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Fluvial gold placers and basin-margin rotation

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Introduction

A single placer field, the Witwatersrand in South Africa, has produced over half the world's gold. Other fluvial placer fields have also been very productive, so that fluvial placer deposits clearly are the most important type of gold deposit. The Witwatersrand field, however, so overwhelms the others in productivity that explanations for its uniqueness have been sought. One likely factor is its great age, over 2.7 billion years; at that time the earth's atmosphere is thought to have been somewhat reducing, leading to an unusual heavy mineral assemblage dominated by pyrite with subordinate uraninite.[2] This factor alone would make the Witwatersrand unusual but not unique.

The Witwatersrand deposits occur in six alluvial fans disposed on an arcuate margin of the Witwatersrand basin (figure 1, right). Alluvial fans in general are a rather uncommon environment for gold concentration. Thus it is of interest to consider what factor has converted a potentially unfavorable environment at Witwatersrand into a favorable one. Such a factor combined with favorable atmospheric composition could have produced a truly unique deposit. Once this factor is known, it would be an exploration tool for fluvial gold placers of any age. The purpose of this paper is to propose such a factor.

Requirements of placer concentration

A placer deposit is by definition a natural enrichment of dense minerals by fluid flow. Recent work (Slingerland, 1977, 1984; Komar and Wang, 1984; Force, 1991a,b) has shown that placer concentration generally occurs by the sequential operation of two or more hydraulic laws on the same grain population, such that the large light

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[2] But why is gold part of this assemblage? Perhaps reducing weathering has disaggregated the source rocks into monocrystalline grains, freeing gold and increasing the ratio of sandstone to conglomerate. See Siever and Woodford (1979).

grains selected by the first process are removed by the second. The first process is generally the sorting of grains by settling velocity (settling equivalence). The overprinting second process, called entrainment equivalence (with some help from transport and dispersive equivalence), is basically an erosional process.

For a placer deposit to form, this hydraulic concentration must be preserved. Preservation is something of a paradox, as it must immediately follow erosion. Thus a general law of placer formation is that the proceeds of net erosion in one part of the cycle must be followed by net deposition in the next part of the cycle, without remixing of grain populations. These requirements are the reason that placer concentrations are seldom encountered in sedimentary sequences. Additional prior requirements for concentrations of specific heavy minerals are outlined by Force (1991b).

Application to basin-margin fans

Let us consider alluvial fans in this context. A normal alluvial fan is an inefficient machine for producing concentrations, because a given locality is either in an aggradational (accumulation) or a degradational (erosional) mode. Erosion is not temporally sandwiched between depositional episodes, except as bank erosion coupled with sporadic sedimentation during downcutting of washes. Resulting shoestring enrichment will be preserved only at the base of the next aggradational cycle. Some exceptions are known (McGowen and Groat, 1971).[3]

In terms of this analysis, however, the Witwatersrand fans are not "normal" alluvial fans. The margins of the Witwatersrand basin were being uplifted relative to its center in such a way that alluvial fans along its margins were being tilted toward the basin as they grew (Pretorius, 1976; Minter, 1982; Minter and others, 1988). So we need to re-analyze this case.

In top-to-the-basin rotation of an alluvial fan about a

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[3]Alluvial fans formed in dry climates suffer an additional disadvantage. Water from a flow is lost into the bed, producing an increasingly viscous flow. Grains are prevented from settling, and rapid flow deceleration telescopes grain populations.

horizontal axis, the depositional equilibrium surface is destroyed by steepening. If the apparent axis of rotation[4] is within the fan, the headward portion of the old surface is eroded, and deposition occurs on its lower portions. The drainage headwaters and its addition of juvenile debris may temporarily decouple from the fan, depending on the behavior of rotation along the fan-bedrock contact.

Figure 2 shows three successive surfaces formed during fan rotation. Rotation makes the headward segment of the oldest surface inactive, and induces erosion there to form depositional unit I. For the moment let us assume no horizontal transport for disseminated gold that is eroded from the headward portion of the oldest surface. This limiting case is somewhat reasonable, as examples abound where detrital gold is transported little when its host is eroded away. In this case, then, gold will line the channel on the intermediate-age surface in interval AB.

To make a gold deposit from this enrichment, we need to preserve it. Preserving all of it would be difficult on this rotating fan, but we can preserve some of it, segment AC, if the fan rotates in such a way that the youngest surface and its associated depositional unit II overlap the intersection of the oldest and the intermediate-age surface (point A). Portion BC of the enrichment is not preserved, but its gold is not wasted to the system; grains eroded from it, and disseminated gold eroded from the headmost portion of the intermediate-age fan, now line the channel of the youngest fan surface in segment BC. Part of this enrichment will also be preserved if fan rotation continues in the same style.

Note that in this limiting case, the apparent axis of fan rotation must move to the left, i.e. toward the margin of the basin, for gold-placer preservation to occur (in order that a segment AC exist). This geometry is commonly observed in the Witwatersrand (figure 3, from Minter and others, 1988; compare with figure 4A). From this analysis it seems that the effect of the observed stratigraphic

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[4] Apparent rotation axis as used here is the intersection of the base of a depositional unit with its top, projected if necessary through overlying units. The term is related to that of a "hinge line" but is better adapted to an incremental (or differential) approach.

geometry is to preserve the valuable concentrations.

Now let us permit some transport of gold. Unlimited transport would disseminate gold through the depositional units, and the concentrations would be destroyed. This consideration and the known transport habits of gold suggest that we specify a very modest transport distance (d). In figure 2, both segment AB where gold lines the channel, and segment AC where enrichment is preserved, would be augmented on the right side by (d). However, enrichments at the downstream end of the lengthened segment would have a tendency to be dispersed in depositional units.

The requirements for motion of the apparent axis of basin rotation are modified by permitting gold transport. Figure 5 maintains the same length of preserved concentration (AC in figure 2) with a lesser rotation-axis migration (AC minus d). One can envisage cases where the preserved segment consists entirely of (d); in this case the apparent axis of rotation remains stationary (figure 4B). Indeed, the preserved segment may consist of only part of (d); in this case the rotation axis may migrate slowly basinward (figure 4C). The Witwatersrand placers provide examples of this phenomenon also (figure 1, left). However, basinward migration of the apparent rotation axis for each successive fan must be less than gold transport distance.

Model

Regardless of the details, we have specified some important requirements for gold concentration in alluvial fans:

1. A wet-climate fan rotates into the basin;
2. The apparent axis of rotation must remain in the fan; and
3. The lateral motion of the rotation axis can be toward the basin margin or stationary. Migration may even be slowly toward the basin if this migration occurs more slowly than basinward gold transport.

These requirements clarify the uniqueness of the Witwatersrand. The basin tectonics met all the above conditions during the accumulation of about 3000 m of fan sediments. This would seem remarkable. Thus the Witwatersrand is apparently unique because two unusual factors combined. The first was the great age of the basin; the second was optimal tilting of the depositional system during accumulation.

Application to related depositional systems

I suspect that application of this analysis may not be restricted to alluvial fans. In this connection it is instructive to address some depositional systems that behaved differently.

Figure 6 (upper) shows the Sacramento Valley basin (Cretaceous through upper Tertiary) along with a reconstruction (by Lindgren, 1911, and Yeend, 1974) of the Eocene fluvial system in the Sierra Nevada foothills. Gravels of this system, fortuitously preserved under lava, were the most productive gold ores of the region. The cross-section (figure 6, bottom) shows the relation of basin geometry to the tilted Sierran block. The axis of apparent rotation of the early Tertiary formations is outside the basin and slightly to the east. This (and other considerations) would explain the lack of placer gold discoveries in the exposed lower Tertiary rocks of the basin. Note, however, that the fluvial gold placers of the foothills coincide roughly with the apparent rotation axis of the basin. This example suggests that extrabasinal gold placers may be controlled by a former tilting geometry. In some districts this fact would have left no trace. In others, like the Sacramento Valley basin, tilting geometry of an adjacent basin can be used to monitor the tilting history of the placer deposit.

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Illustrations

Figure 1. -- Alluvial fans in the Witwatersrand field, South Africa. The disposition of individual fans around the basin margin is shown on the right. The inset, to the left, enlarges the relations of individual placer-bearing subfans in the Klerksdorp fan. The upper Witwatersrand group, containing the main placer deposits, comprises horizons 4 through 7. Depiction modified from Pretorius (1976).

Figure 2. -- Schematic cross-section of three successive fan surfaces on a rotating basin margin. Points A, B, and C on the surface of intermediate age are discussed in the text. Segment d is the distance of gold transport; I and II are depositional units.

Figure 3. -- Cross-section of the Welkom fan, Witwatersrand placer field, South Africa, from Minter and others (1988).

Figure 4. -- Stratigraphy in cross-section resulting from three cases of migration of the apparent axis of rotation. A. Toward the margin of the basin (taken from figure 2, adding erosional truncations); B. Stationary; C. Basinward.

Figure 5. -- Schematic cross-section of three fan surfaces, with notation as in figure 2. The difference in apparent rotation axis migration in this figure and figure 2 is discussed in the text.

Figure 6. -- Map and cross-section of the Sacramento Valley basin and Sierra Nevada foothills. Drainages shown in the Sierra are not modern but Eocene. In the cross-section, only Tertiary units are shown; the bottom two are Eocene.

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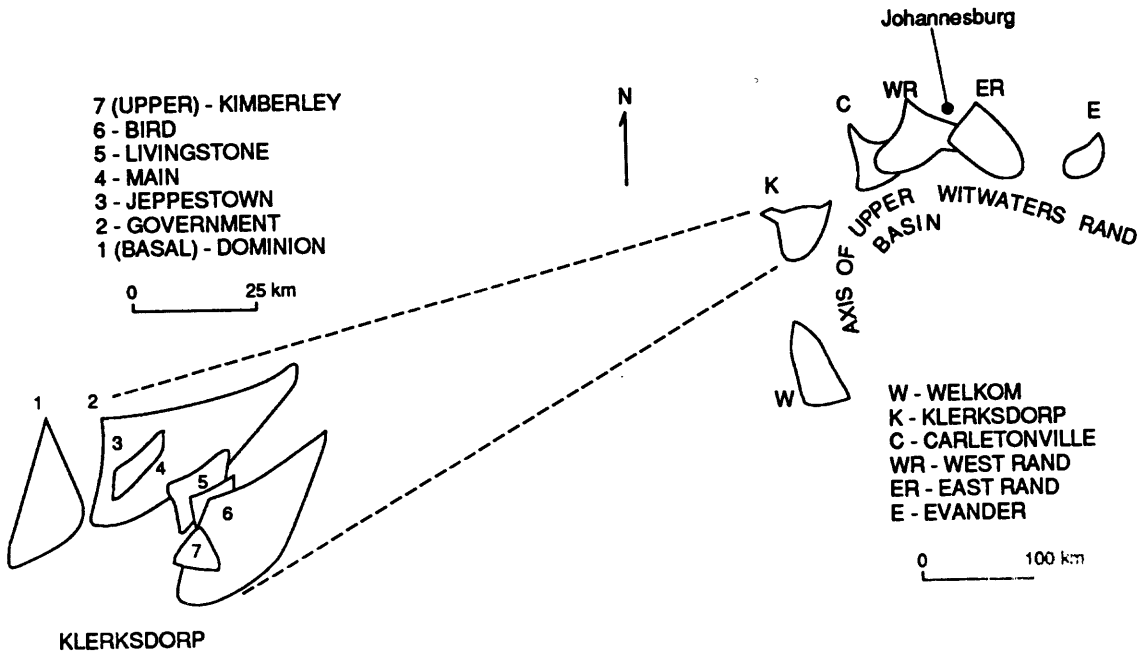
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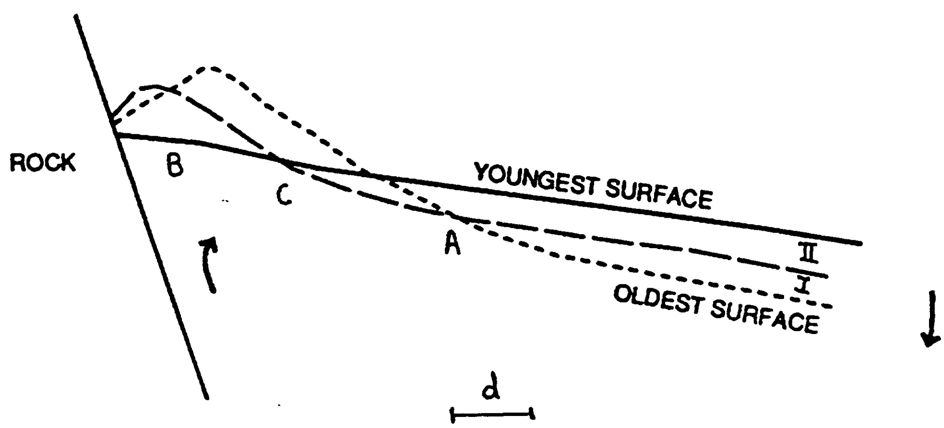

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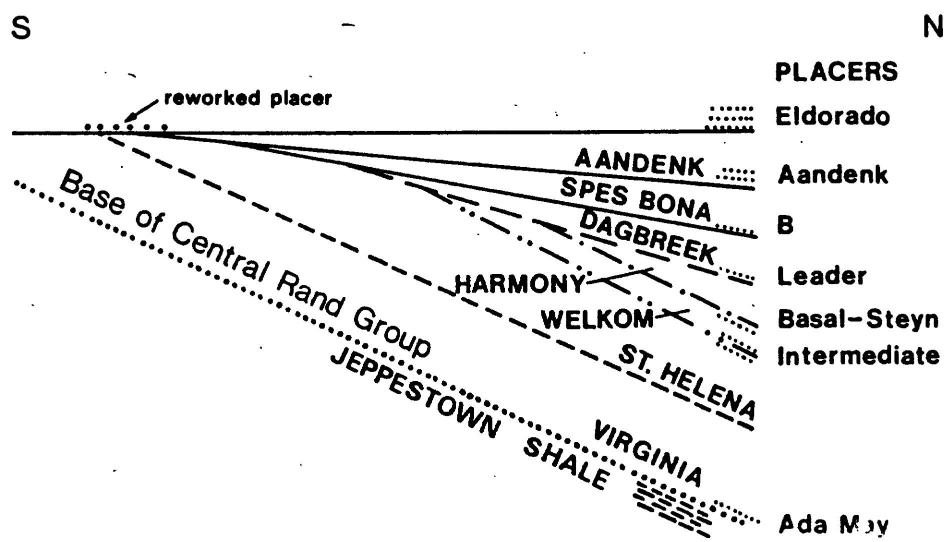

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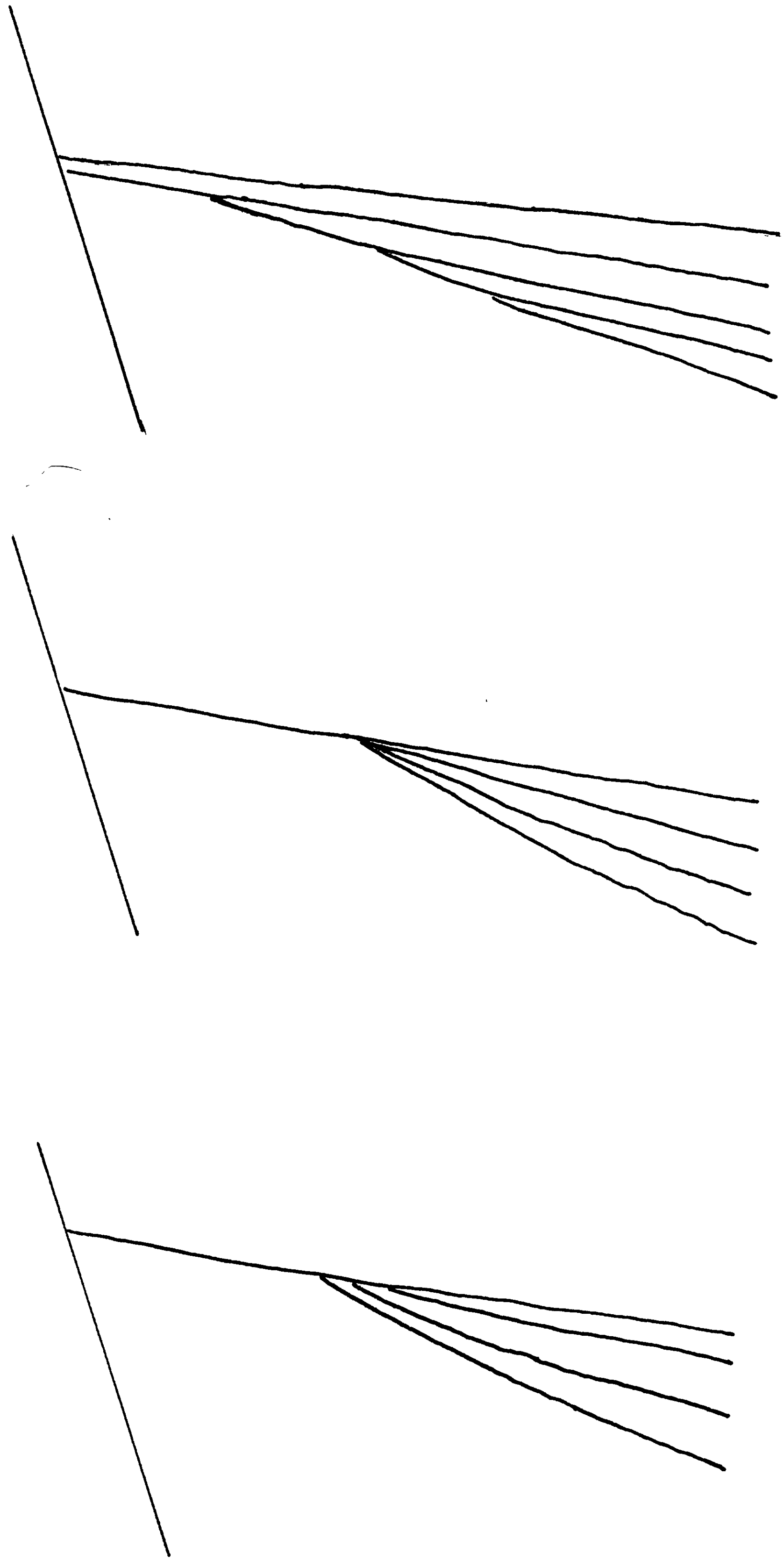

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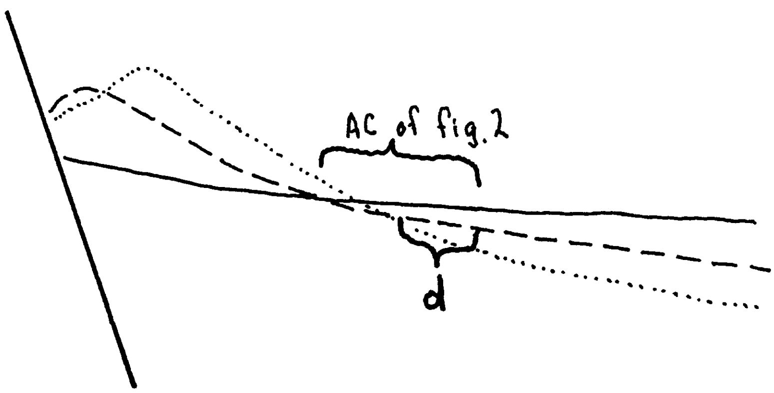

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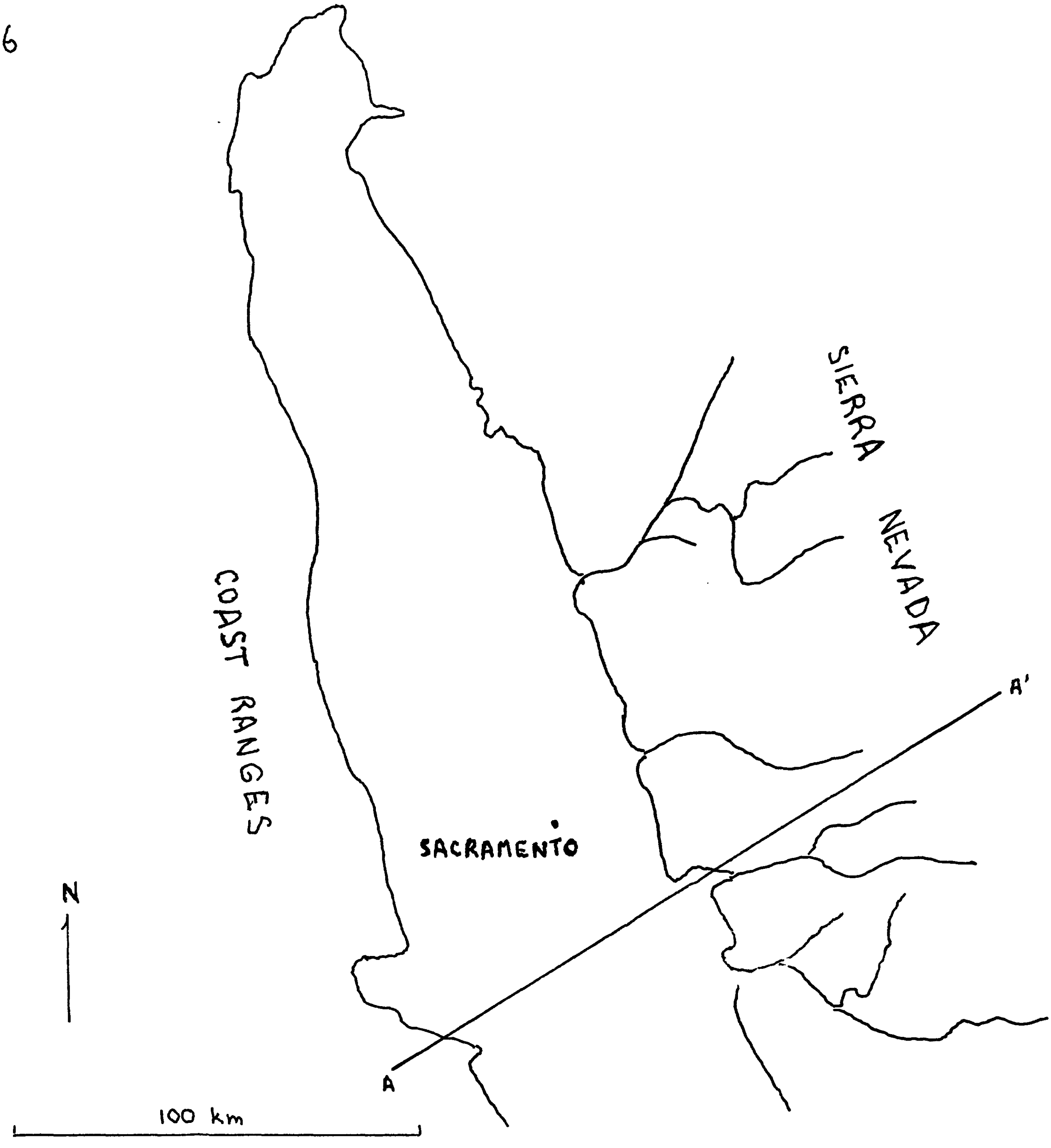
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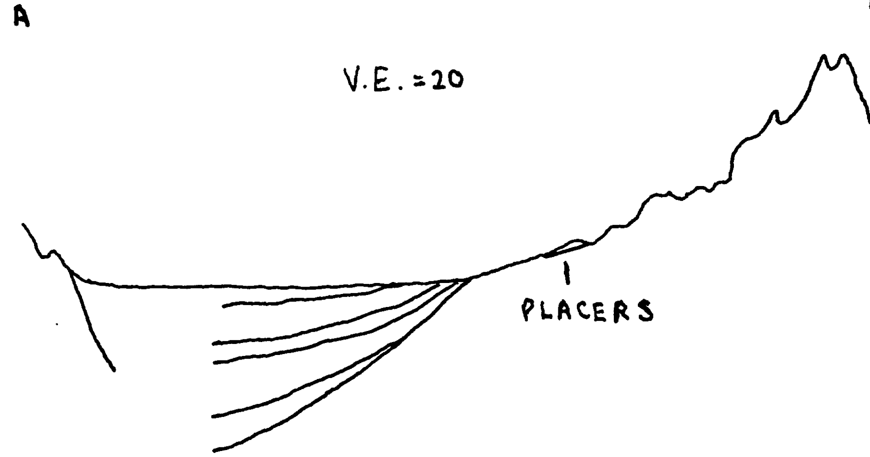
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