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MASS-BALANCE CONSTRAINTS ON FORMATION OF CENOZOIC GOLD PLACERS AND IMPLICATION FOR THE ORIGIN OF WITWATERSRAND GOLD DEPOSITS

JEFFREY S. LOEN

Department of Geology, University of Cape Town. Rondebosch 7700. Republic of South Africa

ABSTRACT: Mass-balance calculations suggest that productive Cenozoic gold placers developed from rocks having low (0.02-6.1 ppb Au) gold contents similar to the crustal abundance of gold in igneous rocks. In addition, gold yield/Ma is positively correlated with drainage basin area, indicating that a larger amount of gold is derived in a given time period from a larger drainage basin.

Witwatersrand deposits appear to fit a placer mechanism because the calculated gold content of inferred source rocks (0.11-0.27 ppb Au) is consistent with that (about 1 ppb Au) of typical Archean granite-greenstone crust, as well as that of source rocks for Cenozoic placers.

RESUME: Les calculs de bilan de masse suggèrent que les placers productifs Cénozoïques se sont développés à partir de l'érosion de roches dont la teneur en or était faible (0.02 à 6,1 ppb), semblable à celle des roches ignées de la croûte. En plus, la quantité d'or fournie par million d'années est corrélée de façon positive avec la surface du bassin versant ce qui indique, pour une période de temps donnée, qu'une plus grande quantité d'or provient d'un bassin versant plus grand.

Les dépôts du Witwatersrand peuvent s'expliquer par les mécanismes qui rendent compte de la formation de placers parce que la teneur en or calculée des roches sources supposées (0,11 à 0,27 ppb Au) est compatible avec celle (environ 1 ppb Au) d'une typique croûte granite-greenstone archéenne, de même qu'avec celle des roches sources des placers Cénozoïques.

INTRODUCTION

Gold placers are one of the best understood of ore deposits in terms of genetic processes (Cox and Singer, 1986), however, few studies have attempted to relate mass-balance constraints to placer formation. A mass-balance approach provides a systematic way to compare placers of differing size and productivity, and may explain why rich placers form in certain areas and not in others. In addition, the approach can be used to test whether ore deposits of uncertain origin fit a placer mechanism.

The objectives of this paper are to describe a general mass-balance model for placers, to apply this model to several Cenozoic placers from western North America, and finally to test whether the Archean Witwatersrand gold deposits of South Africa show similar mass-balance characteristics to known placers.

MASS-BALANCE MODEL

Studies from many parts of the world indicate that gold placers result from the weathering of rocks in a high-standing (typically uplifted) source area and the gradual concentration of resistant heavy minerals into an adjacent sedimentary depository (Lindgren, 1933; Sigov et al., 1972; Henley and Adams, 1979; Sutherland, 1985; Yeend and Shawe, 1989: G1-G2; fig. 1). Assuming that gold in placers is mainly or entirely of detrital origin, the derivation of placer gold (or any other detrital mineral) from source rocks can be treated as a simple volumetric problem which can be expressed by the following mass-balance equation:

$$Au_p = \frac{(D \times A_d \times C \times T \times R)}{100} \times E \qquad \text{(Equation 1)}$$

where

Au_p = Total gold deposited in placer deposit (t)
D = Mean density of source rocks (t/m^3)
C = Mean gold content of source rocks (ppb Au)
A_d = Drainage basin area (km^2)
R = Mean denudation rate (cm/ka)
T = Time (Ma)
E = Efficiency (percent)

The mass-balance equation is based on the assumption that the mass of gold (variable Au_p) that accumulates in a placer is limited by the mass of native gold that can be derived from a given mass of crust (containing mean gold concentration C) that is weathered and decomposed for a given time interval (variable T). The rate at which source rocks are decomposed conforms to the rate at which the Earth's surface is lowered, as expressed by denudation rates (variable R) which are fairly well known for both modern and ancient conditions (Saunders and Young, 1983; Kukal, 1990) (fig. 2). The total mass of source rocks is the product of mean density (variable D) and volume of rock in the source area. The volume of source rocks can be established by multiplying the drainage basin area (variable A_d) of streams associated with the placer by the thickness of crust that is stripped off (as determined by denudation rate [variable R] multiplied by time constraints [variable T] (fig. 3). Obviously, the derivation of gold from source rocks is inefficient; a variable amount (variable E; generally about 50%) is not released by weathering or is chemically and mechanically lost from the system.

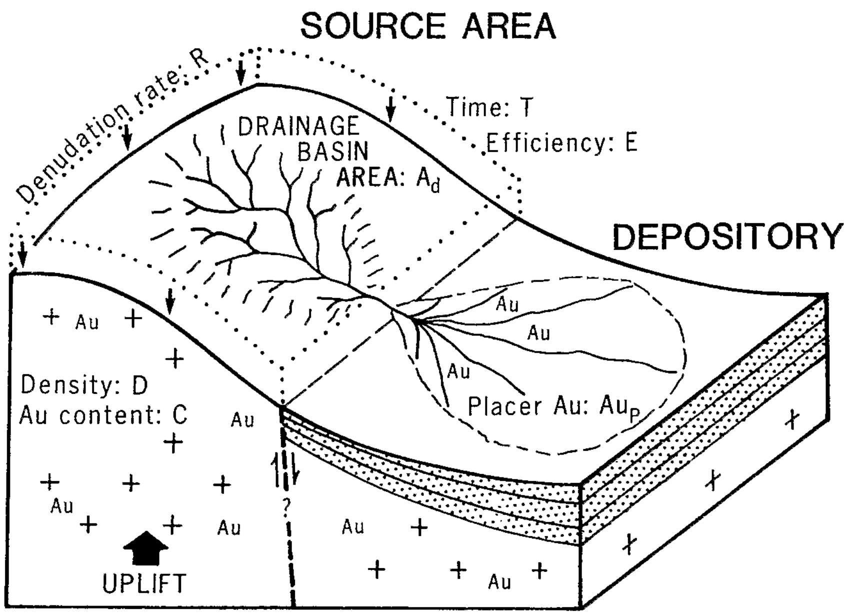

Figure 1. Schematic diagram illustrating constraints on formation of placer deposits. Variables in Eq. 1 are shown in relation to geomorphologic attributes. "Au" indicates gold concentrations. Note: normal fault along edge of basin is not present in all districts.

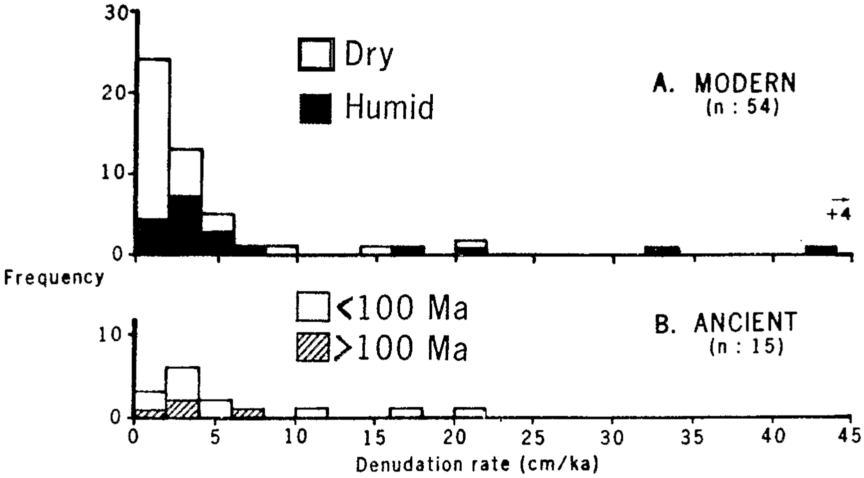

Fig. 2. Denudation rates for modern (A) and ancient (B) conditions (data in A are from Ohmori, 1983, table 3; data in B are from Menard, 1961; Bloom, 1978; and Saunders and Young, 1983, table X). Modern rates (A) are rather similar for both wet and dry climates although extreme values are associated with areas having high relief, such as Japan, Taiwan, and Nepal. In contrast, ancient rates (B) are determined, in part, by the length of time span considered; long time spans (>100 Ma) are associated with relatively slow rates (<7.5 cm/ka) because a larger number of tectonically quiescent periods are included (Plotnick, 1986; Kikal, 1990).

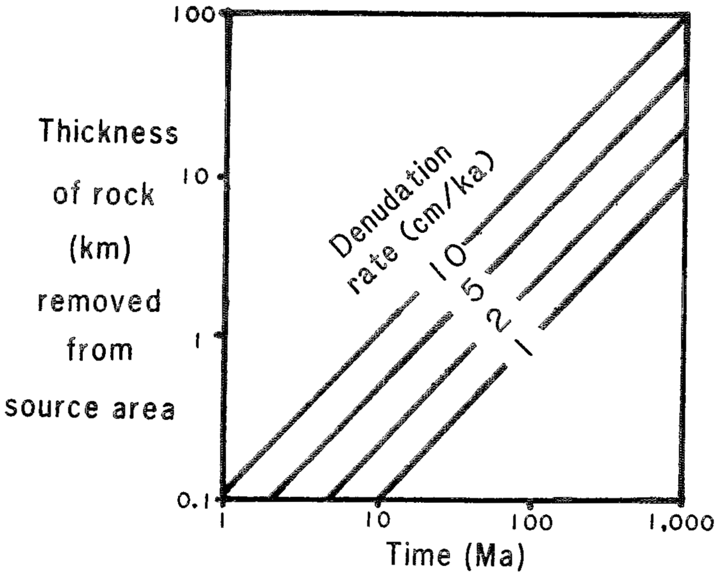

Figure 3. Thickness of source rocks removed in relation to time span and denudation rate.

It is usually possible to estimate minimum and maximum values for all mass-balance variables except C for placer goldfields in which the geology and geomorphology have been adequately studied. It is then possible to solve Equation 1 for C, and this calculated value of source-rock gold content can be compared to crustal abundances of gold as established by geochemical analyses (Crocket, 1991). Therefore, in addition to quantifying the derivation of placer gold from source rocks, the mass-balance method provides a means of comparing the relative enrichment in gold of source rocks for placers of varying productivity.

EXAMPLES OF MASS-BALANCE CALCULATIONS

Information from the literature and unpublished data have been used to estimate mass-balance values for eight Cenozoic placers of varying size and productivity (Table 1). The following section explains how values were chosen for the Sierra Nevada placers of California. In addition, the gold content of source rocks for Witwatersrand gold deposits was calculated based on the volume of rocks in the basin.

SIERRA NEVADA, CALIFORNIA

Placer gold in the Sierra Nevada of California has been recovered from both modern and fossil (Tertiary) placers (Lindgren, 1911; Yeend and Shawe, 1989). The main Tertiary auriferous gravels are probably correlative with the middle Eocene Ione Formation, which consists of as much as 300 m of sand and clay deposited under deltaic and lagoonal conditions, overlying a thick lateritic soil (Bateman and Wahrhaftig, 1966). The gold was eroded mainly during early Tertiary time from the Mother Lode vein system, a mineralized strip of metamorphosed Paleozoic and Mesozoic greenstone rocks and Mesozoic granitic plutons that extends along the western flank of the Sierra Nevada (Bateman and Wahrhaftig, 1966; Koschmann and Bergendahl, 1968).

Table 1. Mass-balance calculations for concentration of gold in source rocks for Cenozoic gold placers and Witwatersrand deposits. Dashes are shown for Witwatersrand values because calculation was based on volume of rocks in basin (see text). Denudation rates were chosen according to length of time span, as follows: 0-2 Ma, 5-10 cm/ka; 2-5 Ma, 2-10 cm/ka; 5-28 Ma, 2-5 cm/ka. Mean density for all deposits is set at 2.65 t/m^3. Age limits for epochs are from Dietrich et al (1982). Gold concentrations for Cenozoic placers are adjusted for Efficiency = 50%. Sources of data are as follows: Witwatersrand, Sierra Nevada (see text); Klondike, Boyle (1979); Breckenridge, Parker (1974); Pioneer, Pardee (1951), Loen (1986, 1989); Fairplay, Parker (1974); Ophir, Loen (1990); Tarryall, Parker (1974).

Placer (age)	Depositional Environment(s)	Total gold content (t)	Drainage basin area (km2)		Mean denudation rate(cm/ka)		Time (Ma)		Mean Au concentration in source rocks(ppb)	
			(Min)	(Max)	(Min)	(Max)	(Min)	(Max)	(Min)	(Max)
Witwatersrand (L. Archean)	Braid-delta, braid-plain, fan	about 80000	--	--	--	--	--	--	0.11	0.27
Sierra Nevada, Calif. (Eocene)	River channel	1959-2177	30000	44000	2	5	20.0	28.0	0.02	0.14
Klondike, Yukon (Miocene-Quat.)	Terrace, River channel	310-390	1800	3000	2	5	5.0	15.0	0.10	1.64
Alder Gulch, MT (Quat.)	Alluvium	80.9	100	120	5	10	2.0	2.0	2.44	6.10
Breckenridge, CO (L. Tert.-Quat.)	Glaciofluvial	20.0-23.5	600	770	2	10	2.0	5.0	0.04	0.74
Pioneer, MT (Miocene-Quat.)	Fan, pediment, glaciofluvial	7.0-9.3	50	100	2	5	5.0	10.0	0.11	1.40
Fairplay, CO (Quaternary)	Glaciofluvial	7.9-8.0	200	230	5	10	0.5	2.0	0.13	1.21
Ophir, MT (Miocene-Quat.)	Terrace, stream channel	7.0-9.0	25	50	2	5	5.0	10.0	0.21	2.81
Tarryall, CO (Quaternary)	Glaciofluvial, pediment	1.5-1.7	50	60	5	10	2.0	2.0	0.10	0.26
								Mean	0.38	2.15

Estimates for mass-balance variables are as follows: The total placer gold production is about 1,306 t, and reserves include about 653-871 t of gold in Tertiary channels (Merwin, 1968), which suggests that Au_p is about 1,959-2,177 t. Density D of granite-greenstone source rocks is assumed to be nearly that of quartz, 2.65 t/m^3. Area A_d of the Tertiary drainage system is about 30,000-44,000 km^2, as measured from Lindgren's (1911, Pl. 1) map, and allowing that the trunk streams may have been as long as 150 km (Yeend, 1974). Time interval T is probably in the range 20-28 Ma, based on fossil and stratigraphic evidence that indicate the Ione Fm was deposited during much of the Eocene and possibly the earliest Oligocene (Yeend, 1974). Denudation rate R may be in the range 2-5 cm/ka, based on an inferred semitropical climate, moderate relief, and an intermediate time span. Efficiency E probably was neither low nor high, hence 50% is used.

These values suggest that 0.4 to 1.4 km of crust was removed from the source area, and that the source area volume was about 12,000 to 56,000 km^3. The gold content C associated with the mass of these source rocks is about 0.01-0.07 ppb Au, and consideration of an efficiency of 50% would double these values (0.02-0.14 ppb Au; Table 1). These results are slightly lower than the gold contents of metavolcanic rocks in the Mother Lode district and igneous rocks in the Sierra Nevada batholith, which are between 1.2-3.4 and 0.3-5.2 ppb Au, respectively (Gottfried et al. 1972; Tilling et al. 1973).

WITWATERSRAND, SOUTH AFRICA

Most geologists accept a placer or modified placer origin for the Archean Witwatersrand gold deposits, which are the most productive gold deposits in the world (Pretorius, 1989; Robb and Meyer, 1990, 1991). However, some authors have concluded that a placer origin is unlikely simply because they consider the source area volumetrically inadequate to account for the huge amount of gold in the sediments (Reimer, 1985; Hutchinson and Viljoen, 1988). Further, evidence exists for movement of ore fluids during metamorphism (Phillips, 1988; Phillips et al, 1987), which suggests to some an epigenetic origin for the gold mineralization.

Central Rand Group (CRG) sediments, which are the major host for the gold deposits, comprise a dominantly arenaceous sequence that accumulated on fluvial fans and braid deltas in a clodes intra-cratonic basin (Vos, 1975; Tankard et al., 1982; McPherson et al., 1987). Little evidence exists concerning the geomorphic setting of the source area, so it si difficult to select reliable mass-balance values for A_d. Likewise, time interval T is loosely constrained for CRG deposits. Consequently, the following mass-balance calculation is based on the volume of sediment in the Witwatersrand basin:

The geometry of CRG deposits can be simplified to an inverted triangular prism 310 km long, 120 km wide, and about 3 km deep (Robb and Meyer, 1986). Consequently, the total volume of sediments, assuming a compaction factor of 2 (Behman and Hamilton, 1976), is 111,600 km^3. However, this value must be adjusted for solution loss of source rocks during severe chemical leaching in the source area, as indicated by results of mineralogical and geochemical studies (Wronkiewicz and Condie, 1987; Sutton et al., 1990). Modern studies indicate that solution loss for siliceous rocks can be as high as 60% (Garrels and MacKenzie, 1971; Saunders and Young, 1983), therefore, the volume of CRG source rocks may have been in the range 111,600-279,000 km^3. The density of a dominantly granitic source area with a minor (<20%) greenstone component (Robb and Meyer, 1990) would have been about 2.65 t/m^3, so the resulting mass of source rocks is 2.96-7.39 x 10^{14} t. Total gold Au_p (production plus reserves) is probably about 80,000 t (Robb and Meyer, 1991), which includes 40,225 t produced through the end of 1988 (Pretorius, 1989) plus estimated reserves and non-economic resources. This amount of gold, divided into the mass of source rocks, suggests source-rock gold concentrations in the range 0.11-0.27 ppb Au.

RESULTS

GOLD CONTENTS OF SOURCE ROCKS FOR PLACER GOLDFIELDS

Calculations of source-rock gold contents for eight Cenozoic placer goldsfields of different size, location, and depositional environment indicate low mean gold contents within the range 0.02-6.1 ppb Au and a mean of about 1.1 ppb au (Table 1; fig. 4). These values are consistent with the range of 0.5-5 ppb gold for igneous rock averages (Crocket, 1991), which suggests that there is no clear correlation between source-rock gold contents and gold productivity for the placers studied. Despite low mean gold contents, historic references to detrital gold nuggets found in many of these placers indicate that these source rocks contained local gold concentrations.

Some authors (e.g. Pardee, 1951) have implied that anomalous gold concentrations in source rocks are a prerequisite for the formation of productive gold placers, although mass-balance considerations suggest that other factors can be of equal or greater importance. It appears that productive placers can develop from source rocks containing rather low mean gold contents provided that geomorphic conditions are favourable for the release and concentration of detrital gold, and sufficient time (or alternatively, a high denudation rate) is available to erode large volumes of rock.

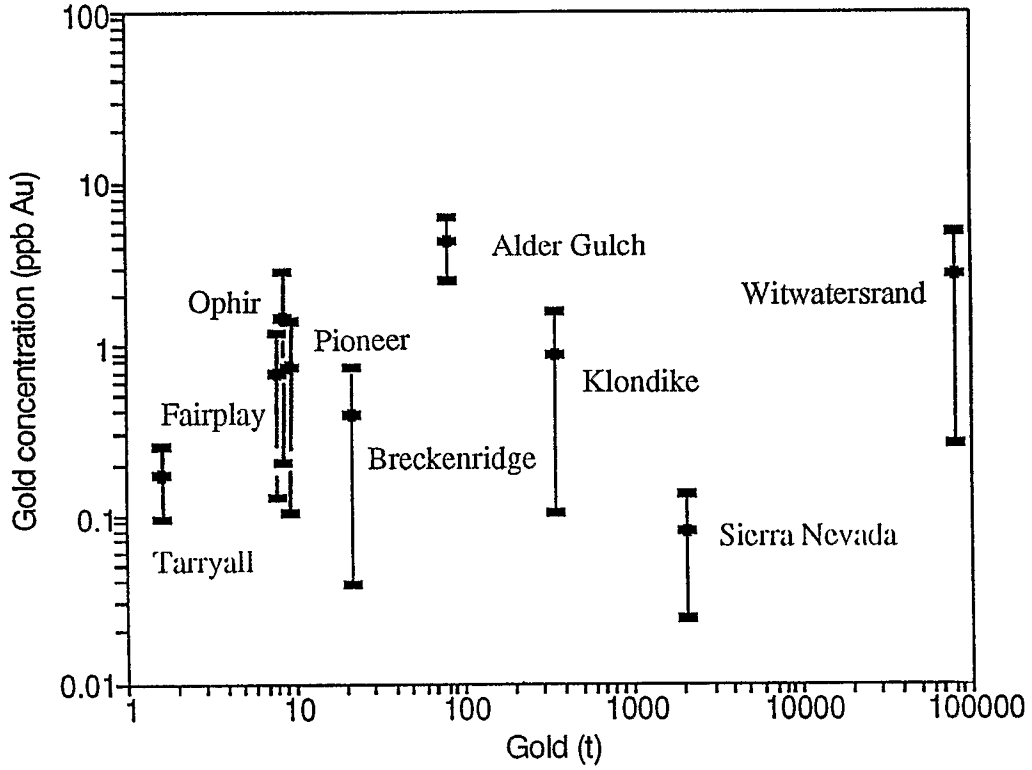

Fig. 4. Mean gold concentration of source rocks for Cenozoic gold placers and Witwatersrand deposits. Gold values for source rocks for Cenozoic placers were calculated using Eq. 1 (see Table 1). Values for Witwatersrand deposits were calculated based on volume of rock in basin (see text). Horizontal lines show maximum and minimum gold contents, mean is indicated by plus sign.

RELATION BETWEEN GOLD YIELD AND DRAINAGE BASIN AREA

A positive relationship exists between gold yield/Ma (variable Au_p/variable T) and drainage basin area (variable A_d) for the districts studied (fig. 5). This indicates that a larger amount of gold is derived in a given time period from larger drainage basins. However, the Alder Gulch placers of Madison County, Montana (Douglass, 1905; Lyden, 1948; Yeend and Shawe, 1989) appear to be an exception to this relationship because more than 80 t of gold were apparently derived during Quaternary (about 2 Ma) time from a source area covering 100-120 km^2 (equals 40 t/Ma; Table 1). This gold yield is remarkably high for such a small drainage area, suggesting either unusually rich source rocks, or preconcentration of gold during an earlier geomorphic stage (Yeend and Shawe, 1989). Preconcentration seems likely considering the favourable conditions for the erosion and concentration of gold that existed in western Montana during Miocene and Pliocene time (Loen, 1989), hence the anomalously high gold yield for Alder Gulch may simply reflect poorly known age constraints.

The relationship between gold yield and drainage basin area may be useful for exploration. For example, large amounts of placer gold (e.g. >100 t Au) may be restricted to sedimentary systems in which large paleo-drainage systems (e.g. >1,000 km^2) were eroded for long time spans (tens of millions of years or more), whereas much smaller amounts of gold would be expected to occur in systems that involve the erosion and concentration of correspondingly smaller masses of source rocks. Therefore, a survey of paleogeographic reconstructions and time constraints on ancient fluvial deposits could suggest sedimentary successsions that are worthy of investigation for placer gold concentrations.

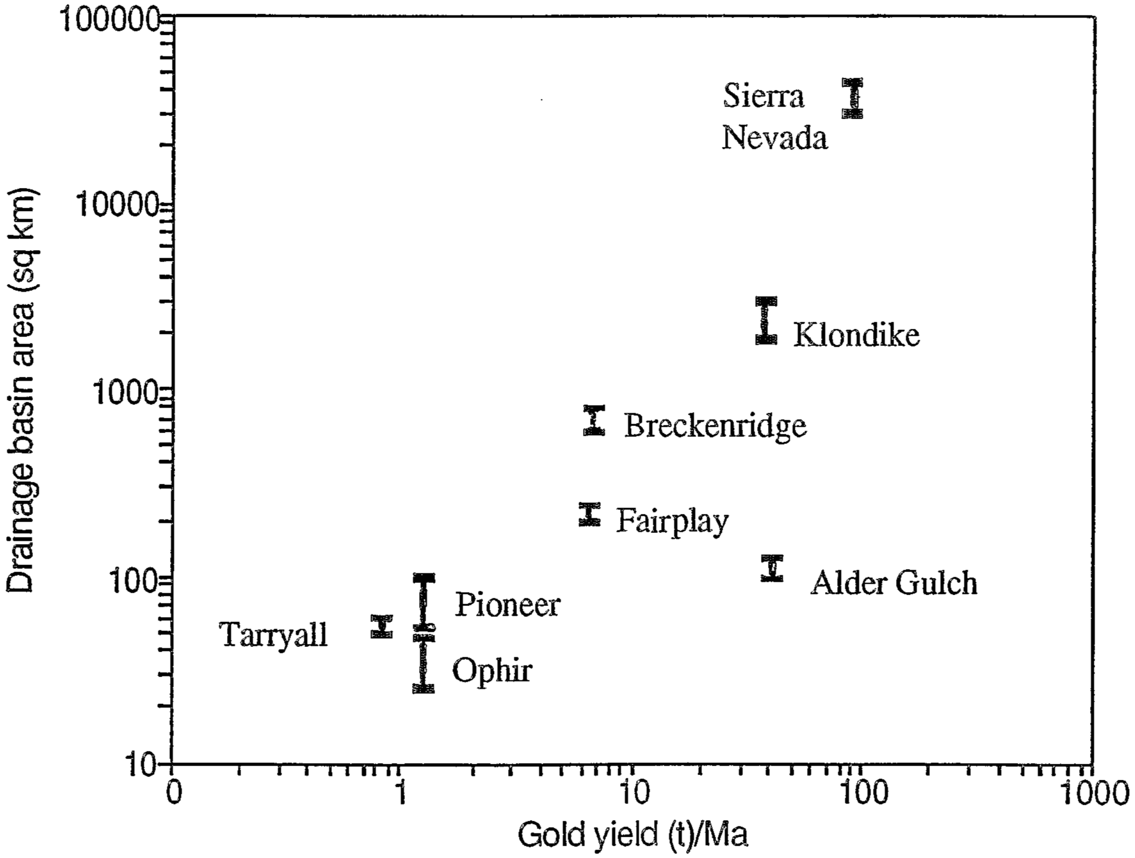

Fig. 5. Relationship between gold yield per million years and drainage basin area for Cenozoic gold placers. Horizontal lines show maximum and minimum basin areas.

IMPLICATIONS FOR WITWATERSRAND GOLD DEPOSITS

The calculated gold content of source rocks for CRG deposits (0.11-0.27 ppb Au) is within the range of source rocks for the Cenozoic placers studied, as well as for Archean granite-greenstone rocks, which are the inferred source materials for CRG fans (Hallbauer, 1984; Hallbauer et al., 1986; Robb and Mayer, 1990; fig. 6). It is therefore evident that Witwatersrand gold could have been derived from the inferred source rocks by erosional processes and that a placer mechanism is viable. The prodigious amount of gold in Witwatersrand deposits is attributed mainly to the much longer amount of time (roughly 126 Ma; Robb et al. 1991) that was available for the erosion and reconcentration of detrital material from the source area.

The finding of low source-rock gold concentrations for the CRG source area contradicts results of previous mass-balance estimates for Witwatersrand deposits (Reimer, 1984; Robb and Meyer: 1990). For example, Robb and Meyer (1990) determined that the source area was anomalously enriched in gold (e.g. 116 ppb Au), based on the assumption that the volume of source rocks was equal to that of rocks in the basin. The requirement of such high source-rock gold contents, combined with the low (< 4 ppb Au) gold contents of Archean crust, has perpetuated the concept of a "source-area problem" for Witwatersrand gold (Robb and Meyer, 1990). However, these authors neglected sediment compaction and solution loss, and consideration of these factors indicates source-area gold concentrations of about the same level as Archean granite-greeenstone rocks (fig. 6), which implies that no so-called "source-area problem" exists.

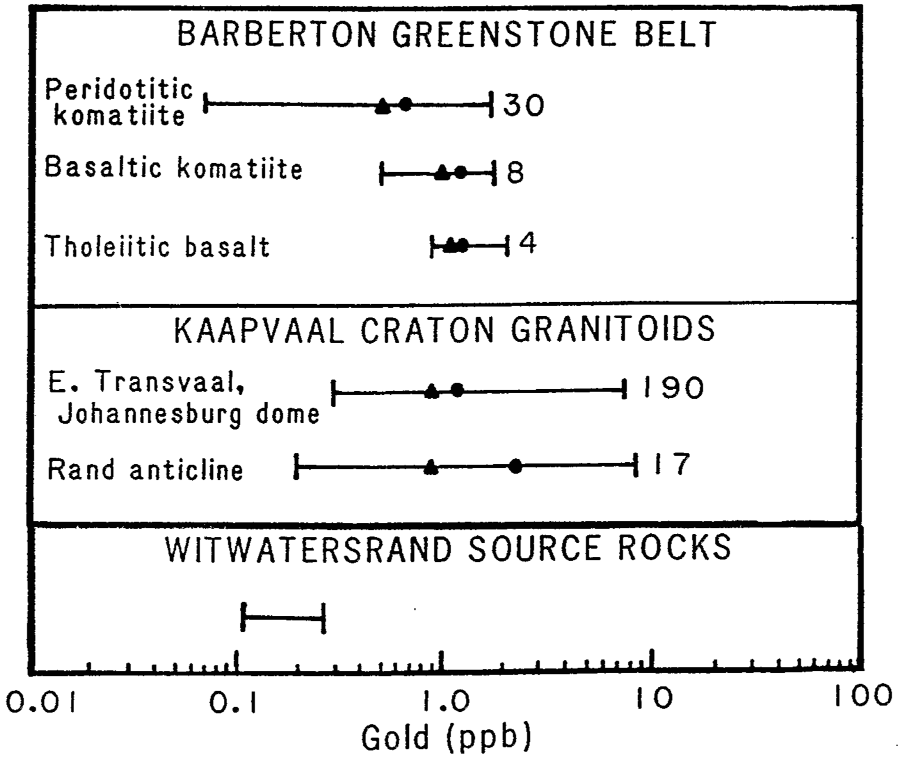

Fig. 6. Comparison of calculated gold concentrations in Witwatersrand source rocks to abundance of gold in Archean rocks. Range, arithmetic mean (dots), geometric mean (triangles), and number of samples are shown. Sources of data are as follows: Barberton greenstone belts, Saager et al., 1982; Kaapvaal craton granitoids, Meyer and Saager, 1985; Robb and Meyer, 1986; Witwatersrand goldfields, this study.

CONCLUSION

It is feasible to use a mass-balance approach to broadly compare placer systems of differing size and type. Such comparisons suggest that the occurrence of placers is controlled by factors such as the gold contents and degree of weathering of source rocks, the length of time that source rocks are eroded, erosion rates, and the size of drainage basins. In many cases, quantitative estimates can be made for variables in a mass-balance equation, and then the equation can be solved for previously unknown variables.

The findings of the present study of eight Cenozoic placer districts call into question the notion that rich source rocks are a prerequisite for the development of productive placer goldfields, because these gold placers were all apparently derived from volumes of crust having rather ordinary mean gold contents. In addition, the calculated gold content of source rocks for Witwatersrand gold deposits of South Africa suggests similar gold contents to source areas for Cenozoic placers as well as South African Archean granite-greenstone crust, which supports a placer origin for Witwatersrand gold.

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REFERENCES

BATEMAN, P.C., & WAHRHAFTIG, C. 1966. Geology of the Sierra Nevada. in E.H. Bailey (ed.). Geology of northern California. Calif. Div. Mines and Geol., Bull. 190, 107-172.

BEHMAN, R.T., & HAMILTON, E.L. 1976. Porosity-depth interrelationship in JOIDES drillings: J. Sediment. Pet., 46, 224-236.

BLOOM, A.L. 1978. Geomorphology, a systematic analysis of late Cenozoic landforms. Englewood Cliffs, New Jersey, Prentice-Hall, 510 pp.

BOYLE, R.W. 1979. The geochemistry of gold and its deposits. Geol. Survey Canada Bull. 280, 584 pp.

COX, D.P. & SINGER, D.A. 1986. Mineral deposit models. U.S. Geol. Survey Bull. 1693, 379 pp.

CROCKET, J.H. 1991. Distribution of gold in the Earth's crust. in R.P. Foster (ed.). Gold metallogeny and exploration. Blackie, London, 1-36.

DIETRICH, R.V., DUTRO, J.T. Jr., & FOOSE, R.M. 1982. AGI data sheets: for geology in the field, laboratory, and office. Alexandria, Va., American Geol. Inst.

DOUGLASS, E. 1905. Source of the placer gold in Alder Gulch, Montana. Mines and Minerals, 25, 353-355.

GARRELS, R.M. & MACKENZIE, F.T. 1971. Evolution of sedimentary rocks. New York, W.W. Norton, 397 pp.

GOTTFRIED, D., ROWE, J.J., & TILLING, R.I. 1972. Distribution of gold in igneous rocks. U.S. Geol. Survey Prof. Paper 727, 42 pp.

HALLBAUER, D.K. 1984. Archean granitic sources for the detrital mineral assemblage in Witwatersrand conglomerates [abs.]. Potchefstroom, Geol. Soc. South Africa, Geocongress '84, Abstracts, 53-56.

HALLBAUER, D.K., KLEMD, R., & VON GEHLEN, K. 1986. A provenance model for the Witwatersrand gold and uranium mineralization and its implications in the recognition of gold-distribution patterns in reefs [abs.]. Johannesburg, Geol. Soc. South Africa, Geocongress '86, Extended Absracts, 133-137.

HENLEY, R.W. & ADAMS, J. 1979. On the evolution of giant gold placers. Inst. Min. Metal., Trans., 88, B41-B50.

HUTCHINSON, R.W., & VILJOEN, R.P. 1988. Re-evaluation of gold source in Witwatersrand ores. South African Jour. Geol., 91, 157-173.

KOSCHMANN, A.H., & BERGENDAHL, M.H. 1968. Principal gold-producing districts of the United States. U.S. Geol. Survey Prof. Paper 610, 283. pp.

KUKAL, Z. 1990. The rate of geological processes. Earth Sci. Rev., 28, n° 1,2,3.

LINDGREN W. 1911. The Tertiary gravels of the Sierra Nevada of California. U.S. Geol. Survey Prof. Paper 73, 226 pp.

---------- 1933. Mineral deposits (4th ed.). New York, McGraw-Hill, 930 pp.

LOEN, J.S. 1986. Origin of gold placers in the Pioneer district, Powell County, Montana. Fort Collins, CO., Colorado State Univ., M.Sc. Thesis (unpublished), 164 pp.

---------- 1989. Climatic and tectonic controls on the formation of Tertiary gold placers, Pioneer district, Powell County, Montana. in Geologic resources of Montana (Montana Centennial volume). Billings, Mont., Montanan Geological Society, 375-381.

--------- 1990. Lode and placer gold deposits of the Ophir district, Powell and Lewis and Clark Counties, Montana. Fort Collins, CO., Colorado State Univ., Ph.D. dissertation (unpublished), 264 pp.

LYDEN, C.J. 1948. The gold placers of Montana. Mont. Bur. Mines and Geol. Mem. 26, 151 pp.

MCPHERSON, J.G. SHANMUGAN, G., & MOIOLA, R.J. 1987. Fan-deltas and braid deltas: Varieties of coarse-grained deltas. Geol. Soc. Amer. Bull. 99, 331-340.

MENARD, H.W. 1961. Some rates of regional erosion. Jour. Geol., 79, 154-161.

MERWIN, R.W. 1968. Gold resources in the Tertiary gravels of California. U.S. Bur. Mines Tech. Prog. Rept., Heavy Metal Program, 14 pp.

MEYER, M., & SAAGER, R. 1985. The gold content of some Archean rocks and their possible relationship to epigenetic gold-quartz vein deposits. Mineralium Deposita, 20, 284-289.

OHMORI, H. 1983. Characteristics of the erosion rate in the Japanese mountains from the viewpoint of climatic geomorpholgy. Zeitsch. für Geomorph., Suppl. Bd. 46, 1-14.

PARKER, B.H. Jr. 1974. Gold placers of Colorado. Colo. School Mines Quart. 69, n° 3, 4.

PARDEE, J.T. 1951. Gold placer deposits of the Pioneer district, Montana. U.S. Geol. Survey Bull. 978-C, 69-99.

PHILLIPS, G.N. 1988. Widespread fluid infiltration during metamorphism of the Witwatersrand goldfields: generation of chloritoid and pyrophyllite. J. Met. Geol., 6, 311-322.

PHILLIPS, G.N., MYERS, P.E., & PALMER, J.A. 1987. Problems with the placer model for Witwatersrand gold. Geol., 15, 1027-1030.

PLOTNICK, R.E. 1986. A fractal model for the distribution of stratigraphic hiatuses. Jour. Geol., 94, 885-890.

PRETORIUS, D.A. 1989. The sources of Witwatersrand gold and uranium: 'A continued difference of opinion'. Univ. Witwatersrand, Johannesburg, Econ. Geol. Res. Unit, Inf. Circ. 206, 43 pp.

REIMER, T.O. 1984. Alternative model for the derivation of gold in the Witwatersrand Supergroup. Geol. Soc. London Jour. 141, 263-272.

ROBB, L.J., DAVIS, D.W. & KAMO, S.L. 1991. Chronological framework for the Witwatersrand basin and environs: towards a time-constrained depositional model. South African Jour. Geol. 4, 86-95.

ROBB, L.J., & MEYER, F.M. 1986. The nature of the Archean basement in the hinterland of the Witwatersrand basin: Part I - The Rand anticline between Randfontein and Rysmierbult. Univ. Witwatersrand, Johannesburg, Econ. Geol. Research Unit, Inf. Circ. 187, 14 pp.

---------- 1990. The nature of the Witwatersrand hinterland: Conjectures on the source-area problem. Econ. Geol., 85, 511-536.

---------- 1991. A contribution to recent debate concerning epigenetic versus syngenetic mineralization processes in the Witwatersrand basin. Econ. Geol., 86, 396-401.

SAAGER, R., MEYER, M., & MUFF, R. 1982. Gold distribution in supracrustal rocks from Archean greenstone belts of southern Africa and from Paleozoic ultramafic complexes of the European Alps: Metallogenic and geochemical implications. Econ. Geol., 77, 1-24.

SAUNDERS, I., & YOUNG, A. 1983. Rates of surface processes. Earth Sur. Proc. and Landforms, 8, 473-501.

SIGOV, A.P., LOMAYEV, A.V., SIGOV, V.A., STOROZHENKO, L.Y., HKRYPOV, V.N., & SHUB, I.Z. 1972. Placers of the Urals, their formation, distribution, and elements of geomorphic prediction. Sov. Geogr., 13, 375-387.

SUTHERLAND, D.G. 1985. Geomorphological controls on the distribution of placers. Jour. Geol. Soc. London, 142, 727-737.

SUTTON, S.J., RITGER, S.D., & MAYNARD, J.B. 1990. Stratigraphic control of chemistry and mineralogy in metamorphosed Witwatersrand quartzites. Jour. Geol. 98, 329-341.

TANKARD, A.J., JACKSON, M.P.A., ERIKSSON, K.A., HOBDAY, D.K., HUNTER, D.R., & MINTER, W.E.L. 1982. Crustal evolution of Southern Africa. New York, Springer-Verlag, 523 pp.

TILLING R.I., GOTTFRIED, D., & ROWE, J.J. 1973. Gold abundance in igneous rocks: Bearing on gold mineralization. Econ. Geol., 68, 168-186.

VOS, R.G. 1975. An alluvial plain and lacustrine model for the Precambrian Witwatersrand deposits of South Africa. Jour. Sed. Pet., 45, 480-493.

WRONKIEWICZ, D.J., & CONDIE, K.C. 1987. Geochemistry of Archean shales from the Witwatersrand Supergroup, South Africa: Source-area weathering and provenance. Geochim. et Cosmochim. Acta, 51, 2401-2416.

YEEND, W.E. 1974. Gold-bearing gravel of the ancestral Yuba River, Sierra Nevada, California. U.S. Geol. Survey Prof. Paper 772, 44 pp.

YEEND, W.E., & SHAWE, D.R. 1989. Gold in placer deposits. U.S. Geol. Survey Bull. 1857-C, 19 pp.