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# THE DEVELOPMENT AND DISTRIBUTION OF HEAVY MINERAL CONCENTRATIONS IN ALLUVIAL SYSTEMS

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A—RIVER. B—WEIR. C—GATE. D—AREA. E—MEADOW. F—FENCE G—DITCH.

FRONTISPIECE. Extraction of placer tin from fluvial gravels. From "De Re Metallica", by Georgius Agricola, 1556.

# ABSTRACT

The objective of this review is to summarise the characteristics, significance and evolution of heavy minerals and their accumulations, and to identify the key controls on the development and distribution of heavy mineral concentrations in alluvial systems. These controls can be boadly classified as tectonic setting, geomorphic setting and grain-scale concentrating processes, each of which is discussed. Based on this review, exploration models are developed which are designed to indicate favourable localities for the accumulation of heavy minerals, and trends likely to be exhibited within these accumulations. The models are structured from the broadest scale of target selection, down to the local scale of sample site selection.

The major conclusion of this work is that an understanding of process geomorphology is required to develop genetic models of placer development, including a detailed evaluation of climatic fluctuations throughout the Caenozoic.

Palaeoplacers such as the Witwatersrand goldfield, are inferred to have formed under similar circumstances of tectonic setting as genetically comparable Caenozoic placers such as those of Otago, New Zealand. The means of preservation of such major basins is however poorly understood.

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# INTRODUCTION

Alluvial placers have historically been important sources of both precious and industrially useful minerals. Much of the impetus given to colonization of the North American western states and the Alaskan Pacific coast came from riches promised by placer gold. Fossil alluvial gold placers currently provide nearly half of the Republic of South Africa's commodity export earnings, whilst alluvial diamonds are important to several central and west African countries. Alluvial tin provides Malaysia and Thailand with significant export earnings.

The recent interest in alluvial placer exploration, and continued use of heavy minerals as pathfinders, has spawned recent research into geomorphic and grain-scale controls on heavy mineral distribution.

The development and distribution of concentrations of heavy minerals in alluvial systems is the result of the interplay between a complex array of processes. These range from the large scale controls of plate tectonics, down to grain-scale processes. An understanding of these processes is not only fundamental to the exploration for, and evaluation of, alluvial placer deposits, but alsoto the exploitation of heavy minerals in streams for prospecting purposes.

After briefly reviewing their characteristics, significance and classification, the evolution and genetic processes involved in placer development are reviewed from the large to the small scale. The concepts thus derived, are assembled into a number of exploration models designed to be used as simple predictive tools to direct the exploration geologist to the most promising localities for heavy mineral accumulation in alluvial sediments, both modern and ancient.

## PART 1 CONCEPTS AND CLASSIFICATIONS

### 1.1 DETRITAL HEAVY MINERALS

The chemical and mechanical processes involved in the genesis of detrital heavy minerals under weathering and transport conditions, restrict them to a limited group that have the following properties:

i) they must be heavier than the associated silicate minerals. The specific gravity (S.G.) of quartz (2.56 g/cm$^3$) is often taken as the minimum value for heavy minerals. In general however, heavy minerals have a S.G. greater than 3, whereas Iridium is the most dense (21.1 g/cm$^3$);

ii) all detrital heavy minerals are resistant, to a greater or lesser degree , to chemical weathering. Many are oxides and are therefore stable in the secondary environment (see section 2.1.2);

iii) they must be physically durable to survive abrasive processes of transport and concentration. Durability is a complex criterion which is influenced by variables such as hardness, crystal system (i.e. strength and orientation of crystalline bonds) and brittleness. For example, some minerals are hard but have a strong cleavage and break down mechanically quite readily (e.g. diopside). Most detrital heavy minerals have a hardness greater than 5, and many are cubic, hence displaying no preferred cleavage. Gold has a low hardness but is malleable and survives transport quite well.

Table I lists some of the more important detrital heavy minerals, and shows properties, common detrital shapes, and sources.

### 1.2 SIGNIFICANCE OF HEAVY MINERALS IN ALLUVIAL SYSTEMS

The concentration of heavy minerals in streams may be of economic importance for two reasons. Firstly, numerous economic placers occur within fluvial sediments, and secondly, heavy minerals may act as pathfinders to economic mineral occurrences of either primary or secondary origin.

| MINERAL | COMPOSITION | RELATIVE DENSITY | HARDNESS | CRYSTAL SYSTEM | DETRITAL SHAPE | SOURCE |
|---|---|---|---|---|---|---|
| NATIVE ELEMENTS | | | | | | |
| Gold | Au | 15.0-19.3 | 2.5-3 | cubic | round or flat grains, rods or flakes | hypo-, meso- and epithermal veins |
| Platinum | Pt | 14.0-19.0 | 4-4.5 | cubic | angular grains and flakes | mafites/ultramafites |
| Other P.G.M. | Pd,Ir,Os | 12.0-21.1 | 4.5-7 | cubic | angular grains | mafites/ultramafites |
| Diamond | C | 3.5 | 10 | cubic | mostly octahedra | cratonic kimberlite/lamproite |
| OXIDES AND HYDROXIDES | | | | | | |
| Magnetite | Fe3O4 | 5.18 | 5.5-6.5 | cubic | octahedra - well-rounded equant grains | mafic igneous rocks |
| Chromite | FeCr2O4 | 4.3-4.6 | 5-6 | cubic | octahedra - well-rounded equant grains | mafites/ultramafites |
| Other Spinels | XY2O4 | 3.6-4.6 | 7.5-4.6 | cubic | octahedra - well-rounded equant grains | ig. rocks and aluminous metasedts. |
| Cassiterite | SnO2 | 6.8-7.1 | 6-7 | Tetrag. | prismatic xtals, angular - rounded grains | S-type granites |
| Rutile | TiO2 | 4.18-4.25 | 6-6.7 | Tetrag. | prismatic xtals, angular - rounded grains | plutonic ig., met. and sedt. rocks |
| Ilmenite | FeTiO3 | 4.5-5 | 5-6 | Hex. | sub-rounded - rounded equant grains | mafites/ultramafites |
| Leucoxene | alteration after ilm. | 3.5-4.5 | variable | Amorphous | rounded - angular irregular coated grains | sedimentary rocks |
| Corundum | Al2O3 | 3.95-4.15 | 9 | Hex. | ang.- rounded irregular fragments | syenite, feldsp.pegmat.,met.shale and lst. |
| Tant.- Columbite | (Fe,Mn)(Nb,Ta)2O6 | 5.2-7.95 | 6-6.5 | Orth. | fracture fragments to sub-rounded grains | granite pegmatite |
| Baddeleyite | ZrO2 | 5.5-6 | 6.5 | Mono. | rounded "beans" | granitoids |
| Uraninite | UO2 | 8-10 | 5-6 | cubic | angular grains | granite pegmatite |
| Thorianite | ThO2 | 9.3 | 6.5 | cubic | angular grains | granite pegmatite |
| Pyrochlore | (NaCa)2(Nb,Ta)2O6(O,OH,F) | 4.2-6.4 | 5-5.5 | cubic | angular grains | alkaline pegmatites |
| SILICATES, TUNGSTATES AND PHOSPHATES | | | | | | |
| Zircon | ZrSiO4 | 4.65-4.7 | 7.5 | Tetrag. | prisms | acid - intermed. igneous rocks |
| Garnet | X3Y2(SiO4)3 | 3.6-4.3 | 6.5-7.5 | cubic | rhombic dodecahedra or fractured to rounded | mainly met. rocks, also some ultramafic rocks |
| Wolframite | (Fe,Mn)WO4 | 7-7.5 | 5-5.5 | Mono. | submetallic cleavage fragments | S-type (and some I-type) granites |
| Kyanite | Al2SiO2 | 3.6-3.7 | 4-7 | Tri | prismatic to rounded stumpy grains | reg. high-grade aluminous metasedts. |
| Tourmaline | complex silicate | 3-3.2 | 7.5 | Trig. | rounded to angular fractures | granites, greisen and granite pegmatites |
| Monazite | (Ce,La,Y,Th)PO4 | 4.6-5.4 | 5-5.5 | Mono. | mainly ellipsoidal, rounded grains | accessory of some granites and syenites |
| Xenotime | YPO4 | 4.59 | 4-5 | Tetrag. | equant to rectangular flakes | accessory of some granites and syenites |
| Apatite | Ca5(PO4)3(F,Cl,OH) | 3.17-3.23 | 5 | Hex. | mainly ellipsoidal, rounded grains | accessory in most igneous rocks |

TABLE I. List of some important detrital heavy minerals found in alluvial systems (sources : Macdonald, 1983 ; Dana, 1932 ; Battey, 1981).

Boyle (1979) has estimated that gold produced from alluvial placers, including palaeoplacers, accounts for two-thirds of the metal ever mined. The most famous palaeoplacers (or "fossil" placers) are those of the Witwatersrand in South Africa, but numerous other examples exist. The Tarkwa goldfield in Ghana is considered by many workers to be of alluvial origin, and is hosted in a clastic sequence of Precambrian age ( Boyle, 1979). The auriferous-uraniferous conglomerates of Jacobina, (Brazil) are also of Precambrian age, and share many similarities to the Witwatersrand deposits (Andrade Romas and Fraenkel, 1974). Carboniferous conglomerates of the Gays River area in Nova Scotia contain gold in the form of nuggets and flakes. The source of this gold appears to be auriferous quartz veins in rocks outcropping in the vicinity (Boyle, 1979).

Recent gold placers include those of the Pilgrim's Rest area in the Transvaal, which are currently undergoing evaluation for potential dredge-mining by Gold Fields of South Africa (Bentley, pers. comm.).

Up to 20% of the world's supply of diamonds comes from alluvial deposits in countries such as Zaire, Brazil, Angola, the Central African Republic, Venezuala and Ghana (Lynn, 1991). About 1% of South Africa's production is from alluvial sources (Axsel, 1988), although historically, this figure was much higher.

In general,tin placer deposits are more productive and more economic to mine than lode deposits. Cassiterite, from which most tin is smelted, is contained in placer concentrates, which also yield valuable amounts of niobium, tantalum, and rare-earth minerals. The main source of tin is the Southeast Asian tin belt, extending more than 2400 km from northern Burma, through western Thailand and Malaysia to Billiton Island (Indonesia). The high concentration of cassiterite-bearing granites coupled with deep and rapid chemical weathering has released large quantites of primary cassiterite from lode sources to produce eluvial, alluvial and marine placers (Hails, 1976).

Stream sampling of heavy minerals is of importance in exploration for a wide range of commodities. In diamond exploration, stream sampling of kimberlitic and lamproitic indicator minerals such as garnet, has been used to locate numerous diamondiferous intrusives. These include the Premier pipe in South Africa (Wagner, 1914), the Ellendale and Argyle lamproites in Western Australia (Atkinson et al., 1984), and the Mir and Udachnaya kimberlite pipes in the U.S.S.R. (Sobolev, 1980).

Heavy mineral stream surveys are also used in exploration for immobile elements such as Au (e.g., Tooms, 1987), Sn (e.g., Sirinawan et al., 1987), W (e.g., Petersen and Stendal, 1987), U (e.g., Frick, 1987) and Ta-Nb (e.g., Watts et al., 1963). In arid environments mechanical dispersion of elements dominates (section 2.1.3) and, heavy mineral concentrates of the coarser fractions may produce anomalies. A classic example is the dispersion of Pb and Zn around the Gamsberg orebody in Bushmanland, South Africa. Pb is dispersed in streams largely as grains of anglesite ($PbSO_4$) derived from gossanous outcrop. Zn occurs both as secondary minerals derived by oxidation of the primary sphalerite, and as the spinel gahnite ($ZnAl_2O_4$), a product of amphibolite-facies metamorphism of the orebody (McLaurin, 1978 ; J.M. Moore, pers. comm.).

In a regional exploration programme for tin (cassiterite) and tungsten (wolframite, scheelite) carried out in a Hercynian granite, migmatite and schist terrain in northwestern Spain, Zantop and Nespereira (1978) reported on the failure of geochemical stream sediment sampling techniques. At a density of 2 - 4 samples per square km, orientation samples in the vicinity of known mineralizations failed to produce anomalies. However an efficient method of detecting anomalies was found to be that of panning of stream sediments, to obtain a heavy mineral concentrate. Visual determination of the heavy minerals was performed by a technician at a rate of 10 to 15 minutes per sample. This method was found to have the following advantages over geochemical methods:

i) a much lower sampling density is sufficient to obtain meaningful results;

ii) the problem of single sample anomalies is largely eliminated ;

iii) results are available almost immediately and can be used to guide the ongoing exploration programme; and

iv) the content of economically exploitable minerals is determined, not the percentage of metal, which could be present in the lattice of non-economic minerals.

## 1.3 CLASSIFICATION OF PLACERS

In this review, the term placer refers to a surficial heavy mineral deposit formed by mechanical concentration of mineral particles from weathered debris.

Numerous classifications of placer deposits have been proposed, usually using such criteria as their major ore minerals qualified in some instances by environmental descriptors. Examples might be as follows; alluvial gold placers, heavy mineral beach placers etc. Such classifications are of little predictive use. Vlasov (1968) and Kartashov (1971) developed a concept of classification in which the first order criterion is distance from source. Hence, placers may be grouped as near source, alluvial or marine. More simply they may be grouped as "autochthonous" (i.e. proximal to source) or "allochthonous" (i.e. distal). This system is an improvement, particularly in combination with the system of Emery and Noakes (1968) who divided placer minerals into "heavy" heavy minerals (gold, tin, platinum), "light" heavy minerals (ilmenite, rutile, zircon and monazite) and diamonds (the extreme durability and value of which sets them apart). Their concept implied that the heaviest minerals would produce more proximal (or "autochthonous") placers. However, the fact that the "light" heavy minerals are most commonly mined in beach environments is more probably a function of the greater tonnages required for these relatively low value commodities, than the fact that they are absent in more proximal settings.

Macdonald (1983) attempted to present a scheme which is suited to exploration and mining. However, this classification (Table II) is (with all respect) clearly written by a mining engineer, not a geologist, and

*The placer environments*

| Environment | Sub environment | Main products | Environmental process elements | Exploration techniques | Mining methods |
|---|---|---|---|---|---|
| Continental | Eluvial | Au, Pt, Sn, $WO_3$ Ta, Nb, gem stones (all varieties) | Percolating waters, chemical and biological reactions, heat, wind and rain | Soil sampling, shallow pitting, churn drilling | Open cast, hydraulic sluicing, hand mining |
|  | Colluvial | Au, Pt, Sn, $WO_3$ Ta, Nb, gem stones (all varieties) | Surface creep, wind, rainwash, elutriation. Frost | Stream and soil sampling, shallow pitting and trenching | Hydraulic sluicing bulldozer and loader—hand mining |
|  | Fluvial | Au, Pt, Sn, rarely Ta, Nb, diamonds and corundums | Flowing streams of water | Stream sampling, geophysics, pitting, churn auger and pit-digging drills, Banka Drills | Bucket dredging in active beds, bucket dredging, hydraulic sluicing and dozer-loader operations in old stream beds |
|  | Desert | Au, Pt, Sn, $WO_3$ Ta, Nb, gem stones (all varieties) | Wind with minor stream flow. Heat and frost | Shallow pitting, churn and pit digging drills, geophysics | Various earth-moving combinations |
|  | Glacial | Au (rarely) | Moving streams of ice and melt waters | Stream sampling and pitting | Hydraulic sluicing |
| Transitional | Strandline | Ti, Zr, Fe, ReO, Au, Pt, Sn | Waves, currents, wind, tides | Hand augering and sludging, sample splitting allowable | Suction cutter dredging, bulldozer and loaders, bucket-wheel dredging |
|  | Coastal Aeolean | Ti, Zr, Fe, ReO | Wind and rain splash | Power augers (hollow), sample splitting allowable | Suction cutter dredging, buldozers and buried loaders |
|  | Deltaic | Ti, Zr, Fe, ReO | Waves, currents, wind, tides and channel flow | Hand augering and sludging, sample splitting allowable | Specially designed shallow depth dredges having great mobility |
| Marine | Drowned placers | Au, Pt, Sn, diamonds, minor Ti, Zr, Fe, ReO industrial sand and gravel | Eustatic, isostatic and tectonic movements—net rise in sea level | Geophysics (seismic refraction and reflection) bottom sampling, remote sensing, hammer, jet, vibro and banka drills, positioning | Bucket line dredging, jetting, clamshell, rarely suction-cutter dredging |

TABLE II. Classification of placer environments (after Macdonald, 1983).

lacks important details of environment and genetic process required by a scheme which can truly be used as an exploration tool.

A scheme which is of use to an explorationist should encompass aspects of environment or <u>where</u> the deposits may be located. Secondly, it should recognise the criteria of processes involved in the genesis of the different types of placer, i.e. <u>how</u> the deposits were formed. Because this assemblage of factors of environment and process is complex, no such classifications have yet been published.

The concepts of where and how are central to the theme of this review. The next section deals with the genesis of alluvial placers.

# PART 2 GENESIS OF ALLUVIAL PLACERS

## 2.1 EVOLUTION OF PLACER DEPOSITS

Accumulations of heavy minerals may occur at many stages of the sedimentary cycle, producing residual, eluvial, alluvial and beach placers. Figure 1 is a diagrammatic representation of this evolution indicating some general features of placer sediments. Whilst the main region of interest covered in this review is the alluvial environment, it is pertinent to outline the processes which resultin the liberation of detrital heavy minerals into this environment. A brief review of weathering processes is given, followed by examples of cassiterite placer evolution involving chemical, and then mechanical weathering processes.

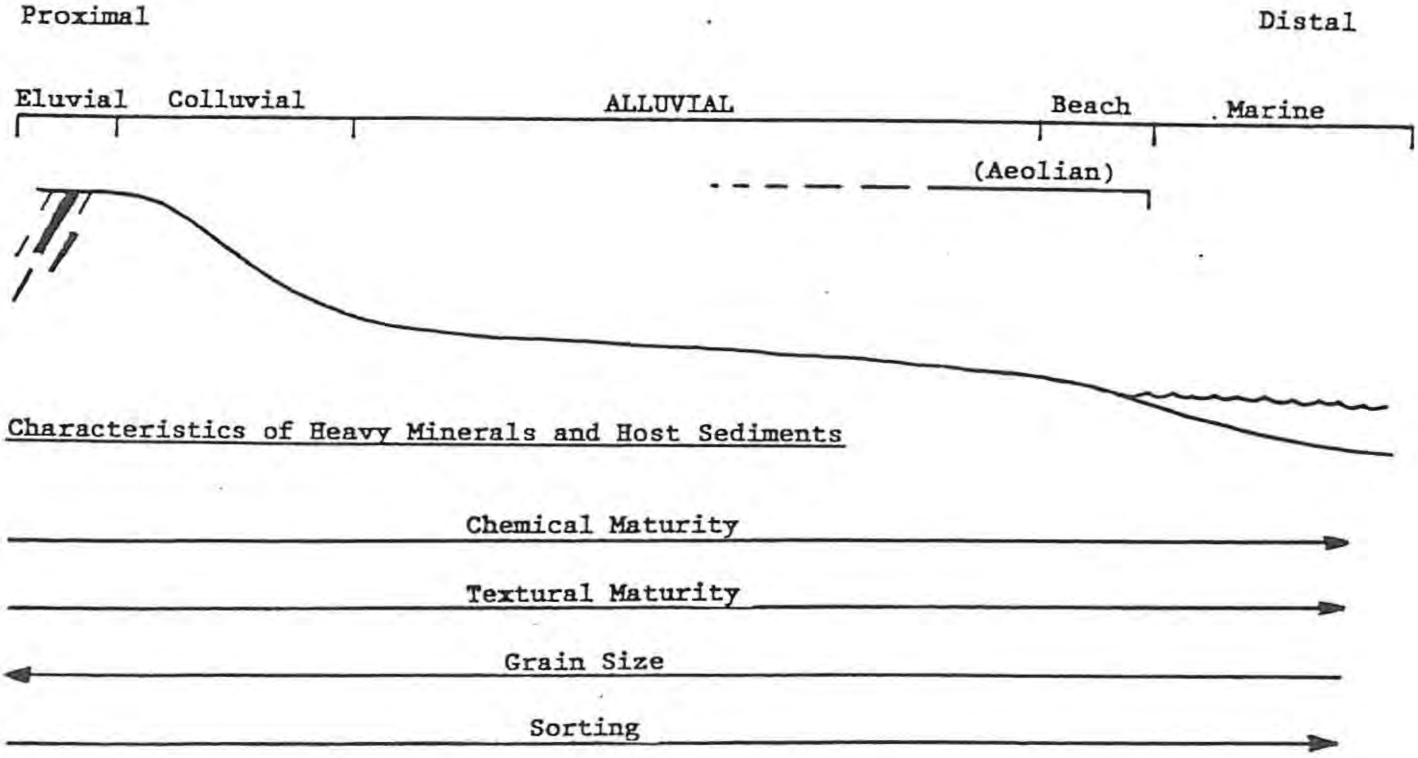


FIG. 1. The evolution of placer deposits.

### 2.1.1 Weathering Processes

The weathering processes responsible for the breakdown of primary rocks can be subdivided into : i) chemical weathering ; and ii) mechanical weathering. Whilst chemical weathering appears to be the more important process in intra-continental areas, placers may also be formed from heavy minerals liberated by predominantly mechanical means particularly in orogenic areas. The following review is taken from Levinson (1974).

### 2.1.2 Chemical Weathering

Chemical weathering may be defined as the chemical reactions between rocks and minerals, and the constituents of air and water at or near the Earth's surface. In this environment, oxygen, carbon dioxide and water are abundant, and the temperatures and pressures are low. Many minerals are unstable in the secondary environment and consequently chemical changes take place during weathering in an attempt to reach equilibrium. The order of resistance to chemical weathering of rock-forming minerals is generally:

oxides > silicates > carbonates > sulphides.

All chemical reactions related to chemical weathering involve four relatively simple processes : ionization ; addition of water and carbon dioxide ; hydrolysis ; and oxidation.

The products of chemical weathering are threefold:

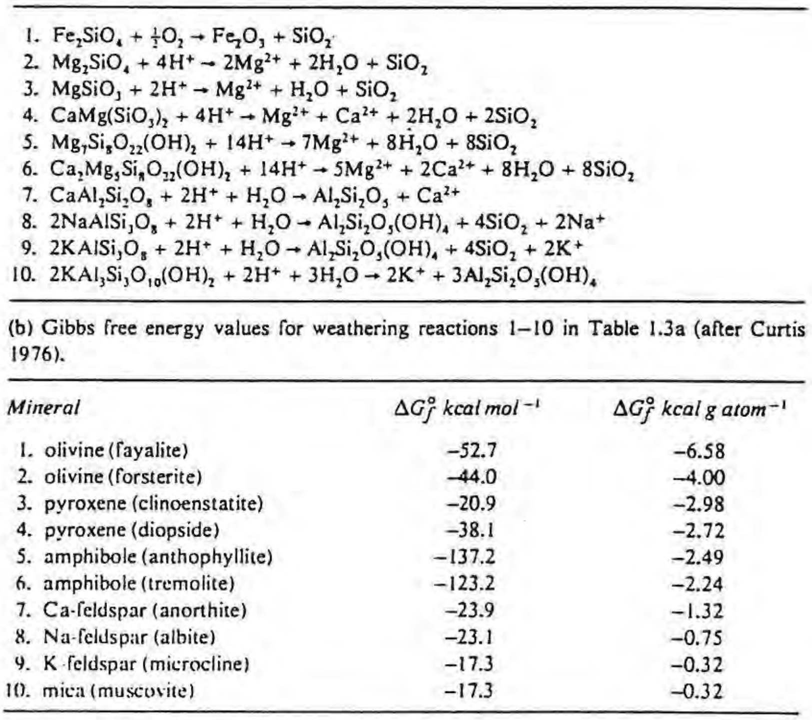
i) soluble constituents (important for geochemical stream sample prospecting) ;

ii) insoluble minerals (producing residual geochemical soil anomalies) ; and

iii) residual primary minerals (including detrital heavy minerals).

Residual primary minerals are often encountered in the zone of weathering because they are not affected by the chemical reactions around them. They include native elements, oxides, some silicates and a few examples of other chemical types such as phosphates (e.g. monazite).

Curtis (1976) used a thermodynamic approach to explain the stabilities of different minerals in the weathering environment. The likelihood of a particular reaction occurring in preference to another reaction may be predicted by reference to the change in free energy of the reactions. The standard free energy change of a reaction is the sum of free energies of formation ($G_f$) of all the reaction products minus the sum of the free energies of the reactants. When calculated free energy changes are negative, reactions will proceed spontaneously. The greater the negative value of the change in free energy, the greater the tendency to react.



1. $Fe_2SiO_4 + \frac{1}{2}O_2 \rightarrow Fe_2O_3 + SiO_2$
2. $Mg_2SiO_4 + 4H^+ \rightarrow 2Mg^{2+} + 2H_2O + SiO_2$
3. $MgSiO_3 + 2H^+ \rightarrow Mg^{2+} + H_2O + SiO_2$
4. $CaMg(SiO_3)_2 + 4H^+ \rightarrow Mg^{2+} + Ca^{2+} + 2H_2O + 2SiO_2$
5. $Mg_7Si_8O_{22}(OH)_2 + 14H^+ \rightarrow 7Mg^{2+} + 8H_2O + 8SiO_2$
6. $Ca_2Mg_5Si_8O_{22}(OH)_2 + 14H^+ \rightarrow 5Mg^{2+} + 2Ca^{2+} + 8H_2O + 8SiO_2$
7. $CaAl_2Si_2O_8 + 2H^+ + H_2O \rightarrow Al_2Si_2O_5 + Ca^{2+}$
8. $2NaAlSi_3O_8 + 2H^+ + H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2Na^+$
9. $2KAlSi_3O_8 + 2H^+ + H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2K^+$
10. $2KAl_3Si_3O_{10}(OH)_2 + 2H^+ + 3H_2O \rightarrow 2K^+ + 3Al_2Si_2O_5(OH)_4$

(b) Gibbs free energy values for weathering reactions 1–10 in Table 1.3a (after Curtis 1976).

| *Mineral* | $\Delta G_f^\circ$ *kcal mol*$^{-1}$ | $\Delta G_f^\circ$ *kcal g atom*$^{-1}$ |
|---|---|---|
| 1. olivine (fayalite) | –52.7 | –6.58 |
| 2. olivine (forsterite) | –44.0 | –4.00 |
| 3. pyroxene (clinoenstatite) | –20.9 | –2.98 |
| 4. pyroxene (diopside) | –38.1 | –2.72 |
| 5. amphibole (anthophyllite) | –137.2 | –2.49 |
| 6. amphibole (tremolite) | –123.2 | –2.24 |
| 7. Ca-feldspar (anorthite) | –23.9 | –1.32 |
| 8. Na-feldspar (albite) | –23.1 | –0.75 |
| 9. K-feldspar (microcline) | –17.3 | –0.32 |
| 10. mica (muscovite) | –17.3 | –0.32 |

TABLE III. a) Weathering equations written with rock-forming silicate minerals as reactants with aqueous phases (after Curtis, 1976).

b) Gibbs free energy values for weathering reactions 1 - 10 in Table IIIa (after Curtis, 1976).

In order to assess stability, specific equations can be written with primary igneous and metamorphic minerals as reactants (Table IIIa). Experimental data on standard free energies of formation for both potential reactants and products are then assembled and the calculated free energy changes tabulated (Table IIIb). An example of such a calculation would be (for anorthite weathering to kaolinite):

$$CaAl_2Si_2O_8 + 2H^+ + H_2O \ -$$

$$Al_2Si_2O_5(OH)_4 + Ca^{2+}$$

Thus:

$$\Delta G_f^\circ = (\Delta G_f^\circ \ Al_2Si_2O_5(OH)_4 + \Delta G_f^\circ Ca^{2+})$$

$$- (\Delta G_f^\circ \ CaAl_2Si_2O_8 + \Delta G_f^\circ \ 2H^+ + \Delta G_f^\circ \ H_2O)$$

$$= (-904 + -132.2) - (-955.6 + 0 + -56.7)$$

$$\Delta G_f^\circ = -1036.2 + 1012.3$$

$$= -23.9 \text{ kcal mol}^{-1}$$

This result states that anorthite will spontaneously react with hydrogen ions in aqueous solutions to form the clay mineral kaolinite and calcium ions. Table IIIa lists the results obtained by this procedure for ten other primary silicates. Note that for the comparison of the free energy values between different reaction equations, the results in kcal $mol^{-1}$ must be changed to kcal gram atom values. This is done by dividing by the number of product atoms for each reaction.

The final results (Table IIIa) show a good correspondence to the stabilities of minerals found in nature, and the order of stabilities is the reverse of Bowen's reaction series for mineral crystallisation from silicate melts. This suggests that, muscovite and K-feldspar as well as quartz should dominate the clastic mineral components derived by erosion from igneous and metamorphic rocks. These should constitute the major mineralogic "background" with which detrital heavy minerals "compete" for transport and concentration. However, there are also important new minerals produced by weathering, including clay minerals.

The hydrolysis and oxidation weathering reactions usually lead to the liberation of the alkali- and alkali-earth elements (Ca, K, Na and Mg) in solution as hydrated ions, with silica and aluminium silicates as by-products. These clay minerals are volumetrically a significant product of weathering in humid regions, and because they are transported in suspension, do not dilute the coarser bedload fractions which tend to host the heavy minerals. Hence, in climatic regions dominated by chemical weathering the generation of coarse sediment is limited.

### 2.1.3 Mechanical Weathering

In nature, four important physical processes lead to the fragmentation of rocks: frost wedging ; expansion resulting from unloading ;thermal expansion ; and organic activity. In general, these processes are far less efficient in liberating detrital minerals from their host rock than chemical weathering processes. However, they increase the surface area of the rocks, thus making them more susceptible to chemical attack.

Frost wedging involves the alternate freezing and thawing of water which has penetrated into cracks in rocks. Water has the unique property of expanding by about 9 per cent as it freezes, thus exerting an outward force, and increasing the dimensions of the cracks. This process is most common in periglacial environments in sub-arctic and mountainous regions.

Unloading produces exfoliation domes caused by the differential reduction in pressure as overlying rock is stripped away. It is particularly well-developed on granites.

Thermal expansion involves the daily cycle of temperature changes, which in arid regions may exceed $30^0$C. Repeated heating and cooling of rocks composed of minerals with different coefficients of thermal expansion is generally believed to result in the rocks disintergration. This process may explain the dominance of mechanical dispersal of elements in arid regions.

Organic activity involves the exploitation of weaknesses in rocks by plants (especially roots) and burrowing animals.

### 2.1.4 **Examples**

#### Placer Evolution By Chemical Weathering

#### An Example From Indonesia

The stanniferous placers of the Tujuh archipelago, Indonesia, have been described by Aleva (1986). 95% of the mineable cassiterite in this province lies on the source bedrock indicating that minimal transport has occurred. The generation of these placers has been the result of the interaction of four factors:

i) the presence of primary source rock ;

ii) the liberation of cassiterite without excessive comminution of the cassiterite grains ;

iii) the mechanical concentration of the now detrital grains ; and

iv) the protection of the placers against mechanical erosion.

The primary source rocks are granitoids intruding Permian clastic sediments. Mineralization occurs as veins, greisen masses and pegmatites in the country rocks above granite cupolas, and as disseminations in the roof zones of the granites.

The liberation of the brittle cassiterite from its encasing minerals in the host rock, has been efficiently effected by deep tropical weathering, which alters most silicates to kaolinite. An example of this reaction is as follows:

orthoclase + water - kaolinite + quartz + alkalic hydroxide

$2KALSi_3O_8 + 3H_2O - Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2KOH$.

Alkalies and earth alkalies are removed by leaching, leaving quartz and cassiterite as residual primary minerals. Granitic rocks are thus altered to a saprolite of plastic to tough clayey consistency composed of quartz (and cassiterite) grains in kaolin, with many relict igneous textures retained. This saprolite may reach tens of metres in thickness and is covered by a residual sandy layer. The sedimentary rocks develop a thinner saprolite of only a few metres because their constituent minerals are already largely in equilibrium with near-surface conditions.

Weathering is greatly promoted by the hot and humid climate which is considered to have been prevalent throughout the Caenozoic (Frakes, 1979). Periods of semi-arid morphogenesis have therefore been absent, reducing the potential for transport by rapid flood events.

The concentration of cassiterite into placers has produced three types of deposits:

i) residual eluvial concentrations or, *Kulit* (Indonesian for "skin"), placers on interfluves and valley-side slopes:

ii) proximal fluvial lags, or *Kaksa* (Chinese for "coarse sand"), placers lying directly on weathered bedrock in main drainage channels ; and

iii) transported alluvial concentrations or *Miencan* (Chinese for "cover-layer") placers comprising cassiterite-rich layers interbedded with alluvial sediments (less than 10% of the mineable cassiterite in Indonesia).

Figure 2 is a map of the Belitung area of Indonesia showing the identified cassiterite deposits up to the late 1950's. Both the eluvial *Kulit* and proximal fluvial *Kaksa* can be seen (the former on the interfluves, and the latter in the valleys). The fluvial lags are largely considered to be fluvially reworked colluvium derived from the interfluves. The mechanism of transport of these eluviated deposits, from the interfluves to the valleys, involves the shrinkage (or slow-motion collapse) of a thick (up to 40m) mantle of weathered bedrock, resulting from humid tropical saprolitic

FIG. 2. Map of the central eastern part of Belitung Island, Indonesia (Lenggang district), showing the present drainage channel (thin lines) and topographic culminations (asterisks ), the contact (heavy broken line) of small granite masses, and the identified cassiterite deposits (black) as of the late 1950's (after Aleva, 1985).

weathering. Gravity movement (colluviation or tropical solifluction) of this mantle occurs continuously toward the nearest topographical low, i.e. the fluvial valley.

The <u>protection</u> of unconsolidated placers is required to prevent destruction by erosional activity. Such protection has been afforded by rises in sea-level, which have effectively prevented rejuvenation of the fluvial systems, and continued tropical climates which have promoted generally sluggish fluvial activity (Aleva, 1983). Rejuvenation of drainage systems brought about by sea-level falls, tectonic uplift events, or periods of semi-arid morphogenesis might erode these placers to form more distal alluvial cassiterite deposits such as those in western Malaysia.

## Placer Evolution By Mechanical Weathering - An Example From Cornwall, England.

The tin province of south-western England is associated with a granitoid intrusion of Permo-Carboniferous age. Only the top, domal parts of the batholith are exposed within Devonian and Carboniferous metasediments. The major styles of primary tin mineralization are stockworks, sheeted veins, hydrothermal breccias and replacements, which are generally associated with the apices of domes and cusps in the intrusion. Their mineralogy is simple, comprising cassiterite in a silicate gangue of quartz and tourmaline.

Camm and Hosking (1985) described the evolution of stanniferous placers in the St.Austell area, and concluded that processes of physical weathering were responsible for the liberation of cassiterite from the primary sources.

During the Quaternary, ice sheets periodically encroached from the north to produce a periglacial environment in the region. Wet phases dominated the interglacial stages, and the last cold phase terminated about 10 000 years BP with amelioration of the climate. The ground preparation for placer development in a cryergic system depends largely upon frost wedging, and on disintegration during rapid and marked variations in temperature of material composed of several mineral species with different coefficients of thermal expansion. This process builds up a layer of unconsolidated debris known locally as "head", which moves downslope by processes of mass wasting, most notably solifluction.

In the interglacial stages, fluvial activity reworked the solifluction debris, transporting and sorting the heavy mineral components.

At Criggan Moor, (Figure 3) the cassiterite fraction of the alluvial deposit is mainly angular and appears to have been derived entirely from the products of solifluction. Many grains are still attached to silicate gangue, implying minimal reworking.

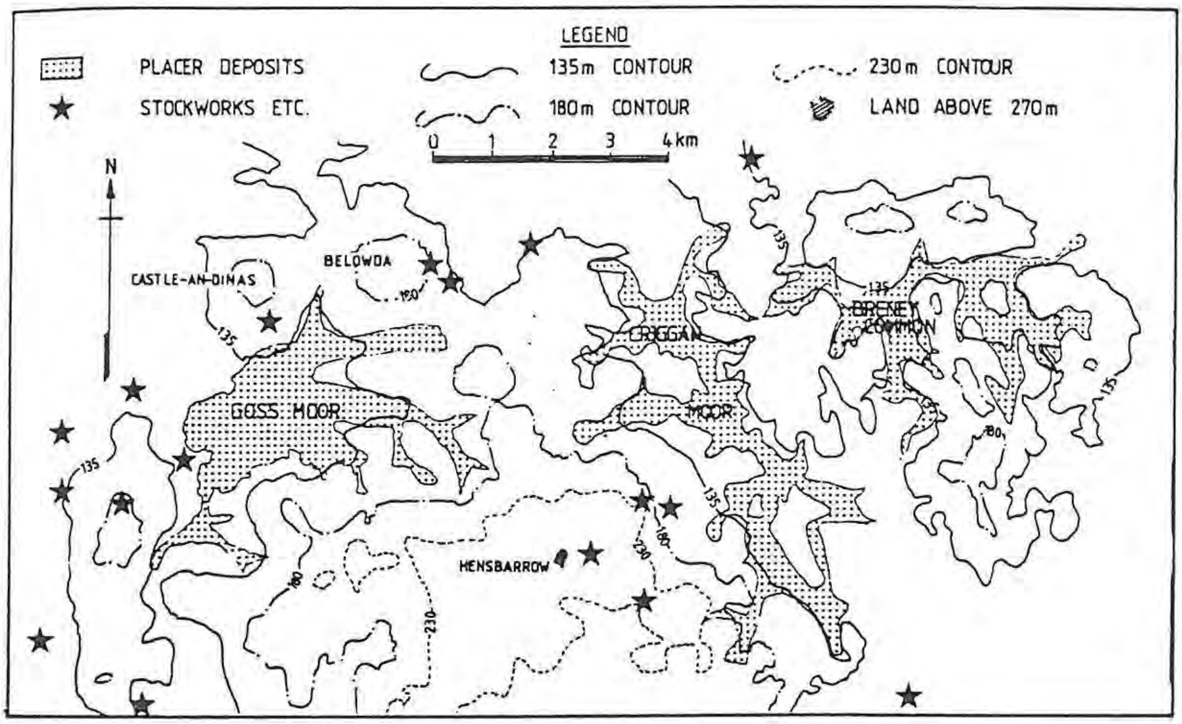


FIG. 3. Map of the North St. Austell area showing disposition of stockwork, sheeted vein and replacement deposits, and of placer deposits (after Camm and Hosking, 1985).

## 2.2 TECTONIC SETTINGS OF ALLUVIAL PLACERS

Whilst it can be convincingly argued that placer deposits do not, strictly speaking, have tectonic settings, the minerals which comprise placers are usually specific to particular settings, and this must affect the distribution of particular mineralogical types of placer.

For example, the primary source rocks of diamonds are kimberlites and certain lamproites, and diamondiferous examples of these igneous intrusions have a strong geographical association with cratonic areas (Dawson, 1980). In some regions such as Ghana and Brazil, economic concentrations of alluvial diamonds have been derived from metamorphosed Precambrian sediments, and, although the primary sources of these diamonds have never been established, their occurrence adds to the association of diamond mineralization with shield areas. The distribution of significant diamond placers is shown in Figure 4. There is a clear correspondence with cratonic areas.

Primary hydrothermal gold, on the other hand, is generally related, to I-type, magnetite series granitoids generated in subduction-related magmatic arcs. This association appears throughout geologic time from the Archean (e.g. in the Barberton greenstone belt of South Africa) to the Tertiary (e.g. Marte in the southern Andean cordillera of Chile) (Mason, 1991; J.J. Latorre, pers.comm.). Figure 5 shows the distribution of primary gold ores of Precambrian, Palaeozoic and Mesozoic-Caenozoic age, and of placer deposits derived from these sources.

The difference in tectonic settings of primary gold and diamond deposits carries significance in terms of the genetic models for gold and diamond placers. Tectonic uplift in regions of plate collision exerts the dominant control on the genesis of the major gold placers (the giant gold placers of Henley and Adams, 1979). In intra-continental settings, climate plays a more important role than tectonic upliftand the genesis of diamond placers reflects this (see example below). Cassiterite placers, although associated with major collision sutures, are associated with late-orogenic S-type granites which undergo relatively little uplift and erosion during the orogenic cycle. Climate is also therefore important in the genesis of cassiterite placers.

It can be concluded that the tectonic setting of the primary source, influences the distribution of the secondary placer.

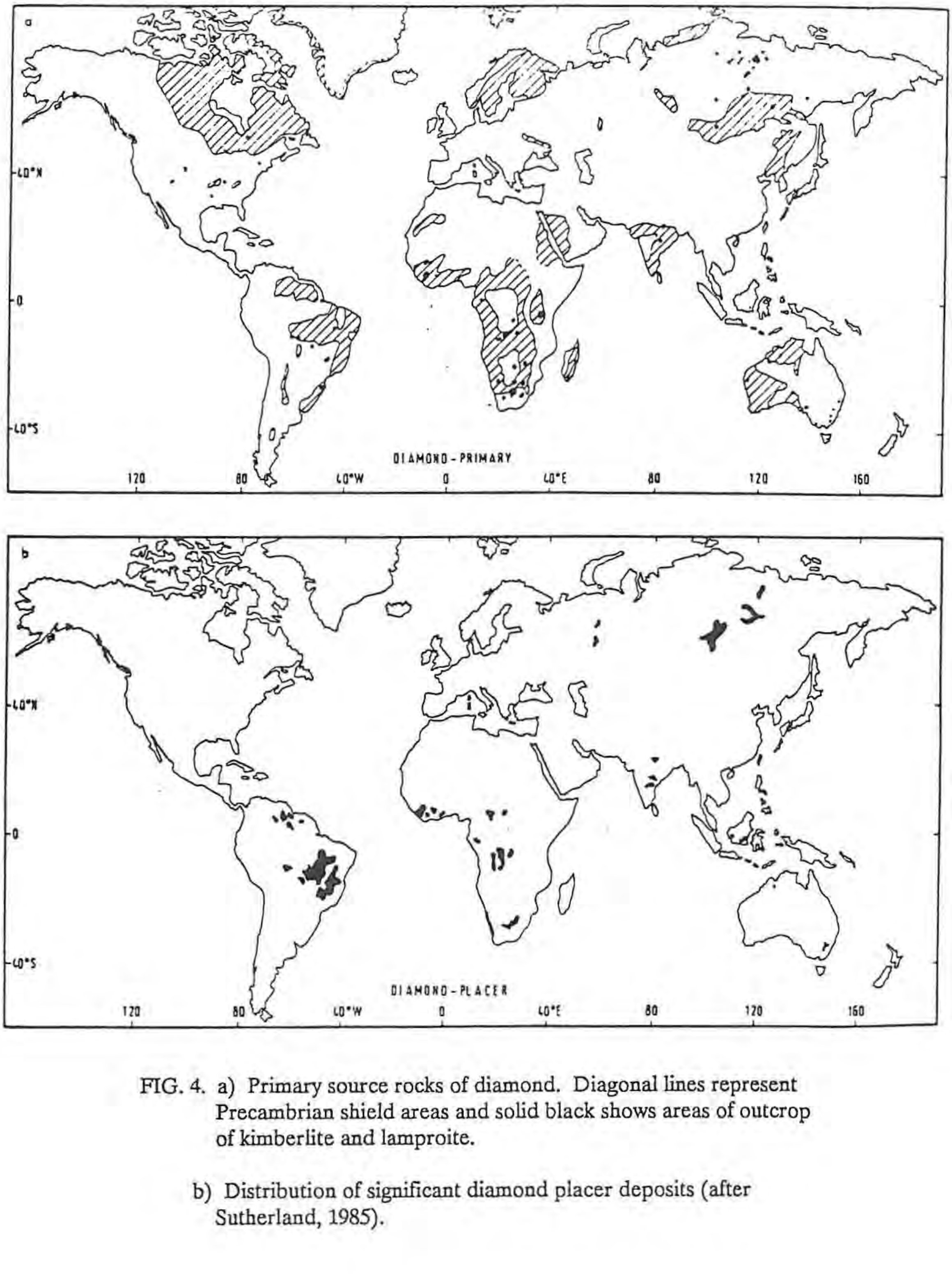


FIG. 4. a) Primary source rocks of diamond. Diagonal lines represent Precambrian shield areas and solid black shows areas of outcrop of kimberlite and lamproite.

b) Distribution of significant diamond placer deposits (after Sutherland, 1985).

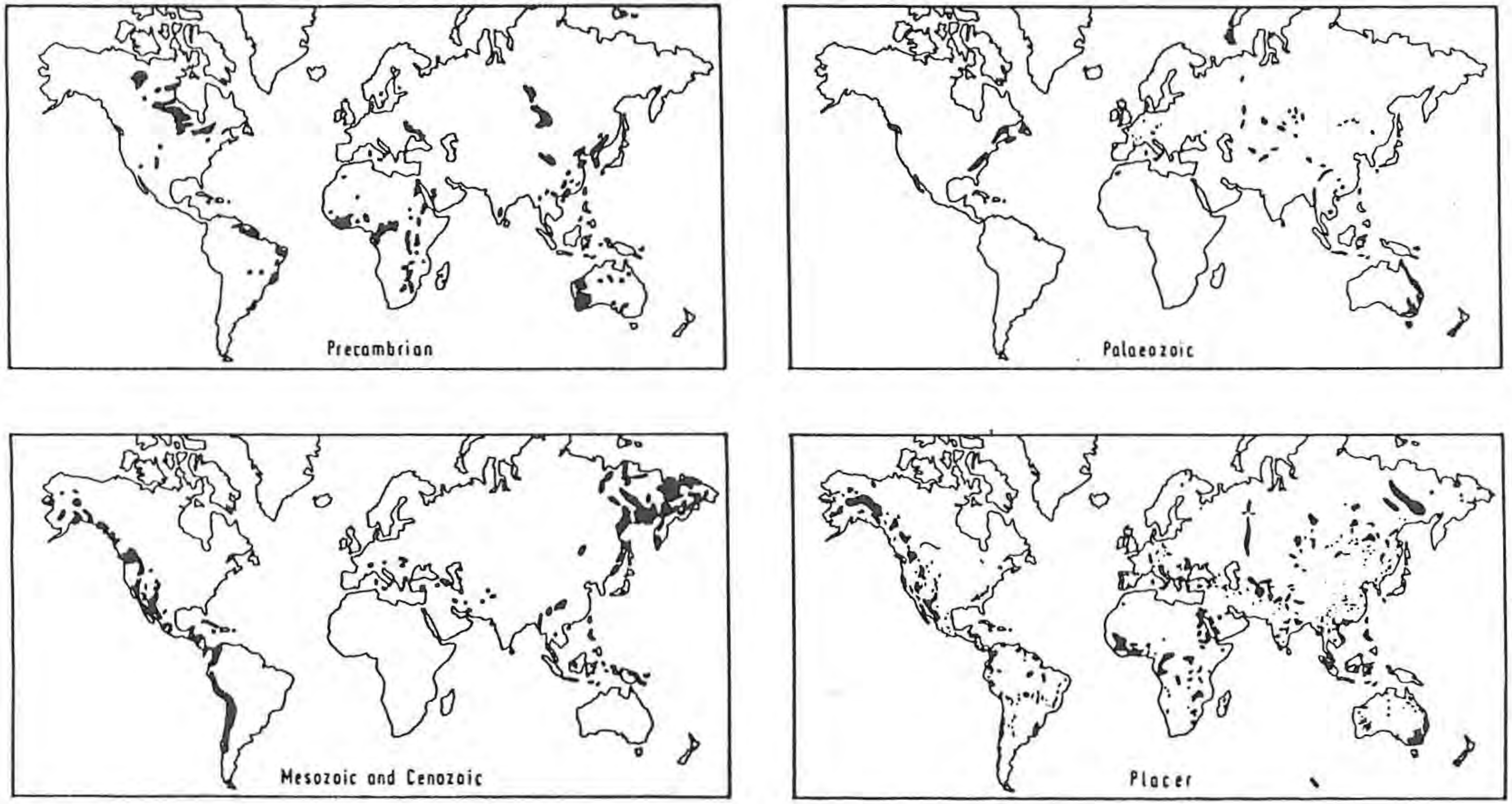


FIG. 5. Distribution of primary gold ores of Precambrian, Palaeozoic and Mesozoic - Cenozoic age, and of placers derived from these sources (after Sutherland, 1985).

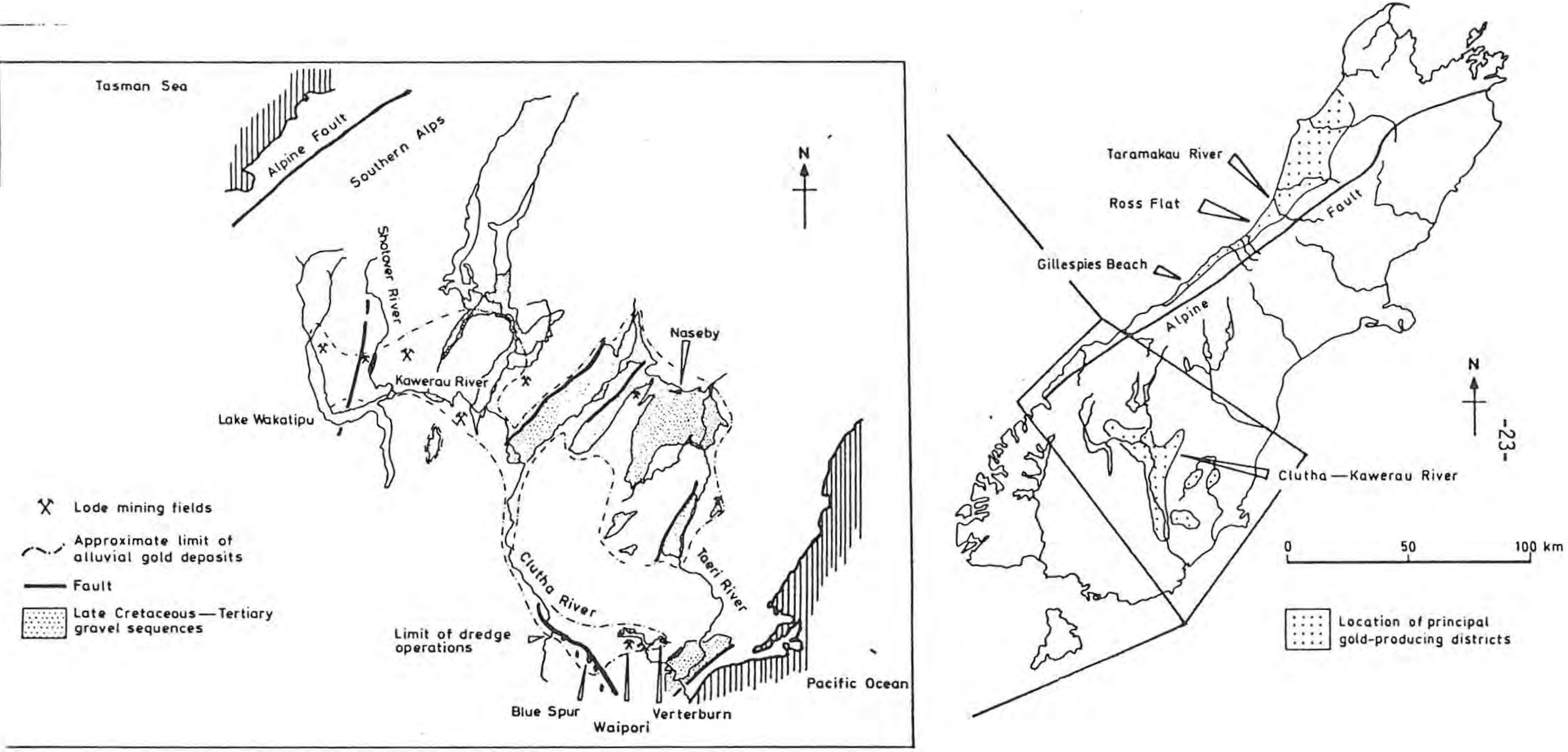


FIG. 6. Auriferous sedimentary basins on the Clutha-Kaweru River system in Otago, South Island, New Zealand (after Henley and Adams, 1979).

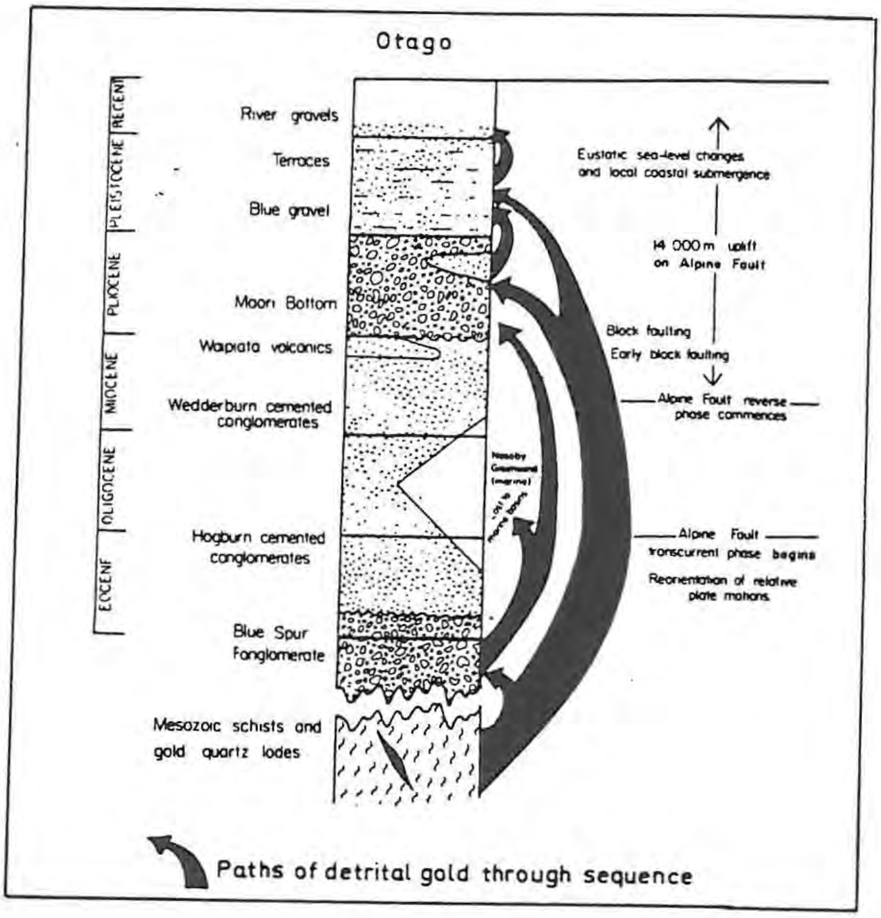


FIG. 7. Stratigraphy and principal tectonic events in the evolution of auriferous gravels of Otago (after Henley and Adams, 1979).

Renewed uplift to form the present day Alpine Mountains induced reworking of the Blue Spur fanglomerates into the Otago basins which had formed on the flanks of the rising mountain chain. Sedimentary reworking in these basins occurred in response to base-level changes due primarily, to episodic regional uplift, as well as eustatic sea-level fluctuations. Adams et al. (1978 ; see also section 2.3.2) suggested that the complex response to a single uplift would produce the multifold reworking of channel alluvium that is required for placer formation. Although such rejuvenation may destroy existing placers, it creates a suitable environment for the formation of new ones. The broad distribution of gold through the stratigraphic column (Figure 7), therefore records the sequence of base-level changes and sediment-supply changes that occurred during the period of episodic uplift.

Hence, tectonic uplift was the primary controlling factor in the genesis of the Otago alluvial gold deposits. This conclusion may be extended to other major alluvial gold deposits, including those of the Witwatersrand, in which the gold is associated with angular unconformities (Els, 1991). Although the Witwatersrand Basin is now part of the Kaapvaal Craton, it is likely to have developed as a foreland basin in a collision setting (Stanistreet and McCarthy, 1991).

## The Birim Alluvial Diamond Placer, Ghana

A study of the late Quaternary alluvial diamond placer on the Birim River in Ghana by Hall et al. (1985) assessed the contributions of both morphogenic and grain-scale concentrating processes in the deposit's formation. Quaternary climatic changes are considered to have been significant in governing the development of many West African diamond placers. The Birim deposit is the downstream continuation of more proximal alluvial and colluvial placers of the Akwatia diamond field.

### Geology

The Birim drainage basin is underlain by Proterozoic metasediments comprising steeply dipping breccias and greywackes which have been identified as the source of the diamonds in the region. Weathering extends to a depth of some 30m and unweathered outcrops are confined to the channels of the Birim River and its major tributaries. Weathering of the metasediments produces a silty-clay saprolite (95% finer than 0.5 mm) and it releases gravel-sized clasts only from quartz veins, delivering a strongly bimodal sediment supply to the river. Figure 8 is a geological map of the region.

### Geomorphology

The Birim River floodplain lies in a wide shallow valley, 30-40 m below broad interfluves which rise to between 155 to 180 m above sea level. The interfluves are capped by a thin laterite which is regarded as the remnant of a Tertiary planation surface. The Birim floodplain displays alternating broad and restricted reaches from 200 to 1500 m in width. The bedrock

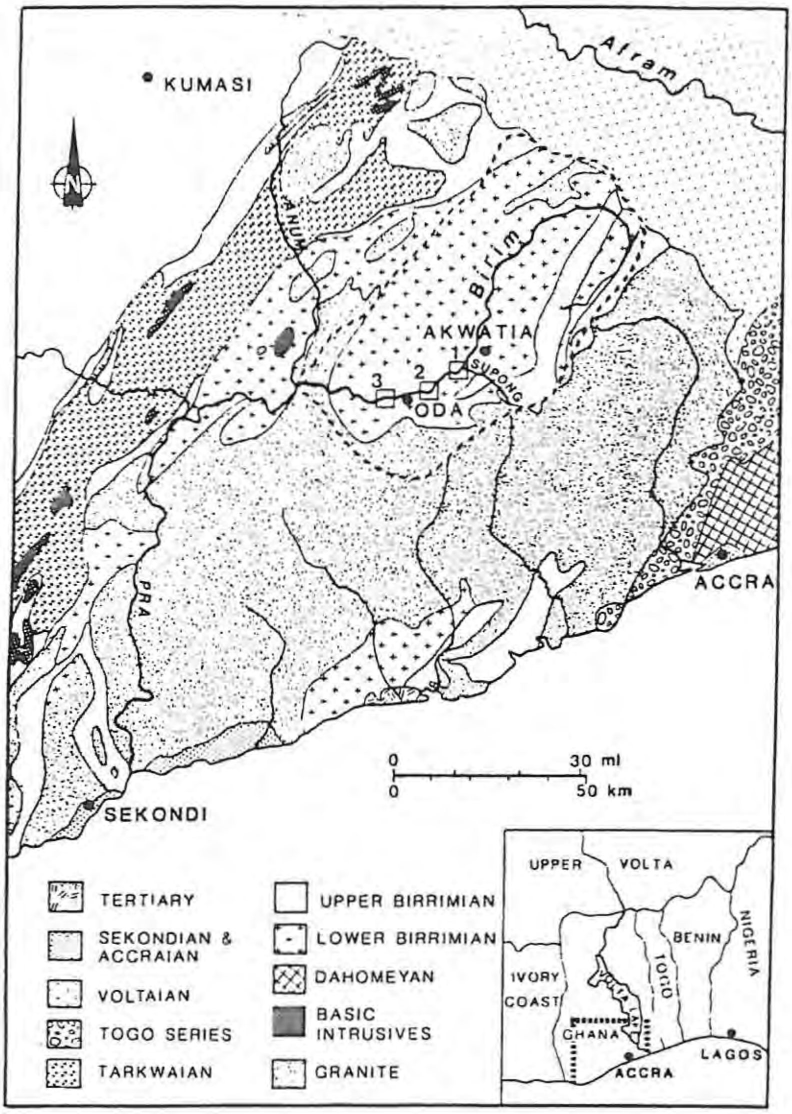


FIG. 8. Geological map of southern Ghana, showing the location of the Birim catchment (broken line). All rocks except intrusives and Tertiary deposits are of Proterozoic age (after Hall et al., 1985).

surface beneath the alluvium varies from planar to highly irregular with discontinuous channels and risers giving a local bedrock topography of up to 9 m. A schematic cross-section is shown in Figure 9.

The river flows in a box-like channel on average 30 m wide and 7 m deep. The river bed comprises coarse gravels, and it's banks, sandy and clayey silts. The channel pattern is irregularly meandering, but the abundant bedload, and the lack of the typical characteristics of a meandering river

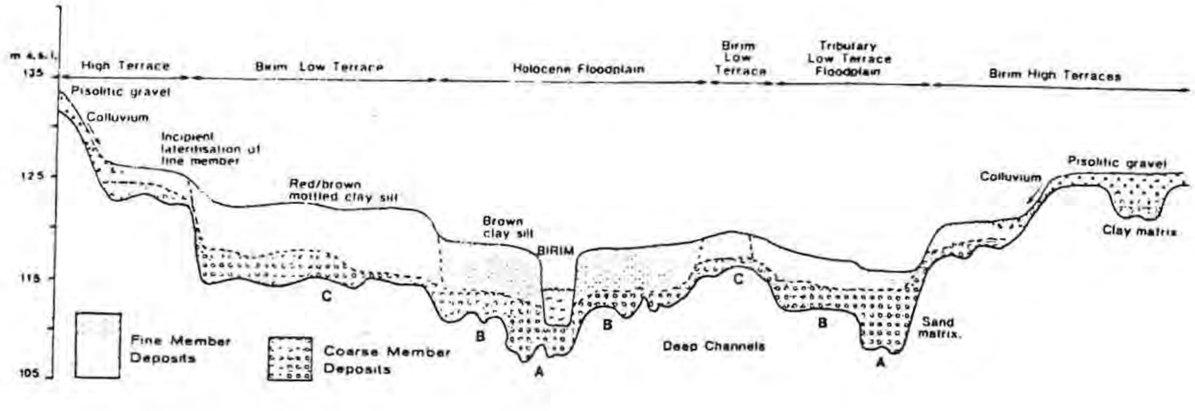


FIG. 9. Schematic cross-section of the Birim River valley near Akwatia. Bedrock levels A, B and C refer to locations of typical vertical sections in Fig. 10 (after Hall et al., 1985).

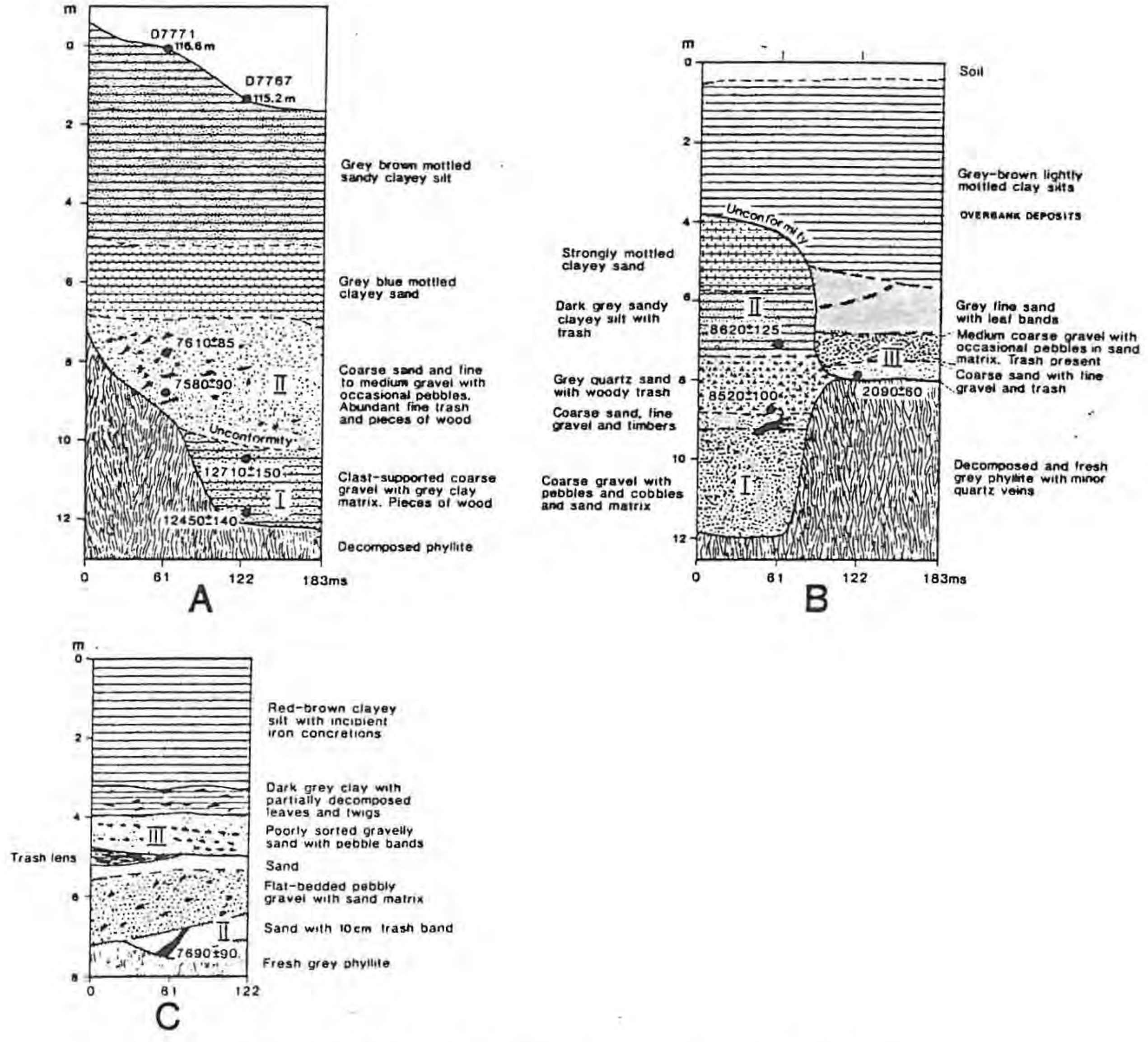


FIG. 10. Vertical sections in the Birim floodplain deposits. A, B and C refer to bedrock levels shown in Fig. 9 (after Hall et al., 1985).

(meander loop cut-offs, point bar deposits etc.) indicates that the general model of channel migration and floodplain development by lateral accretion is not applicable.

Climatically, the region falls into the humid tropical morphogenic region of Sutherland (1985 ; section 2.3.1), but radiocarbon dating of organic material, and stratigraphic correlation, has produced the following inferred sequence of environmental and fluvial conditions in the Birim Valley for the late Quaternary.

*Pre - 21000* years *BP.*. Formation of the lower terraces (Figure 9) during several humid to sub-humid climatic oscillations.

*21000 - 13500* years *BP.*. A contraction of the dry climatic belts and a return to humid pluvial conditions. Extensive erosion of pre-existing sediments and scouring of bedrock. Deposition of basal gravel with high proportions of cobbles and pebbles (Unit I in Figure 10).

*105000 - 7000* years *BP.*. Forested conditions. Continued aggradation of gravels and scouring of bedrock outside main channels (Unit II in Figure 10).

*7000 - 45000 years BP.*. Reduced peak discharges of the river, and limited reworking of uppermost gravels.

*4500 - 3000 years BP.*. Mid-Holocene arid phase. Minimal fluvial activity.

*3000 - modern years BP.*. Increasing discharges and local scouring of channels to bedrock. Deposition of pebbly sands on flanks of present channels (Unit III in figure 10).

The recognition of these palaeo-morphogenic regimes has considerable significance for placer development, implying that gravel and diamond transport, deposition and reworking may have been episodic.

## Diamond Distribution

Diamond distribution in the Birim Valley varies both vertically and spatially at several scales. Only the gravels contain grades of economic interest.

Within the gravels, grades increase downwards and, as with other alluvial diamond placers, relatively high grades and larger stones are often found close to bedrock. Higher grades may also occur well above bedrock and this is ascribed to continued aggradation and multiple periods of reworking. There is a strong correlation of higher grades with coarser gravels. However, where the gravels are less than 1.5m thick they are usually barren.

Spatially, the grades decrease downstream from over 1.5 car./$m^3$ to less than 0.5 car./$m^3$ over the 32 km from locality 1 on Figure 8. Superimposed upon this trend are major grade deviations reflecting local variations in gravel lithology. Higher diamond grades are also associated with points where the floodplain widens to form a braided fan as described by Collinson (1986).

## Diamond Sorting Mechanisms

The disparity in hydraulic equivalence between the diamonds and gravels suggests that the primary process of diamond concentration is interstice entrapment (section 2.4.2). Penetration of diamonds into the gravels may have been aided by shear-sorting (section 2.4.1.1) induced by high bed-shear stresses.

The richest placers were probably formed between 10500 and 7000 years BP. as a result of increased precipitation following the prolonged "Ogolian" dry phase and the deposition of the coarse basal gravels. This combination of circumstances had the following effects:

i) high rates of slope erosion from hillslopes and older terraces ;

ii) flushing of colluvial deposits which had accumulated in small tributary valleys during the "Ogolian" dry phase ;

iii) erosion of pre-Ogolian channel deposits ;

iv) channel scour forming irregular bedrock morphology ; and

v) formation and frequent partial reworking of coarse channel gravels leading to diamond concentration by interstice entrapment and shear - sorting.

Hence the dominant factor controlling the geomorphic evolution of this cratonic tectonic region was climatic.

## 2.3 GEOMORPHIC SETTINGS OF ALLUVIAL PLACERS

Placer mineral concentrations are the product of particular interactions between three distinct sets of variables : the nature of the bedrock ; basin dynamics ; and external processes acting at surface which are mainly controlled by climate. Since geomorphology is the product of the same set of variables, it follows that a geomorphological approach is essential to an understanding of placer deposits at all scales. The global distribution of placer deposits is largely a product of variation, both at present and in the recent geological past, in geomorphological processes acting at the Earth's surface, given that suitable primary mineral sources exist.

### 2.3.1 Influence Of Climate

Climate controls factors such as weathering, rate of erosion, nature of sediment supply and opportunities for sediment reworking. Sutherland (1985) recognises five broad morphogenetic regions which are identified on the basis of distinctive combinations of geomorphological (mainly climatic) processes responsible for placer formation. These are :

1) glacial (ice sheet and mountain) ;

2) cold non-glacial ;

3) humid temperate ;

4) arid and semi-arid ; and

5) humid tropical.

Figure 11 shows the modern distribution of these morphogenetic regions.

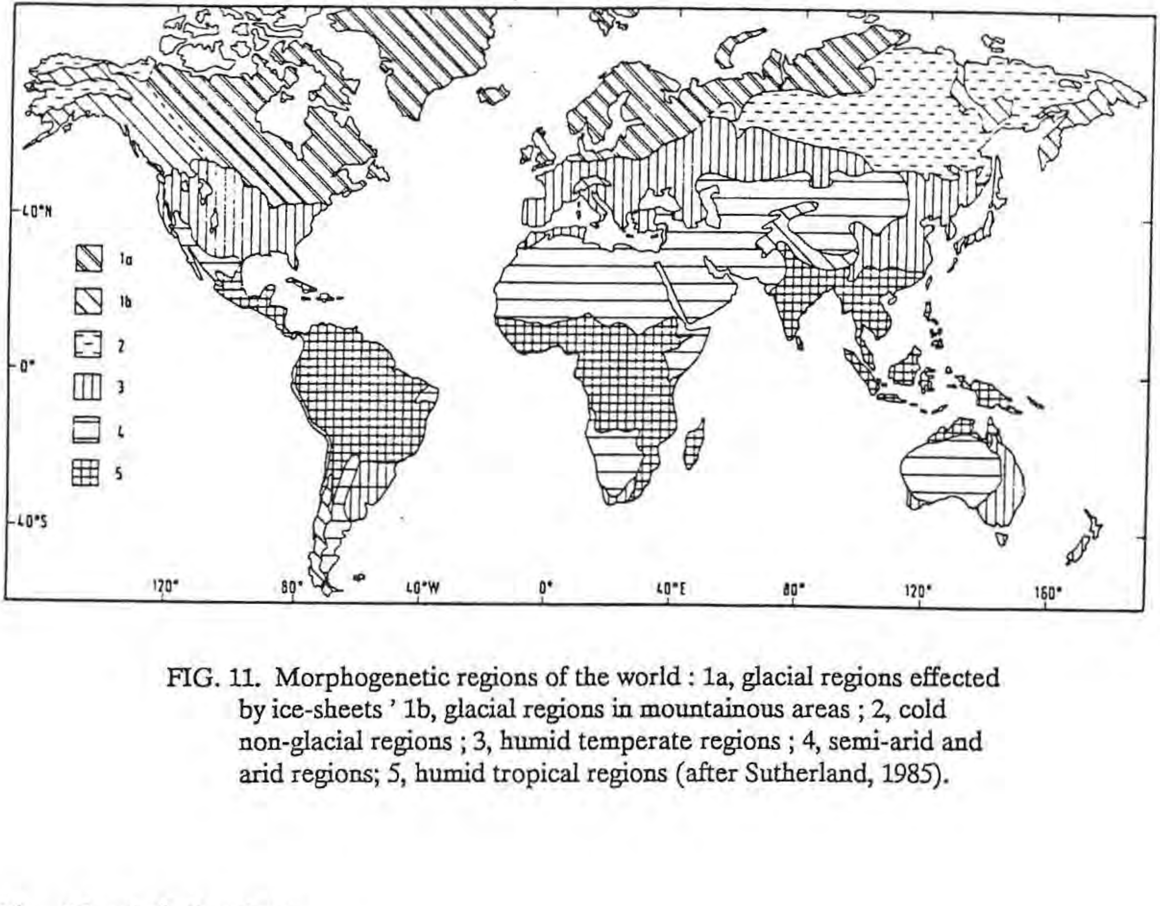


FIG. 11. Morphogenetic regions of the world : 1a, glacial regions effected by ice-sheets ' 1b, glacial regions in mountainous areas ; 2, cold non-glacial regions ; 3, humid temperate regions ; 4, semi-arid and arid regions; 5, humid tropical regions (after Sutherland, 1985).

## 1) Glacial Regions

These are the areas presently glacierized as well as those areas that were extensively glaciated during the Quaternary. A subdivision is indicated between areas of ice-sheet glaciation and mountain glaciation, the latter being restricted by topographic control.

It is a frequently held tenet that glaciation is unfavourable to the development of placers because glacial processes tend to disperse rather than concentrate minerals. Sutherland (op.cit.) quoted studies which documented lower-grade placers within glacial limits than outside them, (e.g. in placers of the Urals). Several examples of economic gold placers do however exist within formerly glaciated areas. Their existence may be explained in terms of three relevant points.

Firstly, glacial or fluvioglacial sediments are deposited rapidly with little sorting and, typically, are disposed in such a manner with respect to the established drainage pattern that there is little opportunity for reworking. Heavy mineral reconcentration is therefore minimal. As a consequence, only highly valuable commodities such as gold may be found to be economic in such deposits (e.g., the auriferous "bench" placers near Nome, Alaska; Cobb, 1973), or alternatively, very proximal deposits of less valuable commodities (e.g., the cassiterite-bearing "morainic debris" in Bolivia ;Breeding, 1968).Secondly, although extensive erosion is characteristic of ice sheets, on the ice sheet margins the cover of ice and glacial sediments may be more protective than erosive, and pre-existing placers may be preserved. Examples of this are cited in Boyle (1979) and include the Chaudiere River area of Quebec, and the Caribou of British Columbia.

Thirdly, glaciers can disperse heavy minerals with little size sorting over considerable distances to give rise to large volumes of very low grade sediment. This protore may be reworked by post-glacial rivers into economically valuable placers. The extensive gold placers along the North Saskatchewan River in Canada are an example. Other possible examples are some of the alluvial diamond deposits of South Africa. Harger (1909) was the first to suggest that at least some of the Vaal River diamonds are derived from pre-Karoo Kimberlites via Permo-Carboniferous Dwyka "conglomerates". This hypothesis is based on the fact the diamond-bearing gravels generally occur in areas where Ventersdorp andesites are associated with the overlying Dwyka diamictite, and the premise that the diamonds have been reworked from low-grade concentrations in the diamictite, into higher grade gravels, by processes of heavy mineral concentration. This suggestion is supported by the fact that the Dwyka diamictite is locally diamondiferous (e.g., at Bosluispan in Bushmansland). Although the Vaal

River is not strictly a post-glacial drainage, it does exploit Dwyka-age valleys (Visser and Loock, 1988).

Despite these examples, it is concluded that placer deposits in formerly glaciated terrain are relatively uncommon.

### 2) Cold non-glacial regions

These areas lie beyond the Quaternary ice sheets, but are characterised by the presence of permafrost. The greatest extent of these regions lies in Siberia, Alaska and Canada.

A thin active soil layer with limited vegetation cover and seasonal thawing combine to produce a short period of intense fluvial activity in late spring and early summer. This temporal concentration together with the contrast in state between the soil in the thawed valley bottoms and frozen interfluves, results in fluvial incision.

Weathering is predominantly mechanical and the nature of the regolith is bedrock dependent. Soil-forming processes produce predominantly coarse material with a low silt and clay content. This material is mainly transported in the fluvial system as bedload. Because the permafrost is subject only to local melting, it prohibits widespread stripping of pre-existing deposits or regoliths inherited from the Tertiary period when more effective chemical weathering processes prevailed. This is of particular significance to placer formation, since the Tertiary regolith may act as a protore. Where the periglacial fluvial system has intersected these earlier sediments, rich placers may be formed.

Examples of such placers include gold in the Yukon River area of Alaska and NW Canada (e.g., Cobb, 1973 ; Boyle, 1979). Sutherland (1985) also recorded examples from the Siberian shield.

### 3) Humid temperate regions

This region includes much of mainland Europe and the U.S.A, with a more restricted distribution in the southern hemisphere. River flow is perennial but strongly modulated by soil cover. Soils are characteristically arenaceous with relatively little clay content (< 10%). This gives rise to large volumes of bedload-sized material that may rapidly dilute heavy minerals with distance away from the source. Thereforethese areas do not possess an optimum balance of placer-forming characteristics.

### 4) Semi-arid to arid regions

Qnaternary climatic change has meant that even the most arid modern environments have probably experienced some fluvial activity in the last three million years, and no distinction is therefore made between semi-arid and arid regions.

This zone is characterized by very high run-off rates produced by infrequent but intense rainfall, and limited interception by a sparse vegetation cover. Weathering is dominated by mechanical processes, and large quantities of bedload-sized material are therefore generated. The large volume of sediment entrained during fluvial events produces a relatively high-density fluid in which heavy minerals are more easily transported. Fluvial activity in arid areas is therefore effective in transporting heavy minerals, but the sediments produced are often poorly sorted, and reworking is less likely than in other geomorphic environments.

The wide dispersion of diamonds in central and southern Africa may be due to transport during arid phases of the Caenozoic, but concentration has been during alluvial or "wet" phases. It is suggested that in arid phases, weathering and fluvial processes are more effective in liberating and transporting heavy minerals, while during "wet" or alluvial phases, the heavy minerals are more effectively concentrated.

An alternation between periods of intense ephemeral fluvial activity and perrenial flow may, therefore, be more important in placer formation than periods of either type of flow alone.

### 5) Humid tropical regions

The humid tropics are characterized by high temperatures, perennial stream flow and an ubiquitous vegetation cover. The extensive chemical weathering which dominates these regions has three significant effects:

i) weathering-resistant minerals are efficiently liberated from their host rocks ;

ii) a clay-particle dominated regolith is produced with relatively little coarse-sand or larger calibre material that might form the bedload in a river system ; and

iii) chemical denudation and mass solution of up to 40% of the bedrock occurs prior to any mechanical erosion of the bedrock (Thomas, 1974).

This last factor produces an enrichment in resistant minerals which is unmatched in any other morphogenetic zone. The combination of this *in situ* enrichment with the removal in suspension of the larger part of the fine particles of the regolith upon mechanical erosion, results in particularly favourable conditions for placer development.

Because vegetation cover inhibits the direct influence of mechanical erosional processes, it may be argued (e.g. Thomas, 1974) that placer deposits would show relatively little evidence of fluvial transport and be dominantly residual in nature in the humid tropics. The stanniferous placers of Banka and Billiton in Indonesia are of this kind, and they may be contrasted with the placers of the Malaysian peninsula and Thailand where there is evidence of greater fluvial transport of the cassiterite (Aleva, 1985).

Sutherland (1985) stated that much of the humid tropical zone has periodically experienced semi-arid conditions throughout the Quaternary. During such periods, fluvial activity may have been particularly efficient in transporting liberated heavy minerals. The return of humid conditions and consequent increase in vegetation cover would reduce sediment supply and encourage reworking of material introduced into the fluvial system during the preceding arid phase. Such a combination of circumstances might produce placer deposits of considerable extent.

## Conclusions - The Role Of Climatic Change

From the foregoing discussion of the five morphogenetic regions of Sutherland (op.cit.), the role of climatic change has been mentioned repeatedly as a key factor in the genesis of fluvial placers. This is because different climatic regimes produce environmental conditions which may be conducive to high degrees of weathering, erosion or fluvial transport, but not all three together.

Figure 12 is a schematic representation of how changes in the Earth's climate during the last 100 Ma have influenced the latitudinal distribution of the morphogenetic regions discussed above. Of course, this distribution is not merely a function of latitude, and the tectonic plate distribution has changed so that the further back in time one goes, the less reliably climate can be discussed with respects to the present latitudinal disposition of the continents. Futhermore, local climatic perturbations of the general latitudinal distribution, such as monsoons and orographic effects, are difficult to trace back in time (Frakes, 1979). Despite these factors, certain patterns do arise.

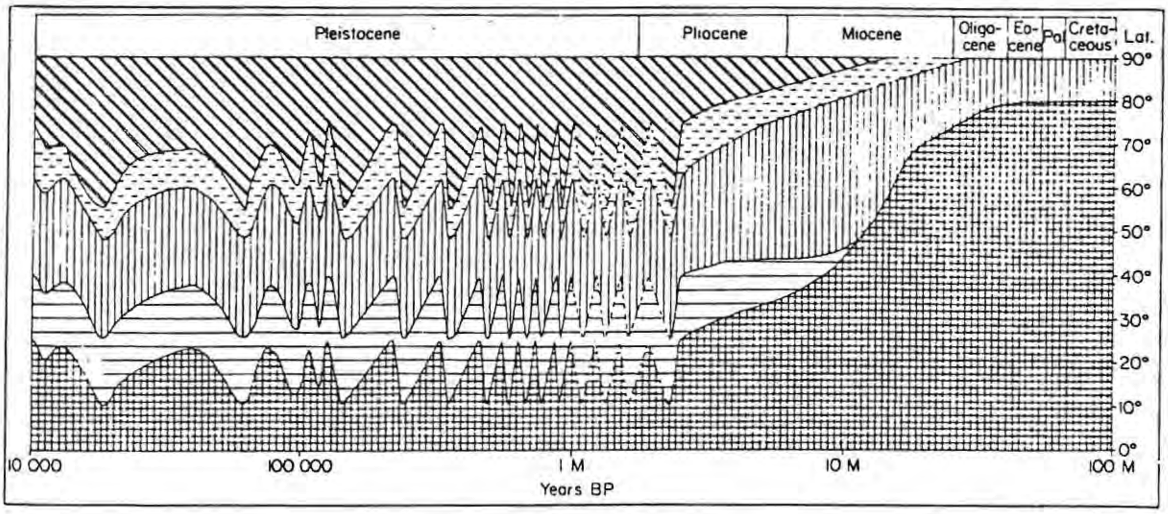


FIG. 12. Schematic representation of the variation in latitudinal distribution of morphogenetic regions during the last 100 Ma. Symbolism as in Fig. 6. Note logarithmic time-scale (after Sutherland, 1985).

During the latter part of the Cretaceous and the early Tertiary, humid tropical processes appear to have operated in mid- to - high latitudes, producing deeply weathered clayey regoliths (Dury, 1971 ; King , 1951 ; Partridge and Maud, 1987). Significant changes occurred in the mid-Tertiary as the climate shifted towards a regime characterized by a sequence of glacial and interglacial periods exhibiting a periodicity of around 0.1 Ma (Shackelton et al., 1984). These glacial cycles involve major climatic changes at all latitudes (Figure 12).

The widespread changes in conditions between periods of deep weathering, stripping and sediment reworking thus implied, suggest that the Quaternary is a period particularly suited to placer genesis.

### 2.3.2 Influence Of Basin Dynamics

The role of basin dynamics and tectonics in the formation of placers has been studied by Adams et al. (1978) in an experimental model of an alluvial drainage basin. The concept of geomorphic thresholds is mentioned in section 3.2.1 where it is noted that channel pattern (the basis on which rivers are classified) is controlled by slope thresholds, for a given discharge, within a fluvial system. This concept has great significance to the morphology of a drainage basin at times of tectonic uplift and drainage rejuvenation. Figure 13 shows how a meandering river first becomes incised, then braided, and finally stabilizes in response to a single rejuvenation event (in this case a lowering of base level).

A second concept of significance to the change in morphology of a drainage basin in response to rejuvenation, is that of complex response (Schumm, 1973 ; Schumm and Parker, 1973). The various components of a drainage basin (floodplain, hillslopes, divides, tributaries and main channel) respond at different times to rejuvenation as follows :

i) incision occurs firstly at the mouth of the system and moves progressively upstream. This process is responsible for successively

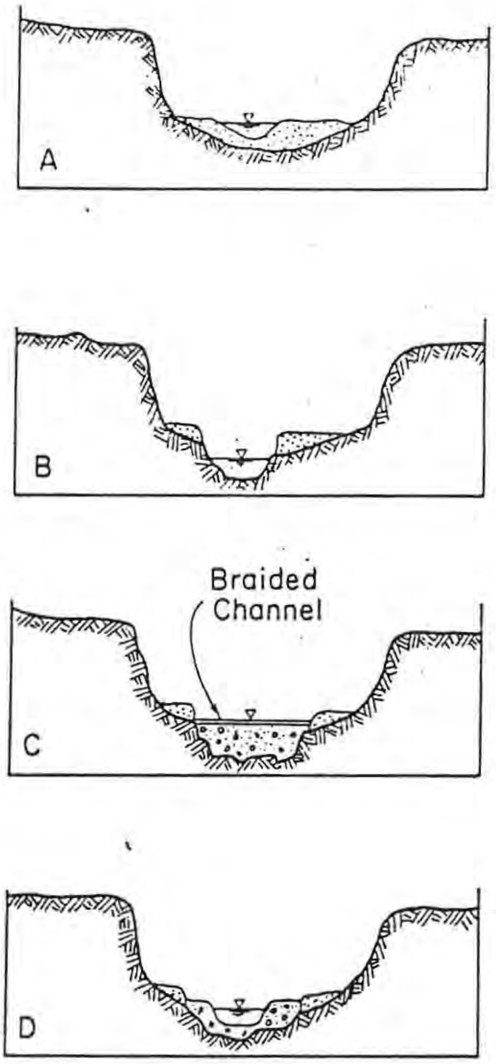


FIG. 13. Diagrammatic cross-sections of an experimental channel showing the response of a meandering channel to one relative lowering of base level.

A. Valley and alluvium prior to base-level lowering. The low width-depth ratio meandering channel flows on alluvium.

B. After base-level lowering, the channel incises into the alluvium and bedrock floor of the valley to form a terrace. Following incision, bank erosion widens channel and partially destroys terrace.

C. An inset alluvial fill is deposited as the sediment discharge from upstream increases. The high width-depth ratio channel is braided and unstable.

D. A second terrace is formed as the channel incises slightly and assumes a low width-depth ratio in response to reduced sediment load. With time, channel migration will destroy part of the lower terrace and a flood plain will form at a lower level. (After Adams et al., 1978).

rejuvenating tributaries, scouring pre-existing alluvium from the valley floor, and forming terraces (Figure 13B);

ii) as erosion progresses upstream, the main channel becomes increasingly choked with sediment and begins aggrading (Figure 13C);

iii) as the tributaries stabilize to the new base - level, sediment loads decrease, and a new phase of channel erosion occurs forming a low terrace (Figure 13D).

Thus, initial channel incision and terrace formation is followed by deposition of an alluvial fill, channel braiding, and lateral erosion. Then as the drainage system achieves stability, renewed incision forms a low alluvial terrace. But how do heavy minerals behave during such a rejuvenation event?

Adams et al. (op. cit.) derived an empirical model in which the processes involved in crossing geomorphic thresholds are superimposed on those involved in complex response as follows:

i) when the lower main channel is degrading (Figure 13B and D) heavy minerals are in transport. When aggrading (Figure 13C) the heavy minerals are stored in the alluvial fill;

ii) superimposed upon this sequence of heavy mineral transport and storage are shorter periods of transport and storage controlled locally by internal thresholds of gradient and discharge. During periods of aggradation, the channel is braided and heavy minerals are stored in the drainage basin. During periods of incision, the channel is meandering or straight, and heavy minerals are reworked and concentrated.

It is concluded that, whilst basin rejuvenation may initially destroy existing placers, conditions following rejuvenation are conducive to placer formation. Indeed placers may be formed during <u>alternating</u> periods of mild aggradation and degradation that result from the exceeding of the internal geomorphic thresholds which may follow rejuvenation.

The preservation of diamondiferous terraces on the Vaal and Orange Rivers in South Africa, and numerous other placer localities worldwide, indicate a response to base-level drop and consequent abandonment. At Auchas on the lower Orange River, terraces of Miocene age (dated with wood and mammal fossils) are currently mined for diamonds. Two distinct facies assemblages are recognised. The first is a valley fill sequence of channels and coarsening - upward sequences interpreted as braid bars. The second is a younger channel fill facies and is incised into the valley fill sequence. This facies assemblage can be interpreted as representing the product of a rejuvenation event, the valley fill sequence representing the aggradation phase (Figure 13C) and the channel fill sequence, the final incision phase (Figure 13D).

The Miocene age of the Auchas gravels corresponds to the uplift event cited by Partridge and Maud (1978) as being responsible for their Post-African I erosion cycle. Note that rejuvenation need not be in response to tectonic uplift, but may be due to a drop in base-level (a eustatic lowering of sea-level for example) as is suggested by Dingle and Hendey (1984) for the late Oligocene - early Miocene rejuvenation event in the western part of southern Africa.

### 2.3.3 Influence Of Bedrock Lithology

The nature of the bedrock influences the nature of sediment liberated into a drainage system, and hence the nature of the material with which heavy minerals must "compete" for transport and deposition. Many fluvial placers are associated with gravels for reasons outlined in section 2.4.2, and it follows that a bedrock which liberates coarse clasts is required by many fluvial placer-forming processes.

For example, consider the alluvial diamond deposits of the northern Cape and western Transvaal in South Africa (Figure 14). The alluvial diamond deposits are virtually confined to a bedrock of Ventersdorp Supergroup lithologies, comprising mainly andesitic lavas. These rocks are resistant

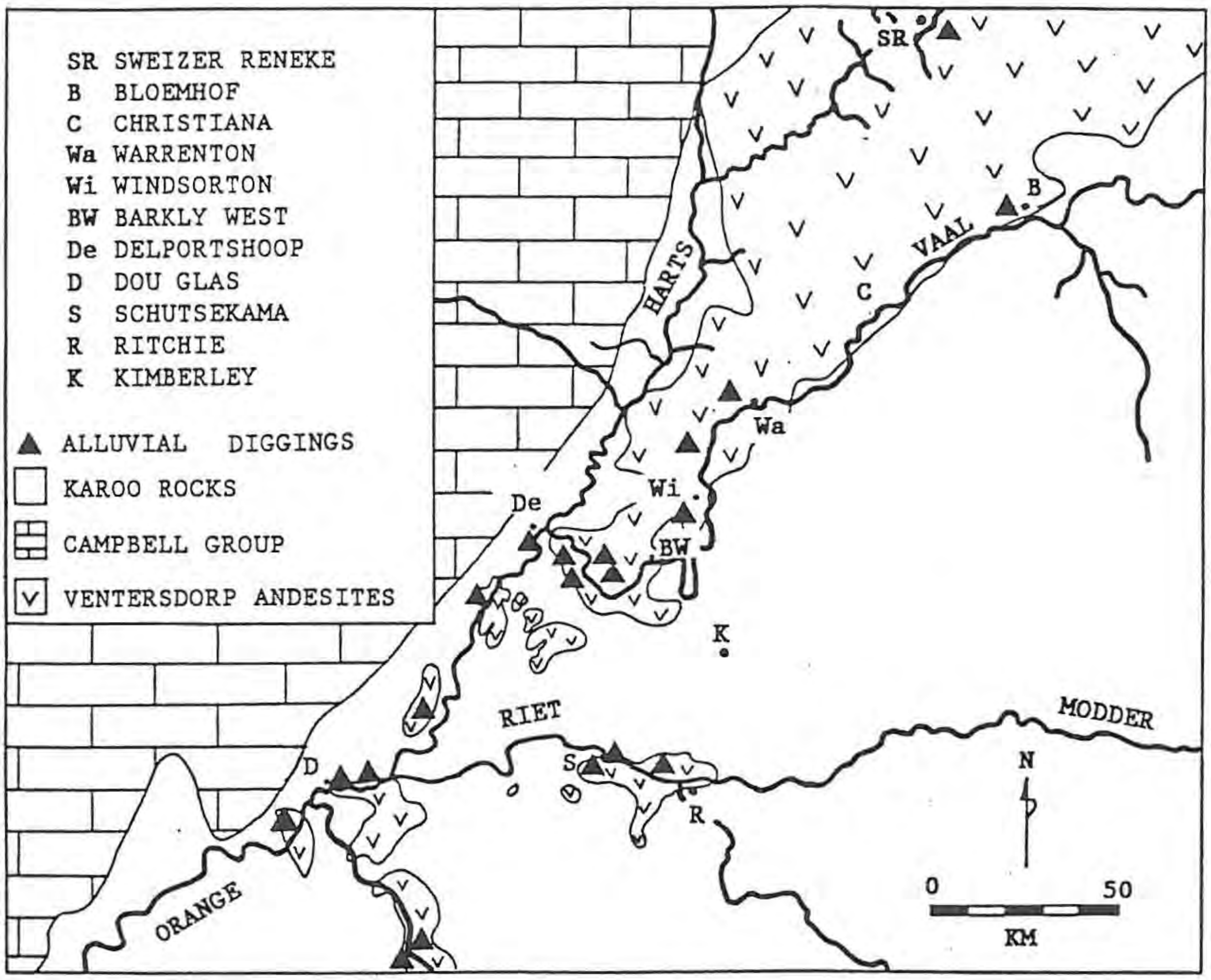


FIG. 14. Geological map showing the alluvial diamond deposits of the northern Cape and western Transvaal, South Africa. Note the association of deposits with Ventersdorp lava bedrock.

and weather spheroidally liberating clasts up to 2m in diameter into the Vaal/Orange drainge basin. The Karoo lithologies of shale, diamictite and dolerite produce relatively fine-grained sediments andplacers are almost absent over these lithologies. Two exceptions to this rule occur:

i) a short distance (up to 5 Km) downstream of Ventersdorp subcrop, placers still occur in coarse gravels transported onto Karoo bedrock ; and

ii) where Ventersdorp bedrock forms a topographic high (an exhumed pre-Karoo high) the drainage is always highly incised thus forming gorges. On the downstream side of such gorges, large alluvial fans have formed, which are the sites of some of the richest deposits.

Examples of the first case are found at Delportshoop, and of the second at Schutsekama (Figure 14).

## 2.4 GRAIN-SCALE CONCENTRATING PROCESSES

Concentrations of heavy minerals can only occur at sites where grain-scale processes dictate, and an understanding of concentrating processes at grain-scale is therefore a prerequisite for successful prospecting. Heavy minerals may be accumulated in either of two ways:

i) by hydraulic sorting (whereby heavy minerals accumulate essentially as lags) ; or

ii) by interstice entrapment.

In this section, these processes are reviewed.

### 2.4.1 Hydraulic Sorting

Rubey (1933) presented the first explanation of hydraulic sorting by defining mineral grains in terms of their settling equivalence with quartz. However, although his concept is useful, it only explains hydraulic equivalence where the grains in transport leave the bed regularly in a series of saltation leaps, or in a longer-lived state of suspension. In other words, where the sediment has the opportunity to fall through a column of water. In most fluvial situations, however, the transport of sediment is largely in the form of a traction carpet, in which cirumstance settling equivalence becomes unimportant as a sorting process. Accordingly, more recent papers (e.g., Slingerland, 1984 ; Reid and Frostick, 1985) have highlighted the importance of entrainment and dispersive equivalence in the concentration of heavy minerals in fluvial systems.

#### 2.4.1.1 Settling Equivalence

The settling velocities of grains immersed in water will depend upon their density if shape and surface texture are similar. Consequently, the size of grains that settle together on the bed will be an inverse function of their density. Figure 15 is a schematic illustration of the quartz settling equivalents of four heavy minerals. It can be seen that a spherical cassiterite grain has a diameter which is only 0.52 of its quartz equivalent (see Callaghan, 1979 for formulae). Gold, with a greater density contrast, has a settling equivalent diameter only 0.32 times that of quartz.

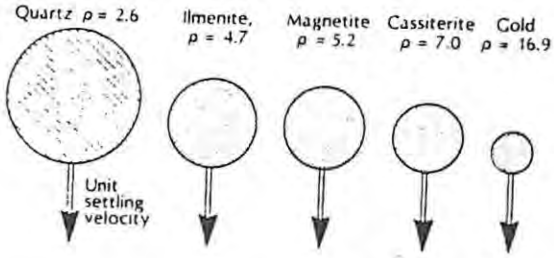


FIG. 15. Spheres of selected minerals that have the hydraulic settling equivalence of quartz. Values of density are given for each mineral (after Reid and Frostick, 1985).

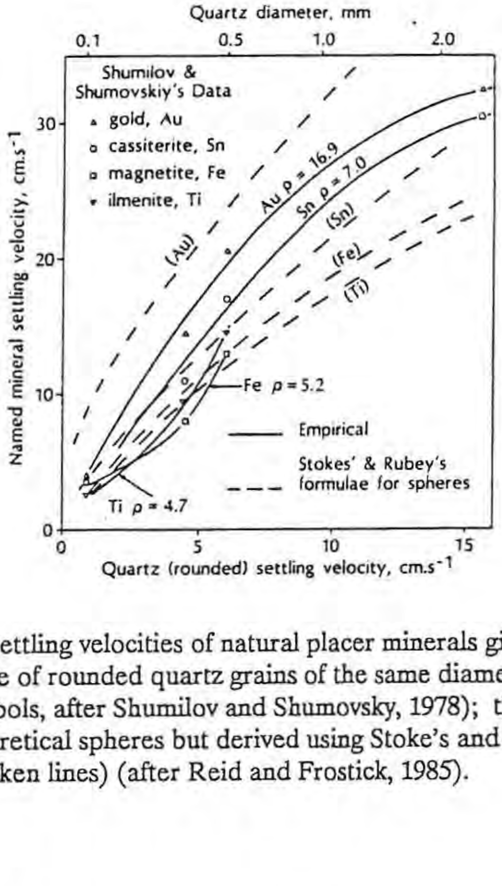


FIG. 16. Settling velocities of natural placer minerals given against those of rounded quartz grains of the same diameter (solid lines and symbols, after Shumilov and Shumovsky, 1978); the same for theoretical spheres but derived using Stoke's and Rubey's equations (broken lines) (after Reid and Frostick, 1985).

The expected fall velocities of spherical mineral grains in a fluid can be predicted by Stokes' (particles < 0.5mm) and Rubey's (> 0.5mm) equations:

STOKES' LAW for grains < 0.5mm ;

$$W = \frac{(\rho_1 - \rho_2)D_s^2}{\mu}$$

RUBEY'S LAW for grains > 0.5 mm ;

$$W = \quad 2/3g . \frac{\rho_1 - \rho_2}{\rho_2} . D_S$$

where, W = fall felocity, $\rho_1$ = specific gravity of mineral, $\rho_2$ = specific gravity of fluid,

$\mu$ = viscosity of fluid, and $D_S$

$D_s$ = grain diameter.

Detrital grains are, however, rarely perfect spheres. Surface irregularities increase the coefficient of drag which leads to a lowering of settling velocity. Elongate particles have lower coefficients of drag when oriented in the direction of fall, and consequently they have higher settling velocities than spheres of the same volume and mass. Empirical data for the settling of natural heavy minerals is compared to predicted values derived from Stokes' and Rubey's equations in Figure 16 (data from Shumilov and Skhumovsky, 1975). It can be seen that, as the density contrast increases, factors such as particle shape become more important in controlling sedimentation. Empirical and theoretical values for ilmenite, magnetite and cassiterite are fairly similar. Grains of gold on the other hand, have asettling velocity that is ony 60% of that predicted by the Stokes - Rubey equations over the range depicted. If follows that gold particles travelling in suspended load, should travel further than predicted by the equations. A complication arises in that malleable gold particles change shape during transport (Hallbauer and Utter, 1977). Gold is particularly susceptible to the effect of repeated impacts which tend to hammer irregularities flat over the first 30 Km or so of transport, thereby increasing settling velocity, and tending to promote sedimentation. Continued transport tends to produce flakes which have lower settling velocities and therefore tend to remain in suspension, with a consequent increase in transport distance.

Different settling velocities give rise to suspension sorting (Slingerland, 1984) which is the fractionation of grains with different settling velocities into different levels off the bed, in a turbulent , open-channel flow. This results in the deposition of suspended sediment in different areas and explains why heavy minerals are most common in the deepest parts of channels and least common on flood-plains (e.g., Muggeridge, 1989). It is suggested that suspension sorting may also govern the stratigraphic level of concentration of heavy minerals in fining-upward point-bar sequences which are the characteristic deposits of meandering river systems. Hence, the coarsest and heaviest minerals might accumulate at the bottom of the sequence, interpreted as the deepest part of the channel (e.g., Allen, 1964) while the finer and "lighter" heavy minerals would be deposited near the top of the sequence (e.g., de Wit, 1983). In a braided alluvial-fan environment, the coarsest and heaviest minerals might accumulate in the more proximal reaches, whilst the "lighter" and finer grained heavy minerals would continue in suspension to the more distal reaches (e.g., Matheys, 1990 ; McGowan and Groat, 1973).

#### 2.4.1.2 Entrainment Equivalence

It has long been recognised that the individual laminae of river deposits often consist of like-size and like-shape particles, regardless of density. This indicates a lack of settling equivalence for the light and heavy minerals in such a layer. In fact, the heavy minerals present are much larger than predicted by consideration of their quartz settling equivalence.

The operation of entrainment equivalence and its tendency to homogenize a sediment in terms of its size distribution has been observed on active beach bars that stand proud of the still-water level, and over which the swash rides as a shallow stream carrying material as bedload (Reid and Frosdick, 1985). Here, the size distributions of light and heavy mineral particles overlap (Figure 17a). Entrainment equivalence is the sorting mechanism, and the heavy minerals are on average, only 13% smaller than the quartz grains. In contrast, the size distributions of the bed material of submerged bars show a distinct size separation of light and heavy mineral particles (Figure 17b). Breaking waves ride over the submerged bar as a relatively deep turbulent flow, thus throwing sediment into suspension. The dominant process here involves settling equivalence, and on average the

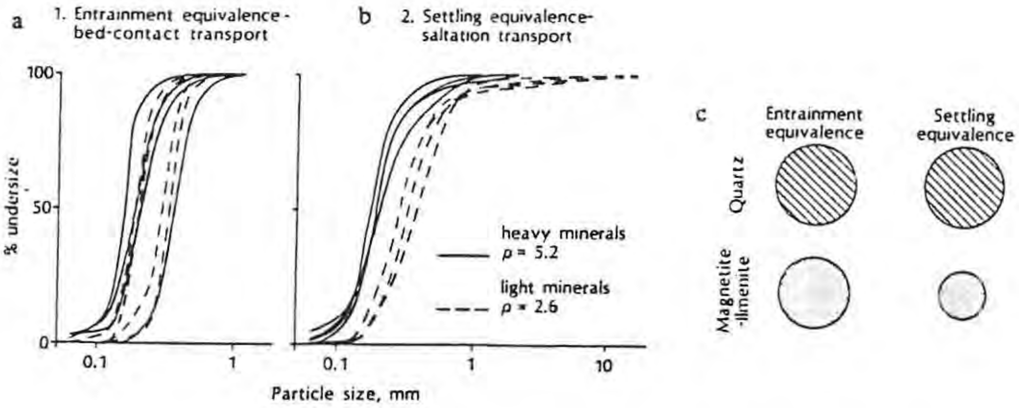


FIG. 17. Typical particle size curves for : a) light and heavy minerals on beach bars of Lake Turkana that stand proud of the still-water level and on which the swash rakes the surface as a shallow flow to produce entrainment equivalence ; and b) for those bars whose crest is just below the still-water level and where breaking waves throw bottom sediment into suspension to produce settling equivalence. c) Schematic relationship between the average median - sized quartz and magnetite - ilmenite particles on the two types of swash bar showing the difference in relative size of each mineral generated by the processes involving entrainment and settling equivalence (after Reid and Frostick, 1985).

diameter of heavy minerals is 40% smaller than that of associated quartz grains. Figure 17c shows schematically the relationship of the average median-sized quartz and magnetite-ilmenite particles on the two types of swash bar, and the relative sizes of each mineral generated by the processes involving entrainment and settling equivalence.

Komar and Wang (1984) have demonstrated that like-size particles congregate because larger particles are removed. They stand proud on the bed and by doing so, they are subject to greater lift and drag.

Because heavy mineral particles tend to dominante the finer fractions, it is these that remain on the bed while the larger, dominantly lighter grains are selectively entrained. This leads to the concentration of the higher density material. Adding to this is the effect of greater inertia inherent in the heavy minerals. Once settled on the stream bed, these particles require larger forces to dislodge them. This accounts for the small difference in size in entrainment equivalence between heavy and light minerals.

If an alluvial fill is scoured, either during a single flood event or as a result of longer-term down-cutting in response to local or regional rejuvenation (as described in section 2.3.2), the smaller and denser grains may be concentrated as a bedrock heavy mineral accumulation through the combined action of these winnowing and inertia-controlled processes.

Slingerland (1984) identified friction velocity (U*), grain diameter, grain density and bottom roughness size (k) as the important variables influencing sorting by differential entrainment. Increased bed roughness decreases transport rate and inhibits grain entrainment.

For example, for a mean friction velocity (U*) of 20.1 cm $s^{-1}$ at a roughness of 5mm, magnetite will not be transported ; if roughness reaches 10mm, the movement of quartz is restricted to particles of up to 0.84 mm diameter only. This suggests that the coarser the stream floor gravel environment, the greater the velocity required to mobilize the lighter minerals and thus concentrate heavy minerals amongst the gravel. Figure 18 shows the predicted concentrations of fine-grained magnetite under different U* and k conditions and for different magnetite concentrations.

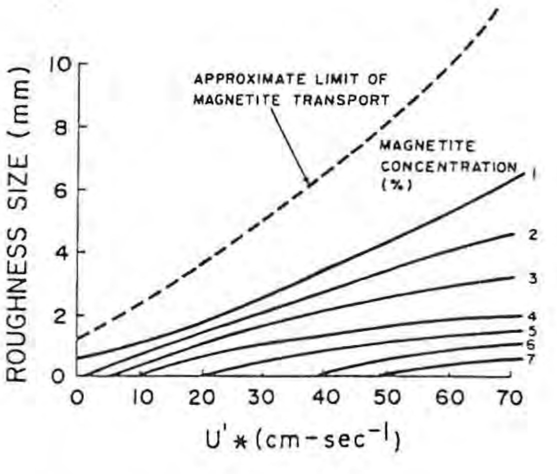


FIG. 18. Predicted magnetite concentrations in a transported sediment comprising 90% quartz and 10% magnetite with quartz mean grain size of 1.23 , and magnetite of 2:15 . Concentrations increase with increasing friction velocity U*, and decrease with increasing bed roughness K (after Slingerland, 1984).

Consider a further example of entrainment sorting. A deposit comprises 10% magnetite and 90% quartz. The mean size of the magnetite grains is smaller than the quartz grains, and their size distribution is better sorted. If this population comes to rest on a substrate with a bottom roughness nearer in size to the smaller, heavy grains, the larger lighter grains will be more susceptible to entrainment. Any lag deposit formed by subsequent flows will then consist of a heavily enriched lamination with a heavy to light settling velocity ratio greater than 1. If the bed roughness size is nearer in scale to the larger lighter grains, then the smaller heavy minerals, even though denser, may be entrained along with the finest of the light grains, as turbulent vortices pluck grains from among roughness elements. The resulting deposit will have a settling velocity ratio of less than 1 and will be less enriched in heavy minerals (Slingerland, 1977).

#### 2.4.1.3 Dispersive Equivalence

Dispersive equivalence of grains leads to shear sorting (Slingerland, 1984 ; Reid and Frostick, 1985). The grains of a sediment which is subjected to a shearing force (e.g., laminar flow), exert a dispersive stress normal to the direction of shear and proportional to the product of the square of grain diameter and density. If this law is applied to non-uniform sizes, it predicts that larger or denser grains will be driven to a free surface. Two grains with different densities coming to rest at the same horizon would have a size ratios given by:

$$\frac{d_n}{d_e} = \left(\frac{P_e}{P_h}\right)^{1/2}$$

Since experience shows that heavy minerals tend to dominate the finer fractions of a sediment (Blatt et al., 1972), the operation of dispersive stress may lead to a concentration of heavy minerals several grain diameters below the bed surface.

Whilst not dismissing the role of shear sorting in the genesis of placers, Komar and Wang (1984) found a wide range in dispersive stress, mineral by mineral, in each of their samples from a beach in Oregon. This leads to the conclusion that, if dispersive stress is of consequence, it is an ancillary process. Its role is to feed larger light-mineral grains to the top of the mobile layer where protrusion tends to promote entrainment as outlined previously.

### 2.4.2 Interstice Entrapment

As noted in section 2.3.3, alluvial gold and diamonds are often associated with coarse-grained deposits (e.g. Witwatersrand gold and Vaal River diamonds). The size contrast between heavy minerals and coarse framework is usually too great to invoke settling or entrainment equivalence to explain the genesis of these deposits. This suggests that such deposits were laid down during two distinct sedimentation events; the larger clasts during extreme flood events; the heavy mineral-bearing matrix, later (possibly during the waning stage of the flood).

Minter and Toens (1970) demonstrated experimentally that heavy minerals can move into the interstices of a simulated river gravel comprising an open framework of densely packed beds of pebbles. Furthermore, they found that the concentrations for heavy minerals in transported bed-loads is increased during passage across a layer of gravel. Smith and Minter (1980) provided convincing evidence of this process having occurred in the coarse-grained Witwatersrand "bankets" (pebble conglomerates). They showed that the conglomerates have concentrations of heavy minerals ten times greater than that of neighbouring sandstones, thus indicating their trap-site qualities. Figure 19shows the concentrations of gold and uranium in sand and gravel facies of a Witwatersrand palaeoplacer. The sandstones have, in general, much lower concentrations of the heavy grains.

A major control on the size of the material which passes into a stream-bed framework and forms a matrix, is the size distribution of the surface pores, i.e. the interstices of the surface, or armour layer. The largest pore dictates the maximum grain size of the matrix, and in the case of a closely packed framework this will be 0.4 times the median framework particle size. (Fraser, 1935).

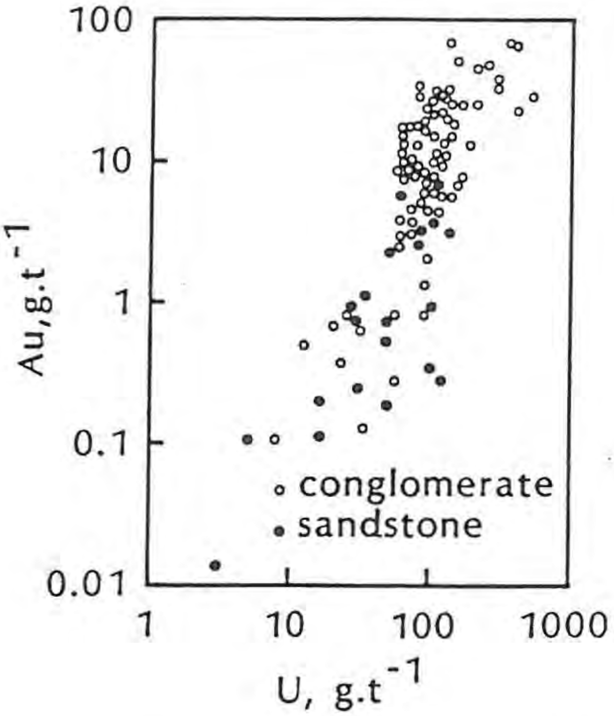


FIG. 19. Gold and uranium concentrations in crossbedded conglomerates and sandstones. Since the heavy minerals cannot be in hydraulic equivalence to the clasts of the conglomerate, the concentrating mechanism here is thought to involve interstice entrapment (after Smith and Minter, 1980).

Frostick et al., (1984) showed that the sub-armour framework also effects the quantity and size distribution of the matrix. In a fining-upward gravel bed in which the ratio of median particle diameter ($D_{50}$) of the armour layer to that of the sub-armour layer is about 0.5, the amount of matrix (and heavy minerals) will be over three times greater than that occurring in a coarsening upwards bed with an armour layer : sub armour layer size ratio of about 2 (Figure 20). This is explained by the fact that where the sub-surface pores are smaller than those of the armour layer (i.e. a coarsening-upward profile), there is a tendency for coarser matrix particles to lodge not far into the framework and thus clog the pores. Consequently, there may be a considerable amount of unfilled pore space below such a matrix plug. The heavy mineral concentrating process is then short-lived and such gravels are unlikely to be sites of preferential heavy mineral accumulation. Conversely, where gravels fine upwards, the pores

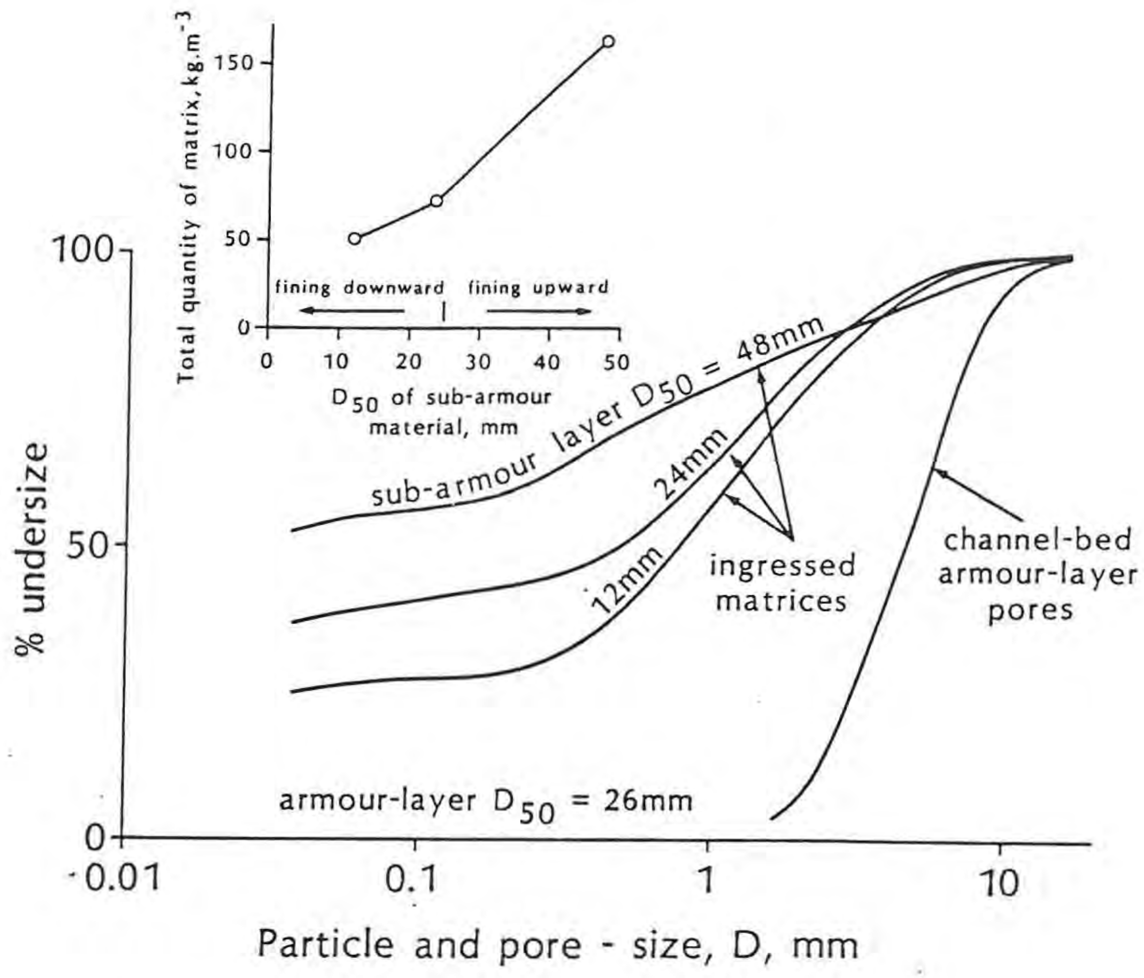


FIG. 20. Size distributions of both the armour layer pores, and of the ingressed matrices where the sub-armour layer framework particles are differentiated according to size, of a gravel-bed stream. The inset shows the total quantity of matrix that accumulates where the the bed sediment either fines or coarsens. $D_{50}$ refers to median clast size (after Frostick et al., 1984).

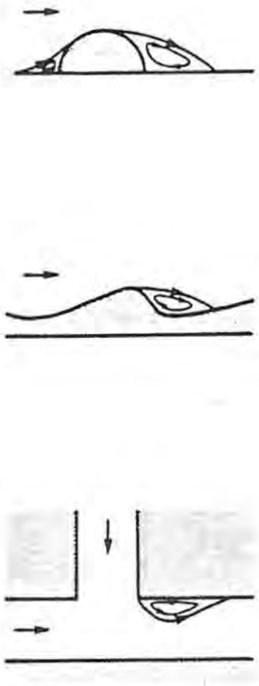
tend to be packed uniformly and over a longer period of time, and the opportunity for heavy mineral accumulation is therefore increased.

This process may explain the distribution of diamonds in the Vaal and Riet River gravels in the northern Cape Province of South Africa. Gravel profiles from the Vaal (Matheys, 1990) and Riet (Dawson, 1990) Rivers closely correspond to the proximal-to-distal facies sequences of alluvial fans (Collinson, 1986). Both sequences occur where the rivers emerge from the confines of a gorge. Both comprise a proximal facies of massive boulder-gravels, a mid-fan facies of interbedded gravels and sands,and a distal facies of coarse, trough-cross bedded pebbly sands. These alluvial fans represent the large-scale morphological features built up by bedload streams and they are characterised by a braided channel pattern. Matheys (op.cit.) noted a decrease in per carat value of diamonds from the Vaal River in a downstream direction, from the proximal facies at Gong Gong to the mid-fan facies at Delpoortshoop (Figure 14). This decrease is ascribed to a decrease in diamond size. A positive correlation exists between clast and diamond sizes suggesting that during the waning water stage of flood events, the largest diamonds were deposited with the coarsest and heaviest matrix in the proximal areas, and progressively finer stones were deposited further and further downstream. A fining-upwards profile has been noted in some of the basal gravel beds which would enhance accumulations as described above.

This model is not in conflict with that proposed by McGowan and Groat (1973) for the Precambrian Van Horn alluvial fan in west Texas. These authors found the greatest concentration of heavy minerals in the trough-cross bedded distal facies of the fan. However, these were relatively fine-grained ilmenite and magnetite grains which would have been carried in suspension by flood events. Matheys (op.cit.) also found abundant fine-grained heavy minerals (chiefly ilmenite) in the more distal facies of the Vaal River gravels.

### 2.4.3 The Role Of Flow Separation

The grain-scale processes of heavy mineral accumulation have been outlined above where it is suggested that particle size and shape are important factors influencing heavy mineral concentration. However, it is local flow dynamics that determine grain-by-grain sorting. A feature of free turbulent flows is the separation of fluids at sites where channel morphology changes (Best and Brayshaw, 1985). At these localities, positive pressure gradients cause the flow to separate from the boundary and radically distort the local flow field, providing opportunities for the processes of entrainment and dispersive sorting, as well as interstice entrapment, to operate. Fluid separation generates a region of high bed-shear stress that can entrain heavy minerals, and a region of low velocity which is a preferred site for the deposition of denser particles. This process may occur at a variety of scales (Figure 21).



| Geomorphological Scale (after Smith & Minter 1980) | Example |
|---|---|
| very small scale | flow around individual grains |
| small scale | flow over ripples & bars |
| intermediate scale | channel confluences<br>meander bends |

FIG. 21. Scales of flow separation in fluvial environments.

Consider first the smaller scale, whereby an obstacle such as a boulder lies in mid-channel. Figure 22 shows the resulting pattern of heavy mineral concentration derived in a flume experiment by Best and Brayshaw (op.cit). An explanation of this pattern may be found by reference to flow structure and fluid forces acting around the isolated obstacle. A dominant feature of flow in the obstacle's vicinity is the system of vortices generated by fluid separation. Three vortex systems are recognised : horseshoe ; trailing, and wake vortices (Figure 23). The pressure distribution on the stream bed will reflect the reorganization of flow which occurs as fluid passes an obstacle (Brayshaw et al., 1983). The most

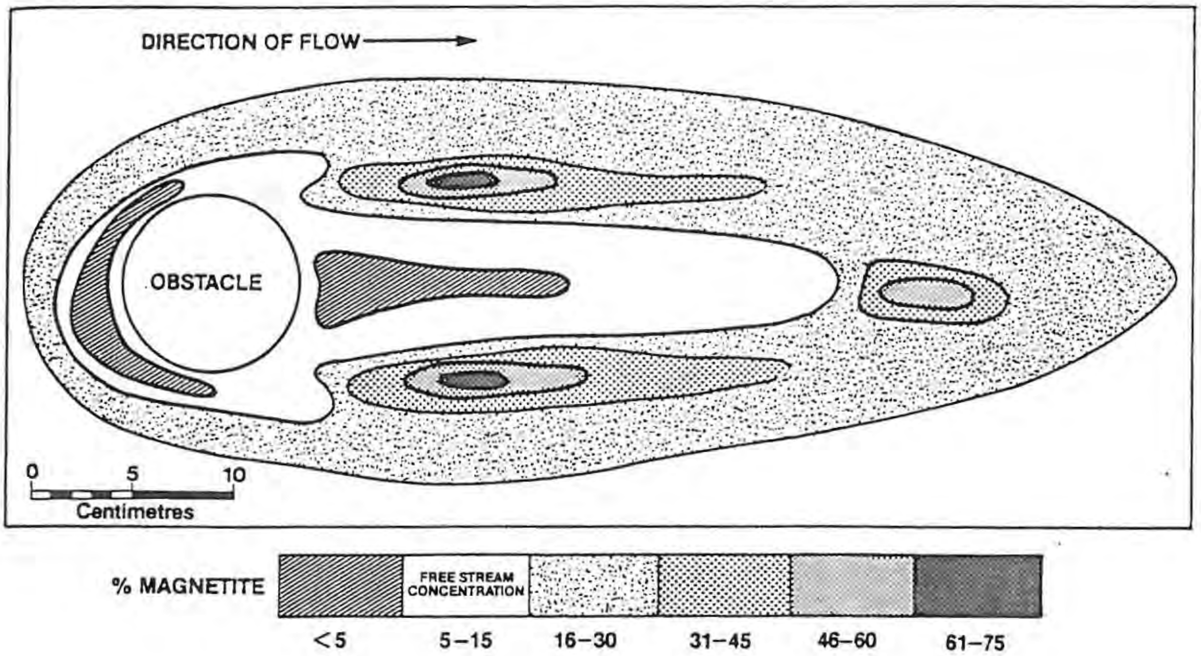


FIG. 22. Concentration of magnetite around an isolated obstacle clast recorded in flume experiments. Free-stream magnetite concentration is 9.0% (after Best and Brayshaw, 1985).

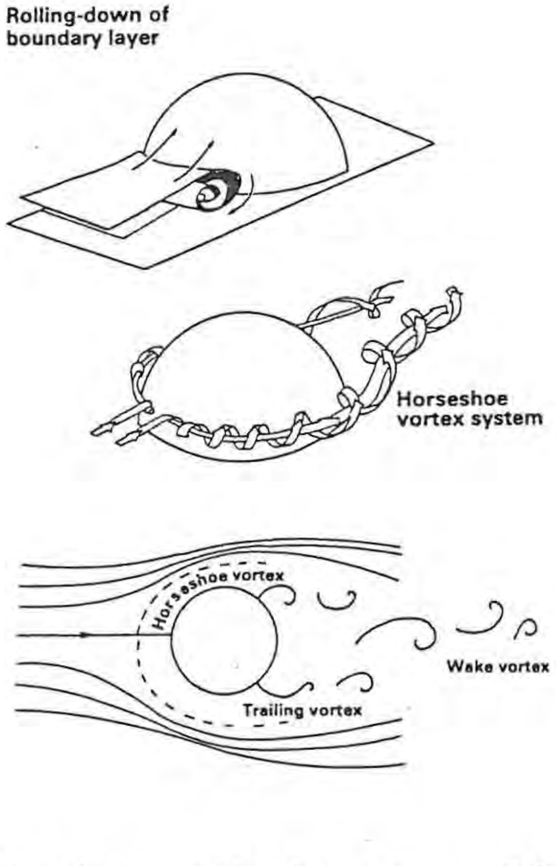


FIG. 23. Schematic representation of vortex systems associated with flow separation around an isolated hemispherical particle (after Best and Brayshaw, 1985).

important result is the generation of a large area of negative bed pressure in the lee of the obstacle. Modification of the flow also produces a complex pattern of flow velocities which exerts considerable control over sediment grain entrainment. The pattern of flow velocities is explained by pressure differences up- and down-stream of the obstacle. Close to the upstream face of the obstacle, fluid is decelerated. High flow velocities bound the wake region but are greatest in the shear layers developed on the obstacle"s flanks. Beyond the obstacle and its wake zone, fluid velocity returns to the free-stream value.

The areas of higher and lower pressures and velocities generated around the obstacles control the behaviour of higher and lower density grains such that sorting can take place. The areas of high concentration which bound the wake region are clearly related to the large fluid forces recorded immediately around the obstacle's flanks. The extremes of both velocity and turbulence will ensure supply of both heavy and light sediment grains to this zone. Downstream, rapid deceleration of fluid sorts the heavy and light minerals. Smaller, denser grains will be more resistant to tractive forces than larger, lower density grains. They will thus be concentrated by the hydraulic processes of settling and selective entrainment of lights. The area of turbulence and variable flow velocity associated with the point of free-stream reattachment (i.e. the point at which bed pressure rises to free-stream levels, immediatetly downstream of the wake of the obstacle) also concentrates heavy minerals (Figure 22).

Zones where heavy minerals are deficient reflect areas of low fluid velocity. For instance, the magnitude of lift and drag may be insufficient to draw grains into the low pressure wake zone. Only lighter grains, which are characterised by lower entrainment thresholds, are carried into such areas, so that their concentration increases above background levels.

Flow separation may also occur at larger scales (Figure 21), for example at a channel confluence. Figure 24 shows the relative concentration of magnetite at an experimental channel confluence with a ratio of tributary channel discharge : main channel discharge of 1.05. The bed morphology

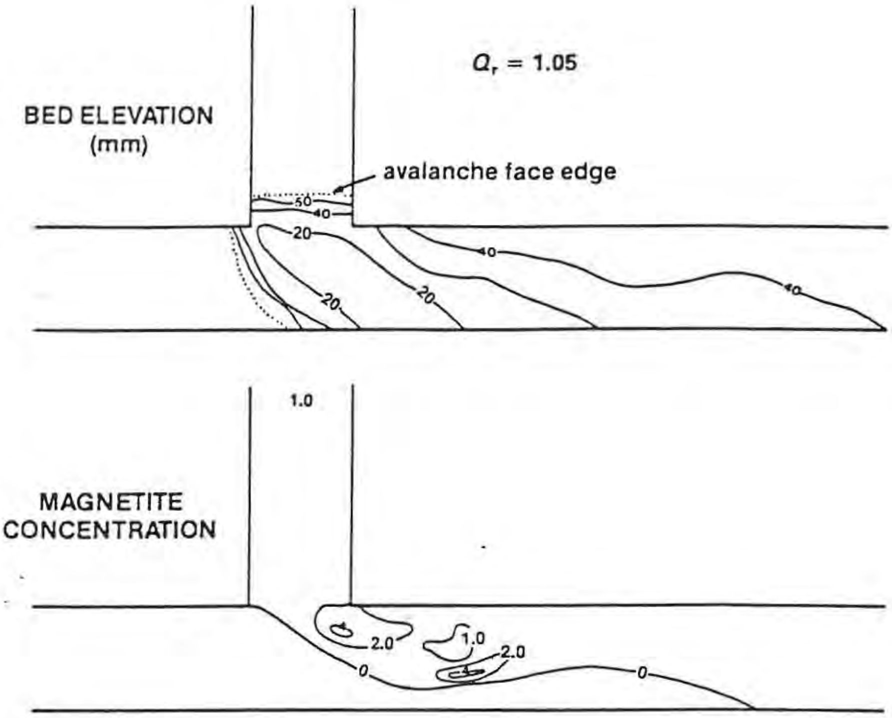


FIG. 24. Bed elevation and magnetite isopleth maps at a channel confluence. Discharge ratio ($Q_r = Q_t/Q_m$, where $Q_t$ = tributary channel discharge and $Q_m$ = main channel discharge) is 1.05. Magnetite concentration is expressed as a ratio with the background concentration of the free stream (after Best and Brayshaw, 1985).

comprises three dominant elements : a central scour ; avalanche faces at the mouth of each channel ; and a bar below the downstream junction corner. It is around the flanks of the bar that significant quantities of magnetite accumulate (Best and Brayshaw, 1985). This pattern of accumulation may again be explained by the distortions of the local flow field caused by flow separation, and the associated processes.

At the downstream corner of the channel junction, a large zone of slowly recirculating separated flow occurs (Best and Reid, 1984). This zone is associated with fluid pressures and velocities that are much lower than the surrounding flow (Figure 25). Additionally, a strong shear layer is formed that bounds the separation zone, and along which powerful vortices are generated. The vortices are responsible for the turbulent character of the flow, engendering close similarities to the characteristics of flow around an isolated obstacle, described above.

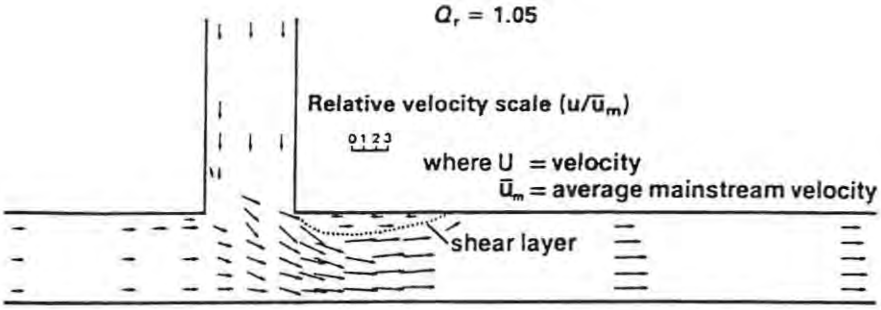


FIG. 25. Near-bed relative velocity vectors at a discharge ratio of 1.05 measured in sediment-free channels. Velocities were measured at a distance above the bed of 0.12 y/Y where y = height of a point in the flow and Y = flow depth (after Best and Brayshaw, 1985).

Flow separation produces two loci for the concentration of heavy minerals. Firstly, the shear layer that bounds the separation zone (Figure 25) induces the necessary shear stresses to provide a lag of heavy minerals by selective entrainment of coarse, light mineral grains. Secondly, the separation zone provides an area of low pressure and shear stress which determines paths of transported grains. It also provides an area of accumulation.

Heavy mineral grains entering the main channel from the tributary, are deflected by the main stream (see vectors in Figure 25). The majority of sediment grains are supplied to a narrow transport zone at the downstream junction corner. Higher density grains are entrained along the shear layer, but heavy minerals are deposited in an area of rapidly decreasing shear stress within the separation zone. Best and Brayshaw (op.cit) found that concentrations of heavy minerals increases with increasing tributary discharge - main channel discharge ratio.

It may be concluded that at both small and intermediate geomporphological scales, flow separation creates a zone of low-pressure, low-velocity fluid which is bounded by powerful shear layers along which vortices are generated. The following consequences are inferred for heavy minerals :

i) turbulent shear layers can provide the shear stresses necessary to entrain and maintain transport of heavy minerals ;

ii) the path of the fluid towards the separation zone carries entrained heavy minerals into an area of lower shear stresses ; and

iii) the area of low-pressure, low velocity separated fluid provides a region of low shear stresses in which lighter minerals are selectively entrained and heavy minerals are concentrated.

It is probable that flow separation is an important process in producing hydrodynamic environments suitable for the operation of grain-scale concentrating processes not only in the situations decribed, but also many others including the following:

- in the lee of negative rock steps (e.g. Muggeridge, 1989) ;
- on the downstream side of ripples, dunes and bars (e.g. Smith and Minter, 1980)
- in bedrock hollows and potholes (e.g. Matheys, 1990) ;
- at channel expansions (e.g. Lidstone, 1981) ; and
- at tight meander bends (e.g. Leeder and bridges, 1975).

## PART 3 DEVELOPMENT OF GEOLOGIC MODELS FOR EXPLORATION

The previous section discussed the influence of tectonic setting, geomorphology and grain-scale processes in controlling the distribution of detrital heavy minerals. In order to develop geologic models for exploration, the consequences of these influences may be considered in terms of heavy mineral accumulation at different scales. The areal concentration of heavy minerals may be classified into four categories which broadly correspond to the spatial scales at which these influences dominate (Table IV). The scales of accumulation are :

a) continental scale ($\sim 10^6$m) ;

b) system (large) scale ($\sim 10^4$m) ;

c) bar (intermediate) scale ($\sim 10^2$m) ; and

d) bed (small) scale ($\sim 10^0$m).

These scales of concentration are hierarchical. An example might be a gold-rich layer on a foreset (d) forming on a channel bend (c) in the distal part of a braid - complex (b) in a cold non-glacial morphogenic region of Alaska (a). This classification may be used as a predictive tool for exploration target selection, and also for reconnaissance-, detailed-, and evaluation-stage sampling. For example, an exploration company is looking for an alluvial gold deposit. They might start with broad-scale target selection (a) and then home-in to a geomorphically promising area (b). Field teams might then search for the best trap-sites for the collection of samples (c and d). Exploration applications are now discussed from the broader to finer scale.

| | CONTROLS | | | |
|---|---|---|---|---|
| SCALE | TECTONIC SETTING | CLIMATE | BASIN DYNAMICS | GRAIN-SCALE PROCESSES |
| CONTINENTAL | ——— | ——— | | |
| LARGE (SYSTEM) | — — | ——— | ——— | |
| INTERMEDIATE (BAR) | | ——— | ——— | |
| SMALL (BED) | | | — — | ——— |

### CONTINENTAL SCALE ($10^6$m)

| | |
|---|---|
| Tectonic settings | (Boyle, 1979) |
| Morphogenic regions | (Sutherland, 1985) |

### SYSTEM SCALE ($10^4$m)

| | |
|---|---|
| Proximal parts of alluvial fans | (Matheys, 1990; Dawson, 1990) |
| Distal parts of alluvial fans | (McGowan and Groat, 1973) |
| Regional angular unconformities | (Minter, 1978; Els, 1991) |
| Regions of suitable bedrock | (this work, Fig. 14) |

### BAR SCALE ($10^2$m)

| | |
|---|---|
| Heads of mid-channel bars | (Smith and Minter, 1980; de Wit, 1983) |
| Heads of distal point bars | (de Wit, 1983) |
| Bedrock riffles and potholes | (Matheys, 1990; Toh, 1978) |
| Sharp bends | (Leeder and Bridges, 1975) |
| Channel confluences | (Best and Brayshaw, 1985; Mosley and Schumm, 1977) |
| Winnowed tops of bars | (McGowan and Groat, 1971) |

### BED SCALE ($10^0$m)

| | |
|---|---|
| Leeward side of obstacles | (Best and Brayshaw, 1985; Lidstone, 1981) |
| Dune and ripple crests | (McQuivey and Keefer, 1969; de Wit, 1983) |
| Dune foresets | (McGowan and Groat, 1971) |
| Scoured bases of trough cross-strata sets | (McGowan and Groat, 1971). |

TABLE IV. Some observed sites of alluvial heavy mineral concentration drawn from the literature, and the key influences which control this distribution at the different scales.

## 3.1 TARGET SELECTION

On the broadest scale, areas favourable for placer development may be identified by the coincidence of favourable aspects including :

i) tectonic setting and occurrence of primary mineral sources ;

ii) the nature and distribution of climatically controlled morphogenic regions ; and

iii) the variation and intensity of specific landforming processes during the last 100 Ma (Sutherland, 1985).

Figure 26 shows those areas in which there is a coincidence of these factors with regard to gold, diamonds and tin. They are areas that should be most favourable to the production of placers and, in fact, they do incorporate zones in which major placer deposits have been found. Examples include the extensive alluvial diamond diggings of Sierra Leone in west Africa (Thomas et al., 1985), and the gold placers of eastern Sumatra in south-east Asia (Toh, 1978). They are also regions in which stream sediment sampling would be most efficient as a mineral exploration

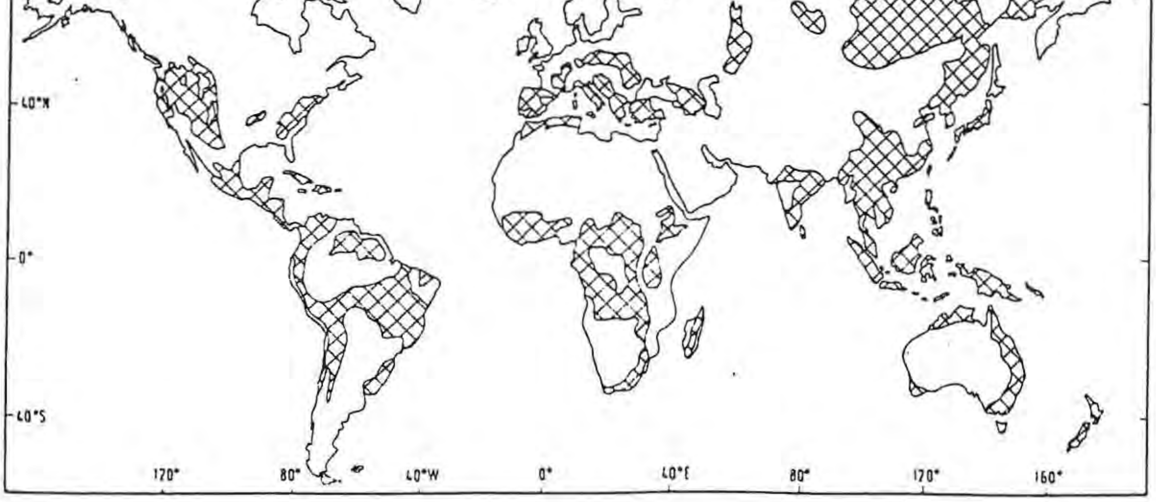


FIG. 26. Areas favourable to placer development in the last 100 Ma (after Sutherland, 1985).

Not all significant placer deposits are included within the regions identified in Figure 26, largely because of climatic change since the time of their formation. In the Vaal River basin of South Africa, over 10 Mct. of alluvial diamonds have been recovered. It is now known that the major period of diamond transport from the Kaapvaal craton to the west coast of South Africa was during the Miocene, as evidenced by the vertebrate assemblage collected at Arrisdrift on the lower Orange River (van Wyk and Piennar, 1986 ; Corbett, 1989). At present, the kimberlite diamond sources in the Vaal River basin are typically sealed by calcrete duricrusts and there is little release of diamonds into the present drainage. It is therefore clear that target areas may be selected on the basis of studies of palaeogeomorphology, which might indicate periods of heavy mineral liberation, transport, reworking and concentration (e.g., Partridge and Maud, 1987 ; Corbett, 1989 ; Thomas et al., 1985 ; de Wit, in prep.).

## 3.2 LOCAL TARGET SELECTION

Local target selection will depend largely upon the type of fluvial system under consideration. A number of prospecting models are presented based upon the criteria discussed in previous sections. The models are specific to classes of fluvial systems, since each class is characterized by a particular assortment of morphological and process parameters. It is therefore pertinent to briefly outline various types of rivers prior to presenting the models. Note that rivers evolve in response to tectonic and climatic changes and therefore may change their character with time.

### 3.2.1 Classification Of Rivers

The underlying causes which produce different types of rivers involve a complex interaction of a number of factors. These include flow, channel geometry, sediment load, bed roughness and climate (Leopold and Wolman, 1957). Because of this complexity, rivers are usually classified on a descriptive rather than a genetic basis. The classification of Miall (1977) recognises four principal river types ; meandering, braided, straight and anastomosing (Figure 27). His system is shown in Table V.

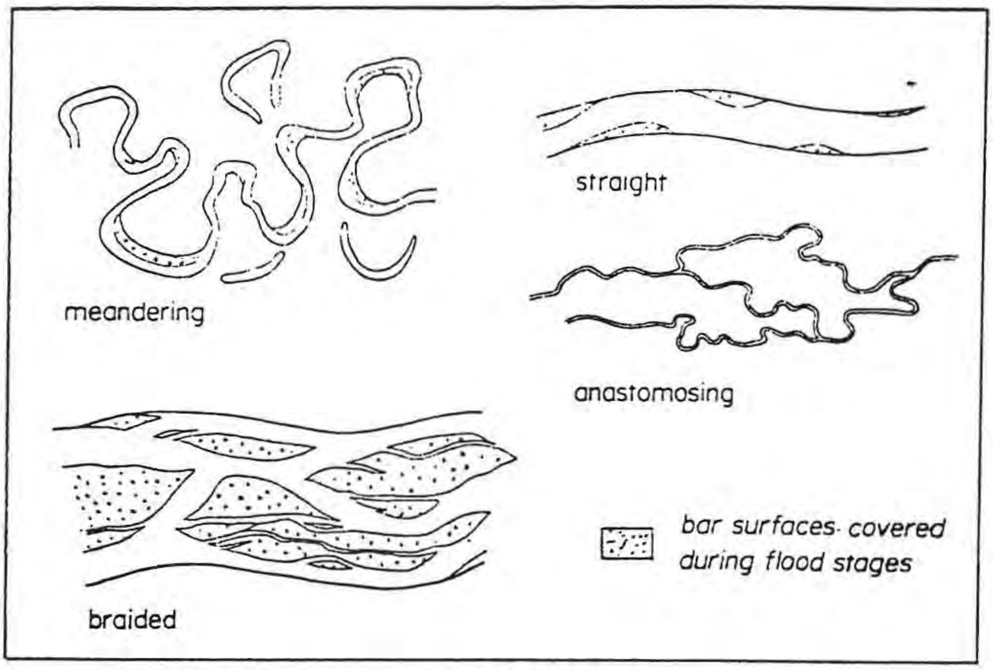


FIG. 27. Principal river types (after Miall, 1977).

The scheme is not entirely satisfactory since the classes are not mutually exclusive, being based on slightly differing criteria. For example braiding refers to multiple channels separated by alluvial islands or bars, whereas meandering refers to sinuous channels (Figure 27). It is thus possible to have a braided channel bed within a meandering channel system. Such complexities are, however, rare. Braided streams are generally wide and shallow with nearly straight channel systems, and meandering streams tend to be relatively deep and narrow and are thus seldom braided. Cross-sections of braided, meandering and straight channels are shown in Figure 28.

Truly straight channels are uncommon in aggrading rivers. They occur most often in degradational (downcutting) settings and therefore seldom provide opportunity for the preservation of their deposits. Anastomosing rivers have received little attention in the literature although Smith and Smith (1980) recognised recent examples from Alberta, and Smith and Eriksson (1979) described probable examples from a Permo-Carboniferous proglacial

| Type | Morphology | Sinuosity | Load type | Bedload per-cent (of total load) | Width/depth ratio | Erosive behaviour | Depositional behaviour |
|---|---|---|---|---|---|---|---|
| Meandering | single channels | >1.3 | suspension or mixed load | <11 | <40 | channel incision, meander widening | point-bar formation |
| Braided | two or more channels with bars and small islands | <1.3 | bedload | >11 | >40 | channel widening | channel aggradation, mid-channel bar formation |
| Straight | single channel with pools and riffles, meandering thalweg | <1.5 | suspension, mixed or bedload | <11 | <40 | minor channel widening and incision | side-channel bar formation |
| Anastomosing | two or more channels with large, stable islands | >2.0 | suspension load | < 3 | <10 | slow meander widening | slow bank accretion |

TABLE V. Classification of river types (after Miall, 1977).

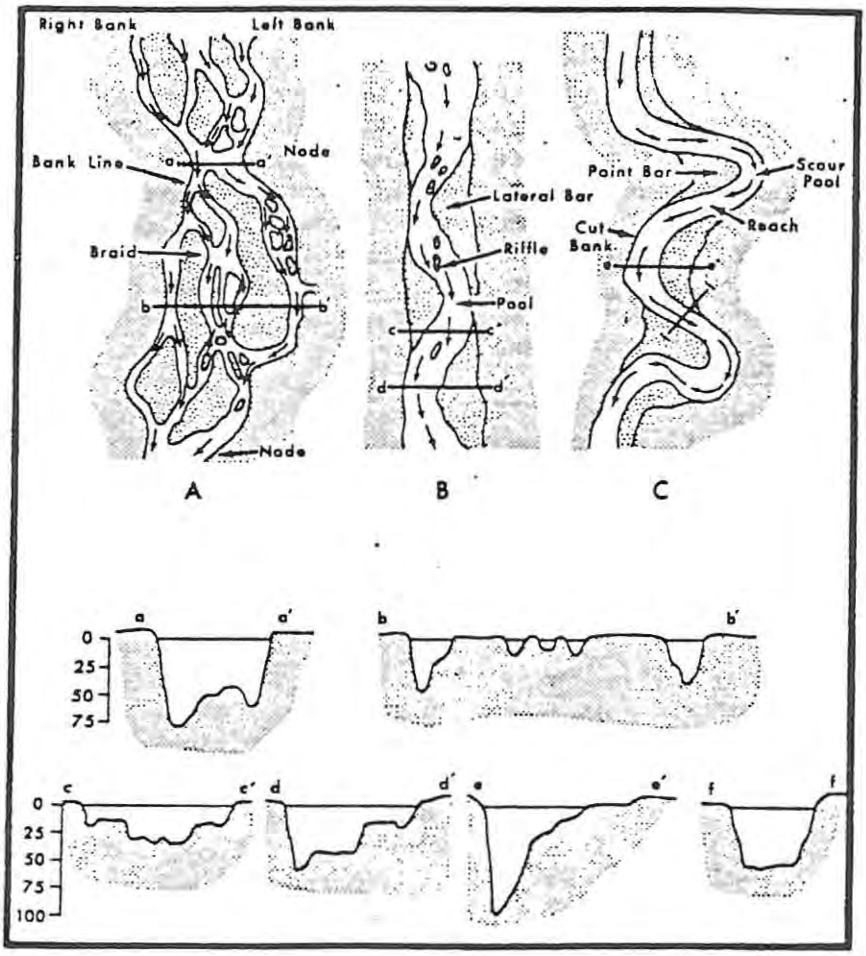


FIG. 28. Typical channel patterns and cross sections in braided (A), straight (B) and meandering (C) reaches of the Brahmaputra River (after Coleman, 1969).

sequence in South Africa. Braided and meandering streams have been emphasized by fluvial sedimentologists as the dominant deposit-forming river types.

Leopold and Wolman (1957) have shown that an empirical relationship exists between channel slope, bankfull discharge and channel pattern (Figure 29). For a given bankfull discharge, braiding is favoured by high slopes, and meandering by low slopes. For a given channel slope, braiding is favoured by larger bankfull discharges and meandering by lesser bankfull discharges.

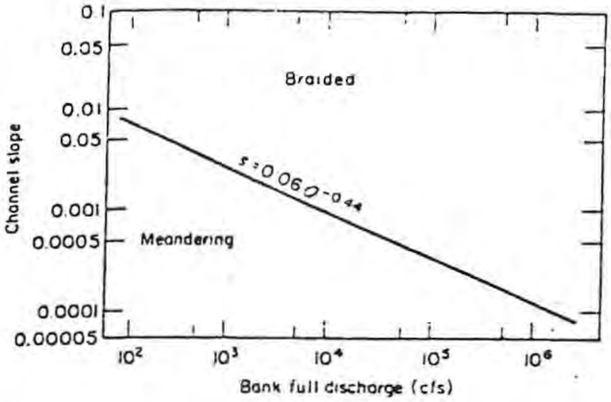


FIG. 29. The relationship between bank-full discharge and channel slope. Braiding is favoured by high slopes and meandering by low slopes. For a given channel slope, braiding is favoured by high discharges, and meandering by lower discharges. Discharges shown in cubic feet per second. 1 cfs ~ 2.8 x $10^{-2}$ $m^3s^{-1}$. (After Leopold and Wolman, 1957).

Braided river systems are favoured over meandering systems for heavy mineral concentration because of their gravel-dominated alluvium and associated fluvial process. In fact Collinson (1986) refers to braided systems as "bedload streams", indicating that the coarser grain-sizes dominate the associated deposits. This assertion is borne out by consideration of the fact that the majority of economic alluvial placers and paleoplacers are associated with the deposits of braided streams. Examples include the diamondiferous gravels of the northern Cape (Dawson, 1990) and the Witwatersrand gold (Minter, 1978) in South Africa, and the stanniferous placers of Ranong Province, Thailand (Aleva et al., 1973).

Alluvial fans are large-scale morphological features built up by bedload streams and they are usually characterized by braided stream patterns. They develop where the stream emerges from the confines of a valley or gorge into a basin. Lack of confinement allows horizontal expansion of the flow, deceleration and deposition of some or all of the sediment load.

Basins into which fans build are quite variable in character. They may be alluvial plains, broad valleys, inland drainage basins or bodies of standing water. The latter case may be termed a "fan delta". There is generally a down-fan reduction in slope, commonly associated with a decrease in the maximum clast size.

### 3.2.2 Alluvial Fan Prospecting Model

McGowan and Groat (1973) have produced an alluvial fan prospecting model for fine-grained gold based on the distribution of other heavy minerals in the Van Horn sandstone of west Texas. They noted that fine-grained heavy minerals (mainly ilmenite and magnetite) occur throughout the fan, but are concentrated in the distal-fan facies where sedimentation units are thin. There is a close spatial association between heavy mineral accumulations and trough crossbeds.

Minter (1978) developed this model in his synthesis of the heavy mineral distribution within the Witwatersrand palaeoplacers. Gold and uranium occur in braided river environments in the mid-fan to distal facies of wet alluvial fan-complexes. Gold concentrations are highest in a strike-parallel band across the fans, between 4 and 10 Km from the entry front (Figure 30). The gold here is mostly concentrated in pebble-supported conglomerates with a maximum clast size of between 2 to 4 cm. The highest uranium values are displaced 2 Km down the palaeoslope (Figure 30). This spatial distribution is controlled largely by the size of heavy and light minerals available. Generally, the clast size of alluvial fans decrease exponentially downslope (Collinson, 1986). It is therefore reasonable that given the source size distributions, and the differential rates of heavy mineral comminution, a strike-parallel band of accumulation would be formed where the ratio of local mean heavy mineral size to local mean light mineral size was appropriate for heavy mineral deposition either by interstice entrapment (more proximally) or by entrainment sorting (more distally). This point would be shifted down palaeoslope for uraninite compared to gold because its lesser density would demand a smaller light mineral entrainment equivalence. The location of this band within the palaeodepositional system might be predicted if the initial settling velocity distributions of the gold were known.

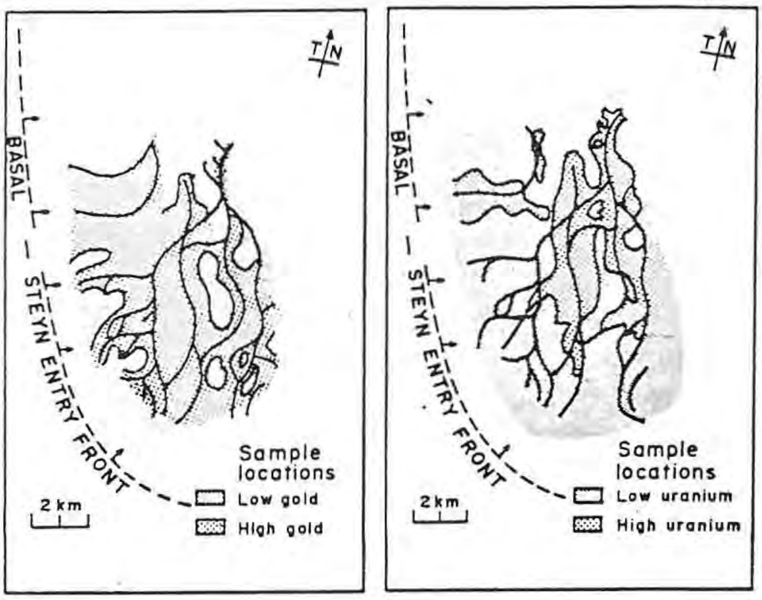


FIG. 30. Heavy mineral enrichment at the system scale. The Steyn and Basal placers of the Witwatersrand goldfield have high gold concentration occurring sourceward of high uranium concentrations. This is a function of the sizes of light and heavy minerals available, and the average roughness size and friction velocities down the fans. (Modified after Minter, 1978).

Frostick and Reid (1985) draw attention to the fact that at the heads of fans, coarse-grained deposits act as natural sieves for the entrapment of saltating heavy minerals. The efficacy of interstice entrapment will decline away from the apical zones of alluvial fans because of the decrease in grain size. Because of the rapid flow associated with these areas, only coarse heavy minerals (larger diamonds, or gold nuggets for example) might be accumulated here (e.g. Matheys, 1990).

Figure 31 is an adaptation of McGowan and Groat's (1973) original alluvial fan prospecting model which takes into account these aspects.

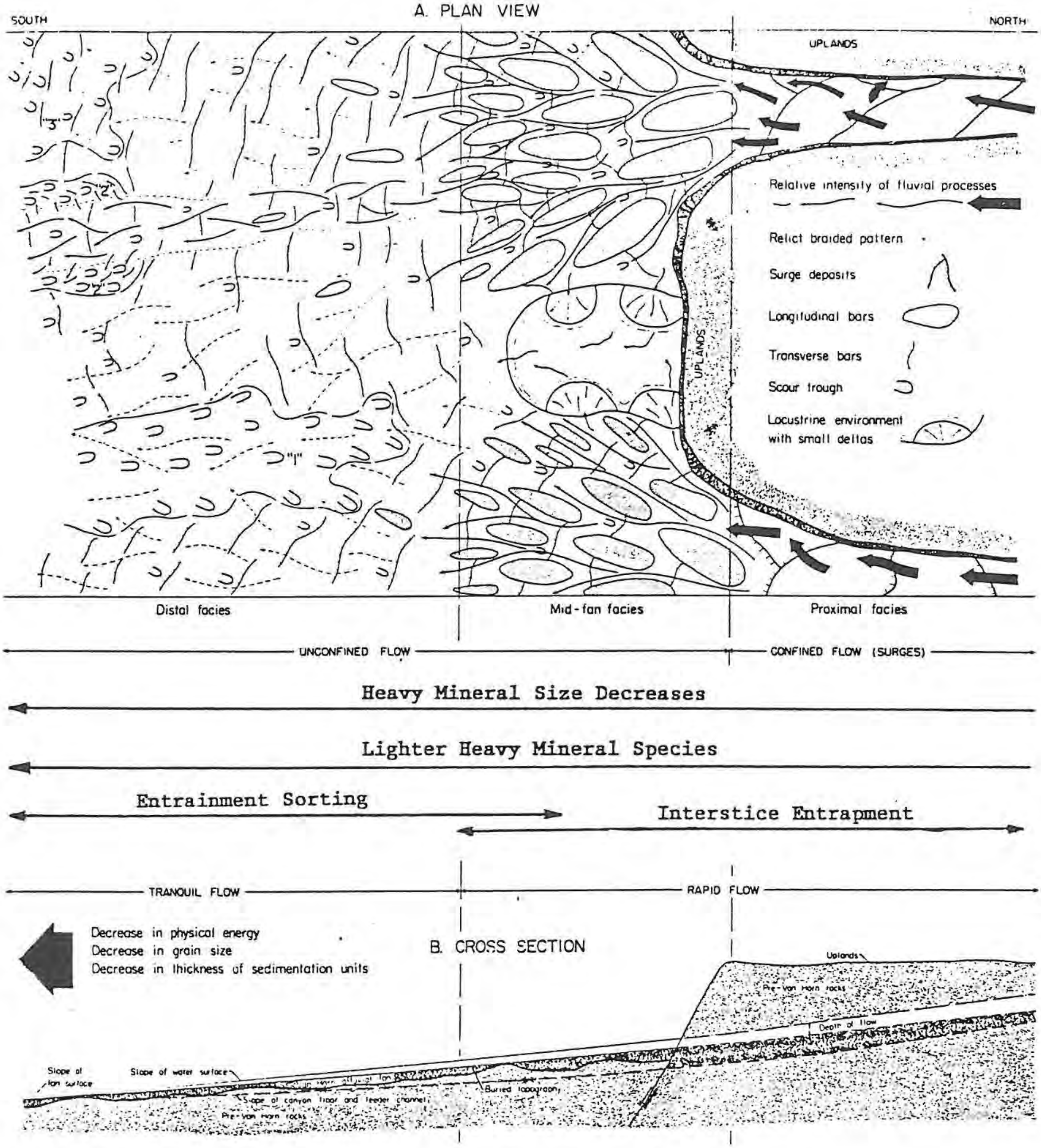


FIG. 31. Alluvial fan prospecting model (modified after McGowan and Groat, 1973).

### 3.2.2 The Braided Stream Prospecting Model

The alluvial fan prospecting model of Figure 31 shows that heavy mineral grain sizes decrease in the down-fan direction, the coarse-grained heavy minerals being concentrated by interstice entrapment, the fine-grained, mainly by processes of hydraulic equivalence. Minter (1978) showed that this trend may be extended to braided systems generally. The Steyn palaeoplacer provides the longest, most extensively accessible, palaeoslope exposure available in the Witwatersrand Basin and affords an ideal opportunity to examine facies and associated changes in the heavy mineral population, related to the decrease in hydraulic energy down the palaeoslope.

Pyrite nodules occur together on foreset planes, trough bottoms and winnowed surfaces, implying that they were deposited by processes of hydraulic equivalence. Figure 32 shows the grain-size decrease down the palaeoslope exhibited by these nodules. The size frequency distribution of sample 1 in Figure 32 appears to be bimodal, possibly as a result of coarse nodules being concentrated in the more proximal regions by interstice entrapment.

Miall (1978) presented a broad classification of the faciesassemblages present in gravel- and sand-dominated braided river deposits (Table VI). This classification is presented graphically in Figure 33 in the form of six vertical profile models for braided stream deposits. Table VII is a list of the lithofacies codes used in Table VI and Figure 33. From the previous discussion, the following inferrences may be made regarding the qualities of the different lithofacies for the concentration of heavy minerals.

- in general, heavy minerals will be associated with G- and S- type lithofacies only, as these mainly represent channel deposits, and suspension sorting (section 2.4.1.1) dictates that heavy minerals tend to congregate in the deeper parts of channels ;

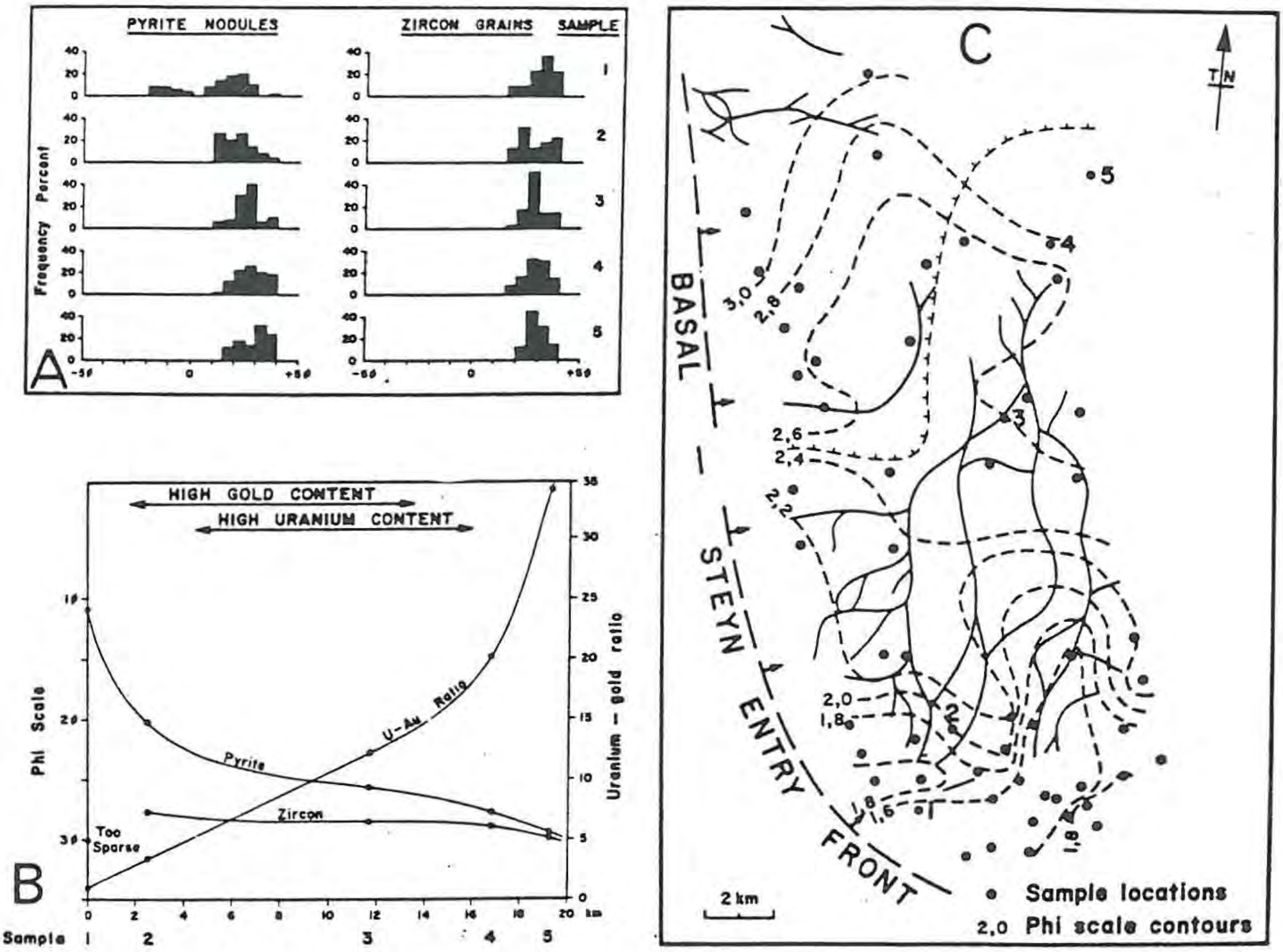


FIG. 32. Size distribution of detrital heavy minerals in the Steyn palaeoplacer of the Witwatersrand gold fields. A : Size frequency distribution of pyrite nodules and zircon grains at five locations distributed down 20 Km of palaeoslope. B : The size relationship between pyrite and zircon is the inverse of that predicted by their S.G. (S.G. of pyrite = 5 ; S.G. of zircon = 4.65) and reflects a lack of coarse zircons in the source area. C : Contours of the mean size of pyrite nodules reveal the palaeoslope dispersal of the Steyn palaeoplacer, and the more distal nature of the Basal palaeoplacer. (After Minter, 1978).

- the Gms facies (representing debris flow deposition) is unlikely to contain heavy minerals, unless resedimented from a pre-existing placer, because its deposition neither involves significant hydraulic sorting processes, nor allows for post-depositional ingression of heavy minerals into an open framework ;

| **Name** | **Environmental setting** | **Main facies** | **Minor facies** |
|---|---|---|---|
| Trollheim type ($G_I$) | proximal rivers (predominantly alluvial fans) subject to debris flows | *Gms, Gm* | *St, Sp, Fl, Fm* |
| Scott type ($G_{II}$) | proximal rivers (including alluvial fans) with stream flows | *Gm* | *Gp, Gt, Sp, St, Sr, Fl, Fm* |
| Donjek type ($G_{III}$) | distal gravelly rivers (cyclic deposits) | *Gm, Gt, St* | *Gp, Sh, Sr, Sp, Fl, Fm* |
| South Saskatchewan type ($S_{II}$) | sandy braided rivers (cyclic deposits) | *St* | *Sp, Se, Sr, Sh, Ss, Sl, Gm, Fl, Fm* |
| Platte type ($S_{II}$) | sandy braided rivers (virtually non cyclic) | *St, Sp* | *Sh, Sr, Ss, Gm, Fl, Fm* |
| Bijou Creek type ($S_I$) | Ephemeral or perennial rivers subject to flash floods | *Sh, Sl* | *Sp, Sr* |

TABLE VI. The six principal facies assemblages in gravel- and sand- dominated braided river deposits (after Miall, 1978). Lithofacies codes as in Table VII.

- the Gm facies is generally the most suited to the process of interstice entrapment, to produce potentially coarse-grained heavy mineral-bearing sieve deposits. The Gt and Gp facies may also be suited to this process ;

- the S-type lithofacies might most often be suited to the concentration of heavy minerals by processes involving hydraulic equivalence, especially entrainment sorting ;

- the classification of Miall (1978 ; Figure 33, Table VI) is structured from the proximal types, which would tend to contain greater concentrations of coarser heavy minerals, to the distal types with finer heavy minerals.

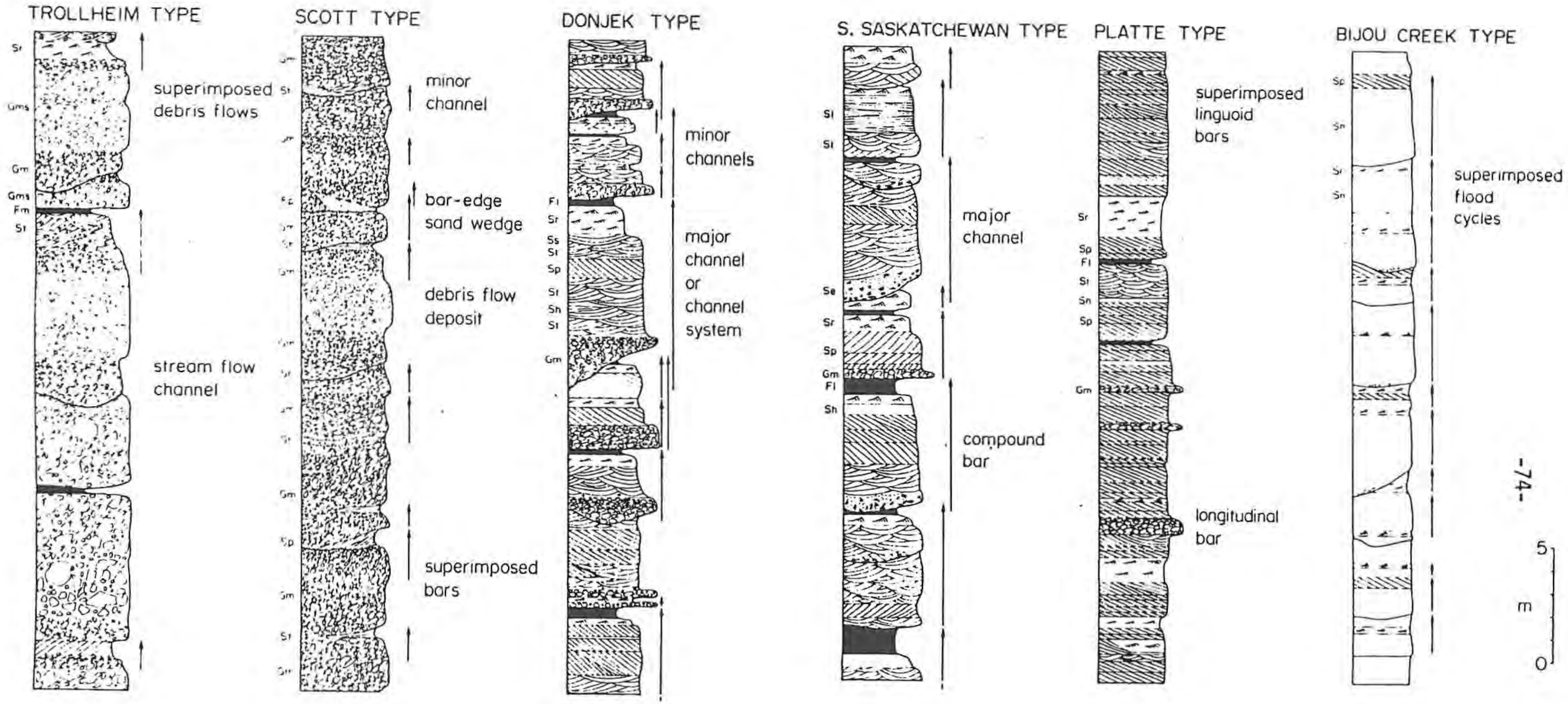


FIG. 33. Vertical profile models for braided stream deposits. Facies codes to left of each column are given in Table VII. Arrows show small-scale cyclic sequences. Conglomerate clasts are not shown to scale. (After Miall, 1978).

| Facies Code | Lithofacies | Sedimentary structures | Interpretation |
|---|---|---|---|
| *Gms* | massive, matrix supported gravel | none | debris flow deposits |
| *Gm* | massive or crudely bedded gravel | horizontal bedding, imbrication | longitudinal bars, lag deposits, sieve deposits |
| *Gt* | gravel, stratified | trough crossbeds | minor channel fills |
| *Gp* | gravel, stratified | planar crossbeds | linguoid bars or deltaic growths from older bar remnants |
| *St* | sand, medium to v. coarse, may be pebbly | solitary (theta) or grouped (pi) trough crossbeds | dunes (lower flow regime) |
| *Sp* | sand, medium to v. coarse, may be pebbly | solitary (alpha) or grouped (omikron) planar crossbeds | linguoid, transverse bars, sand waves (lower flow regime) |
| *Sr* | sand, very fine to coarse | ripple marks of all types | ripples (lower flow regime) |
| *Sh* | sand, very fine to very coarse, may be pebbly | horizontal lamination, parting or streaming lineation | planar bed flow (l. and u. flow regime) |
| *Sl* | sand, fine | low angle (<10°) crossbeds | scour fills, crevasse splays, antidunes |
| *Se* | erosional scours with intraclasts | crude crossbedding | scour fills |
| *Ss* | sand, fine to coarse, may be pebbly | broad, shallow scours including eta cross-stratification | scour fills |
| *Sse, She, Spe* | sand | analogous to *Ss, Sh, Sp* | eolian deposits |
| *Fl* | sand, silt, mud | fine lamination, very small ripples | overbank or waning flood deposits |
| *Fsc* | silt, mud | laminated to massive | backswamp deposits |
| *Fcf* | mud | massive, with freshwater molluscs | backswamp pond deposits |
| *Fm* | mud, silt | massive, desiccation cracks | overbank or drape deposits |
| *Fr* | silt, mud | rootlets | seatearth |
| *C* | coal, carbonaceous mud | plants, mud films | swamp deposits |
| *P* | carbonate | pedogenic features | soil |

TABLE VII. Lithofacies and sedimentary structures of modern and ancient braided stream deposits (after Miall, 1978).

### 3.2.4 Meandering Stream Prospecting ModeL

Channel sinuosity is the normal response of a stream to variations in the resistance of bed- and wall rock formations. It provides a mechanism for absorbing excess stream energy by lengthening the flow paths, thus reducing gradients and increasing friction losses. With respect to heavy mineral transportation and sorting, placer accumulations are restricted, on empirical observation, to streams having sinuosities of less than 1.5 (sinuosity is defined as the ration of thalweg lenth to down-valley distance; Macdonald, 1983). This is probably because highly sinuous streams are too sluggish to transport significant quantities of heavy minerals. Many field investigations suggest that the main, active flow-channel is an important horizon for concentration of heavy minerals whilst flood level areas seem less favourable (e.g. Muggeridge, 1989). This is presumably because of hydraulic sorting processes (see section 2.4.1.1). In an aggrading meandering stream, the most channel sediment is deposited on point bars on the inner part of the curved channels (Smith, 1980). Accordingly point bars constitute the major depositional sites for heavy minerals.

Jensen and Bateman (1979) noted that "placer deposits do not form in the downstream meanders of sluggish, old-age streams, because the stream velocity is insufficient to transport heavy minerals." Kartashov (1970) also noted that the more proximal reaches of rivers were more favourable to placer development, and that finer, and lighter heavy minerals would be transported to, and concentrated at, less proximal sites than coarser and heavier heavy minerals. Thus gold placers might be expected to form close to source, while rutile, ilmenite, zircon and monazite will continue to be transported over considerable distances, leading to their major concentration in coastal regions (e.g., Richard's Bay, South Africa).

The coarsest fractions are deposited in the deepest parts of the channel and the finer sediments in the shallower, upper part of the point bar. As the channel migrates laterally (by erosion of the outer bank), the point bar likewise accretes laterally, forming a tabular deposit that fines upwards. In most cases, the bed-forms are dunes in the deepest part of the channel, and ripples in the shallower upper portion. Hence point-bar deposits show an upward change from large-scale to small-scale cross-stratification as well as a grain-size decrease.

De Wit (1983) discovered that the highest concentrations of fine-grained heavy minerals occurs on the ripple crests on the upstream top surface of distal point bars. Allen (1964) recognised coarser lags in the troughs of cross-beds from the deepest parts of meandering channels of the Devonian Old Red Sandstone in Wales.

Figures 34 and 35 show an exploration model for heavy minerals in a meandering system, based on these aspects.

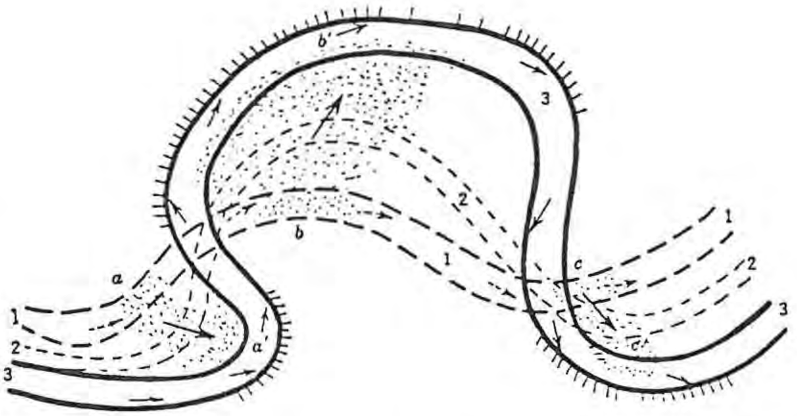


FIG. 34. Meandering stream prospecting model. Gravel deposition and formation of pay streaks in a rapidly flowing meandering stream, in which meanders migrate laterally and downstream. Stream arrows indicate point of cutting.
1, original position ; 2, intermediate position ; and 3, present position of stream. Deposits formed at a, b, c, or at inside of meanders of stream 1, become extended downstream and laterally in direction of heavy arrow to $a^1$, $b^1$ and $c^1$ on the present stream, and buried pay streaks result. (After Jensen and Bateman, 1979).

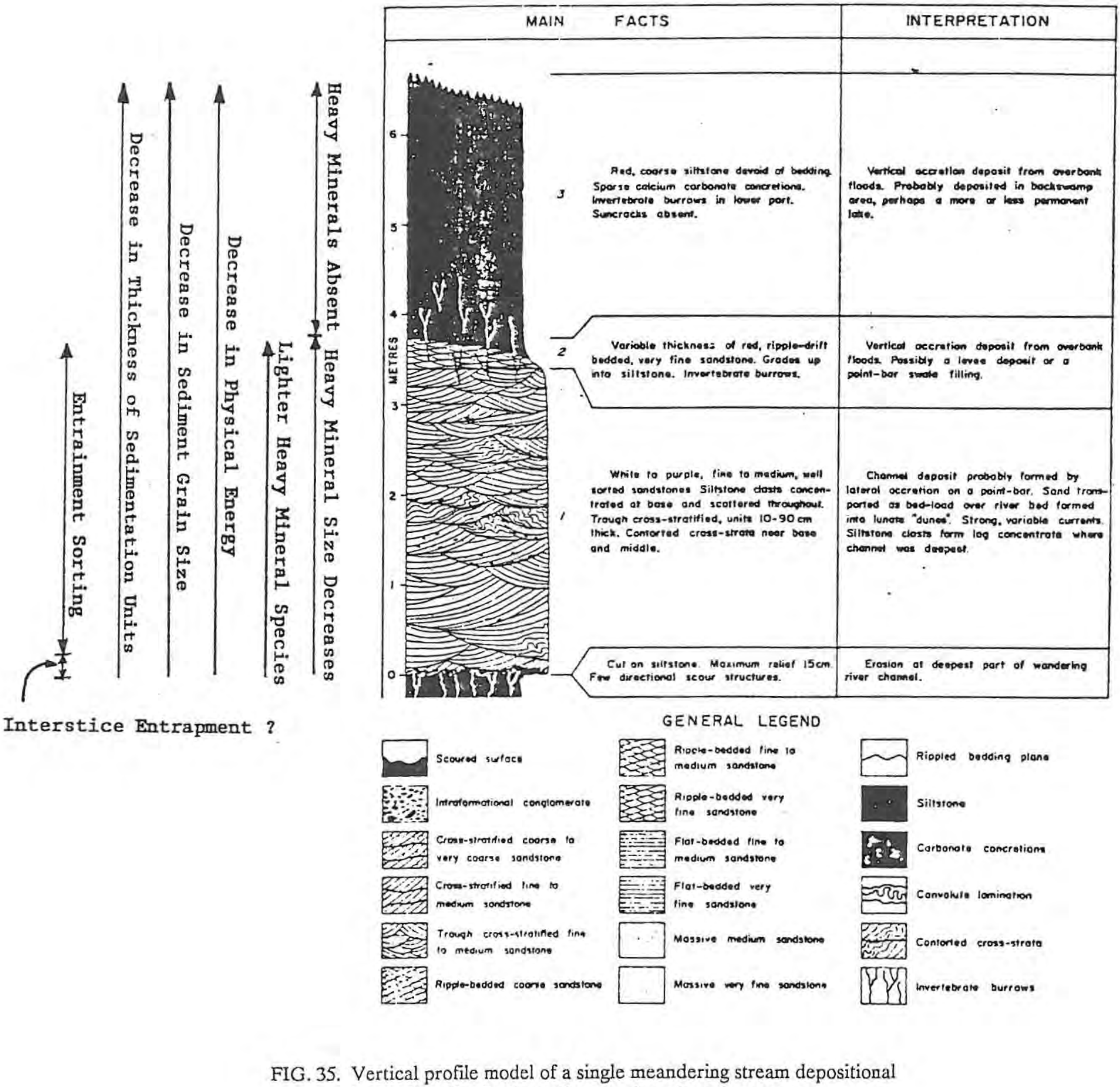


FIG. 35. Vertical profile model of a single meandering stream depositional cycle showing distribution of heavy minerals and processes. (Modified from Allen, 1964).

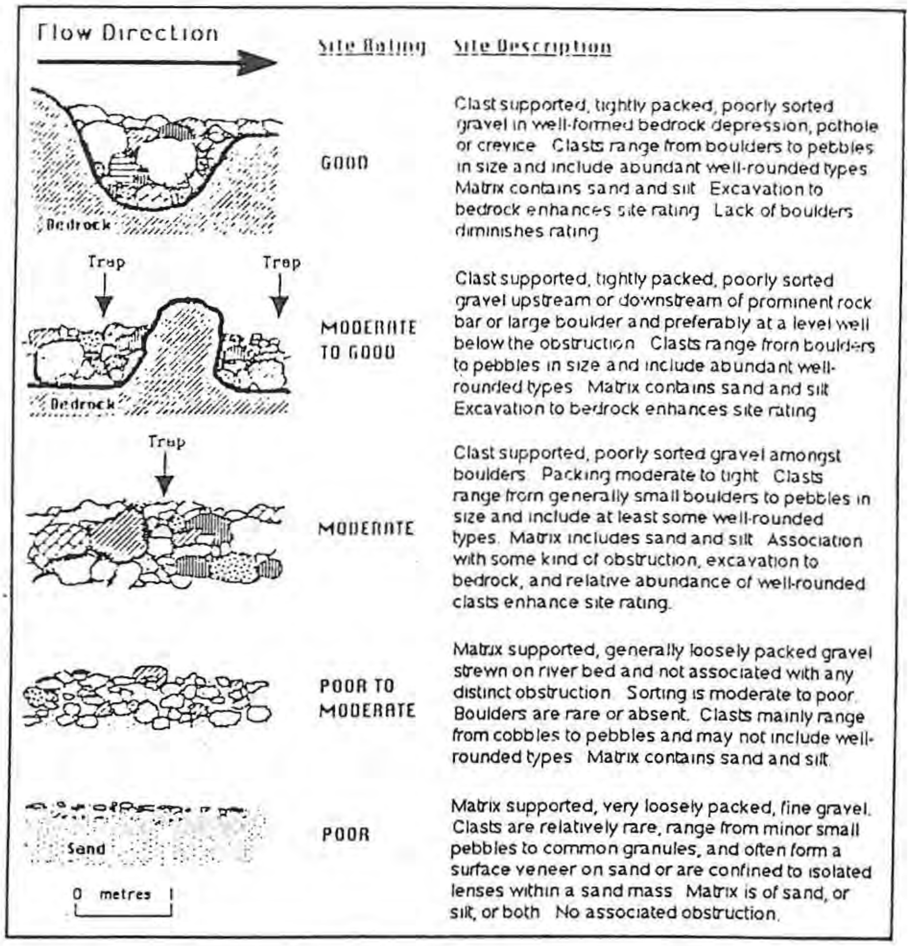
## 3.3 SAMPLE SITE SELECTION

To some extent, the selection of sample sites is obvious from the models presented in the previous sections. However, it is stressed that, as in geochemical sampling, some orientation work is required in order to discover the optimum heavy mineral sampling sites. In arid regions, for example, a surficial lag may develop by wind deflation over unconsolidated fluvial sediments, making this the most attractive sampling horizon. Evaluation of "trap" sites has been performed by various workers in different environments, working with different heavy minerals. Clearly, such studies are of limited use in new areas. However, certain sample sites do appear repeatedly in the literature as representing "good" trap sites. A review of some of these sites follows.

In a field experiment to test the efficiency of fluvial trap sites in concentrating kimberlitic indicator minerals, Muggeridge (1989) was able to rank natural sites in order of effectiveness. The stream chosen was a braided perennial drainage on the Kimberley craton in northern Western Australia. The indicator minerals recovered in the experiment were all in the + 0.4 to - 2 mm size fraction.

The poorest samples were collected at sites with relatively few clasts, although some of these contained concentrations of finer probably non-kimberlitic heavy minerals. Figure 36 summarises the trap sites in terms of efficiency of concentrating the kimberlitic indicators.

A similar study was undertaken by Matheys (1990) on diamondiferous gravels of the Vaal River in South Africa. These gravels comprise a palaeo-braided system in which there is a general decrease in average stone size in a downstream direction. The best proximal trap sites were found to be richest in the coarsest, 1-2 mm size indicators, whereas the best distal trap sites were enriched in the finest 0.3 - 0.5 mm indicators. The characteristics of the best sites were similar to those found in the Australian study.



| Site Rating | Site Description |
|---|---|
| GOOD | Clast supported, tightly packed, poorly sorted gravel in well-formed bedrock depression, pothole or crevice Clasts range from boulders to pebbles in size and include abundant well-rounded types Matrix contains sand and silt Excavation to bedrock enhances site rating Lack of boulders diminishes rating |
| MODERATE TO GOOD | Clast supported, tightly packed, poorly sorted gravel upstream or downstream of prominent rock bar or large boulder and preferably at a level well below the obstruction Clasts range from boulders to pebbles in size and include abundant well-rounded types Matrix contains sand and silt Excavation to bedrock enhances site rating |
| MODERATE | Clast supported, poorly sorted gravel amongst boulders Packing moderate to tight Clasts range from generally small boulders to pebbles in size and include at least some well-rounded types. Matrix includes sand and silt Association with some kind of obstruction, excavation to bedrock, and relative abundance of well-rounded clasts enhance site rating. |
| POOR TO MODERATE | Matrix supported, generally loosely packed gravel strewn on river bed and not associated with any distinct obstruction Sorting is moderate to poor. Boulders are rare or absent. Clasts mainly range from cobbles to pebbles and may not include well-rounded types Matrix contains sand and silt. |
| POOR | Matrix supported, very loosely packed, fine gravel. Clasts are relatively rare, range from minor small pebbles to common granules, and often form a surface veneer on sand or are confined to isolated lenses within a sand mass Matrix is of sand, or silt, or both No associated obstruction. |

FIG. 36. Broad field classification of heavy mineral trap sites. Diagrams are of river bed cross-sections parallel to main water flow direction. (After Muggeridge, 1989).

Fine-grained heavy minerals are particularly susceptible to processes of flow separation as reviewed in section 2.4.3. At sites of abrupt changes in bed geometry, such as obstacles, ripples and bedrock depressions, turbulence caused by flow separation may produce efficient heavy mineral concentration, particularly by selective entrainment of less dense particles. These sites are sometimes clearly visible by the abundance of dark heavy minerals such as magnetite.

For example, McQuivey and Keefer (1969) showed how the intensity of turbulence from the trough to the crest of ripples may be used to explain the segregation of magnetite and other fine heavy minerals behind the crests of ripples. Such studies are particularly useful in indicating sites of concentration in suspension load-dominated meandering streams.

## 3.4 EXPLORATION APPLICATIONS OF TRANSPORT TRENDS

Resistance to change is provided in varying degrees by the chemistry of placer minerals, and by their physical properties of hardness, cleavage, toughness, size, shape and textural associations. Certain minerals survive the processes of weathering, erosion and fluvial transport preferentially compared with many of the rock-forming minerals with which they set out. This was demonstrated by Ruhe and Cady (1967) when they measured the particle size distribution in two different soils. They showed that of the minerals present, zircon persisted better than any others.

The experiments of Linkholm (1968) explained the abundance of gem and the near absence of industrial quality diamonds on the west coast of southern Africa. A ball mill was charged with gravel and steel balls, together with six industrial and six gem quality diamonds. It was then run for a total period of 950 h. Each hour, the contents was washed over a 60 mesh screen and the oversize returned to the mill. After only 7h, the industrial diamonds had disintegrated. After 950 h, the total weight loss of the six gems was hardly measurable at (0.01%), whilst the gravel loss was 40%.

Such studies demonstrate the concept of transport trends, which may be usefully applied to exploration. In the following section, the transport trends of surface textures and population ratios will be outlined in terms of their exploration applications.

### 3.4.1 Surface Textures

Surface textures are microrelief features of the grain surface and are independent of size, shape or roundness. Less abrasion and transport are required to modify these details in comparison with the change of grain-size, shape and roundness. For example Wentworth (1922) determined that about 560 m of fluvial transport would remove glacial striations from limestone pebbles, and Bond (1954) noted that the frosting of sands of the Kalahari desert is lost in less than 64 Km of transport down the Zambezi River. The application of surface texture studies of heavy minerals to determine the distance from source is discussed in two examples : i) kimberlitic indicators ; and ii) detrital gold.

## Kimberlitic Indicators

Despite the recent success of aeromagnetic surveys in the location of alkaline intrusives (e.g., Reed and Sinclair, 1991), the strongest tool in the exploration for diamond-bearing kimberlites remains the field collection of mantle-derived xenocrysts which are disaggregated during emplacement and weathering of the kimberlite and dispersed into the surface environment. The most important indicator xenocrysts are pyrope garnet, picroilmenite, magnesian chromite and chrome diopside. Minerals such as olivine, phlogopite, serpentine and chlorite readily breakdown chemically and/or mechanically and they are therefore generally unsuitable as indicators. Zircon may be a useful indicator, but its kimberlitic nature is difficult to demonstrate (Mosig, 1980). Diamond itself is, of course, a useful indicator, but its high resistance to wear means that surface texture studies are of little practical use in exploration.

The major advantage of the use of indicator minerals in exploration, is that anomalies can be subjected to geochemical analysis and ranked according to a "degree of interest" (e.g. Gurney, 1984 ; Dummett et al., 1987 ; Thompkins, 1987; Gurney and Moore, 1991). In regions of suitable geomorphology, it is most convenient to collect stream samples (e.g. Gregory and White, 1989 - in Western Australia ; Thompkins, 1987 - in Brazil), but in such surveys, the distance from source is difficult to judge, particulary in higher-order drainages. The surface textures of indicators provide a means of estimating distance from source.

Mosig (1980) sub-dived picroilmenite and pyrope garnet into three classes respectively, based upon their degree of wear. This classification can be summarised as follows:

### Picroilmenite

i) Proximate to source. Within 2km of source, about 10-20% of the grains are very angular, with pitted surfaces and very fresh fracture surfaces. The remainder are at least partially coated by porcellaneous leucoxene (presumably formed in the weathering mantle over the kimberlite).

ii) Fresh worn picroilmenite. Grains 2-4 km from source are sub-rounded with matt surfaces, and some are freshly fractured.

iii) Worn picroilmenite. At a distance greater than 4 km from source, grains are rounded, often with percussion marks.

Garnet

i) Proximate to source. Rounded and fractured grains are present, but most retain their kelyphitic rims (kelyphite represents a reaction rim formed between the garnet and the kimberlitic fluid during emplacement). The kelyphite survives up to 1 km.

ii) Fresh-worn garnet. A pitted grain surface is exposed beneath the kelyphite. This surface survives up to 3 km from source.

iii) Worn garnet. At distances greater than 3 km, garnets become smooth and rounded, and some may exhibit frosting.

This summary indicates that surface textures, which can be recognised in the field, may provide useful information regarding proximity to source. It must be remembered, however, that kimberlitic indicators will not behave in this manner in all (or even most) situations. The samples used by Mosig (op.cit.) came from the Pine Creek diatreme in South Australia. It would be unreasonable to assume that the wear criteria described would correspond to similar transport distances in, say, the jungles of Brazil. McCandless (1990) has recognised this problem. In experimental studies of xenocryst wear he found that minerals are transported with less wear when the proportion of fine-grained material is increased. Presumably, the fine-grained component cushions the xenocrysts from contact with other clasts by increasing the overall viscosity of the sediment charge. This suggests that the nature of the bedrock, as well as the stream type and the nature of discharge are key influences in determining the degree of wear.

GOLD

The transport abrasion of detrital gold has been experimentally studied by Yeend (1975), who noted that its malleability results primarily in changes of grain shape and surface textures. The main conclusion of this work is that velocity of the particle appears to be the more important factor controlling abrasion than the distance of transport. For example, a four-fold increase in velocity produced a ten-fold increase in the rate of gold abrasion. Furthermore, the abrasion is higher when a low proportion of fine-grained sediment is present, and vice versa (cf. McCandless, 1990).

Hallbauer and Utter (1977) have studied the morphological characteristics of gold grains in streams draining the Barberton Mountainland of South Africa. Primary gold in the area was found to be crystalline and the preservation of at least part of this morphology was found to be characteristic of alluvial gold particles transported over short distances in rivers.

The characteristics of gold particles transported up to 30 km include numerous scratches on the surface and bent and hammered edges. Nuggets are common. Prolonged transport imparts a "dough-like" microtexture. Repeated folding of previously flattened particles occurs, and scratches on earlier surfaces can be observed on the inner side of the fold edges. Grains transported over 80 km are primarily flakes. The fineness of the gold (Au/Au + Ag x 1000) was also found to increase with transport, presumably because of chemical leaching of silver.

Applying these criteria to the detrital gold from the Witwatersrand, the transport distances for these grains appears to be in the order of 10 to 30 km. It should be noted, however, that much of the gold of the Witwatersrand may have been transported in association with sand-rich sediment charges.

### 3.4.2 Population Ratios

The concept of mineralogical maturity in clastic sediments is well known. The concept can be applied to detrital heavy minerals such that ratios of more-stable to less-stable minerals provide an index of maturity and, assuming only mechanical wear attributable to transport, these indicate proximity to source. For example, diamondiferous gravels of the lower Orange River contain high quality diamonds. Almost all of the flawed stones are inferred to have been destroyed during transport from the cratonic source area to the east, along with the kimberlitic indicator minerals, pyrope garnet, picroilmenite and chrome diopside (van Wyk and Piennar, 1986). Conversely, diamonds in the lower Vaal River basin are associated with kimberlitic indicator minerals and a relatively high proportion of poor-quality stones (Matheys, 1990). These alluvial diamonds are located within a few kilometres of their probable kimberlitic sources..

Mosig (1981) reports that the elongate, fibrous chrome diopsides from South Australian kimberlites are broken down to sizes too small to recover beyond 3 km of transport in streams. Numeric ratios of chrome diopside to, say, garnet may therefore give an indication of proximity to source.

Note, however, that mineralogical ratios may change, not as a consequence of differential survival, but of differential hydraulic equivalence brought about by density, size or shape differences. An example would be the relative displacement of gold- and uranium-rich facies in the Steyn placer of the Witwatersrand goldfield (section 3.2.2). Furthermore, the transport survival of grains is presumably also a function of the parameters identified in the previous section (i.e. proportion of fine-grained sediment, rate of transport, etc). Finally, the study of changes in population ratios requires an estimate of the proportions present in the source, which is, in the case of exploration, unknown.

### 3.4.3 Conclusions

Transport trends are, at first glance, an attractive means of estimating transport distance from source of heavy minerals. However, the abrasion characteristics are found to be determined not only by the quantifiable factor of transport distances, but also by the less quantifiable factors of environmental conditons. One might visualize a fresh, unabraded mineral grain being transported in suspension in a silt-rich sediment charge during a flash flood, and being rapidly deposited without wear at the apex of an alluvial fan system 100 km downstream. The second problem is a practical one. The study of surface textures is skilled (in order to be objective), time-consuming and expensive (especially if a scanning electron microscope is required).

The application of population ratios suffers from the same drawbacks. Furthermore, changes in mineralogical proportions may be effected by hydraulic processes alone, and the exploration geologist is seldom sure of the proportions of minerals present in the source rocks.

It is concluded that, whilst the use of transport trends will remain a tool in mineral exploration, its application is limited to the broad scale, or to projects in which some degree of control exists, derived from orientation studies.

## CONCLUSIONS

Detrital heavy minerals are a limited group with distinct physical and chemical properties. Their presence in alluvial systems of all kinds may be of economic value both as mineral deposits in their own right (i.e. placers) and as pathfinders to deposits drained by rivers.

Economically, the most important alluvial placers comprise gold, diamond and cassiterite deposits. The genesis of these is a consequence of the complex interplay between tectonic setting and geomorphic evolution. It can generally be stated that major alluvial gold placers develop on the flanks of rising mountain chains during orogenesis, where the primary lode gold was emplaced in the overriding plate during subduction of oceanic crust, prior to collision. Where conditions are unfavourable for the emplacement of I-type granitoids (i.e. where subduction of oceanic crust is limited or absent) then primary hydrothermal gold is unlikely to be emplaced, and such orogenies are unlikely to spawn major deposits of alluvial gold. A good example of such a collision belt is provided by the European Alps. Here, the development of oceanic crust was limited and the plate margin motion was dominantly lateral. Subduction of oceanic crust was not therefore developed on any substantial scale, except over an area between Yugoslavia and Iran (Evans, 1975). This has resulted in a lack of I-type magmatism and the consequent absence of hydrothermal gold deposits (as well as related deposits such as porphyry copper). Molasse basins marginal to the European Alps are not therefore likely to host significant gold placers. Of course smaller gold placers may develop locally under suitable conditions, adjacent to any pre-existing gold deposit. An example might be the Caeonozoic alluvial gold deposits at Bourkes Luck on the Blyde River in the eastern Transvaal, which have formed in response to a rejuvenation event (or events) from primary Archaean sources in the Pilgrims Rest goldfield 12 km upstream.

The relatively quiescent tectonics associated with cratonic areas, means that climate plays a far more significant role in the genesis of diamond (and some minor gold) placers. Morphogenic regions in which humid tropical conditions have alternated with semi-arid conditions, are those which may liberate minerals by deep weathering, and transport them during flood events. Such regions have a high potential for the development of alluvial placers.

Rejuvenation events enhance this potential by encouraging reworking of sediment in the drainage channel, and producing terraces, thus preserving placers. Rejuvenation may be as a result of continental upwarping, or base-level falls. These events also produce local braiding of coarse-sediment choked rivers which provides appropriate conditions for the formation of gravel-related placers in regions of suitable bedrock.

The grain-scale concentrating processes which control heavy mineral accumulation can be divided into those involving hydraulic equivalence between the sediment grains deposited (generally finer-grained lag deposits), and those involving interstice entrapment of heavy minerals within gravels.

By far the most important process for concentration of fine-grained heavy minerals involves the concept of entrainment equivalence, whereby generally coarser, lighter minerals are selectively entrained by the stream flow.

Interstice entrapment is the most important mechanism for the accumulation of heavy minerals in most alluvial placers, and may occur in the proximal- to mid - fan reaches of alluvial fan systems as well as the main thalweg of meandering streams containing coarse sediment.

These processes may be enhanced by the occurrence of flow separation at sites where channel morphology changes. These changes in morphology may occur at the large-scale, such as at the confluence of two channels, down to the small-scale, such as in the lee of ripples.

The appreciation of these controls on heavy mineral distribution, enables the development of geologic models which can guide exploration. These models are based upon the dominant influences controlling heavy mineral distribution at different scales. Thus on the continental scale, tectonic and morphogenic setting are the dominant controls; at the system scale, climate and basin dynamics are dominant; and at the bar scale and smaller, flow separation and grain-scale concentrating processes dictate heavy mineral accumulation.

Studies of the dynamics of river systems and their facies models, aided by empirical studies of heavy mineral distribution within rivers, have enabled the development of prospecting models for the two main types of river system ; braided and meandering. These models are intended to guide exploration programmes to the most promising sites of heavy mineral accumulation, and to indicate likely trends in their distribution. Grain size is found to be an important parameter in governing this distribution.

Whilst it has been beyond the intended scope of this review to discuss evaluation of placers, it should be clear that the genetic process history of placers provides an indication of how to subdivide a deposit into separate sampling "strata", each with its own characteristic grade and tonnage. Examples mentioned in this review include the Auchas alluvial diamond deposit on the Orange River in Namibia, which can obviously be subdivided into the valley-fill and channel-fill facies (section 2.3.2); the Otago alluvial gold deposits of South Island, New Zealand, which can be subdivided into cycles of fluvial degradation developed in response to intermittent tectonism (section 2.2.1); and the stanniferous placers of the Tujuh archipelago in Indonesia, which can be subdivided into *Kulit, Kaksa* and *Miencan* concentrations, corresponding to the stages of placer evolution (section 2.1.4). An understanding of the geomorphic history therefore provides descriptive and genetic terrain models which can also be used by mining geologists.

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