ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

SEDIMENTOLOGICAL CONTROLS OF GOLD AND URANIUM IN LOCAL DEVELOPMENTS OF THE LEADER REEF, WELKOM GOLDFIELD, AND ELSBURG No. 5 REEF, KLERKSDORP GOLDFIELD WITWATERSRAND BASIN

N.D. SMITH and W.E.L. MINTER

INFORMATION CIRCULAR No. 137

UNIVERSITY OF THE WITWATERSRAND

JOHANNESBURG

SEDIMENTOLOGICAL CONTROLS OF GOLD AND URANIUM IN LOCAL DEVELOPMENTS OF THE LEADER REEF, WELKOM GOLDFIELD, AND ELSBURG No. 5 REEF, KLERKSDORP GOLDFIELD, WITWATERSRAND BASIN

by

N. D. SMITH

(Department of Geological Sciences, University of Illinois at Chicago Circle, Chicago, U.S.A.)

and

W. E. L. MINTER

(Sedimentological Research, Gold and Uranium Division, Anglo American Corporation of S.A. Ltd., Welkom)

ECONOMIC GEOLOGY RESEARCH UNIT

INFORMATION CIRCULAR No. 137

November, 1979

SEDIMENTOLOGICAL CONTROLS OF GOLD AND URANIUM IN LOCAL DEVELOPMENTS OF THE LEADER REEF, WELKOM GOLDFIELD, AND ELSBURG No. 5 REEF, KLERKSDORP GOLDFIELD, WITWATERSRAND BASIN

ABSTRACT

A study of the relation between mineralization and sedimentary features was conducted on two sub-economic reefs between January and March, 1978, in order to establish criteria that could be used to lead successfully underground development into areas containing potential ore and then to guide selective mining of the economic portions of the orebody.

The results of the study confirmed that the two reefs chosen are ancient braided-stream deposits that were produced by a complex pattern of shifting bars and channels. It was also established, from pebble-size and bed-roughness measurements of the reef exposures chosen, that they correspond to the proximal parts of present-day braided streams. By analogy, channels in such environments are characterized by: steep regional gradients; low sinuosity; easily-eroded banks; high width/depth ratios; abundant bedload; and fluctuating discharges. These features of braided streams are therefore an integral part of placer-forming processes.

An important concept that arose, which concerns the distribution of gold and uranium mineralization on a local scale, is that braided-stream sediments comprising gravel, sand, and heavy minerals are transported spasmodically in response to locally-shifting bars and channels. The sediments, which are temporarily stored during transit in bars, therefore become local sources for downstream gravel deposits and thereby introduce a random element to the source of supply of heavy minerals.

A detailed examination of mineralization on the local scale indicated that a good correlation exists between gold and uranium, which substantiates the hypothesis that both elements are hydraulically concentrated. However, the ratio of their concentrations is not consistent with grade changes in the two reefs examined. Although separate provenances supplying different grain-sizes may account partly for this effect, the hydraulic processes responsible for concentrating high-density particles are poorly understood and progress is likely to be obtained only through hydraulic flume experimentation.

It was found that placer minerals are preferentially concentrated on well-worked scour surfaces and in pebble-supported conglomerates. Rapidly-deposited sandstone bodies and matrix-supported conglomerates are poorly mineralized. Notably well-mineralized, pebble-supported conglomerates were located in: compound longitudinal bars, which are multi-storied deposits; bars at positions of converging flow where, for instance, a channel confluence occurs; and constricted channelways produced by bank-hugging transverse bars. All these features present linear mineralized trends that can be oriented from underground exposures and projected for selective mining.

oOo

SEDIMENTOLOGICAL CONTROLS OF GOLD AND URANIUM IN LOCAL DEVELOPMENTS OF THE LEADER REEF, WELKOM GOLDFIELD, AND ELSBURG No. 5 REEF, KLERKSDORP GOLDFIELD, WITWATERSRAND BASIN

CONTENTS

oOo

ISBN 0 85494 601 2

SEDIMENTOLOGICAL CONTROLS OF GOLD AND URANIUM IN LOCAL DEVELOPMENTS OF THE LEADER REEF, WELKOM GOLDFIELD, AND ELSBURG No. 5 REEF, KLERKSDORP GOLDFIELD, WITWATERSRAND BASIN

INTRODUCTION

The distribution of heavy minerals within a particular placer horizon is ultimately governed by the local hydraulic processes which operated at the time of deposition. These processes vary over wide spatial and temporal ranges, for example, from instantaneous turbulence fluctuations in a space between two sediment particles to gradual downstream changes in depth, velocity, and slope along a river channel system. Areal concentrations of heavy minerals in fluvial systems might be classified into four categories which broadly correspond to spatial scales at which the hydraulic sorting processes operate:

A. Large Scale: Concentrations occur on a regional scale in response to some optimal combination of average size of available heavy minerals and the long-term characteristics of the fluvial environment. Broad bands of placers parallel to depositional strike in alluvial fan deposits would be an example. Width scales range from hundreds of metres to kilometres.

B. Intermediate Scale: Concentrations arise from processes associated with major topographic elements within channel systems, for example, channel bends, braid bars, short channel segments, or channel junctions. Examples from modern streams are given by Crampton (1937). Distribution scales are in the order of metres to tens of metres along widths or lengths.

C. Small Scale: These concentrations and sorting processes occur at the bedform level. Typical examples include heavy-rich laminae in crossbeds and in horizontal (plane) strata. Linear scales commonly range from centimetres to tens of centimetres.

D. Very Small Scale: Concentrations that result from processes operating at the millimetre scale. Examples include small clusters of grains within laminae or within voids between larger grains. Such concentrations arise from very short-term fluid/sediment interactions set up by a rough sediment bed and natural turbulence. The sacle of gold particle concentrations described by Hallbauer (1972) could be included here.

It should be clear that these scales of concentration and their formative processes may be hierarchical. An example might be a cluster of gold particles trapped between two pebbles (D) in a large crossbed (C) forming the accreting margin of a gravel bar in a channel bend (B) within a zone of the channel system where gold is preferentially being deposited (A), the last-mentioned resulting from optimal flow conditions governed, in part, by distance downslope. At present, there is a substantial body of information that demonstrates large-scale (A) concentrations, not only in the Witwatersrand Basin (Minter, 1970, 1976, 1978; Knowles, 1967; Sims, 1969; Vox, 1975) but in other systems as well (Sestini, 1973; McGowen and Groat, 1971). These distributions become apparent only after many samples have been analyzed over wide areas. Except for more-or-less intuitive feelings for sediment baffling mechanisms, for example, entrapment of heavies in spaces between larger grains, little is known of scale D processes. Certainly the pertinent details of the interactions between the fluid processes and sediment particles that operate at such small scales are barely understood and must await considerable experimental and, perhaps, theoretical investigation. Notable recent efforts have been made by Slingerland (1977) and Lowright et al. (1972).

In recent years, a considerable amount of literature concerning fluvial processes at the B and C scales has developed. Although most of our understanding of such processes has arisen from flume experiments and studies of modern rivers, some of the processes can be inferred, at least in a qualitative way, in ancient deposits from preserved sedimentary structures and textures. Unfortunately, in those studies in which transport, deposition, and sorting of sediment have been dealt with, very little attention has been paid specifically to heavy minerals, i.e. grain density, as a variable. Indeed, there is very little information in the present sedimentological or engineering literature that can provide any more than a crudely-qualitative basis for predicting placer occurrences or trends in fluvial sediments at these intermediate and small scale (B and C). If such predictive schemes could be developed, they would be useful for exploration and selective mining purposes.

In an effort to develop a better understanding of gold and uranium distributions at small and intermediate scales, a localized study of two Witwatersrand placers was undertaken with the specific goal of relating concentrations to identifiable and, at least, crudely.interpretable sedimentary structures. The two units, the Leader Reef and the Elsburg No. 5 Reef, were chosen because both are marginally economic and because unmined pillars left for roof support provide excellent three-dimensional exposures for enhanced interpretations of some larger structures, especially channels and bars.

LOCATION AND STRATIGRAPHIC SETTING

The Leader Reef in the Welkom Goldfield (Fig. 1) was examined at Welkom No. 3 shaft where it is stratigraphically situated at the base of the Upper Bird Quartzite. The placer covers an area of approximately 400 square kilometres and rests on an unconformity 20 metres above the Basal and Steyn placers (Fig. 2).

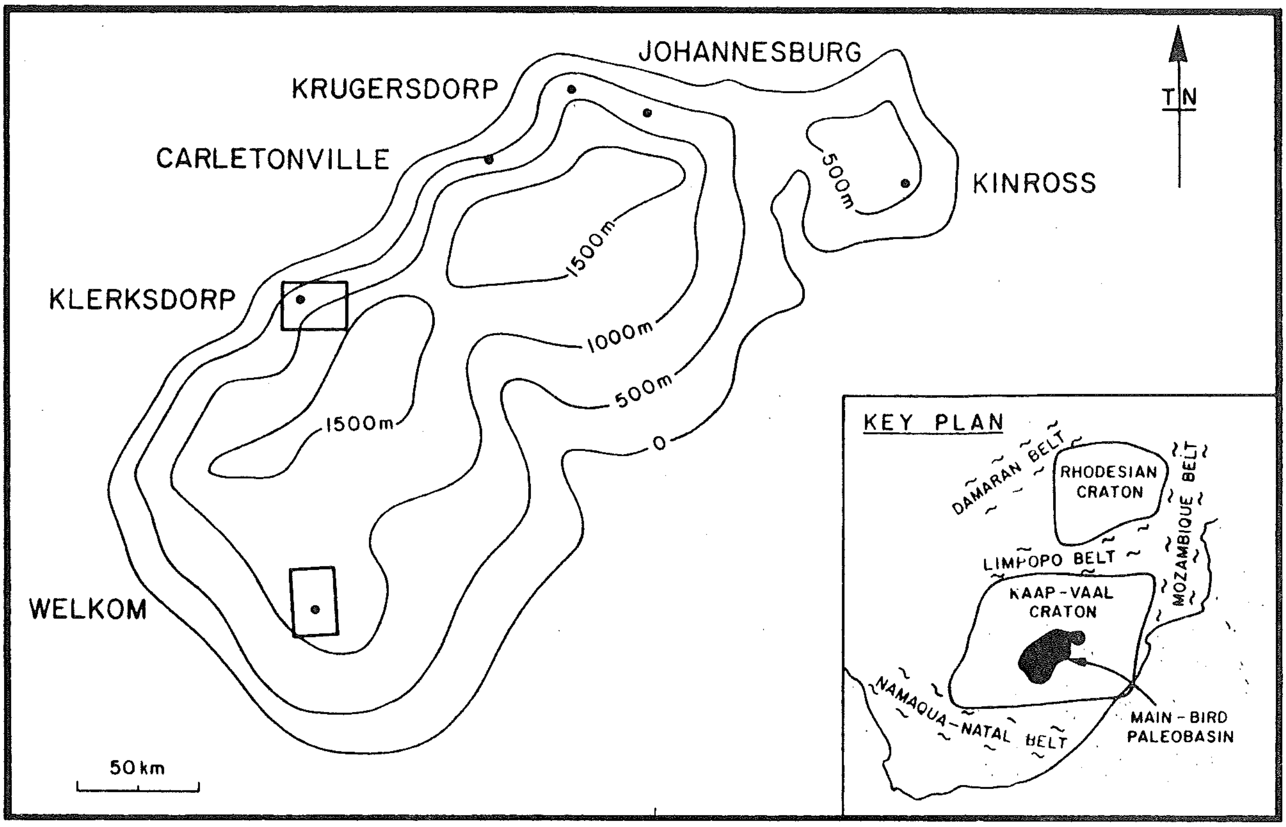

Figure 1 : Isopach map of the Main-Bird sedimentary basin, showing generalized locations of Klerksdorp and Welkom goldfields and the basin's position within the Kaapvaal structural domain.

The Upper Bird Quartzite is composed of coarse basal conglomerates which fine upwards over 14 metres into small-pebble layers and then into khaki-coloured, coarse-grained, argillaceous quartzites. The sequence continues upward through medium-to-fine-grained quartzites with khaki-to-black-coloured shale layers near the top. The sediments are cross-bedded, and foreset azimuths indicate a unimodal transport direction towards the east.

The external geometry of the formation is wedge-shaped, thickening from 25 metres in the west to over 175 metres at a position 30 kilometres to the east (Fig. 3). The westward thinning is partly depositional and partly erosional due to an overlying unconformity associated with the "B" Reef.

Placer conglomerates known as the Elsburg No. 5 Reef were studied in the Vaal Reefs West No. 6 Shaft in the Klerksdorp Goldfield at Orkney (Fig. 1). The placer occurs about 200 metres above the base of the Elsburg Formation, which, in this part of the Klerksdorp Goldfield, is about 275 metres thick. The Elsburg Formation is truncated to the west and north by a major angular unconformity at the base of the Ventersdorp Supergroup.

The formation is composed of medium-to-coarse-grained siliceous quartzites with 6 or 7 conglomeratic zones in the total sequence (Fig. 4). At present, the regional paleocurrent pattern has not been measured. The horizon examined here consists of the lower 4 metres of the No. 5 conglomerate zone. The base of the No. 5 unit is separated from underlying quartzites by an erosion surface.

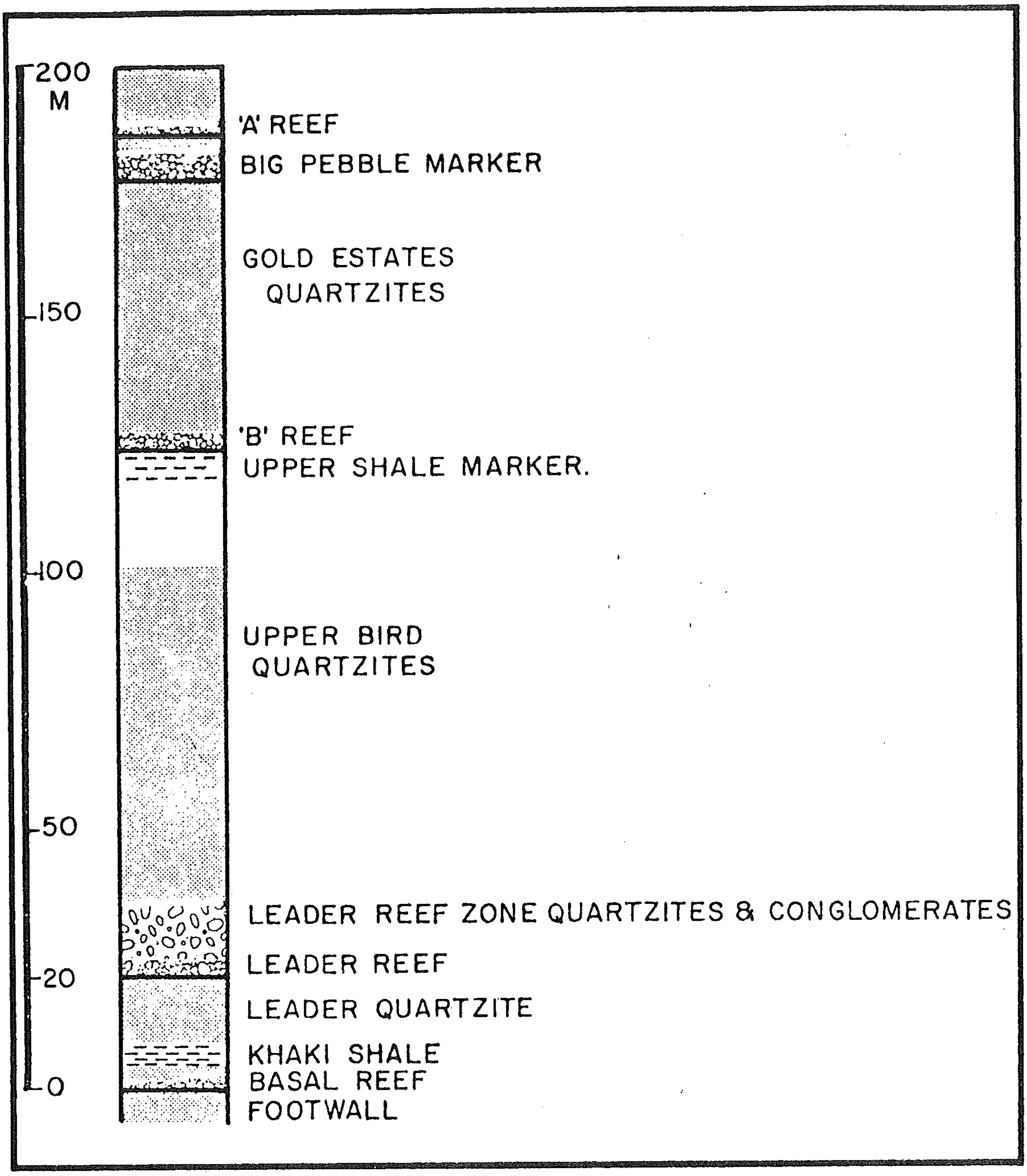

Figure 2 : Schematic stratigraphic column, showing position of the Leader Reef.

DEPOSITIONAL ENVIRONMENT

The results of numerous studies of Witwatersrand sediments suggest that most of the gold and uranium placers were deposited on alluvial fans or fan-deltas (Pretorius, 1976; Vos, 1975). Evidence for this interpretation arises from areal trends of isopachs, paleocurrent patterns, sediment grain-size distributions, facies variations, heavy mineral distributions, and sedimentary structures. The fans were probably of the "wet" rather than the "dry" type, i.e. characterized by perennial, instead of, intermittent flows (Schumm, 1977).

Available evidence, including that examined in this study, suggests that both the Leader and Elsburg units occupied relatively proximal portions of their respective fans and were deposited by shallow, transient, braided streams. This interpretation is supported by several lines of evidence at the local scale. Interbedding of principal lithologies, which include massive, clast-supported conglomerates, sandy conglomerates, pebbly sandstones, and sandstones, indicate flow-velocity fluctuations that were rapid and extreme, typical of proximal braided streams (Church, 1972; Boothroyd and Ashley, 1975; Williams and Rust, 1969). Individual beds tend to be irregular to lenticular over short distances, showing grain-size changes that reflect lateral, as well as,

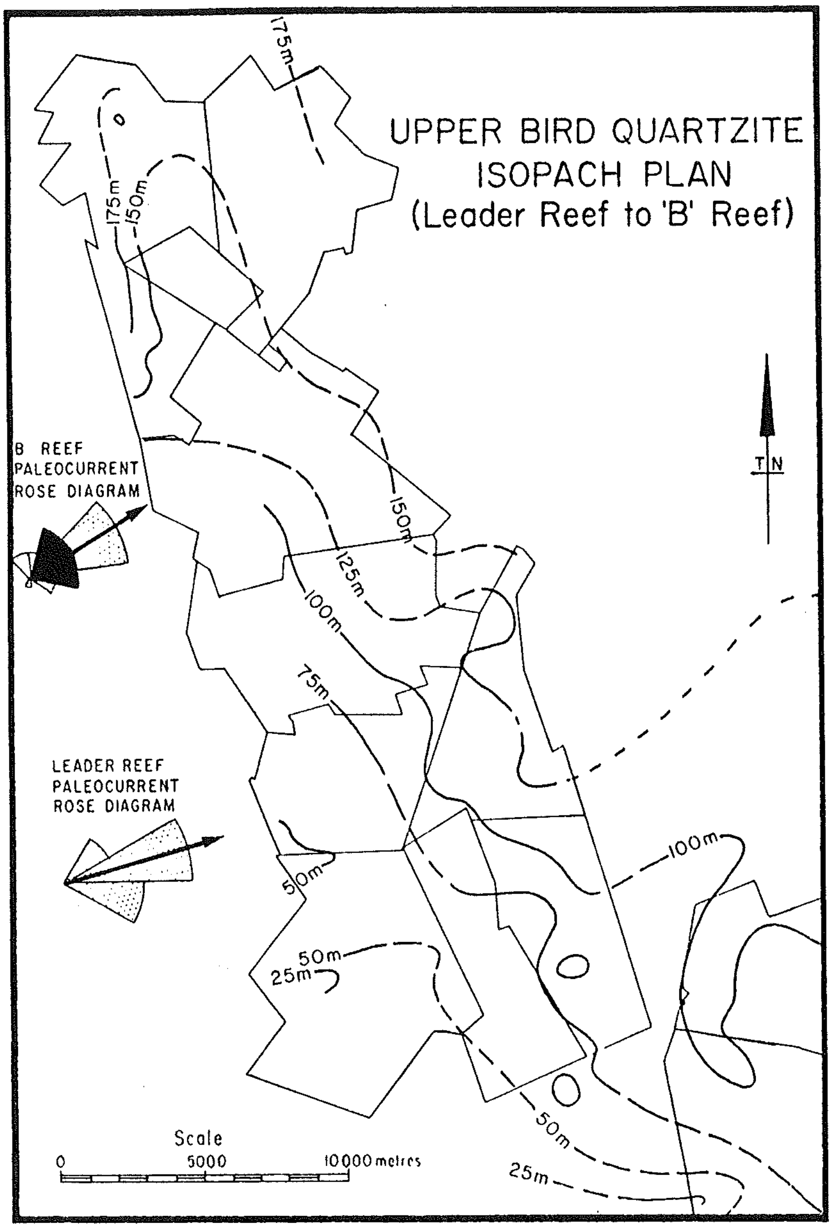

Figure 3 : *Map showing isopachs of strata between Leader Reef and "B" Reef in the Welkom Goldfield. Note strongly unimodal eastward paleocurrent trend.*

vertical changes in the flow-regime. Such uneven bedding, as well as the presence of obvious bar-and-channel topography in some stope-faces, has readily-perceived analogues in modern gravel-bed streams characterized by narrow channels and longitudinal braid-bars. The sizes of such bars and channels are approximately scaled to the dimensions of the fluvial system; for example, individual braid-bars commonly range in length from a few metres, in small streams (Smith, 1974), to hundreds of metres, in large streams (Fahnestock and Bradley, 1973). The local thickness-distribution of the basal conglomerate of the Elsburg study unit is shown in Figure 5. Although isopachs cannot distinguish topographic highs (bars) from lows (channels), the patterns shown in Figure 5 suggest bar-and-channel topography, particularly in view of the unimodal paleocurrent trend which approximately parallels the isopach trends. Strongly unimodal paleocurrent patterns themselves comprise additional evidence for proximal braided streams, especially considering that most sediment is transported during high flows when interference effects of bar topography are minimized (Collinson, 1971). Tabular sets of planar crossbedding occur sporadically in each unit and are identical to structures produced by transverse bars in both gravelly and sandy braided rivers (Smith, 1971, 1974; Collinson, 1970; Cant and Walker, 1978; Hein and Walker, 1977).

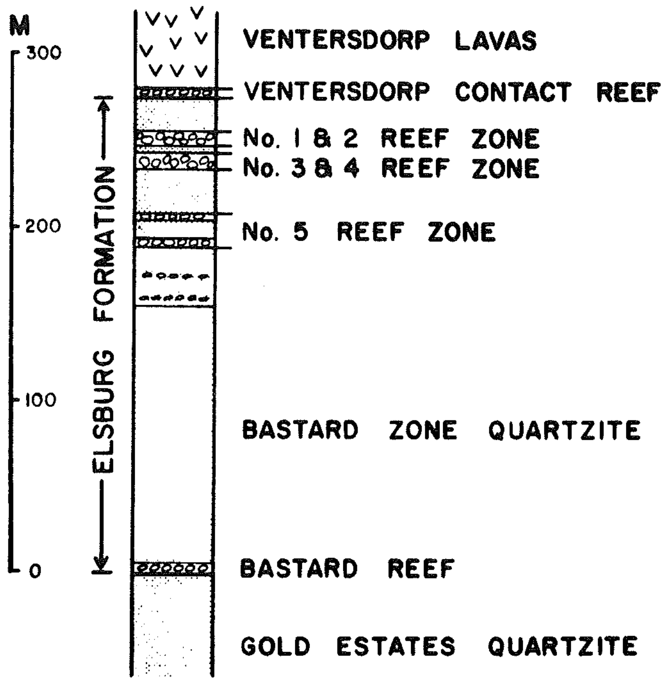

Figure 4 : *Schematic stratigraphic column, showing position of the Elsburg No. 5 Reef Zone in the Klerksdorp Goldfield.*

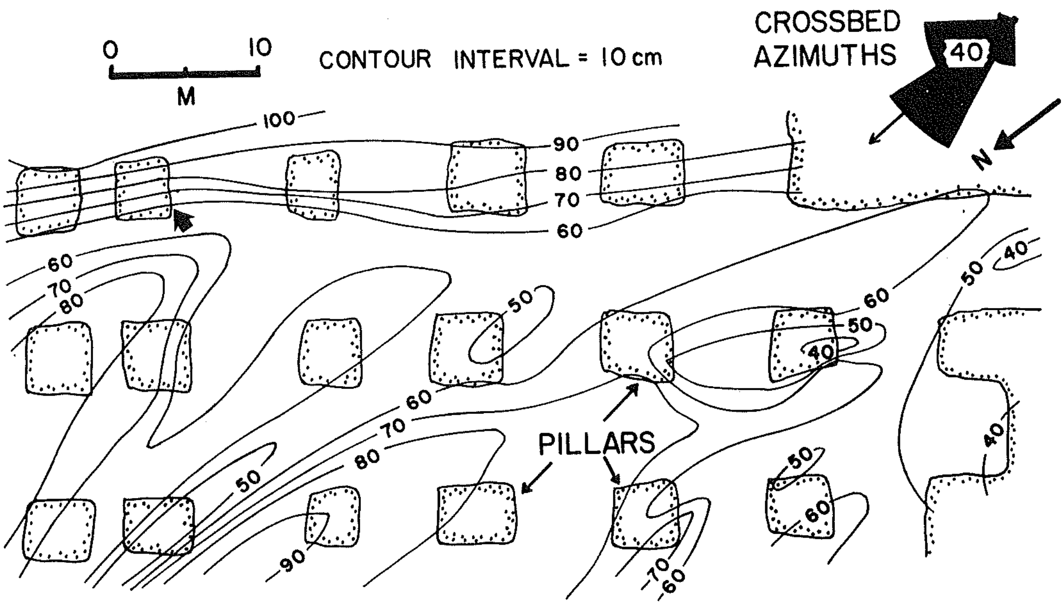

Figure 5 : *Map showing isopachs of the Elsburg No. 5 Reef basal conglomerate bed examined in Vaal Reefs West No. 6 Shaft, Orkney. Note general alignment of isopach trends with paleocurrents (crossbed azimuths), suggesting channel-and-bar topography. Arrow indicates location of photo in Figure 10.*

BRAIDED STREAM PROCESSES

Since we conclude that the Leader and Elsburg units are braided-stream deposits, it is appropriate to consider now some of the sedimentation and hydraulic processes that occur in such streams, particularly those that may affect heavy mineral distributions in the sediments. A recent review of braided stream deposits is given by Miall (1977)

Braided streams comprise complexes of shifting bars and channels. They typically have high width/depth ratios, relatively steep slopes, and low channel sinuosities. The underlying causes of braiding are not clearly understood because they involve complex interactions of several factors, including variables of flow, channel geometry, sediment load, slope, bed roughness, bank stability, and climate (Leopold and Wolman, 1957; Lane, 1957; Henderson, 1963; Schumm, 1968; Schumm and Khan, 1972; Fahnestock; 1963. Osterkamp, 1978). Some of the more-frequently cited explanations for braiding include easily-eroded banks, steep regional gradients, abundant bed-load, fluctuating discharges, and local incompetence. Probably none of these factors is a sole cause of braided patterns, and there is considerable interdependence among them. A common element of most of these explanations, however, is that, at some point, for whatever reason, flow-strength becomes insufficient to move the imposed sediment load through the channel, resulting in modification of the stream bed through either deposition or scouring. In wide, shallow channels, such stream-bed modifications become accentuated during falling-water stages, and braided patterns, i.e. bars separating interconnected channels, emerge. Thus, the process of channel division involves either deposition or erosion, or both; this is termed "primary anastomosis" by Church (1972). In most braided streams, local flows and sediment supply are highly variable, and the channel-and-bar configurations are unstable (Fahnestock, 1963; Krigstrom, 1962; Krumbein and Orme, 1972).

Apart from these general considerations, it is widely agreed that bars are the principal loci of deposition in braided streams and that most braided patterns evolve by either simple emergence (with minimal late-stage erosional modification) or dissection of these bar-forms with lowering of water-levels. In the former case, depositional morphologies and internal textures and structures remain intact; such cases have been termed "unit bars" by Smith (1974). Although such unmodified bars are reasonably common in gravel-bed streams, the transient nature of most braided stream environments makes it highly unlikely that any whole-unit bar will ever be preserved in the alluvium. Rather to be expected are complex deposits representing remnants of unit bars and adjacent channel-fill deposits that somehow managed to escape erosion. On the other hand, many bars in braided streams are actually multi-storied features with complex depositional and erosional histories. Such features, here termed "compound bars", may form by vertical overriding or laterial coalescence of smaller bars, gravel sheets, or small-scale bedforms. Compound bars may be transient or quasi-permanent features. In the latter case, bar stabilization is usually related to the stability and morphology of the channels on either side of the bar, which, in turn, are ultimately controlled by stability and orientation of the channel banks. Such stable bars and channels are likely candidates for placer concentrations because, by virtue of their permanence, they will be reworked often by currents, enhancing probabilities of heavy-mineral entrapment within interstices of coarse bed-material as sediment mixtures are transported over them.

Flows in gravelly braided streams are usually unsteady, often flashy, resulting in variable velocity, depth, and grain-size relationships. Gravel tends to be transported in bursts in response to locally shifting bars and channels. Studies using tagged pebbles (Church, 1972; Smith, 1974; Butler, 1977) suggest that most gravel in transit is temporarily stored in bars, which then become local sources for new gravel deposits when the bar is later eroded; the gravel seldom is transported more than a few metres or tens of metres before it is temporarily re-deposited. Such local point-sources, i.e. temporary deposits within the braided complex, are probably integral parts of the placer-forming process. This will be returned to later.

Sediment erosion, transport, and deposition depend not only on discharge variations and sediment-supply rates, but also on the configuration of flow as governed by stream-bed topography. In braided systems, flow is continually diverted by ever-changing patterns of bars and channels. In plan-view, flows over short reaches may be convergent, parallel, or divergent, depending on the pattern of flow-lines. (Fig. 6). Convergent flows may occur at width constrictions, channel bends, and channel junctions; they are characterized by locally-increased turbulence and velocity on the stream bed. Parallel flows occur over short channel stretches in which neither depth nor width vary; these are the only situations which approach uniform-flow conditions in braided streams. Areas of parallel and especially convergent flows would seem to be likely spots for placer concentrations because of the increased likelihood of sediment reworking. Mosley and Schumm (1977) make a case for the latter, specifically, for channel junctions. Divergent (expanding) flow is usually accompanied by loss of competence, with deposition resulting. Such areas, especially during periods of rapid deposition, could be expected to be poor in heavy-mineral concentrations, except perhaps on newly-formed beds where some entrapment by larger particles might occur after bulk deposition has ceased. Ordinarily, however, such sites are usually areas of relatively rapid deposition and little reworking, such as at the margins of transverse bars and the insides of channel bends.

In streams where sand is abundant as bedload, small-scale bedforms abound on channel floors and submerged bar surfaces. Small segregations of heavy minerals almost invariably occur in these bedforms, especially in ripples and dunes. Brady and Jobson (1973) and McQuivey and Keefer (1969) have experimentally investigated heavy mineral sorting at this scale, and McGowen and Groat (1971) consider such segregations to be the most important type of heavy-mineral enrichment in the early Paleozoic Van Horn Sandstone. Typically, the heavy minerals concentrate as individual laminae within troughs and foresets of crossbeds and as horizontal laminae in planar beds. The sorting mechanisms, however, are not well understood.

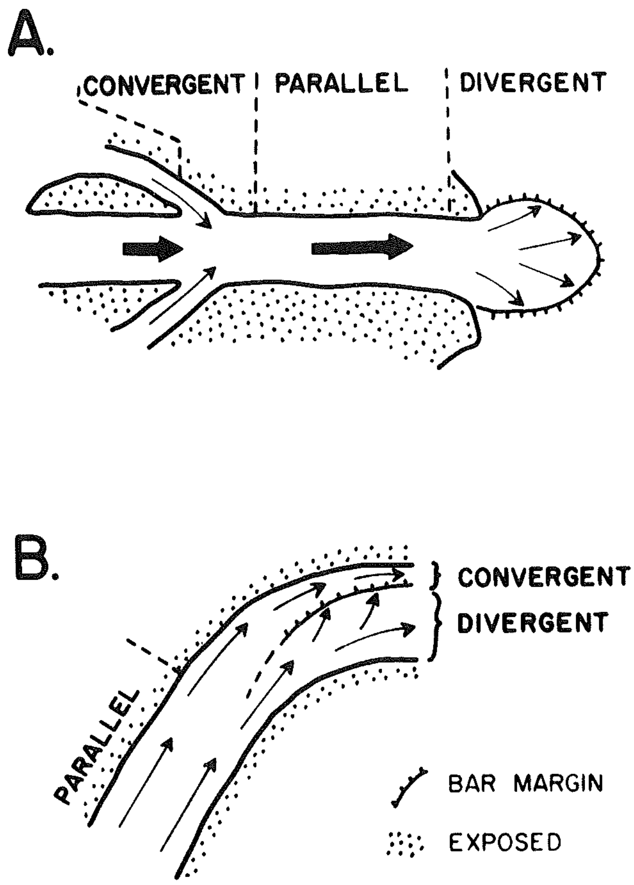

Figure 6 : Plan sketch illustrating convergent, divergent, and parallel flow-lines in (A) a straight reach with tributaries and (b) a curved reach.

METHODS

A major portion of our underground time was spent cleaning, marking and photographing pillar-faces to provide permanent and readily-studiable records of sedimentary structures and stratigraphic relations. Certain structures were examined and later sampled in detail, so that mineralization could be related to sedimentary processes. A total of 109 samples from the Leader and 107 from the Elsburg were thus collected and assayed for gold and uranium by the Anglo American Research Laboratories in Johannesburg.

To enhance recognition and measurement of sedimentary relief elements (e.g. bars and channels), a palaeohorizontal datum, that is, a structurally-reconstructed horizontal plane, was surveyed for the Elsburg, and the intersections of the plane with the pillars were marked on each pillar corner. These marks were then joined by a cord around each pillar to serve as a horizontal datum to which bedding relief could be related. These paleo-horizontal cord-datums also appeared in all photographs, so that stratigraphic correlations between pillars could be effected. A similar effort was made for the Leader, but was less successful because of lower and more irregular stope roofs, debris piled against many pillar faces, and numerous small faults, all of which complicated the surveying. Consequently, a single datum plane could not be constructed for the Leader, as it was for the Elsburg, and correlation between pillars was tenuous.

RESULTS

(a) Elsburg No. 5 Reef

In our study-section, the Elsburg Reef consists of roughly equal proportions of interbedded sandstone and conglomerate. Shale is virtually absent. Conglomerates are mineralogically mature, comprising mostly sub-angular-to-well-rounded quartz and chert pebbles in sandy matrices. Pebbles frequently attain diameters of -6ø (64 mm) or more. Texturally, the conglomerates range from well-sorted and clast-supported to poorly-sorted and matrix-supported. Most are internally massive, though some display large-scale planar crossbedding. Sandstones are predominantly quartzitic and trough-crossbedded, though planar crossbedding and planar stratification are also common. Detrital pyrite is abundant in both the sandstones and conglomerates, occurring most characteristically as (1) matrix in well-sorted conglomerates, (2) concentrates along scour surfaces, and (3) concentrates in crossbed troughs and foresets, and in laminae of planar stratification.

(i) Gold and Uranium Concentrations

Gold and uranium concentrations from all Elsburg samples are plotted in Figure 7, from which two features are readily apparent: Firstly, gold and uranium are significantly correlated ($Au = 0{,}000048U^{2{,}63}$, $r^2 = 63{,}4\%$ $P<0{,}00001$), and, secondly, conglomerates generally contain higher gold and uranium concentrations than sandstones, although there is much overlap. The first observation lends

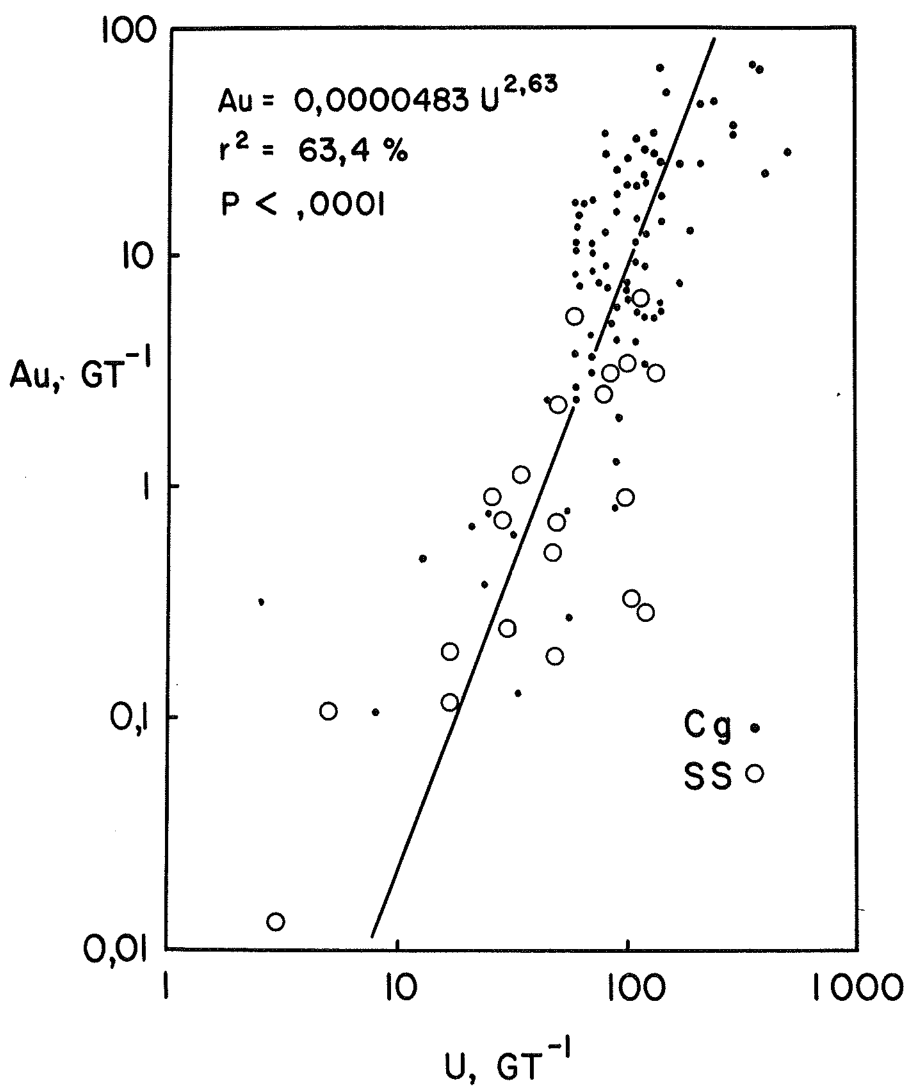

Figure 7 : Gold versus uranium concentrations in Elsburg No. 5 Reef at Vaal Reefs West No. 6 Shaft.

support to the increasingly accepted placer theory for the origin of gold and uranium, viz. both behave as heavy grains physically concentrated by hydraulic sorting processes during transport and deposition. The large positive exponent (2,63) of the regression equation is interesting and not clearly understood (this means that the plot would curve upward on arithmetic coordinates, or, stated another way, that gold/uranium ratios become larger with increasing values of either gold or uranium). Two possible interpretations come to mind. First, the curvilinear relationship may result from grain-size limitations of the uranium mineral (uraninite) imposed by the source. Thus, if increasing gold concentrations were accompanied by increasing proportions of larger gold particles, Hydraulically-equivalent grains of the less-dense uraninite might have been simply unavailable. Downslope distributions of zircon in the Basal Reef may be explained in a similar manner (Minter, 1978), namely by a source-controlled paucity of coarse zircons.

Another possible interpretation for the gold-uranium relationship in Figure 7 lies in the sorting processes which concentrated the heavies. Given the great density-difference between gold and uraninite, processes which optimally concentrate fine gold may not be optimal for concentrating uraninite, even though, in a given case, the latter may be hydraulically equivalent. Interfering effects of grain-density, shape, and surface-area on a rough stream bed in turbulent flow render as suspect, or at least incomplete, any interpretations of sorting based upon simple hydraulic equivalence derived from settling behaviour (for example, see Einstein and Chien, 1953; Brady and Jobson, 1973; Grigg and Rathbun, 1969). In attempting to understand fluid/grain interactions on loose sediment beds, Slingerland (1977), for example, distinguishes "entrainment equivalence" from "hydraulic equivalence" and shows there may be as much as a four-fold difference in the two equivalent sizes when heavies are compared to a quartz standard. Thus, varying grain-properties of gold and uraninite in a changing flow-field may ultimately explain the Figure 7 relation, but we are clearly a long way from understanding the critical grain/fluid interactions that operate at this scale.

The other main feature of Figure 7, i.e. values tending to be higher in conglomerates than sandstones, is well known and bears little comment. Highest concentrations occur in conglomerates that are pebble-supported, well-sorted, and pyrite-rich, giving every indication of being well worked by fluvial flows. Low concentrations occur in poorly-sorted and matrix-supported conglomerates; it is likely that these were deposited rapidly and removed from the sediment/water interface before heavies could concentrate. Several of these examples occur in crossbedded deposits. Sandstones generally contain very low values, except for those with pyrite-rich laminations, which yield some moderate values.

Crossbedded deposits, which form mainly from either migrating trains of dunes (trough crossbeds) or as solitary tabular bodies in expanding flow (planar crossbeds), have generally low gold and uranium concentrations. They represent relatively rapid deposition and provide little opportunity for reworking of bed material. On the other hand, when heavies are supplied and transported with other bedload, local segregations invariably happen in response to hydraulic perturbations imposed by roughness-elements (e.g. ripples and dunes) on the mobile bed. In dune transport, these segregations commonly occur near crests and in troughs. Intermittent avalanching down the dune slip-face (Allen, 1965) may result in redistribution of the heavies from the crest to the crossbed foresets. In some instances, sorting on top of large bedforms (dunes, transverse bars) may be effected by trains of smaller bedforms which spill over the brinkpoint as they migrate downstream (Smith, 1972; Jackson, 1976). The results of these processes are occasional heavy-rich laminations in foresets and troughs of crossbeds, their abundance more a function of supply than of process. Gold and uranium concentrations for several crossbedded deposits are plotted in Figure 8. It is clear that the highest concentrations occur with pyrite-rich deposits, which is interpreted to mean that there was simply a greater local supply of heavy minerals (gold, uraninite, pyrite) for these cases. The local supply was probably a heavy-rich deposit a short distance upstream, formed by some unrelated mechanism. Most non-pyritiferous conglomerates and sandstones have very low concentrations of gold and uranium. Conglomerates are somewhat richer than sandstones, probably because more competent flows, better able to transport heavies, were needed to produce them.

(ii) <u>Bedforms and Channel Morphology</u>

Individual sandstone and conglomerate beds tend to thicken and thin over short distances, as manifestations of bar-and-channel topography. Quantitative estimations of bed irregularity can be computed by a Bed Relief Index (Smith, 1970):

$$BRI = \frac{2[\sum_{i=1}^{n} T \quad \sum_{i=1}^{n} t] \pm Te_1,\ Te_2}{} \times 100$$

in which T is the elevation of a relative high-point between adjacent lows, t the elevation of a low-point between adjacent highs, L the traverse length, and Te_1, Te_2 the elevations of the extreme ends of a traverse, where Te is added if it is a high and subtracted if it is a low. Simply stated, BRI is calculated by subtracting every low point on a bed contact from each of its two adjacent high points, summing the differences, dividing by the traverse length, and multiplying by 100 (to ensure a convenient number greater than 1). Measurements are made from an obvious bedding contact to a datum parallel to average dip (in this case, the surveyed plane marked by cord). BRI for a single bed can be conveniently computed by substituting thickness values for elevations measured from the datum. An example of a BRI calculation is shown in Figure 9.

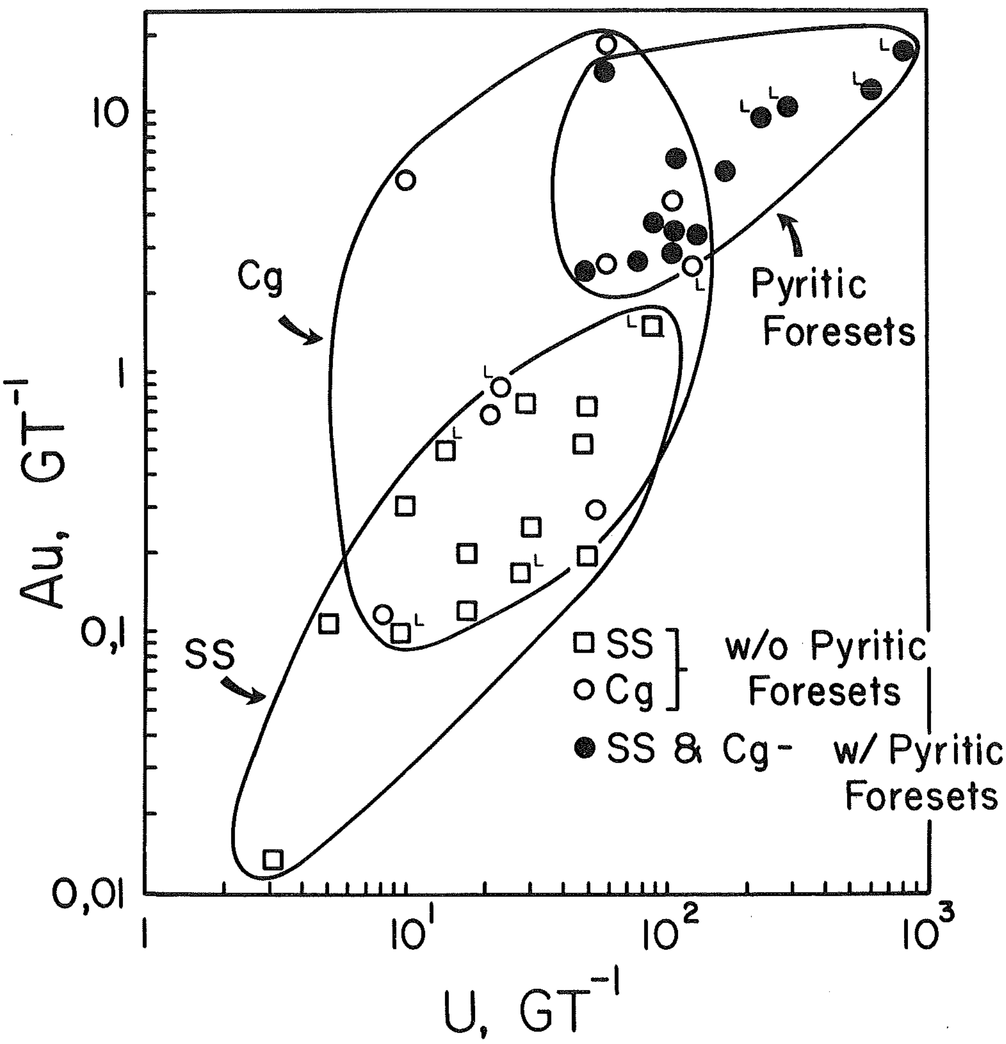

Figure 8 : *Gold and uranium concentrations in crossbedded conglomerates and sandstones. Points marked with L represent Leader Reef specimens; others are Elsburg No. 5 Reef. Note that values are contained by crossbeds with pyritic foresets.*

Bed relief (bedding irregularity) is usually most pronounced in sections transverse to paleoflow because of flow-parallel orientations of bars and channels. This is qualitatively apparent in Figure 5 which shows thickness trends of a conglomerate bed aligned approximately parallel to the mean paleocurrent trend measured from associated crossbeds. The mean BRI computed from SE-NW faces (transverse to flow) is 3,9, whereas the mean value derived from NE-SW faces (parallel to flow) is only 1,5. Significantly, the 3,9 value corresponds closely to values computed for gravelly braided streams dominated by longitudinal bars, from both modern and ancient deposits (Smith, 1970).

The most striking relief feature shown in Figure 5 is a prominent bar form in the (SE) row of pillars (Fig. 10). The bar is succeeded by a sandstone unit composed of a single planar crossbed and a series of trough crossbeds, all indicating unimodal paleocurrents slightly oblique to the bar trend. The bar could be termed longitudinal on the basis of external geometry or diagonal from the orientation of flows over the bar crest (Smith, 1974; Hein and Walker, 1977). Internally, the bar is composed of massive, pebble-supported conglomerates with disseminated pyrite in the matrices. Several distinct pyrite-rich bands occur within the bar; these are interpreted as scour-surfaces upon which pyrite was concentrated between successive events of gravel deposition. The bar is thus a multi-stored feature, a compound longitudinal bar, the form of which was modified frequently by erosion and deposition throughout its history. Such bars are common in some braided streams where channels remain relatively stable (as contrasted with, say, glacial outwash plains where channels and bars tend to be highly transient).

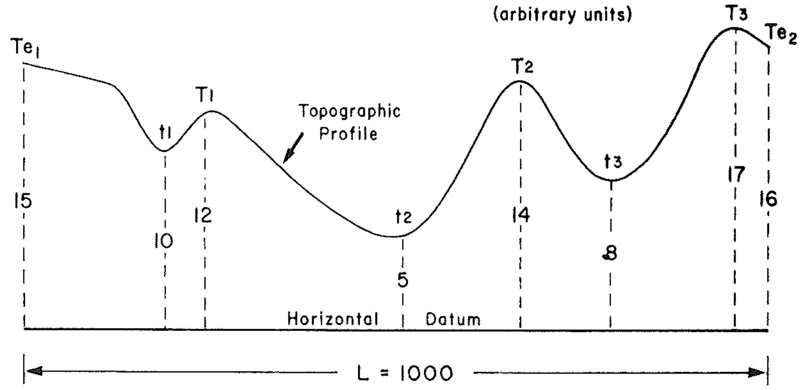

Figure 9 : *Example of bed relief index (BRI) calculation (from Smith, 1970).*

$$BRI = \frac{(15-10) + (12-10) + (12-5) + (14-5) + (14-8) + (17-8) + (17-16)}{1000} \times 100$$

$$= \frac{2[(12 + 14 + 17) - (10 + 5 + 8)] + 15 - 16}{1000} \times 100$$

$$= 3,9$$

(iii) Conclusions

Samples of the bar and overlying sandstones in the Elsburg No. 5 Reef clearly reveal that the highest gold concentrations occur with the pyrite-rich bands (Fig. 11). The maximum concentration observed was 78g/t. Bar samples between pyrite bands invariably contain lower gold values, and none of the sandstone samples revealed significant concentrations. Uranium values likewise tend to be greater in pyrite bands, although their distribution is somewhat more sporadic. Several sandstone samples, usually containing prominent heavy-rich cross-laminations, contained relatively high concentrations, but, overall, the sandstones tend to be poor in uranium as well as gold.

Comparing gold distributions in the conglomerate unit as a whole (of which the bar is a part), the highest concentrations occur within the bar, and values decrease away from the bar axis (Fig. 12). Each "value" in Figure 12 is an average of several channel samples which together represent the entire thickness of the conglomerate bed exposed at that location. The vertical and areal distributions of gold (Figs. 11, 12) lend support to the interpretation that the bar was a relatively stable feature which permitted heavy minerals to concentrate in several horizons during its multi-storied history. For purposes of exploration and selective mining, the relation of the bar's orientation to paleocurrent pattern and bed relief index is worthy of note.

(b) Leader Reef

In gross lithology, the Leader Reef in our study sector is similar to the Elsburg Reef in Klerksdorp. Conglomerates contain mostly quartz and chert pebbles and texturally range from poorly-sorted to well-sorted. Sandstones are mostly crossbedded. The ratio of conglomerate to sandstone in the Leader Reef is similar to that in the Elsburg Reef, but pyrite is less frequent, especially in the sandstones where heavy mineral laminae, so common in the Elsburg Reef, are nearly absent. One significant feature of the Leader Reef not found in the Elsburg Reef is the presence of thin carbonaceous seams along certain bedding contacts. Individual sandstone and conglomerate beds vary in thickness over short lateral distances as reflections of bar-and-channel topography. Bed relief indices could not be measured for reasons mentioned earlier (see "METHODS").

(i) Gold and Uranium Concentration

Gold and uranium concentrations for all Leader Reef samples are shown in Figure 13. As with the Elsburg reef, gold and uranium contents are significantly correlated ($Au = 0{,}045U^{0{,}822}$, $r^2 = 66\%$, $P<0{,}0001$), and well-sorted conglomerates contain higher values than sandstones and poorly-sorted conglomerates. Compared to the Elsburg Reef plot (Fig. 7), two differences are readily apparent: (1) uranium concentrations are much higher in the Leader Reef, and (2) the exponent of the regression (0,822) is less than 1 (Elsburg Reef regression exponent = 2,63). The first

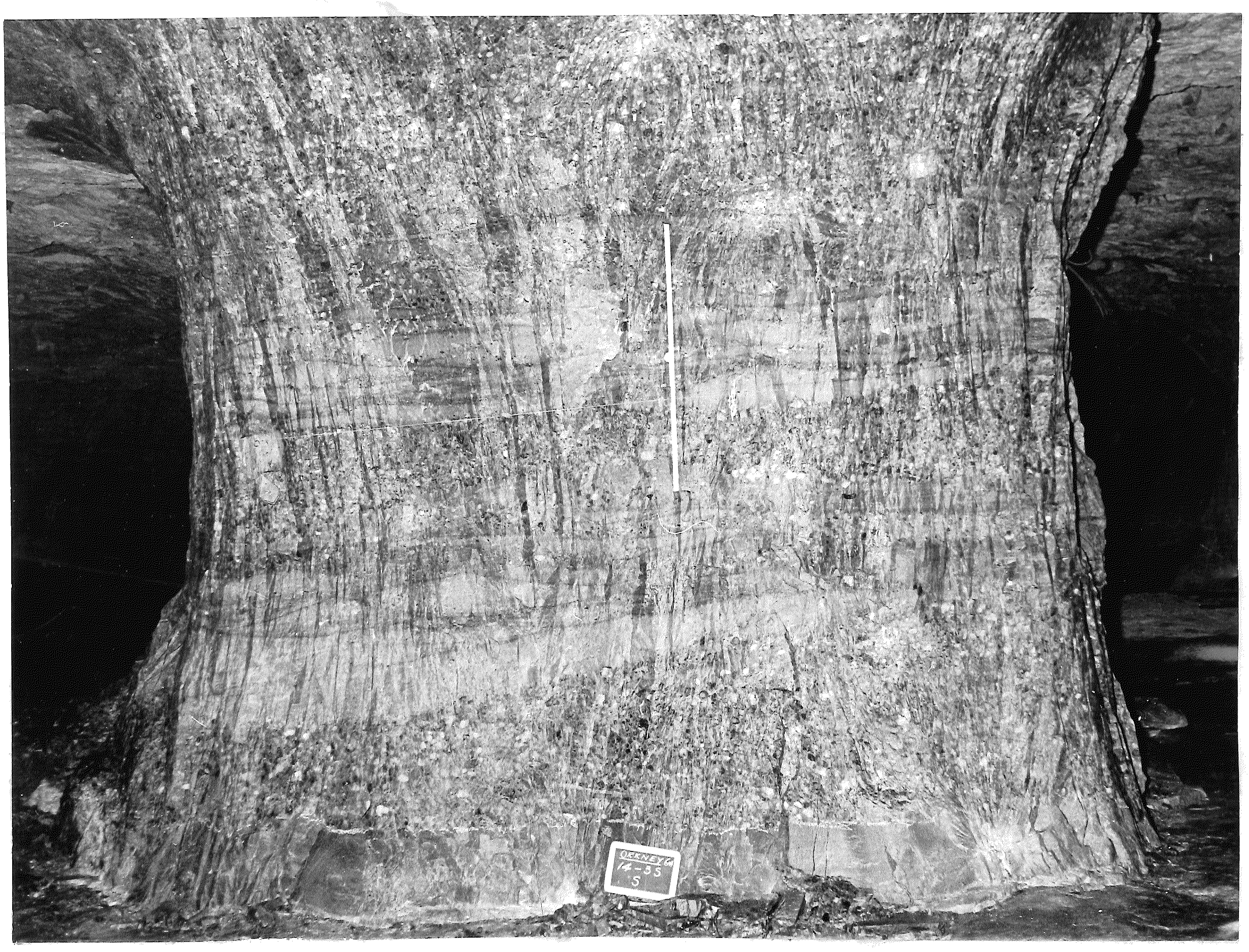

Figure 10 : *Gravel bar form in basal conglomerate of Elsburg No. 5 Reef overlain by crossbedded sandstones. Length of chalkboard is 25 cm. See Figure 5 for location.*

difference is more likely to be due to source-effects than to differences in sorting processes. Pebble-sizes, textures, and sedimentary structures are similar in the two units, and there is no reason to think that their depositional environments were very different (i.e. proximal braided streams). Gold/uranium ratios within a single unit can be expected to change downslope in response to changing stream-power, as shown by Minter (1978) for the Basal Reef, but the Leader and Elsburg Reef sectors examined here probably occupied similar positions in their respective fluvial systems. The significance of the difference between the two regression exponents is less clear. The best-fit line for the Leader Reef data would be slightly curvilinear downward in an arithmetic plot, meaning that gold/uranium ratios decrease with increasing concentrations of either element, a trend opposite of that observed for the Elsburg Reef. Possibly, we are dealing with an unknown sorting effect conditioned by a limited availability of certain grain-sizes in the gold and uraninite populations.

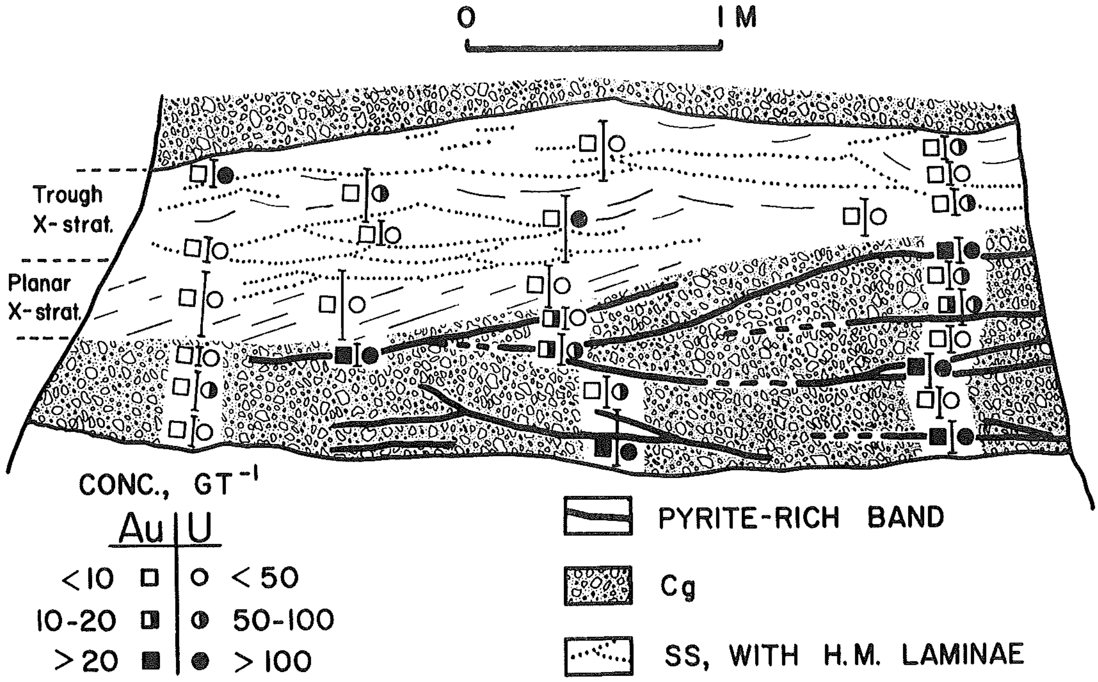

Figure 11 : *Cross-section of gravel bar and overlying sandstones (Fig. 10), showing pyrite-rich and other heavy-mineral (H.M.) bands and distribution of gold and uranium concentrations.*

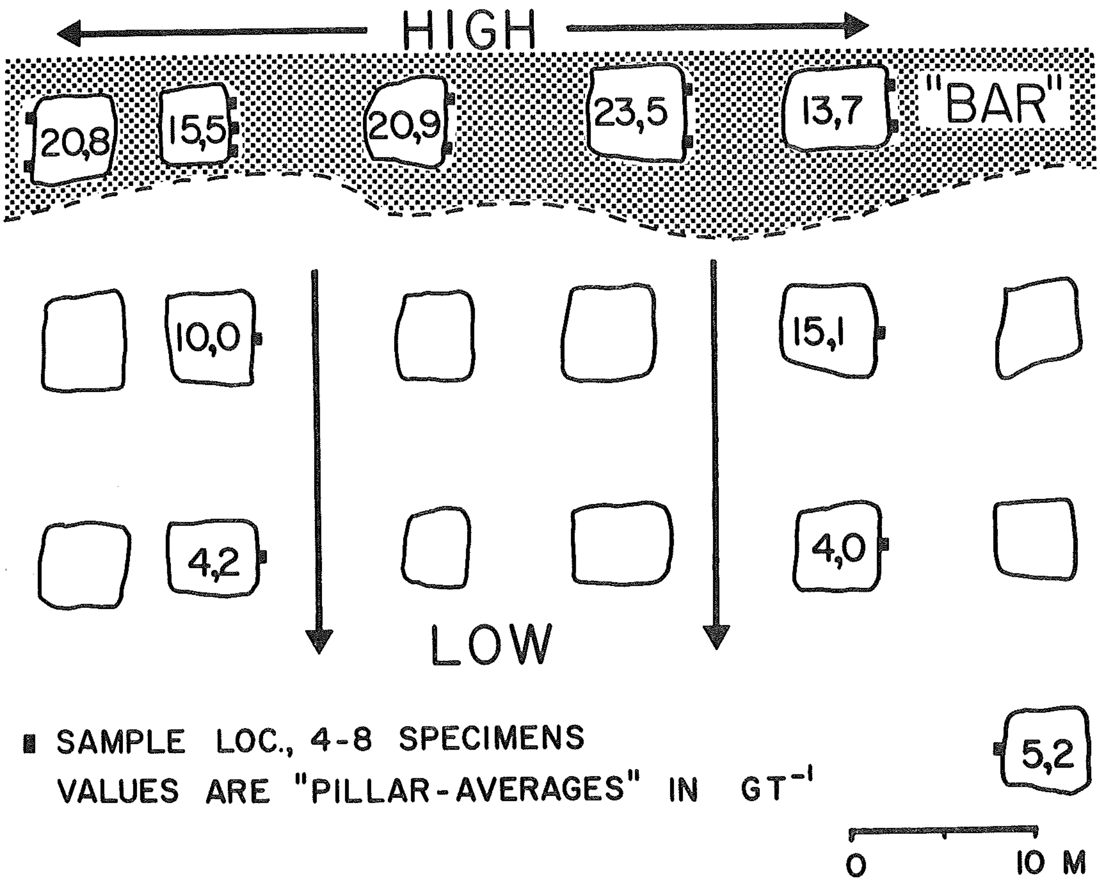

Figure 12 : *Areal distribution of gold values in the Elsburg No. 5 Reef basal conglomerate. Highest values are contained in gravel bar, becoming lower away from bar.*

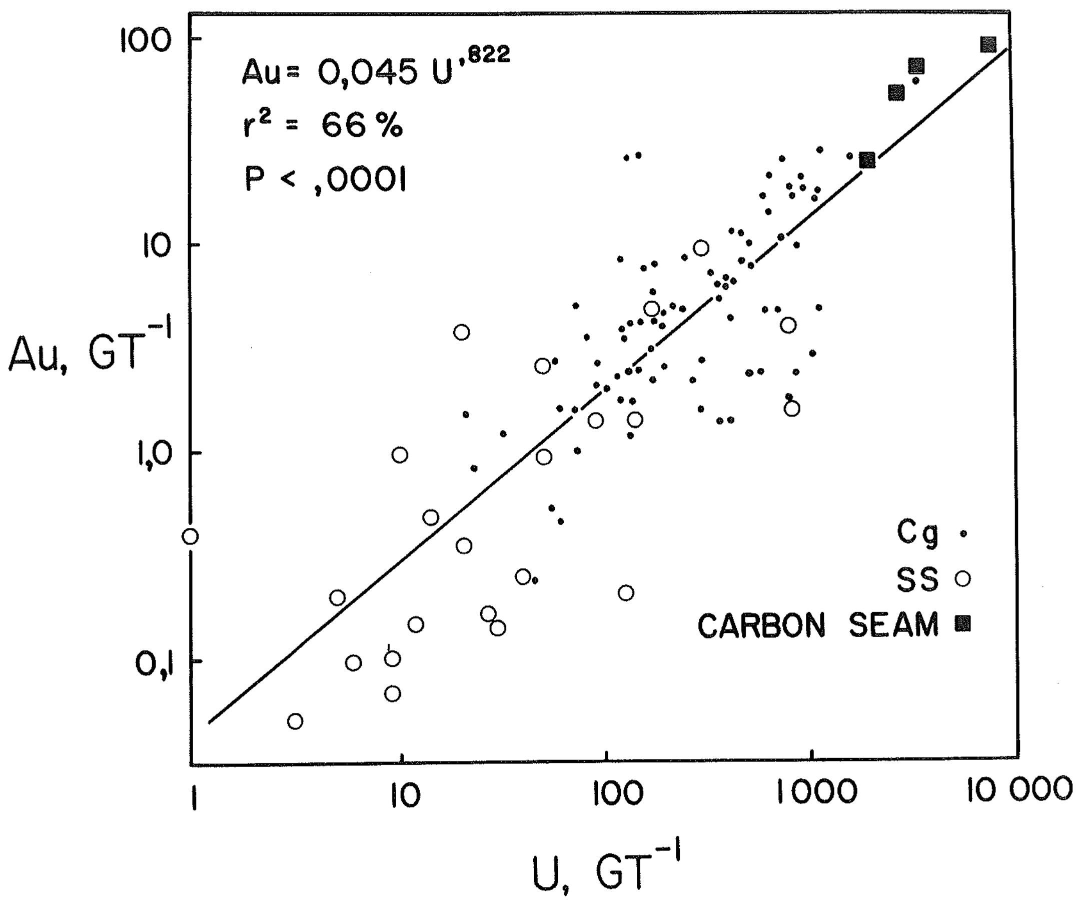

Figure 13 : *Gold versus uranium concentrations in Leader Reef, Welkom No. 3 Shaft, Welkom Goldfield.*

This is purely speculative, of course, but, given the assumption that the depositional processes of the two units were similar, then some kind of source-control explanation for the contrasting plots (Figs. 7, 13) may be tenable. The physical grain-sorting mechanisms that operate with similar depositional environments, however, are varied and complicated, and correct explanation(s) may forever be obscured by the limits of information available from old deposits.

Four samples of conglomerate containing carbonaceous seams yielded very high gold and uranium concentrations (Fig. 13). Interestingly, these samples plot close to the regression line computed for the other samples, suggesting that similar processes operated to concentrate heavies in the carbonaceous seams. These seams are typically associated with scour-surfaces within or at the base of conglomerate beds. We subscribe to the interpretation that the seams are organic (Hallbauer, 1975) and represent tough algal mats which adhered to bar and channel surfaces and baffled fine gold and uraninite particles as sediment mixtures were transported over them. They apparently mark short intervals between episodes of gravel deposition.

Thin conglomerate layers, one or two pebbles thick sandwiched between sandstone beds, are fairly common in the Leader Reef. These pebble-lag deposits probably formed in either of two ways: (1) by short-lived pebble transport over a sand bed, in which case the pebbles simply stopped moving as flow-competence subsided, or (2) by deflation of a pebbly sand deposit, whereby pebbles became exposed and concentrated as a consequence of sand erosion around them. In the first case, pebbles nearly at rest on the sand bed may roll or slide into each other during waning flow until a loosely-packed layer results; this layer effectively armours the underlying sand bed and prevents erosion. The same kind of armouring happens with deflation, only in this case the pebbles are already present within the sand and work to the surface after sand has been removed by currents. This process may operate in water (Gessler, 1967) or air, the latter forming a desert pavement. The effectiveness by which these pebble-lags concentrate heavies were examined by ascertaining gold and uranium contents for several lag samples and their underlying sandstones. Results showed that the lags have higher values than the associated sandstones, but nowhere are values more than moderate (Fig. 14). Depending on which of the two mechanisms operated, the heavies were either trapped by the pebble armour as they were swept over the bed, or they were originally present in the sand and later concentrated at the surface with the pebbles following deflation.

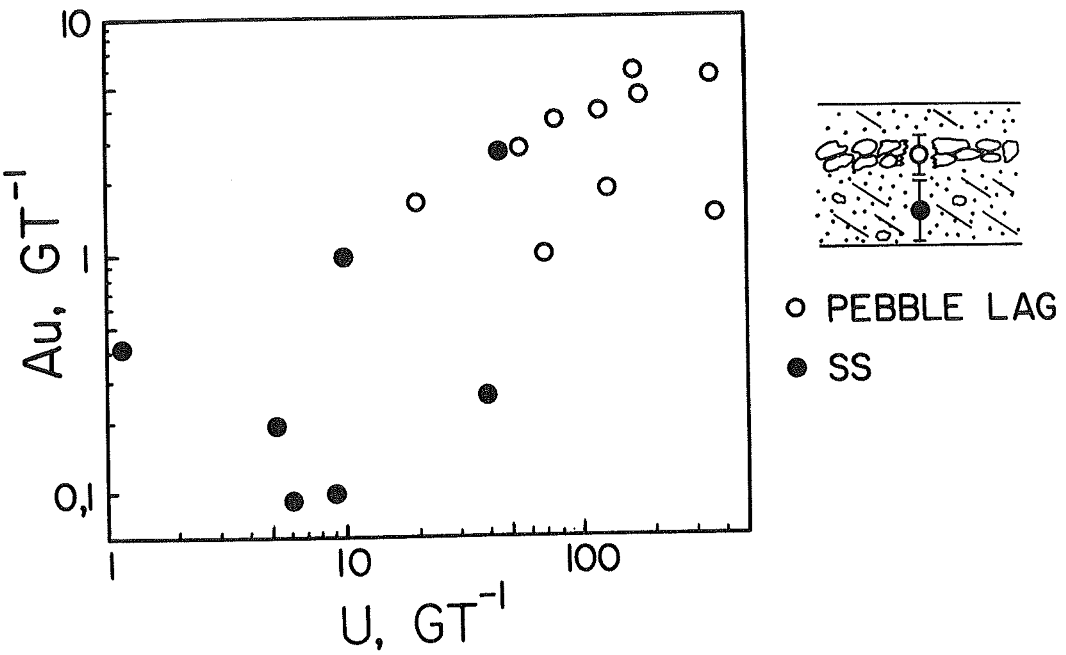

Figure 14 : *Gold and uranium concentrations in pebble lag deposits and underlying sandstones, Leader Reef.*

(ii) Bedforms and Channel Morphology

As in the Elsburg Reef, channel-and-bar forms are characteristic of the Leader Reef. One particularly well-developed channel was examined in detail to see if values could be related to depositional processes inferred from sedimentary structures. In cross-section, the channel margins are exposed in two adjacent pillars showing a width of about 15 metres. One channel margin can be traced some 50 metres along strike, but the deep central portion of the channel is nowhere exposed. Paleocurrents measured from associated trough crossbedding were from the west and northwest.

Gold concentrations are higher on the left side of the channel (facing current) than the right (Fig. 15). Both sides consist of conglomerates along the base overlain by interbedded sandstone and conglomerate. Closer inspection of the left side reveals that the sandstones are composed of mainly planar crossbeds with foresets dipping towards the channel bank. It is likely that these crossbeds were deposited by transverse sand bars formed by backward deflections of currents from the main part of the channel. Such bank-hugger transverse bars are very common in modern braided streams, and, since they are oriented approximately perpendicular to the channel axis, they may add considerable variance to paleocurrent measurements (High and Picard, 1974; Smith, 1972; Cant and Walker, 1976). Bank-hugger bars migrate toward a bank until the increasingly confined flow becomes too strong to permit further growth (Smith, 1971). At this point, sediment transported over the bar edge is carried away by the swift confined flow rather than being deposited at bar foresets. In the Leader Reef example, gold was trapped by gravel that formed the bed of the turbulent bar-to-bank sluiceway. The gold may have been transported over the bar, down the sluiceway, or removed from the adjacent bank material. An interpretive sketch of the Leader channel is shown in Figure 16.

Unfavourable exposure prevented a similar analysis of the other pillars which intercept the channel, making it impossible to discover the channelwise extent of the planar crossbeds shown in Figure 15. It is significant, however, that samples from other pillars along the left channel margin show consistently high values (Fig. 17). Whether these high concentrations are also due to bank-parallel bars is not known, but the linear trend of high values along one easily-recognized channel margin is noteworthy for consideration in selective mining practices.

An interesting two-part deposit is shown in Figure 18. A longitudinal bar composed of well-sorted gravel and oriented parallel to paleoflow was deposited first under swift-flow conditions. Sometime later, under reduced flow, a thin wedge of pyrite-rich sand advanced by foreset accretion over the surface of the bar, which then formed an obstacle on the stream bed. Highest values are found in the sandstone rather than the underlying gravel bar. Ordinarily, the advancing sand-wedge

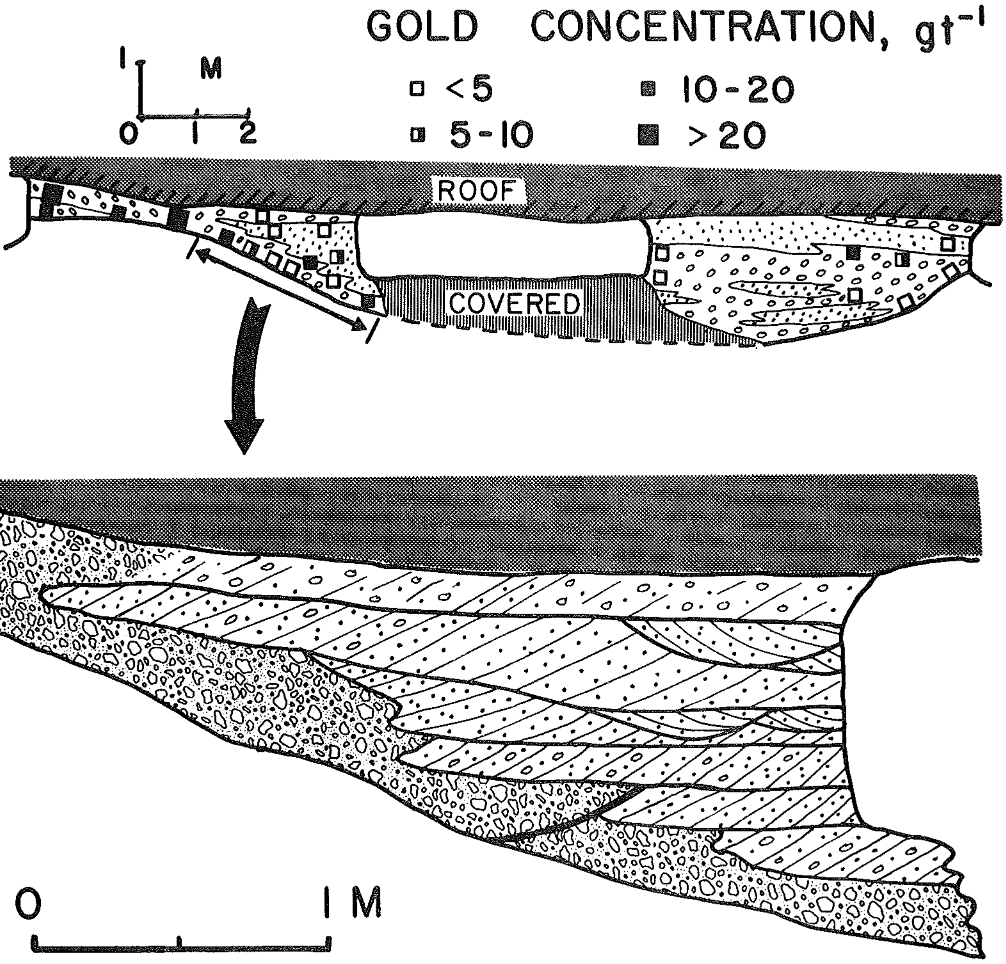

Figure 15 : *Channel structure in Leader Reef exposed in adjacent pillars. Top: distribution of gold, showing higher concentrations on left side of channel. Bottom: enlarged portion of left side of channel, showing channel-bed conglomerate overlain by, and interfingered with, planar crossbedded sandstones with bankward-dipping foresets.*

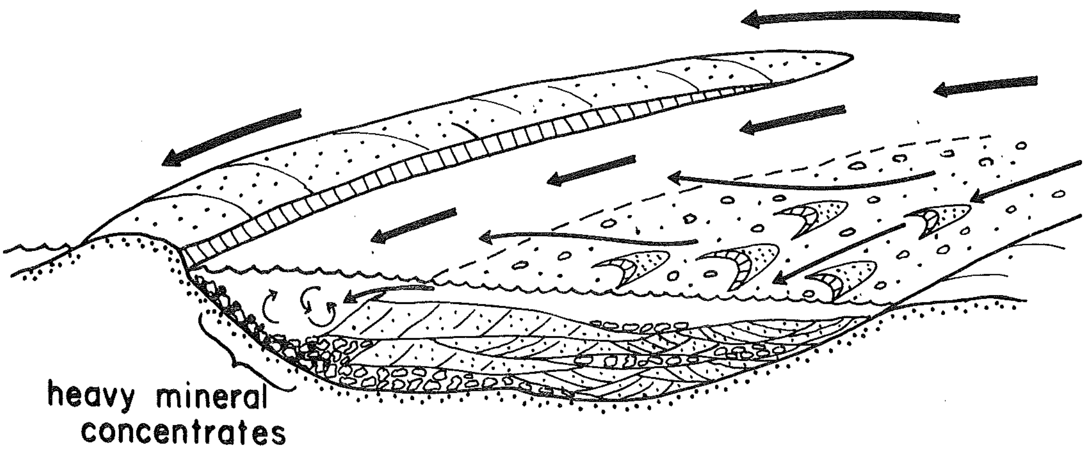

Figure 16 : *Interpretive sketch of Leader Reef channel (Fig. 15). Planar crossbeds are formed by bank-hugger transverse bar enlarging toward bank. Convergent flow becomes increasingly restricted by growing bar margin, reworking channel-bottom sediments and concentrating heavies.*

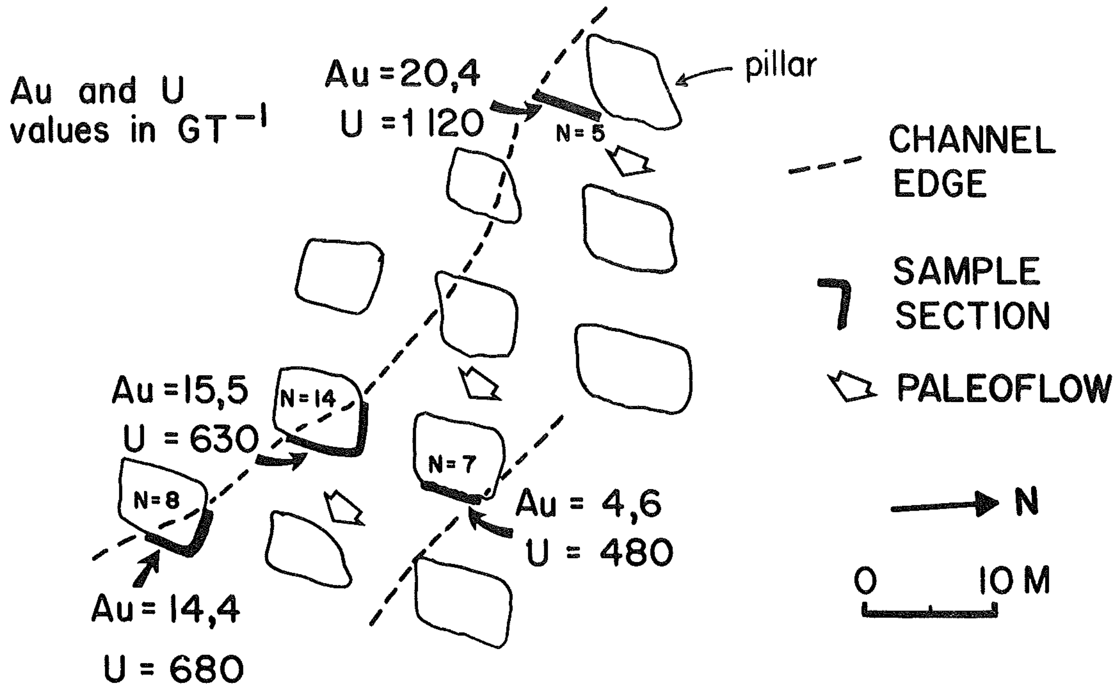

Figure 17 : *Areal distribution of gold and uranium in a Leader Reef channel structure. Values are averages of conglomerate samples only (n = no. of samples per pillar). Note that highest concentration of gold and uranium occurs on left side of channel, facing paleoflow. Pair of pillars near bottom of figure (marked n = 14, n = 7) are source of Figure 15.*

would merely fill in the downstream depression created by the gravel bar, while maintaining a horizontal top-surface parallel to the water surface, a profile of equilibrium as discussed by Jopling (1965). In this case, however, the thickness of the sand unit changed little as it grew over the sloping downstream end of the bar, meaning that the minimum depth in which the sand could be transported became larger in the down-flow direction. This apparent anomaly might be explained by assuming that the total quantity of flow (discharge) was also increasing over the sloping bar surface; thus, increasing depths were compensated for by increasing discharge, so that sediment-transport velocities were maintained along the bed. Such conditions may be obtained at the downstream end of a narrow tapered bar where flows on both sides of the bar merge with flow moving over the bar-surface. Such a zone of flow convergence, as mentioned earlier (Fig. 6), is a likely place to concentrate heavies, which in this case was probably abetted by sorting mechanisms associated with foreset migration. If this interpretation is correct, such a heavy-rich deposit is likely to be very local,i.e. with little lateral extent in any direction.

DISCUSSION AND CONCLUSIONS

In this report, we have attempted to show how some localized gold and uranium concentrations can be explained in terms of sedimentological features and processes inferred from wall-exposures. Some of the local high-value trends are slope-parallel, and their orientations can be reasonably predicted from associated channel and bar orientations, or by paleocurrent measurements. Thus, in such cases, local valuation projections can be extended for greater distances in the direction of paleoflow rather than transverse to paleoflow. Furthermore, stope-wide valuations would be more representative if sampling were done across paleoflow where the maximum number of relief elements (channel and bar forms, highest bed-relief index) would be encountered.

Although certain identifiable structures of the Leader Reef and Elsburg Reef deposits are seen to contain high uranium and gold concentrations, some with predictable linear trends (e.g. the bar and channel forms in Figs. 12 and 17), it should not be assumed that such structures will always yield high values, even if they occur in the same placer horizon and were formed under identical hydraulic conditions. The reason for this lies in the basically random nature of local sediment sources in braided systems. Braided streams, with their constantly-shifting flows and bed-relief elements, can be thought of as a complex environment in which heavies may be either

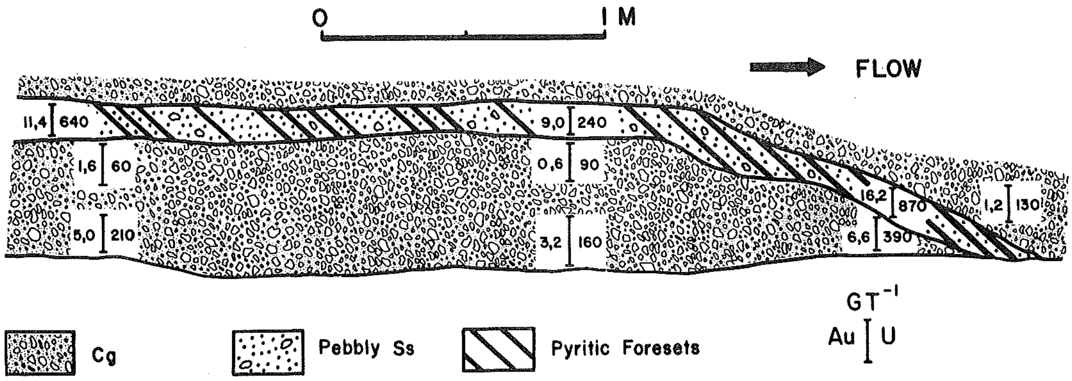

Figure 18 : Longitudinal cross-section of downstream end of longitudinal gravel bar (lower conglomerate) overlain by thin pebbly sandstone with pyritic foresets. Highest gold and uranium concentrations occur in the sandstone.

locally concentrated or dispersed within the alluvium. Certain preferred areas of concentration can be expected in natural streams, for example, in areas of flow convergence (Fig. 6), although, as yet, the locations and causes of such concentrations remain largely uncorroborated from lack of appropriate field studies. Nevertheless, bedload erosion and transport in braided streams tend to be sporadic, and, given the fluctuating and transient character of the local hydraulic environment, we can expect to find very uneven distributions of heavies within the braided deposits. Any local concentration of heavies within the braided complex can thus be thought of as a point-source of heavies for immediate downstream redeposition once that source is reworked (eroded). Downstream processes may then either disperse or concentrate these heavies. On the other hand, if heavies are not supplied to an area of the stream bed where concentration processes are operating, i.e. the upstream point-source is devoid of heavies, a local placer deposit cannot form, no matter how optimal the hydraulic environment may be. In short, to form a local concentration of heavies in braided alluvium, a suitable concentration mechanism and a local point-source deposit containing heavies are both required (Fig. 19).

Such point-sources are, in reality, only temporary deposits in the braided system, such as bar, portion of channel bed, group of dunes, etc. By their nature, therefore, they are transient features. In a slowly-aggrading system, however, some of these temporary deposits inevitably become permanently buried, and the occurrence and lateral extent of any local placer horizon becomes a consequence of both reasonably predictable sedimentologic/hydraulic processes and totally unpredictable local point-sources. For this reason, two deposits having identical sedimentary textures and structures within the same reef may have very different heavy mineral concentrations. The concentrating processes may have been the same, but the compositions of their local point-sources could have been different. Thus, there will probably always be this inherently random element involved in attempts to predict local placer occurrences and trends from sedimentological information.

In spite of this random element, local prediction and valuation can undoubtedly be improved with a better knowledge of placer-forming processes and their relations to identifiable (and preservable) sedimentary features, such as structure and texture. The results of this study are more suggestive than conclusive; we have been able to show that some local concentrations can be reasonably interpreted in terms of sedimentological elements present in braided streams and that certain of these elements have linear trends parallel to paleoflow. The extent to which these features and their associated values are typical must await further studies of this kind.

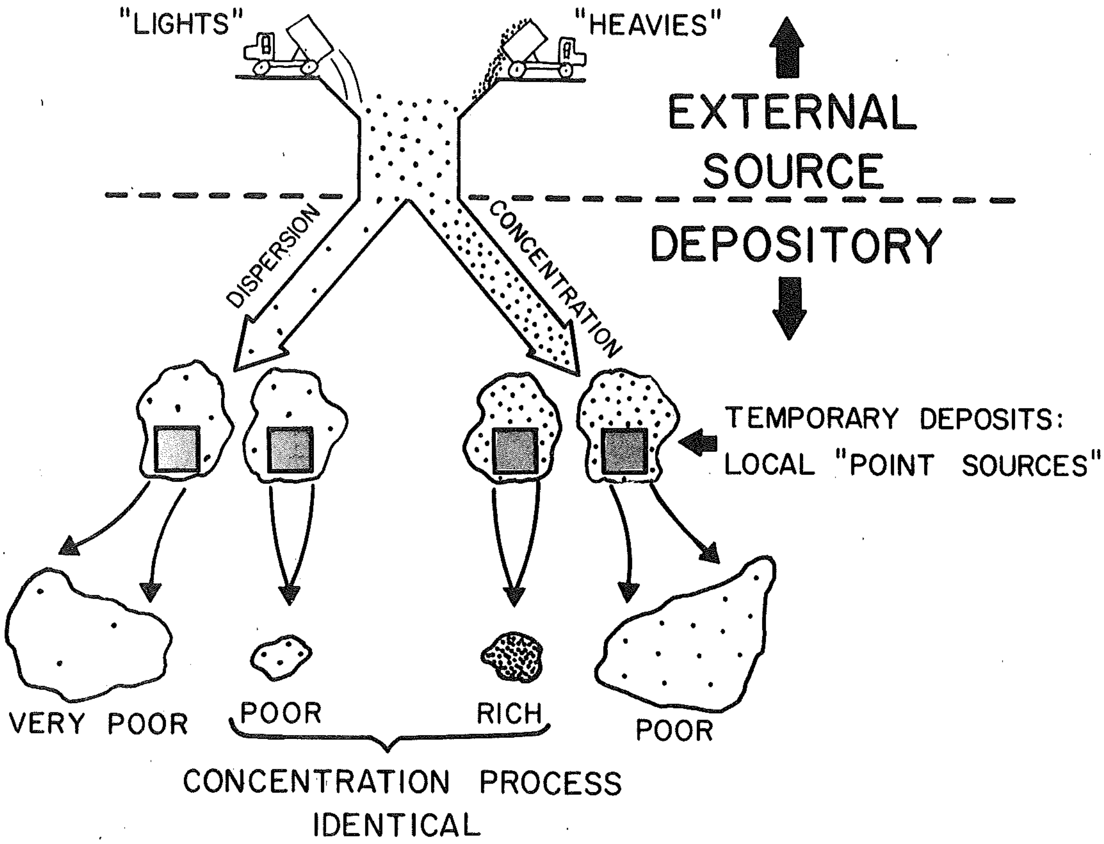

Figure 19 : *Schematic model showing effect of local point-sources in determining local placer occurrences. Deposits rich in heavies are most likely where both an efficient concentrating mechanism operated and where the upstream point-source supplied abundant heavy minerals.*

REFERENCES

Allen, J.R.L. (1965) : Sedimentation to the lee of small underwater sand waves - an experimental study : Jour. Geology, v. 73, p. 95-116.

Boothroyd, J.C., and Ashley, G.M. (1975) : Processes, bar morphology and sedimentary structures on braided outwash fans, northeastern Gulf of Alaska : in Glaciofluvial and glaciolacustrine sedimentation : S.E.P.M. Sp. Pub. 23, p. 193-222.

Brady, L.L., and Jobson, H.E. (1973) : An experimental study of heavy-mineral segregation under alluvial-flow conditions : U.S. Geol. Surv. Prof. Paper 562-K, 38 pp.

Butler, P.R. (1977) : Movement of cobbles in a gravel-bed stream during a flood season : Geol. Soc. Amer. Bull., v. 88, p. 1072-1074.

Cant, D.J., and Walker, R.G. (1976) : Development of a braided-fluvial facies model for the Devonian Battery Point Sandstone, Quebec : Canad. J. Earth Sci., v. 13, p. 102-119.

Cant, D.J., and Walker, R.G. (1978) : Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada : Sedimentology, v. 25, p. 625-648.

Church, M.A. (1972) : Baffin Island sandurs : a study of Arctic fluvial processes : Geol. Surv. Canada Bull. 216, p. 1-208.

Collinson, J.D. (1970) : Bedforms of the Tana River, Norway : Geogr. Annal., v. 52A, p. 31-56.

Collinson, J.D. (1971) : Current vector dispersion in a river of fluctuating discharge : Geologie en Mihnb., v. 50, p. 671-678.

Crampton, F.A. (1937) : Occurrence of gold in stream placers : Mining Jour., v. 20, p. 3-4, 33-34.

Einstein, H.A., and Chien, N. (1953) : Transport of sediment mixtures with large ranges of grain sizes : Univ. California Inst. Engineering Research, Berkeley, Calif., 49 pp.

Fahnestock, R.K. (1963) : Morphology and hydrology of a glacial stream - White River, Mount Rainier, Washington : U.S.G.S. Prof. Paper 422 A, p. 1-70.

Fahnestock, R.K., and Bradley, W.C. (1973) : Knik and Matanuska Rivers, Alaska : a contrast in braiding : in M. Morisawa (ed.), Fluvial Geomorphology, Proc. 4th Annual Geomorph. Symp., SUNY-Binghamton, N.Y., p. 221-250.

Gessler, J. (1967) : The beginning of bedload movement of mixtures investigated as natural armoring in channels : Calif. Inst. of Tech., W.M. Keck Lab. of Hydraulics and Water Resources, Translation T-5, p. 1-89.

Grigg, N.S., and Rathbun, R.E. (1969) : Hydraulic equivalence of minerals with consideration of the re-entrainment process : U.S. Geol. Surv. Prof. Paper 650-B, p. B77-B860.

Hallbauer, D.K. (1972) : Distribution and size of gold particles in reefs : Chamber Mines S. Afr., Ann. Rept., v. 10, p. 24-29.

Hallbauer, D.K. (1975) : Plant origin of the Witwatersrand carbon : Minerals Sci. Engr., v. 7, p. 111-131.

Hein, F.J., and Walker, R.B. (1977) : Bar evolution and development of stratification in the gravelly braided Kicking Horse River, B.C. : Canad. Jour. Earth Sci., v. 14, p. 562-570.

Henderson, F.M. (1963) : Stability of alluvial channels : Amer. Soc. Civil Engrs. Trans., v. 128, p. 657-720 (with discussion).

High, L.R., and Picard, M.D. (1974) : Reliability of cross-stratification types as paleocurrent indicators in fluvial rocks : Jour. Sed. Petrol., v. 44, p. 158-168.

Jackson, R.G. (1976) : Largescale ripples of the lower Wabash River : Sedimentology, v. 23, p. 593-623.

Jopling, A.V. (1965) : Laboratory study of the distribution of grain-sizes in cross-bedded deposits : in Middleton, G.V. (ed.), Primary sedimentary structures and their hydrodynamic interpretation : S.E.P.M. Sp. Pub. 12, p. 53-65.

Knowles, A.G. (1967) : A paleocurrent study of the Ventersdorp Contact Reef at Western Deep Levels Limited on the Far West Rand : unpub. M.Sc. thesis, U. Witwatersrand, Johannesburg, 122 pp.

Krigstrom, A. (1962) : Geomorphological studies of sandur plains and their braided rivers in Iceland : Geog. Annaler., v. 44, p. 328-346.

Krumbein, W.C., and Orme, A.R. (1972) : Field mapping and computer simulation of braided-stream networks : Geol. Soc. America Bull., v. 83, p. 3369-3380.

Lane, E.W. (1957) : A study of the shape of channels formed by natural streams flowing in erodable material : U.S. Army Corps of Engrs., Missouri River Div., Sediment Ser. no. 9, 106 pp.

Leopold, L.B., and Wolman, M.G. (1957) : River channel patterns : braided, meandering, straight : U.S.G.S. Prof. Paper, 282-B, p. 39-85.

Lowright, R., Williams, E.G., and Dachille, F. (1972) : An analysis of factors controlling deviations in hydraulic equivalence in some modern sands : Jour. Sed. Petrol., v. 42, p. 635-645.

McGowen, J.H., and Groat, C.G. (1971) : Van Horn Sandstone, West Texas : an alluvial fan model for mineral exploration : Bureau of Econ. Geol., U. of Texas, Rept. of Investigations No. 72, 57 pp.

McQuivey, R.S., and Keefer, T.N. (1969) : The relation of magnetite over ripples : U.S. Geol. Surv. Prof. Paper 650-D, p. D244-D247.

Miall, A.D. (1977) : A review of the braided-river depositional environment : Earth Sci. Rev., v. 13, p. 1-62.

Minter, W.E.L. (1970) : Gold distribution related to the sedimentology of a Precambrian Witwatersrand conglomerate, South Africa, as outlined by moving-average analysis : Econ. Geol., v. 65, p. 963-969.

Minter, W.E.L. (1976) : Detrital gold, uranium, and pyrite concentrations related to sedimentology in the Precambrian Vaal Reef placer, Witwatersrand, S. Africa : Econ. Geol., v. 76, p. 157-176.

Minter, W.E.L. (1978) : A sedimentological synthesis of placer gold, uranium and pyrite concentrations in Proterozoic Witwatersrand sediments : in A.D. Miall (ed.), Fluvial Sedimentology, Canad. Soc. Petrol. Geol. Mem. 5, p. 801-829.

Mosley, M.P., and Schumm, S.A. (1977) : Stream junctions - a probable location for bedrock placers : Econ. Geol., v. 72, p. 691-694.

Osterkamp, W.R. (1978) : Gradient, discharge, and particle-size relations of alluvial channels in Kansas, with observations on braiding : Amer. Jour. Sci., v. 278, p. 1253-1268.

Pretorius, D.A. (1976) : The nature of the Witwatersrand gold-uranium deposits : K.H. Wolf (ed.), Handbook of strata-bound and stratiform ore deposits : Elsevier Publishing Co., Amsterdam, p. 29-88.

Schumm, S.A. (1968) : Speculations concerning paleohydrologic controls of terrestrial sedimentation : Geol. Soc. Amer. Bull., v. 79, p. 1573-1588.

Schumm, S.A. (1977) : The fluvial system : J. Wiley & Sons, New York, 338 pp.

Schumm, S.A., and Khan, H.R. (1972) : Experimental study of channel patterns : Geol. Soc. Amer. Bull., v. 83, p. 1755-1770.

Sestini, G. (1973) : Sedimentology of a placeoplacer : the gold-bearing Tarkwaian of Ghana : in: G.C. Amstutz and A.J. Bernard (eds.), Ores in Sediments, Springer-Verlag, Berlin, p. 275-306.

Sims, J.F.M. (1969) : The stratigraphy and paleocurrent history of the Upper Division of the Witwatersrand system on President Steyn mine and adjacent areas in the Orange Free State goldfield, with specific reference to the origin of auriferous reefs : unpub. Ph.D. thesis, U. Witwatersrand, Johannesburg, 181 pp.

Slingerland, R.L. (1977) : The effects of entrainment on the hydraulic equivalence relationships of light and heavy minerals in sands : Jour. Sed. Petrol., v. 47, p. 753-770.

Smith, N.D. (1970) : The braided stream depositional environment : comparison of the Platte River with some Silurian clastic rocks, north-central Appalachians : Geol. Soc. Amer. Bull., v. 81, p. 2993-3014.

Smith, N.D. (1971) : Transverse bars and braiding in the Lower Platte River, Nebraska : Geol. Soc. Amer. Bull., v. 82, p. 3407-3420.

Smith, N.D. (1972) : Some sedimentological aspects of planar cross-stratification in a sandy braided river : Jour. Sed. Petrology, v. 42, p. 624-634.

Smith, N.D. (1974) : Sedimentology and bar formation in the Upper Kicking Horse River, a braided outwash stream : Jour. Geol., v. 81, p. 205-223.

Vos, R.G. (1975) : An alluvial plain and lacustrine model for the Precambrian Witwatersrand deposits of South Africa : Jour. Sed. Petrol., v. 45, p. 480-493.

Williams, P.F., and Rust, B.R. (1969) : The sedimentology of a braided river : Jour. Sed. Petrol., v. 39, p. 649-679.

] [