THE DISTRIBUTION OF TIN AND CERTAIN OTHER 'HEAVY' METALS IN THE SUPERFICIAL PORTIONS OF THE GWITHIAN/HAYLE BEACH OF WEST CORNWALL

by K. F. G. HOSKING, M.Sc., Ph.D., M.I.M.M., F.G.S. and P. M. ONG, B.Sc., D.M.T.

(Department of Geology, Camborne School of Metalliferous Mining, Cornwall)

SYNOPSIS

The main object of this study was to test the possibility of using semi-quantitative colorimetric methods of analysis to supply data from which isopleth maps of various metals could be drawn which would not only enable the economic potential of a beach to be determined rapidly but would also be of value during other littoral zone investigations. In addition, the study was designed to determine to what extent rapid chemical and mineralogical examinations of such deposits could indicate the economic potential of those parts of the hinterland which were drained by rivers feeding the beaches. Finally, it sought to discover if the rapid methods, noted above, could facilitate an understanding of the heavy-mineral concentrating processes operating on beaches.

The Gwithian/Hayle stanniferous beach, which was selected as the study area, is gently shelving, wide and *ca.* 3½ miles long. It trends *ca.* N.N.E. - S.S.W., fringes a part of the St. Ives Bay, and is bounded by the Red River to the north and by Estuarine reaches of the Hayle River to the south. The central portion is backed by dunes, whilst the extremities abut against cliffs of Lower Palaeozoic slates and grits from which a number of lead/zinc veins outcrop. Tin-bearing lodes occur in the Black Cliffs to the south but are not exposed in the cliff face. Vast quantities of 'tailings' have been transported to the Bay by the Red River from the major Sn/Cu/W/As - mining area of Camborne/Redruth, and although the Hayle River also drains a mining area of some importance, the fact that it terminates in an estuary has precluded it from contributing significant amounts of heavy metals to the beach.

FIELD AND LABORATORY WORK. Field work involved the mapping and sampling of profiles exposed in trenches and the collection of further samples along traverse lines. Laboratory work entailed, in addition to mineralogical and size-distribution studies, the analysis of various fractions of the 300, or so, samples collected for Sn, Cu, W, Pb, Zn, As, Ti, and Fe.

RESULTS. In general, the work confirmed that semi-quantitative analyses supported by field and mineralogical studies, enable the broad economic potential of beaches to be determined rapidly; permit the construction of isopleth maps; indicate the economic potential of the hinterland drained by rivers which contribute *directly* to the beaches, and facilitate an understanding of the ways in which concentration takes place in the littoral zone.

In particular, the investigation established that most of the 'ore metals' concentrated in the Gwithian/Hayle beach have been transported there by the Red River. (This is indicated not only by the results of mineralogical and size-analysis studies, but also by the fact that the concentration patterns of Sn, W, and As are virtually identical. The Pb and Zn patterns have been determined, to a considerable extent, by the presence of local primary sources.) The finer material carried to the Bay by the Red River is transported by lateral currents, and subject to submarine processes which result in the local concentration of fine cassiterite off shore, whilst the sand fraction is swept towards Godrevy or Hayle, depending on the direction of the wind, and during calm periods contributes to the development of a broad flat berm—extending from the dune/cliff line to *ca.* 30 feet below low water mark. During the construction of the berm the dark, dense grains are concentrated, by a gentle tabling process initiated by the waves, in a series of thin, near-horizontal sheets: these are separated by 'white' bands of low density grains which are formed in part by the action of moving water and in part by that of the wind. During on-shore gales, large waves erode the beach, creating a prominent ridge near the cliff/dune base, and at the same time they concentrate the dense fractions which report as a series of flat, near horizontal sheets which are comparatively thick when compared with their 'calm period' counterparts. Concentration is predominently by processes akin to tabling, heavy media separation and jigging, and in plan the values are distributed in elongate zones whose long axes parallel the dune/beach line, and whose maximum values occur in the zone between spring- and neap-tide high-water lines.

Wind facilitates concentration by blowing the less dense grains preferentially from the beach to the dunes. On the other hand it effects considerable dilution near the dunes by blowing 'barren' sand from the latter on to the beach and by drying dune sands, thus permitting slides of sand on to the beach. Wind also spreads 'barren' sand over the darker, denser sheets.

INTRODUCTION

Over a period of many years cassiterite has been recovered on a commercial scale intermittently from the top few feet of stretches of the Gwithian/Hayle beach, in West Cornwall, and in recent years, owing to a world shortage of tin and the steadily rising price of this commodity, interest in the cassiterite potential of this coastal strip has been renewed.

The initial phases of the study which forms the basis of this paper were carried out on behalf of a local company which was interested in the amount, distribution, and general characteristics of the cassiterite in the strip of beach, a few hundred feet wide, which fringes the dunes and cliffs of Upton Towans, about half-way between the Gwithian and Hayle portions of the beach.

In order to arrive at the required data trenches up to *ca.* 4 feet deep were dug (the depth varying with the water-table) at right-angles to the dune/cliff edge. The trench profiles were sketch-mapped, and bulk samples were taken for mineral beneficiation tests. In addition, vertical channel samples were collected at intervals of 5 feet, and also, locally, samples of each of the variously coloured sand bands: all were subsequently analyzed for tin and a number of other elements.

The results of these analyses, together with the geological sections of the trenches, provided a great deal of the data on which this paper is based. However, later, additional samples were taken along traverse lines, from the 'top' of the beach to low-water mark, which were so spaced that the whole of the Gwithian/Hayle stretch was covered, and also, locally, from the crests, sides and troughs of ripples, and these were analyzed for several metals in order to obtain a fuller understanding of the distribution patterns and modes of concentration of the elements of interest. The work was further supplemented by size analyses of selected samples, and by fragmental petrological studies, as the initial investigation changed from one devised primarily to establish the distribution and amount of cassiterite in a comparatively limited portion of the beach to one aimed at revealing the distribution patterns of a number of metals, discovering something of the factors which determined the nature of these patterns, and establishing the sources of the elements studied.

Additional new relevant data were obtained from unpublished work in which one of us (K.H.) participated, and which was concerned primarily with the distribution of certain metals and minerals in the active and buried sediments of the Red and Hayle Rivers' systems.

ANALYTICAL METHODS

Excepting where noted, the minus-80-mesh (B.S.S.) fractions only were analyzed, and analyses were effected by means of rapid semi-quantitative colorimetric methods currently widely used by applied geochemists. This was done largely in order to establish to what extent the employment of such methods could facilitate studies of the type under review.

THE GEOLOGICAL SETTING (Figs. 1 and 2)

The broad beach which fringes St. Ives Bay between Hayle and Gwithian trends *ca.* N.N.E. - S.S.W. and is approximately 3½ miles long. It is backed in part by comparatively low cliffs of Lower Palaeozoic slates and grits and in part by dunes, and is terminated to the north by the Red River which embouches directly on to the beach, and to the south by the Hayle River, which unlike the former, possesses a well-defined estuarine tract composed of mudbanks which are flooded at high tide.

The following brief review of the geologic nature of the hinterland is important if the sources of some of the beach components are to be established with certainty:—

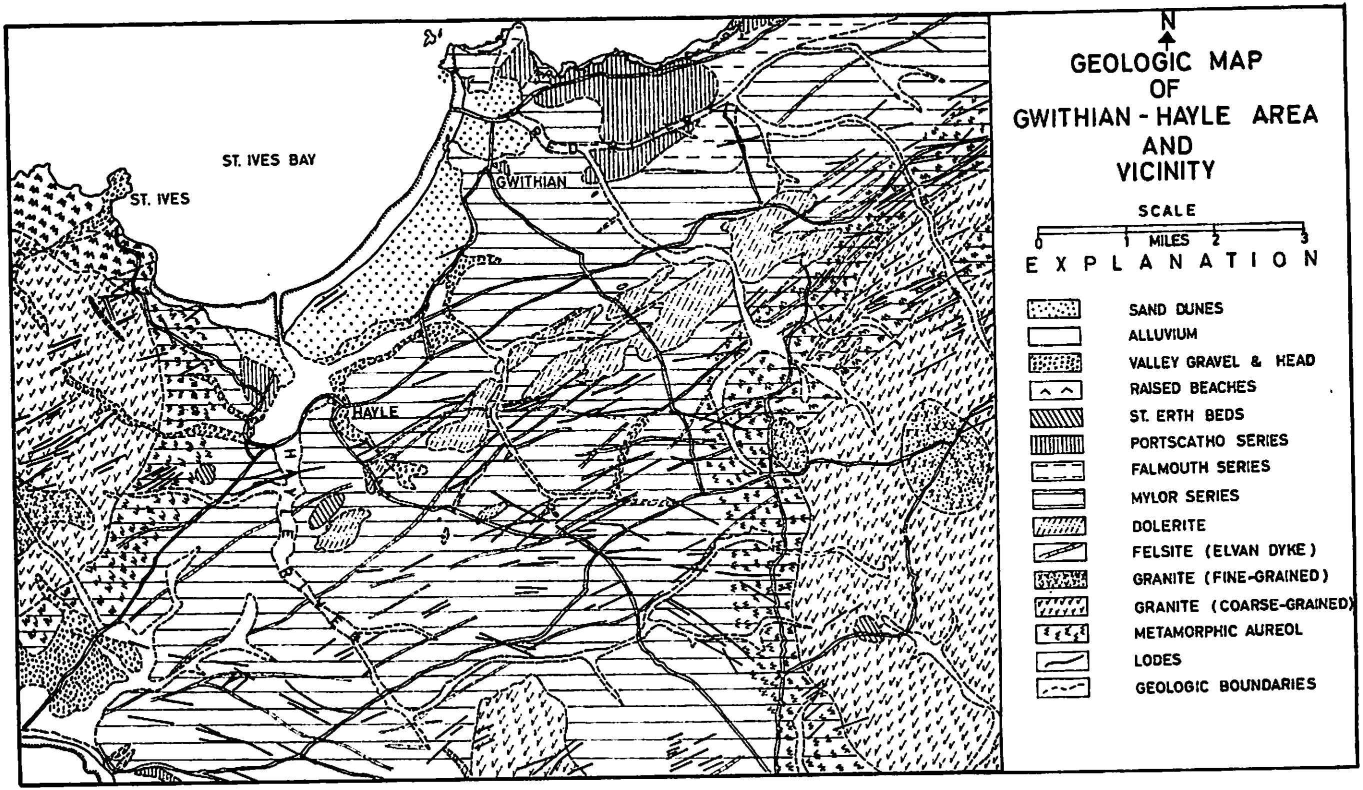


FIG. 1. (Based on Crown Copyright Geological Survey map by permission of the Controller of H.M. Stationery Office).

The hinterland consists essentially of the Permo-Carboniferous granite masses of Carn Brea, Carnmenellis, Godolphin/Tregonning and the Land's End. These are exposed portions of a great batholith, with an irregular surface, which extends from the Scilly Isles in the south-west to Dartmoor in the north-east, and which, in the area of interest, invaded Devonian non-calcareous arenaceous and argillaceous sedimentary rocks and intercalated greenstones, locally thermally and chemically altering them.

Associated with the batholith are many granitic dykes which tend to strike parallel to the ridges on the surface of the major intrusive.

Generally, after the emplacement of the minor acid intrusives, swarms of hypothermal lodes were developed which contain variable amounts of cassiterite, wolframite, arsenopyrite, chalcopyrite and pyrite, associated with a number of non-metallic gangue minerals of which quartz, tourmaline, sericite, chlorite, hematite and fluorite are the most important. Such lodes, which tend to strike parallel to the granite ridges and porphyry dykes, are usually steeply dipping, average only a few feet in width, and, when of major economic importance, are structurally complex, having been repeatedly reopened. Subsequently mesothermal minerals were deposited in the uppermost parts of hypothermal lodes, occasionally in their deeper portions where the mesothermal species commonly occupy late-developed central fissures, and in later fracture zones which tend to strike at right-angles, and to displace, the dominantly hypothermal bodies. Generally, however, as the distance from the granite contact increases, hypothermal deposits tend to give way to mesothermal ones: that is to say primary zoning occurs, but the pattern is far less clear than that which is described in many of the writings dealing with the subject, in part, perhaps, because mesothermal minerals were deposited under conditions of waning regional temperature for such a long period that ultimately they were laid down, as noted above, in what were originally hypothermal zones. However, the complexities of the present pattern may be the product of a number of distinct periods of mineralisation which were separated by geologically long periods when virtually no 'ore minerals' were being deposited. It is probable that although the major phase of mineralisation was genetically related to the Permo-

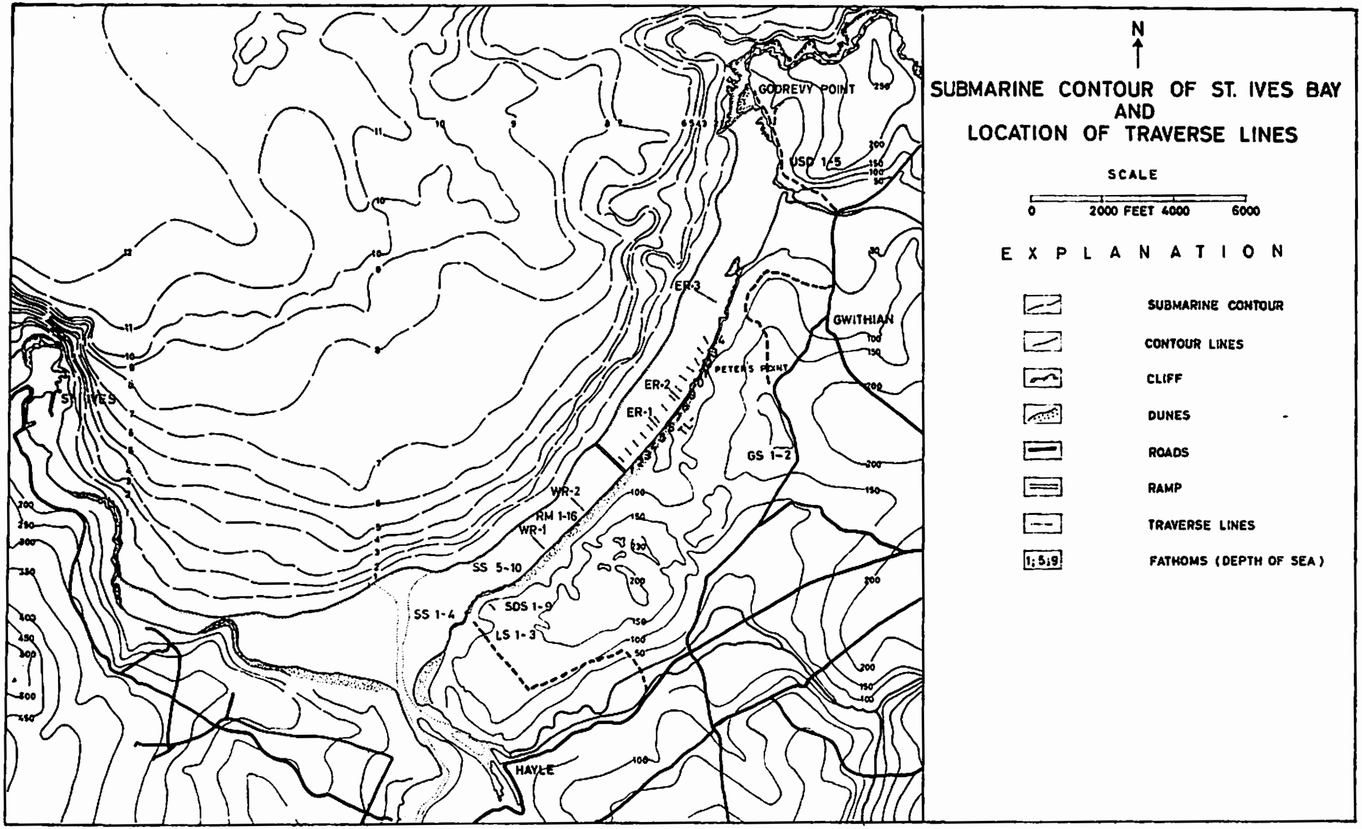
Carboniferous granite and temporally closely related to the emplacement of the latter, further, probably minor, phases of mineralisation occurred in Jurassic and Tertiary times.

During the Mesozoic the South-West was land, and the granites and exposed lodes were modified by sub-aerial agents, but in the Pliocene all but the high granitic masses were submerged. Subsequently elevation occurred in stages, leading to the development of a series of marine platforms, of which the so-called 400-foot one is the most prominent. In recent times the hard-rock floors at the mouths of river valleys were depressed some 30 feet below the present low-water level, and at present these lower reaches are filled with estuarine, marine and fluviatile deposits, peat beds, and occasionally head-of-rubble (a periglacial solifluction product which accumulated during interglacial and immediately post-glacial times). Some of the rivers, of which the Hayle and Red Rivers are examples, contain stanniferous alluvium which tends to be largely concentrated immediately above the bed-rock.

Also during the cold periods icebergs were stranded on what is now the 10-foot raised beach, and on melting they dumped their considerable cargoes of erratics. On the northern part of the beach under review, and more particularly on its Godrevy extension, tons of such erratics (sandstones, conglomerates, limestones, granites, spilites, etc.) occur.

The sand dunes, which locally back the Gwithian/Hayle beach, developed subsequent to the deposition of the head-of-rubble and the drowning of the valleys, and locally they, and the present beach deposits, have completely obliterated a valley along which the Angarrack stream may have entered the St. Ives Bay at Upton Towans. (This valley was discovered during a recent examination of the beach deposits by Banka drilling, and will be referred to again later.)

As might be expected, all the river valleys, regardless of the time when they were first formed, are fairly steep-sided and generally immature in character because of the rapid deepening which followed the Post-Pliocene elevation.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SUBMARINE CONTOUR OF ST. IVES BAY
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DUNES
ROADS
RAMP
TRAVERSE LINES
FATHOMS (DEPTH OF SEA)
GODREVY POINT
USD 1-5
GWITHIAN
PETER'S POINT
ER-3
ER-2
ER-1
TL
GS 1-2
WR-2
RM 1-16
WR-1
SS 5-10
SS 1-4
SOS 1-9
LS 1-3
ST. IVES
HAYLE

FIG. 2.

GWITHIAN/HAYLE CLIFF-LODES. A number of lodes occur in the cliffs fringing the study area, but only some of them are capable of contributing material to the beach because some, as at Wheal Lucy (Hayle), which consist of quartz, cassiterite, and chlorite, strike parallel to the coastline.

At Boiling Well Mine, which occupies the landward fringe of the Upton dune strip, lodes occur which consist of chalcopyrite, sphalerite, pyrite and argentiferous galena in a chlorite/quartz matrix. Some of these ore-bodies; or unworked parallel ones, also contain a little cassiterite, as unbroken geniculately twinned acicular crystals of this mineral, which clearly could not have travelled far, were recovered from the bottom of the sand-obscured valley noted above, whether sub-outcropping lodes parallel to the Boiling Well group occur beneath the beach, and/or offshore, is unknown. Such occurrences are distinctly possible as the granite can exist at no great depths there, because veins consisting of quartz, pink feldspar (sometimes with an adularia habit) and chlorite are found at Peter's Point and elsewhere as far north as Godrevy Headland. Furthermore, in the last-mentioned locality, at least one vein, consisting of minor pyrite and chalcopyrite in a quartz matrix, occurs in the 10-foot platform, and possesses a strike which suggests that it probably extends for some unknown distance under the Bay.

Near Peter's Point a small vein of quartz and galena (the latter superficially converted to cerussite, and possibly laurionite) occurs, whilst between this point and the Strap Rocks (where the Red River originally entered the sea) several small veins, containing sphalerite with ex-solution bodies of chalcopyrite, outcrop in the cliffs. Also, immediately behind the Strap Rocks are the small dumps of the long abandoned and unimportant Wheal Emily, which was a lead and copper mine. Lode material in these dumps consists of slate fragments cemented by quartz, siderite, sphalerite, pyrite, together with a little chalcopyrite and galena. Similar material occurs in the vicinity of a shaft in the low ground between the Gwithian dunes and the man-made channel now occupied by the Red River.

THE NATURE, ETC., OF THE SEDIMENTS OF THE RED AND HAYLE RIVERS

The general character of the sediments of the lower reaches of the river systems has already been noted, but recent Banka drilling in the vicinity of the Gwithian coastal road and to the seaward side of it has thrown considerable new light on the nature of the sediments which occupy the old estuarine tract of the Red River, and has permitted sections, of which the one included here (Table 1) is typical. Briefly, the work established a number of fluviatile, marine and estuarine beds with intercalated bands of peat and a basal stanniferous zone which, in the centre of the valley, is *ca.* 30 feet below the present surface.

Examination of vanned concentrates from the basal horizon has established that they contain cassiterite, topaz, tourmaline, zircon, sphaeroidal pyrite, fragments of chalcopyrite, chalcocite, arsenopyrite and sphalerite and, due to imperfect separation of the lighter fractions, some free quartz and muscovite. The cassiterite is in part free and in part a component of composite grains in which it is accompanied by quartz and sometimes also by tourmaline and/or mica. The sphaeroidal pyrite has, beyond reasonable doubt, been derived from the overlying peat, and it is thought that the other sulphides may have been washed down from the uppermost horizons as a result of imperfect drilling. If this is so it follows that some of the cassiterite recovered from near the bedrock may also have been derived from the surface layers, but most of it has surely been derived from upstream lodes by natural processes.

Less is known about the nature of the deeper sediments in the lower reaches of the Hayle River Valley, but drilling during the 1939—45 War as far down the valley as St. Erth Church suggests that they are probably much the same as those of the Red River. (For details of this work see Gregory, 1947.).

Whilst it is likely that as a result of submarine erosion the stanniferous basal layers of the submerged extensions of the Red and Hayle rivers have contributed, and are contributing, some cassiterite to the submarine deposits of St. Ives Bay (which must also locally contain a certain, probably limited, amount of cassiterite which was *deposited* by the two rivers *before* the recent submergence) there is strong reason for believing, as will be shown later, that most of the cassiterite, and other 'ore-minerals', now found in the superficial horizons of the beach and submarine deposits, have been largely derived from inland sources during

TABLE 1:

Nature of the sediments in the Red River Valley, just to the east of the main coast road and near the present course of the river, as revealed by Banka drilling.

Feet from surface	Nature of ground intersected	Percentage of total cassiterite recovered
0—8	Loose slimey ground.	67 (Tailings)
8—8.5	Peat.	
8.5—12	Loose grey sand.	3
12—12.5	Peat.	
12.5—17	Loose grey sand.	
17—20	Peaty sand.	
20—22	Grey sand.	
22—28	Peat: somewhat muddy.*	Trace.
28—29	Green clay.	
29—30	Sand and gravel.	
30—31	Sand with only a little gravel.	14
31—33	Sand and gravel: clayey at 33 feet.	4
33—35	Sand and gravel: clayey at 35 feet.	12
35—36	Killas.	

* Considerable quantities of framboidal pyrite were found by one of us (K.H.) in this peat, which has a pH of 7.5 and an Eh of —0.4

The authors are grateful to T. Penhale Esq, for supplying the above data.

the past century or so. It is, therefore, of importance to consider the nature, etc., of the superficial sediments of the feeder rivers.

Both the rivers in question have been the recipients of vast amounts of mill tailings from the numerous, essentially tin and copper, mines in and around their basins and, indeed, the Red River, which has always been the major recipient, is currently transporting tailings from the operating South Crofty Mine and also from several stream works in its upper reaches in which cassiterite is recovered from the South Crofty tailings and also from mine and mill rejects which are transported to the recovery sites by the companies concerned.

At the 59th Annual General Meeting of the South Crofty shareholders it was reported that during the working year 88,410 tons of ore, grading 25.18 lbs of cassiterite, were treated in the mill (Mining Journal, May 28, 1965, p.435), and as it is likely, in the writers' view, that the recovery was of the order of 80 per cent, it is clear that an appreciable quantity of cassiterite found its way into the Red River. However, the percentage of tin being lost by South Crofty, which is probably considerably less than that lost by the majority of active mines in the world, is modest when compared with the losses from every mine in the district which was working during the hey-day of the industry. Thus Thomas (1913, p.57) records that in 1890 the 15 mines operating in the Camborne/Redruth district sold 7,131 tons of tin concentrate for £386,029, whilst streamers recovering cassiterite from the tailings of these mines in the Red and Portreath Rivers sold, during the same period, 1,730 tons of concentrate for £69,208. The same writer (*op.cit.*, p.62) concluded that "if all sources of loss are taken into account and due allowance made for inaccurate weighing of the veinstuff before crushing, the average loss of tin in Cornish mines at the present time (i.e., 1913) is not less than 30 per cent". He further states that he "does not know a Cornish mine where the loss is less than 30 per cent. He knows of some where it exceeds 40 per cent and in two cases which he investigated it approached 60 per cent."

These excessive losses in the past were due, to no small extent, to inadequate classification, the production of excessive amounts of stones and to poorly controlled calcination, which amongst other undesirable things caused cassiterite grains to become coated with iron oxide, thus decreasing their density, and on occasion, converted some of the tin present to sulphide.

The present losses are due, to no small measure, to the fact that at South Crofty appreciable amounts of cassiterite in some of the ore are in the form of small crystals or fragments in either earthy iron oxide or chlorite. As neither of these investing minerals are readily removed during the usual mineral beneficiation processes (in the case of chlorite the reason is because the mineral is flexible) it follows that appreciable quantities of comparatively low specific gravity, cassiterite—bearing composite grains persist throughout the milling process and subsequently report as tailings. Doubtless further losses accrue from the unavoidable generation of slimes from which a large percentage of the cassiterite grains are particularly difficult to recover by gravity processes because they are coated with iron oxide. In addition, crushing and grinding converts an unknown fraction of the total cassiterite in the 'feed' to colloidal and near colloidal size particles—a fact confirmed by one of us (K.H.) during laboratory studies, but one which was known long ago: Hutchin (Thomas, *op.cit.*, p.69), for example, noted that "some extremely fine tin (as cassiterite) required a week or fortnight to settle", whilst Beringer (Thomas, *op.cit.*, p.69) stated that some of the cassiterite which he had seen in mill products "was so fine that it would go on floating for ever . . . . ." It might not be irrelevant to note that these investigators were well aware of the fact that both wolframite and arsenopyrite slimed much more readily than cassiterite.

Today, as in the past, most of the cassiterite being transported by the Red River is in the form of slime tin and as components of composite sand grains in which it occurs with quartz, but more particularly with chlorite and hematite. Naturally, a very limited amount of comparatively coarse 'free' cassiterite is present, and a very small fraction of the tin which reports in chemical analyses occurs within the lattices of certain silicates, particularly biotite, and as sub-micron cassiterite crystals between the cleavage planes of muscovite.

Because of the difficulty of readily liberating the cassiterite from the composite sand grains, streamers, particularly in the past, have tended to confine their attention largely to the recovery of

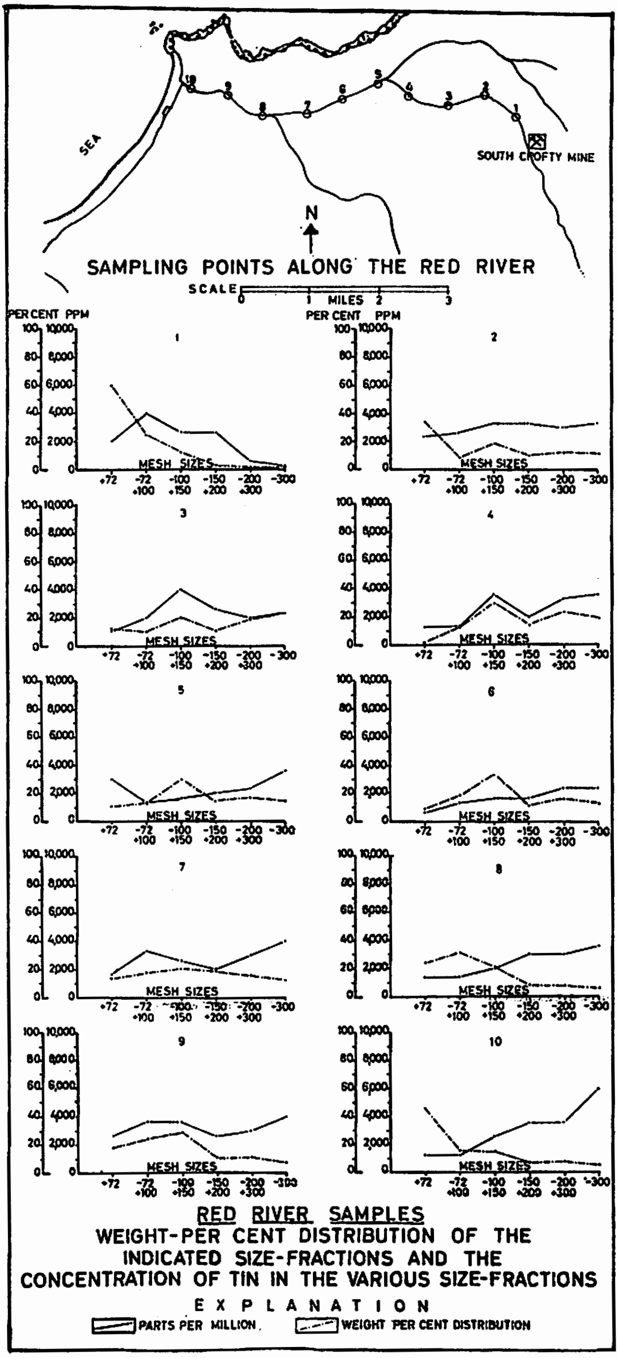


FIG. 3. (Based on the unpublished studies of Hosking, Brett, Dobson, Gahan, Gombe and Lau, 1961).

'slime tin' (an operation which is more efficient if the slimes are first allowed to age in settling pits—perhaps because the specific gravity of the cassiterite grains increases with time as a result of changes which convert the 'fluffy' iron oxide coating to a more compact one). This preferential treatment not only tends to modify the size distribution patters of the sediments along the river but, more particularly, it permits the sandy stanniferous 'middling' to pass unimpeded to the sea where it is available for reconcentration on the beaches. Some idea of the distribution of various size fractions in samples of the active sediment of the Red River, in 1960, and of their tin content, is indicated in Fig. 3. However, the results are to some extent a distortion of the truth, as the method of sampling was such that a portion of the finer fractions always escaped collection, and size analyses were effected by dry screening which permits some of the finer particles to remain attached to the coarse gains and, therefore, to report with the latter. In addition, the tin content was determined by the semiquantitative gallein/methylene blue colorimetric method.

Despite the numerous stream works which operated on the Red River during the more active mining periods, they failed to recover anything like the whole of the 'slime tin' available to them, and large quantities must have been dumped in St. Ives Bay where it also was transported by longshore currents, etc., and locally concentrated. Depending on the direction, strength and duration of the wind, and on the state of the tide, dominant movement of the slimes was, and is, sometimes towards Godrevy and on other occasions towards Hayle: this is clearly indicated because the slime-charged sea water is 'stained' by a red suspension of iron oxide.

Appreciable quantities of sulphides and fluorite have also been transported from the mines by the Red River, and chalcopyrite, pyrite and arsenopyrite grains can always be recovered from samples of the active sediments throughout the length of the valley.

It might be assumed that such sulphides would rapidly decompose in such an environment, but such is not the case. However, in the low-lying tract between the coastal road and the sea, which was periodically flooded before a straight artificial channel was cut for the river, appreciable amounts of copper and iron are mobilised from such 'stranded' grains—a fact indicated in a spectacular manner by the occurrence of teeth of ruminants and other animals in the red flood-deposited sediment which have been in part converted to a green copper-bearing mineral and to odontolite. (The high concentration of mobilised copper, and possibly other ore-derived elements, probably also accounts largely for the fact that the higher forms of vegetation are confined to sand hummocks on these flats).

The state of affairs in the Hayle River is appreciably different from that in the Red River. The former never received as much mine tailings as the latter and has not received any for many years. During the last war a certain limited amount of tailings were added to it as a result of the alluvial mining which was then being carried on, but these differed significantly from the tailings from a mill beneficiating hard-rock ore and would not, for example, contain any man-made slimes. Furthermore, as noted earlier, the Hayle River differs from the Red, in that its waters are transported to the sea via a 'normal' estuarine tract which is flooded during high tide. Examination, by geochemical methods of analysis, of sediments from the fluviatile and estuarine portions of this river indicate that both locally contain appreciable quantities of tin, copper, tungsten and arsenic[1] (Table 2.), whilst samples of sediment from that part of the river which crosses the Hayle sands are extremely low in these elements (as in the sand of its banks and of the beach adjacent to them). It seems certain, therefore, that the Hayle estuary has effectively trapped, and is trapping, most of the resistate ore-minerals and also those originally mobilised ore-elements which have been transported by the river as adsorbed components of colloids. For reasons which will be apparent later it seems probable that the small fraction of ore-derived components which pass through the trap are transported by the sea towards Lelant, that is, away from the beach strip under review.

1. Other 'ore-elements' may also be present in anomalous amounts, for example, cobalt derived from Enys Wheal Virgin dump which is on the valley side, but the study was restricted to the elements noted in the text.

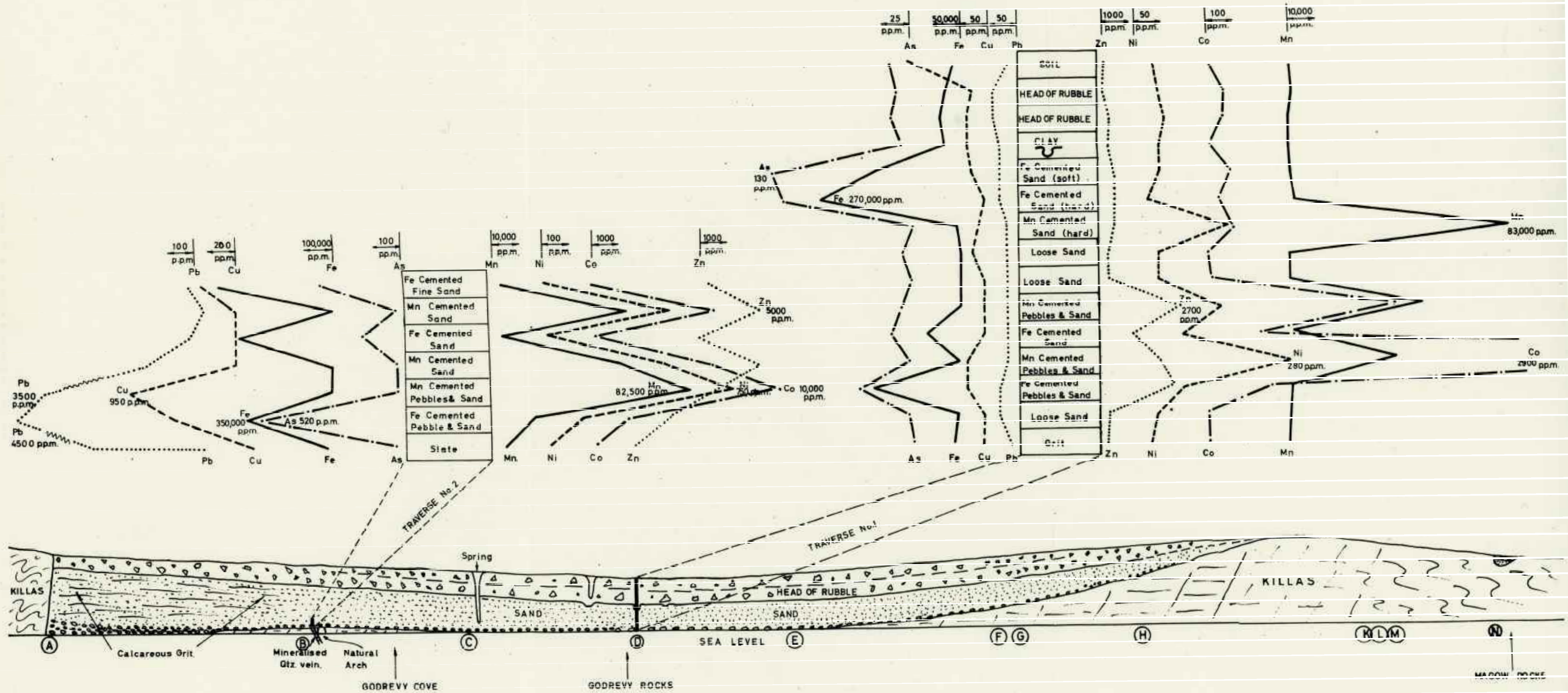


FIG. 3. Diagrammatic longitudinal section of the Godrevy Raised Beach. A—N are sample sections. Scales; Hor. 1 : 1000, Vert. 1 : 300.

TABLE 2:

Concentration of Sn, Cu, W and As in the superficial deposits of the Hayle Estuary.

(Hosking, K. F. G., *et al.*, 1963, unpublished studies.)

(Values in parts per million)

	Total no. of samples	Sn	Cu	W	As
Active sediments of the main distributary channels.	26				
Highest value		1,000	1,000	280	600
Lowest value		63	200	8	75
Average of the 26 samples		380	472	30	229
Superficial portions (i.e., to a depth of *ca.* 6 in.) of the mud banks	12				
Highest value		1,000	2,000	40	325
Lowest value		100	300	16	75
Average of the 12 samples.		641	896	31	177

THE BEACH: ITS PHYSICAL AND MINERALOGICAL CHARACTERISTICS, ETC.

The Gwithian/Hayle beach is broad and gently sloping, but is inclined to steepen appreciably between the Strap Rocks and the Red River, perhaps, in part, because this stretch is backed by the remains of an iron beach defense system against which onshore wind and blown sand and sand transported by storm waves during spring tides can accumulate.

In common with beaches generally this one is subject to marked physical changes which depend primarily on the relationships existing at any given time between the strength, duration and direction of the wind, and the 'state' of the tide. Rain is also of some importance in that by damping the beach and dune sands it makes them less readily transportable by wind.

When long periods of calm weather occur, a broad flat berm (the 'beach' of the man-in-the-street) builds up from the base of the dunes and cliffs to *ca.* 30 feet below low-water mark. Naturally, this feature is most likely to reach its most mature form during summer, but in this area considerable periods of calm weather also occur in the winter, particularly in November, and then the profile of the beach may go far towards assuming its summer character.

On the other hand, when the beach is subject to on-shore gales it is strongly eroded, and this results in the development, near the dune/cliff base, of a sand ridge, with a steep seaward-facing face: this ridge may be increased in height by the piling up of sand on it by storm waves. Obviously the beach most commonly displays this character during the winter months, but not infrequently this section of the coast is subject to heavy seas during the summer; then the beach assumes a winter profile.

Whilst the profile of the beach and the character of its surface may be profoundly altered in a comparatively short space of time during any season of the year, it may happen that sand only a few feet beneath the surface, in the upper reaches of the beach, at least, may remain undisturbed for a considerable period. This was spectacularly demonstrated during the study by the discovery, in one of the trenches, not more than *ca.* 1 foot below the surface, of the lower portion of the vertebral column of a seal (which had originally become detached from a decomposing carcase) from which all soft intervertebral, and other tissue, had disappeared, but which had not been disturbed since its burial, as the vertebrae had not been displaced[1] (Pls. 1 and 2). Professor Westoll (*private communication*) is of the opinion that in such an environment the soft tissue would take at least eighteen months to disappear. It is, of course, appreciated that for some unknown length of time subsequent to its burial the specimen may have been covered by several feet of berm which, at the time of its discovery, had been removed.

Although the surface of the beach generally consists of a thin veneer of pale-coloured sand, the uppermost few feet of the beach, despite the weather conditions prevailing at the time of examination are seen, when a profile is exposed in a trench to be composed of numerous black, grey and "white" bands varying in thickness from a few inches to a small fraction of an inch (Pls. 3 and 4). The darker bands are most strongly developed throughout the profile between neap and spring high-tide lines. Generally they are near horizontal, and although individual bands commonly vary in width and eventually die out when traced along lines either parallel to, or transverse to, the cliff/beach line, they rarely display marked distortion. The impression obtained by studying profiles and the plan patterns of the distribution of various metals in the superficial portions of the beach (which are described later) is that each 'band' revealed in a vertical section is, in fact, a section of a body which commonly broadly approximates to a flat ellipsoid whose long axis tends to parallel the beach/cliff line. Occasionally, however, vertical sections do show contorted bands and these owe their anomalous character largely to human activity, such as the digging of pits in the sand by children in summer, and one distorted zone which was exposed possesses the form of a sand volcano (Pl. 4).

1. The writers are grateful to Mr. J. A. Hosking for appreciating the significance of the specimen and carefully excavating and photographing it.

Particularly near the upper limit of the beach, one or more near-horizontal layers of pebbles interrupt the sequence of sand deposits, and where the beach is thin a marked accumulation of pebbles rests directly on the slate platform. On occasion, a band of fine dark sand, comparatively rich in tin, occurs immediately beneath a band of small, well-sorted pebbles, and suggests that the latter may have played a concentrating role similar to that of ragging in a jig.

In trenches near the base of the dunes one finds black bands separated by white sand wedges which thicken landwards: this phenomenon is clearly due to the sand blowing on to the beach from the dune slopes.

Whilst a discussion of the ways in which the wind and the waves operate to develop those characteristics of the beach noted above is deferred until later, it is pertinent to note here that both these agents effect a number of modifications of the surface of the beach which locally facilitate concentration of the denser sand fractions: of these, ripples, and dendritic distributary channels, due to the action of water, and small pebble-capped sand cones, due to the action of wind, are, perhaps, the most important.

The mineralogical character of this beach was first investigated by Crook and Davies (1909) who noted the presence of light and dark streaks and who observed (*op. cit.*, p.121) that " where heavy minerals abound, tidal action can be seen to have effected a persistent concentration about the mean high-water mark, where the heavier ingredients predominate for at least a foot beneath the surface." A specimen, collected by them, of the dark near-surface sand in the Upton area contained about 30 per cent. of shelly matter, and the residue left after the calcareous material had been removed by treatment with cold dilute acid was shown to have the following mineral composition:—

			Per Cent	
Strongly magnetic	Magnetic iron oxide		1	Dark-coloured portion.
Weakly magnetic	Killas fragments Tourmaline Impure quartz Brown biotite Chlorite Siderite		14	
Non-magnetic	Quartz Feldspar Killas fragments	S.G. <2.84 (bromoform)	10	Light-coloured portion
	Fluorspar Andalusite	S.G. >2.84 <3.32	15 (almost wholly fluorspar)	
	Topaz Free tinstone Killas fragments impregnated with tinstone Zircon Spinel	S.G. >3.32 (methylene iodide)		

Crook and Davies also recorded that "a lighter-coloured sand from near low-water mark at the same locality, and another from near Lelant about half a mile to the west of Hayle River, both contained about 70 per cent. of shell fragments, etc. Their insoluble residues contained the same ingredients as the specimen already described, but in different proportions; and the heavier minerals were present only in small amounts" (*op. cit.*, p. 122.)

They conclude (*op. cit.*, p. 122) "that there can be little doubt that the non-calcareous portion of these sands consist chiefly of the products of mining activity brought down to the coast by the Red River. It appears to be practically identical in its general character with the Red River sand described by the officers of the Geological Survey (see Memoir "Geology of Falmouth and Camborne", 1906, p. 273)".

One of the interesting aspects of their conclusions is the fact that no mention is made of the Hayle River. Clearly Crook and Davies must have held essentially the same views as to the present writers re the rôle this river has played in the development of the beach, namely that it is a negligible one. However, the latter think that the small proportion of heavy minerals in the Lelant beach may have been contributed, in part, at least, by the Hayle River, although an unknown proportion of them may have been transported by the sea from the neighbouring beach of Carbis Bay, where once cassiterite was recovered from tailings carried there by a stream from the Carbis Bay group of mines.

Stuart and Simpson (1937) broadly confirmed the findings discovered above and observed (p. 24) that " another striking feature is the great influx of fluorite (together with siderite and hematite) north of the Red River, in St. Ives Bay, confirming the conclusions of Crook and Davies as to the great influence which mining activity has had in determining the constitution of sands in this locality ".

Much more recent work by one of us (K.H.) has confirmed that all the mineral species recorded by the earlier workers as being present in the beach sands are, indeed, still to be found in them, and by using small-scale flotation procedures he has been able to show that fresh sulphides, particularly chalcopyrite, arsenopyrite, pyrite and sphalerite are also present. His findings, however, differ in one important respect from those of Crook and Davies in that all his work indicates that the bulk of the cassiterite, which consists of entire crystals and fragments generally within the 5 to 50 micron range, occurs not in slate fragments but in composite grains accompanied by varying amounts of one or more of the following:— quartz, chlorite, white mica, tourmaline, ' hematite '. Very little free cassiterite occurs and that which is present is largely in the finer fractions.

Samples from near the bottom of the sand-filled valley (noted earlier) were also of considerable interest, particularly because their heavy fractions contained an appreciable proportion of framboidal pyrite, whilst samples from a little nearer the surface contained an abundance of siderite spherules which, when attacked with cold dilute HCl, left a residue of white hollow spherical bodies of, as yet, uncertain composition. The genesis of these spherules is also, at present, in doubt. (See Hosking, K. F. G., 1963, for a photomicrograph of a thin section of sand containing these curious specimens.)

The tin content of the sands under review has been the subject of intermittent investigation for many years, but as it varies from place to place, from season to season, and from year to year, close agreement of the results is not to be expected. Hutchin (1913, p. 37) notes that from the published figures of the sampling of Gwithian Beach " the assay-value of the sands as a whole appears to be about 8.5 lb. metal " (per long ton). This figure agrees very well with the average of numerous assay results obtained some years ago by one of us (K.H.) when working with samples submitted for analysis from Upton Beach by the then owner of the foreshore. However, one sample assayed *ca.* 38 lb. tin per long ton!

Thomas (1913, p. 60) records that " about three years ago the author sampled the foreshores for about threequarters of a mile along the beach between Gwithian and Hayle. The samples were from a strip of mine sand which existed at high water mark under the sea sand and ran from a few inches up to rather over a foot in thickness. Samples were all taken from within about 10 feet of high water mark. They ranged from between 17 and 28 lbs. and averaged 20 lbs. by vanning ".

Thomas obtained a bulk sample of several tons weight from the same source and some of it was subjected to two mill tests with the following results (*op. cit.*, p. 60) which clearly indicate that there was little, or no, free cassiterite present:—

EXPERIMENT 1

One ton, hand fed to Buss table, yielded:—

	cwts.	qrs.	lbs.		lbs.		
Head	0	2	0	@	269	per ton	= 6.7 lbs.
Middles ...	3	1	0	@	28	„ „	= 5.0 lbs.
Tailings, remainder—				@	5½	„ „	= 5.0 lbs.
							16.7 lbs.

EXPERIMENT 2

Two tons, pulverised by tube-mill and fed to Frue-vanner without classification:—

	cwts.	qrs.	lbs.		lbs.			
Head ……	1	1	7	@	694 per ton	=	36 lbs.
Tailings, remainder—				@	$3\frac{1}{2}$ „ „	=	7 lbs.
							43 lbs.

Equal to 21.3 lbs. per ton.

The results of more recent studies of the tin content of sand samples from the beach, which were carried out by one of us (K.H.) are shown in Tables 3 and 4. One of the most important features of Table 3 is clear confirmation of the fact that in the coaser fractions most of the cassiterite occurs in composite grains. Table 4 reveals the further interesting fact that in the sample examined almost as much cassiterite is 'locked' in magnetic grains as occurs in the non-magnetic fraction. The reason for this is that appreciable quantities of cassiterite occur in distinctly magnetic chlorite and in close association with magnetic iron oxide (possibly in part maghemite or gamma hematite). The iron oxide is probably largely primary, as in the Camborne/Redruth mines cassiterite is often intimately associated with earthy 'hematite', but some of the cassiterite grains may have received a coating of iron oxide during calcination (an operation which was only abandoned a few years ago at South Crofty Mine). A very limited amount of iron oxide-coated cassiterite could have been derived from the ferruginous basal beds of the 10-ft raised beach which certainly contain a little cassiterite in the Godrevy section where they are particularly strongly developed. In addition some cassiterite (probably a very small proportion of the total present) may have obtained a coating of the type in question *after* transportation to the beach, as in some of the Upton trenches which were receiving water from the Boiling Well Mine adit the

TABLE 3:
Analysis of Gwithian Beach tin-bearing sand
(Hosking, K. F. G., Sept. 1960, unpublished studies)

Mesh (B.S.S.)		+3.51 sp.gr.	− 3.50 sp.gr. to 3.26 sp.gr.	− 3.25 sp.gr. to 3.01 sp.gr.	− 3.00 sp.gr. to 2.76 sp.gr.	− 2.75 sp.gr.
+16	Rejected (≡ 0.06%, by weight, of total sample).					
	% weight of mesh range	0.47	0.80	15.5	30.13	53.09
− 16	% weight of sample	0.11	0.18	3.54	6.89	12.15
+ 60	% tin of sp.gr. group	4.59	10.36	16.27	17.14	16.18
	% tin of mesh range	12.62	20.95	37.26	22.86	6.31
	% tin of total sample	0.007	0.012	0.021	0.013	0.004
	% weight of mesh range	0.80	1.09	23.43	37.33	37.33
− 60	% weight of sample	0.17	0.24	5.17	8.23	8.23
+ 72	% tin of sp.gr. group	7.65	7.55	29.33	23.67	18.25
	% tin of mesh range	14.51	10.80	47.50	22.32	4.84
	% tin of total sample	0.012	0.009	0.038	0.018	0.004
	% weight of mesh range	0.41	1.60	26.2	38.37	33.08
− 72	% weight of sample	0.12	0.56	7.56	11.06	9.53
+ 85	% tin of sp.gr. group	4.02	17.71	24.71	16.55	15.61
	% tin of mesh range	8.76	27.26	43.09	16.79	4.46
	% tin of total sample	0.006	0.020	0.032	0. 013	0.003
	% weight of mesh range	6.64	7.53	39.05	24.74	22.13
− 85	% weight of sample	1.70	2.00	10.22	6.48	5.79
	% tin of sp.gr. group	83.90	64.39	29.70	42.62	49.33
	% tin of mesh range	45.73	25.84	13.50	11.28	3.67
	% tin of total sample	0.131	0.074	0.039	0.032	0.011

TABLE 4:

The distribution of Tin (Sn) in certain size fractions of the non-magnetic and magnetic portions (obtained by means of a magnetic separator), before and after cleaning with hot hydrochloric acid, of a sample of Gwithian sand from the upper reaches of the beach.

(Hosking, K. F. G., 1960, unpublished studies.)

NON-MAGNETIC PORTION

Percentage loss of weight on acid cleaning = *ca.* 36.

Not Acid-Cleaned

Mesh (B.S.S.)	Weight per cent	Percentage Sn in fraction	Percentage Sn of whole sample
+36	Nil.	—	—
-36/+52	3.65	0.13	1.11
-52/+72	34.42	0.21	14.08
-72/+100	54.04	0.48	50.36
-100/+150	7.89	2.30	34.81
-150/+200			
-200/+300	Nil.	—	—
-300			

Lbs. tin per ton = 11.73

Acid-Cleaned

Mesh (B.S.S.)	Weight per cent	Percentage Sn in fraction	Percentage Sn of whole sample
+36	Nil.	—	—
-36/+52	3.13	0.35	1.15
-52/+72	27.94	0.70	17.82
-72/+100	60.56	0.75	41.96
-100/+150	7.19	3.91	25.86
-150/+200			
-200/+300	1.19	11.99	13.79
-300			

Lbs. tin per ton = 15.59

TABLE 4: contd.

MAGNETIC PORTION

Percentage loss of weight on acid cleaning = *ca.* 36.

Not Acid-Cleaned

Mesh (B.S.S.)	Weight per cent	Percentage Sn in fraction	Percentage Sn of whole sample
+36	Nil.	—	—
−36/+52	1.74	0.42	1.77
−52/+72	29.28	0.27	18.14
−72/+100	56.43	0.38	48.68
−100/+150	12.21	0.91	25.66
−150/+200			
−200/+300	0.33	7.86	5.75
−300			

Lbs. tin per ton = 9.78

Acid-Cleaned

Mesh (B.S.S.)	Weight per cent	Percentage Sn in fraction	Percentage Sn of whole sample
+36	Nil.	—	—
−36/+52	28.59	0.54	22.64
−52/+72		0.54	46.23
−72/+100	57.35	1.07	18.86
−100/+150	11.65	2.95	6.61
−150/+200	1.51		
−200/+300	0.88	4.47	5.66
−300			

Lbs. tin per ton = 9.50

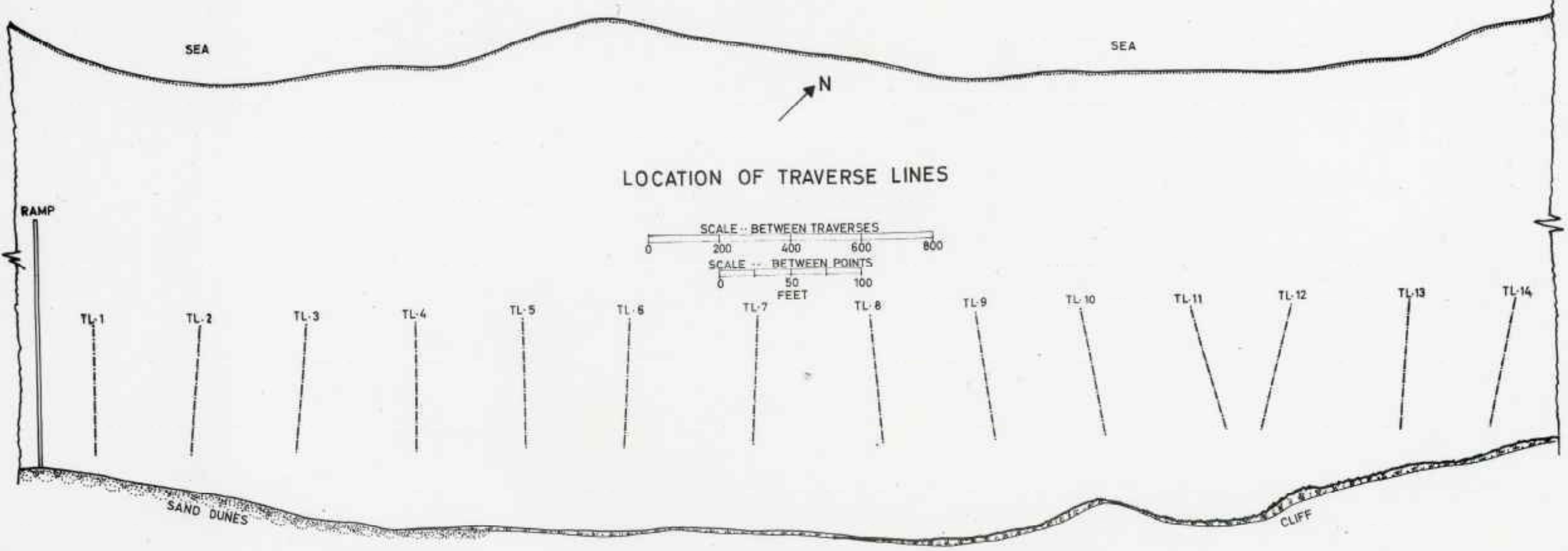
groundwater became distinctly brownish as it flowed seaward. This was because it was charged with iron ions which it had collected during its journey through actively oxidising sulphidic lodes, and as its pH was raised by reaction with the carbonate fragments of the beach, or with occluded seawater, a point was reached at which ferric hydroxide was precipitated.

DISTRIBUTION PATTERNS OF TIN AND CERTAIN OTHER ELEMENTS ON THE BEACH

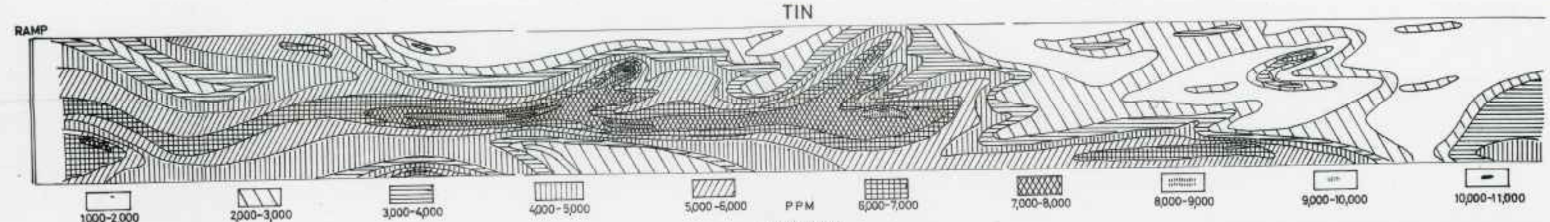
Primarily because of the limited time available for the work it was felt that it would be more rewarding to study intensively the distribution of a number of metals in the Upton section than to attempt to 'cover' the whole beach by examining samples taken on a large grid. Subsequent work confirmed the decision, as it indicated that comparatively close sampling is necessary to reveal, in any detail, the distribution in plan, of those elements which were studied. It is, however, felt that the results obtained in the Upton section are *broadly* the same as those which would have been obtained were another section studied intensively. Nevertheless, for reasons which will be apparent later, a limited number of samples from outside the Upton section were examined.

The plan distribution characteristics of tin and a number of other elements in the uppermost few feet of sand in the Upton section is shown on Fig. 4. This figure was established by analyzing the minus-80-mesh (B.S.S.) fraction of vertical channel samples taken at 5-foot intervals along the walls of a series of trenches. Evidence available suggests that had 'whole' samples been analyzed instead of the minus-80-mesh fraction the distribution patterns would not have been greatly different from those figured, but the work involved would have been considerably prolonged as each fraction would have had to be ground to minus-80-mesh for satisfactory analyses to have been effected.

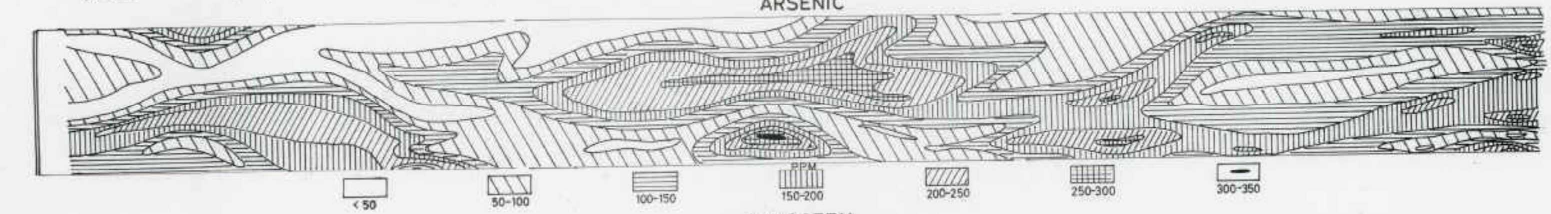
Fig. 4 also clearly shows that several of the elements, particularly tin, tungsten and arsenic, tend to concentrate (at least, on occasion) most markedly in the upper reaches of the beach and broadly between neap and spring high-tide lines. In plan the zones of concentration are elongated approximately parallel to



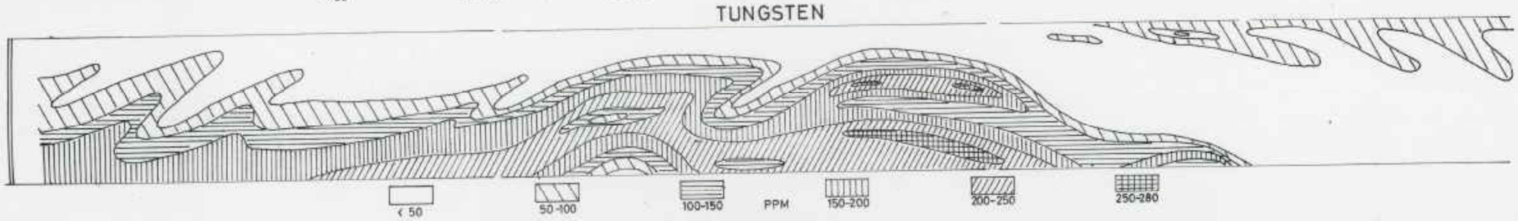
TIN



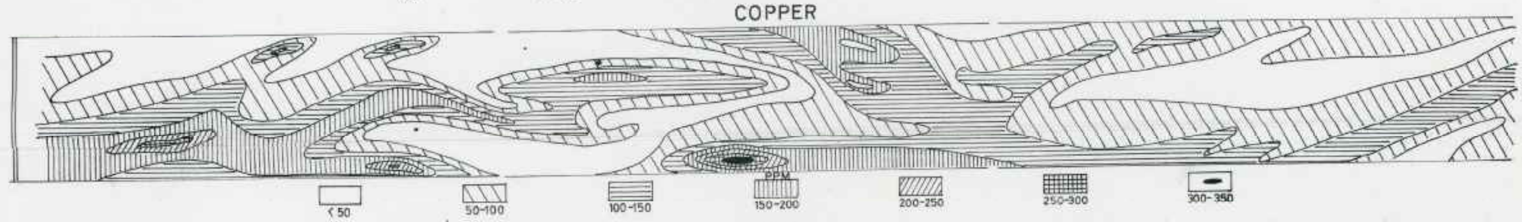
ARSENIC



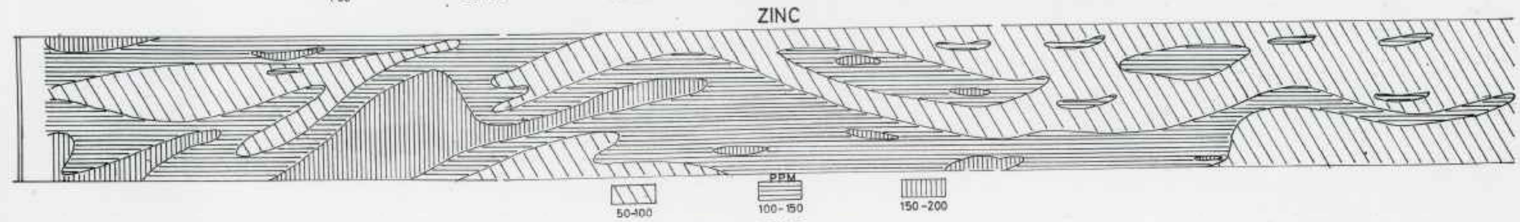
TUNGSTEN



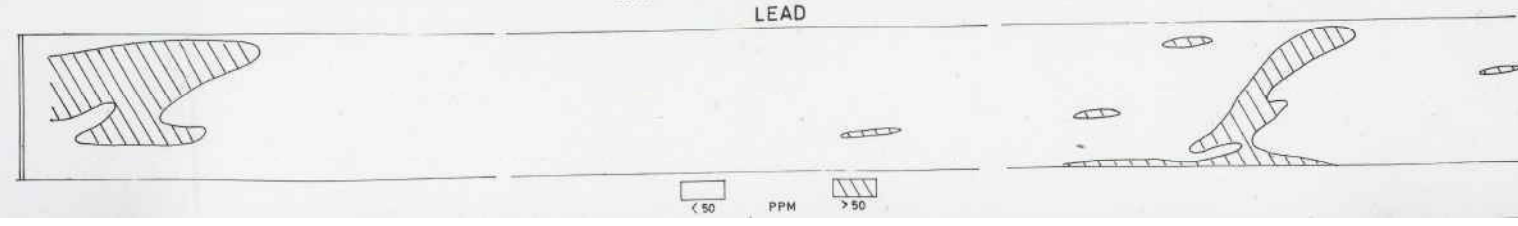
COPPER



ZINC



LEAD



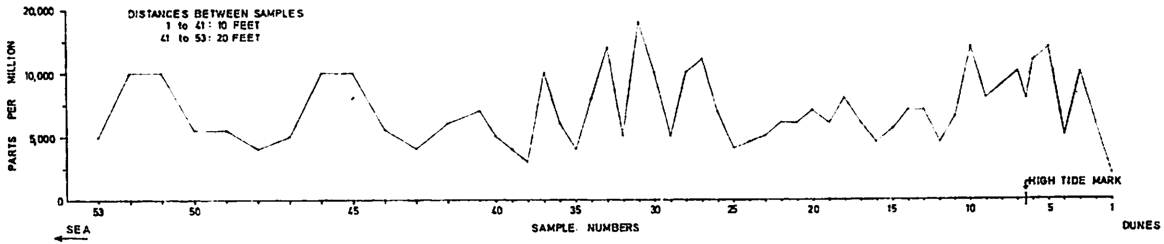
the dune/cliff line and the irregular plan-forms which they display may be largely due to the fact that each is a synthesis of crudely elliptical zones of concentration which occur at different horizons and which are laterally displaced with respect to each other to varying degrees. Spring tides locally reach the base of the dunes and cliffs, but the reason why maximum concentration does not occur along this " line " is in part due to the fact that it is, on occasion, locally occupied by a berm ridge, and in part because of the local dilution occasioned by dune sand which is transported down dune valleys by wind and gravity and dumped there.

The close similarity between the tin, arsenic, and tungsten patterns, and their broad spatial coincidence, strongly suggest that these elements were being made available for concentration on the beach at the same time, that they all experienced the same concentrating processes, and that they were all derived from the same primary source: it cannot be concluded, however, that all three elements necessarily, or even commonly, occur as components of the same composite grains. The conditions assumed to be necessary for the development of these similar patterns are most convincingly satisfied by accepting that the primary sources are the lodes of the Camborne/Redruth mines in which cassiterite, arsenopyrite and wolframite are commonly closely associated, and that losses from the beneficiation of ore derived from these are carried by the Red River to Gwithian where the minerals containing the elements under review are simultaneously reconcentrated.

The copper pattern departs considerably from those of the three elements discussed above for the following reasons: Copper-bearing minerals are only sporadically distributed in most of those parts of the Camborne/Redruth lodes which have been worked during this century primarily for tin. This means, amongst other things, that the ratio of copper to tin in the Red River sediments varies with time much more than do the ratios of tin to arsenic and tin to tungsten. In addition, in the past numerous copper mines in the area deposited tailings into the river which were rich in copper but virtually lacking in tin, tungsten and arsenic. Doubtless a considerable proportion of the copper minerals (largely sulphides) in the tailings found their way, via the Red River, more-or-less directly to the sea and were in part, reconcentrated on the beaches. To what extent this early ' beach copper ' has been permanently removed by processes of disintegration and decomposition is unknown, but it is likely that a portion of it, possibly a very appreciable portion, still remains, as there is evidence that sulphides on beaches are much more resistant to processes calculated to eliminate them than is generally appreciated. (See Hosking, 1960.) A considerable proportion, however, of the early copper tailings were stranded on the valley floor as a result of frequent flooding, due largely to the fact that the course of the river was allowed to become seriously obstructed by mine sand. Thus Stephens (1899, pp. 330-1) notes the presence of fragments of copper ore (mostly chalcocite) in ' gravel ' immediately beneath the surface in the valley, that it was most noticeable near Nancemellin, and that it was due to the fact that before 1860 " the copper mines discharged vast quantities of debris down the Red River, which then wandered anywhere about the valley." Possibly some of this stranded sulphide is being washed back into the main drainage system and is contributing now to the beach; it is, however, unlikely that the amount is large. Finally, a certain amount of copper must be contributed to the beach by the essentially sphalerite-bearing cliff lodes, as the zinc sulphide in them is peppered with ex-solution bodies of chalcopyrite.

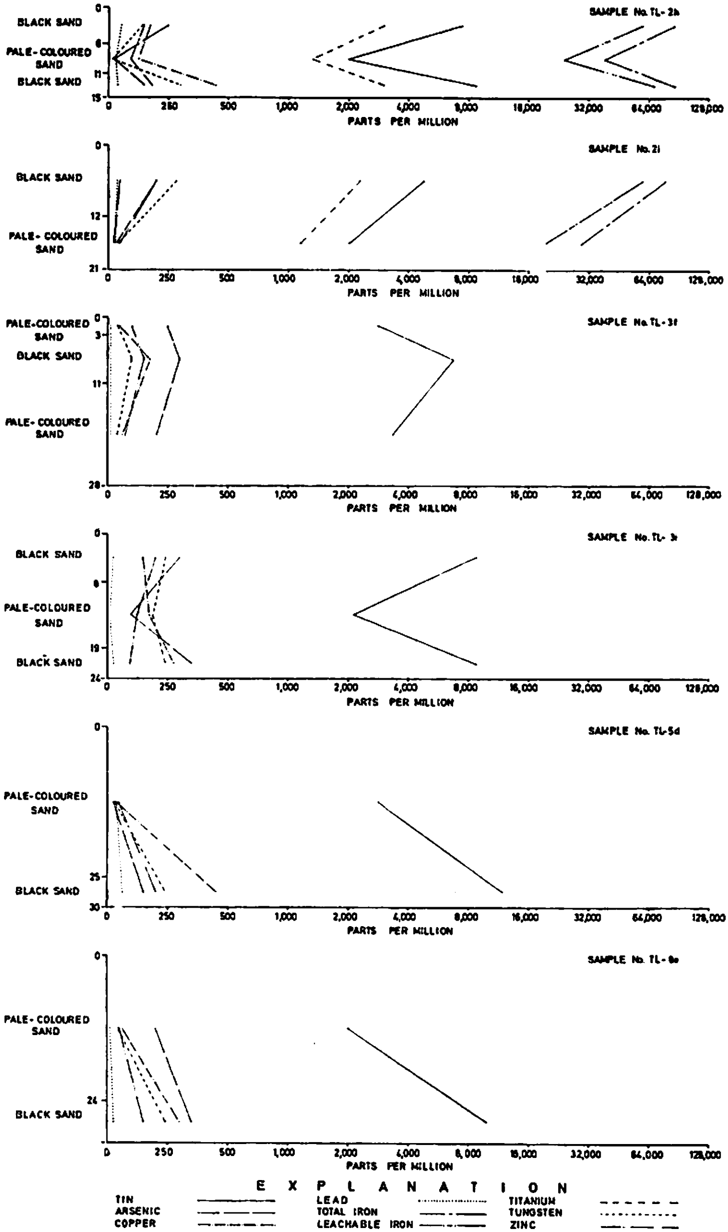
The zinc pattern differs from those discussed above because sphalerite is less dense than the species containing tin, tungsten, arsenic and copper; also because the mine-derived zinc species (essentially sphalerite) on the beach were probably largely transported there when lodes in the copper/zinc zone were being actively exploited, and because a considerable proportion of the sphalerite on the beach has probably been derived from the cliff lodes.

The lead pattern, which when compared with the others is quite unique, has been determined by the disposition of strictly local lodes. The more easterly, major high zone, stems from the liberation of galena and secondary lead minerals from a lode which outcrops near Peter's Point: the other major one is more difficult to account for as no cliffs are exposed near where it occurs: possibly it, and the small anomalous zones, are due essentially to the deposition of lead from the adit waters of Boiling Well Mine.



DISTRIBUTION OF TIN IN THE MINUS-80-MESH (B.S.S.) FRACTION OF SAMPLES TAKEN DURING THE SUMMER OF 1962 ALONG A LINE FROM THE BASE OF THE DUNES TOWARDS THE SEA. THE LINE WHICH IS APPROXIMATELY NORMAL TO THE DUNE-BEACH CONTACT IS SITUATED AT 25 YARDS NORTHEAST OF THE RAMP

FIG. 5.



CONCENTRATION OF TIN, ARSENIC, TUNGSTEN, COPPER, LEAD, ZINC, TOTAL AND LEACHABLE IRON, AND TITANIUM IN THE DIFFERENT LAYERS OF THE BEACH

FIG. 6.

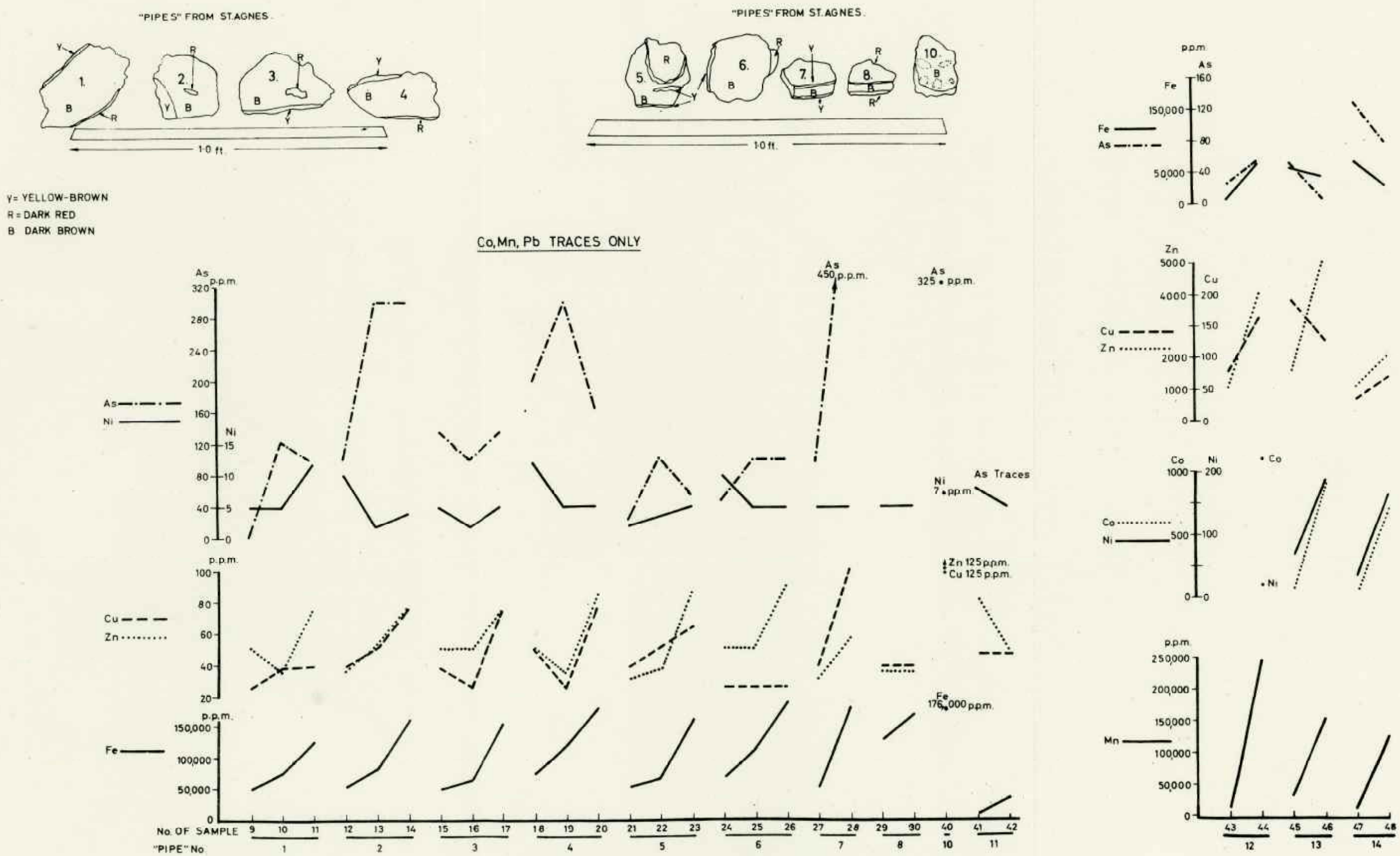


FIG. 6. Distribution of various elements in Deposition "Pipes" from the St. Agnes Pliocene Beds and Godrevy Raised Beach.
"Pipes" 1—12 from St. Agnes, 13 and 14 from Godrevy,
1—11 essentially ferruginous cement and
12—14 essentially manganiferous cement.

On Fig. 5 are recorded the concentrations of tin in the minus-80-mesh fractions of a series of sand samples which was taken after a long period of calm summer weather, from the top six inches of the beach, along a line extending from the dunes to low-water mark. It demonstrates that during such periods tin, in the uppermost horizons, at least, is not markedly preferentially concentrated near the high-tide lines. This was well known to those who recovered tin from the beach fifty years, or more ago: these workers only removed sand for treatment during periods immediately after on-shore gales, and they confined their attention largely to the strip immediately in front of the crest of the berm. (Hosking. Unpublished notes of recollections of Cornish streamers.)

Fig. 6 indicates what also has, in fact, long been known by those who recovered tin from the beach, namely that the darkest bands in any given section are the richest in tin. However, it further demonstrates that the highest concentrations of the other elements investigated, also, not unexpectedly, occur in the darkest bands.

The results of carrying out size analyses on a number of samples of sand taken from the uppermost six inches of the beach along a series of widely spaced lines across the Gwithian/Hayle beach, and approximately transverse to the cliff/dune line, following a considerable period of calm summer weather, are plotted on Fig. 7. They clearly indicate that the overwhelming majority of the grains falls within the minus—38/plus—80 (B.S.S.) range, but that there is a tendency for the finer fractions to increase as the distance from the Red River increases. On the other hand, although the percentages of the various size fractions vary along each traverse line, the changes down the beach are not progressive, but why this is so is not understood.

Each fraction obtained during the above study was analyzed for a number of elements, but for economic reasons only the results obtained from the investigation of samples from one traverse line are included here: these are shown in graphical form in Fig. 8. and are fundamentally the same as those revealed by study of material from the other lines. Briefly, they indicate that in any sample the maximum concentration of every element determined occurs in the minus—80/plus—97 (B.S.S.) fraction, but that the

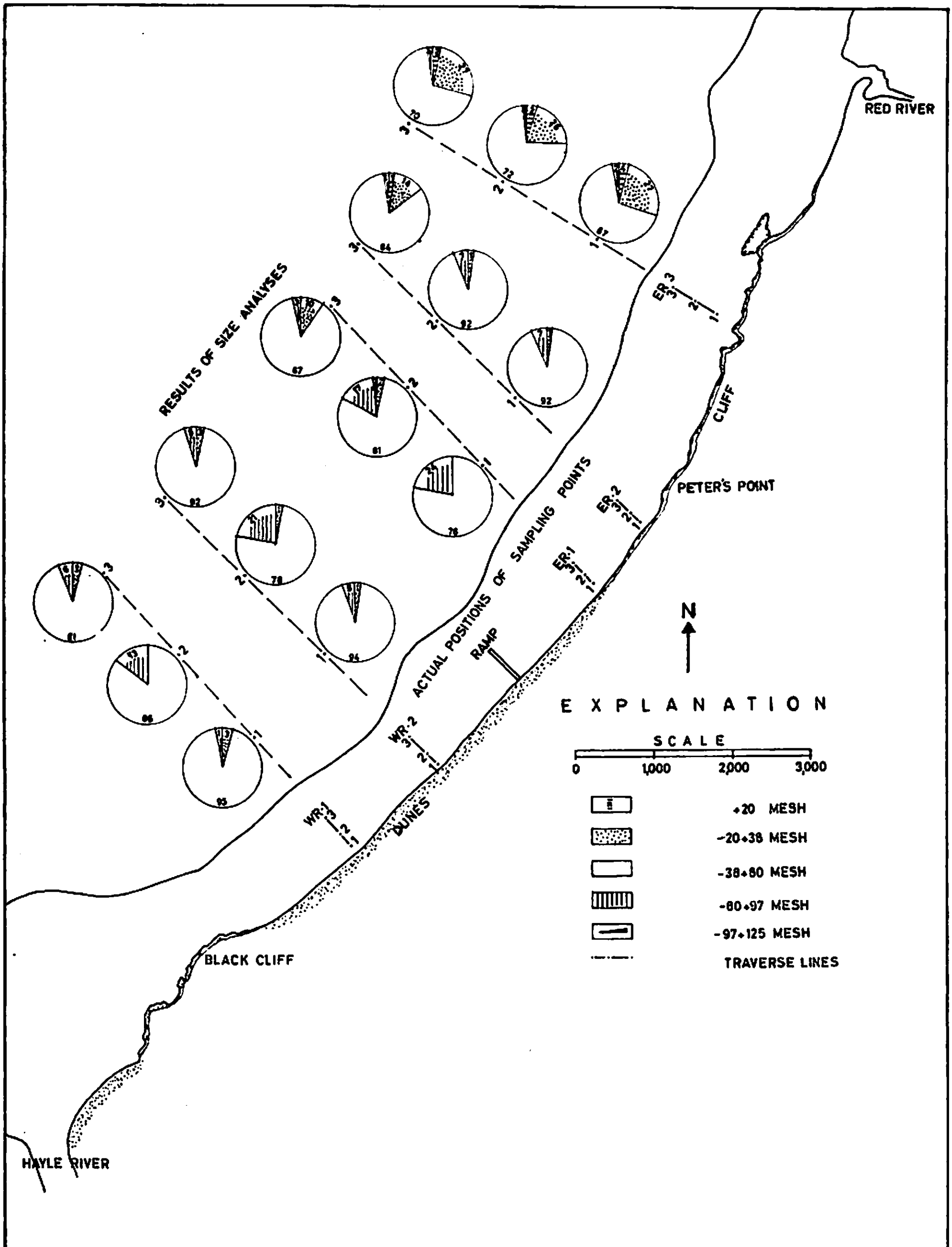
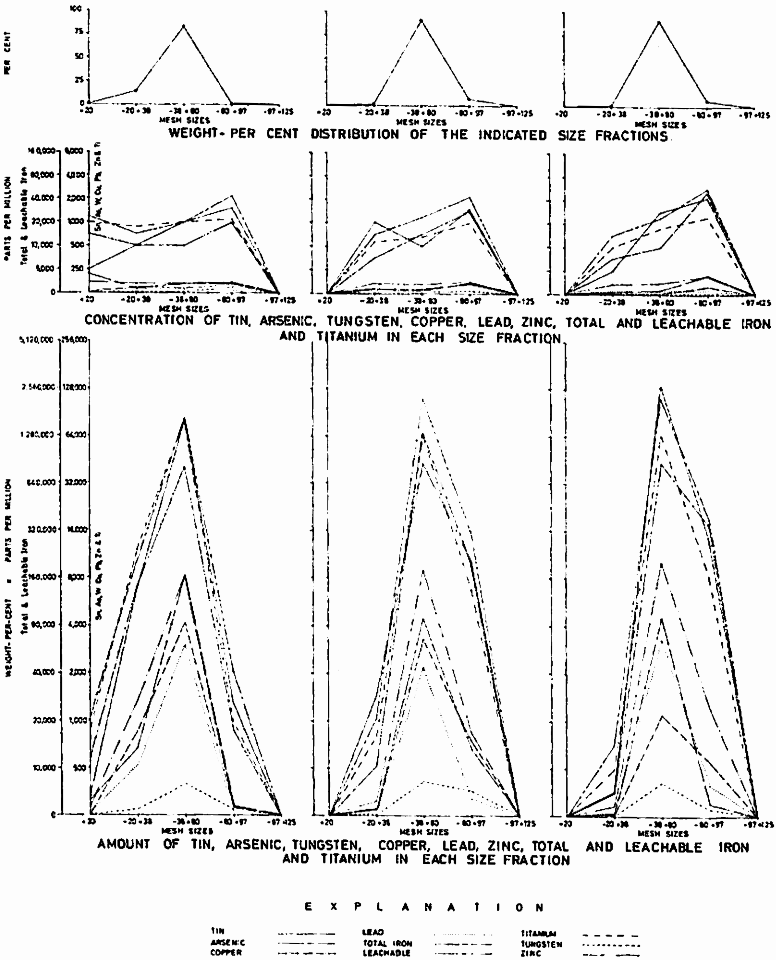


DIAGRAM INDICATING THE PERCENTAGES OF THE VARIOUS FRACTIONS OBTAINED BY DRY SCREEN-ANALYSES OF FIFTEEN SAND SAMPLES FROM THE TOP SIX INCHES OF GWITHIAN-HAYLE BEACH

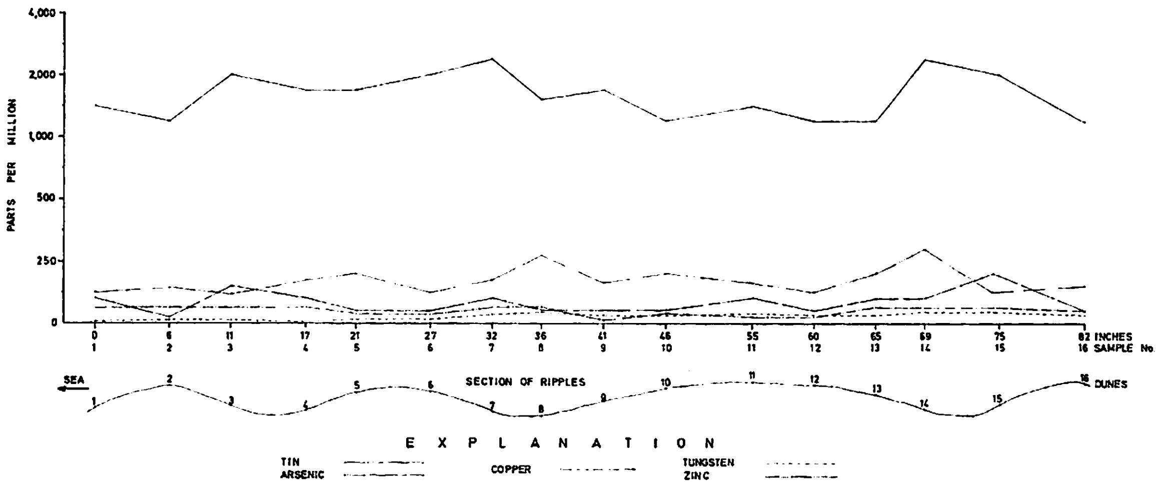
FIG. 7.



SIZE ANALYSIS OF THREE SAMPLES TAKEN ACROSS THE BEACH ALONG TRAVERSE ER-2
800 YARDS NORTHEAST OF THE RAMP

FIG. 8.

maximum amount of each element is in the minus—38/plus—80 fraction. From the economic point of view it suggests that the recovery of tin from the superficial parts of the beach, at any rate, involve essentially the liberation and subsequent concentration of cassiterite from sand grains within the minus—38/plus—97 (B.S.S.)



DISTRIBUTION OF TIN, ARSENIC, COPPER, TUNGSTEN, AND ZINC ON THE RIPPLE MARKS

FIG. 9.

range: cassiterite which, as noted earlier, falls essentially within the 5-50 micron range!

Finally, the fact that surface irregularities of the beach play a part in determining the distribution patterns of the elements investigated is indicated by the results of analyses of sand samples taken from the surface of a rippled portion. These are shown in Fig. 9 and indicate a distinct tendency for the denser grains, containing cassiterite, etc., to collect in the depressions.

GENESIS OF THE STANNIFEROUS BEACH DEPOSITS

From the evidence presented in this paper it is clear that most of the tin and other heavy elements investigated which occur in the superficial portions of the beach are tailings from the mines in the Camborne/Redruth area which have been transported to the study area by the Red River: an unknown, but not insignificant proportion of some of the elements, notably zinc and lead, has been derived from cliff lodes.

During the transportation of the tailings by the Red River to the sea, tin, largely as "slime cassiterite", has been preferentially removed by streamers, but certainly less than 50 per cent of that which was present at any time was recovered. On entering the sea the finer fractions—slime cassiterite, hematite, clay, etc—are transported by long-shore currents parallel to the coast—the dominant direction of movement at any given time depending on the state of the tide and the direction and intensity of the wind—and where conditions are favourable the fine cassiterite is concentrated.[1]

The *sand* fraction of the Red River's load consists in part of comparatively low specific gravity grains of gangue minerals and country rock, and in part of denser grains, largely composite in nature, which contain one or more 'ore minerals'. On reaching the sea these grains, together with locally derived shell fragments and lode, and other, material from the neighbouring cliffs, are eventually transported by lateral waves along the beach, either

1. Recent offshore studies have substantiated the above statement, have also demonstrated that most of the submarine cassiterite is concentrated in a band parallel to the coast-line, and have shown that only a small percentage of it exists in composite grains, and so is much more readily recovered by the usual beneficiation processes than is that in the beach deposits where most of it does so occur.

towards Godrevy or Hayle, depending on the direction of the wind. The general conditions are such that the percentage of finer fractions in any given sample of sand increases towards Hayle.

As noted earlier, during periods of prolonged calm, which occur most commonly during the summer, but which are not unknown during other seasons, the small waves of low energy level tend to build up a broad flat berm which, when mature, extends from the dune/cliff base to *ca.* 30 feet below the low-water line. Under such conditions the denser sand fractions of the fairly well graded beach material are concentrated as a number of thin near-horizontal superimposed 'sheets' which individually, it is thought, commonly take the form of flat ellipsoids whose long axes approximately parallel the dune/cliff base. These thin dark bands are separated by pale-coloured sheets composed essentially of quartz, shell fragments and white mica.

It is not known how many processes are involved in the concentration of the denser components, but it is thought by the writers that the dominant one is akin to the wet tabling processes used in mills. The energy level of the small breaking waves is such that only surface sand, and that very near the surface are subject to concentration. Clearly, some sort of separation of the dense and light grains of the agitated sand occurs each time a breaking wave advances up the beach. It will carry landward a load consisting of dense and light grains: however, as much of the invading water sinks into the beach, that which returns to the sea along the surface has a much reduced transporting power and hence it preferentially carries the lighter grains seaward. There is little point in prolonging discussion on this subject as much more field and laboratory work involving tank studies, etc., is needed before further useful pronouncements can be made on this subject.

During storms, which are most common in winter, but which are not unknown during the other seasons of the year, and when the winds are blowing on-shore, heavy seas erode the beach. If the erosion is prolonged, much of the sand is transported seaward where it forms off-shore bars; the beach develops a concave profile, and terminates near the dune/cliff base as a marked ridge which possesses a steep seaward-facing face and which may increase in height as a result of storm waves piling sand on it.

Under such circumstances the denser fractions are concentrated as a series of near-horizontal 'sheets' which are commonly much thicker than their calm weather counterparts.

Again, the processes of concentration involved are not well understood, but the writers believe that, as in the periods of calm, that which is essentially one of tabling is the dominant. However, when storms prevail, considerable thicknesses of the sandy floor are periodically suspended in water in the breaker zone, and the intense agitation of the grains then probably initiates further concentration processes similar to heavy media separation and jigging. Grains of intermediate specific gravity suspended and agitated in water behave as a heavy medium through which low specific gravity grains rise and high specific gravity grains sink. If a layer of pebbles occur towards the base of the heavy medium band it will behave as ragging in a jig and a fine, very dense sand fraction will collect immediately below it. An example of such an occurrence has been noted earlier in the paper.

Throughout the year concentration is also locally assisted by the presence of surface irregularities, particularly ripples and distributary channels, and both these features effect concentration of the denser sand components in much the same way as it is effected in a sluice box.

On-shore wind may also facilitate concentration of the denser fractions by preferentially transporting the low specific gravity fragments of the well-classified sands from the beach to the dunes. On the other hand, off-shore winds carry sands from the dunes to the beach and so tend to off-set the work of the concentrating agents. Strong on-shore winds also tend to locally oppose the concentration of the heavy fractions in that they dry the superficial sands in the seaward-facing dune valleys thus facilitating the flow of dune sand on to the beach. In addition, on-shore and long-shore winds spread low specific gravity sand over the darker sheets of essentially sea-concentrated dense grains.

CONCLUSION

Whilst the foregoing account adds something to the carpus of knowledge of the Gwithian/Hayle beach in particular, and of beaches in general, and indicates under what circumstances a study of the element and mineral content of a beach may reveal something of the economic potential of the hinterland drained by rivers feeding the beach; and whilst it demonstrates that rapid semiquantitative colorimetric methods of analysis can be a powerful tool in the hands of those carrying out investigations of the type under review, it also serves to emphasise that the character of a beach at any given time is the product of a complex interplay between numerous processes, which constantly vary in relative importance, and which are, for the most part, still imperfectly understood.

It is hoped that by 'high-lighting' some of the numerous problems still awaiting solution, this paper will induce others to investigate this complex dynamic feature which is called a beach.

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PLATE 1. Plan view of the excavated lower portion of the vertebral column of a seal embedded in the beach at Upton. The column is orientated parallel to the dune base. A half-crown on one of the vertebrae indicates size.

PLATE 2. "End view" of the column shown in Pl. 1.

PLATE 3. Dark and light bands revealed in the side of a trench, excavated transverse to the dune base, at Upton. The uppermost dark zone, *ca.* 12-in. thick, was developed, it is thought, during periods of heavy seas. S indicates the beach surface.

PLATE 4. The seaward end of a trench at Upton showing dark and light bands of sand and a 'sand volcano'.

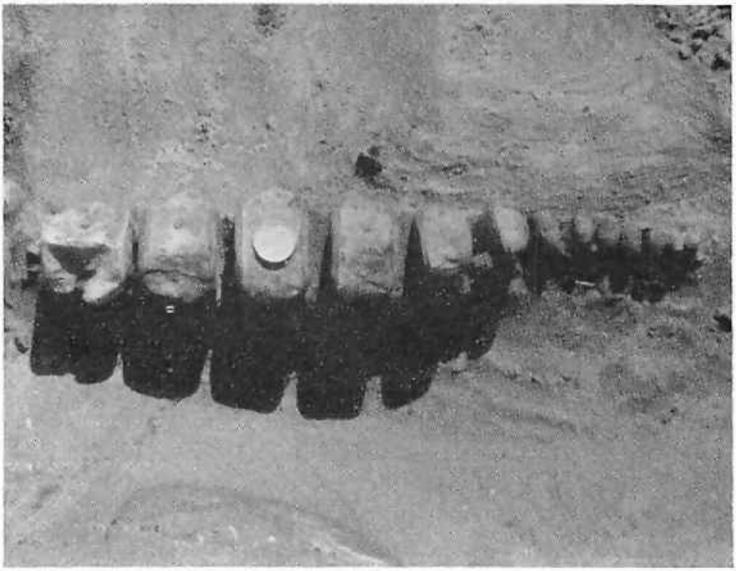

PLATE 1.

PLATE 2.

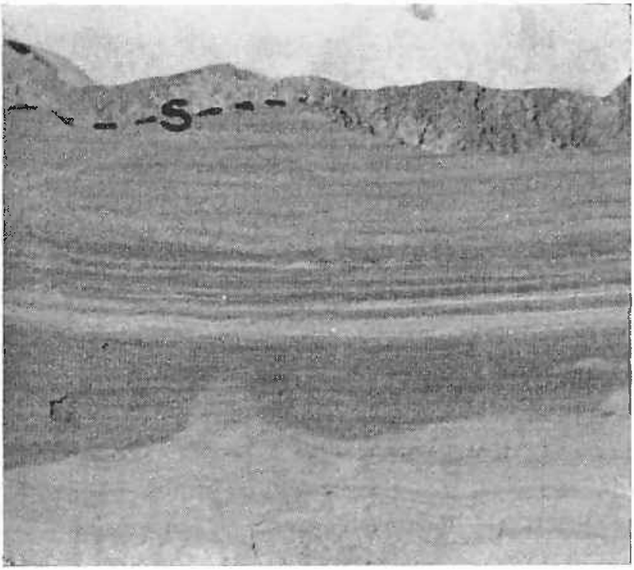

PLATE 3.

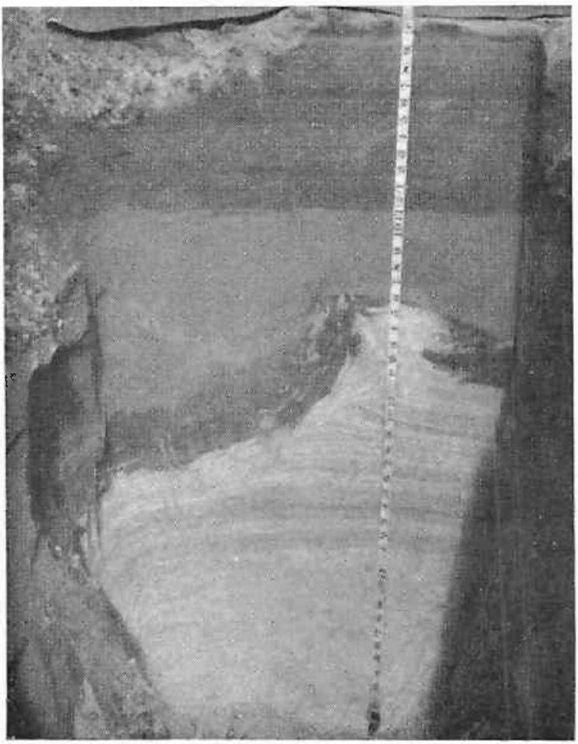

PLATE 4.