbonate rocks were deposited subsequently on passive margins, and perhaps in later collision related basins, on the Superior Province, the Wyoming Province, and the Baltic Shield. The Witwatersrand Supergroup, along with pyritic paleoplacer-bearing rocks in Brazil, Australia, and India, might have been involved in a similar sequence of events from 3.0 to 2.6 Ga.

Age of paleoplacers

Pyritic paleoplacers (subtype 1.1.1) occur in strata 3.0 Ga old and older in southern Africa (Saager and Muff, 1978), Australia (Carter and Gee, 1987), and India (Srinivasan and Ojakangas, 1986). Gold-uranium pyritic paleoplacers in the Dominion Group are 3.07 Ga; those in the Witwatersrand Supergroup, between 2.95 and 2.71 Ga, according to the U-Pb isotopic ages of zircons from associated volcanic formations and intrusive or unconformably underlying felsic igneous rocks. Huronian pyritic paleoplacer uranium ores are nearly coeval with rhyolite of the Coppercliff Formation dated at 2.45 Ga according to U-Pb zircon data of Krogh et al. (1984) and with Matachewan diabase dykes of this age (Heaman, 1988). No succession containing pyritic paleoplacers has been found to be younger than 2.4 Ga, although some have younger possible minimum ages, in the range 2.2 Ga to 1.9 Ga.

Hematitic paleoplacers (subtype 1.1.2) comparable to recently formed placers, on the other hand, have not been found in strata older than 2.4 Ga. Ancient strata containing pyritic conglomerates differ in additional respects from younger strata containing hematitic (black sand) detrital heavy minerals. They lack redbeds, authigenic pyrite is present in lieu of authigenic ferric oxide, and associated paleosols also lack ferric iron oxides. This time-dependent transition in weathering and oxidation of fluvial sediments has been linked to atmospheric evolution and termed *oxyatmoversion* (Roscoe, 1969, 1981). The Huronian Supergroup and the Snowy Pass Supergroup in Wyoming (Karlstrom et al., 1983) contain pyritic conglomerates in lower units, and hematitic conglomerates and redbeds in upper units, so their deposition spans the oxyatmoversion. This event is constrained by U-Pb ages for rhyolite of the Coppercliff Formation (2450 +25/-10 Ma, Krogh et al., 1984) and on Nipissing gabbro (2219.4 +3.6/-3.5 Ma, Corfu and Andrews, 1986), which has intruded folded strata of the uppermost, post-oxyatmoversion Huronian Supergroup. The Huronian sediments were likely deposited in a period considerably less than the 230 Ma between these two events, so the transition may have occurred at about 2.4 Ga. In Africa, it is constrained between 2.6 and 2.2 Ga.

DEFINITIVE CHARACTERISTICS

The prime diagnostic feature of paleoplacers is the presence of concentrations of individual grains of heavy minerals in clastic sedimentary rocks that have been deposited and sorted by strong currents. Hematitic paleoplacers (subtype 1.1.2) due to diagenetic and metamorphic modifications, may differ mineralogically, but not chemically, from unconsolidated placers. Pyritic paleoplacers (subtype 1.1.1) differ from common hematitic paleoplacers in their high sulphur content, absence of magnetite and ferric oxide, and relatively high U/Th ratios. Isolated occurrences may be difficult to distinguish from stratabound epigenetic sulphide-rich gold or uranium concentrations. The epigenetic origin of the latter can be diagnosed if hematitic paleoplacers or redbeds are present in correlative or older strata.

Differences between Huronian (uraniferous) and gold-rich Witwatersrand pyritic paleoplacers

The gold content of the South African ores is two orders of magnitude greater than that of most large exploitable placers, hematitic paleoplacers, and Elliot Lake uranium ores. What differences are there between Witwatersrand and Elliot Lake pyritic paleoplacers that might provide some insight into the reason for the different gold contents?

Some differences of Witwatersrand ores and rocks compared to those of the Huronian are: (1) quartz arenites and conglomerates are texturally and mineralogically more mature; any feldspar not destroyed during weathering and transport was diagenetically altered to phyllosilicates; (2) considerable detritus from underlying sands and gravels were eroded and incorporated in many succeeding beds – in other words, there was likely more reworking; (3) ratios of uraninite to other radioactive minerals and of U/Th ratios in uraninite and in ores are higher; (4) clasts, including pyrite and uraninite grains, are more rounded; ventifacts have been noted; (5) pyrite contains more Ni and less Co; (6) heavy minerals include more chromite and less monazite; (7) kerogen is much more abundant; (8) pyrite 'mudballs' are abundant in some 'Wits' conglomerates, but are rare or absent in the Huronian; (9) arsenopyrite, other sulpharsenides, and probably some sulphides, are more abundant; (10) pyrite (average 3%) is less abundant; (11) it has been inferred that some Witwatersrand ore-bearing zones were likely deposited near shorelines and are intertongued with marine or lacustrine sediments (e.g., Minter, 1981); there is no evidence that Huronian conglomeratic ores were deposited in a littoral environment; (12) it has been suggested that altered zones ('hags') in granitic basement rocks could represent roots of gold deposits that were sources of detrital gold in nearby Witwatersrand goldfields (Robb and Meyer, 1985); and (13) Witwatersrand gold paleoplacers are older (between 3.07 and 2.71 Ga) than Huronian uranium paleoplacers (close to 2.45 Ga).

The hypothesis most commonly advanced for the different U/Au ratios in Witwatersrand and Huronian ores relates them to inferred differences in provenance. This cannot be assessed satisfactorily. Exposures of Witwatersrand source rocks are limited and do not include important gold deposits, whereas the Huronian provenance almost certainly included part of the Abitibi belt, which has produced more gold than any other Archean greenstone belt. It is difficult in any case to imagine any source area capable of supplying quantities of particulate gold comparable to the gold present in Witwatersrand deposits. More gold has been produced from 'Wits' than has been found in all of the 'lode' gold deposits of the world put together (possibly excluding the former U.S.S.R.). The possibility that the most favourable conditions for formation of auriferous paleoplacers might have been attained prior to formation of the Huronian ores must be considered (Hutchinson, 1987). We do not have adequate data, however, to determine whether the age difference between Witwatersrand and Huronian paleoplacers applies generally to gold-rich and gold-poor pyritic paleoplacers. Age certainly could not be the only factor, as older (ca. 3.07 Ga) Dominion paleoplacers have higher U/Au ratios than the considerably younger Venterpost paleoplacers (ca. 2.64 Ga).

GENETIC MODEL

It is doubtful if any genetic model has been more usefully applied to exploration and mine development than the modified placer model, which is almost universally accepted by people involved in these activities with respect to pyritic quartz pebble conglomerate deposits. This does not mean that it is correct in all respects as it is applied; only that no other model has been devised that has comparable predictive value. Many features consistent with the placer model have been cited above. These include detrital shapes and modes of occurrence of uraninite and evidence of hydraulic sorting.

It has been suggested that peculiarities of the pyritic conglomeratic ores, as compared to hematitic paleoplacers and unconsolidated placers, are the result of an early atmosphere devoid, or nearly devoid, of free oxygen (Roscoe, 1973). A time-dependent change is certainly involved and it seems unlikely that this could have been a change in epigenetic processes. No variation of the placer model, however, provides satisfactory explanations for all features of pyritic conglomeratic ores; nor does any other model. It is particularly difficult to conceive of an adequate source for the immense amount of gold in Witwatersrand strata, regardless of how it may have been concentrated therein. Necessary widespread sources for detrital uraninite and a source for sulphur in ubiquitous authigenic, as well as allogenic, pyrite are also problematical.

EXPLORATION GUIDES

Paleoplacer gold and uranium deposits occur in Archean to Early Proterozoic fluvial to littoral clastic sedimentary sequences, dominated by quartz arenite units, that are older than about 2.4 Ga. The host units are pyritic, mature arenites, and oligomictic (quartz pebble) conglomerates produced by multiple cycles of erosion and redeposition. Deposition of these sequences occurred on and adjacent to stable Archean cratons and at the margins of, and within, intracratonic grabens or aulacogens, or within basins formed by downwarping due to tectonic processes other than rifting. Ore zones are in some cases controlled by basement topography, and paystreaks within the Witwatersrand goldfields radiate from fan apices within huge deltaic fan sequences.

Favourable environments for gold and other paleoplacers in consolidated rocks are the same as those for placers in unconsolidated rocks – high energy environments where heavy detrital mineral grains have been concentrated relative to lighter detrital mineral grains by stream currents, wave action, or wind. To be of economic interest, the concentrations must be much greater than those present in most of the unconsolidated placers that have been exploited. Pyritic paleoplacers (subtype 1.1.1) are far more favourable targets than hematitic, or black sand, paleoplacers (subtype 1.1.2), but they occur only in quartzose arenite formations older than 2.4 Ga. All such formations should be prospected for pyrite-dominated heavy mineral concentrations in quartz pebble layers. These are invariably more radioactive than host quartzites, so a scintillometer is an indispensable field tool. Rusty weathered bands in coarse or pebbly quartzite is a common clue. If analyses reveal slight enrichments in gold and uranium, a search for richer, sourceward concentrations may be considered. This may require special mapping and sedimentological studies to determine the extent of the formation, facies variations within it, foreset dips, and other directional features. Exploration in any extension of the formation 'upstream' from sub-ore grade paleoplacer outcrops will require core drilling and application of subsurface stratigraphic study techniques of various parameters, such as changes from hole to hole in pebble sizes, bed thicknesses, and U/Th ratios, as well as gold and uranium analyses.

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1.2 PLACER GOLD, PLATINUM

C.R. McLeod and S.R. Morison

INTRODUCTION

Placer deposits are accumulations of heavy minerals that have been eroded from lode sources and concentrated by sedimentation processes involving gravity, water, wind, or ice. In this description we also include those minerals (especially gold) that may have formed in situ as a result of chemical transport and precipitation. Gold placers commonly occur in stream gravels in uplifted, unglaciated areas containing primary, auriferous source rocks. Silver is recovered from placer gold in the refining process; platinum is a byproduct of placer gold mining in some localities, or, as at Tulameen, British Columbia, platinum was the primary metal recovered and gold was a byproduct (O'Neill and Gunning, 1934).

Numerous placer gold deposits have been and continue to be mined in Canada, particularly in the Cordilleran region. Important examples include the Klondike-Clear Creek area, Yukon Territory; Atlin and Cariboo districts, British Columbia; and the Chaudière River Basin, Quebec. The most significant examples of foreign placer gold districts are Sierra Nevada, California; Victoria, Australia; Lena, Aldan, and Amur rivers, Russia; and Choco, Colombia.

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IMPORTANCE

Historically, placer deposits have contributed more than 7% of the total recorded Canadian gold production of 6.9 million kilograms (222 million fine ounces) (Robinson, 1935; Dominion Bureau of Statistics annual reports, 1923-1949, 1951-1955; Canadian Minerals Yearbooks, 1960-1963, 1965-1990; LeBarge and Morison, 1990; Latoski, 1993; INAC, 1994). Total recorded placer production, about 515 000 kg to 1988, has come chiefly from Yukon Territory (72%) and British Columbia (27%). Minor contributions from the Chaudière region in Quebec, the Saskatchewan River in Alberta, and a small amount from beaches in Nova Scotia make up the remaining 1%. Perhaps as much as 20% of placer production has gone unreported, but this amount is difficult to estimate and is not reflected in the above figures.

In the 1980s, placers contributed 3.5% of the total Canadian gold production; this represents an increase from a low of 0.2% in the early 1970s. In 1900 when the Klondike production was at its peak and British Columbia production was at about one third of the maximum for the province (reached in 1863), placer gold accounted for 85% of the Canadian total. The Chaudière River Basin, Quebec, was the most productive Canadian placer district east of British Columbia. Within this basin about 100 000 fine ounces (more than 3000 kg) of gold was recovered from preglacial, interglacial, and postglacial placers (Boyle, 1979), chiefly between 1860 and 1885.

Platinum and platinum group elements (PGE) have been reported from several Canadian placer gold deposits in British Columbia, Yukon Territory, and the North Saskatchewan River, Alberta (O'Neill and Gunning, 1934).

Contents

Platinum production from the Tulameen district, British Columbia, in the latter part of the nineteenth and early part of this century totalled about 20 000 troy ounces (622 000 g). Placers have been a major source of platinum production in Colombia, United States (Goodnews Bay, Alaska), and the former U.S.S.R. (Mertie, 1969).

SIZE AND GRADE OF DEPOSITS

Placer deposits range greatly in size and grade, from small, local, near-source concentrations that may be profitable to work on a small scale, to much larger deposits of sparsely disseminated, fine grained gold in alluvial sediments associated with regional drainage basins. In some instances, as distance from the source increases, the grain size of placer gold decreases. With dilution from nonauriferous tributaries, the gold values in alluvial placers diminish, more or less gradationally, to low grade, uneconomic disseminations.

In the Klondike area, Yukon Territory, more than 200 km of valley bottoms have been worked in Bonanza, Hunker, Dominion, Sulphur, Quartz, and Bear creeks and their tributaries. Richer pay streaks, or parts of them, were originally mined by sinking shafts and drifting along the bedrock surface. Subsequent reworking by open cuts or dredging, in many areas more than once, and the lack of detailed records on the amount of gold recovered, render it difficult to compile accurate "grade-tonnage" relationships. McConnell (1907) estimated production from four miles of pay streak on Eldorado Creek, Yukon Territory, at CAN. $25 000 000, and probable future output at an additional $2 600 000. This would represent more than 6000 g of gold per metre for a distance of 6 km. Production from Eldorado Creek since 1906 has probably equalled or exceeded that during the first 10 years it was worked, making it one of the richest creeks found in Canada.

Placer concentrations of other mineral commodities are also known in Canada. Along the north shore of the St. Lawrence River, concentrations of magnetite, ilmenite, and titaniferous magnetite occur as black sand beds several centimetres thick in postglacial fluvial, deltaic sands which have been partially reworked by wave and tidal action. Drilling near the mouth of the Natashquan River indicated 1.5 billion tonnes of sand containing 3.7% iron (Gross, 1967). Near Steep Rock Lake, Ontario, more than 600 000 t of iron concentrate was produced between 1959 and 1964 from hematite-goethite glacial gravels (Prest, 1970). In the Dublin Gulch area, Yukon Territory, minor quantities of scheelite were recovered from placer workings during the Second World War and again between 1977 and 1981 when more elaborate methods (vibrating sluice, jigs, spiral concentrators, separation tables) were used (Debicki, 1983). However, the scheelite recovery process proved to be uneconomic (LeBarge and Morison, 1990).

GEOLOGICAL FEATURES

Canadian Cordilleran placer deposits occur in both glaciated and unglaciated terrains, and it is assumed that gold was released from bedrock or paleoplacer sources through weathering processes during nonglacial periods or interglacial intervals. These deposits are found in five sedimentary settings (Table 1.2-1; Morison, 1989), which can be summarized as follows: 1) Pliocene to early Pleistocene alluvial placer deposits which are preserved as high level terraces buried beneath nonauriferous overburden; 2) Pleistocene nonglacial alluvial placer deposits that occur as valley-bottom fill and low to high level terraces in unglaciated terrain; 3) interglacial placer deposits that occur as valley-bottom alluvial fill or low terraces in drainage systems that have escaped the effects of glacial erosion; 4) glacial placer deposits that have formed when gold from regional bedrock or paleoplacer sources was incorporated into some types of glacial drift, such as glaciofluvial or ice contact deposits, moraines, and stratified till deposits; and 5) Recent placer deposits which are found as colluvial deposits, valley-bottom alluvial blankets in gulches and other tributary valleys, bar deposits in major river systems and beach and nearshore marine deposits.

Economic placer gold districts are found throughout the Canadian Cordillera (Fig. 1.2-1) and include all of the preceding placer deposit settings, each with a unique depositional history. For example, in the Clear Creek drainage basin in the Yukon Territory (area 4 of Fig. 1.2-1), placer gold is found in valley-bottom creek and gulch gravel, glacial gravel, and buried preglacial fluvial gravel (Fig. 1.2-2) (Morison, 1985a). In the Mayo district (area 5 of Fig. 1.2-1), small colluvial placers have been developed from local bedrock sources (Boyle, 1979). Pliocene to early Pleistocene White Channel placer deposits in the Klondike district (Fig. 1.2-3; area 4 of Fig. 1.2-1) form high level terraces 50 to 100 m above present day stream levels. White Channel alluvium ranges in thickness from a few metres to more than 35 m, and is characterized by 14 lithofacies types which were deposited in a braided river environment with valley wall alluvial fan and debris flow sedimentation (Morison, 1985b). Lebarge (1993) concluded that placer gold in the Mount Nansen area (Fig. 1.2-1), in central Yukon Territory, is found in valley bottom alluvium, Pleistocene alluvial terraces, and early Pleistocene proglacial gravelly terraces and diamicton that is interpreted as glacial till or resedimented till. In the Cariboo district of British Columbia (area 19 of Fig. 1.2-1), placer deposit settings include Tertiary and interglacial gravel, glacial outwash gravel, and postglacial stream gravel (Boyle, 1979). Clague (1987) identified a previously unknown Pleistocene buried valley near the Bullion mine in the Cariboo district and suggested there may be other such valleys in the region. Levson and Giles (1993) identified the following placer settings in the Cariboo region of British Columbia: Tertiary and pre-late Wisconsinan paleochannel and paleofan settings; Late Wisconsinan glacial and glaciofluvial environments and Holocene high and low terraces, colluvium, and alluvial fan settings. They further concluded that five main auriferous lithofacies types characterize placer deposit settings in this area of British Columbia. Beach placer deposits on the Queen Charlotte Islands (area 14 of Fig. 1.2-1) formed through wind and wave erosion of auriferous glacial sediments (Boyle, 1979).

Placer gold deposits in Alberta and Saskatchewan occur as Recent and modern stream deposits in major drainage basins, such as the North Saskatchewan River (Giusti, 1983; Coombe, 1984). The recovery of placer gold in Alberta is primarily due to gravel washing plants that process late Tertiary, preglacial gravels and sands of river channel deposits in the Edmonton area. In Quebec and Ontario placer gold deposits and occurrences are found in both recent and interglacial stream gravel and glacial drift (Ferguson and Freeman, 1978; LaSalle, 1980). In coastal

Contents

Table 1.2-1. Stratigraphy and general characteristics of placer gold deposits in Canada (from Morison, 1989).

Time Period	Tertiary	Quaternary, Pleistocene, preglacial or nonglacial	Interglacial	Glacial	Holocene
Placer environment and geomorphic location	Buried alluvial sediments in benches above valley floors	Buried alluvial sediments in benches above valley floors; valley fill alluvial sediments; alluvial terraces	Valley fill alluvial sediments; alluvial terraces	Benches of proglacial and ice contact deposits; moraines and drifts	Valley bottom alluvial plains and terraces; colluvium and slope deposits; beach and nearshore marine deposits
General sediment characteristics	Mature sediments; well sorted alluvium with a diverse assemblage of sediment types	Locally derived gravel lithology; moderately to well sorted alluvium which is crudely to distinctly stratified	Mixed gravel lithology; moderately to well sorted alluvium which is crudely to distinctly stratified	Regionally derived gravel lithology; variable sorting and stratfication depending upon type of glacial drift	Mixed gravel lithology; moderately to well sorted alluvium which is crudely to distinctly stratified; poorly sorted, massive slope deposits; well sorted beach sand
Gold distribution	Greater concentration with depth	Discrete concentrations throughout to pay streaks at base of alluvium	Discrete concentrations throughout to pay streaks at base of alluvium	Dispersed throughout	Discrete concentrations throughout to pay streaks at base of alluvium; pay streaks follow slope morphology and strandline trend
Mining problems	Thick overburden	Thick overburden; variable grade	Variable grade	Low grade	Variable grade and low volume of auriferous sediment
Examples	"White Channel Gravel" of the Klondike area, Yukon Territory	Preglacial fluvial gravels, Clear Creek drainage basin and unglaciated terrain in Yukon Territory	Interglacial stream gravels in Atlin and Cariboo mining districts, British Columbia	Glaciofluvial gravel, Clear Creek drainage basin, Yukon Territory	Valley bottom creek and gulch placers, Clear Creek drainage basin, colluvial placers in Dublin Gulch area, Yukon Territory; beach placers, Queen Charlotte Islands, British Columbia

areas (Graham Island, British Columbia; southern Nova Scotia; Seward Peninsula, Alaska) placer gold deposits and auriferous sands and gravels occur in submerged, raised, and modern beaches and in submarine drainage channels (Boyle, 1979).

Geological setting

Placer gold deposits are commonly found in deeply weathered unglaciated terrain within a stable craton that contains auriferous source rocks. Deposits occur in the weathered zone of all rock types but are especially common in metamorphic rocks. Sources of placer gold include gold-bearing quartz veins, felsic intrusions, sulphide deposits (skarns, veins, massive sulphides), paleoplacers, and porphyry copper deposits. Both epithermal and mesothermal gold deposits may also give rise to gold placers. However, economic placers may well be derived only from specific types of gold-bearing deposits.

Age of host rocks and mineralization

Unconsolidated placers in Canada are chiefly of Quaternary age, but late Tertiary gravels, particularly in the Klondike district, Yukon Territory, have yielded considerable amounts of placer gold. The geology of these Tertiary deposits has been described in detail by Morison (1985b), Dufresne et al. (1986), and Morison and Hein (1987). Primary and secondary (intermediate collector sediment) sources of gold can range from Precambrian to Tertiary. Boyle (1979) linked the preponderance of rich, productive Tertiary and later placers chiefly to first generation sediments that contain coarse gold. Multiple cycles of erosion and deposition result in comminution and dispersal of gold as fine particles.

Form of deposits and distribution of ore minerals

Coarse placer gold tends to be concentrated in pay streaks, commonly on or near the bedrock surface or on compacted, relatively impervious sediments above bedrock. Factors that control the location of pay streaks are not well understood, but in narrow gulches and creeks they are generally on the bedrock surface in the deepest part of the valleys. Wider, mature valleys contain discontinuous pay streaks and discrete concentrations of placer gold, both on the bedrock surface and within the gravelly sediments. Uplift and downcutting may leave bench placers as stream terraces or may result in the redistribution of gold into creek, river, floodplain, deltaic, and beach placers. In delta and flood plain environments, gold is commonly in very fine flakes and particles, and pay streaks are irregularly distributed as a result of complex channel migration and the large volume of sediments.

Mineralogy

Gold (or electrum) is the prime mineral of interest in Canadian placer deposits, but minor quantities of platinum group metals, scheelite, wolframite, and cassiterite have also been recovered. Common heavy minerals found in black sand include amphibole, pyroxene, tourmaline, topaz, beryl, garnet, chromite, sphene, rutile, goethite, magnetite, ilmenite, pyrite, cassiterite, wolframite, and scheelite. "Uranianpyrochlore", euxenite, and "uranothorite" have been reported from postglacial outwash gravels in Bugaboo Creek, Spillimacheen district, British Columbia (Merrett, 1957). Platinum-iron alloy grains are the most common platinum group minerals found in Yukon Territory, British Columbia, and Alberta placers

Contents

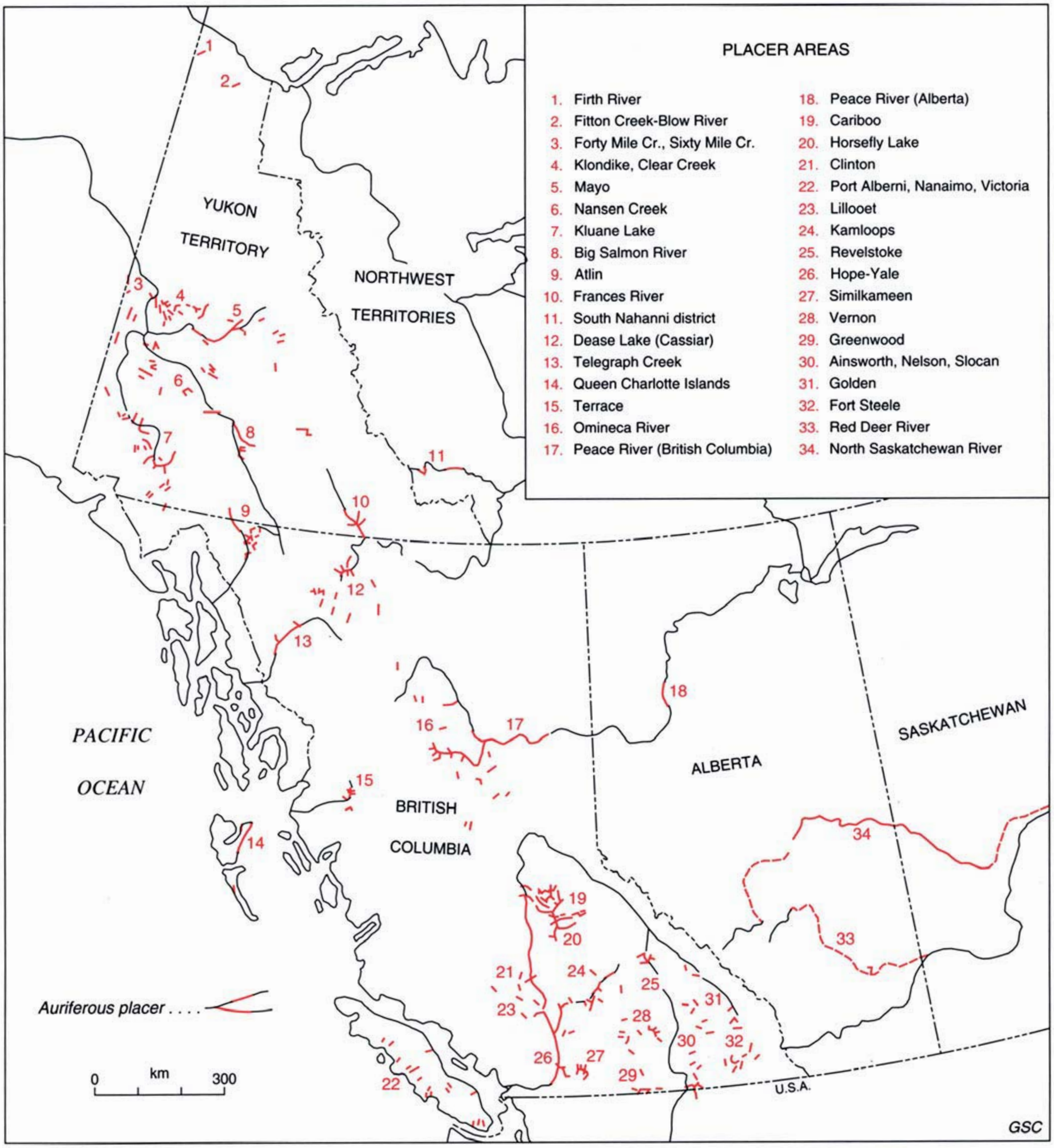

Figure 1.2-1. Placer gold districts in western Canada (from Boyle, 1979).

(Nixon et al., 1989; Ballantyne and Harris, 1991; S.B. Ballantyne and D.C. Harris, unpub. data, GSC Minerals Colloquium, January 22-24, 1992, Ottawa, Ontario; Harris and Ballantyne, 1994), whereas Os-Ir-Ru grains are found in the Atlin district, British Columbia, and North Saskatchewan River, Alberta (Harris and Cabri, 1973; Harris and Ballantyne, 1994). Minerals that may become economically extractable in the future include monazite, pyrochlore, tantalite, columbite, fergusonite, bastnaesite, xenotime, zircon, baddeleyite, euxenite, samarskite, and cinnabar. Placer minerals are characteristically highly resistant to mechanical breakdown and chemical dissolution in the surface environment.

Placer gold is found in a wide variety of shapes and sizes, but most common are dust and small scales, or particles in the 0.1-2 mm range. The morphology of grains has been characterized by various investigators, e.g., Ballantyne and MacKinnon (1986), Ebert and Kern (1988), and Knight et al. (1994). As a general rule, placer gold near its source is relatively coarse and rough; with transport the particles become smaller, smoother, and more flattened. These effects are the result of both physical and chemical processes (Boyle, 1979), but the natural milling of a high energy stream system appears to play a major role in modifying the size and morphology of gold particles during transport.

Electron microprobe investigations have shown that spongy marginal rims on placer gold commonly have a higher fineness than grain interiors ("fineness" refers to the proportion of gold in the naturally occurring metal; it is calculated and expressed in parts per thousand). Leaching of silver was proposed as the cause of this enrichment by several workers (e.g., Giusti and Smith, 1984; Michailidis, 1989; Knight et al., 1994), but Groen et al. (1990) considered the rims to be formed either by precipitation of gold from the surrounding solution or by "self-electrorefining" of placer electrum grains. Giusti and Smith (1984) recognized a general increase in fineness with decreasing grain size,

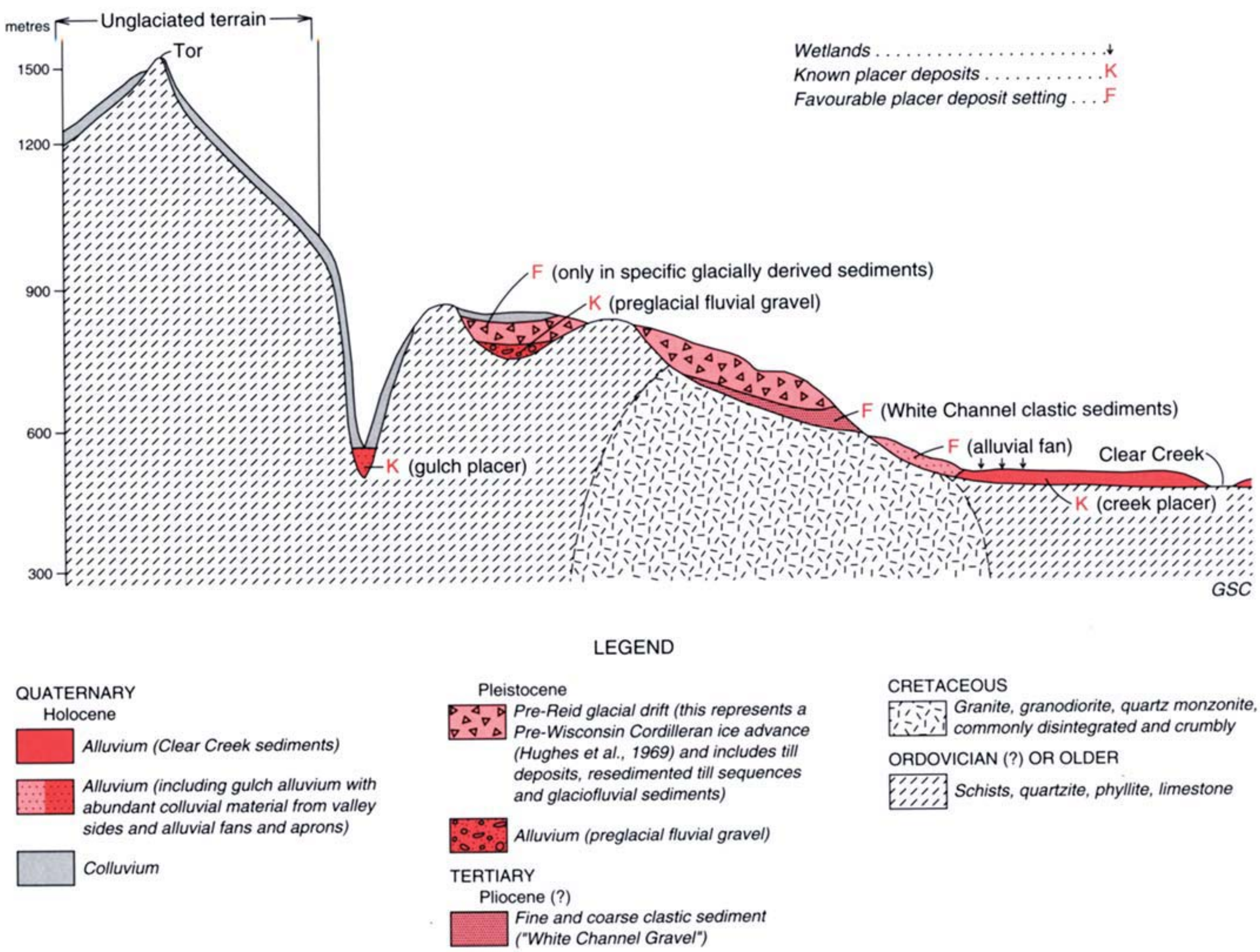

Figure 1.2-2. Schematic profile of the Clear Creek, Yukon Territory drainage basin showing types of placer deposits and Quaternary deposits (from Morison, 1985a, 1989).

Contents

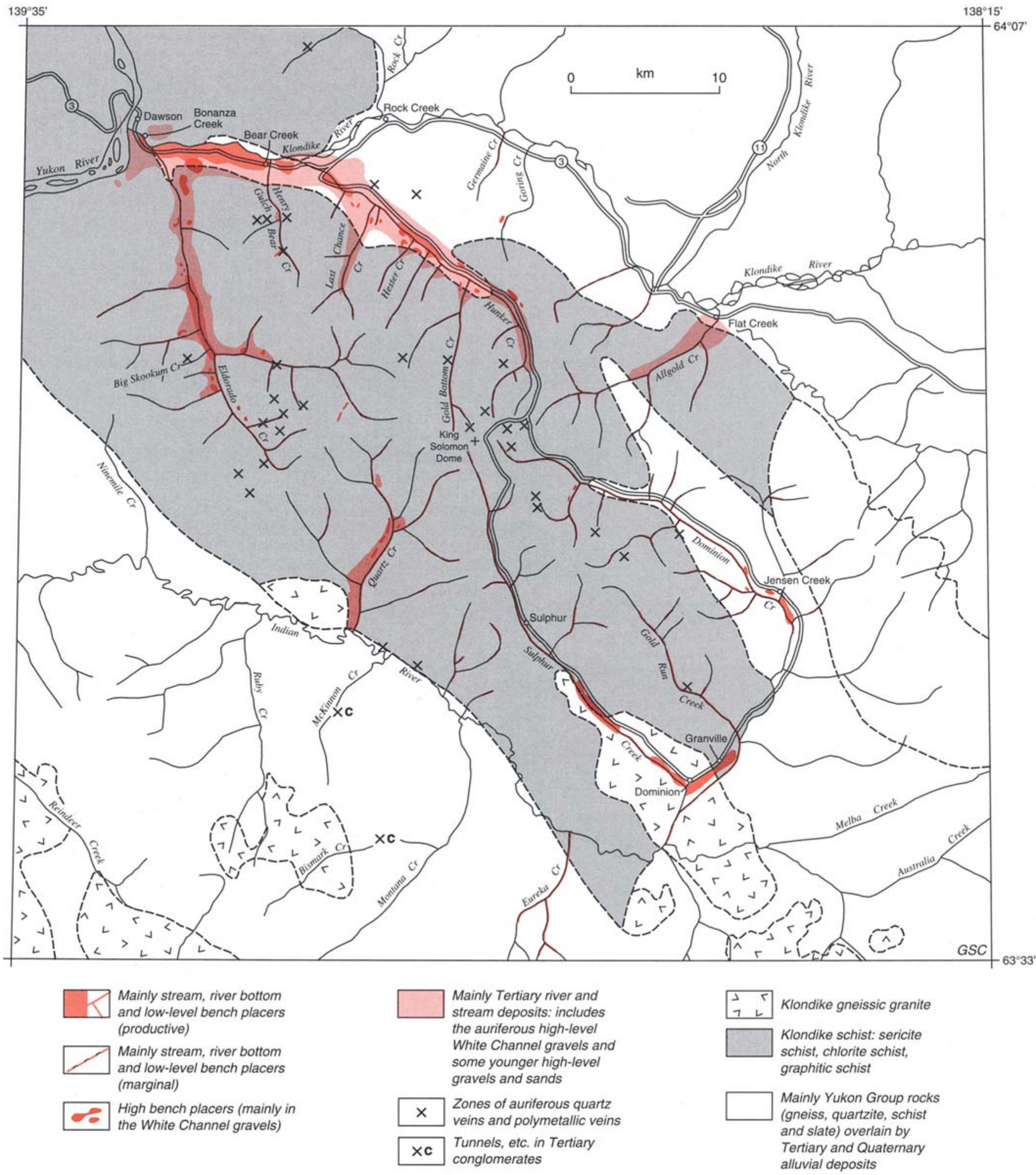

Figure 1.2-3. Generalized geology of the Klondike (Dawson) district, Yukon Territory showing the relationship of the gold placers to the Klondike schist and other rock units (from Boyle, 1979).

Contents

attributable to the gold-rich rims; Groen et al. (1990) found the thickest rims were usually on flake-shaped (most transported) grains. S.B. Ballantyne and D.C. Harris (unpub. data, GSC Minerals Colloquium, January 22-24, 1992, Ottawa, Ontario); reported the discovery of "new" gold in the five micrometre size range on the surfaces of placer heavy minerals, such as zircon, monazite, scheelite, and ilmenite, from the alluvial platinum-gold placers of Florence Creek, Yukon Territory. Geochemical variations in placer gold have been related to the depositional environments of the primary gold sources (e.g., Ballantyne and MacKinnon, 1986; Michailidis; 1989: Mosier et al., 1989; Knight et al., 1994). Knight et al. (1994) studied the shape and composition of some 2700 gold particles from lode occurrences and placer deposits in the Klondike area and demonstrated that compositional data may be used to link placer gold with specific lode sources.

Mertie (1969) reported that placer platinoid grains commonly consist of two principal types of PGE alloys; one is dominantly platinum with varying contents of the other five PGEs, whereas the other consists of alloys composed chiefly of iridium and osmium. Both alloy types can contain intimate intergrowths with, and minute inclusions of, the other. More detailed electron microprobe studies (e.g., Cabri and Harris, 1975; Cousins and Kinloch, 1976) confirmed the complex compositions and interrelationships of PGE minerals in placer grains. Compositional zoning in such grains was considered to be primary by Cabri and Harris (1975), but indicative of accretion and secondary growth by Cousins and Kinloch (1976). Rosenblum et al. (1986) found that magnetic concentrates from Goodnews Bay, Alaska, contained discrete grains of PGE minerals, PGE minerals as inclusions in magnetite, and PGEs that had apparently diffused into the magnetite lattice adjacent to PGE minerals. Mardock and Barker (1991) reported that placer platinum group metal minerals from Goodnews Bay exhibit characteristics attributable to both mechanical and accretionary processes of formation. In Canada recent studies have characterized placer platinum group metal minerals in British Columbia, Yukon Territory, and Alberta (see respectively, Nixon et al., 1989; Ballantyne and Harris, 1991; S.B. Ballantyne and D.C. Harris, unpub. data, GSC Minerals Colloquium, January 22-24, 1992, Ottawa, Ontario; S.B. Ballantyne and D.C. Harris, unpub. data, GSC Minerals Colloquium, January 17-19, 1994, Ottawa, Ontario; and Harris and Ballantyne, 1994).

DEFINITIVE CHARACTERISTICS

Placer deposits are commonly found in deeply weathered, unglaciated terrain with subdued topography, represented by broad valleys and accordant rounded hills that have been dissected by a moderately mature drainage system made up of numerous small streams tributary to the main water courses. Auriferous source rocks are a prime prerequisite for the formation of placer deposits. Near the source, gold is coarse and is found in fairly well-defined pay streaks on bedrock; the grain size decreases with transport but fineness of the gold commonly increases. Heavy minerals that accumulate with gold are usually from primary gold deposits or local country rocks. Fine grained gold that is transported to larger stream and river systems is erratically distributed by more complex fluvial processes, but local concentrations may result under favourable depositional conditions. For example, Hou and Fletcher (1992) reported a (slight) increase in the abundance and size of gold grains downstream in the Harris Creek catchment basin of southern British Columbia.

GENETIC MODEL

The first requirement for the formation of a placer is the presence of auriferous source rocks, which can include gold-bearing quartz veins, large silicified bodies that contain disseminated gold, porphyry copper deposits, disseminated pyritic and massive sulphide deposits, pre-existing placers, and trace contents of gold in otherwise unmineralized rock.

During the weathering cycle, chemical and mechanical processes remove gangue or interstitial host rock material that is far less resistant to structural breakdown and chemical decomposition during weathering than is gold. This can result in low-grade, in situ or residual accumulations that have experienced little, if any, mechanical transport. In Canada such placers are rare and small in size, in part because of extensive glaciation. However, as a first stage of a model for placer formation, the generation of eluvial or residual gold accumulations probably reflects the start of a lengthy and complex process that eventually gives rise to extensive and rich placer deposits and districts.

Deep secular weathering of source rocks, particularly where undisturbed by glaciation, results in the preconcentration of gold in, on, or near the bedrock surface by gravity, creep, frost action, and solifluction processes. Gravity and stream hydrodynamic processes concentrate gold into pay streaks in the alluvium, especially on irregular bedrock surfaces, in much the same manner as that which takes place in a sluice box. These processes can also result in concentrations of gold on impervious layers within the alluvium. Beach placers, such as those on Graham Island (Queen Charlotte Islands), British Columbia, form due to tidal and wave action.

Extremely fine gold particles are more readily transported, and their concentration (or dissemination) in the fluvial or littoral environment is determined by hydraulic sorting (flow separation), which is dependent on such factors as the size, shape, and specific gravity of individual grains in the sediment load, the velocity and degree of turbulence of the water flow, and the nature of the stream bed (Best and Brayshaw, 1985; Reid and Frostick, 1985). Grains of equidimensional character are more effectively trapped and concentrated than scaly or flaky particles. Additional concentration of gold may accompany tectonic uplift, with the resulting incision of stream valleys and the reworking of existing auriferous unconsolidated sediments, and the deposition of new alluvial deposits. In the Klondike area, deep weathering, tectonic uplift, and the absence of glaciation that would disperse accumulations of gold, have combined to contribute to the formation and preservation of Canada's richest placer district. It is evident that the formation of placers is the result of a complex interaction of processes that operate at scales ranging from landform (the abrupt widening of a valley) to the microenvironment (the interstices between sediment clasts in the stream bed that entrap heavy mineral grains) (Slingerland, 1984; Hou and Fletcher, 1992). Time and climatic constraints on these processes are not well understood.

The model summarized above is based on a clastogene process whereby discrete gold grains are released by weathering processes and subsequently concentrated in a stream environment. The role of chemical transport in the formation of placers, and the proportion of gold that is contributed or redistributed in this manner, are not well understood. Whether chemical processes are expressed mainly by dissolution and local reprecipitation, with little transportation, is not known. Boyle (1979) reviewed the criteria for detrital versus chemical origin of nuggets and placer gold and concluded that both processes may be active, but one or the other may predominate, depending on local conditions. Watterson (1985) noted that physical, chemical (particularly organic complexes), and electrical effects, which appear to be connected with freezing action, may influence the weathering of auriferous rocks, the chemical complexing of gold, and its subsequent dissolution, mobilization, and redeposition. These effects, in part, could be responsible for the large number of placer deposits at high latitudes. Knight et al. (1994), however, concluded that the bulk of the gold extracted from the White Channel Gravel deposits in the Klondike area is detrital in origin despite the presence of hydrothermal alteration in both footwall rock and the overlying gravel in some of the White Channel exposures in the Klondike area.

In summary, the distribution of placer deposits is controlled by (a) primary sources and their tectonic setting, and (b) geomorphological processes, both of which are affected by climatic conditions superimposed on them. In discussing geomorphological controls on the global distribution of placer deposits, Sutherland (1985) recognized that the processes responsible for the formation of placer deposits vary markedly throughout the world and that placers in different morphoclimatic regions should exhibit characteristics that are distinctive for, and dependent on, the conditions under which they were deposited.

RELATED DEPOSIT TYPES

Paleoplacer gold deposits (deposit subtype 1.1) presumably formed in much the same manner as modern placers, but may have undergone considerable modification since their deposition. At least part of the gold they contain is detrital, but a considerable portion of it may have been recrystallized or chemically remobilized, transported, and precipitated (Lowey, 1985).

Gold-bearing deposits of almost any type apparently may serve as the source of gold in the formation of placer gold deposits (see "Geological setting"), provided the appropriate conditions exist for release, transport, and concentration of the gold.

Aside from gold and platinum, the only commodities contained in placer deposits that have proven to be of economic interest (only marginally) in Canada are magnetite, hematite-goethite, and scheelite. Elsewhere in the world there are, in addition, important cassiterite (tin), heavy mineral (e.g., rutile, ilmenite, zircon, monazite, magnetite), and diamond placers in stream, beach, and offshore deposits. However, placers or even minor concentrations of heavy minerals may be useful indicators of the presence of, or potential for, primary mineral deposits.

EXPLORATION GUIDES

Guidelines to exploration for placers include:

1. Location of areas of gold-bearing source rocks such as auriferous quartz veins and polymetallic sulphide or porphyry deposits; slightly auriferous quartz stringers and veins in schists and gneisses; slightly auriferous minerals such as pyrite and other sulphides in graphitic schists; and slightly auriferous conglomerates, sandstones, and quartzites, or paleoplacers.
2. Recognition of evidence for deep secular chemical and mechanical weathering of potential source rocks on a comparatively mature topographic surface, or the presence of alteration zones within these rocks.
3. Preservation of a weathered profile in unglaciated areas or in areas protected from glacial advances (e.g., trunk valleys oblique or normal to ice direction). This may indicate potential for preglaciation placers.
4. Identification of areas of uplift in which superposed moderately incised drainage has developed.
5. Location of concentrations of gold in a variety of favourable depositional sites in fluvial systems, e.g., on irregular bedrock surfaces, at the heads of midchannel bars, on point bars, and at abrupt valley widenings. This requires an understanding of the hydraulic conditions which control concentrating processes at all scales.
6. Use of remotely sensed imagery (LANDSAT, RADARSAT, side-looking radar, side-looking airborne radar) taken during different times of the year to enhance contour map and aerial photograph interpretation of features such as denudation, sediment accumulation, aggradation, and neotectonic movements.
7. Use of modern geophysical methods (hammer seismic, ground-penetrating radar, magnetic, electrical) to help delineate buried channels and the profile of the bedrock surface along which pay streaks may be found.
8. Use of stream sediment geochemical surveys for associated elements or gold itself to indicate anomalous areas.
9. Use of testing techniques (e.g., panning, rocker, portable sluice box, systematic pitting or trenching, reverse circulation, or sonic drilling) to establish gold distribution, concentration levels, and reserves.
10. Use of specialized gold separation and concentration techniques, which optimize the retention of fine grained gold, for the treatment of bulk samples (e.g., head grade evaluation).
11. Use of highly sensitive analytical techniques to accurately determine the gold contents of samples.

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