A

THESIS

entitled

SOME ASPECTS OF THE GEOCHEMISTRY OF TIN AND OTHER ELEMENTS IN SEDIMENTS OFF NORTH CORNWALL

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ABSTRACT

The lateral distribution of tin in the surface marine sediments off the St. Agnes Head/Portreath coast, North Cornwall, has been investigated using geochemical and sedimentological techniques, and its distribution has been related to eluvial and alluvial sources.

A rapid geochemical technique for tin determination using atomic absorption spectrophotometry has been devised and applied to marine sediments, after the preliminary removal of shells. The difficulty of sampling high density cassiterite present in sediments both in the form of composite and discrete grains has been evaluated, and the representative sample size required is found to be dependant on the grain size, the tin content and the ratio of availability between composite and mono-mineralic cassiterite grains. The application of hydraulic equivalence to cassiterite has been examined, and it is concluded that quantitative studies on statistically representative samples of only mono-mineralic grains, is necessary to obtain meaningful results.

The study area contains an extensive sheet of medium to fine-grained sand, enriched in tin in the surface horizon which decreases in content away from the coast. Textural studies have revealed an area with very well-sorted sand similar to that found on the present day beach but with significantly finer mean size, this suggests the existence of strong bottom currents off St. Agnes Head. Towards the supposed offshore extension of the Towanwrath tin lode, the basal sediment shows enrichment in tin which may be related to submarine bedrock mineralisation. However, the enrichment is much lower than in the surface sediment because of secondary tin dispersion from land which has affected only the surface sediment.

Investigation of surficial sediments affected by present day mine tailing discharge in St. Ives Bay and off Pendeen indicate that similar conditions must have existed in the past when mines were in operation in the St. Agnes Head/Portreath area. Evidence from present day stream sediments and sediments trapped within the Hayle Estuary emphasize the important contribution of tin in mine tailings to its content in marine sediments.

Anomalous samples of the offshore surficial sediments are found to be enriched in copper, iron, arsenic and tungsten as well as in tin. The abundance of these elements are also thought to be related to contamination from mining on land.

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CHAPTER 1. INTRODUCTION

1.1.0. General

During the last twenty years, there has been a marked growth of interest in marine mineral deposits. The reasons for this are due firstly, to the exhaustion of many easily assessible supply of minerals on land; secondly, to the rise in demand for these minerals; and thirdly, to their resultant increase in price.

Tooms (1967) classified mineral deposits of the sea floor into f~~ive~~our categories.

(a) Deposits within the consolidated sea floor beneath the recent marine sediments including coal seams, tin lodes, oil and natural gas.

(b) Detrital or placer deposits on the continental shelf including tin, diamond, gold and other resistant heavy minerals.

(c) Precipitates on the continental shelf, namely phosphates.

(d) Mineral deposits in the deeps beyond the continental shelf including manganese nodules and encrustations.

Out of these four categories, the first category has by far the longest history of exploitation. Coal seams have long been known to extend beneath the sea bed and in the British Isles, submarine coal seams have been worked in the Cumberland Coalfield dating at least as far back as the sixteenth century. Similarly undersea lodes have been worked in the tin and copper mining districts of South-west England, notably the Levant Mine, where workings extend almost one mile out to sea from shafts on the land, and to a depth of over two thousand feet.

The most productive marine mineral deposits at the present time belong to the second category. Emery and Noakes (1968) have sub-divided these deposits into three categories.

(a) Heavy heavy minerals of specific gravity 6.8-21, including cassiterite (tin oxide), native gold, native platinum which occur often in stream sediments.

(b) Light heavy minerals of specific gravity 4.2-5.3, including ilmenite, rutile, zircon, monazite and magnetite which occur chiefly on beaches and submerged beaches.

(c) Gems of specific gravity 2.9-4.1, including diamonds.

In Table 1.1. are shown the world production figures for various heavy minerals and offshore areas of operation for the main placer deposits of these minerals.

The increasing recovery of these minerals from the sea make it essential that prospecting techniques be further developed to overcome the problems of an as yet little known and 'hostile' environment, and to cut exploration costs.

In the present study, geochemical prospecting techniques have been used in the study of cassiterite, a heavy mineral found in both primary and secondary deposits off the North Cornish coast.

Table 1.1. World production figures for heavy minerals during 1960-5. Based on Emery and Noakes (1968).

Mineral	Total Production	Placer Production	% Placer Production	Area
Gold	199 m. oz.	25 m. oz.	11	Alaska
Tin	1,020,000 long tons	765,000 long tons	75	Thailand, Indonesia
Platinum	11.2 m. oz.	1.45 m. oz.	13	Oregon
Ilmenite	16.3 m. tons	5 m. tons	30	Australia, Ceylon
Rutile	0.96 m. tons	0.94 m. tons	98	
Zircon	1.4 m. tons	1.4 m. tons	100	
Monazite	39,000 tons	31,000 tons	80	India
Diamonds	168 m. carats	151 m. carats	90	S.W.Africa

1.2.0. Previous work

While numerous geochemical surveys for tin in stream and soil sediments have been carried out in Cornwall, the study of tin in offshore sediments has only been attempted recently. From 1960 onwards, mining companies, universities and government departments have embarked on exploring and exploiting the offshore tin potential.

The earliest work done on beach and offshore geology in Cornwall was a study of the mineralogical composition of beach sediments collected from the High Water Mark, where concentrations of heavy minerals occur. Crook and Davis (1909) and Stuart and Simpson (1937) gave descriptions of beach samples taken from the Gwithian-Hayle Beach, and Robson (1943-4) gave brief descriptions of beach and dune sediments from all over Cornwall. More recently, Garnett (1962) used scuba divers to map the sea bed between St. Agnes Head and Cligga Head, and in 1972 the Institute of Geological Sciences published a map of the sub-Pleistocene geology of the British Isles and the adjacent continental shelf in a scale of 1:2,500,000. In addition, Hill and Parker (1970) examined the distribution of tin and zirconium in beach sediments in Cornwall as part of a reconnaissance survey around the British Isles.

Work carried out at the Camborne School of Mines on beach and estuarine sediments has involved the use of semi-quantitative colorimetric methods of analysis to relate the distribution of tin and its associated elements to local geology, mineralisation and mining activity. Ong (1962) investigated the superficial distribution of tin and its associated elements in the Gwithian-Hayle Beach, Krishnan (1963) also studied the vertical distribution of tin and its associated elements at the same locality, and

Pisarski (1964) studied the superficial distribution of tin and its associated elements in Perran Beach. Geochemical investigations were undertaken by Hosking et al. (1963) on the distribution of tin and chromium in Cornish beach sands, by Hosking and Obial (1966) on tin and other elements in the sediments and waters of Carrick Roads and of its 'feeder' rivers, and a reconnaissance investigation on surficial intertidal sediments in South-west Cornwall was undertaken by Yim (1972).

Exploration work for tin by mining companies has been carried out in Cornwall both from the land and offshore. In 1961, Geevor Tin Mines explored the area seawards between St. Agnes Head and Perranporth by inclined diamond drilling, and Coastal Prospecting Limited in 1961-1965 sought for tin placers in St. Ives Bay (Lee 1968), partly on the basis of a Sparker survey carried out to determine the sediment thickness (Taylor Smith 1962, unpub. rep.). In 1968, Amalgamated Roadstone Corporation investigated the Wherry Town tin-bearing elvan dyke by diamond drilling from a platform constructed on the beach (Dunham and Shepard 1969). Furthermore, from 1965-1968, the Marine Mining Company carried out a geophysical exploration programme covering an extensive area of offshore Cornwall using a Sparker for the purpose of ascertaining the possible presence of placer tin deposits (McGuinness and Hamilton 1972), and deposits of particular interest were subsequently sampled by vibrocoring.

In Mount's Bay, the Royal School of Mines has carried out a number of geochemical and geophysical prospecting studies (Tooms et al. 1965; Ong, 1966; and Hazelhoff Roelfzema, 1968) to determine whether geochemical anomalies occur in surficial sediments overlying tin lodes. The present project is a continuation of this Applied Geochemistry Research Group programme into heavy mineral dispersion.

1.3.0. Objectives

The main ojective of the present research is to investigate the present day tin distribution in surficial offshore Cornish sediments, and to interpret the results in terms of (a) the relationship of tin in the sediments to submarine bedrock mineralisation and, (b) environmental factors which include both marine and fluvial processes of tin concentration, and mining contamination.

On account of the high specific gravity of cassiterite, compared with its associated minerals in sediment, an attempt has been made to evaluate sampling reproducibility. In addition, the matrix effect of the sample in geochemical determination for tin utilising the ammonium iodide method of extraction has been examined, and other methods of tin determination used in geochemical prospecting for tin have been evaluated.

As an aid to interpretating the tin sources, the hydraulic equivalence theory first applied to cassiterite by Hazelhoff Roelfzema and Tooms (1969) has been examined. In addition, some other heavy metals found associated with tin mineralisation have been analysed. The past and present sources of tin originating from the hinterland of the study area have been investigated by the examination of stream sediments, beach sediments and estuarine sediments; and an attempt has been made to evaluate the part played by rivers and streams affected by present day mine tailing discharge in tin dispersion. The vertical distribution of tin in offshore sediment which is as yet very poorly understood has also been studied, but only a limited number of cores were available. Finally, an attempt has been made to develop techniques for the geochemical prospecting of offshore tin deposits.

1.4.0. Choice of area

In order to select a suitable area to carry out this investigation two basic requirements had to be satisfied. The area must have tin mineralisation with tin lodes at or near the coast, and must not be too badly contaminated by mine tailings which might conceal anomalies due to dispersion from a primary source.

The St. Agnes Head/Portreath area was selected on account of the following factors.

(1) The Towanwrath Lode in the area is essentially a tin lode, compared to the Trewavas Head lodes in Mount's Bay previously investigated by Ong (1966) which are more noted for their abundance in copper (Dines 1956). The cliff exposure shows the Lode to vary between 4-6 ft. and the cassiterite occurs on the hanging wall (Dines 1956).

(2) Offshore rocks in the area are also likely to be mineralsed, as the tin zone of the St. Agnes Beacon Granite, including the Towanwrath Lode, extends seawards; and the trend projections of the mineral lodes merge with those of lodes from the Land's End Granite occurring between Hayle and St. Ives.

(3) The existence of an extensive sheet of sand offshore which has been found by McGuinness and Hamilton (1972) to contain detrital tin.

(4) The coastline is undergoing degradation with cliffs of over 200 ft. fringing the coast.

(5) There is no present day mining activity in the hinterland, the Towanwrath Lode working having closed in 1913 (Dines 1956).

(6) There are no major streams draining into the offshore study area, and thus past mining contamination is less severe than, for example, in the Red River in St. Ives Bay (Hosking and Ong 1963-4). In addition, a beach sediment regional geochemical reconnaissance survey by Yim (1972) also suggested that this area is not as badly affected by mining contamination.

(7) The sea floor slopes gradually down to a depth of over 120 ft. about three miles from the Low Water Mark. Therefore, the behavior of tin in different energy environments can be studied.

(8) As far as the writer is aware, no harbour dredgings have been dumped in the area. This contrasts with Mount's Bay for example, where tin rich sand and silt dredged to deepen the Penzance and Newlyn Harbours, have been dumped in an area of spoil ground in the middle of the Bay (Cotton 1972, personal comm.).

1.5.0. Layout of thesis

This thesis is divided into eight chapters. Chapter two gives the general background of the hinterland including a review of past mining activity and likely sources of past and present contamination. Chapter three gives an account of the field and laboratory procedures used and includes investigations on sampling reproducibility, a rapid technique for tin determination in sediments and the application of hydraulic equivalence. Chapter four gives the general background of the offshore environment based on available information and data obtained from sedimentological studies by the writer. Chapter five gives an account of the geochemical investigations, including studies on possible path-finder elements in the St. Agnes Head/Portreath sediments. Chapter six gives follow-up investigations especially on specific areas affected by present day mining contamination and studies on streams to determine the present day supply of alluvial tin to offshore areas. The results are further discussed in Chapter seven and a summary of the main conclusions together with recommendations for future work is given in Chapter eight.

The Appendix contains information on wind strength and direction during the sampling periods, sample locations and characteristics, and results of granulometric analysis.

CHAPTER 2. GENERAL BACKGROUND OF THE HINTERLAND

2.1.0. Location

Cornwall together with Devon and parts of Somerset make up the South-west Peninsula of the United Kingdom, while Cornwall forms the most south-westerly of all English counties. The county itself is bounded to the north by the Bristol Channel and to the south by the English Channel, and is exposed to the influence of the North Atlantic Drift.

The offshore areas of study (Fig. 2.1.) lie between Cligga Head and Cape Cornwall to the west of the Newquay/Falmouth line. Garnett (1960-1) has pointed out that the area of the land surface to the west of this line excluding the Scilly Isles, is approximately 440 sq. miles. However, between the Low Water Mark and the two-mile line is a tidal area of 240 sq. miles. Thus, by including the offshore areas in the total prospecting ground, the area of South-west Cornwall is increased by 55 percent.

2.2.0. Climate

The area of study is under the influence of the prevailing westerly winds which are relatively warm and moist. They are responsible for the mild winters and the high annual rainfall experienced in the county, which is in the range of 40 to over 80 inches per annum, depending on aspects. The winter months are characterised by stormy weather and gale-force winds.

Data on the wind strength and direction, recorded four times daily at 6-hour intervals during 1969 and 1970, were obtained from the Kehelland Meteorological Station, situated near Camborne (Fig. 2.1.). The wind rose diagram (Fig. 2.2.) and the wind strength data give further confirmation that wind from a westerly source

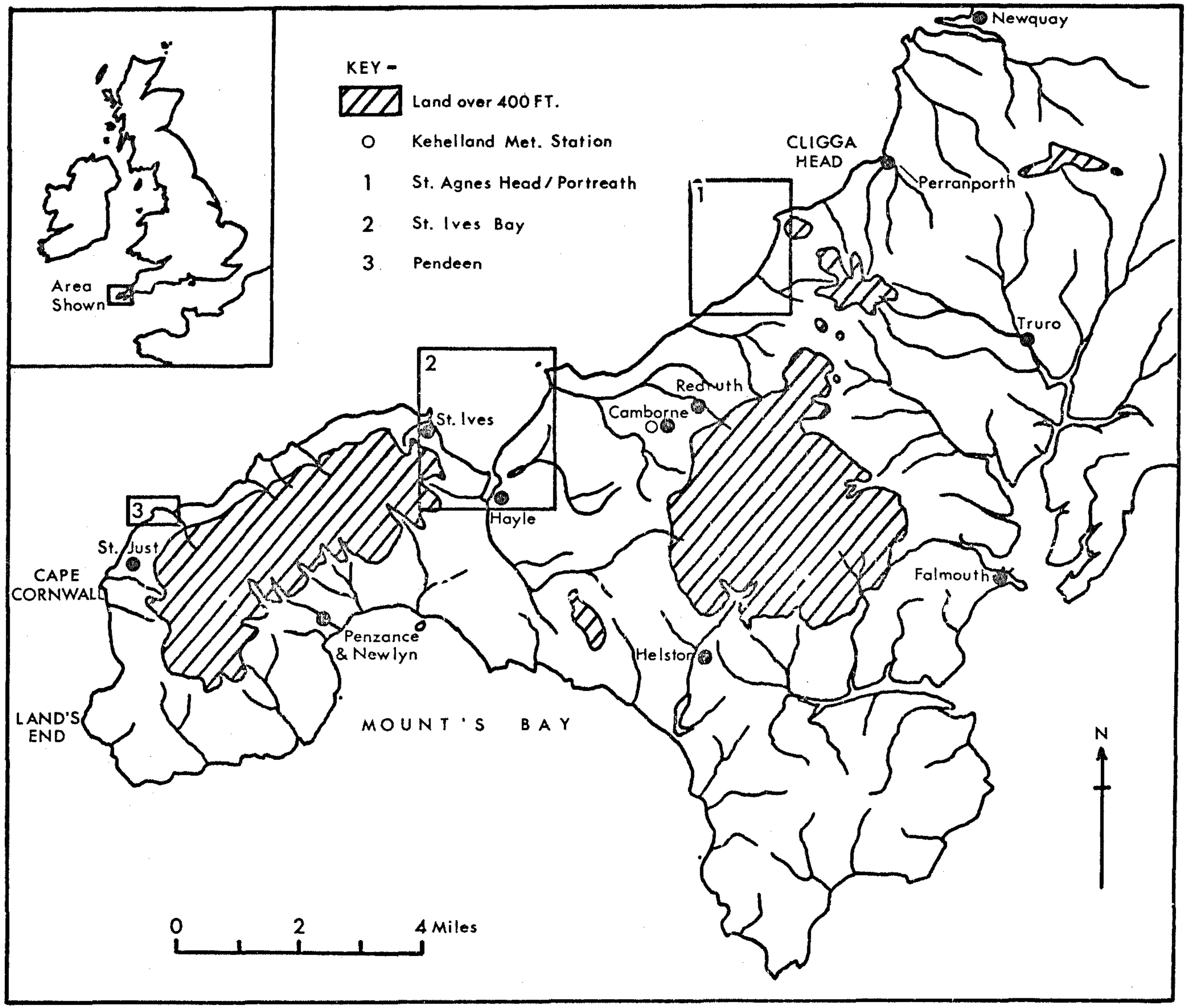
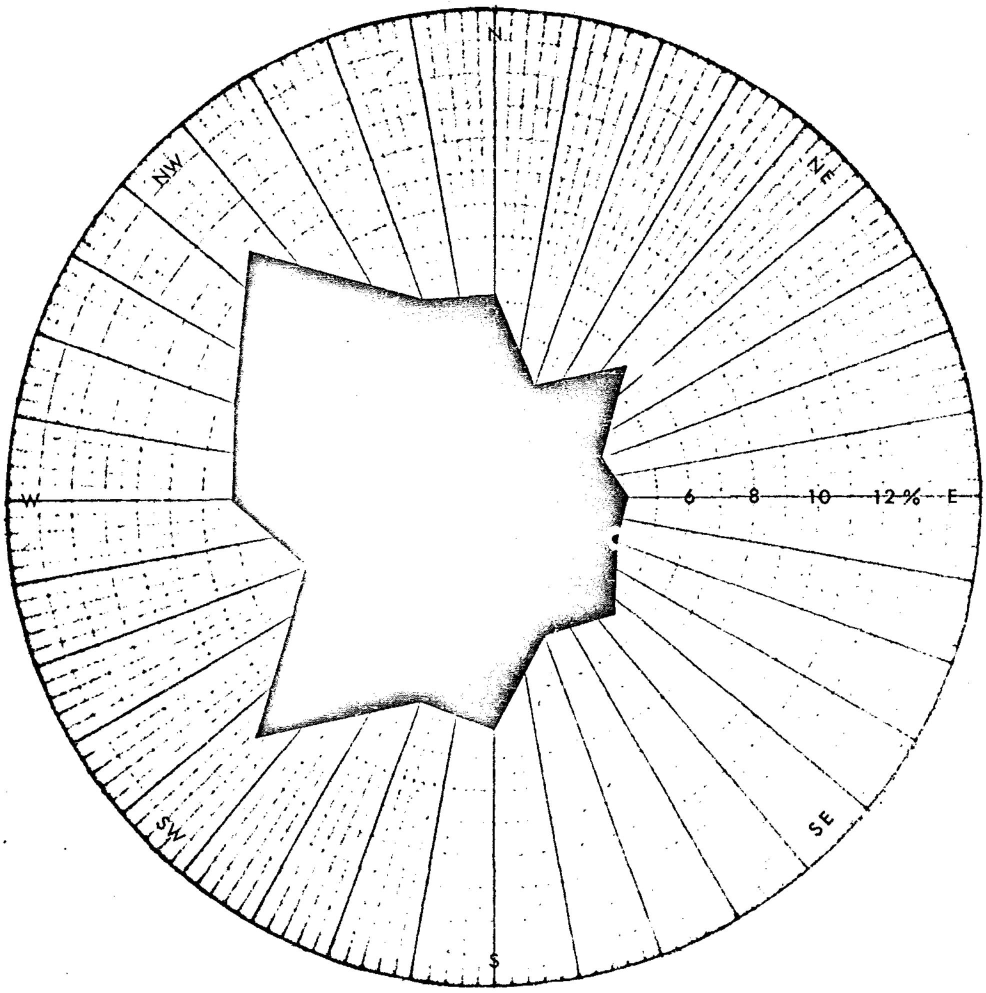


Fig. 2.1. Location map of the offshore study areas.



KEY-

N - 351- 10°
NNE - 11- 30°
NE - 31- 60°
ENE - 61- 80°
E - 81-100°
ESE - 101-120°
SE - 121-150°
SSE - 151-170°
S - 171-190°
SSW - 191-210°
SW - 211-240°
WSW - 241-260°
W - 261-280°
WNW - 281-300°
NW - 301-330°
NNW - 331-350°

Fig. 2.2. Wind rose diagram to show the frequency of wind direction during 1969 and 1970 at the Kehelland Meteorological Station.

has the greatest influence in the study area. Wind data collected immediately prior to and during the periods of beach and offshore sampling are shown in the Appendix.

2.3.0. Relief and drainage

The terrain is one of dissected granite uplands fringed by areas of lower relief in less resistant rocks. Stream valleys are in their youthful stage of development and because of their steep gradients, rapid downcutting of the basement rock is in progress leading to high stream load transportation. However, despite the rapid rate of erosion, remnants of former erosional surfaces are preserved in the landscape. The area has undergone recent submergence, much of the coastline is fringed by high cliffs reaching over 250 ft., with breaks at the mouth of major streams which often terminate in estuaries.

2.4.0. Geological setting

2.4.1. Introduction

The geology of South-west England has received a great deal of attention in the past mainly because of the immense variety of mineral deposits found in Cornwall and Devon. Description of the geology has been very well documented in the past, and in this account, only the geology of South-west Cornwall is described. However, the nature of mineralisation and the recent geology have important bearings on the secondary dispersion of tin, and thus are examined in more detail.

Table 2.1. shows the geological succession of South-west Cornwall based on Edmonds et al. (1969) and memoirs of the Geological Survey (Hill and MacAlister, 1906; Reid and Scrivenor, 1906; Reid and Flett, 1907 and Flett, 1946), the geological map is shown in Fig. 2.3.

Table 2.1. Geological succession of South-west Cornwall.

	Age (m. yrs.)	Type of Deposits
Quaternary -		
Holocene	0.1	Beach deposits; peat; alluvium blown sand & river gravels.
Pleistocene	3	Head & raised beach deposits.
Tertiary -		
Pliocene	12	St. Erth Beds - clay & sand; Crousa Gravels; Gravels of Polcrebo; St. Agnes Sands - sand & candle clay.
Palaeozoic -		
Devonian	400	Grampound Grits - calcareous sandstone & slate; Meadfoot Series - black calcareous slate & limestone.
? Devonian		Portscatho Series - sandstone & slate; Falmouth Series - sandstone & slate often variegated; Mylor Series - siltstone & slate knotted near granite; Gramscatho Beds - interbedded greywacke & slate with conglomerate.
Unknown Age -		
Lizard Series		Spilitic lava; granite gneiss; epidiorite; gabbro-troctolite; serpentine; Treleaque Quartzite; mica-schist granulite & hornblende schist.
Intrusive Igneous Rocks -		
Granite		
Aplite; pegmatite & porphyry (elvan)		
Lamprophyre		
Dolerite (greenstone)		
Associated Lode Metals -		
Antimony, arsenic, bismuth, copper, iron, lead, silver, tin, tungsten, uranium & zinc.		

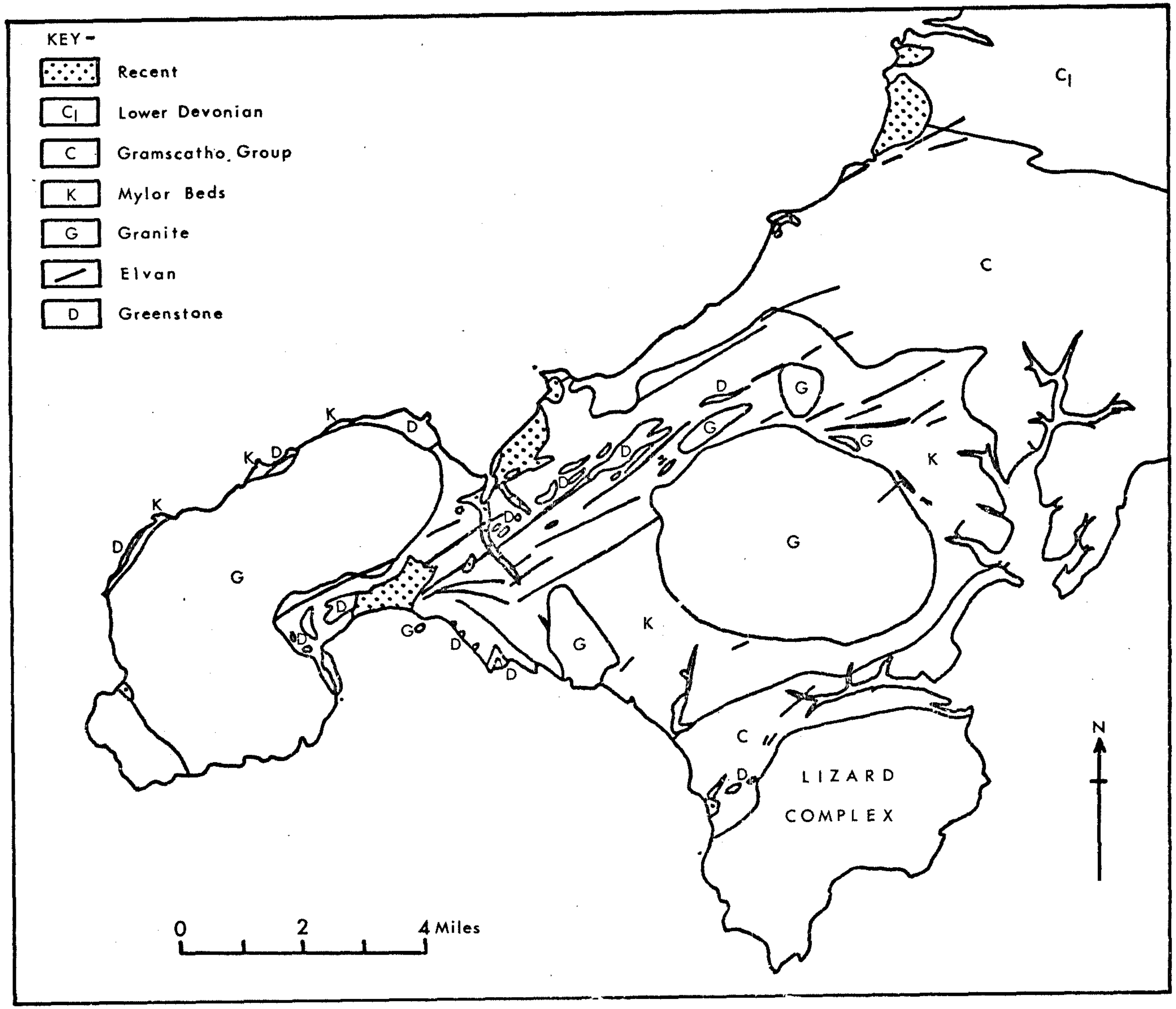


Fig. 2.3. Geological map of South-west Cronwall.
After Geological Survey 1:250,000 map.

2.4.2. Pre-Tertiary geology

The oldest known rock to occur belongs to the Lizard Series. This is a series of regionally metamorphosed sedimentary rocks which has been intruded by basic and ultrabasic igneous rocks, and associated with spilitic lavas. These rocks have been thrusted northwards over the younger Devonian rocks during the Variscan orogeny.

The Devonian rocks, known locally as 'killas', are essentially an alternating series of non-calcareous sandstones and slates which have been laid down in an east-west trending syncline. These rocks have been intruded by dolerite, known locally as 'greenstone', in the form of sills, and they are frequently domed by later intrusion of granite masses, and dip away from them (Robson 1964).

The time of granite emplacement was at the end of the Carboniferous Period or possibly at the beginning of the Permian (Butcher 1961); radiometric age determination indicate an age of 280 ± 10 million years (Long 1962). The granite intrusion was probably in the form of a batholith (Hosking 1949), which is supported by the gravity measurements of Bott et al. (1958). The exposed surfaces of the granite at Cligga Head, St. Agnes Beacon, Carn Brea, Carn Marth, Carn Menellis, Godolphin, St. Michael's Mount, Land's End and the Scilly Isles are cupolas on the surface of the batholith. The sedimentary rock cover over the remainder of the granite is unlikely to attain a great thickness, probably reaching a maximum of 1 kilometre between the Land's End and Godolphin outcrops (Bott et al. 1958).

Associated with the granite are numerous north-east south-west trending mineral lodes and porphyry dykes, the latter known locally as 'elvan' dykes. These lodes have been enriched in hydrothermal minerals containing antimony, arsenic, bismuth, copper, iron, lead, silver, tin, tungsten and zinc. Four main mineral zones occurring consecuetively further away from the granite have been identified (Dewey 1925 and others). These are :-

(1) Tin zone associated with cassiterite and wolframite.

(2) Copper zone associated with chalcopyrite and arsenopyrite.

(3) Lead-zinc-silver zone associated with galena, sphalerite and argentite.

(4) Iron zone associated with haematite and stibnite.

Mineral lodes outcropping along the coast are numerous in the vicinity of St. Just, where the lodes exhibit a north-west south-east trend, St. Agnes and Cligga Head (Fig. 2.4.). They occur less extensively in St. Ives Bay, Perran Sands and Mount's Bay. The elvan dykes are also mineralised adjacent to or within the granite, for example, in Wherry Town where the dyke was formerly worked for tin (Russel 1949), but are barren away from it.

Zoning in the metamorphic aureoles of the granite cupolas is, in general, not clear-cut. However Knuckey (1957) has identified four zones of thermal metamorphism decreasing in grade away from the Cligga Head Granite. These are:-

(1) Andalusite-biotite Hornfels, up to 6 inches.

(2) Tourmaline-biotite Hornfels, grading into Tourmaline Schist, 50 ft.

(3) Muscovite-sericite zone of bleached slates, 750-1000 ft.

(4) Chlorite zone typified by spotted slates.

2.4.3. Post-Tertiary geology and geomorphology

A few remnants of probably Tertiary marine deposits occur. These include the clays, sands and gravels at St. Erth, St. Agnes, Polcrebo, Crousa Common and Pendarves, and, with the exception of

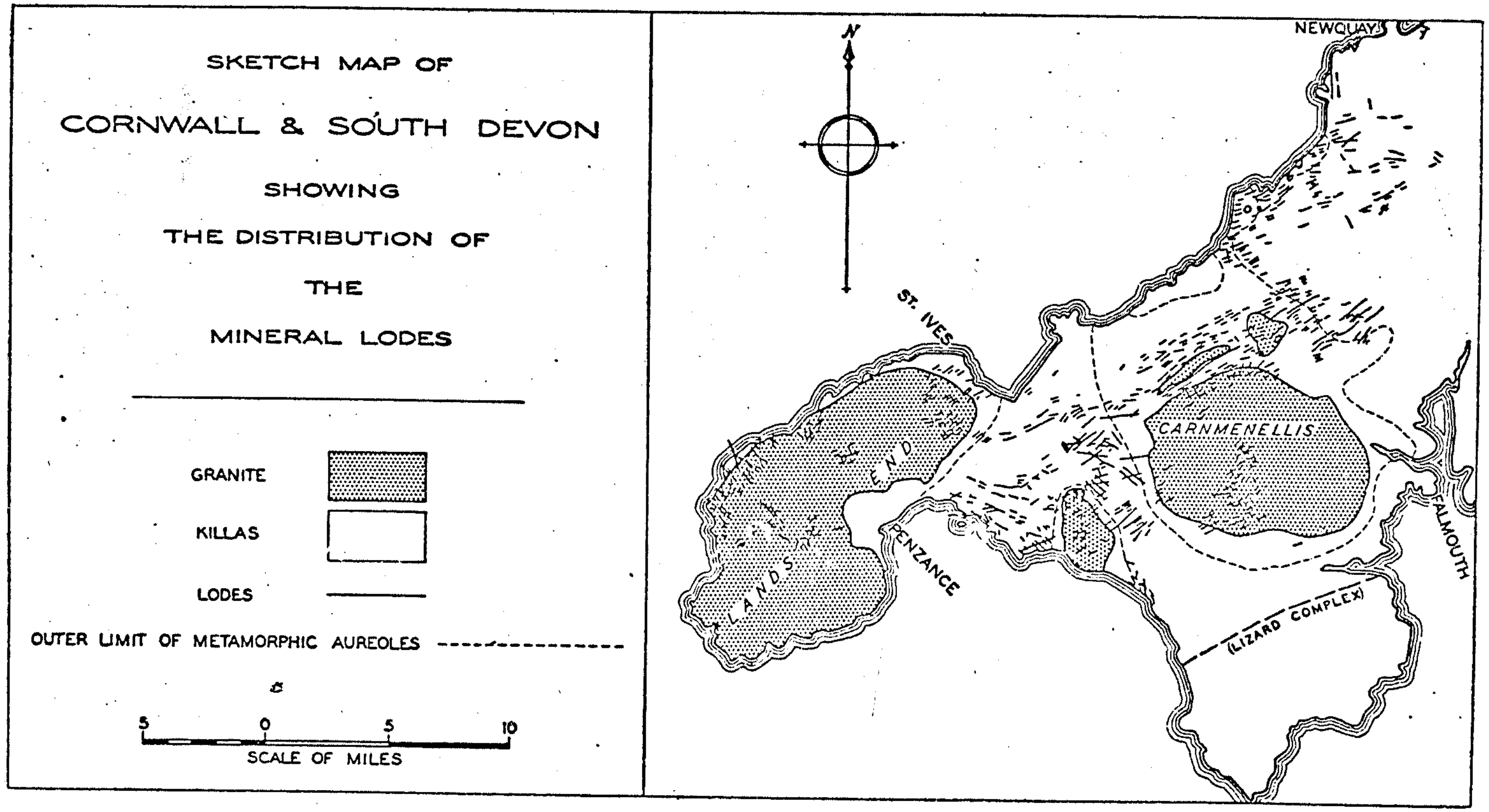


Fig. 2.4. Sketch map showing the distribution of the mineral lodes. From Dines (1956).

the St. Erth deposit which occurs at 100 ft. Ordnance Datum (O.D.), all these deposits occur at between 350-500 ft. O.D. In all cases they are found in well-protected depressions in bedrock which are favourable for their preservation.

The age and origin of these deposits has been the subject of great controversey, and as a result they have received a great deal of attention. Of special interest in the context of the present study are investigations on the mineralogical composition of these deposits. Milner (1922) studied the mineralogical composition of these deposits, and using an abundance scale of minerals ranging from very rare (1), rare (2), very scarce (3), scarce (4), common (5), very common (6), abundant (7), very abundant (8) and dominant (9), gave descriptions of the occurrence of cassiterite in the non-magnetic heavy mineral fractions (Table 2.2.).

Table 2.2. Abundance of cassiterite in the Pliocene deposits of Cornwall. After Milner (1922).

Locality	Horizons						
	A	B	C	D	E	F	G
Crousa Common	4	4	1	4			
St. Agnes	1	none	1	1			
St. Erth	4	4	-	none	none	none	4

Milner found that cassiterite is by no means common in the St. Agnes deposit, and no trace of the mineral was found in the red sand of the deposit. In the basal sands and also in the clay, however, one or two dusky-brown, rounded tetragonal crystals of cassiterite were observed measuring about 0.2 mm. Assuming that Milner's findings are correct, it is difficult to explain why the St. Agnes deposit, which in an area with surface outcropping tin lodes, has much lower tin concentrations compared to the Crousa Common deposit which is near no tin lodes. However, Milner's data may be inaccurate because of the small sample size used. Nevertheless, another quantitative mineralogical study by Boswell (1923) using an almost identical scale of mineral abundance, found that cassiterite occurred frequently (5) in the Oligocene Bovey Basin of Devon but was scarce (4) in the Pliocene deposits of Cornwall including the St. Agnes deposit, supporting the findings of Milner.

On the basis of the occurrence of boulder clay deposits on St. Martin's in the Scilly Isles (Mitchell and Orme 1967) and at Fremington in North Devon (Maw 1964), it would appear that the southern most limit of Wolstonian ice reached as far south as near the present day coastline of North Cornwall (Sparks and West 1972). Periglacial or head deposits formed by solifluction occur resting on raised beaches. Good exposure of this material can be seen near Godrevy in St. Ives Bay and near Marazion in Mount's Bay.

Numerous erosional surfaces, or platforms, whose formation is thought to be related to the changing sea level during the Tertiary and Quaternary Periods, have been recognised in the South-west Peninsula. The presence of marine deposits on some of these platforms favours a marine erosional origin, although Tricart (1969) suggests that they may have been formed by differential frost shattering under periglacial conditions. In South-west Cornwall, erosional surfaces have been recognised at 750 ft. O.D., of post-Eocene possibly Miocene age; at 430 ft. O.D., of Pliocene age; at 200 ft. O.D., 65 ft. O.D. and 10 ft. O.D., of Pleistocene age (Robson 1943-4 and 1950). Most of these surfaces are of limited extent, but in the St. Agnes Beacon Granite near St. Agnes Head and in the Carn Menellis Granite at Polcrebo, the 430 ft. O.D. surface is particularly well preserved together with a Pliocene deposit.

Recent deposits of importance in the context of this study include the tin-bearing alluvial deposits of Cornwall. Robson (1943-4) has divided these deposits into high level gravels found chiefly on the soft, kaolinised and highly mineralised St. Austell Granite, and the low level gravels found in the Carnon, the Red River and the Hayle River. The low level gravels have been described by Robson who stated, 'the tinstone is well-rounded despite its hardness, and an assortment of country rock, pebbles and boulders both angular and round, were found, admixed with sand and clay: the deposit is loose, fluctuates much in thickness (1-12 ft.) beneath wide floodplains outsize for the present small streams.' Other recent deposits include blown sand, submerged forest and beach deposits, these deposits will be examined in Chapter four.

2.5.0. Geology of tin lodes

2.5.1. General characteristics of tin lodes

Within the 'normal' hydrothermal lodes in Cornwall the distribution of tin is highly irregular (Garnett 1966). Successive movements accompanied the several phases of mineralisation and allowed some tin in the form of cassiterite and much more rarely stannite (a sulphide of tin, copper and iron), to be deposited beyond the old fractures imposed by the cross-joints. The lode fissure is infilled with cassiterite-bearing material, often veined by later quartz, and the whole is bordered by altered granite, killas or elvan which often contains more cassiterite. The minerals usually found in association with cassiterite include the gangue minerals - chlorite, quartz, fluorite and tourmaline, the sulphides of arsenic, copper, zinc and iron, and tungsten minerals mainly as wolframite.

The grade of tin ore mined at the present time averages around 15 lbs. tin/ton. However, in parts of the lode the grade may be higher than 100 lbs. tin/ton. In general, the steepest dipping sections of the lodes are richest in tin and the ore tends to be concentrated at the vicinity of changes in strike and at intersections with other structures.

The length and width of tin lodes are subjected to great variations (Hosking 1969). The Great Flat Lode for example, is at least three miles long. Others may be mineralised over dip lengths of several thousands of feet as in the Dolcoath Main Lode which has been worked to a vertical depth of 3300 ft. Some of the lodes are 50 ft. or more in width but the majority are between 4-5 ft., and at Geevor Tin Mines, the average width is from 1½-2 ft. However, as mentioned, the width of a given lode may be subject to marked variations. At Geevor, the average length over which the lodes contain payable ore is approximately 1000 ft. with a maximum of 5000 ft., and the vertical extent of the lodes with payable ore varies between 300 ft. and nearly 1000 ft.

2.5.2. Tin mineralogy

Hosking (1969) has examined the variation in cassiterite grain size in South-west England. In general, the cassiterite crystals show great variation in length from 1 inch to a fraction of a micron. The common occurrence of large crystals of cassiterite is characteristic of comparatively poor veins. In the rich lodes, restriction in the size of individual crystals, except in druses, is due to the initiation of many closely-spaced crystallisation centres. Beringer (1915) noted that in quartz/tourmaline/cassiterite ore from Dolcoath, grains of cassiterite in the ranges of 100-200 microns and 50-100 microns were very abundant, and that there were also large patches, veinlets and dispersed granules of cassiterite measuring from 50 microns down to a fraction of a micron.

Venugopal (1952) has determined the concentrations of various trace elements in cassiterites and concluded that Cornish samples contain high concentrations of tungsten relative to samples from other areas of mineralisation. The Cornish cassiterite commonly has a tungsten content in excess of 1 percent. Pseudomorphs of cassiterite after feldspar have been described by Coon (1934) in Wheal Coates, and in other areas by Collins (1871). Common inclusions within Cornish cassiterite crystals include iron oxides, tourmaline, quartz and chlorite, in addition to wolframite.

2.6.0. Towanwrath Lode and the Wheal Coates Mine

Towanwrath Lode, the main tin lode of the Wheal Coates Mine, is the only tin lode to outcrop on the cliff at sea level between St. Agnes Head and Portreath. The lode forms a westerly offshoot from the St. Agnes Beacon Granite and occurs in metamorphosed killas which shows metamorphic zoning. At the cliff, the lode has been stoped into a cavern and the hanging wall is an 8 ft. wide elvan dyke. The cliff exposure shows the lode to vary between 4-6 ft. in width consisting of brecciated killas cemented by banded quartz and with much red staining due to haematisation. The lode underground is from 2-12 ft. wide and consists of quartz with patches and veins of red and brown haematite (Foster 1878). The cassiterite occurs either as patches in the quartz or more commonly in the killas of the hanging wall which has been altered to a dark tourmaline schist. On the footwall side, the tin veinlets are less common and do not extend far from the lode.

The shaft adjacent to the cliff is vertical to the 50 fathoms level and reaches a maximum depth of 80 fathoms below sea level

(Dines 1956). Though old, the mine has been active only intermittently, being worked in a small scale until 1889. Records of output are 335 tons of 9 percent copper ore and 700 tons of black tin in 1836 and 1861-1889. In 1912, the production was 17½ tons of black tin and the mine was eventually closed in 1913. An attempt to reopen the mine in 1929 was unsuccessful.

Scattered on the slopes adjacent to the public footpath near the Towanwrath Shaft, there are mine dumps from past workings. Some of the tin in these must have found its way down the cliff onto the beach through gravitational processes.

Away from the cliff and towards the St. Agnes Beacon Granite, there are a number of tin and copper lodes outcropping on the land surface. However, none of these lodes outcrop on the cliff even though the tin zone of the Granite has been shown to extend seawards.

2.7.0. Mining activity

2.7.1. Past

'If one is willing to take the word of the antiquarians, it would appear that Phoenicians carried their tin from Cornwall to Cadiz, which from say 1000 to 200 B.C. remained the entrepot for most if not all of the Cornish product, receiving the tin from the Pheonician galleys....' - Lewis (1908). The 'Cassiterides', known by the Carthaginians infact fitted well into the description of Cornwall, and Marazion, near St. Michael's Mount has been suggested to be the old port used during the early tin trading activity (Gath Whitley 1915 and others).

In the early days of tin mining, alluvial tin mining known as 'stream tinning', prevailed to the exclusion of lode mining, except in areas with extremely rich lodes at shallow depths, as in Botallack near St. Just. According to Lewis early old stream works occur at Porth, near the shore of Trewardreth Bay, St. Blazey, St. Austell Moor, St. Stephens in Brounell and St. Ewe. The exhaustion of stream tin in the sixteenth to seventeenth century led to the tapping of lode tin following major advances in rock mining technology. Ancient rock mining known as 'daylight mining' was in openpits, found in rich areas as in St. Just, Carclase near St. Austell, Gwenapp and the Isle of Trescaw in the Scilly Isles. Sharp rises in production took place in the latter half of the seventeenth to the early eighteenth century, following improvement in mineral dressing, and the introduction of the steam engine and the reverberatory furnace during this period opened up new frontiers. The nineteenth century saw a change from manual labour to machines, stamps used in breaking the ore were heavier and more numerous, also during this period the crushing mill, the sizing-trommel, the classifier, the continuous jigger, the automatic frame and the self-acting calciner were introduced (see Lewis 1908 for a description), and in 1871, following record tin prices, a peak in production of 16,272 tons tin concentrate or 10,900 tons metallic tin was reached (Barton 1967). However, Lewis pointed out that 'in spite of the progress which has taken place and the proverbial skill and cleverness of the Cornish miner, the wastage at the smelting-works is still enormous, and the tin mining industry as a whole lags far behind metallic mining elsewhere in England.'

Figure 2.5. shows the metallic tin production in Cornwall and Devon from the thirteenth century onwards based on Dines (1956).

2.7.2. Present

Only two tin mines, Geevor near St. Just and South Crofty between Camborne and Redruth have survived through the Second World War. The breach in the sea bed at the old Levant Mine, now part of

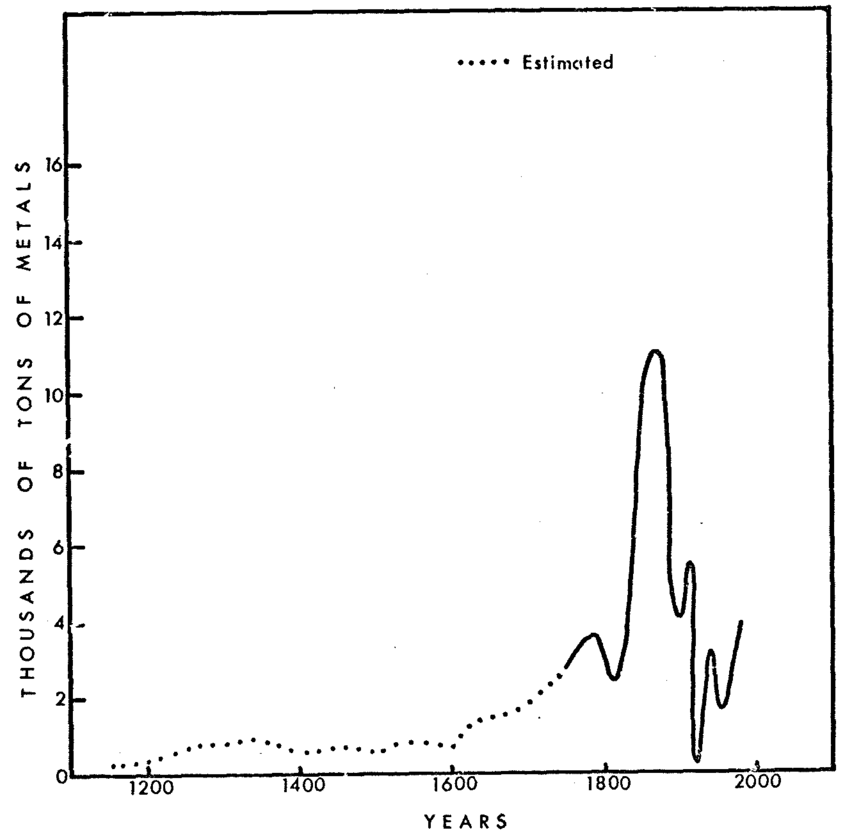


Fig. 2.5. Tin production in Cornwall and Devon. Based on Dines (1956) and Tin International statistical supplement.

Geevor has been sealed successfully (Batchelor and Wardle 1969) and new exploration work has been carried out. Both these mines average just over 1000 tons tin concentrate per annum.

During 1970, a new tin mine was opened at Pendarves near the old Pendarves Mine immediately to the west of Camborne, the crushed ore was transported by road to a mineral dressing plant at Roscroggan two miles away from the mine site. However, due to mineral dressing difficulties, the mine was closed for a short period, but is now back in production even though the Roscroggan plant has been closed and the mineral dressing is now carried out in another plant further up the Red River near Brea. The output of this mine is estimated by the writer, from the tonnage and average grade of ore raised weekly to be not more than 300 tons tin concentrate per annum.

In 1971, following a programme of diamond drilling and exploration geochemistry (Wilson 1969), the old Wheal Jane Mine near Truro was reopened. And during 1973, the output reached 1600 tons, the highest in all existing mines in Cornwall. This production figure is a major achievement when considering the short length of time the mine has been back in operation. The tin ore obtained is extremely fine-grained by Cornish standards and is associated with sulphide minerals. The mine currently utilises a cassiterite floatation section as a major part of the concentration circuit, without which recovery would have been extremely difficult (Anonymous 1974).

2.8.0. Contamination

2.8.1. Introduction

In this section, a review is given of the main sources of mining contamination in the study area, both past and present. Bacause of the long history of mining activity and the extensive distribution of mine workings in South-west Cornwall, it is essential in an investigation like the subject of this thesis to determine their effects. The liberation of tin from bedrock mining, has provided a 'tracer', and through the studies made on the tin distribution in sediments, a better understanding of the geochemical dispersion of tin in the terrestrial and offshore environment may be obtained.

2.8.2. Sources of contamination

Previous geochemical investigations on soil and stream sediments by Hosking and others at the Camborne School of Mines and by Dunlop (1973) emphasized the importance of mining contamination in accounting for some geochemical anomalies in South-west Cornwall. Hosking (1971) has examined the sources of contamination which are of concern to the applied geochemist. They are:-

(1) Contamination due to mining and allied activities.

(2) Contamination due to agricultural activities.

(3) Contamination due to industries other than those of mining and agriculture.

(4) Contamination due to domestic and allied activities.

Of these four sources, the first is by far the most important in affecting the distribution of tin in soil and stream sediments. Hosking has further sub-divided this into four categories.

(a) Contamination due to mineral exploration.

(b) Contamination due to mining and quarrying.

(c) Contamination due to mineral benefication.

(d) Contamination due to smelting.

Of these four categories, the greatest wastage of tin comes from mine tailings. Cassiterite, because of its chemical stability and high specific gravity has relatively little mobility compared to the light minerals, and normally remains as a residual mineral near to its original source, unless in a very fine state.

2.8.3. Evaluation of past contamination

The extent to which soil and stream sediments have been contaminated in the past by tin lost as mine tailings is dependant on the former scale of mining activity and the efficiency of mineral recovery techniques used. Hosking (1971) has already pointed out that in the past, the losses may have been considerable. This was demonstrated by Thomas (1913) on losses in the treatment of Cornish tin ores during the late nineteenth century and the early twentieth century. In 1890, the fifteen mines operating in the Camborne-Redruth district sold 7,131 tons of tin concentrate, while streamers recovering cassiterite from the tailings of these mines in the Red River and the Portreath River, sold during the same period 1,730 tons of tin concentrate. This 1,730 tons is astonishing in that it is still greater than the output of the Wheal Jane Mine, currently the largest tin mine in Cornwall with 1,600 tons of tin concentrate in 1973. Thomas in fact estimated that the average loss in dressing tin during the early twentieth century must have exceeded 33 percent, and in two cases which he had investigated, it approached 60 percent.

Good evidence for revealing the degree of contamination can be seen in the Banka Drill information supplied by Penhale and shown in Hosking and Ong (1963-4), Table 2.3. The drill was taken immediately to the east of the main coast road near the present channel of the Red River which at this point has a floodplain half a mile in width, and which according to Stephens (1899) consists of estuarine deposits, laid down when the lower course of the Red River valley was submerged. Sixty-seven percent of the total

Table 2.3. Banka drill in the lower Red River valley. Based on Hosking and Ong (1963-4).

Depth (ft.)	Sediment Type	% SnO_2 Recovered	Origin of Deposits
0 - 8	Loose slimey ground	67	River Channel
8 - 8½	Peat	3	Marsh
8½ - 12	Loose slimey sand		Estuarine
12 - 12½	Peat		Marsh
12½ - 17	Loose grey sand		Estuarine
17 - 20	Peaty sand	Trace	Marsh
20 - 22	Grey sand		Estuarine
22 - 28	Muddy peat with framboidal pyrite		Rapid Submergence
28 - 29	Green clay		
29 - 30	Sand & gravel	14	
30 - 31	Sand with some gravel		
31 - 33	Sand & gravel clayey at 33 ft.	4	
33 - 35	Sand & gravel clayey at 35 ft.	12	
35 - 36	Killas		

cassiterite in the core was recovered from the top 8 ft. compared with only 12 percent in the basal horizon where the tin is expected to be normally concentrated. If the top 8 ft. of the sediment can be correlated with the era of mining activity, this means that contamination through human disturbances in the Camborne mining district has contributed at least over 5½ times the natural tin concentration in the deposits of the Red River.

Stephens stated that the mines find the Red River very useful for their ore dressing operations, and below the mines themselves a large number of works have been erected for the purpose of treating the slimes and sands washed down the Red River. He pointed out the difference between the modern tin streamers who dealt with material which was the waste of mining operations and ancient tin streamers who dealt with alluvial tin gravels from the Roseworthy valley, a tributary of the Red River which in former times was very rich in alluvial tin gravel, now exhausted. He found no evidence that the early tin streamers touched the alluvial deposits beyond the confluence point of the two valleys and this led him to carry out drilling in the lower portion of the Red River. His findings confirmed that only poor tin gravel occurs in the deposits away from the existing channel of the Red River, the average grade being only 1-1¼ lbs. tin/ton.

The efficiency of tin recovery techniques is entirely dependant on the nature of the ore, mainly the grain size and mineralogical associations of cassiterite. The recovery of fine-grained cassiterite has always been a major problem in Cornwall and in the heyday of tin production 1870-1872, no less than 41 separate concerns worked the Red River for tin tailings. These tin streamers were however more capable dressers than the miners, and it was not uncommon for a streamer to make a handsome profit from treating the waste of a mine that was making a recurrent loss (Barton 1967).

Acicular crystals of cassiterite may have a diameter down to a fraction of a micron and could only be liberated as broken fragments on crushing. Such crystals are considerably more common in Cornish tin ores than has been generally supposed, and the recovery of this type of cassiterite would be very poor (Hosking 1969). Crushing and grinding of tin ores also converts a variable amount of cassiterite to near colloidal size particles, depending on the nature of the ore, which according to Hosking and Ong (1963-4) will remain in suspension for a long period of time, and is thus lost as tailings.

In former times, with the comparatively primitive methods of mineral recovery, mining contamination through losses in mineral dressing must have been considerable. However, in the era of pre-rock mining, beacause of the much smaller scale of mining activity which was restricted to stream-tinning in the exceptionally rich areas, contamination ia likely to have been far less significant.

In Fig. 2.6. is shown the location of the principal tin smelting houses and the distribution of principal sites of tin production in South-west Cornwall. Of the four smelting houses affecting the St. Agnes Head/Portreath area, Redruth and Cornish were by far the largest, having been in operation from 1862-1923 and 1887-1931 respectively. Portreath (1814-1825), the leading smelter in Cornwall during 1822, had a harbour built to import coal from South Wales, because there are very few suitable harbour sites on the north coast of Cornwall. Ore was transported by tram-road from the North Downs and St. Day mines to be smelted at Portreath (Barton 1970). There is little information available on Porthowan, the least important of the four smelting houses. Contamination from this smelting house was unlikely to be as significant because the area produced only minor quantities of tin. The fine components of slag heaps may find their way into streams. Concentrations of tin up to over 2,500 parts per million (ppm) in the minus-80-mesh (B.S.S.) fraction have been found in the Truro River by Hosking and Obial (1966) and may be due to contamination from the tin smelters in the vicinity.

In addition to tin in waste from smelters, tin ore recovered in association with marketable copper was discarded as waste during periods when its price was too low to warrant production. It was

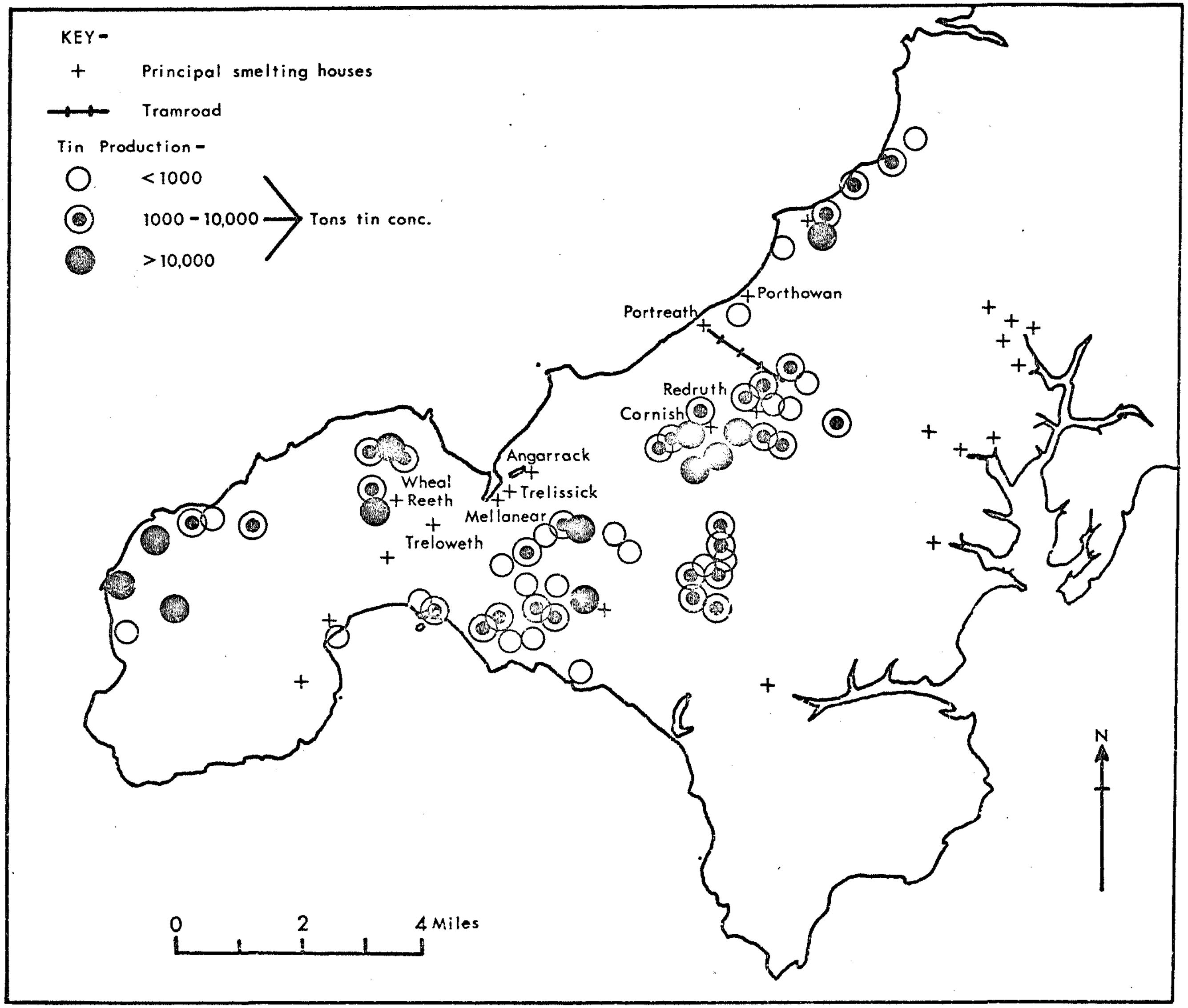


Fig. 2.6. Location of principal tin smelting houses and the distribution of principal sites of tin production in South-west Cornwall. Based on Dines (1956), Barton (1967) and Dunlop (1973).

not until the recovery of tin prices and the decline in copper mining that production recovered to such an extent that some mine dumps from the old copper mines were reworked for tin. Some of these dumps have in fact survived to the present day, as in the mines of the St. Day area, and are thus a potential source of tin contamination to streams and the offshore area.

2.8.4. Evaluation of present day contamination

At the present day, St. Ives Bay and the Pendeen area on the north coast of Cornwall receive the discharge of mine wastes, the former from the South Crofty and Pendarves Tin Mines via the Red River and the latter from Geevor Tin Mines. In both these localities, the sea water is stained reddish-brown due to suspended particles of haematite which is derived from milling and crushing operations.

With the progress in technology in the present century, mineral recovery has improved. At Geevor, the overall recovery from the whole ore treatment process is between 81-82 percent (Geevor Tin Mines 1972, unpub. rep.). However the recovery of locked tin and very fine tin still presents major difficulties. The former is found associated with haematite, quartz, sulphides, tourmaline and chlorite in the mineral lodes and poor separation from these minerals during ore dressing lowers the overall specific gravity of the cassiterite-bearing grains. If the specific gravity difference is extreme, the mineral is very often lost in gravity concentration processes. Also, if cassiterite occurs as inclusions within other minerals as in the St. Ives Bay offshore tin sands, the recovery would be extremely poor (Warren Spring 1962, unpub. rep.)

With the introduction of new floatation techniques and the Bartles-Mozley concentrator (Osborne 1973), the recovery of fine tin tailings has improved, but nevertheless is still of concern. The procedure adopted at Geevor Tin Mines recovers cassiterite of 5-20 microns at 35-40 percent and the overall recovery of the under 5 micron cassiterite is only 3 percent (Geevor Tin Mines 1972, unpub. rep.). This suggests that rich tin slimes are still finding their way downstream into the sea quite freely, as is evident in both St. Ives Bay ~~and the Pendeen area~~ in the present day.

CHAPTER 3. SAMPLING AND LABORATORY PROCEDURES

3.1.0. Field techniques

3.1.1. Stream sediment sampling

The stream sediment samples used in this work were almost entirely collected in the summer of 1969. They were samples used in the Atlas Project, in the course of which nearly 10,000 samples were collected in South-west England by 11 two-men teams. Duplicate samples were taken at stream-road intersections at an average density of 1 sample/sq. mile, and were collected with care being excercised in order to avoid collapsed bank material and organic and ferruginous ooze. The samples were placed in pre-numbered kraft paper bags, their positions were located on 1-inch O.S. maps, and their nature together with stream bed character were noted. In the detailed study of the Red River, sampling points were at closer intervals and water samples of 10-litre volume were taken at selected localities, and kept in polythene bottles.

3.1.2. Beach sediment sampling

Surficial beach sediments in St. Ives Bay less than 6 inches from the surface were sampled by hand along traverses from the High Water Mark to the Low Water Mark by means of a 100-ft. line. On other beaches, a random sampling scheme was adopted and the sample locations were identified using compass bearings to reference points on the O.S. 6-inch maps. The sample weight taken was about 2 kg.

3.1.3. Sampling of alluvial and estuarine sediments

The vertical sections of these sediments were sampled using a 15 cm. diameter bucket auger at selected locations. The location of these sites were plotted on 6-inch O.S. maps and the samples were described, labelled and transferred into polythene bags in situ. Because of the design of the bucket auger, some sample mixing was unavoidable, and special care was taken during the lowering and removal of the auger from the drill-hole to avoid scrapping material from another horizon.

3.1.4. Marine sediment sampling

Surficial marine sediments were sampled using a Shipek grab (Fig. 3.1, Plate I.) during June 28th - July 4th, 1972. The vessel used was the Cornish Queen, a trawler with a 2½ ft. draught which is equipped with an electrical winch, Decca Navigator and echo-sounder. In all a total of 381 stations were occupied, 321 from the St. Agnes Head/Portreath area, 50 from St. Ives Bay and 10 from the Pendeen area. The stations were fixed using the green and purple co-ordinates of the Decca Navigator (listed in Appendix), their locations are shown in Fig. 3.3A-C.

An average of 3-4 kg. of sample was taken at each station. In the St. Agnes Head/Portreath area were made four main sampling traverses paraellel to the coastline, and cuts at a sharp angle to the trend of the known mineral lodes found on the hinterland. These sampling traverses were spaced at approximately 750-metre intervals, and the sample spacing along the individual traverses were at on average between 60-80 metres.

In the follow-up studies during September 1972, after initial trial runs in Mount's Bay, cores were taken in the St. Agnes Head/ Portreath area using a vibratory corer made by Hydrowerkstatten, model VK 300 (Fig. 3.2.). The ship used was the M. V. Observer which has a 12½ ft. draught. This corer is claimed by the manufacturer to be capable of taking practically undisturbed cores from sandy sediments. After the vibrocorer has reached the greatest depth of penetration, it switches off automatically and the underwater winch comes into action extracting the corebox. When the vibrator has reached its uppermost position, the winch is

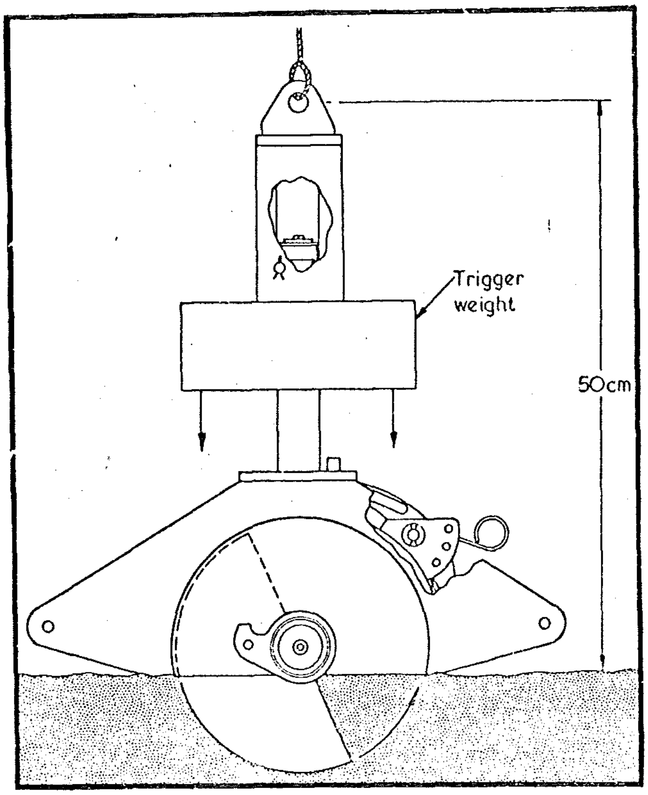


Fig. 3.1. The dimensions of the Shipek grab.

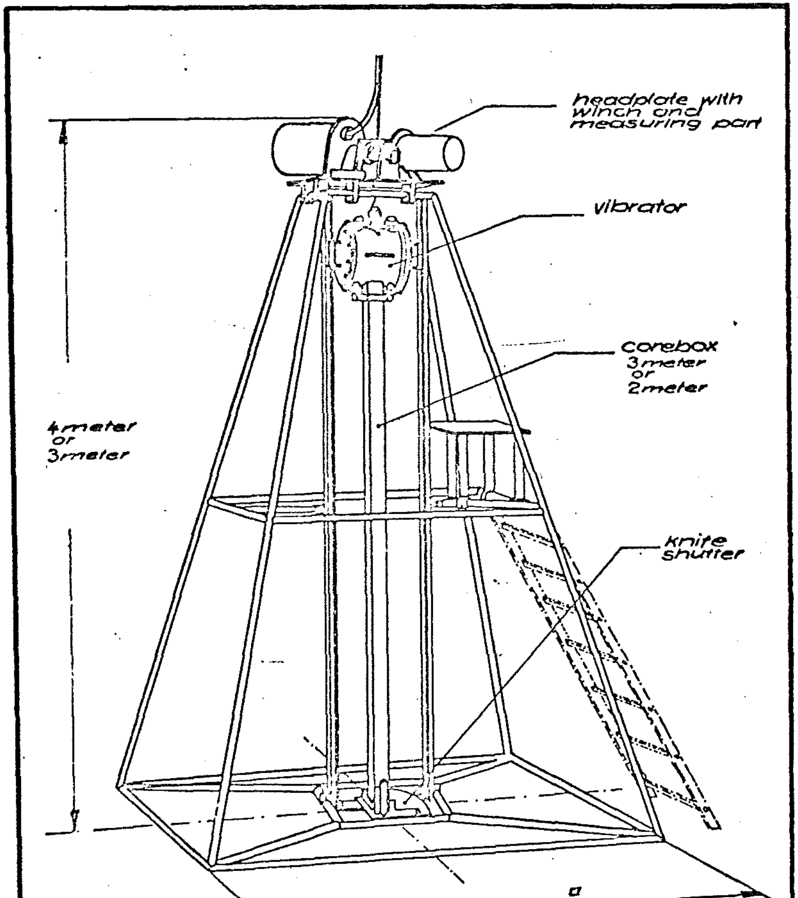


Fig. 3.2. The Hydrowerkstatten vibrocorer.

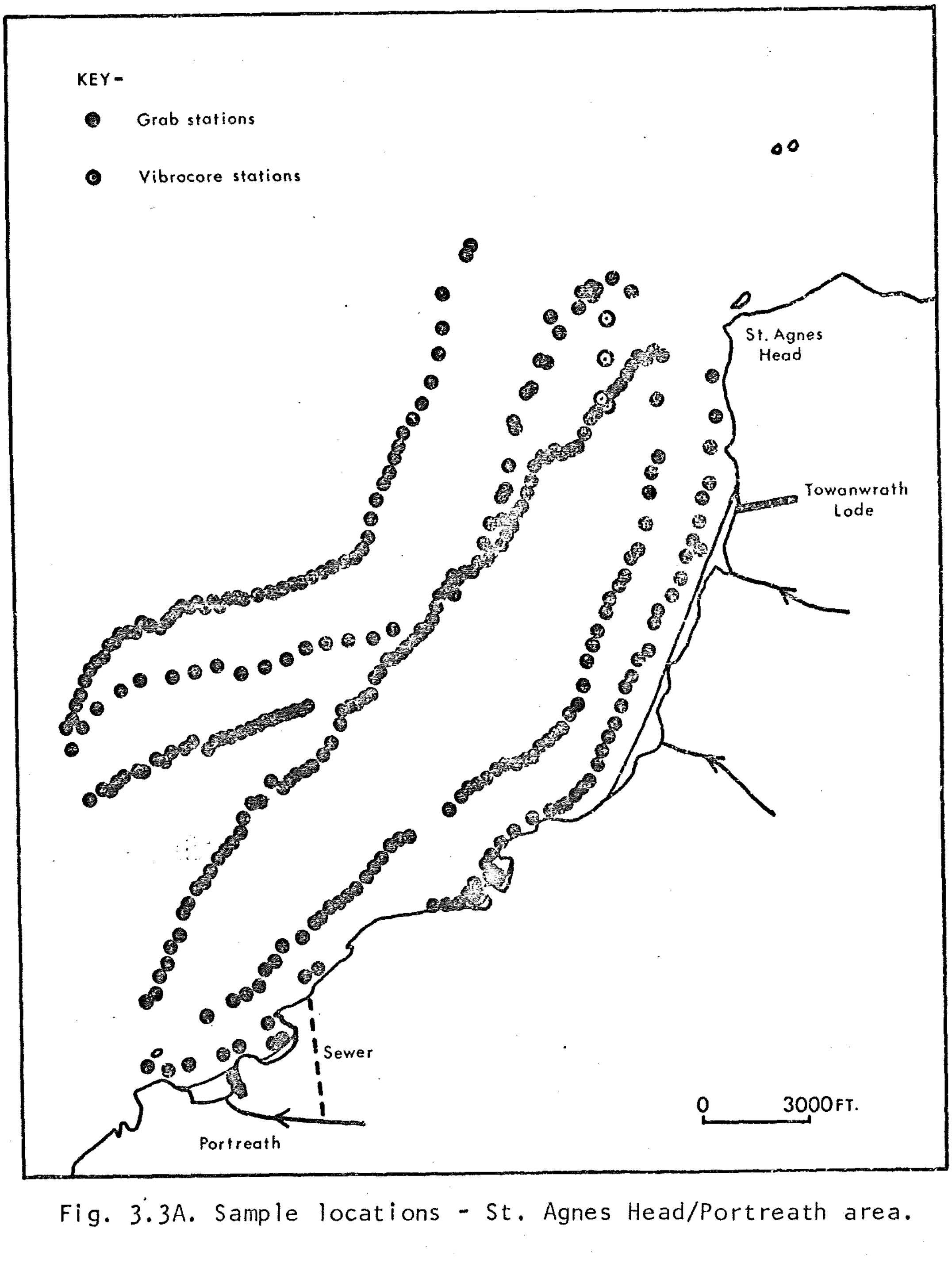


Fig. 3.3A. Sample locations - St. Agnes Head/Portreath area.

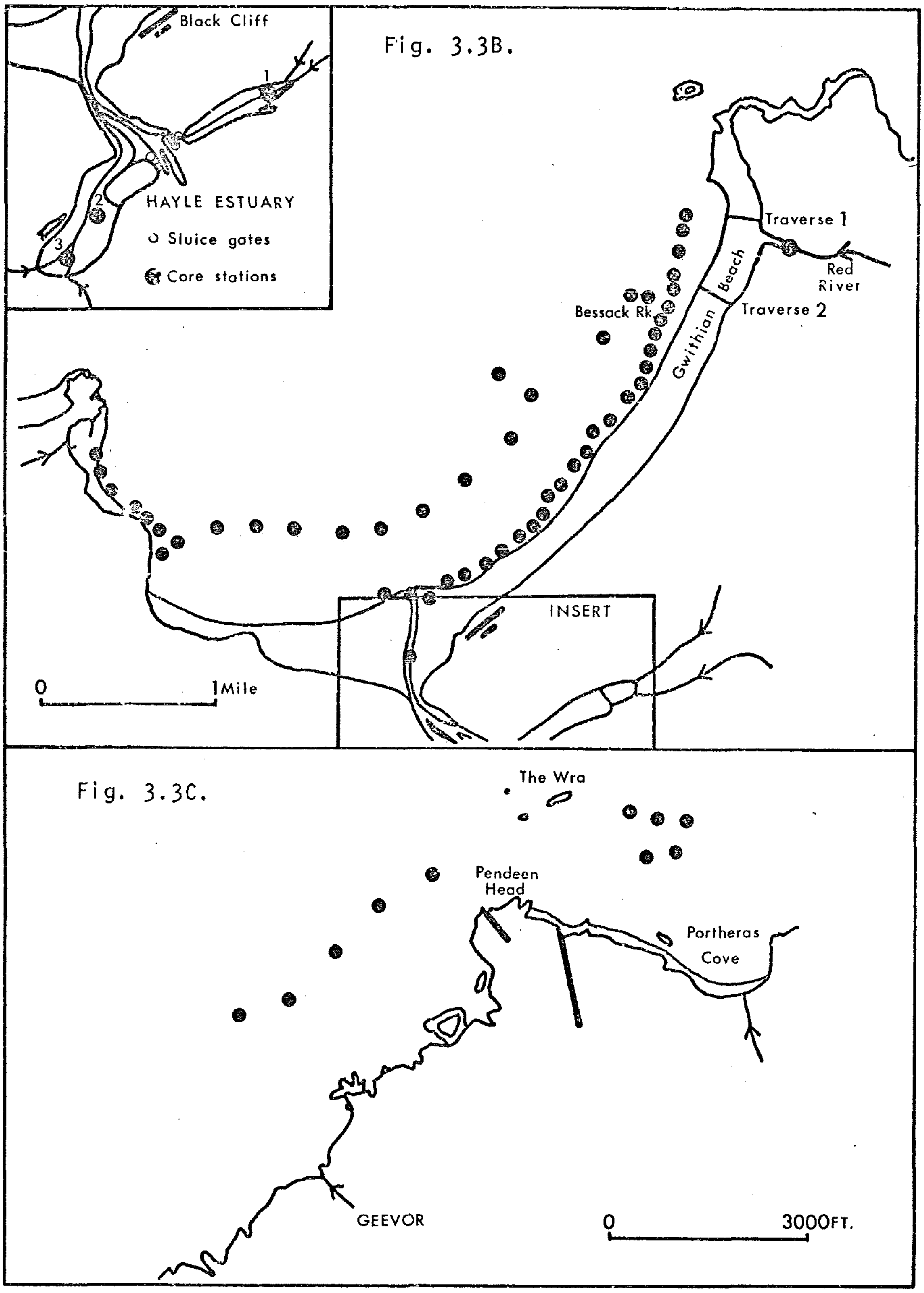


Fig. 3.3B. St. Ives Bay.
Fig. 3.3C. Pendeen area.

again switched off automatically, and there is a knife shutter in the lower part of the support frame to prevent the core from being washed out on retrieval of the corer. The specifications of the vibrocorer are as follows:-

Operational depth	up to 400 m.
Length of core	up to 3 m.
Striking force	ca. 700 kp.
Total weight	ca. 600 kg.
Electrical output	0,8 KW at 380 V.
Energy source	5 KW

On board, the corebox was removed from the frame, the diagonally screwed square-boxes (10 X 10 cm.) were removed and the core was split into two halves with a stainless-steel pellet knife. Half the core split was transferred into a plastic gutter, sealed in polythene core liner using lassovic tape and kept for reference. The other half was described and sampled according to grain size and colour variations, labelled and kept in polythene bags.

The longest core obtained during the cruise was just over 2 m. in length, and on average about five to six cores could be obtained during one 8-hour working day. However, due to rough sea condition and electrical problems, only two cores were obtained from the St. Agnes Head/Portreath area.

3.2.0. Preliminary investigations on laboratory procedures

3.2.1. Investigation on sampling reproducibility

Even though the sampling problem of tin ores is very well known to mineral technologists, the problem has been much neglected in geochemical prospecting. In the latter, which is used primarily to cut costs in place of drilling in the location of mineral deposits, it would be too expensive and far too time consuming to analyse bulk samples, and thus representative small samples must be used. However, if small samples are used, are the final results valid? In this section, the problem of sampling high density discrete mineral grains present in minor quantities in geochemical samples is examined.

In general, there are two types of sampling errors. Firstly, those due to inherent inaccuracies of the method or due to bias in the analyst known as systematic errors, and secondly, those due additionally to sampling, such as are introduced by taking dip samples from the sample container. The latter are known as random errors. Two common solutions for these errors are the use of standards, based on the assumption that the errors affect both the known and unknown samples to the same degree; and the use of duplicates and/or different methods of analysis. However, these solutions only apply when the sample units used are representative of the sample population.

The sampling problem of cassiterite-bearing sand is largely the result of four factors.

(1) Cassiterite normally occurs as discrete or mono-mineralic grains.

(2) The high density of cassiterite 6.98-7.02 results in its separation from other minerals by gravity.

(3) The cassiterite grains present in the sand are usually appreciably finer than the other mineral constituents.

(4) Cassiterite is usually present in low abundance.

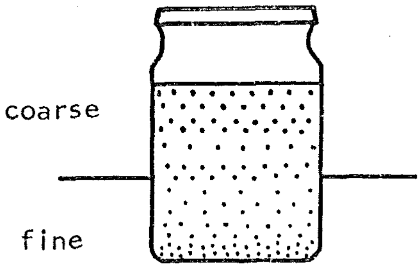
Beacause of these factors acting in combination, representative sampling of cassiterite-bearing sands with variable grain size distribution is difficult to achieve.

In an even-grained rock with a grain diameter of 1.2 mm. a representative sample requires a 1,000 g. sample weight, for it is necessary to have at least 10^7 grains if the specific gravity is 2.7 (Edelman 1972). At 45-mesh and 70-mesh, the representative sample weights are 100 g. and 20 g. respectively. If less than 0.5 g. sample is used in chemical analysis, it is necessary to grind 5 g. of the 120-mesh fraction more finely (Kluman 1967). Cassiterite which is present as discrete mineral grains in samples are even more susceptible to sampling error than other minerals due to seg~~g~~regation of the mineral because of its high specific gravity, and a even larger sample than normal like those recommended by Gy (Ottley 1966) will be required in order to obtain a representative sample.

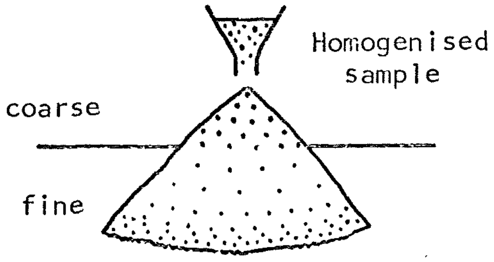
Figure 3.4. show some examples of ways by which heavy mineral seggregation can take place during sample preparation. It can be seen from these examples that it is vital to use thoroughly homogenised samples by grinding a representative sample unit to a sufficiently fine size to minimise the movement of heavy mineral grains within the sample. The analytical results of both Ong (1966) and Hazelhoff Roelfzema (1968) may therefore be erroroneous as their analyses were on unground minus-80-mesh fraction.

In the St. Agnes Head/Portreath area, the grain size of the sediments is highly variable, the deposits ranging from gravel to fine sand and silt. Consequently the minimum size of the sample unit needed to be representative varies according to the type of sample. It is possible to make a rough estimate of the number of cassiterite grains in the different size fractions by making a number of assumptions. The assumptions are firstly that all the tin is available as mono-mineralic cassiterite grains, secondly, all the grains within the sediment are spherical and thirdly, the

(a) Seggregation of heavy minerals in a sample container.



(b) In cone splitting, heavy mineral grains fall fastest and seggregate on the margins of the cone.



(c) Sampling error in weighing using a Mettler spatula.

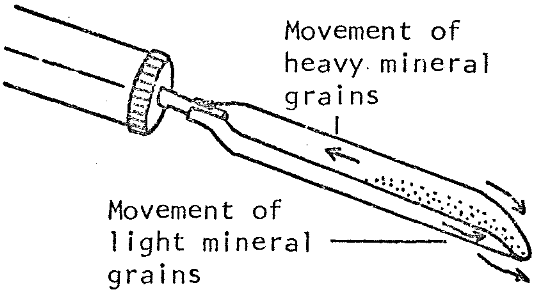


Fig. 3.4. Illustrations showing three common problems associated with sampling unground samples. In these examples, the heavy mineral grains (shown in black) work their way downwards through the interstices of the lighter coarse grains.

average density of the sediment is 2.8. On the basis of these assumptions, it is possible to calculate the number of grain particles within any size fraction with given grain diameter, and by assigning different tin concentration values to the size fractions, the number of mono-mineralic grains within the size fractions can be estimated (Table 3.1.). It can be seen from Table 3.1. that the minimum size of a representative sample unit is dependant on both the grain size and the actual tin content. It is evident that it is difficult to weigh out a representative sample when only a fraction of a gram of the unground sample, a common practice in geochemical prospecting is taken, although the sampling error is relatively small in the finest fraction since a larger number of grains are present. However, since composite grains of cassiterite may occur together with mono-mineralic grains, the sampling error is much less than with mono-mineralic grains alone since the composite grains are much lighter and seggregation within the sample is less severe.

In order to minimise the sampling error in the current study, it was decided to use all the sample available. For grab samples, whole samples were dried and then split down manually using a Jones riffle. The prior removal of shells from the samples has the advantage that the sampling error is lessened and the concentration of tin in the remaining material is upgraded.

In an attempt to get over the problem of heavy mineral seggregation, all the samples for analyses were ground to minus-200-mesh and homogenised, using a Tema mill. As large a sample as possible was used, but in some of the size fractions with only small sample weights available, homogenisation was taken as far as possible by grinding using an agate pestle and mortar, and the

Table 3.1. Relationship between grain size, tin content and the number of cassiterite grains in 0.2 g. of unground sample, based on the assumption that all the tin is present as discrete cassiterite grains.

Grain Size (microns)		170-250	124-170	90-124	Under 90
Estimated No. of Grains	Minimum	8,727	27,757	71,521	187,056
	Maximum	27,756	71,520	187,055	187,056
Tin Content (ppm)		No. of Grains			
100		0.4-1.4	1.4-3.6	3.6-9.5	9.5
1,000		4- 14	14- 36	36- 95	95
5,000		22- 70	70-181	181-475	475
10,000		88-141	141-363	363-950	950

results were treated cautiously during the final interpretation.

Duplicate splits were made on 5 percent of the samples to check the sampling reproducibility. The analyses indicate a satisfactory precision in the sampling technique, within the precision of the method used (Fig. 3.5.). A comparison of tin analysis on ground and unground samples is shown in Fig. 3.6. The results for unground samples tend to be erratic and thus the importance of representative sampling is confirmed.

3.2.2. Investigation for an analytical technique for tin

There are three methods in common use for the analysis of tin in geochemical prospecting. Two of these are the emission spectrographic method of Nichol and Henderson-Hamilton (1965) and the colorimetric method of Stanton and McDonald (1961-2), which according to Dunlop (1973) have a precision at the 95 percent confidence level of ± 62.5 percent and ± 23.5 percent respectively for Cornish soil and stream sediments. The other method is the use of a portable radioisotopic X-ray fluorescence analyser (Bowie et al. 1964-5), which according to Garson and Bateson (1967) at

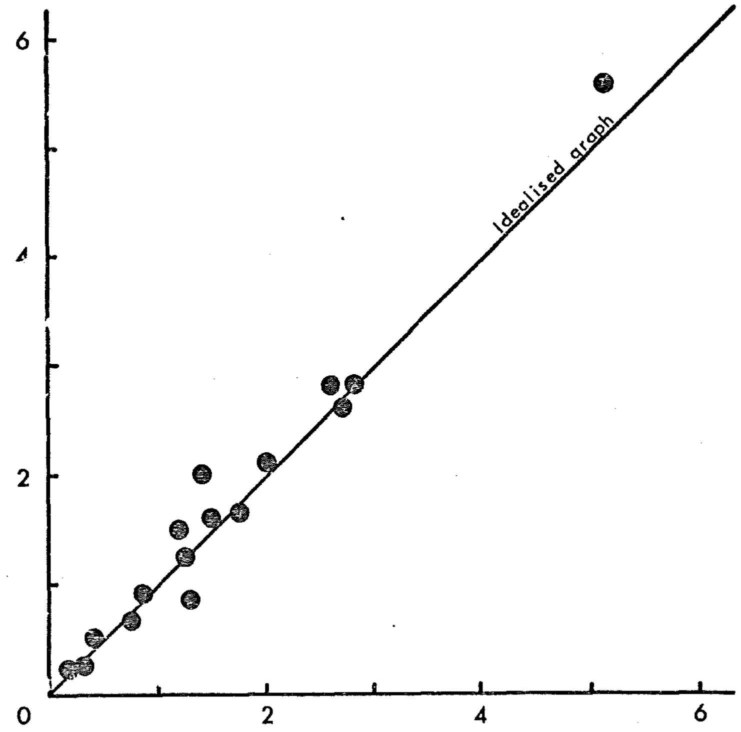


Fig. 3.5. Plots of tin results determined by atomic absorption for duplicate splits from the bulk sample in the minus-8-mesh shell-free fraction.

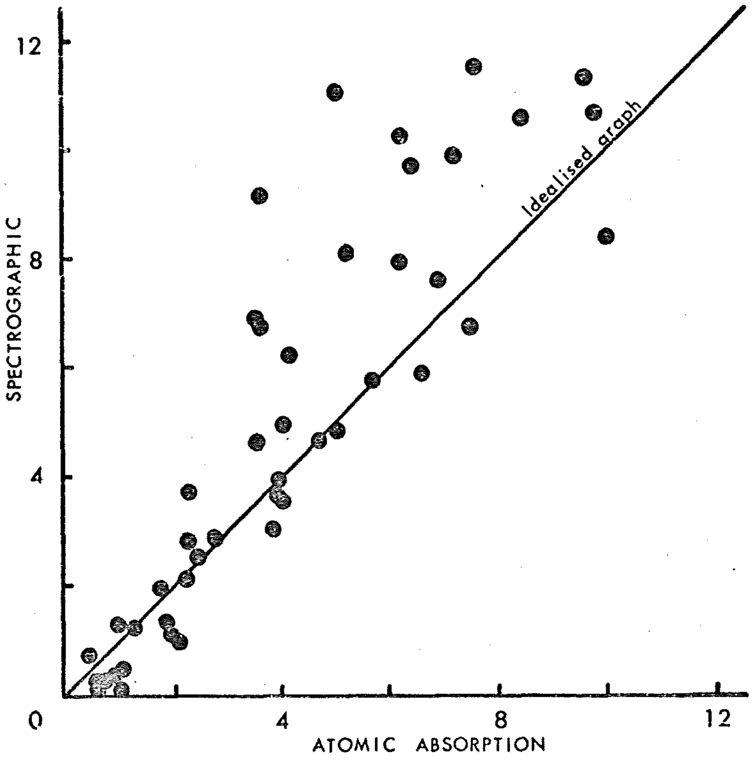


Fig. 3.6. Comparison between emission spectrograph results of unmilled samples and atomic absorption results.

concentrations above the 150 ppm level, over 80 percent of the readings are within ± 33⅓ percent of the mean.

Of these three methods, the colorimetric method has by far the best precision and the greatest sensitivity. This method, although designed primarily for soil and stream sediments, has been adopted by a number of previous workers for beach sediments (Hosking and Ong 1963-4 and others) and marine sediments (Ong 1966 and Hazelhoff Roelfzema 1968) also. In addition to the better precision and sensitivity, the method is rapid and inexpensive compared to the emission spectrographic method, especially when tin is the only element of interest. The radioisotopic X-ray fluorescence method on the other hand, has not yet been tested for marine sediments, but work on crushed ore has suggested that the grain size of material and the sample homogeneity are of critical importance (Darnley and Leamy 1966). Of the three methods, only the colorimetric method was considered to be sufficiently precise to be of application in the present investigation, but it was decided to make further tests to determine its suitability for marine sediments.

The colorimetric method involves the use of ammonium iodide for attacking cassiterite present in the sample. In marine sediments, the samples are often characterised by very high shell or calcium carbonate content which may in cases be over 90 percent. If a sample with high shell content is attacked using ammonium iodide, the hydrogen iodide liberated has acidic properties will attack the shells in the sample prior to attacking the cassiterite. Thus, less hydrogen iodide is available for attacking the cassiterite and it is therefore advantageous to remove the shells prior to the attack. Possible reactions with shells present are:-

$$\underset{\text{Ammonium Iodide}}{NH_4I} \xrightarrow[\text{Heat}]{} \underset{\text{Ammonia}}{NH_3} + \underset{\text{Hydrogen Iodide}}{HI}$$

$$2HI + \underset{\text{Calcium Carbonate}}{CaCO_3} \longrightarrow \underset{\text{Calcium Iodide}}{CaI_2} + \underset{\text{Steam}}{H_2O} + \underset{\text{Carbon Dioxide}}{CO_2}$$

$$CaCO_3 \xrightarrow[\text{Heat}]{} \underset{\text{Calcium Oxide}}{CaO} + CO_2$$

$$CaO + 2HI \longrightarrow CaI_2 + H_2O$$

$$\underset{\text{Cassiterite}}{SnO_2} + 4HI \longrightarrow \underset{\text{Stannic Iodide}}{SnI_4} + 2H_2O$$

The interference caused by the shell content is indicated by the results in Table 3.2, which also suggests that the 1 g. sample weight recommended by Stanton and McDonald (1961-2) is too large for marine sediments. It was therefore necessary to determine the best sample weight to use for the attack.

There are two possible solutions to the problem of obtaining a complete attack after the preliminary removal of shells. Firstly to use a larger quantity of ammonium iodide, and secondly to use a smaller sample weight. There are a number of disadvantages in

Table 3.2. The relationship between sample weight and the efficiency of the ammonium iodide attack on one sample containing 32.5 percent shells using the colorimetric method. (in ppm)

Sample Wt. (g.)	Mean Assay Value of 1st Fusion	Mean Assay Value of Residue
0.1	875	190
0.25	640	320
0.5	200	700
0.75	17	500
1	<12.5	400

increasing the quantity of ammonium iodide.

(1) The heating will be much slower. With 1 g. ammonium iodide, the heating requires on average 4-5 minutes, if the weight of ammonium iodide is increased to 2 g., 10-12 minutes will be required.

(2) Using 18 X 180 mm. test tubes, an increase in the weight of ammonium iodide used, results in increase in the likelihood of fumes which may carry away stannic iodide.

(3) The increase in costs for the reagents and also for labour.

(4) The leaching is also less efficient and if a larger volume of acid is used, the dilution factor increases which results in a lowering of the sensitivity.

Tests were therefore carried out with varying sample weights in order to determine the sample weight needed to obtain an efficient attack. The results (Table 3.3.) show it is difficult to achieve a good fusion if 0.5 g. or over 0.5 g. sample is used with 1 g. ammonium iodide in the attack because of bad mixing, the range of results being relatively large. The best sample weight was found to be around 0.2 g., with a range of results of only 200 ppm.

Table 3.3. The relationship between sample weight and the weight of ammonium iodide on one sample with a mean composition of 3586 ppm tin. Based on triplicate analysis.

Sample Wt. (g.)	Wt. NH_4I	Ratio	Mean	Range (ppm)	Difference
0.2	1	1 : 5	3600	3500-3700	200
0.5	1	1 : 2	3280	2960-3760	800
0.75	1	3 : 4	3005	2667-3467	800
1	1	1 : 1	3120	2840-3440	600

Comparable results were obtained by taking less than 0.2 g. sample using a sample to ammonium iodide ratio of 1 : 5 even though the sample size error and the weighing error are likely to be increased in the smaller samples. It was therefore decided to use 0.2 g. sample and 1 g. ammonium iodide or a ratio of 1 : 5 in all the subsequent analyses.

Residues from the first attack were attacked a second time to determine the completeness of the first attack. First, however, the residues were thoroughly washed with molar hydrochloric acid followed by deionised water to ensure that all the soluble tin extracted in the first attack had been removed. The results show that the attack using a 0.2 g. to 1 g. sample to ammonium iodide ratio is better than 90 percent efficient (Table 3.4.).

Table 3.4. Efficiency of the ammonium iodide attack using a 0.2 g. sample to 1 g. flux ratio. (in ppm)

Sample No.	1st Attack	2nd Attack	% Efficiency of 1st Attack
1	2250	100	95.6
2	2500	200	92
3	4500	250	94.5
4	1800	< 50	97.3
5	6000	150	97.5

A number of problems were encountered in the colorimetric analysis of tin and at the end it was decided to abandon the technique and an alternative method using atomic absorption spectrophotometry was sought. The main difficulty with the colorimetric technique occurs in the matching of the sample with the standard solutions. It was found that most of of the samples had a yellowish-green to yellowish-pink colour compared to bluish-green to bluish-pink in the standards, and reading the sample concentration with accuracy was found to be very difficult in many cases. This colour interference is likely to be the result of the high iron content in the samples.

In recent years, atomic absorption spectrophotometry has played an increasingly important role in geochemical exploration. The superiority of this technique, mainly due to its speed and better precision, over the traditional techniques has already been described by Ward et al. (1969), Angino and Billings (1972) and others. However, because of the complex nature of geochemical samples, tin, always a difficult element to determine precisely, is subjected to complex interferences. Allan (1963) reported a sensitivity of 0.4 ppm using a relatively low temperature air/hydrogen flame which is prone to interferences, while Amos and Willis (1965) used a hotter nitrous oxide/acetylene flame which is less sensitive but seemingly without interference. Subsequently Bowman (1968) adopted this technique for analysing tin ores and concentrates, and Guru (1972) used a similar method in determining tin in sediments from the South China Sea. It was decided to test the suitability of this method in the present investigation.

The instrumentation on the Perkin-Elmer atomic absorption spectrophotometer model 403 used is shown in Fig. 3.7. For the nitrous oxide/acetylene flame, a 5 cm. single slot burner is used, and because of the relative low tin concentration in the samples (under 4 percent), the most sensitive spectral line 2246.1 Å was selected for use. The acetylene flow rate was adjusted to give the maximum 'red feather' without the flame being luminous, in order to minimise carbon deposits forming in the burner slot which would result in a decrease in sensitivity, and the maximum absorption

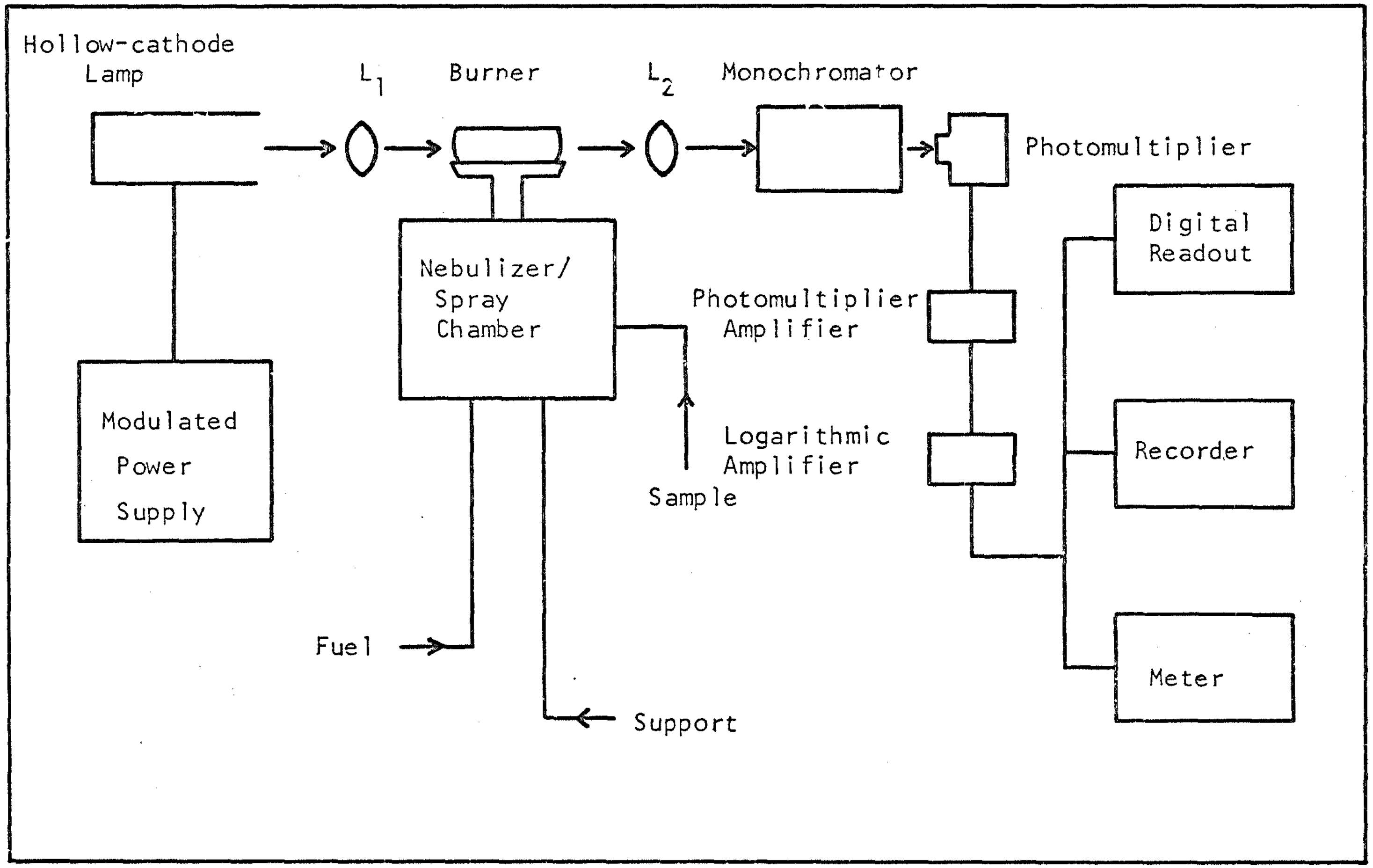


Fig. 3.7. Simplified block diagram to show the major components of the Perkin-Elmer atomic absorption spectrophotometer model 403.

was obtained by adjusting the burner height. Sample digestion was with ammonium iodide after shell removal which is essential to minimise molecular and other interferences caused by the presence of large quantities of calcium in the sample solution during the atomic absorption measurements.

Table 3.5. shows the concentration working range for sample solutions with different dilution factors. The detection limit is 2 ug/ml. or a sample concentration of 50 ppm tin and the calibration curve was found to be linear up to 200 ug/ml. (Fig. 3.8.). No curvature correction was therefore required below this concentration, and results were obtained directly using a digital readout. Ammonium iodide in molar hydrochloric acid did not disturb the structure of the nitrous oxide/acetylene flame but varying concentrations of ammonium iodide did result in slight enhancement of tin absorbance. In order to remove this enhancement, equivalent amounts of ammonium iodide (weight/volume) were added to the standards. The operating conditions of this technique are described in section 3.4.1.

Table 3.5. Dilution, percent ammonium iodide and the concentration working range for 0.2 g. sample to 1 g. flux ratio.

Final Vol. of Leach Soln. (mls.)	% Ammonium Iodide in Standards	Tin Concentration Range (ppm)
5	20	50- 5000
10	10	100-10,000
20	5	200-20,000
40	2.5	400-40,000

The results of the atomic absorption technique show a marked improvement in precision over the colorimetric technique. The results of duplicate determinations by this technique have been

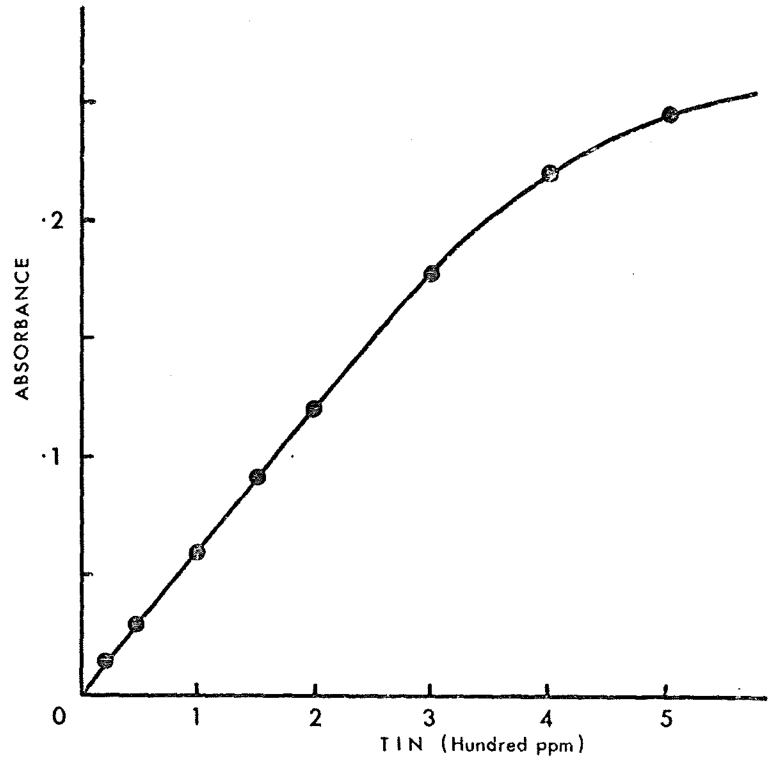


Fig. 3.8. Calibration curve for tin at 2246.1 Å in molar hydrochloric acid containing 10 percent (weight/volume) ammonium iodide.

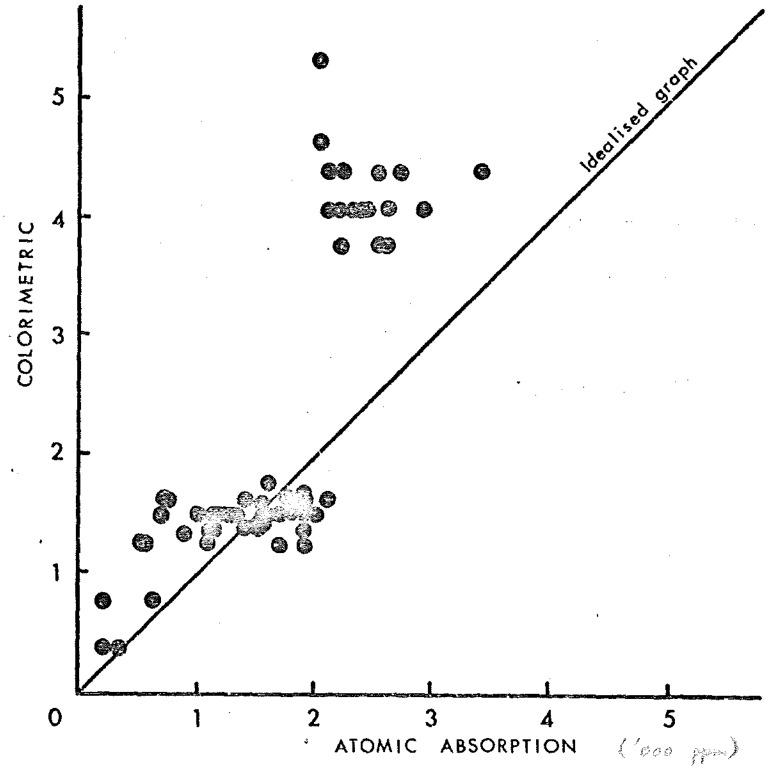


Fig. 3.9. Comparison between atomic absorption results and colorimetric results.

computed to determine the precision at different concentrations using the method of Thompson and Howarth (1973) and they are summarised in Table 3.6. The precision found at concentrations of 500 ppm and above are superior to those quoted for the colorimetric method (Stanton and McDonald 1961-2), however, at concentrations below 250 ppm, due to the background noise the precision is poorer. Comparison between the colorimetric technique and the atomic absorption technique (Fig. 3.9.) suggests that results using the former are, in general, significantly higher, and the absence of values between 2000-3500 ppm suggests analytical error possibly due to interference.

Table 3.6. The relationship between tin concentration and precision of the atomic absorption technique based on 197 duplicates.

Tin Concentration (ppm)	Precision at the 95 % Confidence Level
100	54.8
250	27.4
500	18.3
1000	13.7
5000	10.1
10,000	9.6
15,000	9.4

To check the validity of the atomic absorption results, comparisons were made using the volumetric method of tin determination (Pantony 1956), by titration with iodine following the reduction of tin using nickel. Tin results using the volumetric method have been examined in an inter-laboratory survey of the accuracy of ore analysis by Lister and Gallagher (1970), and was found to be fairly reliable. Fig. 3.10. shows that the atomic

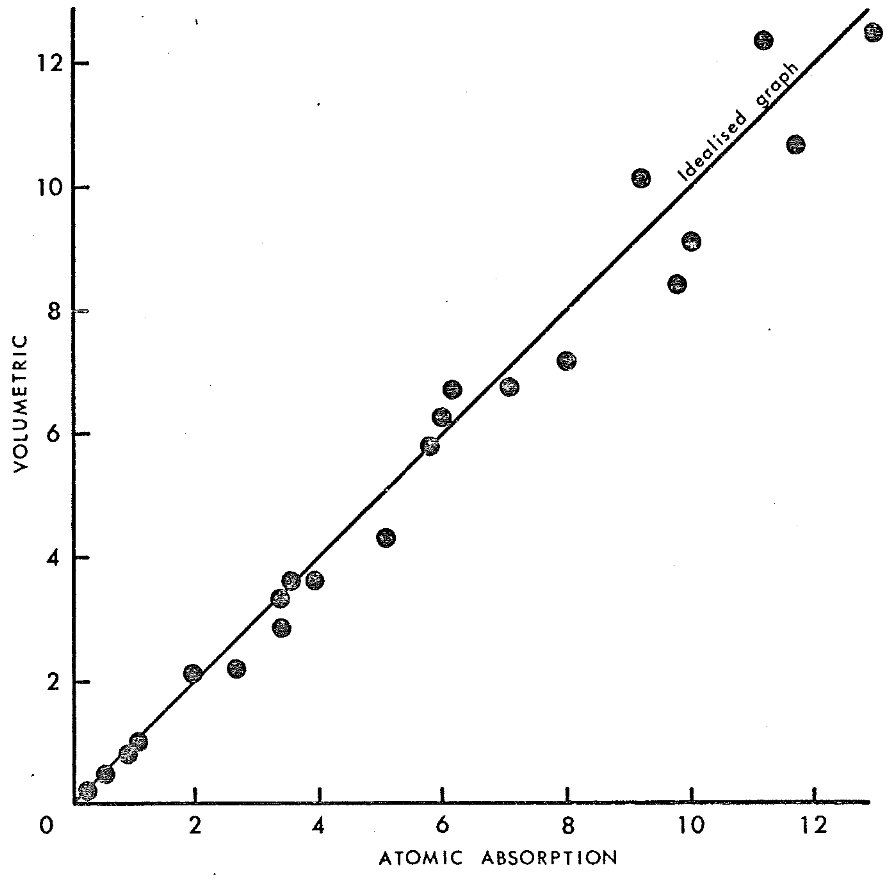


Fig. 3.10. Comparison between atomic absorption results and volumetric results.

absorption results and the volumetric results correlate well and thus the atomic absorption method was adopted for subsequent tin determinations.

3.3.0. Laboratory techniques

3.3.1. Preliminary treatment of samples

Entire samples were oven-dried at about 60°C on porcelain dishes of 6-inch diameter, and the beach and marine sediment samples were previously washed three times with deionised water to remove salt. During each washing, the samples were mixed thoroughly with the deionised water using a glass stirrer and sufficient time was allowed for settlement before decantation of the deionised water in order to prevent the loss of the fine fraction.

After drying, the samples were hand sieved to remove the gravel size fraction using an 8-inch diameter 2057 micron (8-mesh approximately) test sieve. The gravel fraction was examined visually and its composition described. The minus-8-mesh fraction of the samples were then split into two halves using a Jones riffle. Half the split was bagged and kept for future reference and the other half was split down further for the various treatments.

3.3.2. Textural analysis

All the marine sediment samples were subjected to granulometric analysis. Sub-samples of the minus-8-mesh fraction split down to between 50-100 g. in weight were sieved through a set of 3½-inch diameter perspex sieves fitted with heavy quality nylon monofilament bolting cloth. The aperture of the sieves were chosen at 0.5 phi intervals, and were shaken for 30 minutes using a Pascall Engineering sieve shaker. The sieves used were :-

Nearest B.S.S.No.	Microns	Phi	Sediment Type (Wentworth Scale)
8	2057	-1.041	Very Coarse & Coarse Sand
30	500	1.000	
44	350	1.515	Medium Sand
60	250	2.000	
85	170	2.557	Fine Sand
120	124	3.011	
Pan	<124	>3.011	Very Fine Sand & Silt

The sieve fractions collected were wieghed, converted to percentages, and the mean size and sorting coefficient were determined by plotting cumulative frequency curves graphically and applying the formulae set out by Folk (1968).

$$\text{Mean Size} \quad M_Z = \frac{(\phi 16 + \phi 50 + \phi 84)}{3}$$

$$\text{Sorting Coefficient} \quad O_1 = \frac{(\phi 84 - \phi 16)}{4} + \frac{(\phi 95 - \phi 5)}{6.6}$$

3.3.3. Shell removal and shell content analysis

Acetic acid (GPR grade) was used to remove shells, because of the insolubility of cassiterite in the weak acid. After initial tests to determine a suitable concentration to use, 15 percent (volume/volume) acetic acid was selected. Table 3.7, shows that a significant amount of copper and zinc may be leached depending on the volume and concentration of dilute acetic acid used, furthermore, the duration of the leach is also likely to be of importance. The results are based on atomic absorption measurements following an ADPC solvent extraction to concentrate the metals for analysis, as well as removing calcium.

Table 3.7. The effect of strength and volume of dilute acetic acid on leaching copper and zinc in the unground minus-8-mesh fraction of one sample containing 39.6 percent shells.

Strength of Acetic Acid (%)	5	10	15	20	25
Final Vol. of Solution (mls.)	400	250	200	200	200
Glacial Acetic Acid Used	20	25	30	40	50
Cu in Insoluble Frac. (ppm)	80	74	73	71	65
Cu in Leached Solution	10	11	11	12	12.5
Zn in Insoluble Frac.	120	117	113	116	115
Zn in Leached Solution	35.5	26.5	12	14	14

Procedure

(1) Weigh out between 300-800 g. of the minus-8-mesh fraction of the sample, using a Jones riffle for splitting down to the weight required. The weight of the sample used is dependant on its shell content, but sufficient sample should be taken to ensure that the detrital fraction is at least around 100 g.

(2) Add 15 percent acetic acid in portions of up to 600 mls. with care in order to avoid overflowing of carbon dioxide bubbles which can cause sample loss. When the reaction has subsided, stirr well with a glass rod and allow 30 minutes for settling.

(3) Decant the leach solution carefully to avoid sample loss and add fresh portions of 15 percent acetic acid and repeat the procedure until effervescence has ceased. Record the volumes of acetic acid used.

(4) Decant the leach solution and transfer the insoluble residue into a 6-inch diameter funnel fitted with Whatman's no. 1 filter paper. Wash the residue thoroughly in deionised water.

(5) Dry the residue in an electric oven at 60°C and when cooled,

weigh the residue.

In the calculation of the percentage shells in the samples, the shell content was taken as the percentage weight of the fraction soluble in the 15 percent acetic acid solution.

3.3.4. Milling and homogenisation

All the samples were ground and homogenised using an agate Tema mill of 50 g. capacity. The size fractions of the samples were ground and homogenised using a 20 g. capacity tungsten carbide Tema mill and for small samples under 2 g. by hand using an agate pestle and mortar. Special care was taken to split all the samples for milling representatively with a Jones riffle.

3.4.0. Analytical techniques

3.4.1. Determination of tin

Procedure

(1) Weigh 0.2 g. of ground sample into a boro-silicate test-tube (18 X 180 mm.).

(2) Add 1 g. of hand-ground ammonium iodide and mix thoroughly.

(3) Heat over a low flame for 4-5 minutes, with frequent rotation and agitation of the tube until the ammonium iodide ceases to sublime, and the residue reaches a dull red colour.

(4) After cooling, add 5 mls. of molar hydrochloric acid, mix well and leach on a sand-tray or in a water bath at 80°C for 20 minutes.

(5) Dilute further if necessary with molar hydrochloric acid, mix well and leave to settle for 1 hour before spraying the solutions through the atomic absorption spectrophotometer.

Preparation of Standards

(1) Stock tin standard 1000 ug/ml. Dissolve 1000 mg. of A.R. grade

tin powder in 100 mls. of 10 molar hydrochloric acid and dilute to 1 litre with deionised water.

(2) Working standards. Prepare solutions for calibration by diluting the stock 1000 ug/ml. tin standard to 10, 50, 100, 150 and 200 ug/ml. of tin respectively with molar hydrochloric acid, and add 20 percent (weight/volume) or the appropriate amount (Table 3.5.) of ammonium iodide before making up to the final volumes.

Operating Conditions

Instrument	Perkin-Elmer atomic absorption spectrophotometer model 403	
Wavelength	2246.1 Å	
Slit Width	4	
Lamp Current	30 mA	
Burner Height	18	
Burner	5 cm. single slot	
Flame	Nitrous oxide/acetylene	
Support	Air	
Flow	Nitrous oxide	40 lbs./sq. in.
	Acetylene	12 lbs./sq. in.

Analytical Control and Productivity

Analytical control was maintained by comparing observed values of duplicate standards submitted with each sample batch. About 10 percent of each sample batch was made up of standards, blanks and duplicates which were mixed and submitted in random with the samples in order to eliminate analytical bias. 100-150 samples may be analysed per man-day. A plot of the duplicate results is shown in Fig. 3.11.

3.4.2. Determination of copper, zinc, iron, manganese and calcium

All these elements were determined on atomic absorption

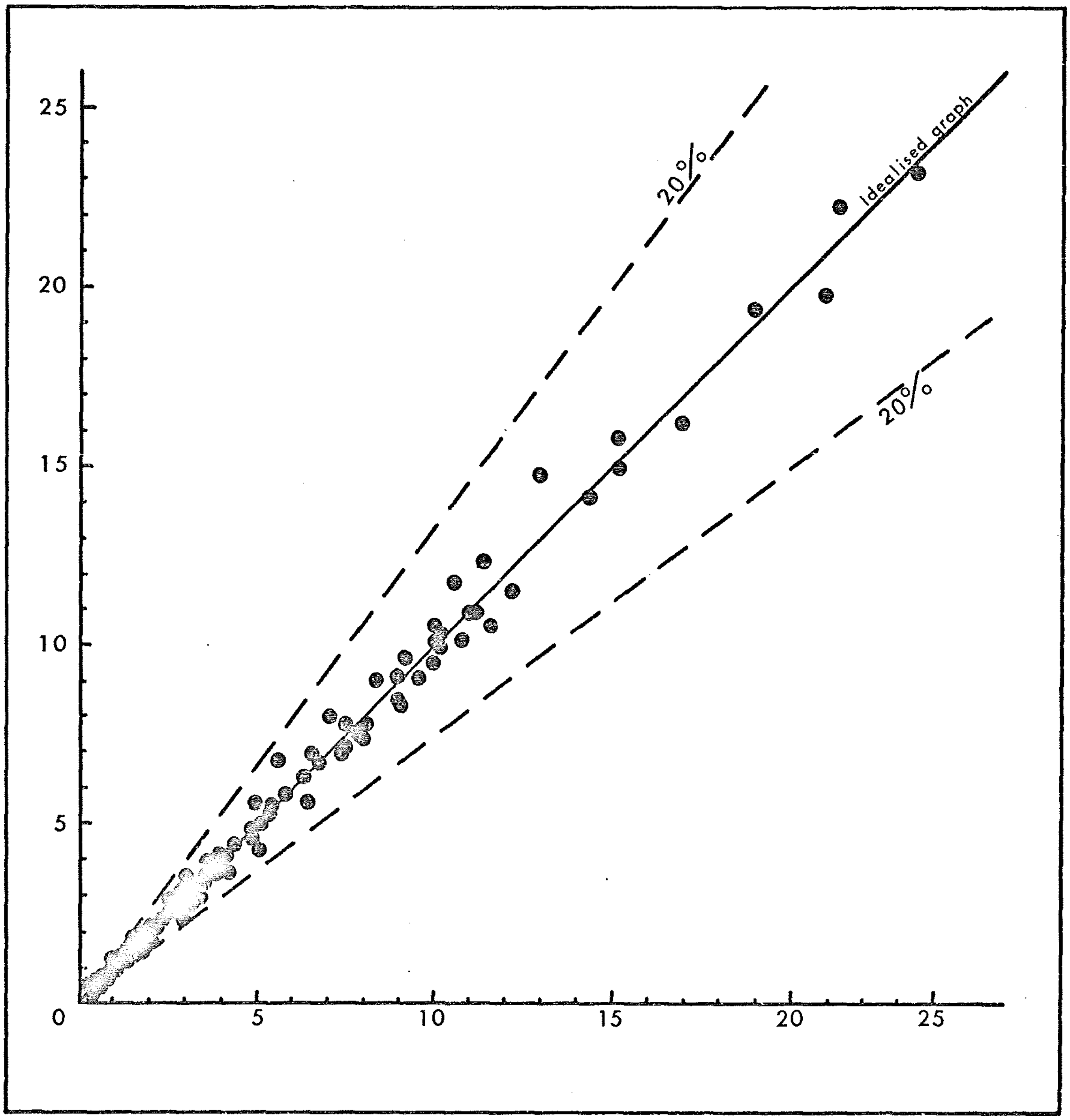


Fig. 3.11. Plots of duplicate tin results for Cornish stream and marine sediments. (in thousands of ppm)

following an acid leach. Calcium was determined only for beach and estuarine sediment samples not preliminary treated with 15 percent acetic acid to remove shells.

Procedure of Acid Leach

(1) Weigh 0.25 g. of sample into a boro-silicate test-tube (18 X 150 mm.).

(2) Add 5 mls. of 4 : 1 nitric acid/perchloric acid mixture.

(3) Heat over an airbath overnight and evaporate to white fumes of perchloric acid, making sure to avoid baking.

(4) Leach in 2 mls. of 6 molar hydrochloric acid, warming the tube on a sand bath set at 80°C for about 15 minutes until all coloured oxides were solubilised and the residue changed to a white colour.

(5) Add 10 mls. of deionised water and homogenise solution using a whirl-mixer.

(6) Leave to settle before spraying the solutions through the atomic absorption spectrophotometer.

The operating conditions used are summarised in Table 3.8, and about 10 percent of each sample batch made up of standards, blanks and duplicates were submitted in random for spraying. The precision for these metals are better than ± 10 percent at the 95 percent confidence level.

Table 3.8. Operating conditions on the Perkin-Elmer atomic absorption spectrophotometer model 403 for Cu, Zn, Fe, Mn and Ca.

Element	Wavelength (Å)	Lamp Current (mA.)	Slit Width	Flame	Sensitivity (mg./ml.)
Cu	3247	15	4	Air/C_2H_2	0.01
Zn	2138	15	4	"	0.01
Fe	2050	20	3	"	0.1
Mn	3719	20	3	"	0.01
Ca	4227	10	4	"	1

3.4.3. Determination of arsenic

A colorimetirc technique similar to that of Almond (1953) and Stanton (1966) was used. The nitric acid/perchloric acid attack was found to be capable of producing arsenic results comparable to those obtained by potassium bisulphate fusion in sediments (Table 3.9.). The attack was therefore adopted to save time and cost, as the samples are prepared for atomic absorption measurements using a nitric acid/perchloric acid attack. The precision of this method is better than ± 25 percent at the 95 percent confidence level.

Table 3.9. Comparison between the nitric acid/perchloric acid attack and the potassium bisulphate fusion in the colorimetric determination of arsenic. (in ppm)

Sample No.	$HNO_3/HClO_4$ Attack	$KHSO_4$ Attack
1	24	25
2	60	75
3	96	75
4	768	850
5	288	300
6	192	250
7	850	800

3.4.4. Determination of tungsten

Tungsten in the samples was determined colorimetrically using zinc dithiol (Stanton 1970). The precision of this technique is better than ± 25 percent at the 95 percent confidence level. Stanton found that copper is masked by iodide and amounts in excess of 0.5 mg. (500 ppm) in the samples will interfere by consumption of dithiol. Therefore samples with copper concentrations exceeding this amount especially in stream sediments should be treated with caution although an attempt to reduce the copper interference was made by further addition of iodide.

3.5.0. Application of hydraulic equivalence

The concept of hydraulic equivalence based on Stokes Law was first introduced by Rubey (1933), who examined the controlling factors on the size distribution of heavy minerals within a water laid sandstone. Subsequently, Rittenhouse (1943) used the concept to develop a method of computing hydraulic equivalent sizes, and introduced the term 'hydraulic ratio' which measures directly the relative availability of heavy and light minerals of equivalent hydraulic value. This idea was taken up by Hazelhoff Roelfzema and Tooms (1969) who applied it to cassiterite in the marine sediments of Mount's Bay to aid interpretation of geochemical results on sediments with multiple tin sources. The theory of the concept is summarised diagrammatically in Fig. 3.12, from this it can be seen that submarine sources of tin can result in anomalies in the tin trend surface distribution.

Stokes Law states that the settling velocity of a spherical particle vary as the square of the particle diameter, as the effective density of the particle in the fluid, and inversely as the viscosity of the fluid. In other words, specific grains of different specific gravities will be taken into suspension by a given current.

Stokes Law $$V = \frac{g}{18} \cdot \frac{p_q - p_w}{n} d_q^2$$

(Where V - settling velocity of both grains in cm./sec.
p_q - specific gravity of quartz
p_w - specific gravity of water
d_q - diameter of quartz grain in cm.
n - coefficient of viscosity of water
g - acceleration due to gravity)

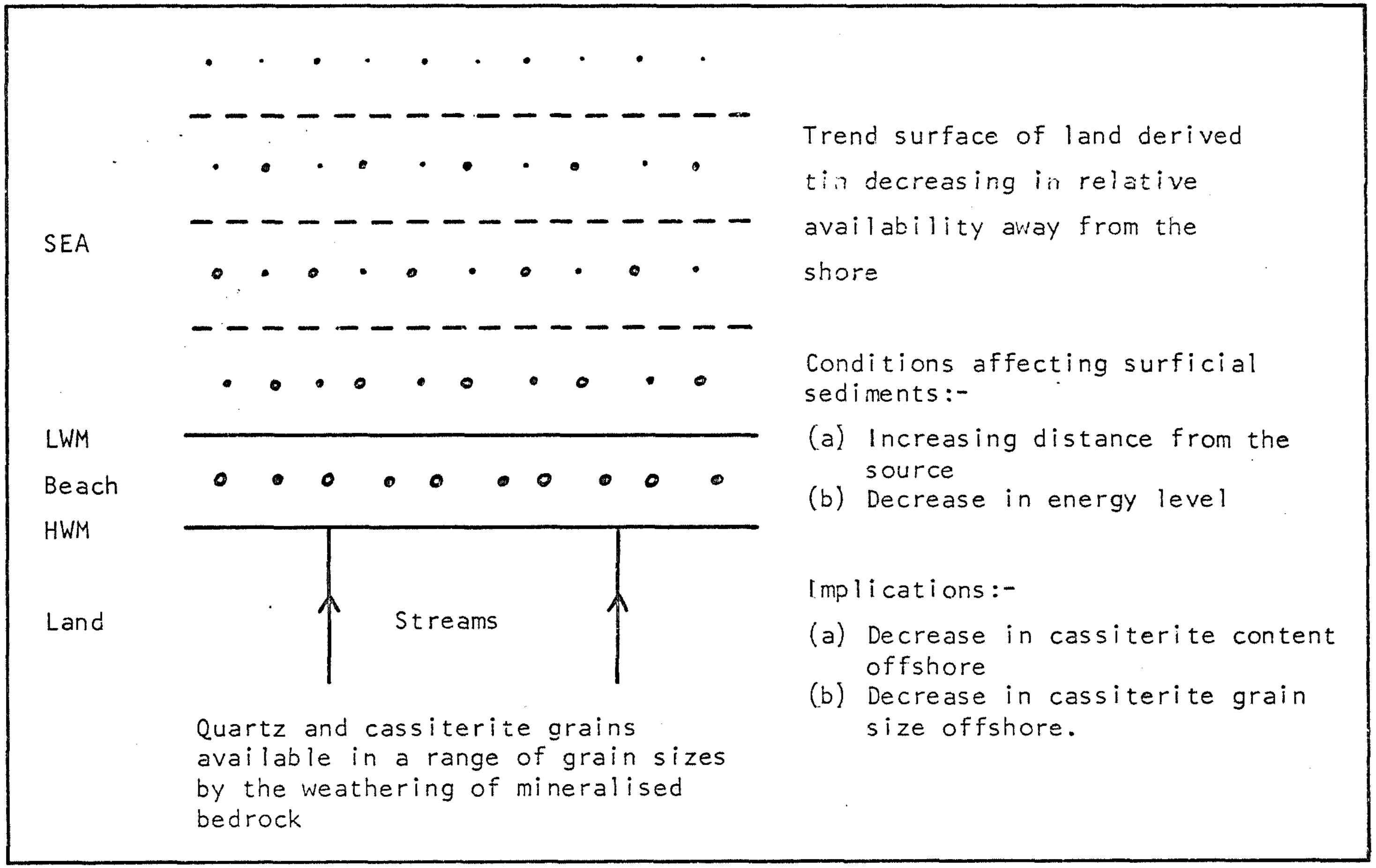


Fig. 3.12. Simplified diagram to illustrate the theory of hydraulic equivalence under idealised conditions. (Plan view)

and $$V = \frac{g}{18} \cdot \frac{p_c - p_w}{n} d_c^2$$

(Where p_c - specific gravity of cassiterite
d_c - diameter of cassiterite grain)

Since the settling velocity is constant

$$\frac{g}{18} \cdot \frac{p_q - p_w}{n} d_q^2 = \frac{g}{18} \cdot \frac{p_c - p_w}{n} d_c^2$$

$$(2.66 - 1.00)\, d_q^2 = (7.00 - 1.00)\, d_c^2$$

$$d_q = \sqrt{\frac{(7.00 - 1.00)}{(2.66 - 1.00)}}\, d_c$$

$$= 1.901\, d_c$$

Therefore, the equivalent diameter of quartz is equal to the known diameter of cassiterite multiplied by a factor of 1.901.

However, Stokes Law is adhered to only under certain conditions.

(1) Grain particles are spherical.

(2) The mineral grains are mono-mineralic.

(3) Applies only to certain grain size particles settling through an infinitely large quiescent volume of water under free settling conditions. Pryor et al. (1952) determined using the Reynold's number (Re) found that the minimum size of quartz spheres that will obey Stokes Law at 18°C is below 50 microns when $Re = 0.1$.

(4) The proportion of solids does not exceed 0.5 percent by volume.

(5) The temperature remains constant during the period of settling.

Hydraulic equivalence in the settling of quartz and cassiterite grains has been demonstrated by elutriation experiments using a Blyth elutriator (Ong 1966 and Hazelhoff Roelfzema 1968). The advantage of elutriation over dry-sieving is that the former takes account of the hydraulic properties of the material treated which includes specific gravity in addition to particle size. These experiments have confirmed that the size frequency distribution of cassiterite grains is essentially similar to that of the light fraction minerals, and that the displacement towards finer sizes of cassiterite, is largely due to differences in specific gravity. Plate II. illustrates elutriation of light minerals, mainly shells, by sheetwash down the beach slope selectively, leaving dark heavy mineral grains behind which are also finer and much more difficulty entrained.

As hydraulic equivalence applies only to mono-mineralic grains, it is necessary to show that mono-mineralic grains of cassiterite exist in the size fractions chosen for determining the hydraulic ratio. Heavy mineral separations using methylene iodide (specific gravity 3.32) were made on the detrital size fractions of a selected sample. The heavy fractions were then cleaned of magnetic minerals using a hand magnet and the non-magnetic heavy mineral fractions were mounted on resin, sectioned and subjected to quantitative mineralogical studies. The number of mono-mineralic grains of cassiterite, and the number of cassiterite-bearing grains were counted using a stage counting device fitted onto a petrological microscope. In addition, the identification of cassiterite was aided by 'tinning' using zinc powder and dilute hydrochloric acid. The results are summarised in Table 3.10.

It can be seen from Table 3.10. that the bulk of the mono-mineralic cassiterite grains occur in the finest fraction of the sample and thus there may be little validity in applying hydraulic equivalence to the coarse size fractions. However, since grinding has been shown to be necessary in order to minimise sampling error,

Table 3.10. The relative abundance of cassiterite mono-mineralic and cassiterite-bearing composite grains in the S.G. greater than 3.32 size fractions of one sample.

Sample No.	Grain Size (microns)	% Fraction < 3.32	% Fraction > 3.32	% Mono-Mineralic Grains	% Composite Grains	No. of Grains Counted
15-P2	170-250	99.9	Trace	-	100	5
15-P3	124-170	99.7	0.3	21	79	33
15-P4	90-124	97.9	2.1	72	28	98
15-P5	< 90	95.9	4.3	90	10	76

Note: The light fraction S.G. less than 3.32 may also contain appreciable quantities of composite cassiterite grains.

analysis based on the ground fraction may be totally misleading due to the liberation of cassiterite from composite grains.

In conclusion, because of the numerous departures from Stokes Law and the confirmation that the bulk of the mono-mineralic cassiterite grains occur in the finest fraction, hydraulic equivalence in the format of Hazelhoff Roelfzema and Tooms (1969) has not been applied.

CHAPTER 4. OFFSHORE ENVIRONMENT

4.1.0. Introduction

It is necessary in the present study to have a clear picture of the submarine geology, and the bathymetry and currents in the area under study. In this chapter, sedimentological techniques have been used in order to elucidate marine processes which may be responsible for the concentration of heavy minerals.

4.2.0. Submarine geology

The offshore solid geology of the study area shown in Fig. 4.1, is based largely on Continuous Seismic Profiler (Sparker) records carried out by a number of Universities. The geological evolution of this area has been described by Curry et al. (1970). Devonian-Carboniferous rocks are found to the south, west and north-west of the Cornubian Peninsula, which are predominantly grey or dark grey shales and slates, and which form the seaward extension of those rocks which outcrop on land. The rock groups of the Lizard Peninsula do not occur at any great distance offshore. The Permo-Triassic rocks which are absent on the Cornubian Peninsula do outcrop offshore, and rest unconformably on the eroded land surface formed by both the older Devonian-Carboniferous rocks and rocks of the Lizard-Start Complex.

The offshore Devonian-Carboniferous rocks are similar to their counterparts on the hinterland and have been intruded by granite plutons which may form parts of the batholith postulated by Hosking (1949). The Haig Fras Granite at 50° 10' N, 7° 50' W, has been described by Smith et al. (1965). Echo-sounding has revealed, the existence of low level terraces on the Granite down to 360 ft. below the present sea level, and radiometric dating by

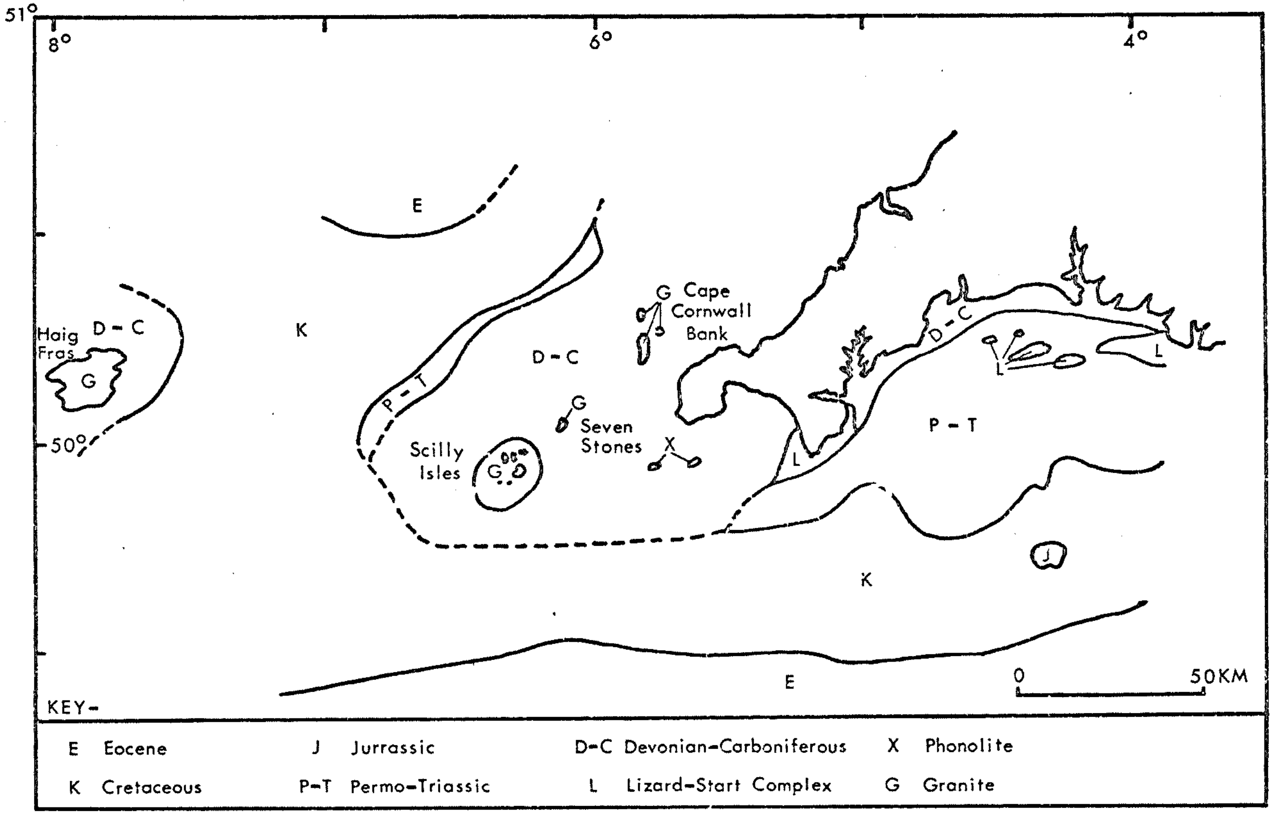


Fig. 4.1. Solid geology off the Cornubian Peninsula.
After Curry et al. (1970).

Sabine (1965) gives an age of 277 ± 10 million years. However, it appears to resemble the Amorican granites of Brittany more than the other granites of South-west England. The Seven Stones Granite at 50° 2' N, 6° 7' W near the Scilly Isles has an age of 281 ± 9 million years (Sabine and Snelling 1969). No dating as yet has been made on the granites around 50° 10' N, 5° 48' W, although coring by Day (1958) in the vicinity shows the existence of felsite which has been suggested by Day to derive from an elvan possibly associated with the Land's End Granite. In addition to granite, phonolite has been intruded into the Devonian-Carboniferous rocks, and outcrops at Wolf Rock and Epsom Shoals in the south coast.

Unconformably above the earlier beds are strongly transgressive Upper Cretaceous rocks, which are in turn onlapped unconformably by Eocene beds which tend to thicken towards the centre of the English and Bristol Channels.

4.3.0. Offshore mineral potential

Hosking and Trounson (1958) have noted that the centres of mineralisation of the study area are associated with 'high spots' on the granite ridges, and the strongest hypothermal mineralisation in any given area is developed on the vicinity of the largest cusp. On this basis, the ground beneath the sea immediately to the north of the St. Agnes and Cligga cusps is well worth prospecting. On the coastline between Cape Cornwall and Pendeen numerous north-west south-east trending lodes pass seawards of which the most notable are the lodes of the old Levant Mine which have been followed offshore beneath the sea. These lodes cut the killas/granite contact approximately at right angles and since the principal mineralisation follows the contact in its dip seawards, but at a smaller angle, this coast is of considerable potential.

In Fig. 4.2. are shown the high potential areas of submarine bedrock mineralisation based on the projected direction of lodes from existing coastal lodes known on land on the North Cornish coast. Since mineralisation follows structural zones of weaknesses, these projected lode trends may reveal offshore areas with mineral potential. Two striking features can be seen from this figure, firstly, the trends of the St. Ives Bay lodes and the St. Agnes Head and Cligga Head lodes coincide, and secondly, the lodes in the vicinity of St. Just trend towards the submarine granites on the Cape Cornwall Bank. The inference from these two features are that the St. Ives Bay and the area adjacent to the coastline between Portreath and Perranporth may contain mineral lodes, and that the offshore area between St. Just and Cape Cornwall Bank is likely to be extensively mineralised.

4.4.0. Coastline development

According to Robson (1950), the present day Cornish coast is essentially one of emergence, which has been modified by some submergence and deposition. Robson concluded that coastal erosion in the area has been extremely slow and that very little sediment has been derived from the cliffs.

On the basis of the Pliocene deposits and planation surfaces occurring in the hinterland, it seems likely that almost complete submergence of the Cornubian Peninsula took place during the late Tertiary. Eustatic fluctuations in sea level resulted in emergence in stages during the Quaternary and each stable phase was associated with a marine platform. Robson (1950) found good evidence for recent submergence to near the present 10-fathom line, indicated by submerged forests preserved in the alluvial valleys of existing

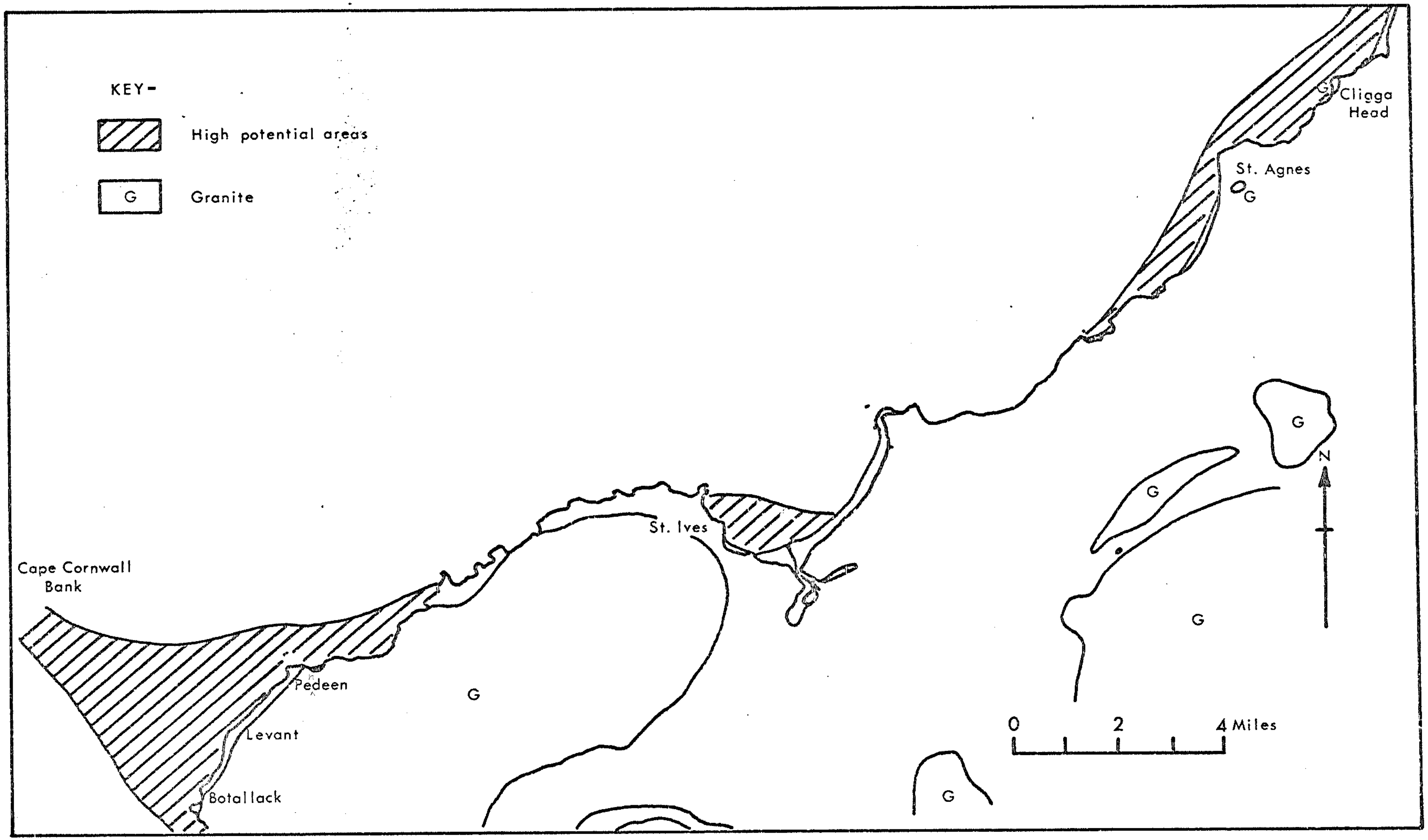


Fig. 4.2. Potential areas of submarine bedrock mineralisation off the North Cornish coast.

major rivers. Indications of submergences of an earlier age have been suggested by Smith et al. (1965) who identified low level terraces on the Haig Fras Granite at 50 fathoms, between 52 and 53 fathoms, at 55 fathoms, 57 fathoms and at 60 fathoms.

The configuration of the present day coastline is strongly influenced by the distribution of rock types, namely the more resistant granite and the less resistant killas. Most strikingly shown are the granite headlands of the Cligga Head, Land's End and Godolphin granites compared to the killas areas which have been eroded relatively rapidly to form bays and estuaries as in St. Ives Bay, Mount's Bay, Hayle Estuary, Helford Estuary and the Fal Estuary. In addition to the granite, the greenstone found near the killas/granite contact zone and the metamorphosed killas are also resistant, the former due to its original nature and the latter due to its properties resulting from metamorphism. Thus, St. Agnes Head is a headland not only because of the St. Agnes Beacon Granite which outcrops near the present day coastline, but also because of its associated metamorphic aureole. Therefore it is evident that coastal configuration is largely controlled by the shape and roof topography of the granite plutons.

In Fig. 4.3. are shown the geomorphological features adjacent to the North Cornish coast in the study area. The cliff types are based on that of Everard et al. (1964) who divided the cliff profiles observed into three types.

(1) Hog's backed cliff which are largely dependant on geological structure and develop where the strike approximately parallels the coast. These are found on coasts protected from the dominant direction of wave attack.

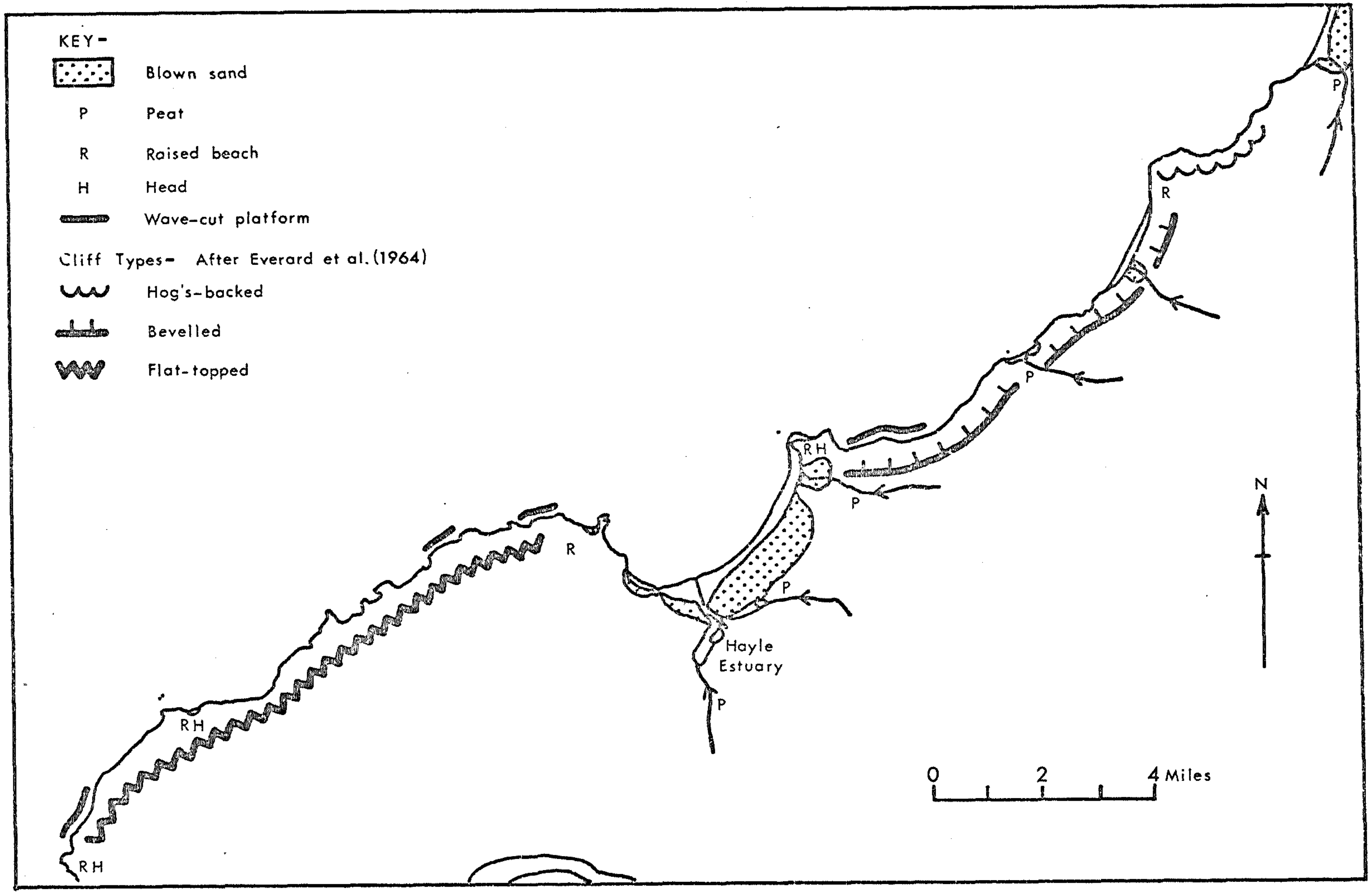


Fig. 4.3. Major geomorphological features of the North Cornish coast.

(2) Bevelled cliffs which are of sub-aerial origin and not developed under present conditions. The profile tends to be concave on granites but is broadly convex elsewhere.

(3) Flat-topped cliffs which are vertical cliffs developed on very exposed parts of the coast and are actively retreating, especially in areas of relatively weak rocks and where the coastline cuts across the strike.

The distribution of blown sand and peat deposits is restricted to relatively flat areas where there are major valleys adjacent to the sea. The blown sand deposits were all formed quite recently during abnormally stormy periods, as did the Upton Towans in St. Ives Bay which were formed in two great storms in 1750 and 1869 (Salmon 1973). Much of these deposits are now overgrown by artificially planted marram grass and appear to be virtually dormant.

Wave-cut platforms are poorly represented in the area. Those found are all of very limited extent, except for the North Cliffs between Godrevy Head and Portreath where the cliff retreat is relatively rapid due to weak rocks. It seems likely that either the post-glacial rise in sea level has been too rapid for wave-cut platforms to develop, or that recent submergence has resulted in the rapid influx of shell material from offshore, concealing possible lower level wave-cut platforms. Observations by the writer during periods of offshore sediment transport on the Gwithian Beach near Godrevy Head has confirmed the existence of a wave-cut platform normally concealed by beach sediments, which is exposed after periods of exceptionally strong onshore winds.

4.5.0. Bathymetry

In Fig. 4.4. is shown the bathymetry off the North Cornish

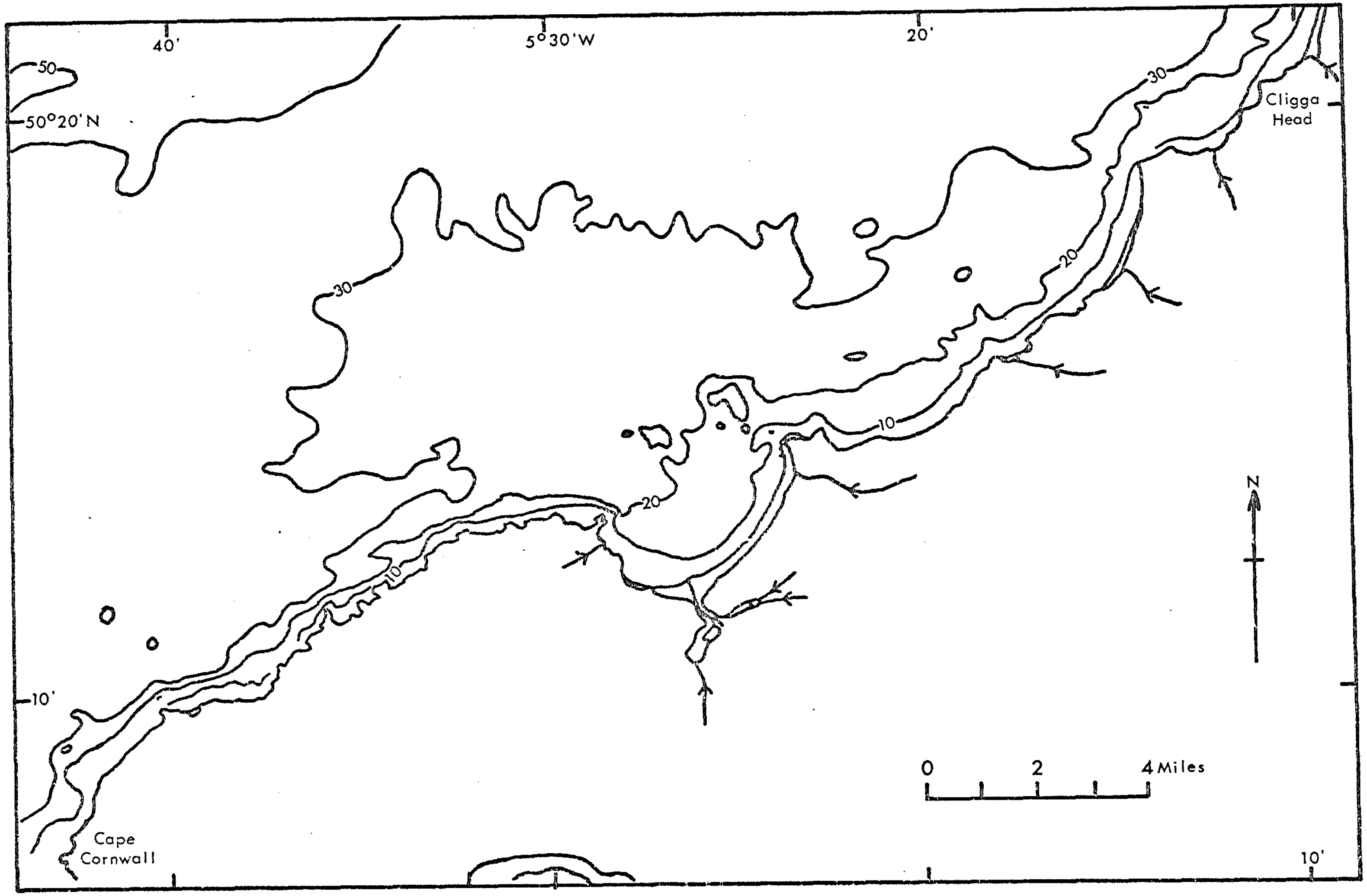


Fig. 4.4. Bathymetric map of the North Cornish coast between Cligga Head and Cape Cornwall. (contours at 10-metre intervals)

coast between Perranporth and Cape Cornwall based on Admiralty Chart no. 1149. For the St. Agnes Head/Portreath area a more detailed map on a scale of 1 : 20,000 with depth contours at 10-ft. intervals, surveyed by the Marine Mining Company (Unpub. rep. 1968), was used (Fig. 4.5.). For St. Ives Bay, Admiralty Chart no. 1168 for St. Ives Bay Harbour on a scale of 1 : 25,000 was used (Fig. 4.6.).

Beyond the present day Low Water Mark, the sea bed drops rapidly to about 10 fathoms. It then forms a gently sloping platform although not as well developed as off the St. Agnes Head/Cligga Head area (Fig. 4.7.), which Garnett (1962) suggested has a likely marine-erosional origin. Also in the St. Agnes Head/Cligga Head area, Garnett found another rapid drop to 16-17 fathoms which may be another marine platform with a wave-cut cliff between 11 and 17 fathoms. However, this is not evident in the St. Agnes Head/Portreath area.

In St. Ives Bay (Fig. 4.6.), the beach averages about 1200 ft. in width at low tide, reaching a maximum of almost 3000 ft. at the mouth of the Hayle Estuary. Beyond the Low Water Mark, the sea bed slopes gently down to about 45 ft. and then levels off at 50-60 ft. North of the Godrevy Head/St. Ives Head line, the platform is broken by another steeper slope which again shelves off at about 11 fathoms.

On the north coast of the Land's End Peninsula, Admiralty echo-soundings indicate a steep drop of the sea floor off the headlands. However two platforms at approximately the same level to those mentioned previously in other areas appear to be present, but more detailed echo-sounding is necessary to confirm this.

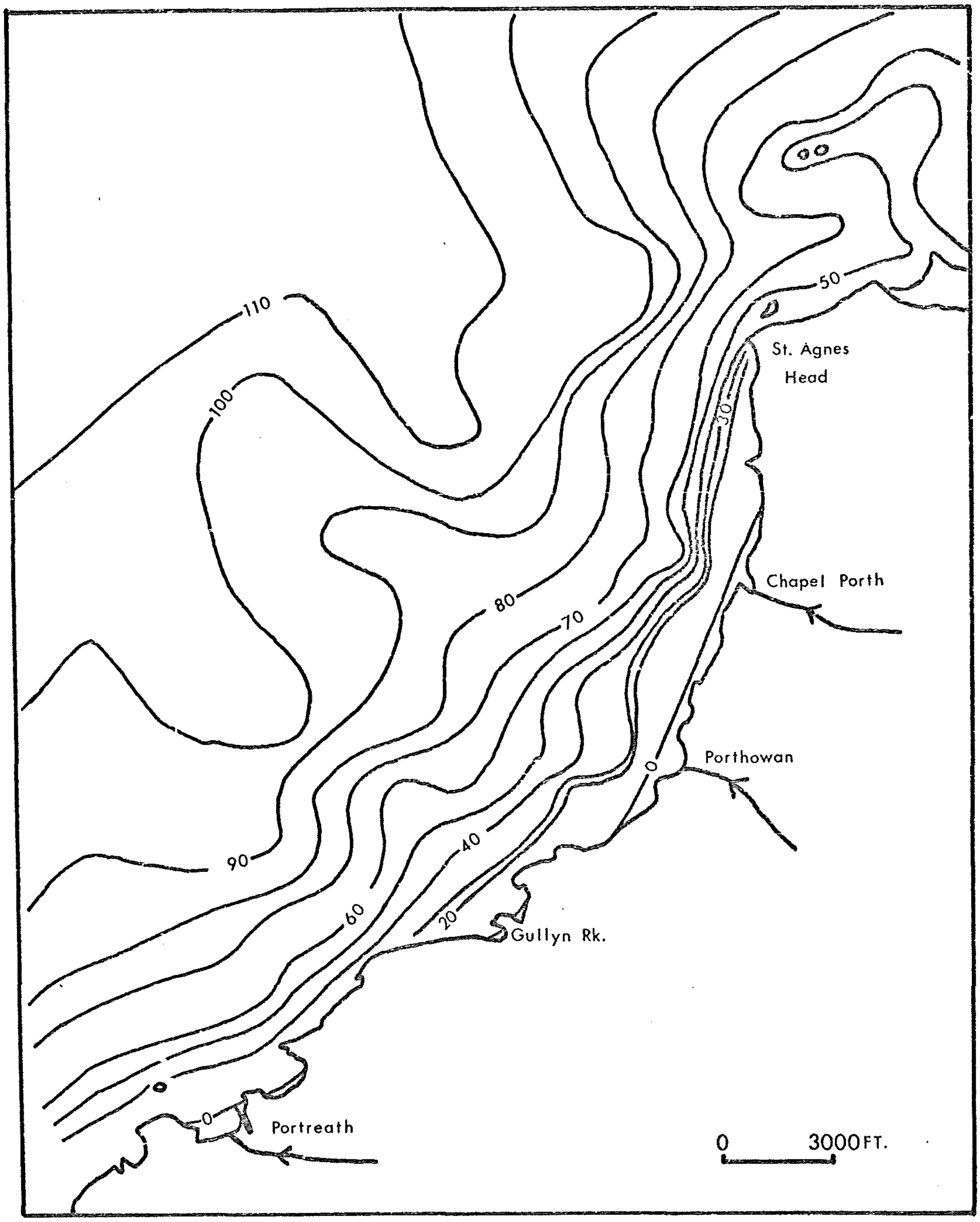


Fig. 4.5. Bathymetric map of the St. Agnes Head/Portreath area. (contours at 10-ft. intervals)

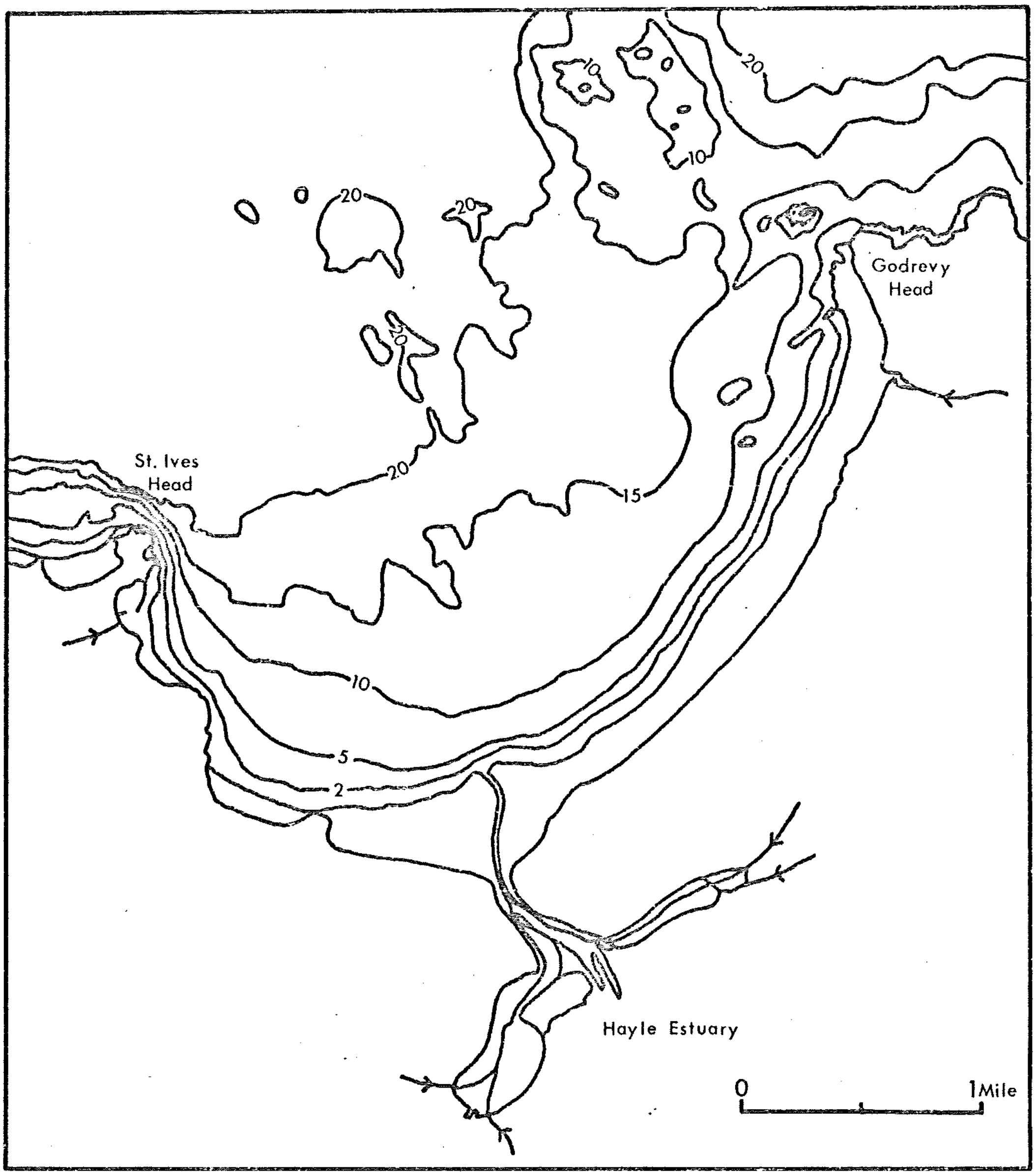


Fig. 4.6. Bathymetric map of St. Ives Bay. (contours in metres)

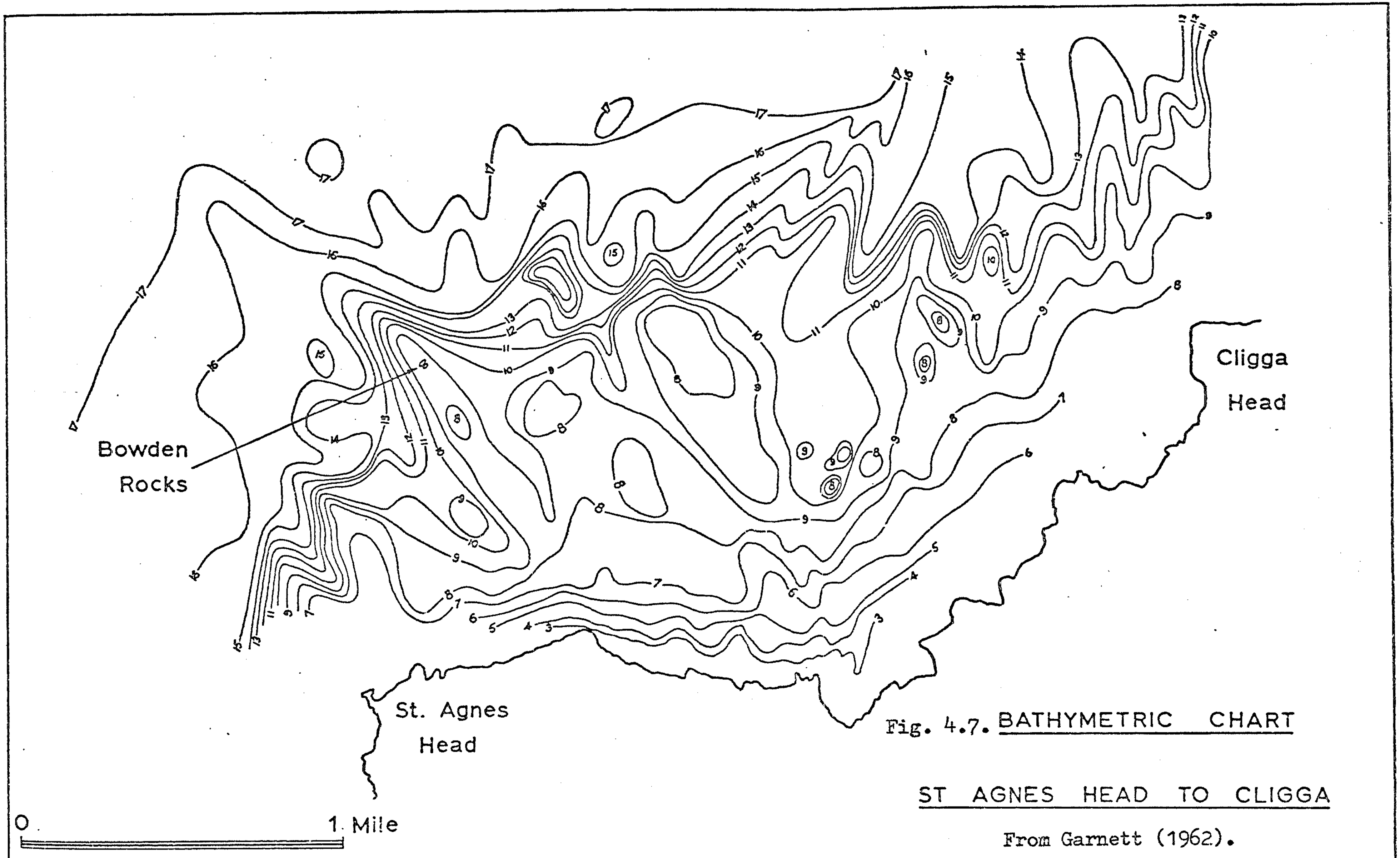


Fig. 4.7. BATHYMETRIC CHART

ST AGNES HEAD TO CLIGGA

From Garnett (1962).

All Depths are given in Fathoms

R.H.T.G.

4.6.0. Currents

In Fig. 4.8. are shown the tidal streams off Cornwall. The tidal range in the area varies between 12 and 20 ft. Currents are influenced by winds, and in open waters winds of any appreciable force or persistence will set up a current in the upper layers of the water. In inshore areas, the currents depend largely upon the trend of the coast and the extent to which the wind has caused the water level to rise on the shore. It is evident therefore that the transportation of land derived material can be expected to reach a peak when storms augment the effects of spring tides.

The tidal streams between Cape Cornwall and St. Agnes Head are strong off the headlands, but weak in the bays. In St. Ives Bay, the north-east stream is very weak, but the south-west stream is stronger (West Coast of England Pilot 1960). The streams in both directions run fairly strongly past Godrevy Island, and there is no sediment in the vicinity.

4.7.0. Bedrock topography and sediment thickness

The sediment thickness off the St. Agnes Head/Portreath area shown in Fig. 4.9. is based largely on cores and Sparker profiles obtained by the Marine Mining Company, and areas of no sediment have been delineated by grabbing. However, because of the wide spacing of the Sparker lines and the core stations, only general conclusions regarding sediment thickness can be made. In near-shore areas, little information is available because of the difficulty in operating a vessel of any size in shallow waters.

The area off St. Agnes Head and off Portreath has little or no sediment cover except close inshore (Fig. 4.9.). Between these two areas of rock outcrop is an essentially continuous sheet of sediment which appears to infill elongated depressions under the sea which

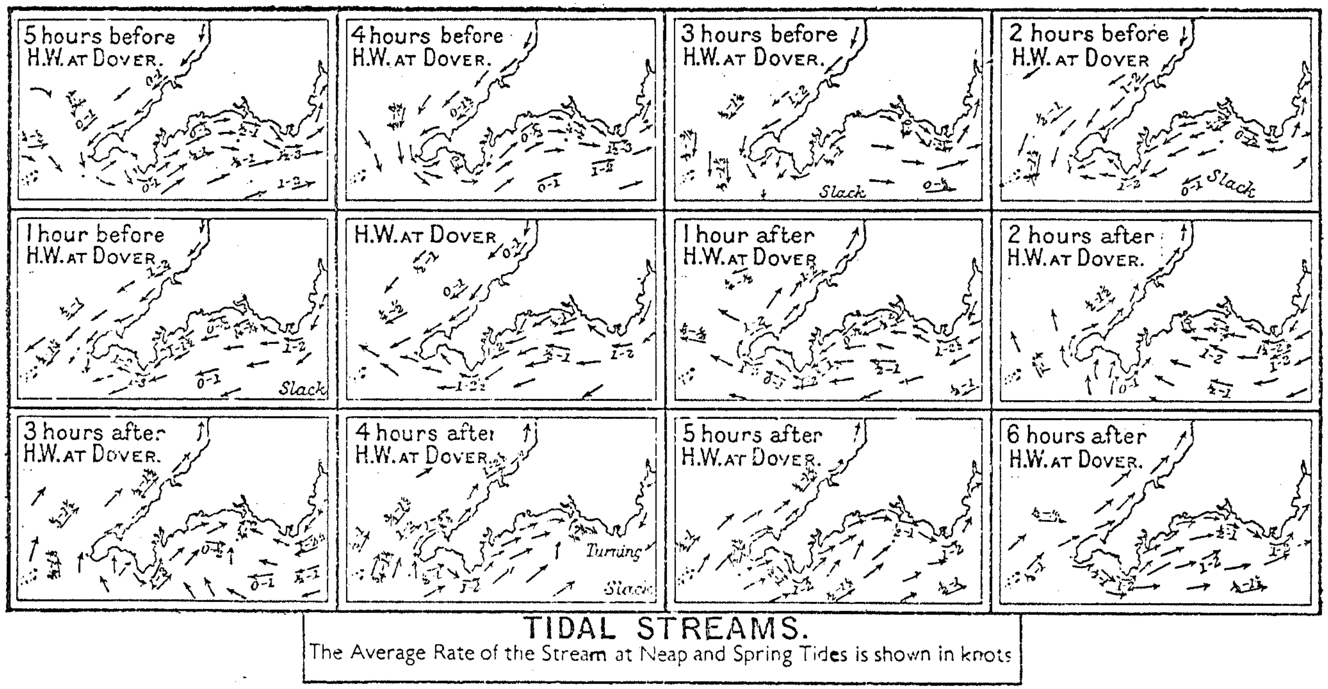


Fig. 4.8. Tidal streams off Cornwall. From Standford's Chart (1971).

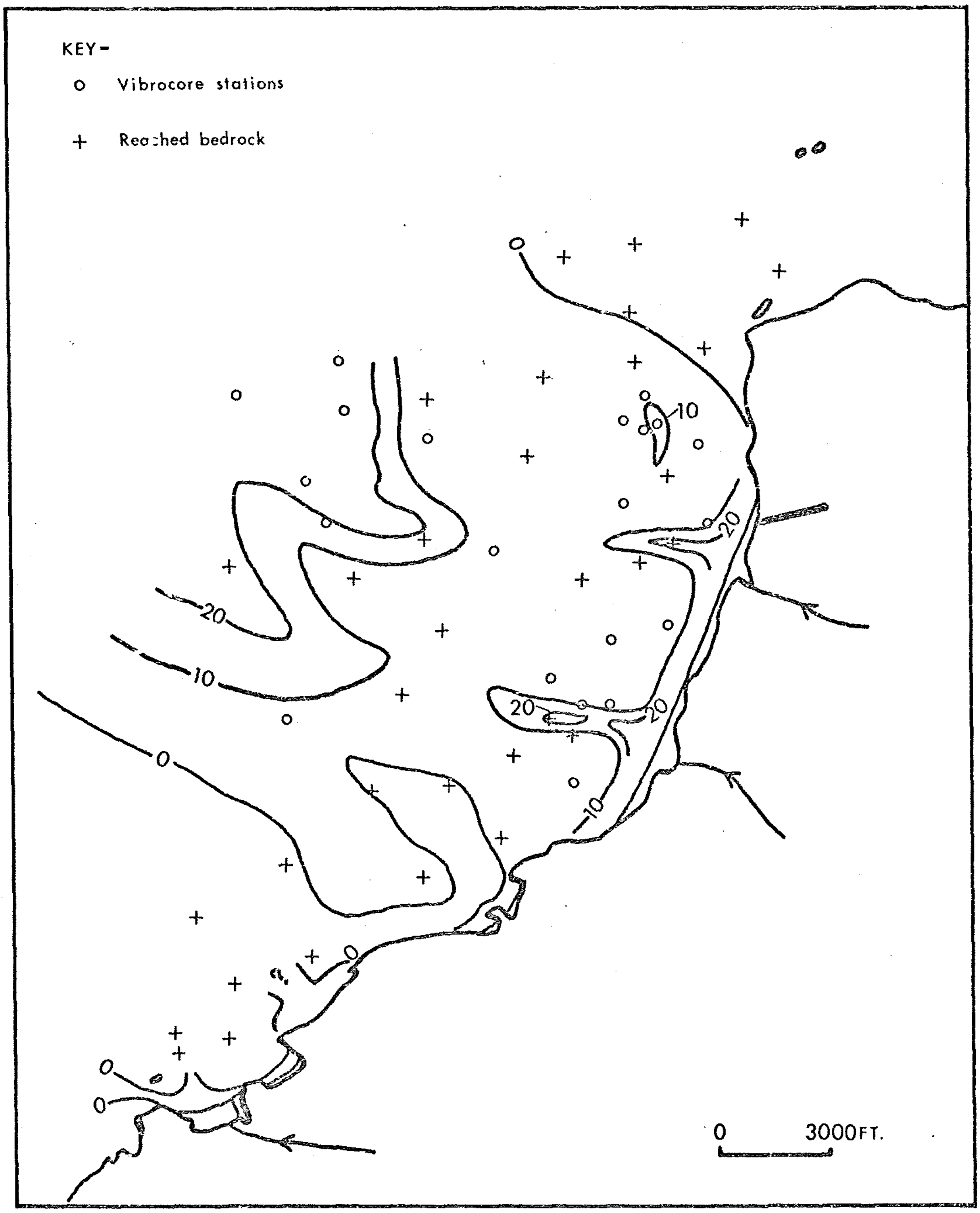


Fig. 4.9. Sediment thickness and distribution in the St. Agnes Head/Portreath area. Based on cores, grabs and Sparker data. (contours at 10-ft. intervals)

occur at the mouths of present day streams draining into the area. This is very similar to what was found by Ong (1966) in Mount's Bay. These sediments have been interpreted as being alluvial in origin and, formed when the sea level was lower. They reach a maximum thickness of over 20 ft. immediately off Porthowan and Chapel Porth and also appear to thicken at the present day Low Water Mark. Further offshore, the sediments only attain a thickness in excess of 20 ft. in the central part of the sediment sheet, and in a small area about a quarter of a mile west-south-west of St. Agnes Head. Off Gullyn Rock, the sediment is much more patchy and appears to be broken up by an area of rock outcrop into a sediment tongue.

In St. Ives Bay, information on sediment thickness is available mainly because of a Sparker survey with closely-spaced traverses carried out by Taylor Smith (Unpub. rep. 1962). However, no cores are available with which to verify the Sparker data. The Sparker survey shows that the Bay is covered by a continuous sheet of sediment which extends offshore as far as the line adjoining Godrevy Head and St. Ives Head. Immediately north-west of the mouth of the Red River, the sediment is patchy due to rock outcrop, but there are bedrock depressions filled with sediment which may be alluvial channels both here and off the Hayle Estuary. In the latter area, the sediment over the bedrock depressions attains a thickness of greater than 50 ft. Near the Low Water Mark over much of the coast, the sediment varies from 30 to over 40 ft. in thickness, and then thins out seawards to nothing at a depth of about 8 fathoms.

Very little data on sediment thickness are available for the area immediately off the Pendeen coast. A Sparker survey by

McCullough (1973) in the area further offshore has revealed an elongated trough, trending parallel to the coast in which is sediment in excess of 60 ft. thick. Closer inshore, echo-sounding and grab sampling shows a sheet of sediment, on either side of the Wra reef (Fig. 3.3C.), which is very similar in composition to sediments in Portheras Cove, and appears to thicken in that direction.

4.8.0. Sedimentological studies

4.8.1. General

In this section, grain size, sorting and shell content of sediment from the St. Agnes Head/Portreath area have been examined. In addition, St. Ives Bay and Pendeen sediments have been studied for comparison for their depositional conditions differ from those in the St. Agnes Head/Portreath area. The former is a low and the latter a relatively high energy environment.

4.8.2. Grain size distribution

Figure 4.10A-C. shows the graphic mean size distribution of sediments in the three areas investigated. The sediment type has been classified using the Wentworth scale into gravel, very coarse and coarse sand, medium sand and fine sand. The composite mean size frequency distribution is shown in Fig. 4.11, and frequency histograms for weight percent size fractions in the very coarse and coarse sand, medium sand, fine sand, and very fine sand and silt range have been plotted in Fig. 4.12A-C.

In the St. Agnes Head/Portreath area, the data show:-

(1) The area consists essentially of medium to fine sand with a mean size averaging about 2 phi.

(2) The mean size increases towards the present day High Water Mark.

(3) Towards submarine rock outcrop and marginal areas, the mean

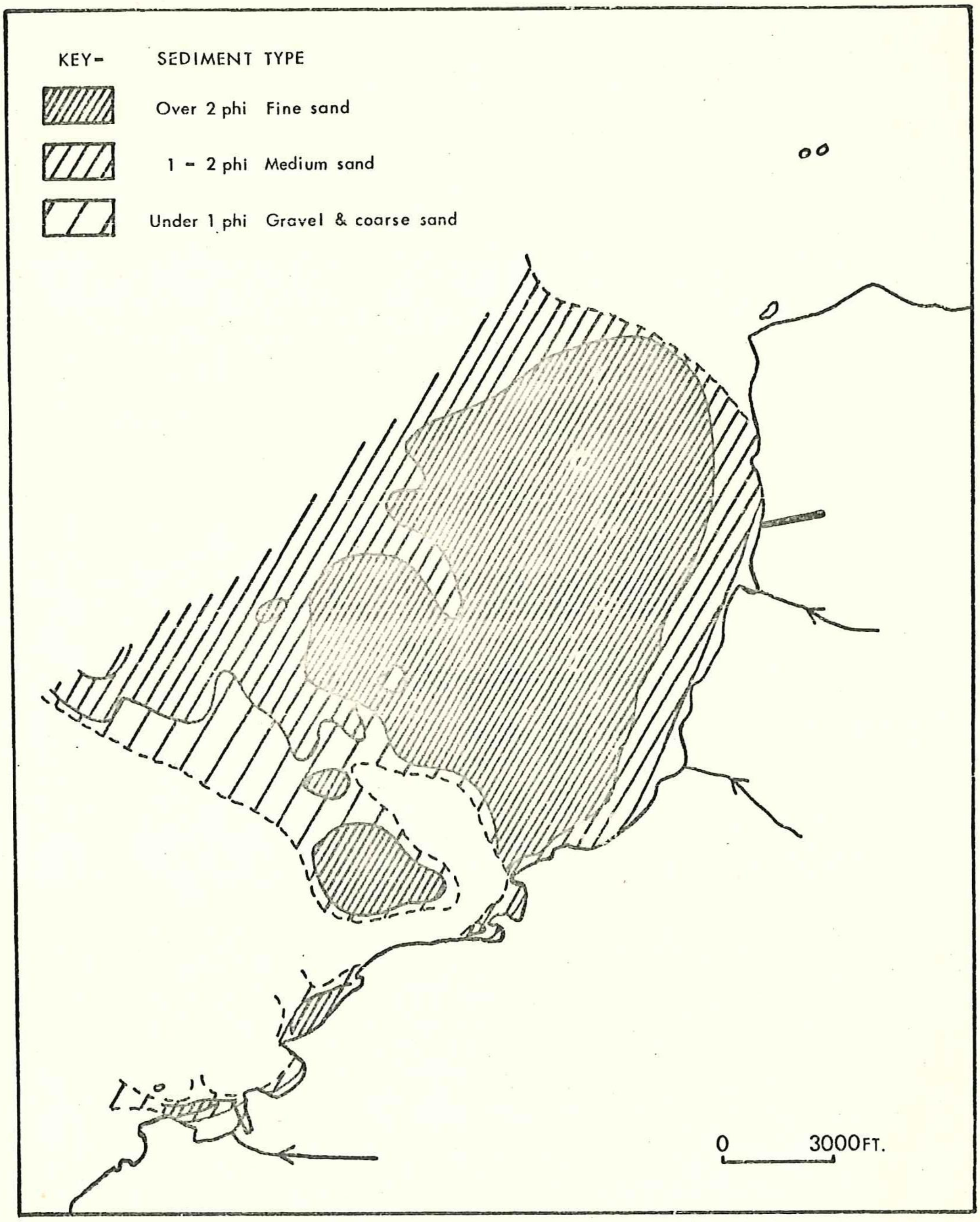


Fig. 4.10A. Distribution of sediment type - St. Agnes Head/ Portreath area.

Fig. 4.10B.

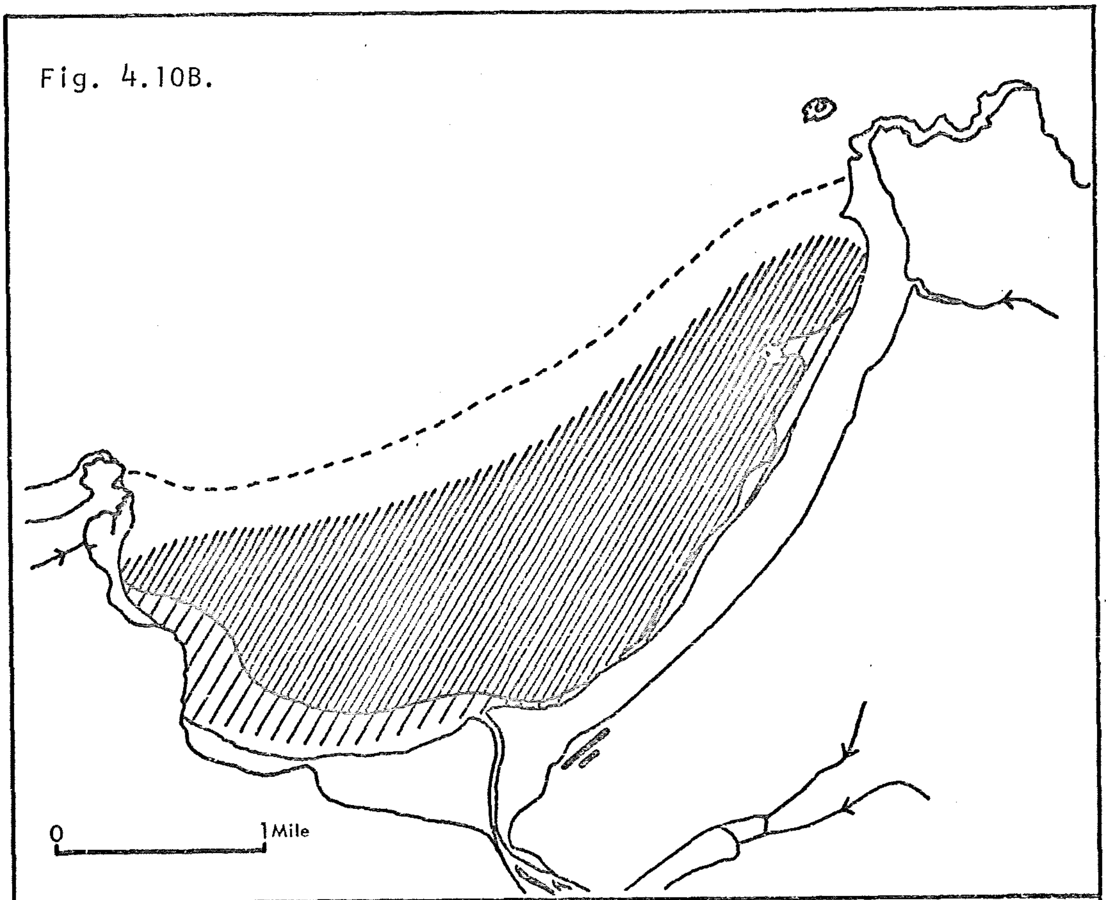


Fig. 4.10C.

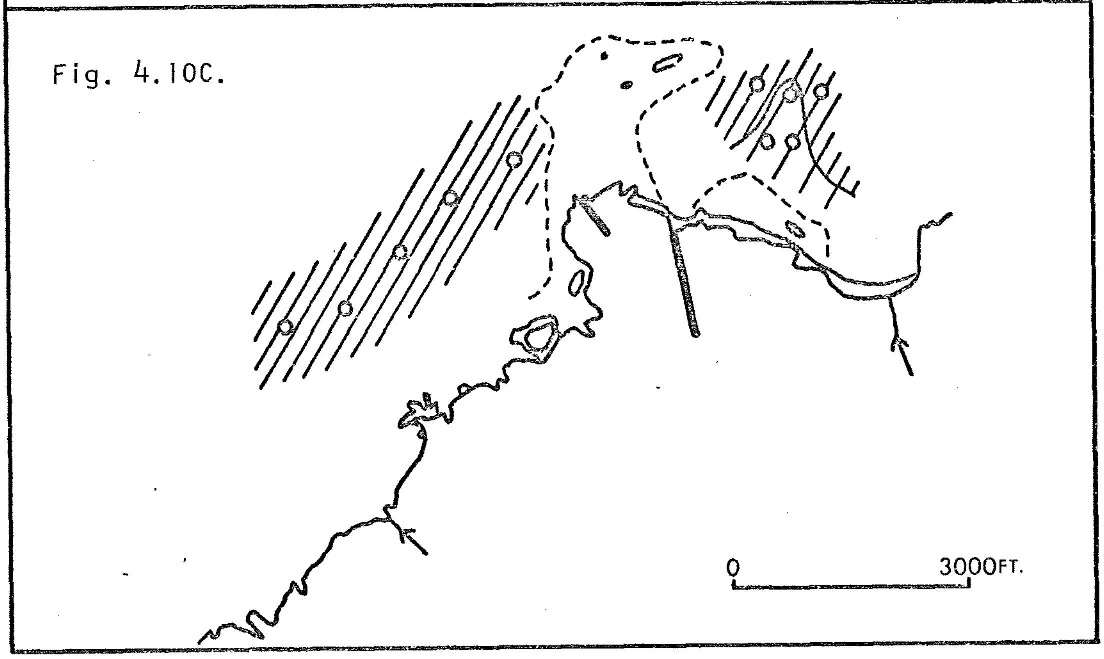


Fig. 4.10B. St. Ives Bay.
Fig. 4.10C. Pendeen area.

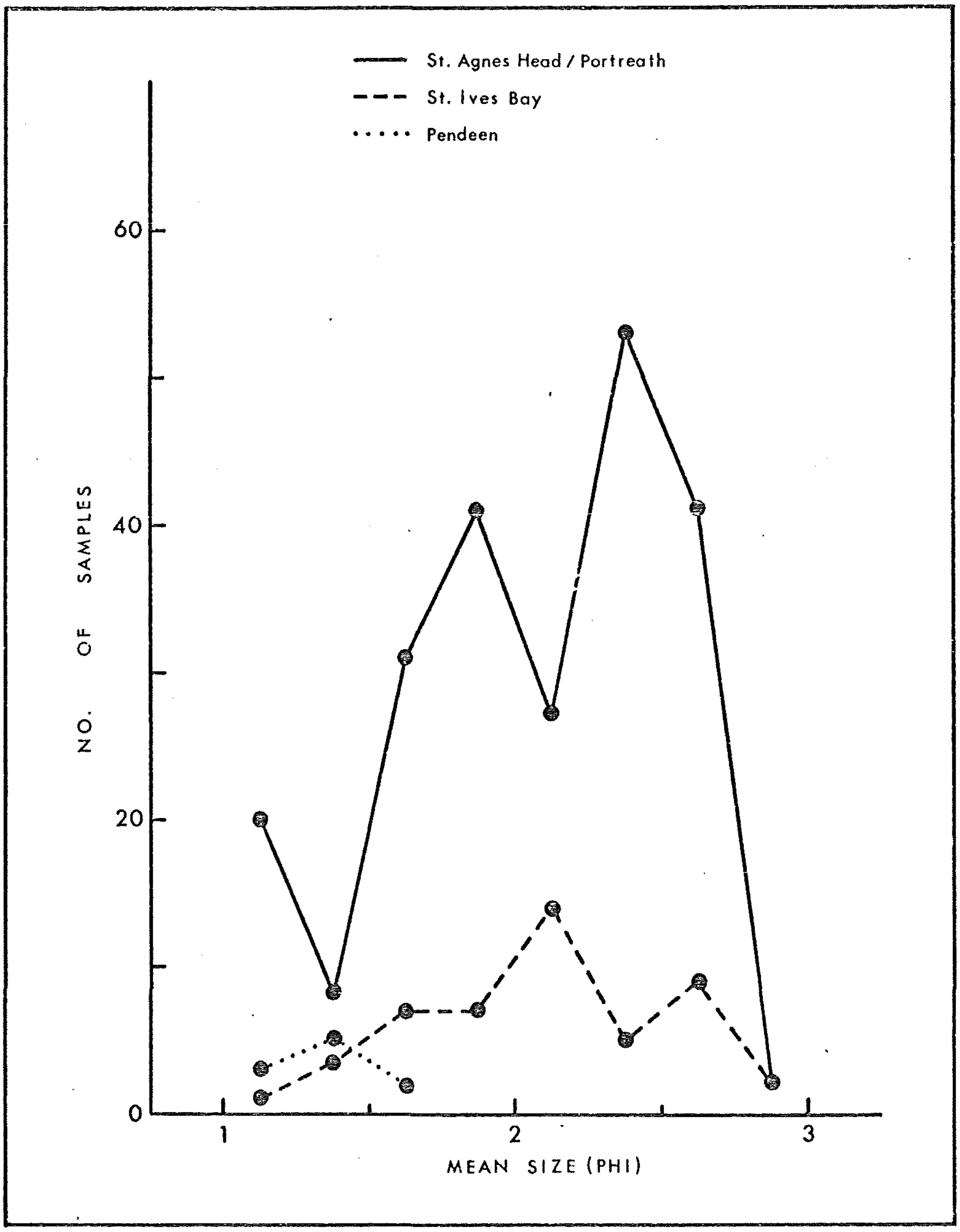


Fig. 4.11. Composite mean size frequency distribution of minus-8-mesh sediment from the three offshore areas investigated.

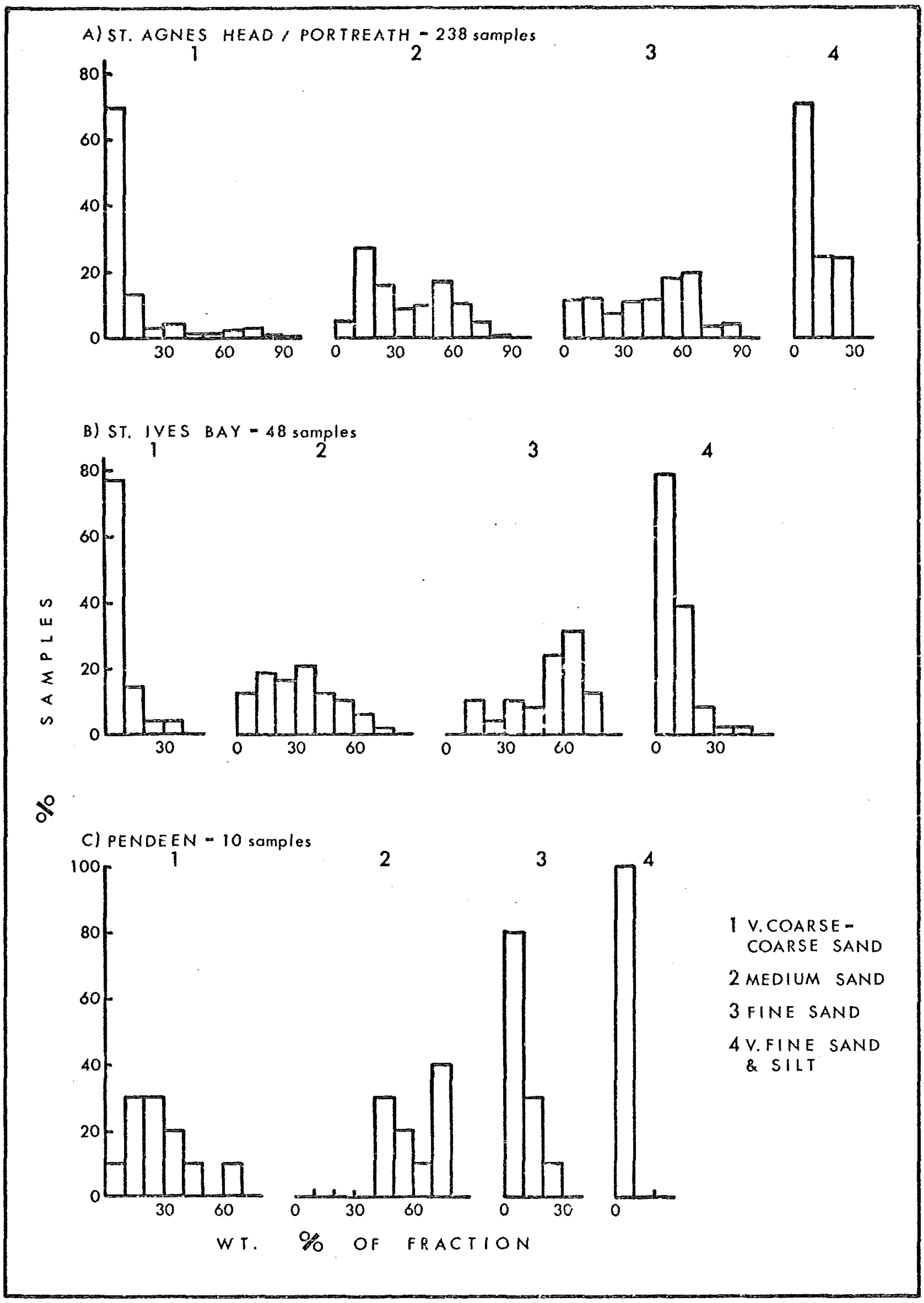


Fig. 4.12A-C. Grain size frequency distribution of minus-8-mesh sediment.

size becomes coarser.

(4) Close inshore, gravel mean sizes indicate areas where the sediment cover is relatively thin. Grab sampling has shown that gravel samples from close inshore occur only in marginal areas of the sediment sheet adjacent to areas with submarine rock outcrop.

(5) The composite histogram (Fig. 4.12A.) shows a bimodal grain-size distribution in the very coarse to fine sand ranges.

In St. Ives Bay, the data show:-

(1) The area consists essentially of medium to fine-grained sand with a mean size averaging about 2.2 phi.

(2) The mean size again increases towards the present day High Water Mark and decreases to very fine sand away from the coast.

(3) Towards the mouth of the Red River, the mean size decreases markedly indicating the influences of land derived alluvial sediment including present day mine tailings in the offshore area.

(4) The composite histogram (Fig. 4.12B.) shows a bimodal grain size distribution for the fine sand range.

In the Pendeen area, the data show:-

(1) The area consists of medium to coarse sand, with a mean size averaging about 1.4 phi.

(2) The mean size again increases towards the present day High Water Mark.

(3) The composite histogram (Fig. 4.12C.) shows a bimodal grain size distribution in the medium sand range.

4.8.3. Sorting

Figure 4.13A-C. shows the sorting of sediment in the three areas investigated which has been classified using the scale recommended by Folk and Ward (1957).

Terminology	Sorting Coefficient (ø)
Very well-sorted	Under 0.35
Well-sorted	0.35 - 0.5
Moderately sorted	0.5 - 1.0
Poorly sorted	1.0 - 2.0
Very poorly sorted	2.0 - 4.0
Extremely poorly sorted	Over 4.0

In the St. Agnes Head/Portreath area, the data show:-

(1) The area consists essentially of well-sorted to moderately sorted sand.

(2) Towards the High Water Mark, the sediment becomes progressively better sorted which may be a reflection of increasing energy input in shallow water.

(3) The present day beach sediment is well-sorted to very well-sorted.

(4) There is a small area off St. Agnes Head at a depth of about 10 fathoms with very well-sorted sand.

(5) Towards submarine rock outcrop, sorting becomes progressively poorer and also varies with sediment thickness close inshore. This is due to the availability of shells and country rock fragments in the gravel size range.

(6) Towards the relatively protected coves at Chapel Porth and Porthowan where there are streams, sorting is relatively poor.

In St. Ives Bay, the data show:-

(1) The area consists of well-sorted to moderately sorted sand.

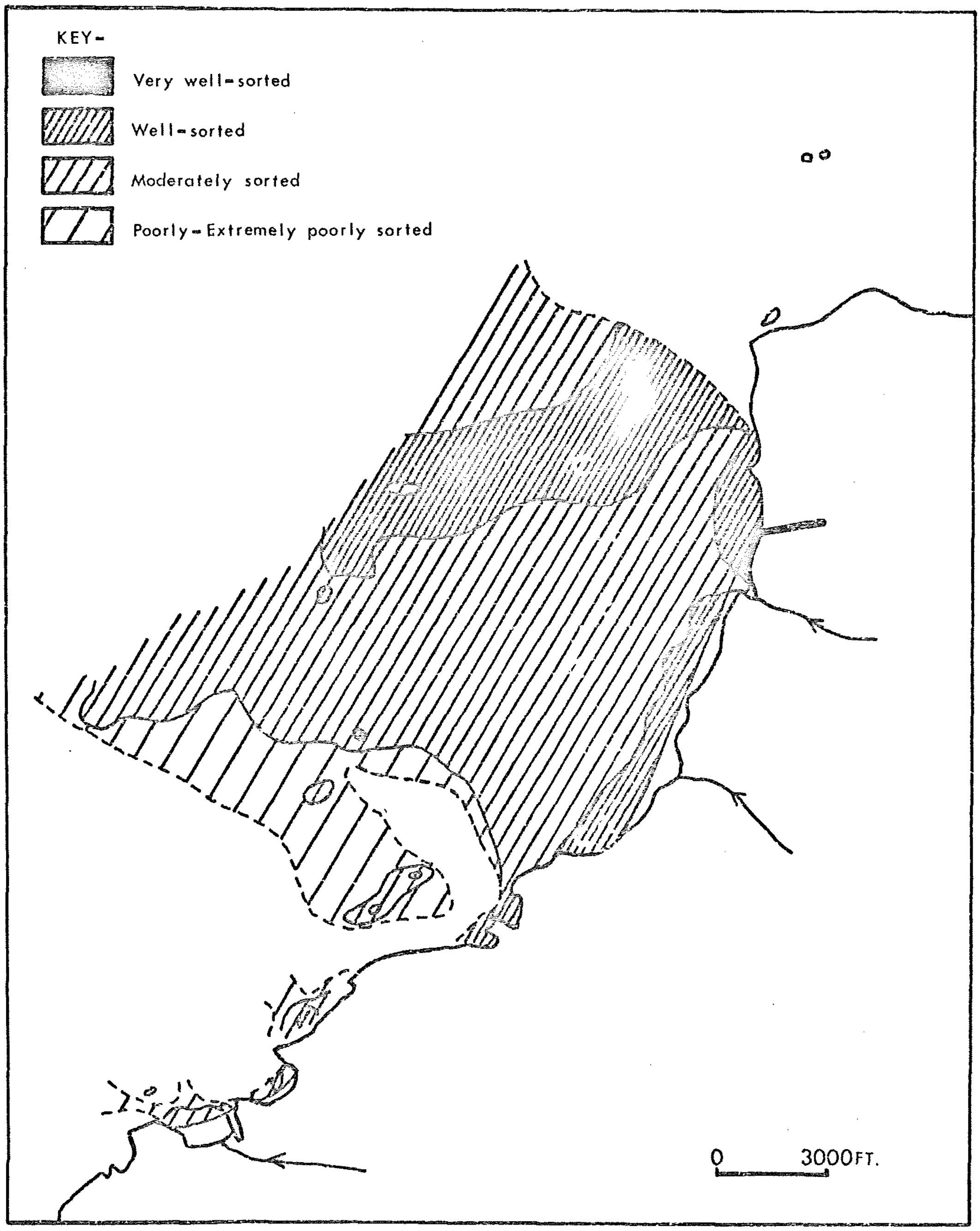


Fig. 4.13A. Sediment sorting - St. Agnes Head/Portreath area.

Fig. 4.13B.

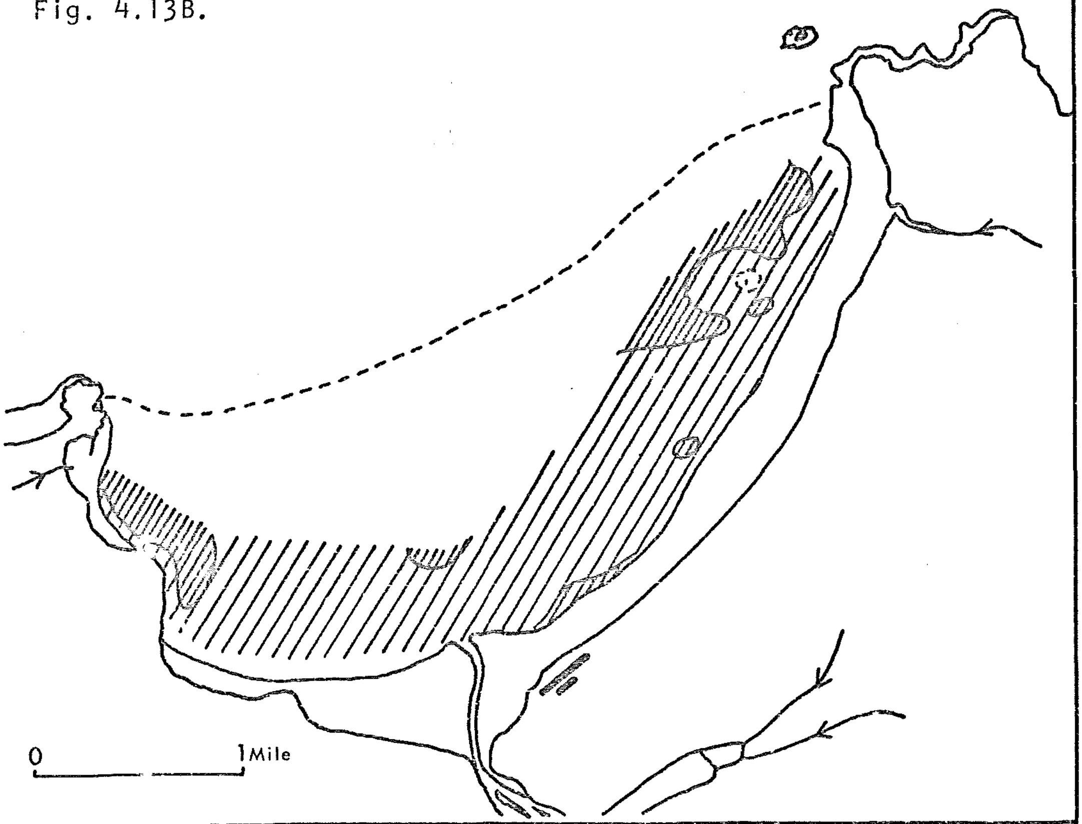


Fig. 4.13C.

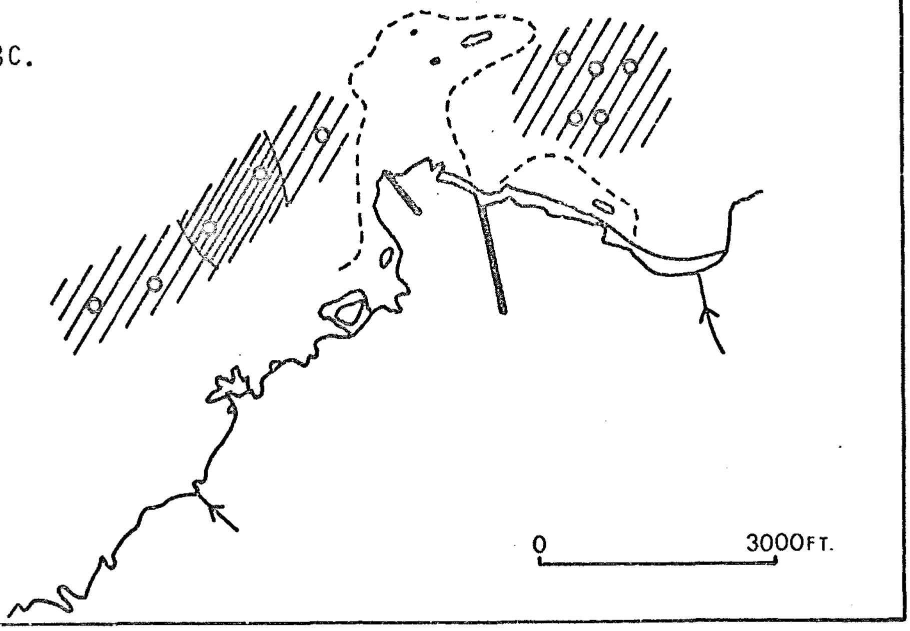


Fig. 4.13B. St. Ives Bay.
Fig. 4.13C. Pendeen area.

(2) Beach sediment at the mouth of the Red River is relatively poorly sorted due to mixing of well-sorted beach material with poorly sorted alluvial material.

(3) Sorting again improves towards the High Water Mark.

In the Pendeen area, the data show:-

(1) The area consists essentially of moderately sorted sand.

(2) In Portheras Cove, the beach sediment has a similar sorting coefficient to the offshore sediment. However the sediment east of the Wra which is protected at its western margin by rock outcrop partially exposed at low tide (Fig. 4.13C.), is relatively poorly sorted compared to sediment west of it where the inshore areas are exposed to the full force of the prevailing westerlies.

4.8.4. Mean size versus sorting

In order to determine whether the well-sorted sands half a mile west of St. Agnes Head are remnants of a fossil beach formed during a former low sea level, the interrelationship of the two textural parameters mean size and sorting were studied. The plot of mean size versus sorting of present day beach sediment from between St. Agnes Head and Chapel Porth and offshore sediment from the area is shown in Fig. 4.14. From this diagram, it can be seen that the present day beach sediment is essentially very well-sorted, with the exception of some samples within Chapel Porth which are relatively well-protected and are influenced by the stream draining into the Cove, and has similar sorting coefficients to those in the offshore area. However, there is a difference in mean size of almost one phi unit between the beach and offshore sediments. Therefore unless conditions during the formation of the supposed fossil beach differ from those at present, it is likely that local

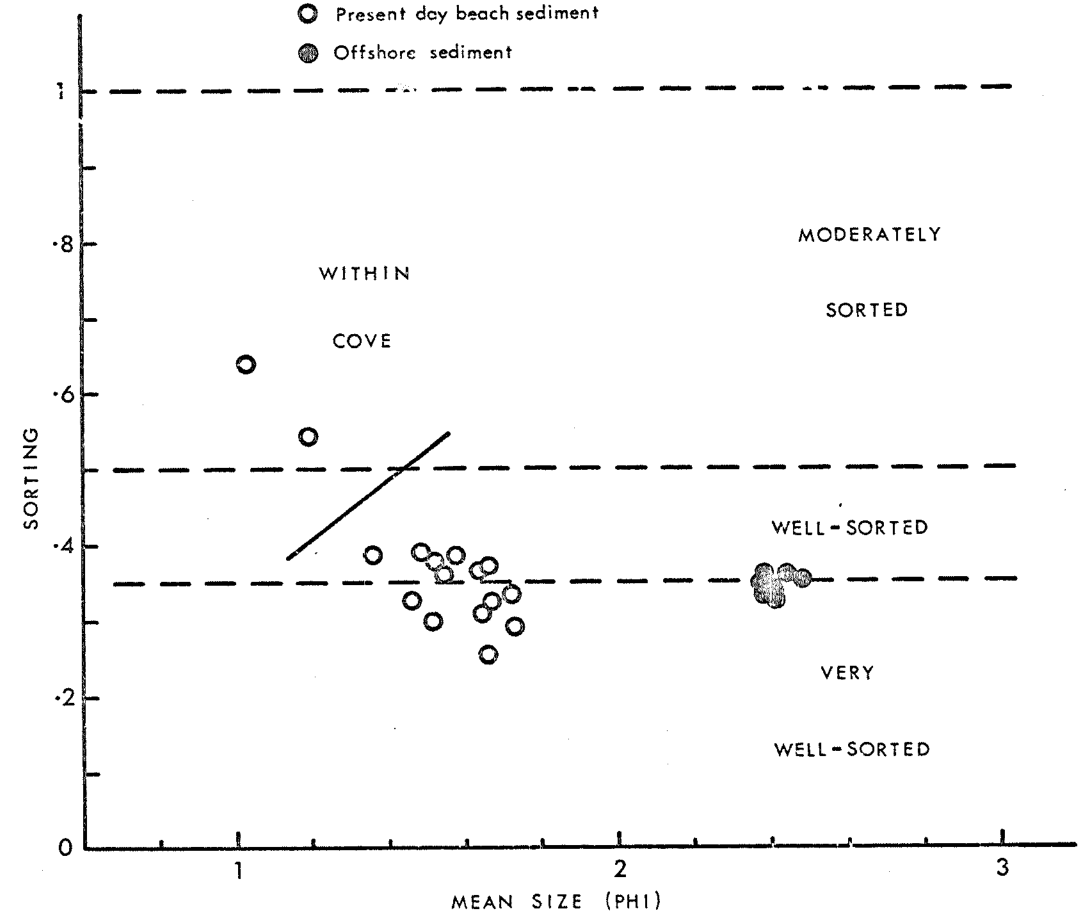


Fig. 4.14. Plot of mean size versus sorting coefficient for probable fossil beach sediment and present day beach sediment from between St. Agnes Head and Chapel Porth.

bottom currents may be responsible for the sorting as well as the finer mean size of the sand.

4.8.5. Distribution of shells and acid insoluble residue

Figure 4.15A-C. shows the shell distribution in the minus-8-mesh fraction of the sediment in the three areas investigated.

In the St. Agnes Head/Portreath area, the data show:-

(1) A gradational increase in shell content away from the High Water Mark.

(2) There are no decreases in shell content in sediment at the mouth of existing streams, suggesting either that the near-shore sediment in this area is continuously subjected to reworking or that little material is being supplied by the streams.

(3) The bedrock topography exerts a control on the distribution of shells. Where there are submarine bedrock ridges as off Gullyn Rock, the shell content increases. In addition, towards the marginal areas of the sediment where there are bedrock outcrops, the shell content increases markedly. This can be either explained by the relatively slow rate of submarine erosion which has produced little bedrock detritus, or that the shells have originated in the vicinity.

(4) In the traverse furthest away from the coast (Fig. 3.3A.), at depths up to over 18 fathoms, the high shell content appears to be largely of accumulated shell detritus including mussel shells, Mytilus edulis L., which are normally found in the shallow marine habitat up to a few fathoms or within the intertidal zone (Tebble 1966). This

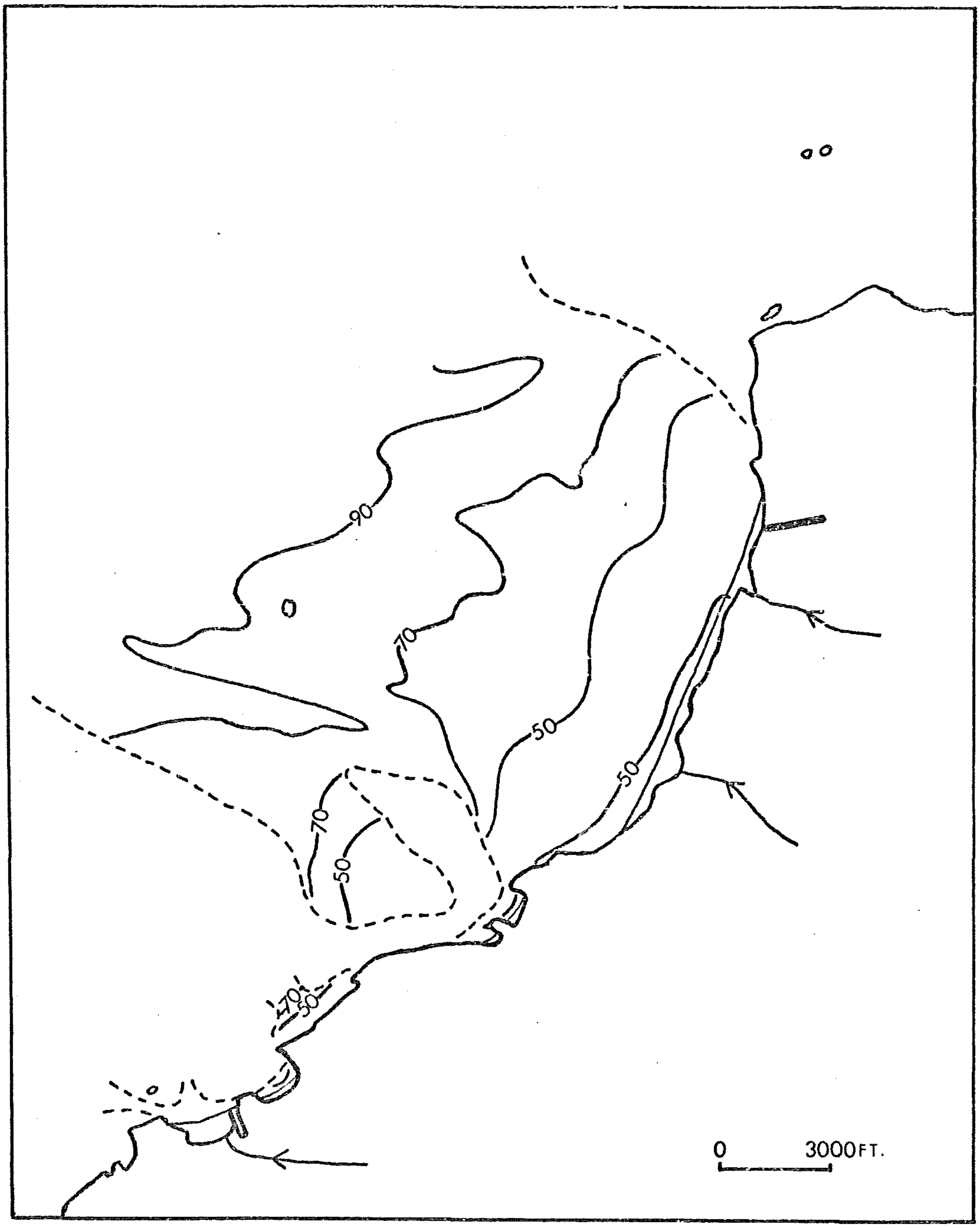


Fig. 4.15A. Shell distribution - St. Agnes Head/Portreath area. (contours in percent)

Fig. 4.15B.

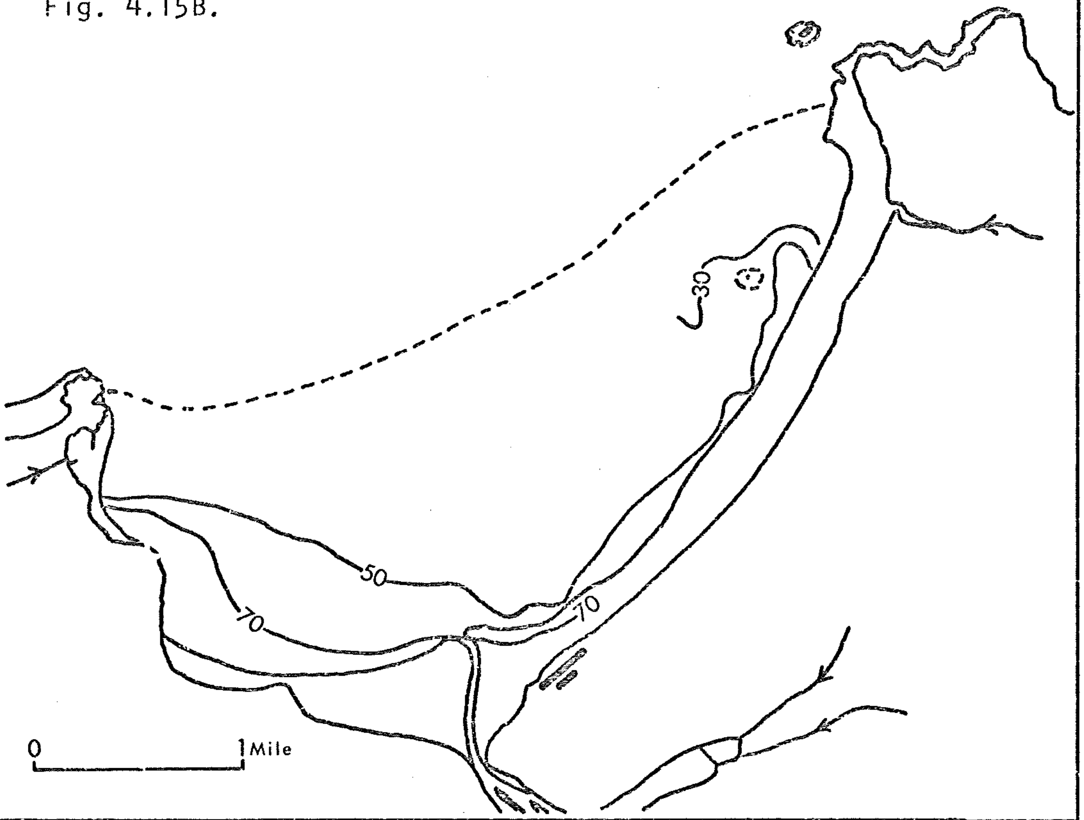


Fig. 4.15C.

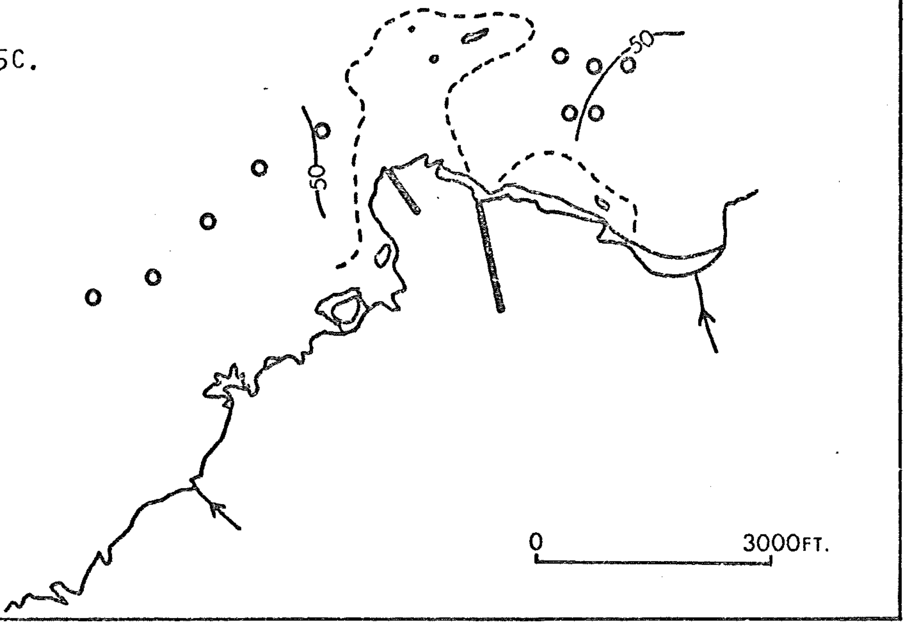


Fig. 4.15B. St. Ives Bay.
Fig. 4.15C. Pendeen area.

shell detritus consisting almost entirely of broken shell fragments may be remants of residual marine deposits whose origin, as indicated by the presence of the genus of mussel, is likely to be related to a former low sea level.

In St. Ives Bay, the data show:-

(1) The shell content increases towards the western part of the Bay and also increases towards the middle portion of the Gwithian-Hayle Beach which is fringed by extensive stretches of sand dunes.

(2) Towards the mouth of the Red River, the shell content decreases markedly showing the influence of land derived sediment.

(3) Towards the centre of the Bay, the shell content decreases.

(4) The high shell content in the Hayle Estuary channel indicates that there may only be little land derived material finding its way into the Bay because the Estuary acts as an efficient sediment trap. However the channel was sampled at high tide, at low tide conditions differ.

In the Pendeen area, the data show:-

(1) There are areas with variable shell content which are probably related to bedrock topography.

(2) The area east of the Wra is higher in shell content than those to the west, which may reflect the amount of sediment coming from the land.

4.8.6. Discussion

Variables in the marine environment (after D'Olier 1971) include the amount and type of sediment, proximity to the sediment source area, the degree of turbulence and intensity of wave action, the intensity of current action both tidal and wind induced, the direction and duration of currents, and the bedrock topography.

In the deposition of sediment, the controlling factors are bottom roughness, settling velocities of material in water, and current velocities necessary to move material. The interaction of these factors are highly complex, but the sorting and mean diameter of the sediments give some indications of their importance in the study area.

Sources of sediment include river-borne material, locally derived material from submarine erosion and reworked marine sediments. At present, the streams draining off the coast in the study area do not appear to be major sources of sediment supply with the exception of the Red River. However studies by Hazelhoff Roelfzema (1968) on the Marazion River has shown that other rivers are capable of transporting sediment containing tin, but due to a combination of factors which include the climate, the thin soil cover and relatively resistant bedrock, the streams in the area are unlikely to be eroding much at the present day. Nevertheless, during the era of peak mining production when tailings were supplied to the streams, their capacity to transport this material must have led to it having a considerable effect on the composition of near-shore surficial sediment, as in evident at present in St. Ives Bay.

Former periods of lower and more stable sea level than present are indicated by marine platforms. Marine transgression up to the present day coastline must have subjected the entire offshore area covered in this study to shallow water conditions where littoral sorting processes were active. This is indicated by the general well-sorted nature of surficial sediment.

The prevailing wind which is from a westerly direction may be responsible for much offshore sediment transport in the Pendeen and St. Agnes Head/Portreath areas. During periods of strong westerly winds, the high waves generated transport sediment from the beach to the foreshore zone. On the other hand, offshore winds will result in constructive waves with small wave height and the net movement of sediment is onshore (King 1971). Because of this variability of wind determined sediment transport, a study of the wind strength and direction during the period of sampling was necessary before examining surficial sediments from the mobile foreshore and intertidal zones. The period of grab sampling in this study was preceded by periods of westerly winds (see Appendix), which are typical for South-west England, and thus the sedimentary processes in operation prior to sampling were probably normal for the area.

The bimodal composite grain size distribution of the sediments noted in section 4.8.2. can be attributed to the difference in energy level in the different environments. Close inshore, the sediment is coarse, most probably as a result of wave action, and offshore it is generally finer. The bimodal composite distribution is essentially a reflection of the numbers of samples collected in the two areas.

4.8.7. Conclusions

The main conclusions reached in this chapter are:-

(1) In areas where the sediment cover is relatively thin, grab sampling can provide a great deal of information on the depositional history.

(2) The 10 fathom sea level proposed by Robson (1950) and the 8-10 fathom platform of Garnett (1962) is represented in the study area.

(3) The highest energy level is found near the High Water Mark, which is reflected in increased mean size and better sorting of the sediment. These sediments are likely to contain the coarse land derived heavy minerals.

(4) Present day streams have a relatively insignificant effect on the composition of surficial sediments, with the exception of the Red River.

(5) Where the stream load in the past was affected by human interference through dumping of mine tailings, the sediment would probably have been similar to that in the Red River draining into St. Ives Bay in the present time.

(6) The well-sorted nature of offshore sediment suggests that littoral sorting processes have taken place in the past.

(7) Strong bottom currents may exist off St. Agnes Head.

(8) The influence of wind must be taken into account in determining sediment movement near-shore.

CHAPTER 5. Geochemical results in St. Agnes Head/Portreath sediments

5.1.0. Introduction

In this chapter, all geochemical results are presented on a shell-free basis, because shells dilute the tin content of the detrital sediments.

Local variations in energy level and the occurrence of submarine mineralisation can be reflected in the grain size distribution of tin in sediment. While the energy level of the sediment formation is indicated by the mean size and sorting coefficient, distance from source can be expected to govern the grain size distribution of tin. In order to investigate this, the tin distribution in four fine size fraction of the sediments (under 250 microns) have been examined, together with the minus-8-mesh total tin. Size fractions coarser than 250 microns have been ignored because the majority of the samples contain only small fractions of detrital sediment of this size, and which are poor in tin compared to the finer fractions. In addition, the increasing likelihood of a greater sampling error when dealing with coarse sediments containing low tin concentrations has already been demonstrated in section 3.2.1.

Six other elements - copper, zinc, iron, manganese, arsenic and tungsten, found commonly associated with primary tin lodes, have been chosen to determine their role as possible pathfinder elements in the location of submarine tin lodes. Out of these, most noticeably copper and arsenic have already been demonstrated as being of use in this context on land (Dunlop and Meyer 1973). The minerals containing these metals are generally less stable and more mobile than cassiterite because of their chemical reactivity and their low densities, and may therefore provide wider dispersion haloes than occur in the case of tin. According to Dunlop and Meyer (1973), anomalous concentrations of copper and arsenic associated with anomalous tin concentration are good indicators of primary tin mineralisation, while low concentrations of copper and arsenic associated with anomalous tin concentration indicates reworked detrital deposits. These elements have been determined in the minus-8-mesh shell-free fraction of samples from two traverses, a total of 106 samples.

The vertical distribution of tin and other elements in sediments has been examined in two cores. These two cores are used in order to study the element distribution in surficial and basal sediments, and to obtain evidence on the source of the tin.

The geochemical results are summarised in Table 5.1A & B. Because of the very well-sorted nature of some of the samples, especially those from the traverse closest to shore, insufficient quantity of the finest fractions could be obtained and some of them are therefore omitted. In data interpretation, the background for convenience is taken as the minimum concentration, the threshold as the value plus two standard deviations from the mean concentration,

Table 5.1A. Distribution of tin in St. Agnes Head/Portreath sediments in the shell-free basis. (in ppm)

Size Fraction (microns)	No.of Samples	Mean	Range	Standard Deviation	Threshold	Anomaly
< 2057	238	1337	150- 7300	1151	3638	4789
170- 250	236	726	100- 3500	589	1904	2492
124- 170	235	1415	100- 7300	1358	4132	5490
90- 124	222	3873	900-38,500	4012	11,898	15,910
< 90	201	11,828	2500-60,000	8781	29,390	38,171

Table 5.1B. Distribution of other elements in St. Agnes Head/ Portreath sediments in the minus-8-mesh shell-free fraction. (in ppm)

Element	Mean	Range	Standard Deviation	Threshold	Anomaly
Copper	52	30- 97	16	73	99
Zinc	112	78- 178	20	152	171
Iron	34,338	26,400-49,920	4871	44,080	48,951
Manganese	494	331- 715	90	673	763
Arsenic	98	24- 204	32	161	192
Tungsten	36	2- 110	25	86	110

Table 5.2A. Samples with tin concentration(s) above the threshold values shown in Table 5.1A. in the St. Agnes Head/Portreath area. (in ppm)

Sample No.	< 2057u	170-250u	124-170u	90-124u	< 90u
41			7150*	38,500*	
43			4300		
47		2150	7300*		
48		2500*	6700*		
49			4400		
51		2450	6800*		
52		2000	5800*		
71					38,000
73					36,500
74				15,000	55,000*
75				32,500*	
94				13,200	60,000*
309	3650				
314	4000				
315	6200*				
317	4200				
320				32,000*	
321	3800			35,000*	
322			4350		
326	4650				
327	4300				
328	4100				
329	4700				
330	6200*				44,000*
331	7300*		4250		38,000
332	6500*				37,000
333	5100*		4700	15,000	52,000*
334		3500*			
338		2000	4600	12,800	
339		2300			
340		2100			

* - Anomalous samples.

and anomaly is taken as the value plus three standard deviations from the mean concentration. Table 5.2A & B. gives a list of the samples above the threshold so defined.

Table 5.2B. Samples with concentration(s) of other elements above the threshold values shown in Table 5.1B. in the St. Agnes Head/Portreath area. (in ppm)

Sample No.	Copper	Zinc	Iron	Manganese	Arsenic	Tungsten
218				710		
220	92					
223				691		
232				696		
312		156				
315	84					110
325		178*				
327	78					
328	75		45,120			
329	78		48,000	677	180	
330	90		47,040	682	192	
331	97		49,920	715	204*	100
332	86		44,640		192	
333	87					

* - Anomalous samples.

5.2.0. Distribution of tin in surficial sediment

The tin results obtained have been compiled, and frequency distribution graphs (Fig. 5.1A-E.) and contour distribution maps have been drawn (Fig. 5.2A-E.). These contour maps based on widely-spaced sampling traverses are subjective in nature, and in the interpretation of these maps this limitation must be taken into account. In all cases, the contours were chosen at intervals greater than the precision of the analytical technique used.

5.2.1. Distribution of minus-8-mesh total tin

Figure 5.1A. shows the tin frequency distribution for the samples analysed and the minus-8-mesh total tin distribution is shown in Fig. 5.2A. The following features in tin distribution are

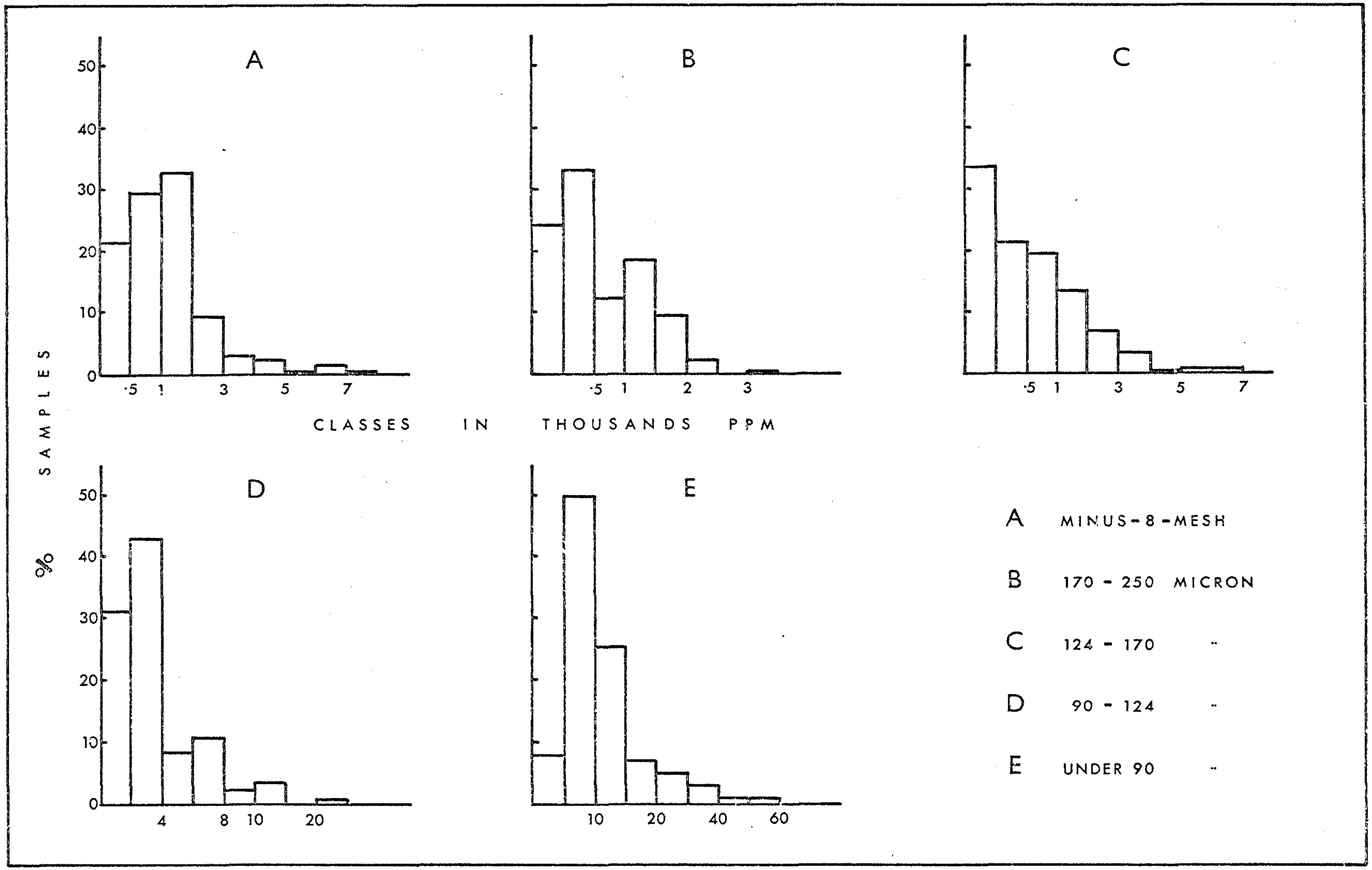


Fig. 5.1A-E. Frequency distribution of tin.

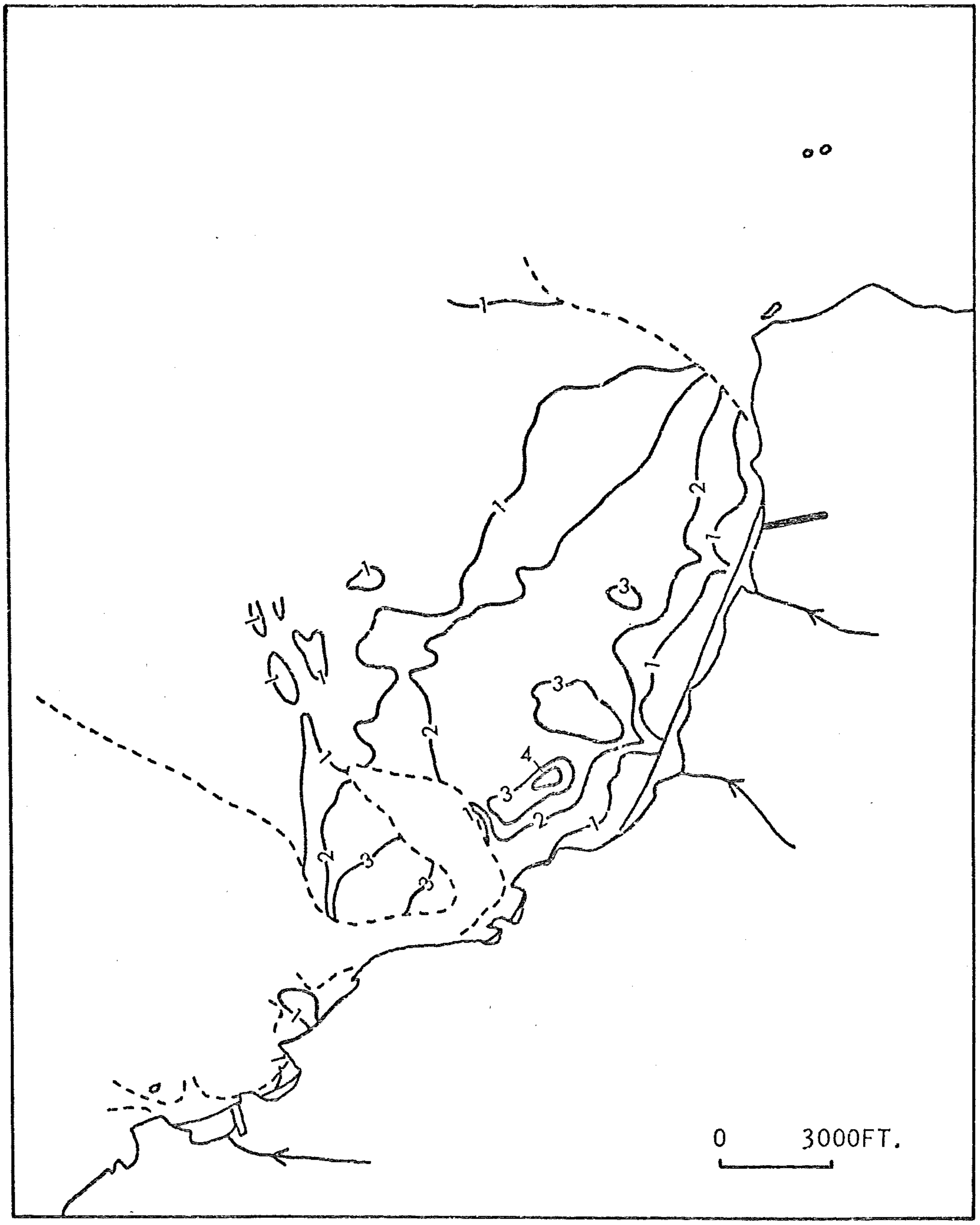


Fig. 5.2A. Distribution of minus-8-mesh tin. (contours in thousands of ppm)

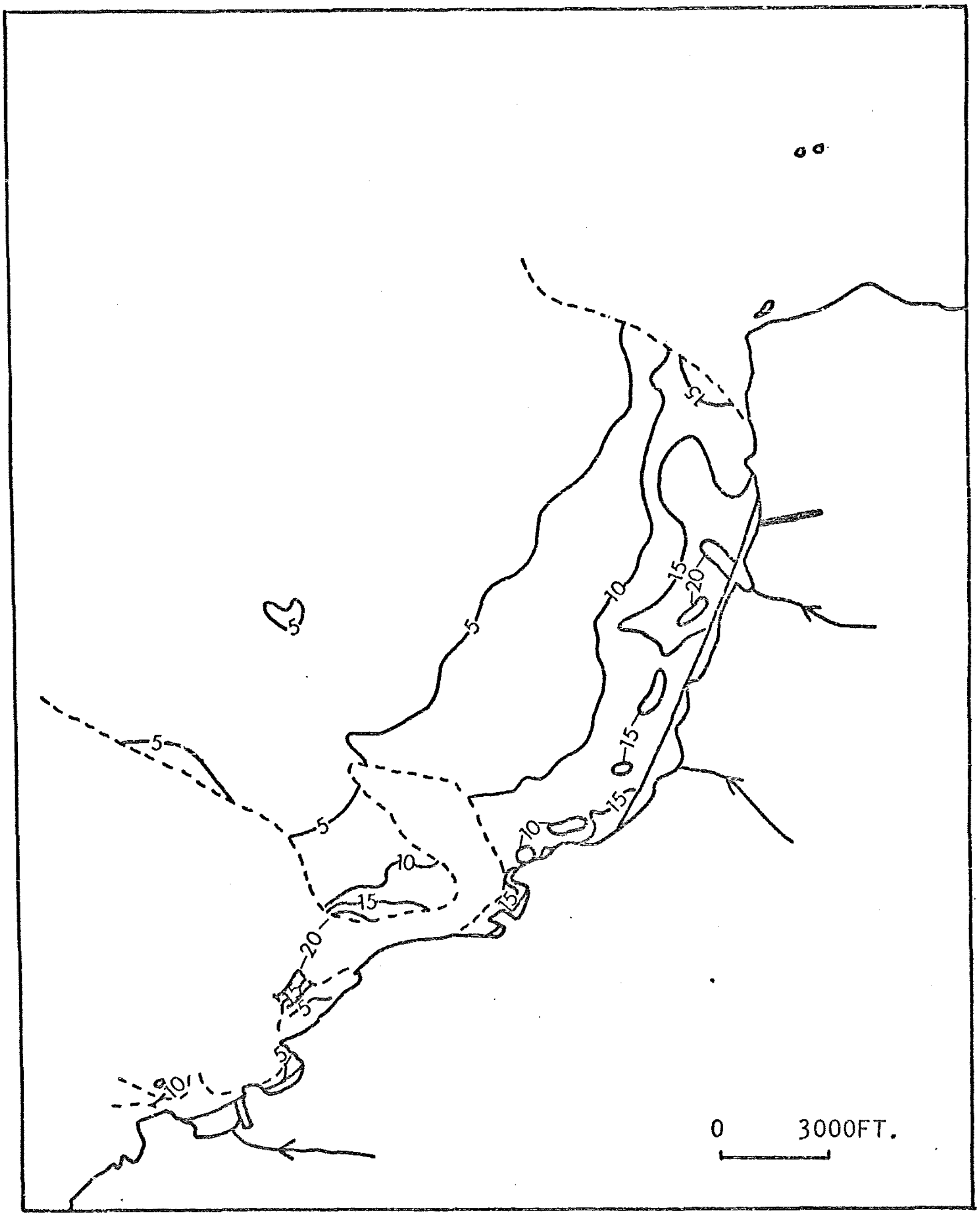


Fig. 5.2B. Distribution of 170-250 micron tin. (contours in hundreds of ppm)

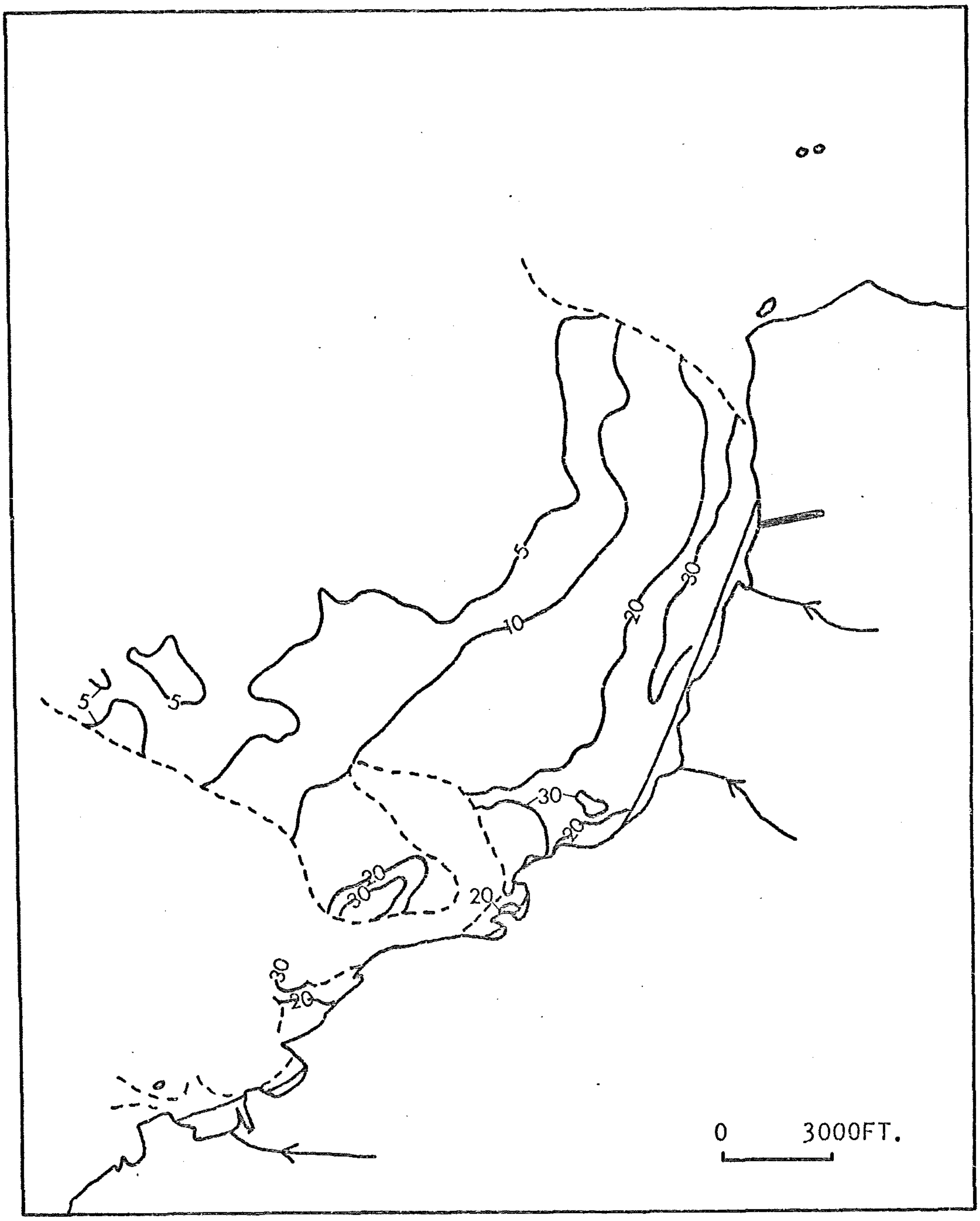


Fig. 5.2C. Distribution of 124-170 micron tin. (contours in hundreds of ppm)

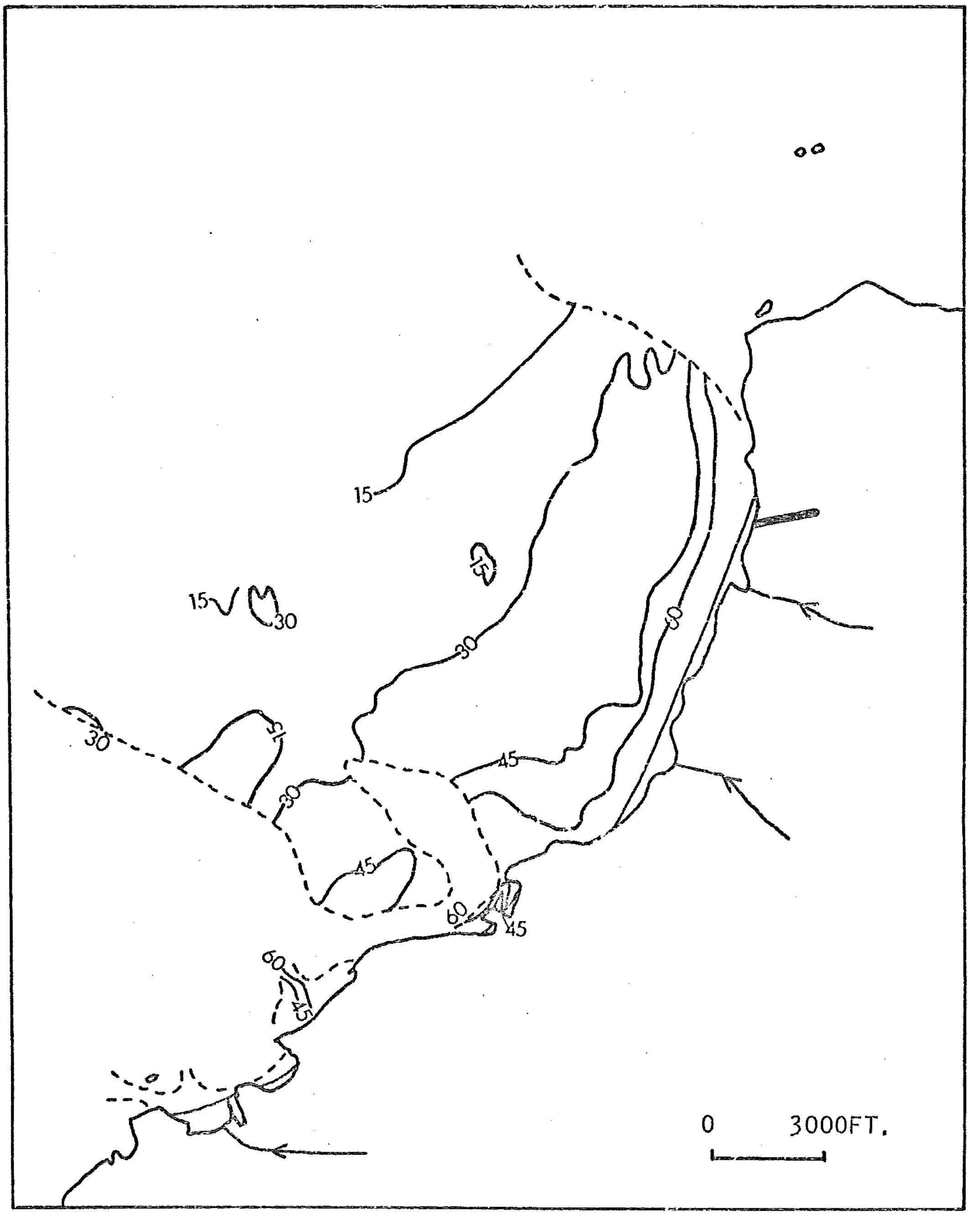


Fig. 5.2D. Distribution of 90-124 micron tin. (contours in hundreds of ppm)

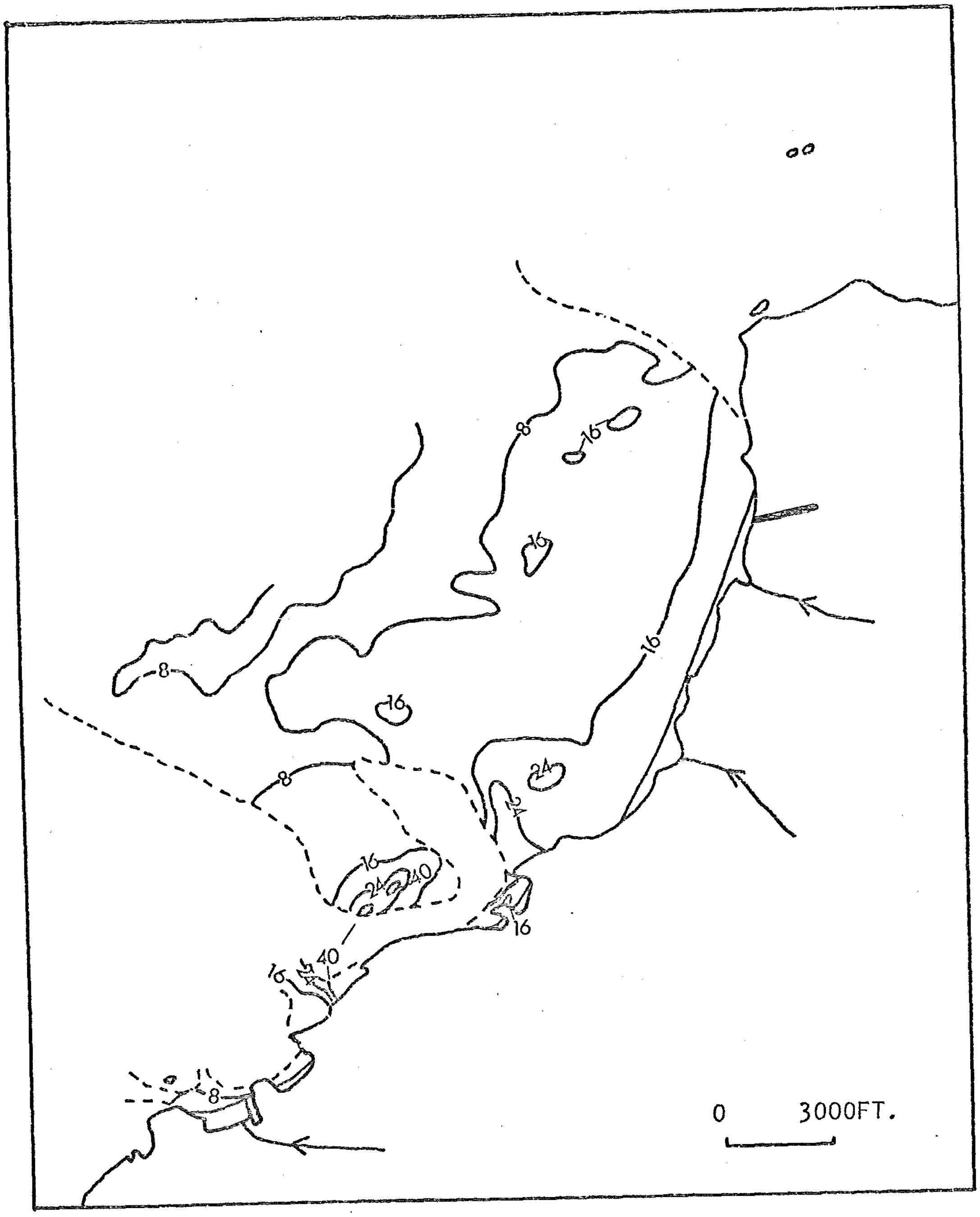


Fig. 5.2E. Distribution of under 90 micron tin. (contours in thousands of ppm)

apparent:-

(1) The sediment becomes generally poorer in tin with increasing distance from shore and with increasing water depth. The exception is the traverse closest to the shore which shows a reversal, the tin concentration here is lower than that in the next traverse further offshore.

(2) Off the mouth of the Chapel Porth, Porthowan and Portreath rivers the sediment are enriched in tin.

(3) Samples with tin concentration above the threshold are found only along traverses in the foreshore zone at a water depth of approximately 40-60 ft. The richest samples occur off the coast between Porthowan and Portreath, towards the southern end of the main sediment body.

(4) Towards the margin of the main sediment body near St. Agnes Head, which is near to the known tin zone on land, the tin concentration increases, and decreases towards the south-western margin which is well outside the tin zone of the St. Agnes Beacon Granite.

(5) Fine sand generally contains more tin than the medium and coarse sand.

(6) Very well-sorted samples are the richest in tin. Samples with tin concentration above the threshold are generally well-sorted to moderately sorted with sorting coefficients ranging between 0.49-0.59.

(7) Along the traverse nearest to the shore, the highest tin concentration (1750 ppm) occurs within the rocky cove approximately half way between Porthowan and Portreath.

5.2.2. Size distribution of tin

Four size fractions - 170-250, 124-170, 90-124 and under 90 microns respectively, sieved from the minus-8-mesh shell-free fraction of the sediments have been examined. Tin occurring in size fractions coarser than 124 microns (approximately 120-mesh) are more likely to be in the form of composite mineral grains than as discrete mineral grains, because cassiterite grain sizes in the source rock are usually finer than this. For this reason, in the weathering of submarine mineralised bedrock, the tin may be in the form of relatively large composite tin-bearing grains as well as in discrete grains in the fine sizes. Therefore anomalous concentration of tin in all size fractions of the same sample is likely to indicate submarine bedrock mineralisation, while on the other hand, anomalous concentration of tin in the finest fraction only is more likely to indicate contamination from fine mine tailings.

In this section, the tin distribution pattern in the various size fractions are described in two sub-sections under the headings common features and distinctive features to only one or a few groups. Fig. 5.1B-E. shows the frequency distribution of tin concentrations in the four size fractions and Fig. 5.2B-E. shows the tin distribution in the four size fractions.

5.2.2A. Common features in tin distribution

The following features (except 5) are very similar to those of the minus-8-mesh total tin distribution. They are:-

(1) The sediment becomes generally poorer in tin with increasing distance from shore and with increasing water depth.

(2) Off the mouth of the Chapel Porth, Porthowan and Portreath rivers, the sediments are relatively enriched in tin along the two traverses nearest to the shore.

(3) Samples with tin concentration above the threshold are

found only along traverses in the foreshore zone at water depths of less than 60 ft., particularly towards the southern end of the main sediment body.

(4) Towards the margin of the main sediment body near St. Agnes Head the tin concentration increases but decreases towards the margin of the sediment tongue between Porthowan and Portreath, which is well outside the tin zone of the St. Agnes Beacon Granite.

(5) Offshore between St. Agnes Head and Porthowan, the sediment nearest to the Low Water Mark shows the highest tin concentration in all four size fractions.

5.2.2B. Specific features in tin distribution

(1) Adjacent to the Low Water Mark, the sediment off the mouth of the Chapel Porth River which is nearest to the tin zone of the St. Agnes Beacon Granite is enriched in tin in the coarsest size fraction.

(2) The very well-sorted sand occurring half a mile west of St. Agnes Head is relatively enriched in tin in the 124-170 and 90-124 micron size fractions compared with adjacent samples, and less clearly in the 170-250 micron size fraction. The under 90 micron size fraction shows lower tin concentrations compared to adjacent samples.

(3) Towards the southern margin of the main sediment body where the water depth is less than 60 ft., tin concentrations in the 90-124 and under 90 micron size fractions decrease, while further offshore at greater depths the situation is reversed.

(4) The sediment along the 80 ft. depth contour and within the main sediment body appears to be locally enriched to over

16,000 ppm in the under 90 micron size fraction.

(5) In the traverse furthest offshore, the tin concentration in the under 90 micron size fraction increases towards the central part of the main sediment body.

(6) Table 5.3. summarises the mean sizes and sorting coefficients of the total sediment with size fractions containing tin concentrations above the thresholds. The total number of samples with one or more size fractions with tin concentrations above the respective threshold value is 23.

Table 5.3. Mean size and sorting coefficient ranges in sediments with size fractions above the respective threshold value according to sediment type.

Size Fraction (microns)		170-250	124-170	90-124	< 90
Mean Size Range (phi)	Fine Sand		2.32-2.54	2.10-2.32	2.01-2.55
	Medium Sand	1.34-1.54	1.19-1.57	1.19-1.85	
	Coarse Sand				
	Gravel*	-1.00	-1.00	-1.00	
Sorting Coefficient Range	Fine Sand		0.52-0.55	0.52-0.53	0.41-0.68
	Medium Sand	0.46-0.61	0.36-0.61	0.36-0.68	
	Coarse Sand				
	Gravel*	2.00-4.00	2.00-4.00	2.00-4.00	

* - Based on visual estimate.

5.3.0. Distribution of other elements in surficial sediment

Elements other than tin have been determined in the sediments after the preliminary removal of shells. The shell removal technique (see section 3.3.3.) will remove metals which may be held by grain adsorption. Consequently, it is necessary to take this into account in data interpretation. The results obtained will reflect the element abundances in the detrital sediments.

Figure 5.3A-F. shows the frequency distribution of these elements and their distribution is presented in the form of proportional pie graphs instead of contours in Fig. 5.4A-F, because only samples from two traverses have been used. The pie graph class intervals are chosen with consideration to the precision of the analytical techniques used, in all cases the class intervals chosen are greater than the precision.

5.3.1. Common features in the distribution of copper, zinc, iron, manganese, arsenic and tungsten

The following features are apparent:-

(1) Within the main sediment body, there is a general decrease in concentration of elements with increasing distance from the shore and with increasing water depth.

(2) Off the mouth of the Chapel Porth and Porthowan rivers the sediments are relatively enriched in all the elements.

(3) Sample with element concentrations above the threshold can be found in the area towards the southern end of the main sediment body at water depths of under 60 ft.

(4) The very well-sorted sand half a mile west of St. Agnes Head is relatively enriched in all elements compared to adjacent samples.

Of these features (1) and (2) are similar to those of the minus-8-mesh total tin and size tin distribution, and with the exception of zinc and manganese in the traverse furthest offshore, the distribution of all the elements correlate well with that for tin. Feature (4) differs from the under 90 micron tin distribution.

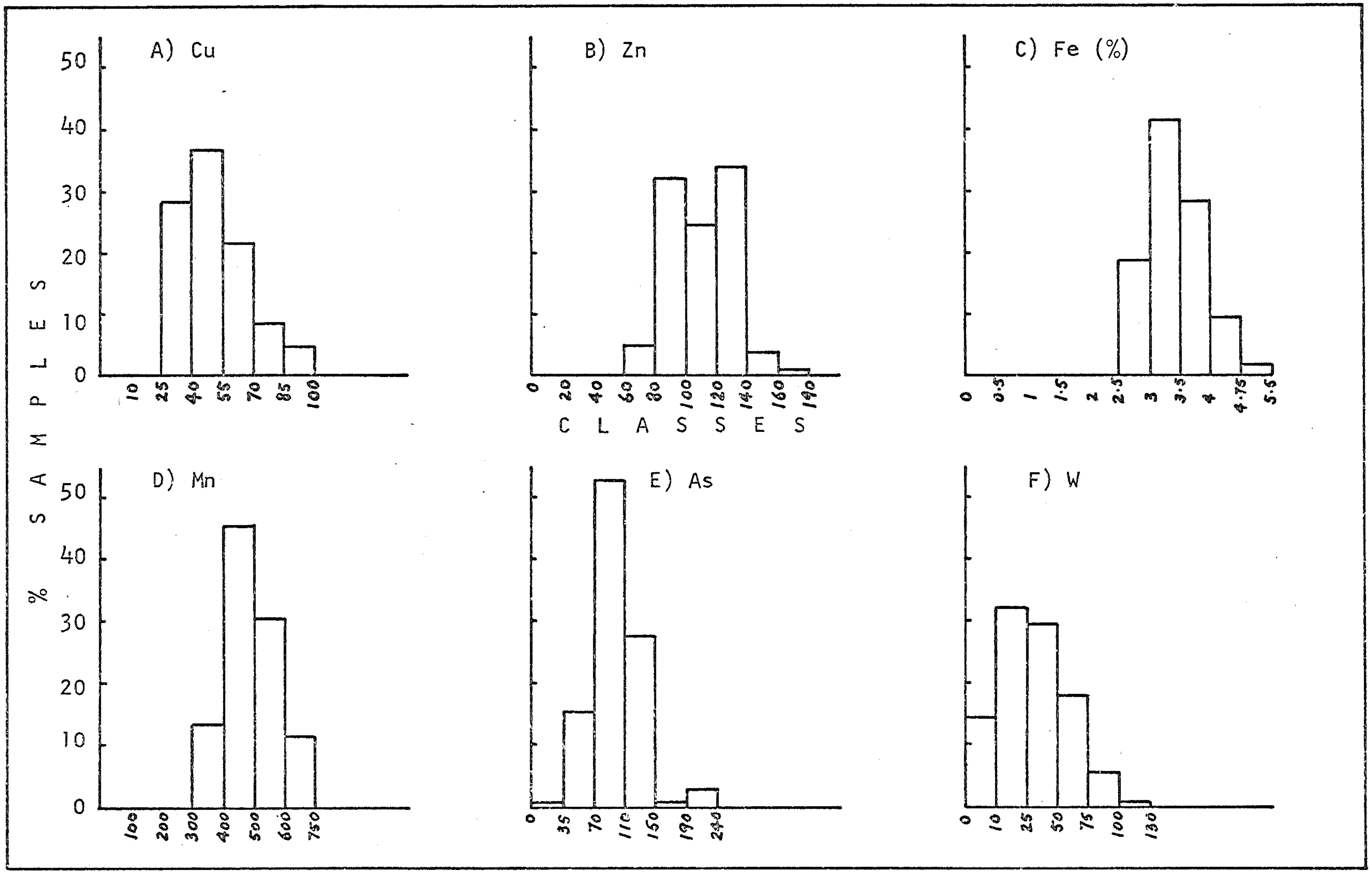


Fig. 5.3A-F. Frequency distribution of other elements. (in ppm unless specified)

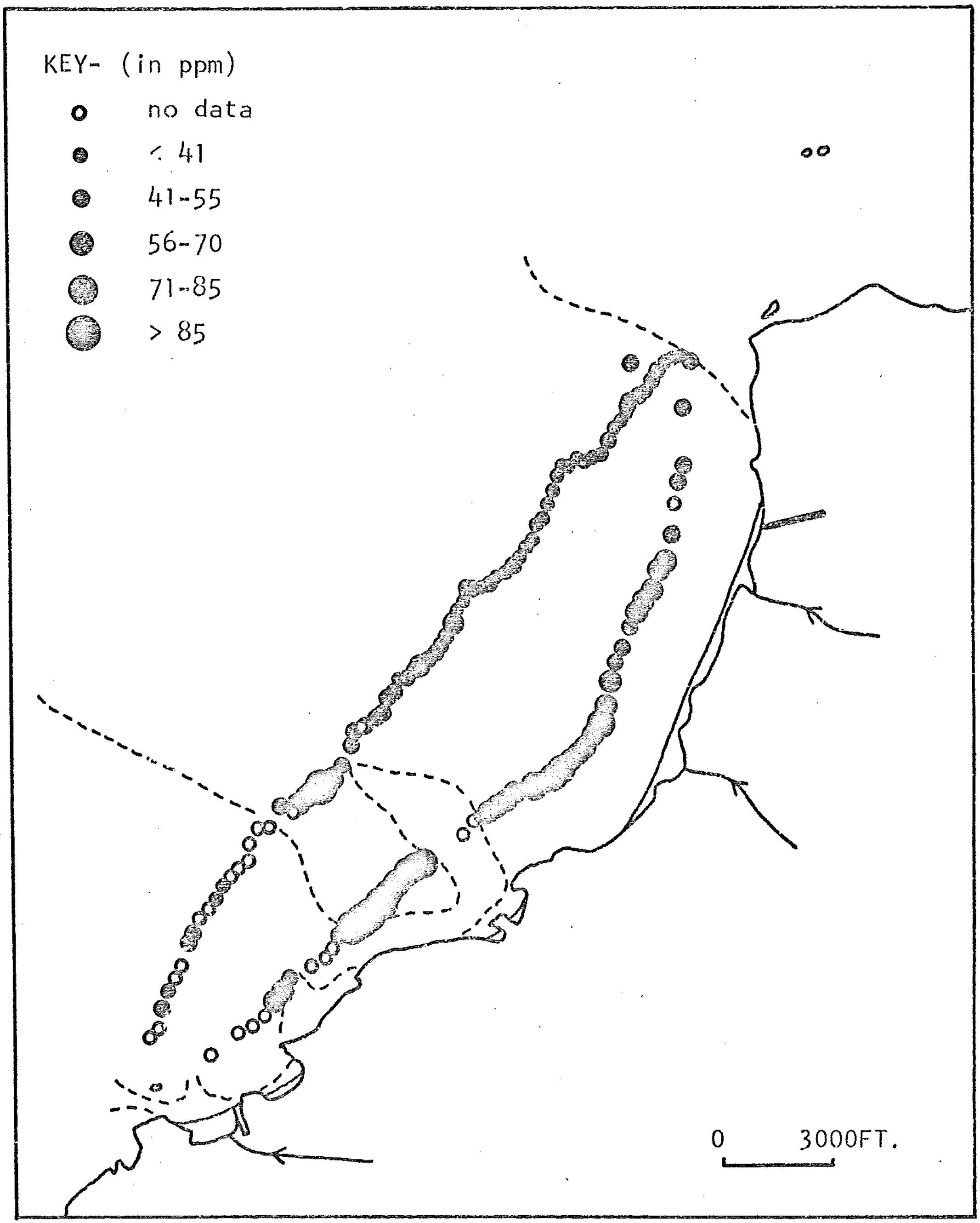


Fig. 5.4A. Distribution of minus-8-mesh copper.

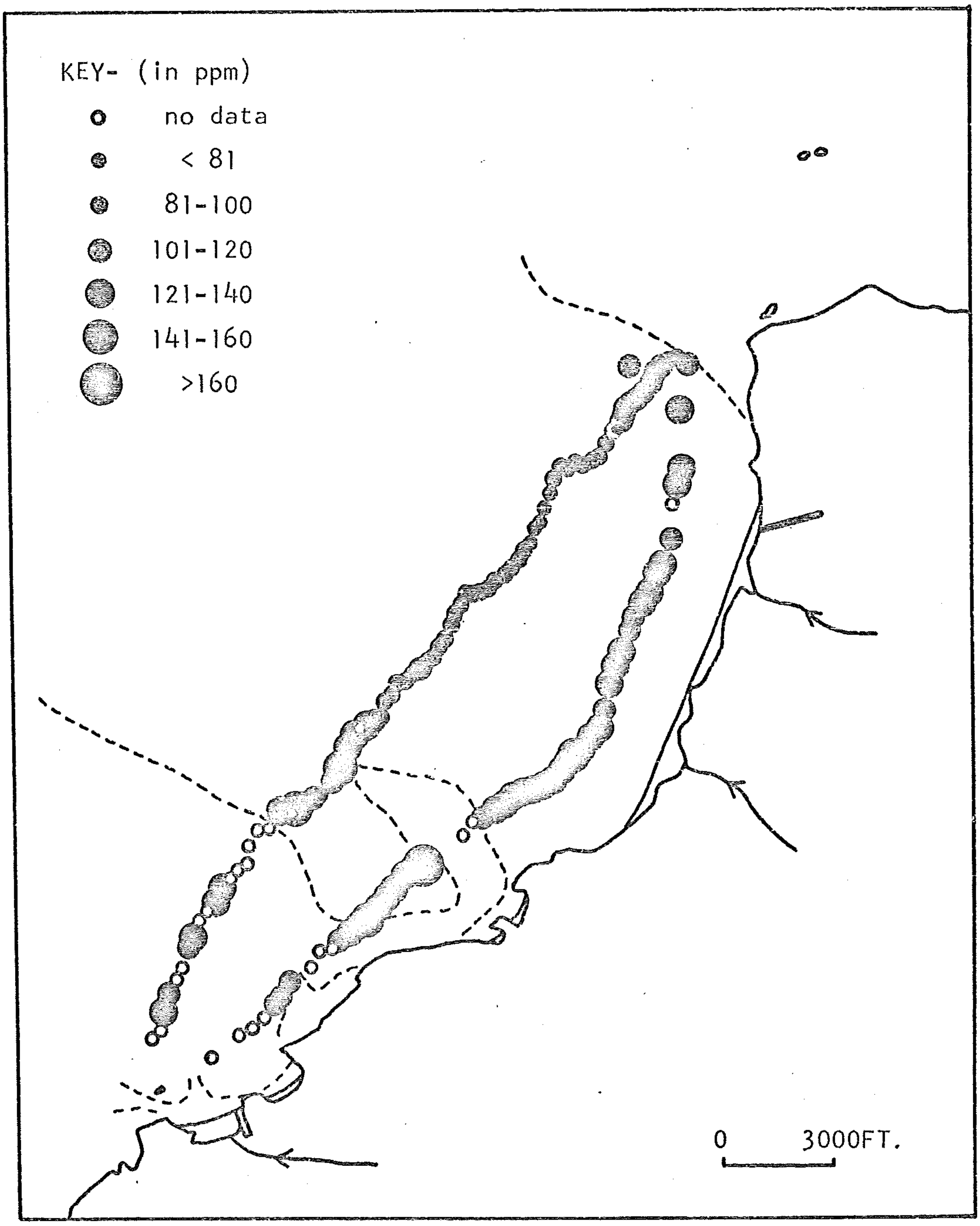


Fig. 5.4B. Distribution of minus-8-mesh zinc.

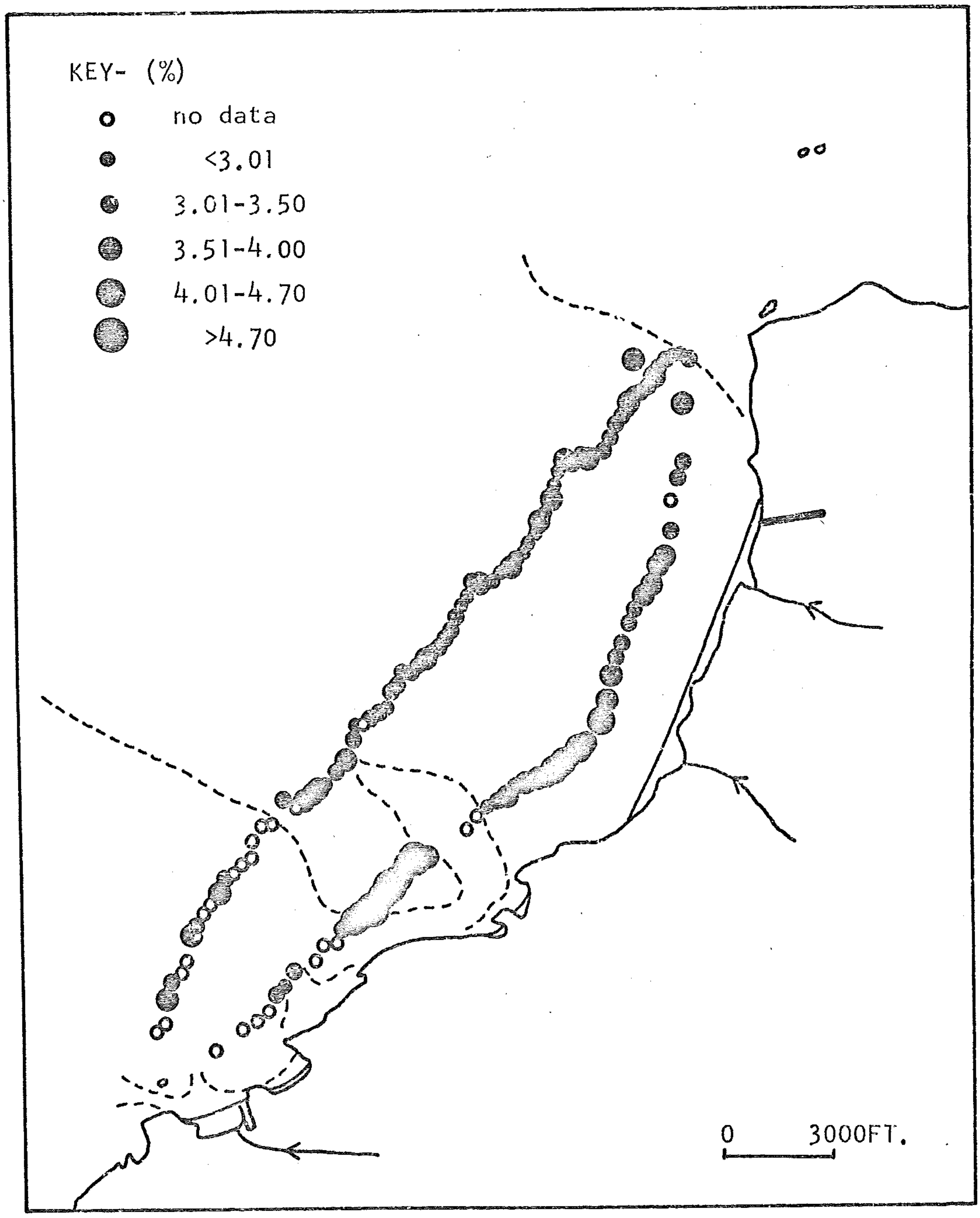


Fig. 5.4C. Distribution of minus-8-mesh iron.

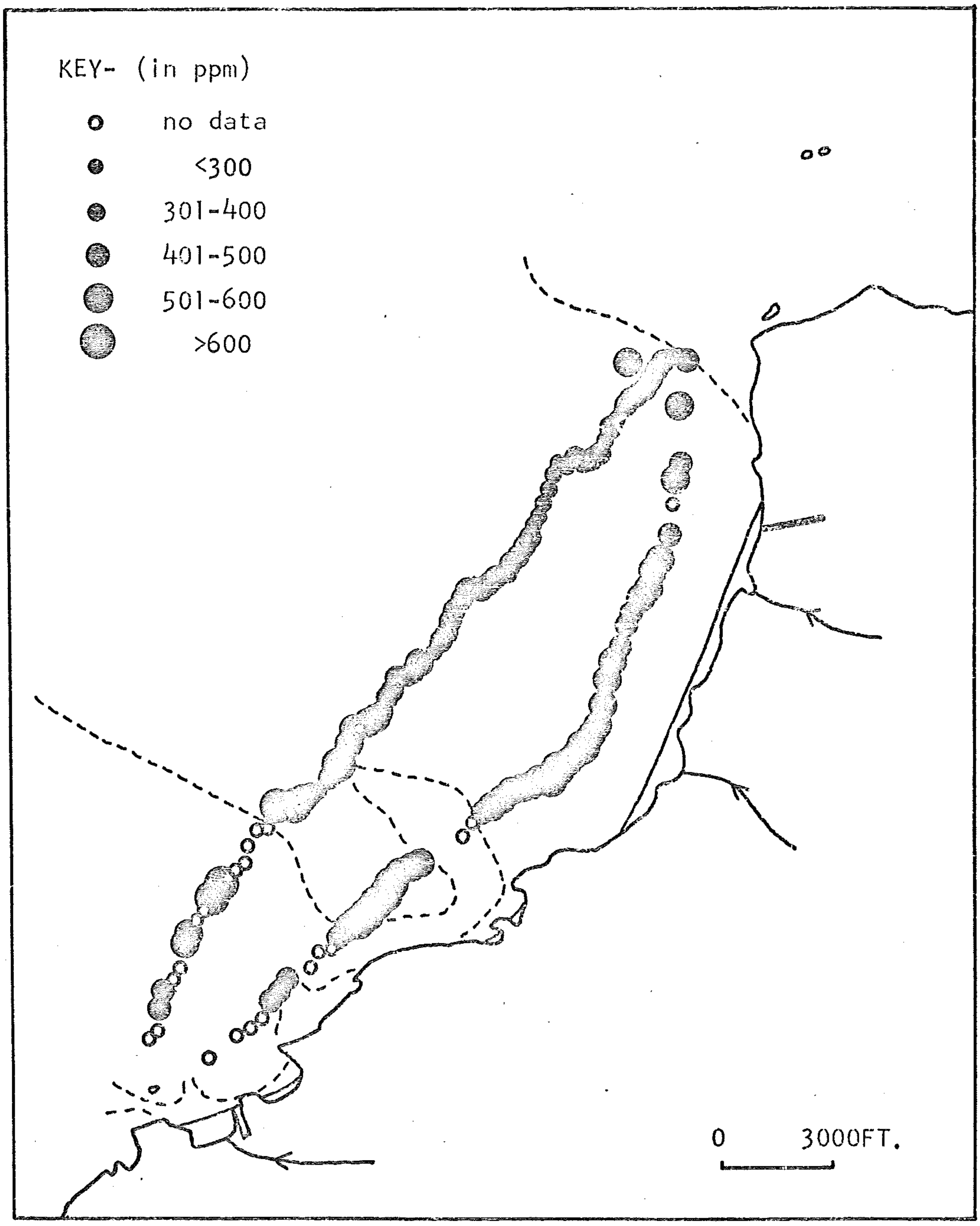


Fig. 5.4D. Distribution of minus-8-mesh manganese.

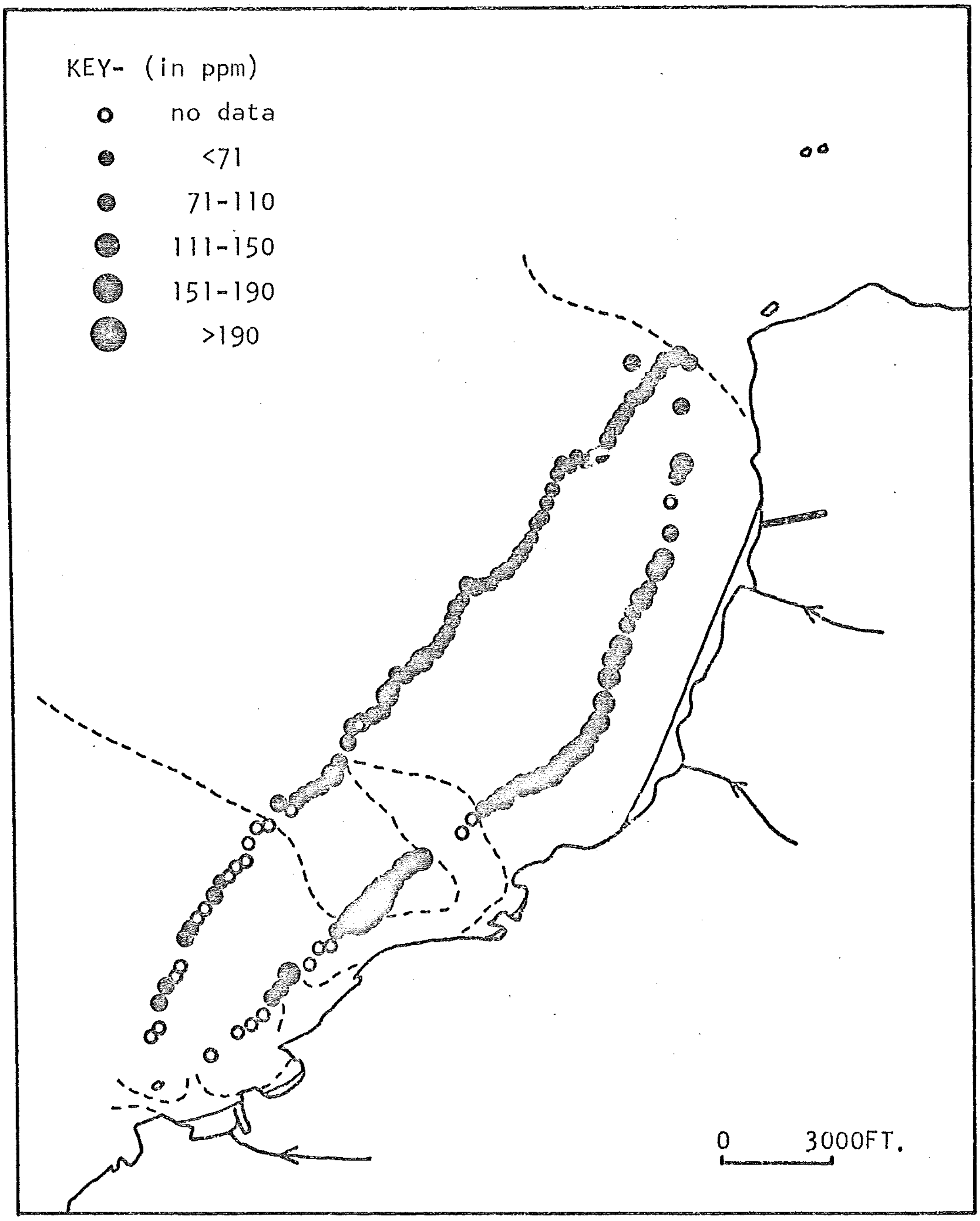


Fig. 5.4E. Distribution of minus-8-mesh arsenic.

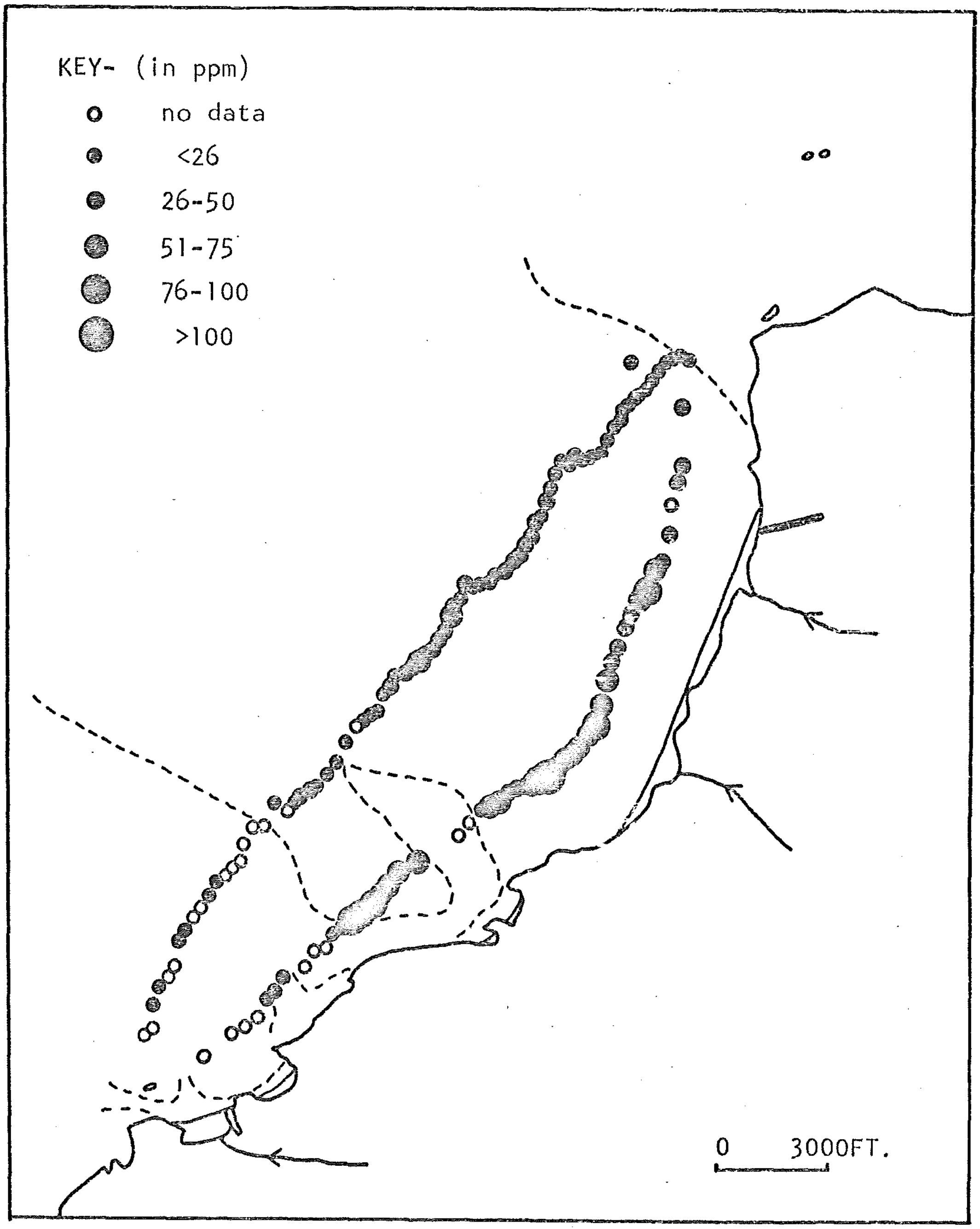


Fig. 5.4F. Distribution of minus-8-mesh tungsten.

5.3.2. Specific features in the distribution of copper, zinc, iron, manganese, arsenic and tungsten

(1) Towards the south-western margin of the main sediment body, copper, iron, arsenic and tungsten show decreases in concentration where the sediment cover is thin and patchy.

(2) Where the sediment cover is thin and towards areas with submarine bedrock outcrop the zinc concentration increases.

(3) Along the south-western end of the traverses, the manganese concentration tends to decrease towards the margin of the sediment body in the traverse nearest to shore. In the traverse further offshore, the concentration increases towards the sediment margin.

(4) Table 5.4. summarises the mean size and sorting coefficients of the total sediment with size fractions containing element concentrations above the thresholds. The total number of samples with element concentrations above the respective threshold value is 14.

Table 5.4. Mean size and sorting coefficient ranges in sediments with other element concentrations above the respective threshold value according to sediment type.

Element		Copper	Zinc	Iron	Manganese	Arsenic	Tungsten
Mean Size Range (phi)	F. Sand	2.32-2.58	2.61	2.47-2.58	2.54-2.58	2.47-2.58	2.54
	M. Sand		1.73				
	C. Sand				-1.00-1.00		
	Gravel*				-1.00		
Sorting Coeff. Range	F. Sand	0.48-0.65	0.53	0.49-0.55	0.49-0.55	0.49-0.55	0.55-0.59
	M. Sand		0.48				
	C. Sand				1.00-2.00		
	Gravel*				2.00-4.00		

* - Based on visual estimate.

5.4.0. Distribution of tin in cores

In order to permit comparison with tin distribution in the surficial sediment all core splits from the two cores (045 and 046) have been treated in the same manner as the surface samples. The mean size, sorting coefficient and shell content of the core splits are shown in the Appendix and Fig. 5.5A & B. show the distribution of tin in the two cores.

During sediment removal from the core barrel, it was noticed that the surficial sediment down to 10 cm. is liable to mixing due to washing as a result of leakages during corer retrieval. This could be prevented by making sure the sides of the core barrel are properly sealed. In core 046, the shell gravel encountered in the basal horizon has been taken as an indicator that the corer reached bedrock.

5.4.1. Core 045

The following features are apparent:-

(1) The surficial sediments down to 95 cm. are enriched in tin in all size fractions. Most significant is the enrichment in the under 90 micron fraction which is about 15 times greater than that found in the basal horizon. Tin enrichment in the coarser fractions decreases with increasing grain size.

(2) The surficial sediment down to 10 cm. is relatively enriched in tin in all size fractions compared to sediment from 10-60 cm.

(3) There is another relative increase in tin enrichment in sediment from 60-75 cm.

(4) The decrease in tin content in sediment from 10-60 cm. is

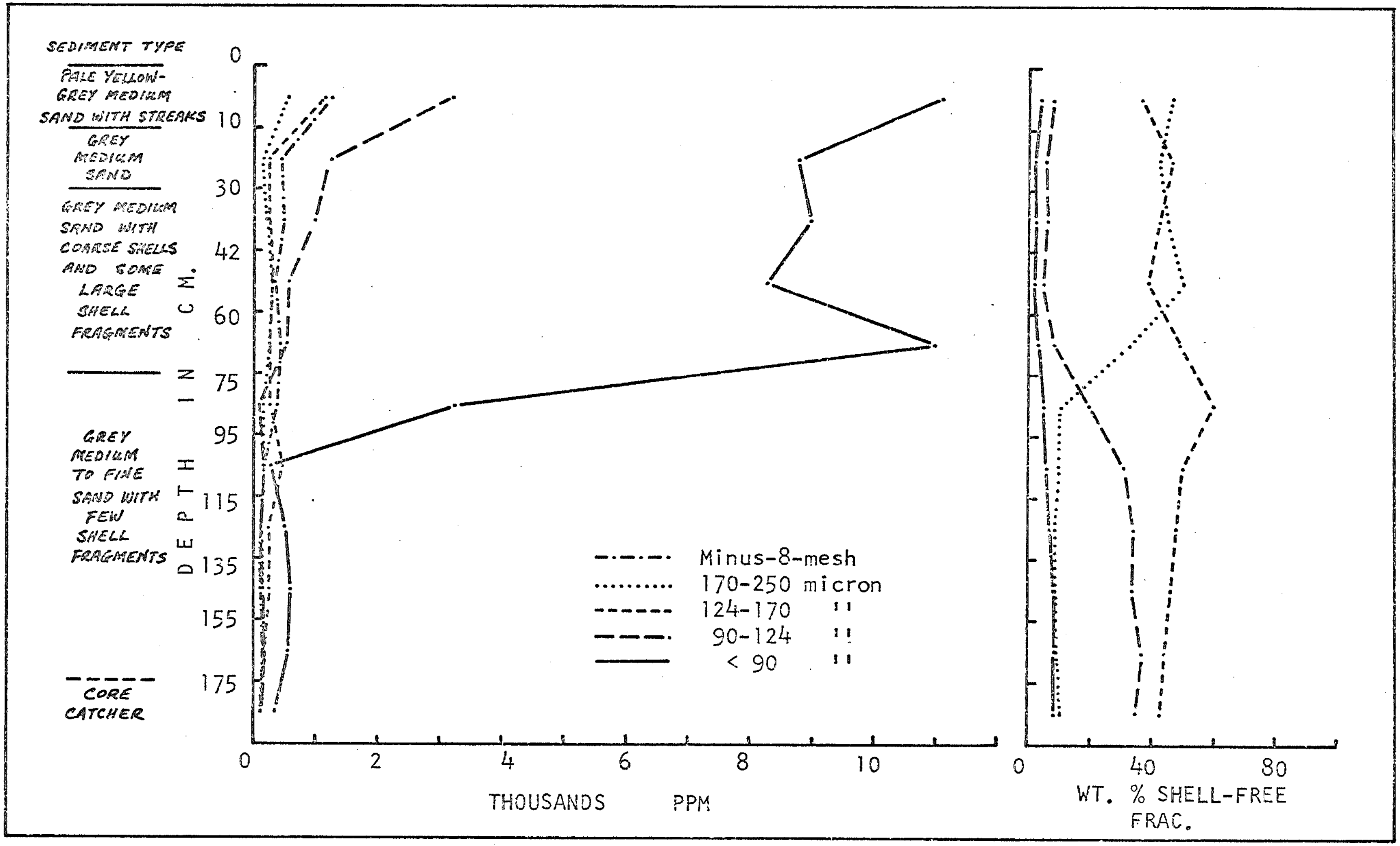


Fig. 5.5A. Sediment type and tin distribution in core 045.

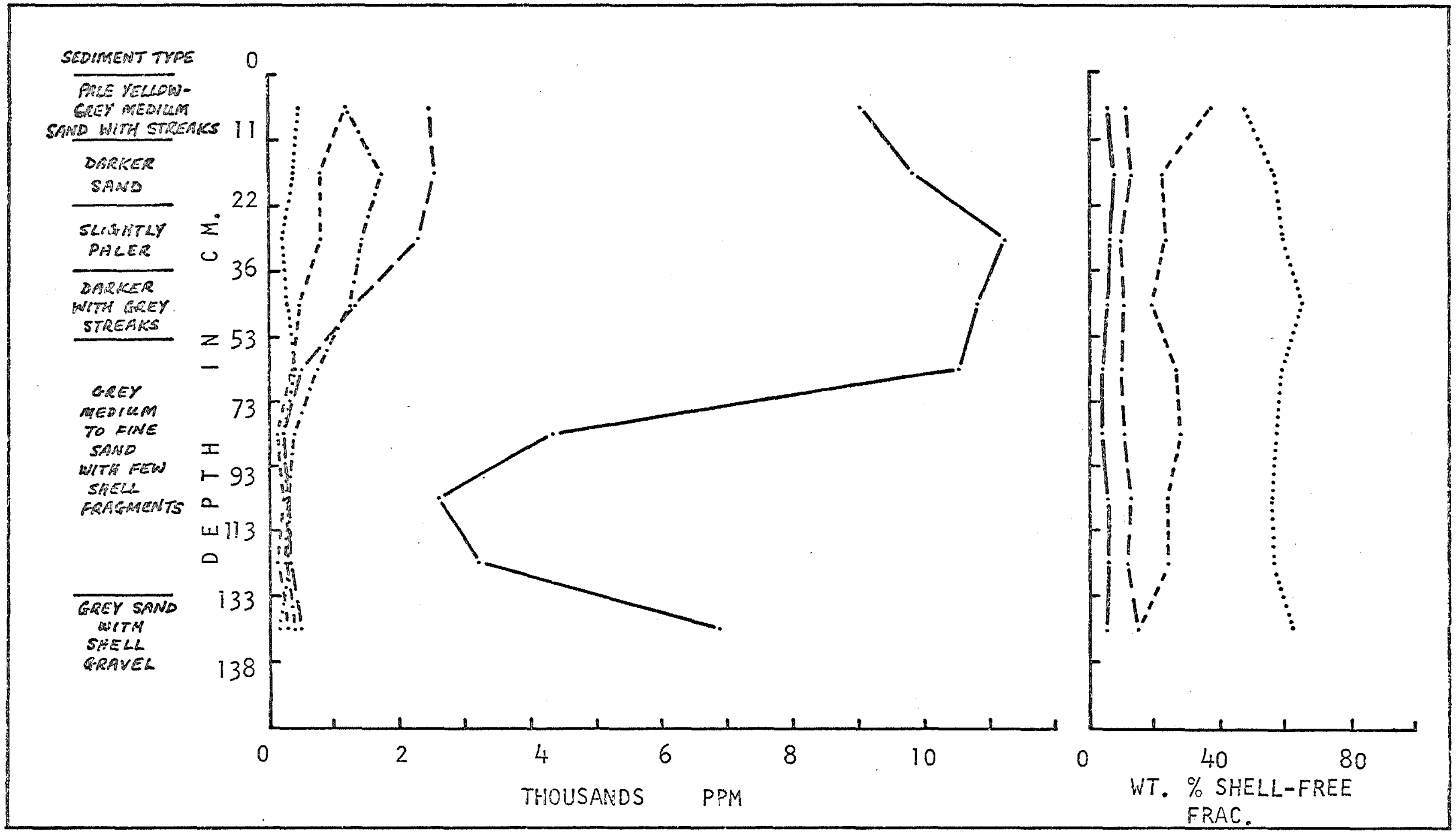


Fig. 5.5B. Sediment type and tin distribution in core 046.

accompanied by an increase in mean size and better sorting.

(5) The relatively tin poor basal sediment below 95 cm. is less well-sorted, has a finer mean size and has a lower shell content than the surficial sediment.

5.4.2. Core 046

The following features are apparent:-

(1) The surficial sediment down to 93 cm. is enriched in tin in all size fractions but particularly in the finest under 90 micron fraction, and the enrichment is in the same order as in core 045.

(2) Within the sediment between 0-93 cm., there is a relative decrease in tin enrichment in the under 90 micron fraction at 0-11 cm.

(3) The basal sediment at 133-138 cm. shows a relative increase in tin enrichment compared to the sediment between 73-133 cm., although the enrichment is not in the same order as for the surficial sediment.

(4) The decrease in tin content at 73-113 cm. is accompanied by an increase in mean size and a marginally higher shell content.

(5) The tin enriched basal sediment at 133-138 cm. is less well-sorted and has a finer mean size than the sediment immediately above between 93-133 cm.

5.5.0. Distribution of other elements in cores

Only the minus-8-mesh fraction of the core split has been analysed for the five elements - copper, zinc, iron, manganese and arsenic. The distributions are shown in Fig. 5.6A & B. Tungsten has not been determined because of the low concentration of tungsten found in surficial sediment adjacent to the core stations.

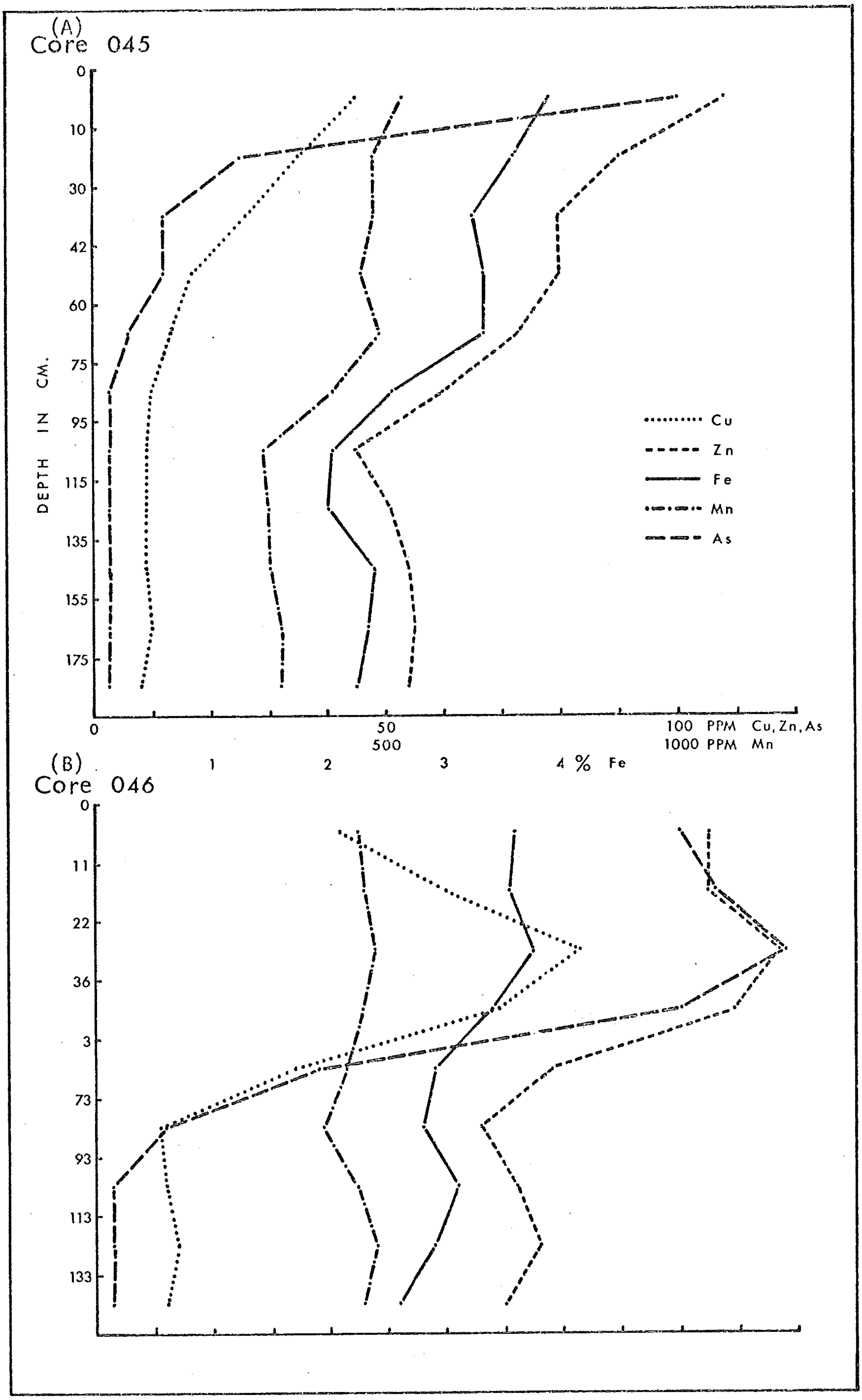


Fig. 5.6A & B. Distribution of other elements in cores.

5.5.1. Core 045

All the elements have been found to be enriched in the surficial sediment from 0-10 cm. which is very similar to the minus-8-mesh tin distribution pattern. Out of these elements, arsenic shows a marked decrease at 10-30 cm. from 100 ppm to 25 ppm arsenic and then falls off to a background level of under 5 ppm arsenic. Copper shows the most regular decrease from 45 ppm at 10-30 cm. down to a background level of 10 ppm copper below 75 cm. Zinc, iron and manganese on the other hand show more irregular decrease with increasing depth, lows in zinc, iron and manganese occur at 95-115 cm. which coincides with that for tin and in addition, zinc and iron are marginally enriched at 135-155 cm. The better sorted and coarser sized sands are in general found to be enriched in these elements compared to the poorer sorted and finer basal sediment from deeper than 95 cm.

5.5.2. Core 046

With the exception of manganese, all elements have been found to be enriched in surficial sediment from 0-73 cm. and the variation within this depth range is also very similar to the minus-8-mesh tin distribution pattern. All the elements reach peak concentration at 22-36 cm. which coincides with the under 90 micron tin peak. Arsenic, as in core 045, shows the most marked decrease from this depth, from 100 ppm to 36 ppm arsenic at 53-73 cm., before falling off to under 5 ppm arsenic below 93 cm. Copper shows the next most marked decrease from 22-36 cm. towards the basal horizon and is very similar to the arsenic distribution except that the background level in the basal sediment is marginally higher than in core 045. Zinc and iron again show very similar variations in their distribution. Manganese, however, shows very little variation, the core splits vary from 430-480 ppm manganese only. The increase in tin at 133-138 cm. is not accompanied by any increases in other elements, zinc, iron and manganese in fact show minor decreases at this depth. The better sorted sediments are again found to be enriched in these elements compared to the poorer sorted and slightly finer sediment from deeper than 73 cm.

5.6.0. General discussion

The distribution of tin, copper, iron, tungsten and arsenic, and less clearly zinc and manganese in surficial sediment have been found to decrease away from the shore with increasing water depth, and away from the river outlets. This can be taken to indicate the importance of distance from source in controlling elemental distribution patterns.

Since the sea bed deepens with increasing distance from land, the velocity of bottom currents driven under the influence of wind waves and the tide must generally decrease away from the coast. Although the bed shear stress due to wind waves and the tide cannot be accurately expressed, the magnitude of the stress is directly proportional to the velocity near the bottom (Allen 1970). Sediment carried by rivers enter the sea at points on the coast, and is distributed parallel to shore by longshore and other currents. It can be seen that a particle of cohesionless sediment (coarse silt, sand and gravel) cannot travel into a depth greater than that at which the threshold stress for that size of grain equals the maximum instantaneous stress exerted on the bottom due to the simultaneous action of the various currents. Allen has pointed out that at a defined wave spectrum and tidal range, there exists on the shelf an energy 'fence' which limits, in terms of distance from land and water depth, the outward travel of particles of each size.

Grains can be re-eroded only if they lie landward of the 'fence', where the maximum instantaneous stress exceeds the threshold required to move them. However, because of seasonal variation of conditions and sea level changes as well as tidal changes, the 'fence' for a given particle can change somewhat in position. By applying these considerations to land derived mineral particles of a broad range of sizes within the general cohesionless class, the metal bearing phases in the surficial sediment must decrease in grain size as well as in content from the shore outward to deeper water. If however, there are submarine sources of metal bearing minerals, this pattern is likely to be distorted.

In the St. Agnes Head/Portreath area, the High Water Mark is above the cliff base along much of the coast except at the river mouths, where in the case of Porthowan and Portreath there are also small stretches of blown sand fringing the sea. At high tide or near high tide, with a prevailing wind from a westerly direction, waves strike the cliff orthogonally or at steep angles induce turbulence and cause sediment entrainment which is transported offshore along with the reflected ground swell rebounding off the cliff. This type of situation occurs quite frequently throughout the year and was experienced during the sampling period when there were onshore westerly winds with strengths up to over 20 knots. During periods with offshore wind which is far less common because of the climatic regime, the wave height of onshore waves are suppressed and will result in a reversal in condition leading to onshore sediment transport (King 1971).

The tin concentrations in the coarsest size fractions of the surficial sediment are generally insignificant compared to the finest fractions, although the weight percentage of tin in the finest fractions are small compared to the whole sample. The higher concentration in the coarsest size fraction from the traverse nearest to shore may be taken as an indication of an onshore source for tin. However, since the area along the present day Low Water Mark shows consistently high tin concentrations in the 170-250 micron size fraction away from the tin zone of the St. Agnes Beacon Granite, there is likely to be reworking of tin by selective sorting and concentration processes related to the high energy level of the surf zone environment.

All the traverses invariably show some variations in metal distribution. This has been attributed mainly to (a) the influence of alluvial sediments, (b) bedrock topography and (c) selective sorting and concentration processes.

The enrichment in tin in all size fractions at the mouth of the Porthowan and Chapel Porth rivers suggest that this tin has originally been derived from the land, transported by the streams, and deposited on the sea bed. Observations made on the beach at low tide revealed beach cusps formed by the swash and backwash of waves (King 1972), which in the St. Agnes Head/Portreath area may be up to 40 metres in width and which are separated by depressions containing finer sand with lower shell content and higher tin and other elements. These depressions invariably occur off the coves and the cusps off headlands; and thus their formation may be related to bedrock topography beneath the sediment cover influencing wave activity. Therefore the cusps, which exert control over the composition of sediment through selective sorting and concentration, may be responsible for variations in tin distribution along the foreshore zone.

The anomalous area in the southern part of the main sediment body cannot be accounted for without recourse to selective sorting and concentration processes, assuming that the submarine rocks are unmineralised. The latter is suggested by the absence of tin lodes on the adjacent land, the mineral veins encountered in the sewer tunnel near Portreath (Fig. 3.3A.) show that the rocks on the hinterland are outside the tin zone (Fig. 5.7.). The highest tin values occur at a water depth of between 40-60 ft. and the coastline here swings from a westerly direction to a more northerly direction. The main sediment body in the vicinity becomes discontinuous and there is a sediment tongue branching out from it which is separated from the main sediment body by shallower areas with bedrock outcrop. This area therefore may be relatively protected and may contain residual sediments enriched in tin, copper, iron, arsenic and tungsten which are likely to have been deposited after transport during past mining operations via the Porthowan and Portreath rivers.

In general the tin results in the surficial sediment show close agreement with patterns for the other elements with the exception of high zinc and manganese in areas where the sediment is thin and patchy along the traverse furthest offshore. Hosking (1964) found that the zinc content of killas from barren areas outside the metamorphic aureole of the Carn Menellis Granite is between 120-800 ppm zinc, with a mean of 247 ppm zinc. Therefore, the high zinc concentrations in these sediments may be due to their thinness leading to an abundance of locally derived killas fragments from bedrock. If so the zinc distribution may reflect the sediment thickness in areas unaffected by mine tailings. The high manganese concentrations may also be accounted for in a similar manner. High manganese samples in the traverse furthest from the

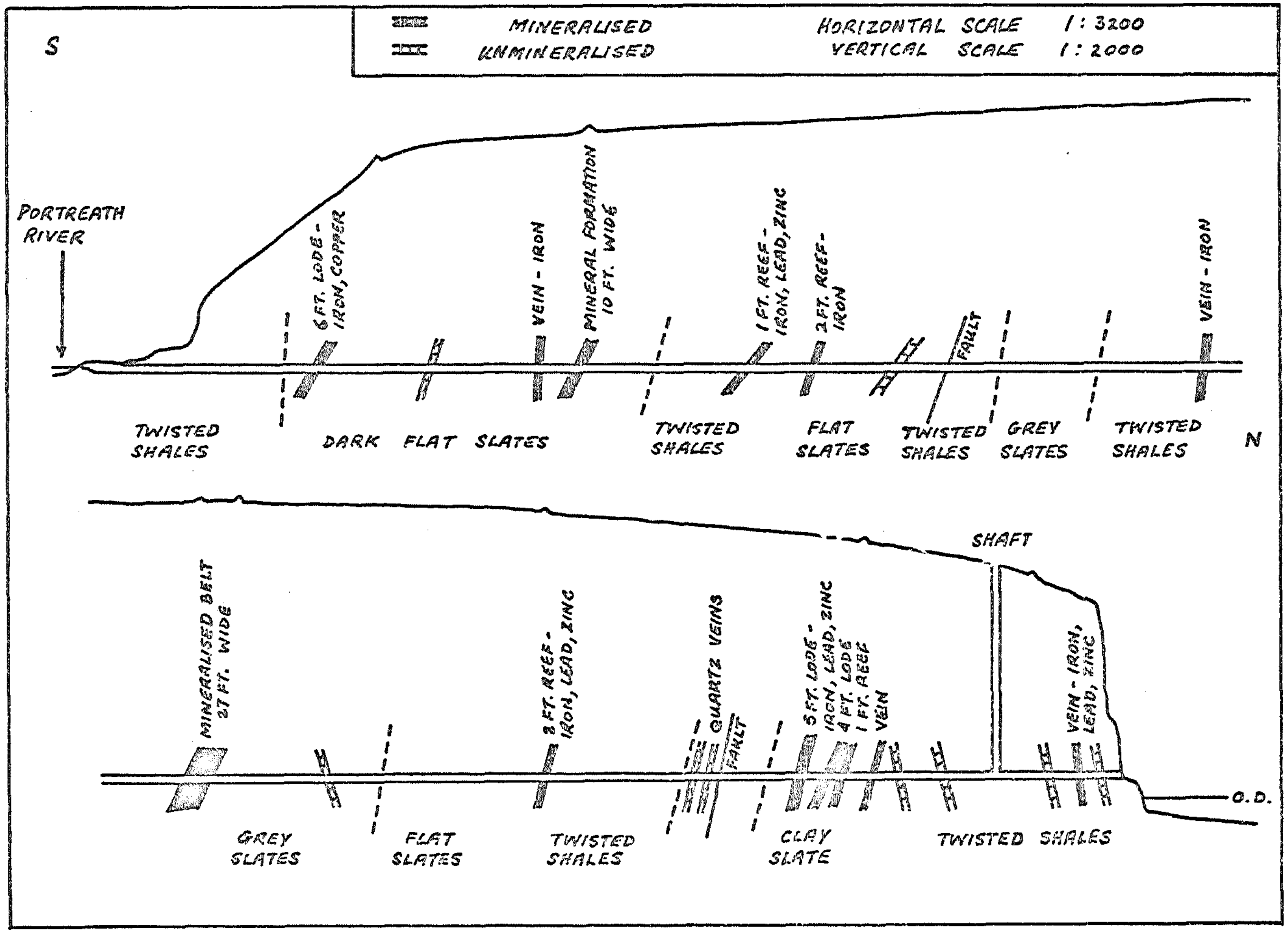


Fig. 5.7. Geology of the Redruth Joint Sewerage Tunnel. Surveyed by Kitto (1930).

shore also contain numerous fragments of killas.

Copper, zinc, iron, arsenic and tungsten are all present as lode minerals in the source rock, and manganese, because of its similar ionic radius to iron, subsitutes into crystal lattices of iron minerals quite freely. Out of these elements, copper, zinc and arsenic are present mainly as sulphide minerals within the lodes. High concentration of these elements are found to accompany that of tin in the surficial sediment, and since these elements are lower in the basal sediment, those in the surface sediments are likely to be largely land derived. It is likely that the minerals containing these elements have been introduced into the sea bed recently through mining operations, and have not been subjected to the long processes of 'normal' weathering and erosion. Their low values in the basal sediment, which probably pre-dated the mining era, most probably reflects only limited material supply of these elements to the sea floor. If the tin content in the basal horizon of core 045 does represent sediment of pre-mining activity, then mining contamination has enriched the upper sediment by about 15 times in tin. The tin enrichment in the basal sediment of core 046 may be either eluvial or alluvial in origin.

The very well-sorted sand half a mile off St. Agnes Head has been found to contain a greater abundance of tin in the fractions coarser than 90 microns compared to adjacent samples. This pattern is very similar to the sediment from near the present day Low Water Mark and may be indicative of sediment found in a high energy environment. Accompanying this tin pattern, the minus-8-mesh content of copper, zinc, iron, arsenic and tungsten are also relatively enriched which requires explanation if the sediments are those of a fossil beach which pre-dated mining activity. The sediment (examined in section 4.8.4.) is very well-sorted although the mean size is about 1 phi unit less than the present day beach sediment found in the surf zone. The relatively high concentration of coarse tin and other elements suggest that the sediment has formed during or after the mining era, and is therefore unlikely to belong to a fossil beach. Beacuse the sediment occurs off an exposed headland, reworking by bottom currents may have been responsible for the selective sorting and concentration of metal bearing minerals due to a local increase in energy level.

CHAPTER 6. FOLLOW-UP INVESTIGATIONS INCLUDING THOSE ON PAST AND PRESENT MINING CONTAMINATION

6.1.0. Introduction

In order to evaluate the effect of mining contamination from former times in influencing the composition of sediment in the St. Agnes Head/Portreath area, further investigations outside the area were carried out together with a study on the present day beach sediment between St. Agnes Head and Chapel Porth. A stream sediment reconnaissance survey has been carried out to determine the tin supply in streams draining the North Cornish coast between Cligga Head and Cape Cornwall, and two offshore areas St. Ives Bay and Pendeen, both affected at the present day by the discharge of mine tailings have been investigated in order to elucidate past conditions in the St. Agnes Head/Portreath area. In St. Ives Bay, the role of the Red River in transporting tailings has been investigated, together with the beach sediments at the mouth of the River and the estuarine sediment in the Hayle Estuary, which forms a sediment trap for the land derived detritus. In Pendeen, where the conditions are not unlike those of the St. Agnes Head/Portreath area, namely the disposition of the coastline and the geology, the beach sediment in Portheras Cove has been investigated in addition to the marine sediment.

6.2.0. Distribution of tin in beach sediment between St. Agnes Head and Chapel Porth

Fifteen surficial sediment samples were collected from the beach zone and except in two cases, all the samples were taken as close to the High Water Mark as possible for two resons:-

(1) Likely area for heavy mineral concentration.

(2) Ease of sample location.

The samples were treated in the same manner as the offshore grab samples. However, because of the coarse grain size and the well-sorted nature of the sediment, the size fractions finer than 170 microns have been analysed only in a few samples. Fig. 6.1A-F. shows the results of the sedimentological and tin analysis, the 250-2057 micron (approximately minus-8-mesh to plus-60-mesh) fraction which constitutes the bulk of the samples has also been analysed in addition to the under 250 micron size fractions.

The relatively coarse grain size and the well-sorted nature of the sediment with sorting coefficients between 0.29-0.39, excluding sediment from within Chapel Porth which is less well-sorted, reflects the high energy level of the beach environment. However, variations in mean size as well as sorting in the surficial sediment exist, as in the case within Chapel Porth (Fig. 6.1A & B.) due to the influence of river-borne material and the relatively shethered position of the cove. The very well-sorted sample on the Chapel Porth River which is also relatively fine and appreciably enriched in tin has been attributed to selective sorting and concentration through the action of running water. Off the Towanwrath Lode, probably due to the bedrock topography, sea water has collected in pools at the foot of the cliff at low tide and has eventually breached the beach sediment and run into the sea in the form of a stream. The sediment sample taken along the course of this stream is fine, well-sorted and enriched in tin.

In general, the best sorted sediments are found to be the richest in tin and to have relatively high shell contents. From this, it can be concluded that the tin content is more likely to be due to selective sorting than other factors. The minus-8-mesh

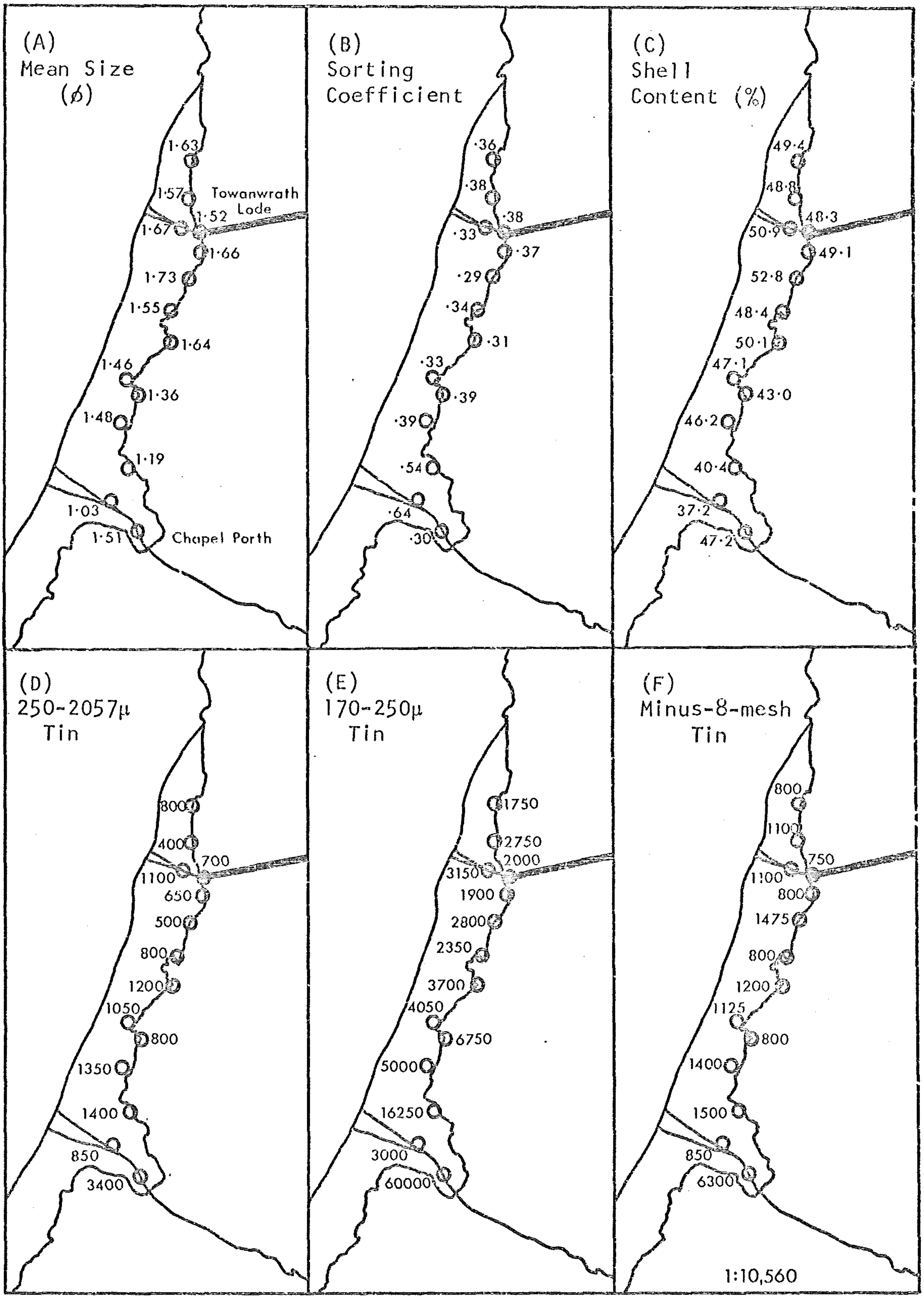


Fig. 6.1A-F. Distribution of mean size, sorting coefficient, shell content and tin in surficial beach sediment between St. Agnes Head and Chapel Porth. (tin results in ppm)

tin content compares well with the 250-2057 micron tin content, but the fine fractions are the most enriched in tin.

6.3.0. Distribution of tin in stream sediments

In order to evaluate the contribution of tin tailings to marine sediments, a stream sediment reconnaissance survey has been carried out. The minus-80-mesh fraction of all samples collected was analysed after being hand-ground to minimise sampling and analytical error. In addition, the Red River has been investigated in detail using closely spaced sampling intervals in the collection of both stream bed sediment and suspended sediment.

6.3.1. Distribution of tin in the minus-80-mesh stream sediment between Cligga Head and Cape Cornwall

Figure 6.2. shows the distribution of tin in the minus-80-mesh stream sediment in rivers and streams draining into the North Cornish coast between Cligga Head and Cape Cornwall. The values obtained range from 650-85,000 ppm tin, with over 40 percent of the samples containing over 10,000 ppm and over 20 percent of the samples greater than 20,000 ppm tin. The following patterns of tin distribution are noted:-

(1) Generally there is a good correlation of tin distribution with known tin mineralisation areas, which occur at or near the margins of the granites.

(2) In addition to (1), there is also a good correlation with the intensity of mining activity, the rich areas show the highest tin concentrations.

(3) In some areas where tin mineralisation is known but is not the main ore element, as in Porthowan, the high concentration of tin may be related to contamination from former mills and smelting houses using ores from other

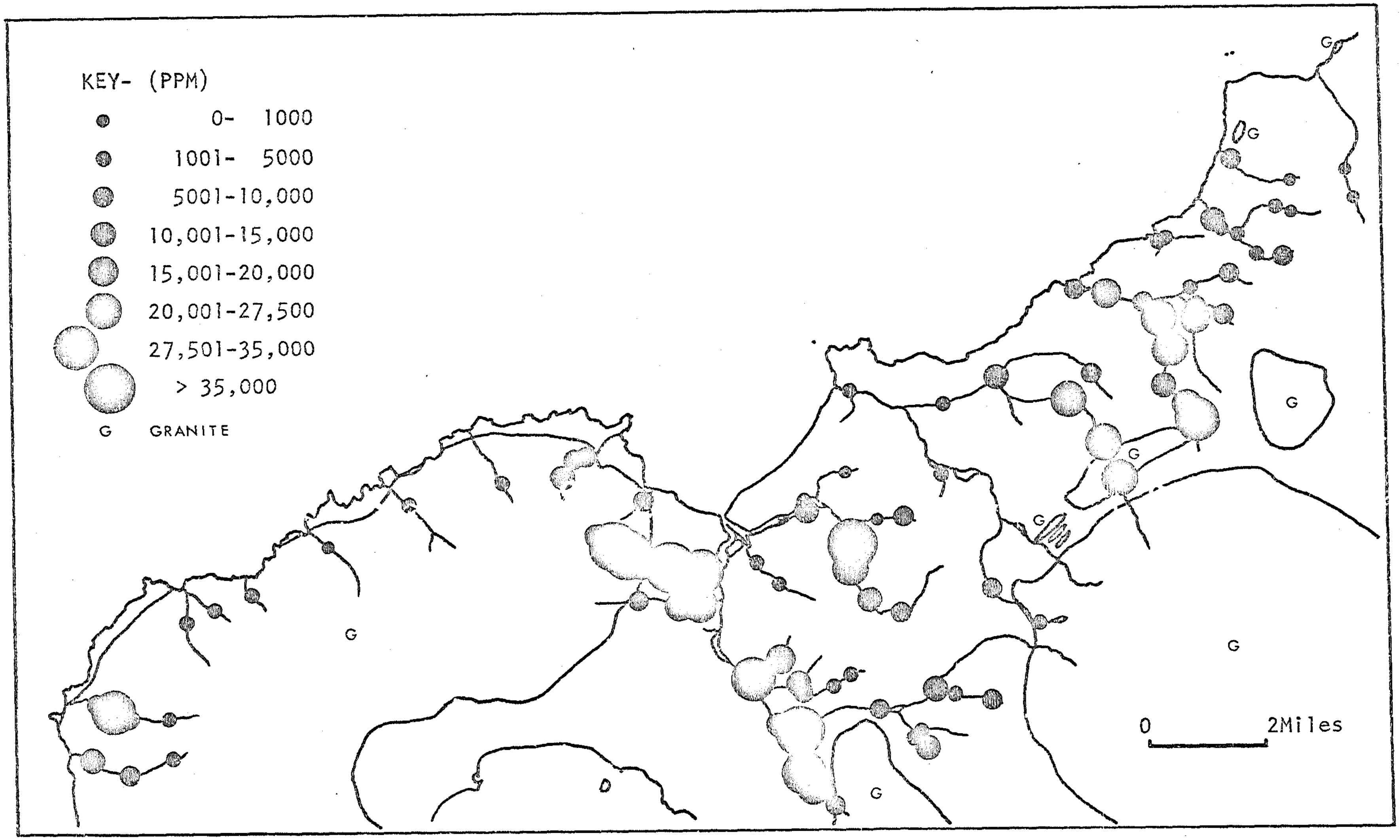


Fig. 6.2. Distribution of tin in the minus-80-mesh stream sediment in streams draining into the North Cornish coast between Cligga Head and Cape Cornwall.

areas.

(4) There are local variations in tin concentration along the rivers and streams which appear to be the result of selective concentration processes as has been noted by Dunlop (1973), who suggested them to be due to variations in the gradient of the river bed.

(5) The Red River shows a general decrease in tin concentration towards the sea and away from the mineralised area.

(6) In extremely poorly-sorted stream sediment, ranging from gravel down to clay size, the tin concentration is generally lower than in better sorted stream sediment. The highest tin concentrations are in fine well-sorted sands entrapped in the spaces between gravel particles.

Conditions found in the Portreath River and the Hayle River in the past must have been similar to those in the Red River at present, when mines were operating in these areas and were making use of the rivers for tailing disposal. Both the Portreath and Hayle rivers, as well as the Marazion River, which drains south into Mount's Bay, have all been known under the same name- 'Red River' in the past. The wastage of tin slimes down these rivers must have been great as, according to Barton (1967), in 1873 there were no less than 41 separate concerns working the Red River proper for tin with another 14 on the Portreath River.

6.3.2. Follow-up investigation on the Red River

Thirteen stream bed sediment samples have been collected from the Red River in order that the tin distribution in the grain size fractions may be studied. In addition, five water samples were collected at five of the sampling sites in order that the suspended sediment undergoing active fluvial transportation could be studied.

The elements copper, zinc, iron, manganese, arsenic and tungsten have also been determined in the minus-8-mesh fraction in the stream bed sediment and in the suspended sediment in the water samples.

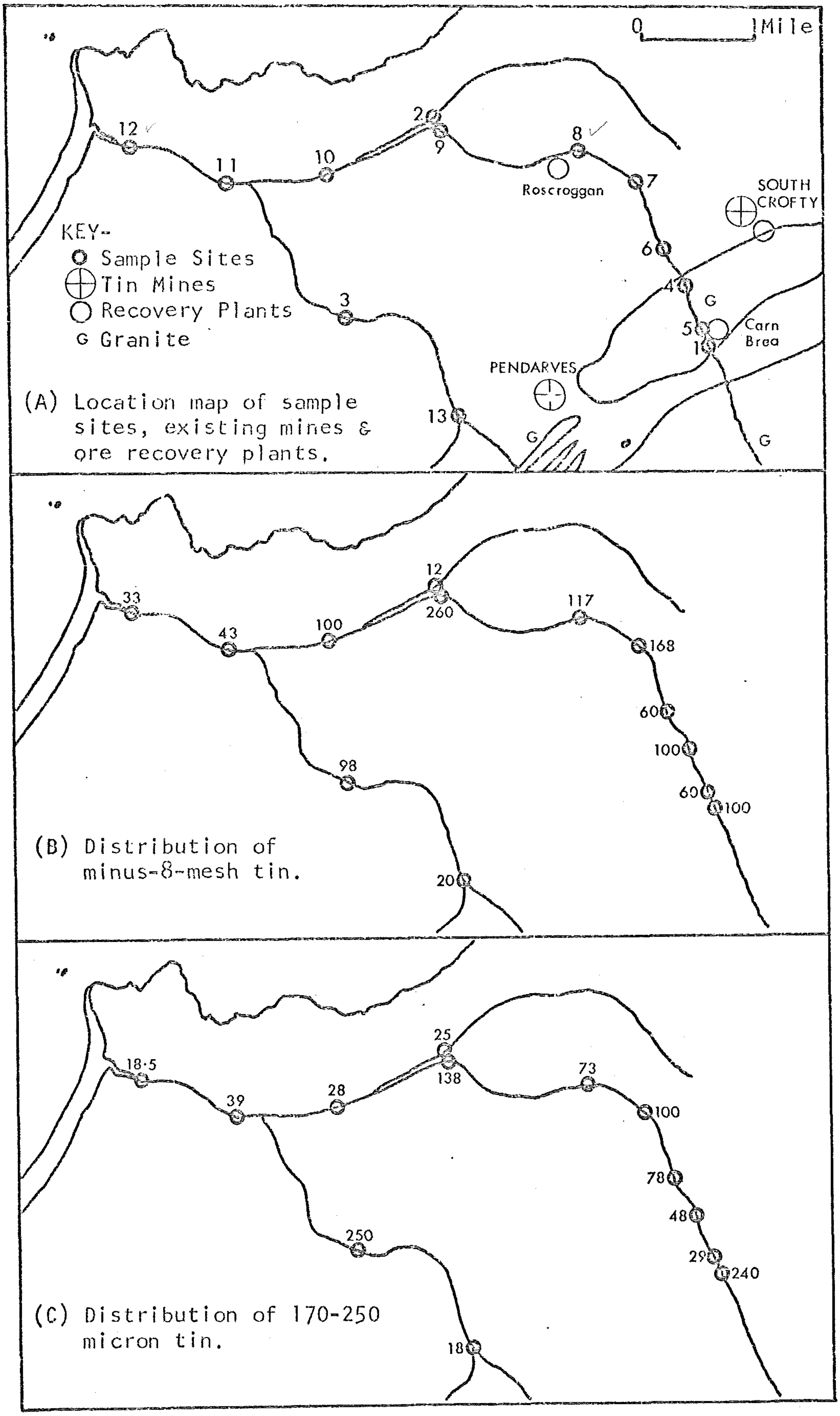
Figure 6.3A. shows the sampling sites, and the location of existing mines and ore recovery treatment plants. The river water of the Red River becomes turbid along the main channel downstream from the Carn Brea Tin Works. The tin distribution in the minus-8-mesh fraction and in the size fractions are shown in Fig. 6.3B-F. and the mean size and sorting of the stream bed sediment are shown in Table 6.1.

The tin distribution in the minus-8-mesh fraction along the main channel of the Red River shows a general decrease downstream from Roscroggan. However, from Roscroggan upstream, the tin distribution is highly irregular ranging from 6000-16,800 ppm tin. This irregular pattern may be related to the location of present

Table 6.1. Mean size and sorting in Red River sediment.

Sample No.	Mean Size	Sorting Coefficient	Observations
1	Gravel*	2.00 - 4.00*	
2	Gravel*	2.00 - 4.00*	
3	Gravel*	2.00 - 4.00*	
4	3.15	0.49	Water Turbid
5	3.03	0.73	"
6	2.53	0.60	"
7	2.64	0.84	"
8	3.09	0.69	"
9	2.51	0.70	"
10	3.57	0.52	"
11	2.56	0.64	"
12	2.56	0.56	"
13	Gravel*	2.00 - 4.00*	

* - Based on visual estimate.



(A) Location map of sample sites, existing mines & ore recovery plants.

(B) Distribution of minus-8-mesh tin.

(C) Distribution of 170-250 micron tin.

Fig. 6.3A-C. Red River stream sediment. (tin results in hundreds ppm in Fig. 6.3B-F)

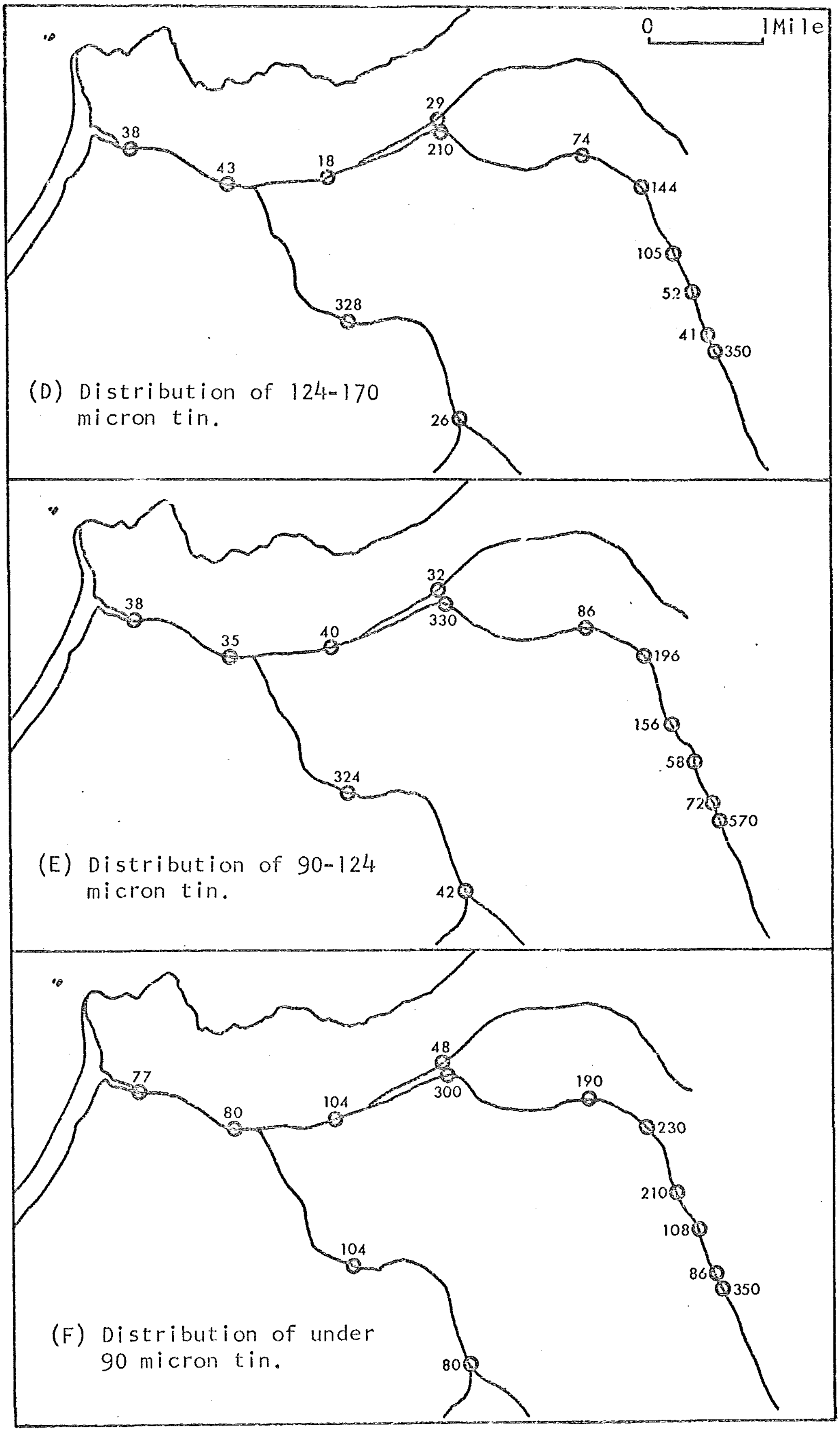


Fig. 6.3D-F. Red River stream sediment.

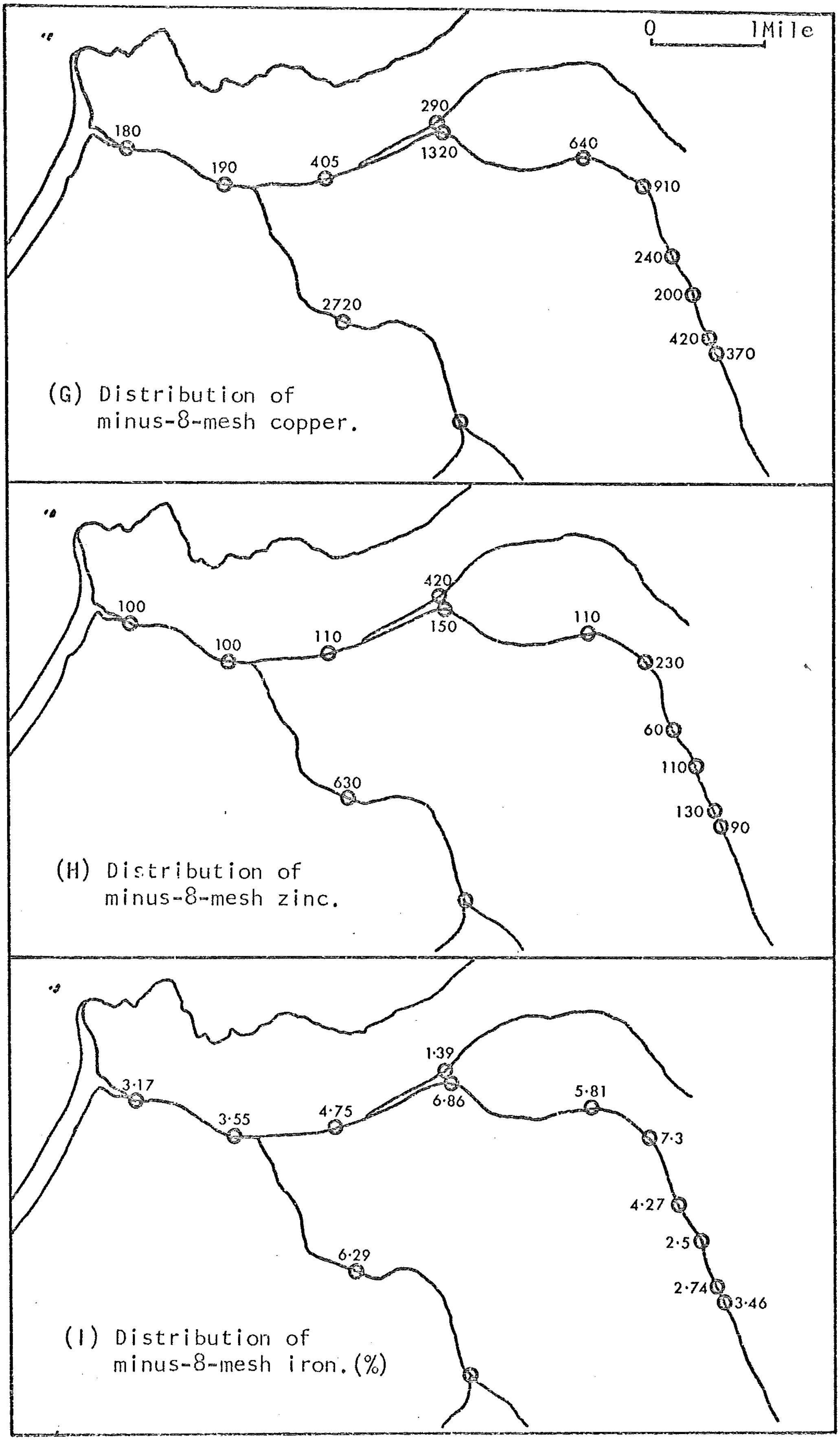
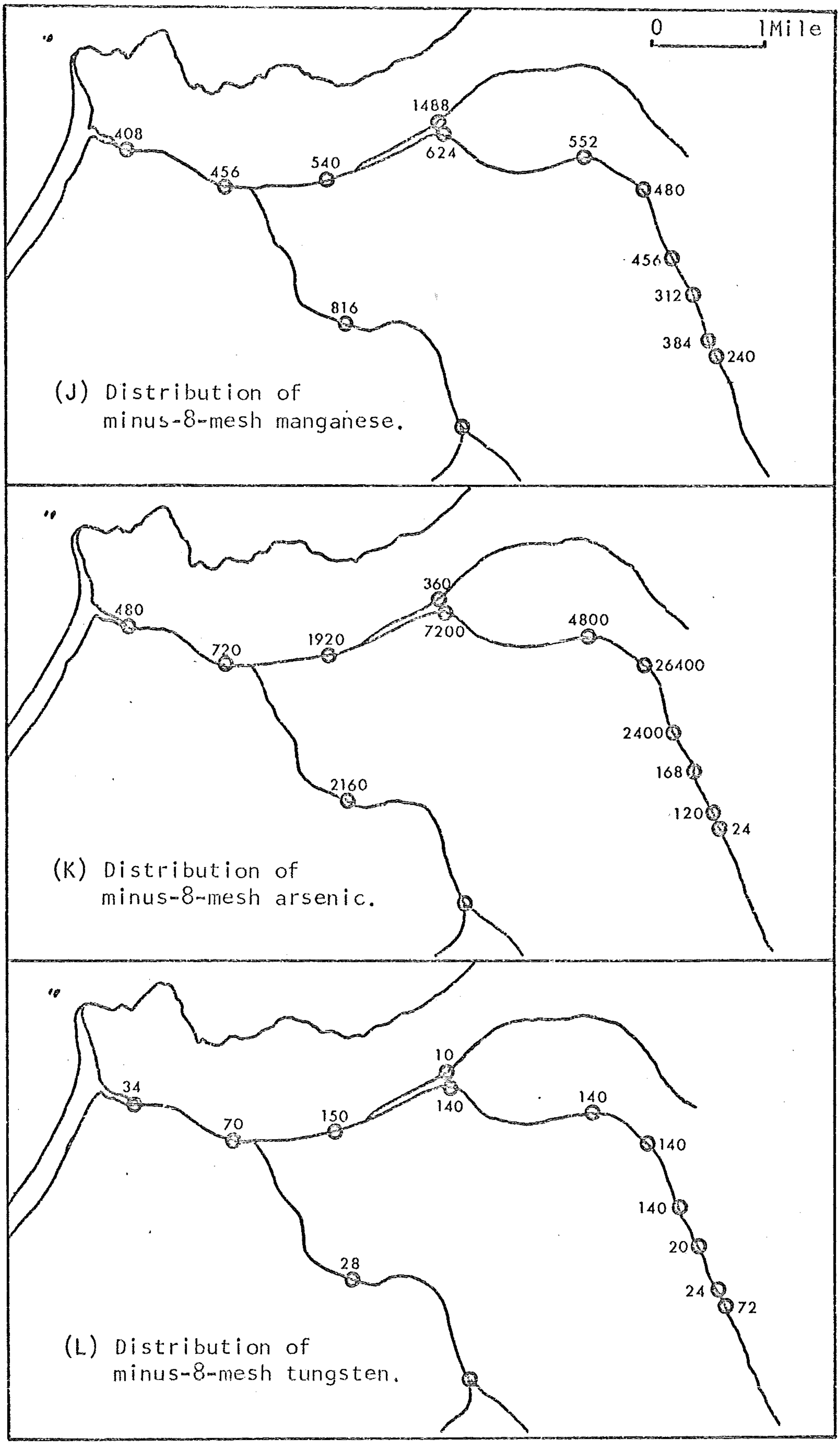


Fig. 6.3G-I. Red River stream sediment. (in ppm unless specified)



(J) Distribution of minus-8-mesh manganese.

(K) Distribution of minus-8-mesh arsenic.

(L) Distribution of minus-8-mesh tungsten.

Fig. 6.3J-L. Red River stream sediment. (in ppm) day mine workings rather than being due to selective concentration by fluvial processes on the stream bed, for the tin results generally show poor correlation with the sorting coefficients. Above the present day Carn Brea Tin Works where there is a mill and recovery plant, the river water is clear, and the tin concentration is significantly higher than sample 5 which is much finer and is taken from a slime pool along the River. This may be the result of natural erosion of tin lodes outcropping on the river bed coupled with old mine tailings from upstream. Further downstream, the River is flanked by mine dumps and old alluvial workings, sample 4 is the best sorted sample and shows an increase in tin concentration while sample 6, which is coarser and less well-sorted, is lower in tin. This lower concentration may be due to dilution by the discharge of mine tailings containing less tin from the South Crofty Mine, which has caused the River to change to a dark brown colour compared to its normal red colour. Below this point, sample 7 and 8 show increase in tin concentration and are also less well-sorted compared to sample 6. Sample 9 reached even higher to 26,000 ppm tin and may reflect local concentration along the river bed. The lower tin concentrations beyond sample 9 is likely to be caused by dilution from tributary streams draining from comparatively barren areas. Sample 3 from the Pendarves valley with 9800 ppm tin which is comparable to the values found along the Red River main channel may indicate primary detrital tin gravel. Contamination from the new Pendarves Mine through the Pendarves River has been ruled out because ore from the Mine was transported by road via Camborne to Roscroggan during 1970-1972 to be crushed and concentrated, and more recently the Roscroggan recovery plant has been closed, and the ore is now sent to the Carn Brea Tin

Works. This is confirmed by the lower tin concentration for sample 13.

The tin distribution in the under 250 micron size fractions generally show that tin is concentrated in the finest fraction, with the exception of samples 1 and 3, both gravel samples and which occur where the river water is clear. Sample 1 contains a maximum of 57,000 ppm tin in the 90-124 micron fraction compared to sample 3 with a maximum of 32,800 ppm tin in the 124-170 micron fraction. In both samples appreciable quantities of tin also occur in the coarser fractions. Beacause coarse tin is much more difficult to mobilise by fluvial processes than fine tin, this can be taken as a good indication that the tin found has a primary origin directly related to the weathering of tin lodes which are known to outcrop on the river bed in the vicinity, although a large proportion of the coarse tin must also have derived from the mine tailings resulted from old workings of these lodes. In the lower portion of the Red River, as shown by samples 10, 11 and 12, the lower tin concentrations are reflected in all the size fractions. Downstream of sample 8, the river gradient is reduced resulting in a reduction in stream velocity and causing tin deposition in the middle portion of the valley. This is also shown by the progressive decrease in tin concentration in the under 90 micron fraction downstream from sample 9.

Figure 6.3G-L. shows the distribution of copper, zinc, iron, manganese, arsenic and tungsten in the minus-8-mesh stream sediment. The distribution of copper, iron, arsenic and tungsten were found to show very similar patterns to that of tin and may serve as useful pathfinder elements for tin. However, the association of these elements may be caused by mining activity which has liberated fresh minerals bearing those elements. Under 'normal' erosion, which is a much more gradual process, it is unlikely that the easily oxidised sulphide minerals including those of copper, zinc, iron and arsenic would not be abundant in the stream sediment. Sample 7 with 26,400 ppm arsenic cannot be accounted for satisfactorily by bedrock mineralisation alone and it is necessary to invoke a selective concentration of tailings from the South Crofty Mine. In sample 3, where the coarse tin has been thought to have been derived from 'normal' erosion of mineralised bedrock, many of the river gravel fragments can be seen to contain fresh sulphide minerals which may have been broken and detached during fluvial erosion and may account satisfactorily for the 2160 ppm arsenic found in this sample. Mineralogical studies made on sample 3 using the binocular microscope have revealed numerous mono-mineralic sulphide grains with fresh appearance, showing well-developed crystal faces and little sign of abrasion or oxidation, which supports the theory that the sulphide minerals have only been liberated from the source rock recently.

Sample 1 from within the Carn Brea Granite has lower zinc, manganese and arsenic suggesting that minerals bearing these elements are associated with rocks occurring outside or near the granite margin. Samples 2 and 3 both from barren killas areas are highest in both zinc and manganese, due to the abundance of killas fragments in the samples, as has already been suggested for some sediment in the St. Agnes Head/Portreath area (section 5.6.0.). All the elements have been found to decrease downstream in the lower portion of the Red River valley which can be explained by dilution of sediment by barren material with increasing distance away from the source. The variations found along the main channel of the Red River from Carn

Brea downstream to Roscroggan can again be explained by the location of mineral workings. In general, elements which are present as stable heavy minerals in stream sediment, such as iron in haematite, magnetite and ilmenite, and tungsten in wolframite, are found to have very similar patterns to that for tin.

At sample sites 4, 7, 8, 9 and 10, water samples containing very fine sand, silt and clay in suspension, which forms the bulk of the land derived detritus to marine sediment in St. Ives Bay, have been collected in order that their tin and content of other elements may be determined. The results are shown in Table 6.2.

Table 6.2. Total content of tin and other elements in suspended sediment of the Red River. (in ppm)

Sampling Site	Sn	Cu	Zn	Fe	Mn	As	W	Pb
4	2700	230	235	25,920	384	60	24	59
7	3900	1250	310	54,240	792	1680	64	59
8	3700	560	210	47,040	624	1440	220	41
9	3800	580	300	53,760	840	1440	140	46
10	4400	430	320	55,200	672	1080	140	41

In contrast to the minus-8-mesh sediment, the suspended sediment shows much smaller variations in element concentrations. Sample 4 shows the lowest concentration for all the elements and this can be explained by the fact that the South Crofty Mine discharges its tailings below this point and that the sample is within the Carn Brea Granite. Sample 7 which is below South Crofty reflects mining contamination due to the Mine in the order of 1200 ppm tin, 1020 ppm copper, 75 ppm zinc, 28,320 ppm iron, 408 ppm manganese, 1620 ppm arsenic and 40 ppm tungsten, on the basis of the values for sample 4 being taken as the background of the suspended sediment before it is mixed with mine tailings from the South Crofty Mine. The highest copper and arsenic concentrations found in sample 7 can be related to the enrichment of sulphide minerals bearing these metals from the copper zone immediately upstream, because the stream bed sediment at this locality also contains high concentrations of these elements. The variations downstream of this point may be a reflection of the susceptibility of the minerals bearing these elements to break down by abrasion and chemical processes. It is significant that the sulphide minerals vary both in hardness and in specific gravity (Table 6.3.); the lower hardness can result in rapid break down to fine particles and the lower specific gravity can result in increased mobility. Other factors including crystal shape, flexibility, elasticity, the presence or absence of cleavages, the perfection of any cleavage etc. (Hosking 1960) may also be important in determining mineral abundances. The small variation found in the zinc concentrations in the suspended sediment seems to suggest that because both sphalerite and chalcopyrite are softer and less dense than pyrite and arsenopyrite, they are much more easily broken down and mobilised. This has subsequently been confirmed by mineralogical studies which has shown the dominance of arsenopyrite and pyrite as the main sulphide

Table 6.3. Hardness and specific gravity of sulphide minerals associated with tin. Based on Deer et al. (1966).

Mineral	Hardness	S. G.
Chalcopyrite	3.5 - 4	4.1 - 4.3
Sphalerite	3.5 - 4	4.1
Arsenopyrite	5.5 - 6	5.9 - 6.2
Pyrite	6 - 6.5	4.95 - 5.03

minerals in stream bed sediment.

Below Roscroggan in samples 9 and 10, copper, manganese and arsenic all show lower concentrations while tin, zinc and iron increase marginally. The increase in tin is thought to be due to selective concentration and indicate that very fine sand to silt and clay grade tin is transported down the Red River and eventually into St. Ives Bay under normal flow conditions without much difficulty.

One bucket auger core has been taken on the floodplain of the Red River near its entrance point into St. Ives Bay (Fig. 3.3B.) and the minus-8-mesh fraction of core-splits have been analysed for tin and other elements. The results (Table 6.4.) show that the red clay on the surface which represents flood deposits contain the highest concentrations of tin, iron, arsenic and tungsten while the coarser grey-green sand and silt immediately below have lower concentrations. Towards the basal horizon of the core, which may have reached bedrock, as is suggested by the presence of gravel size rock fragments, copper, iron, arsenic and tungsten as well as tin all show some increase in their concentrations.

Table 6.4. Distribution of tin and other elements in the minus-8-mesh fraction of a bucket auger core taken from the floodplain near the mouth of the Red River. (in ppm)

Sediment Type	Depth (cm.)	Sn	Cu	Zn	Fe	Mn	As	W
Red Clay	0 - 7.5	7000	220	160	60,480	696	720	550
Fine Grey-green Sand	7.5-18	2200	72	120	44,160	816	120	60
Alternating Horizons of Red Clay & Green Silt	18 -35.5	3800	190	240	51,840	888	360	120
Fine Sand	35.5-76	3800	170	150	26,400	480	240	20
Sand with Clay & Gravel	76 -91.5	4150	210	150	35,040	552	480	50

In order to determine the nature of mine tailings from present day mining contamination, a sample of tin concentrate with 218,000 ppm tin from ore raised at the Pendarves Mine crushed and concentrated on jigs at the Carn Brea Tin Works was examined. Table 6.5. shows the grain size and tin distribution of the concentrate and the results show overwhelmingly the dominance of tin finer than 90 microns. Within this size fraction, tin finer than 20 microns is liable to heavy loss during recovery even with modern improvements in recovery techniques notably with the introduction of the Bartles-Mozley concentrator (Burt and Ottley 1973) which is now commonly used in Cornwall for the recovery of fine tin slimes. Table 6.6. from Burt (personal comm. 1974) shows that the percentage recovery of two fine-grained tin ores using the concentrator average at not more than 50 percent for tin finer than 10 microns.

Table 6.5. Grain size and tin distribution in a tin ore concentrate from Pendarves Mine.

Size Fraction (microns)	Weight (%)	Tin Content (ppm)
500 - 2057	4.30	8500
250 - 500	11.85	28,000
170 - 250	8.46	66,500
124 - 170	11.72	148,000
90 - 124	6.88	188,000
< 90	56.81	390,000

The minus-8-mesh fraction of the ore concentrate has also been analysed for copper, zinc, iron, manganese and arsenic and was found to contain 11,700 ppm copper, 600 ppm zinc, 205,000 ppm iron, 1510 ppm manganese and 7500 ppm arsenic, confirming the association

Table 6.6. Percentage recovery of tin in two fine-grained tin ores using the Bartles-Mozley concentrator.

Grain Size (microns)	% Recovery	
	Ore A	Ore B
> 20	86.8	82.7
10 - 20	78.3	83.2
5 - 10	41.3	60.5
< 5	51.7	6.1
Total	70.2	64.4

of copper, iron and arsenic with tin in the recovery processes. Most significantly high is the iron content which may be present in tin lodes both as granular crystals or as inclusions within cassiterite grains. Iron minerals present in sediment, such as haematite, magnetite and ilmenite, because of their high stability, may therefore be a better pathfinder element for tin lodes than metals present in sulphide minerals. Zinc and manganese also show higher concentrations as compared to the stream sediment on the Carn Brea Granite, indicating that they are also relatively enriched in the tin lodes. However since killas fragments can also contain high concentrations of these metals, their use as pathfinders are restricted to granite areas only.

6.4.0. Investigation on Hayle Estuary sediments

Many workers have already demonstrated the important part played by estuaries in trapping land derived detritus, resulting in high concentration of heavy metals in estuarine sediments. In the Hayle Estuary, Hosking and Ong (1963-4) and Yim (1972) found a progressive decrease in the concentration of tin, copper, zinc, manganese and arsenic towards the mouth of the Estuary. Therefore, the Hayle Estuary which receives streams draining from the old mining districts of the Carn Menellis, Land's End and Godolphin Granites can be expected to preserve mine tailings derived from these districts before their closure. High concentrations of tin in the minus-80-mesh stream sediment in streams draining into the Estuary has already been demonstrated in section 6.3.1.

In this study, the main aim was to determine the vertical distribution of tin and other elements in the estuarine sediment, and to evaluate their significance in reflecting past mining contamination. To this end three bucket auger cores were taken, one from the eastern branch and two from the western branch of the Estuary (Fig. 3.3B.). The descriptions of the sediment type in the cores are shown in Fig. 6.4. and the geochemical results on these different sediment types are shown in Table 6.7. The geochemical results are however not in the shell-free basis because of the presence of appreciable clay size fraction in the sediment which is difficult to recover during shell removal. Tin has been determined spectrographically instead of by atomic absorption because the former method is not so prone to calcium interferences as the latter.

The main interest in these cores is in the shell-poor sediments, since they represent undiluted land derived detritus. However, because of the presence of blown sand deposits in the vicinity of the Estuary, wind transported shells originating from the sand dunes fringing the coast are blown into the Estuary during storms and dilute the land derived detrital sediments. Core 1 was taken from the eastern branch of the Estuary on the bank of the main river channel which has its source in the Gwinear Downs mining district. This part of the Estuary has been used as part of a sluicing system (Fig. 3.3B.), as a sluice pool for trapping sea water at high tide

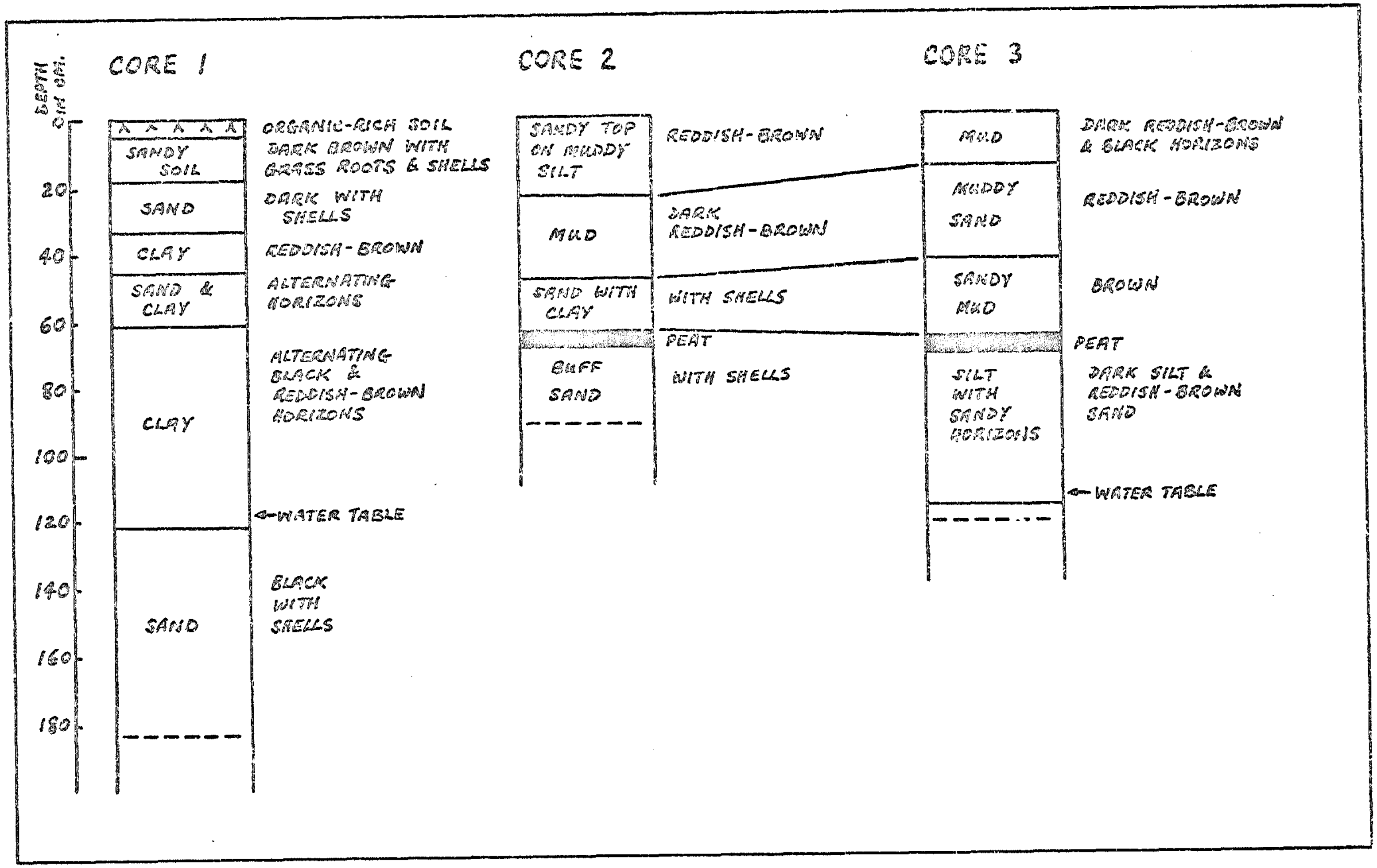


Fig. 6.4. Vertical distribution of sediment type in Hayle Estuary bucket auger cores.

Table 6.7. Distribution of tin and other elements in the minus-8-mesh fraction of Hayle Estuary sediments in bucket auger cores 1-3. (in ppm)

Core No.	Depth (cm.)	% Shells*	Sn+	Cu	Zn	Fe	Mn	As	W
1	5 - 18	11.0	1000	570	900	35,520	768	768	350
	20 - 30.5	17.3	850	430	900	22,320	1020	720	44
	35.5- 45.5	7.3	1000	1260	2290	55,680	864	1680	32
	45.5- 61	14.5	1000	810	930	34,080	504	960	220
	61 - 91.5	0.3	10,000	2000	1590	96,000	1368	3600	320
	106.5-122	0.3	10,000	2600	1880	93,600	1512	4080	360
	122 -152.5	24.8	1600	270	560	17,760	312	240	350
	Below 152.5	23.3	2000	290	730	21,120	336	360	650
2	0 - 20.5	1.0	5000	1700	690	54,720	792	720	56
	25.5- 45.5	0.4	10,000	2060	1220	77,760	1080	1920	56
	51 - 66	24.2	1300	890	640	21,360	336	240	9
	71 - 91.5	31.2	50	68	80	3840	48	12	4
3	0 - 15	0.8	1600	1240	740	55,200	696	840	56
	20.5- 40.5	0.2	1300	1090	470	45,600	624	720	56
	45.5- 61	0.2	1300	1750	710	48,960	720	720	44
	66 - 71	1.0	10,000	2760	3450	53,760	648	840	52
	71 - 91.5	0.2	10,000	540	440	26,880	336	240	24
	96.5-112	0.4	10,000	480	540	26,400	360	120	28
	Below 112	0.5	1600	480	460	28,080	336	300	28

* - Estimated from ppm calcium determined by atomic absorption.

\+ - Determined spectrographically.

which is released through the sluice gates at mid-tide to wash the channel of the main harbour free of sand (Spring 1974, personal comm.). Cores 2 and 3 were taken from near the banks of the River Hayle channel on the western branch of the Estuary. Both these cores show an organic-rich peat horizon approximately 5 cm thick which may relate to a former lower stand of sea level.

In core 1 the highest concentration of tin, copper, iron, manganese and arsenic are all found in the alternating black and reddish-brown clay horizons at 61-122 cm., which coincide with the lowest shell concentrations. The high concentration of these elements together with the nature of the sediment suggests that they may be fine mine tailings transported into the Estuary by fluvial processes downstream from the Gwinear Downs mining district, and the tin smelter at Angarrack 1704-1881 (Barton 1967). If the relatively shell-rich sediment in the upper horizon of the core originated during the second great storm in the formation of the Upton Towans in 1869, then these clay horizons must have been formed during an earlier period. If this is the case, then there is good agreement with the mining records which show~~s~~ that the peak production period in the Tremayne group of mines of the Gwinear Downs mining district and the Angarrack tin smelter predated 1869. Dines (1956) recorded that in this district, the Providence Mine 1820-1862 produced 14,450 tons of black tin while between 1848-1868 in the Tremayne Mine proper, the output was 1,492 tons of black tin, giving a total of just under 16,000 tons of black tin for the group of mines. Therefore with such large scale mining activity on the hinterland of the Estuary, and with the poor recovery of fine tin associated with this period together with the efficiency of the Estuary in acting as a filter for the land derived detritus, the high concentration of all the elements within these horizons can be explained. The decrease in concentration in tin, copper, zinc, iron, manganese and arsenic at depths of greater than 122 cm. is accompanied by an increase in shells. If these shell fragments have derived from the first great storm in 1750 during the formation of the Upton Towans, then the distribution of elements would correlate very well with the much smaller scale mining activity on the land prior to this period.

Core 2 shows a marked increase in shell content towards the basal horizon at depths of greater than 51 cm. which is also poorer in all the elements in comparison to the sediment above. Core 3 on the other hand, which is located nearer to the present High Water Mark and to the main channel of the River Hayle in the intertidal zone of the Estuary shows less than 1 percent shells throughout its length. This low shell content may be explained by its protected position from wind blown shells originating in the coastal dunes, or shells washed into the Estuary on a rising tide. The peat horizons encountered in core 2 at 63.5-68.5 cm. and in core 3 at 66-71 cm. indicate rapid burial probably related to a recent change in condition within the Estuary. Both horizons may have the same age and origin, on the basis of their thickness and depth of occurrence. The construction of the second sluice pool and the Harbour probably at around 1830 (Cotton 1974, personal comm.) has effectively reduced the intertidal area within the western branch of the Estuary by over a quarter. Consequently, the reduction in area within this part of the Estuary has led to rapid silting and the formation of the peat horizon. If this is the case and the peat horizons in core 2 and 3 do correlate in age, then the high shell concentration below 68.5 cm. in core 2 may be related to the first great storm in 1750 during the formation of the Upton Towans. On this basis, the sediment below the peat horizon in core 3 may be related to mining contamination from the pre-1830 mining era, and likewise the sediments above the peat horizon in both cores are likely to post-date 1830.

In the surficial horizons of both cores 2 and 3, the sediments are found to be enriched in all the elements. The tungsten concentrations in both cores are much lower in comparison to core 1 which suggests that the source rocks in the hinterland differ in tungsten enrichment. However, the sediment with highest concentration of tin in core 3 at 96.5-112 cm. is not as enriched in other elements as compared to the sediment above. The mining records shown in Dines (1956) indicate that most of the mines in the vicinity between Leedstown and St. Hilary, north of the Godolphin Granite, whose tailings were discharged into the River Hayle, are very old. The peak activity in the Leedstown area seems to have declined before 1850 and many of the mines in the St. Hilary area date back at least to the eighteenth century. In the Trencrom Hill area, tailings were discharged down the small but steep gradient stream valley draining into the Hayle Estuary, which has been shown in the minus-80-mesh stream sediment reconnaissance survey to contain tin in excess of 35,000 ppm. The peak production in mines of this area was reached after about 1830 with 13,000 tons of black tin since about 1825. Because the course length of the River Hayle is appreciably longer than the smaller streams originating in the vicinity of Trencrom Hill and because of the peak production periods of the two catchment areas differ, the high tin concentration with relatively low concentration of other elements below the peat horizon in core 3 may be related to tailings from the River Hayle catchment area, while the high element concentrations above the peat horizon may be related to tailings from the Trencrom Hill mining district where the peak production period was reached after 1825-1830. However, the sediment within this portion of the Estuary is also complicated by the contribution of wastes from three smelting houses located in the vicinity at Mellanear 1837-1905, Treloweth 1715-1883 and Wheal Reeth 1823-1824 (Fig. 2.6.), and more recently by the establishment of an iron foundry near the Harbour.

6.5.0. Investigations on offshore areas affected by present day mining contamination

In this section, the beach and offshore sediment in St. Ives Bay and the Pendeen area have been examined. The beach sediment results are not in the shell-free basis and for this reason tin has been determined spectrographically. Calcium was determined by atomic absorption in the estimation of shell content. On the other hand, the offshore grab samples have been treated identically to the St. Agnes Head/Portreath grab samples. However only the Pendeen grab samples have been analysed for copper, zinc, iron, manganese, arsenic and tungsten because of the similarity in the conditions of the area to the St. Agnes Head/Portreath area, mainly in the disposition of the coastline and the geology. The tin results for the grab samples from St. Ives Bay and the Pendeen area are shown in Fig. 6.5A-E.

6.5.1. Distribution of tin and other elements in beach sediments

6.5.1A. St. Ives Bay beach sediment

In St. Ives Bay, during a period of beach aggradation associated with offshore wind, two beach sediment sampling traverses 1 and 2 (Fig. 3.3B.) from the High Water Mark to the Low Water Mark with samples at 50-ft. intervals were carried out near the mouth of the Red River on the Gwithian Beach. The total minus-8-mesh fractions were analysed for copper, zinc, iron, manganese and arsenic as well as tin and the results are presented in Fig. 6.6A & B.

Traverse 1 from north of the mouth of the Red River towards Godrevy Head is flanked by low cliffs which lie in an exposed position in the path of the prevailing westerlies. Traverse 2 on the other hand lies south of the mouth of the Red River, is flanked by

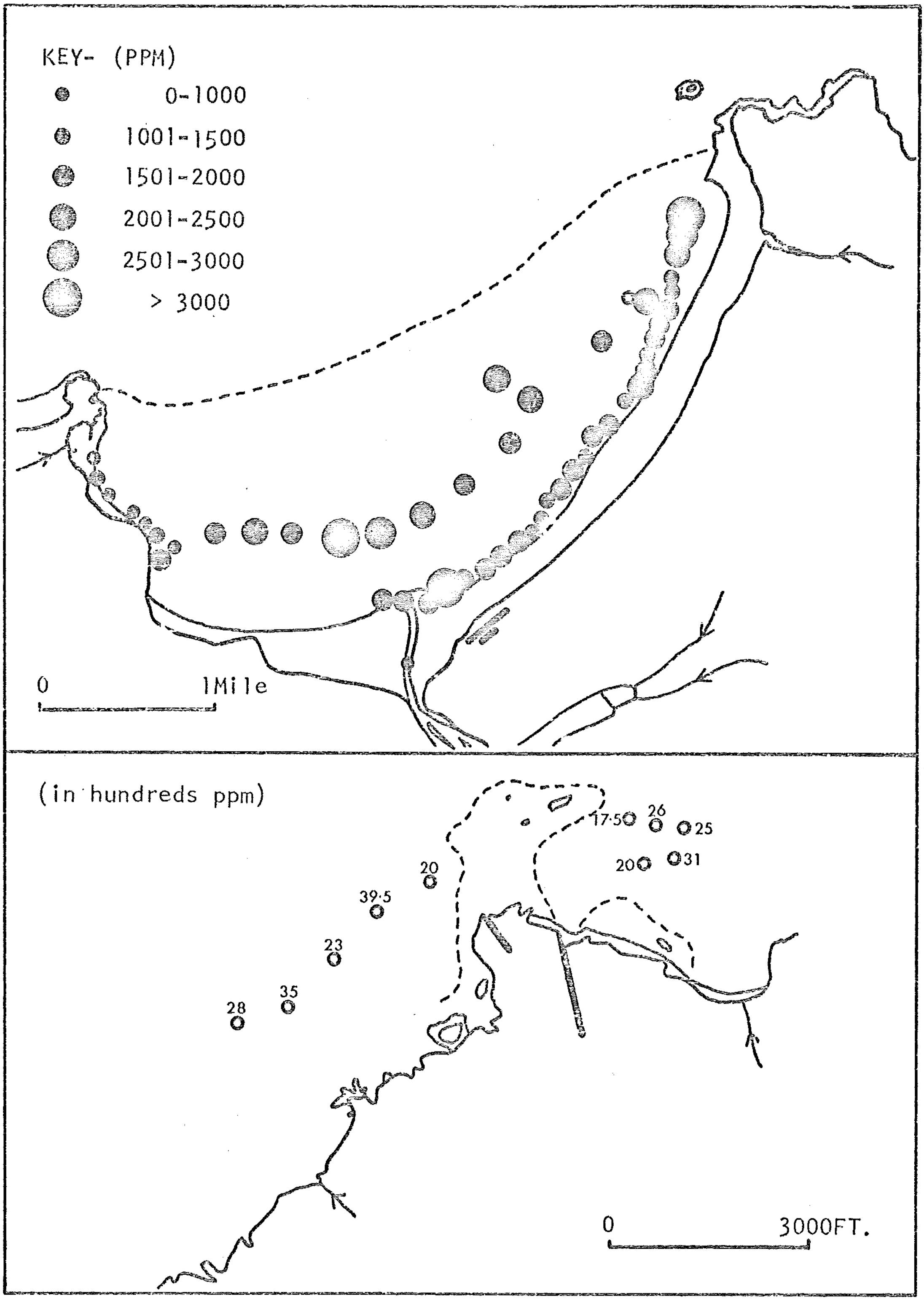


Fig. 6.5A. Distribution of minus-8-mesh tin in St. Ives Bay and Pendeen.

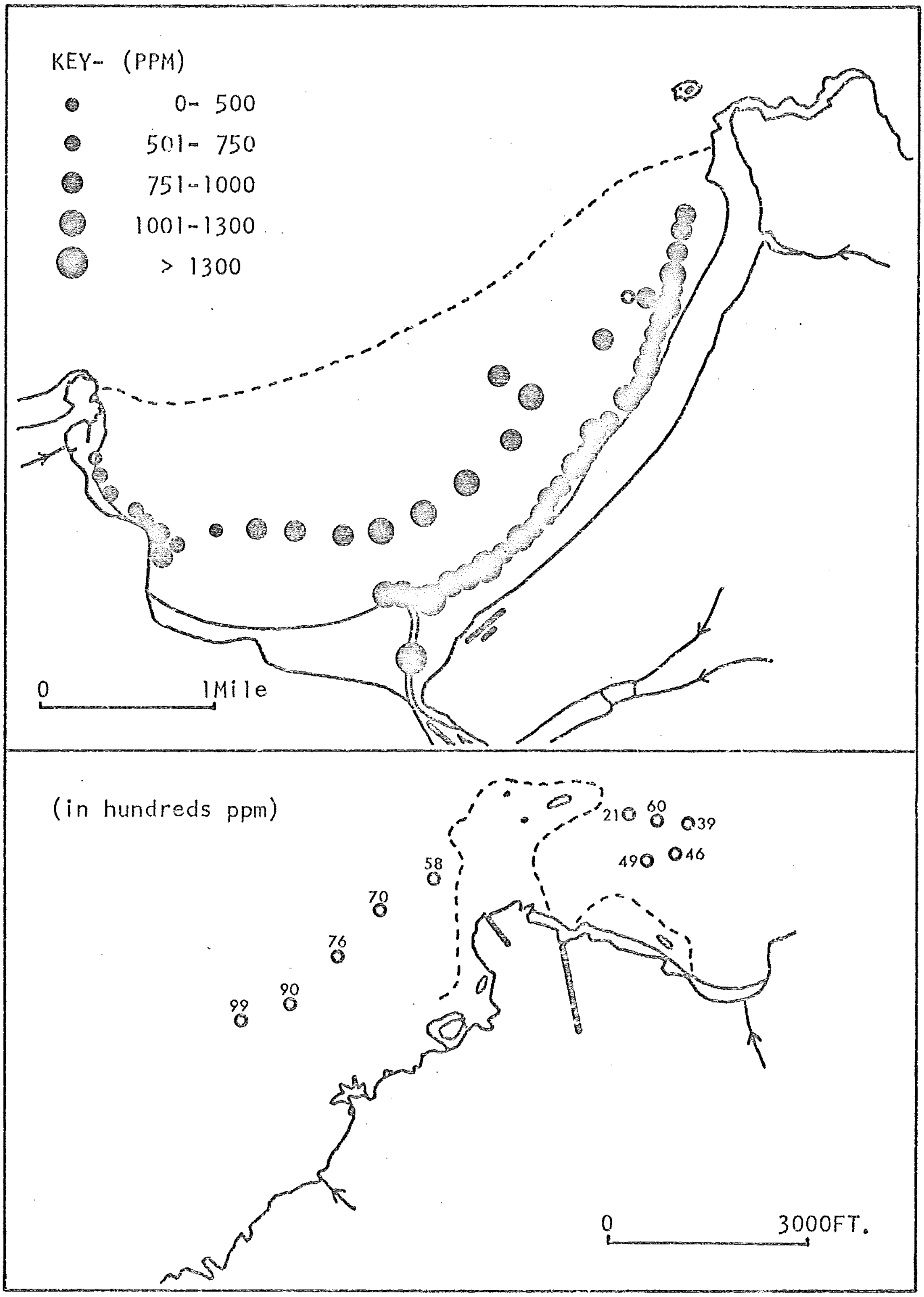


Fig. 6.5B. Distribution of 170-250 micron tin in St. Ives Bay and Pendeen.

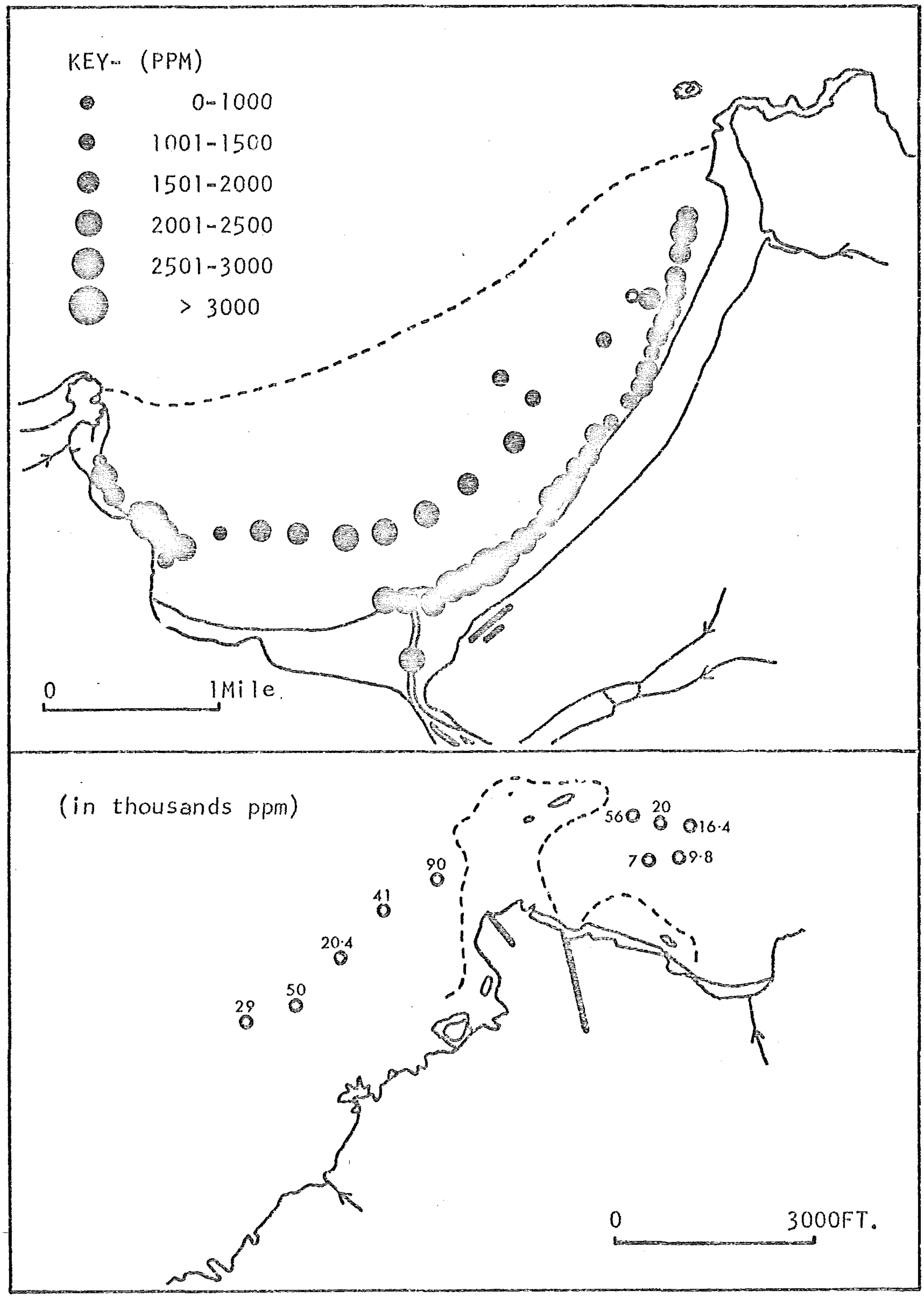


Fig. 6.5C. Distribution of 124-170 micron tin in St. Ives Bay and Pendeen.

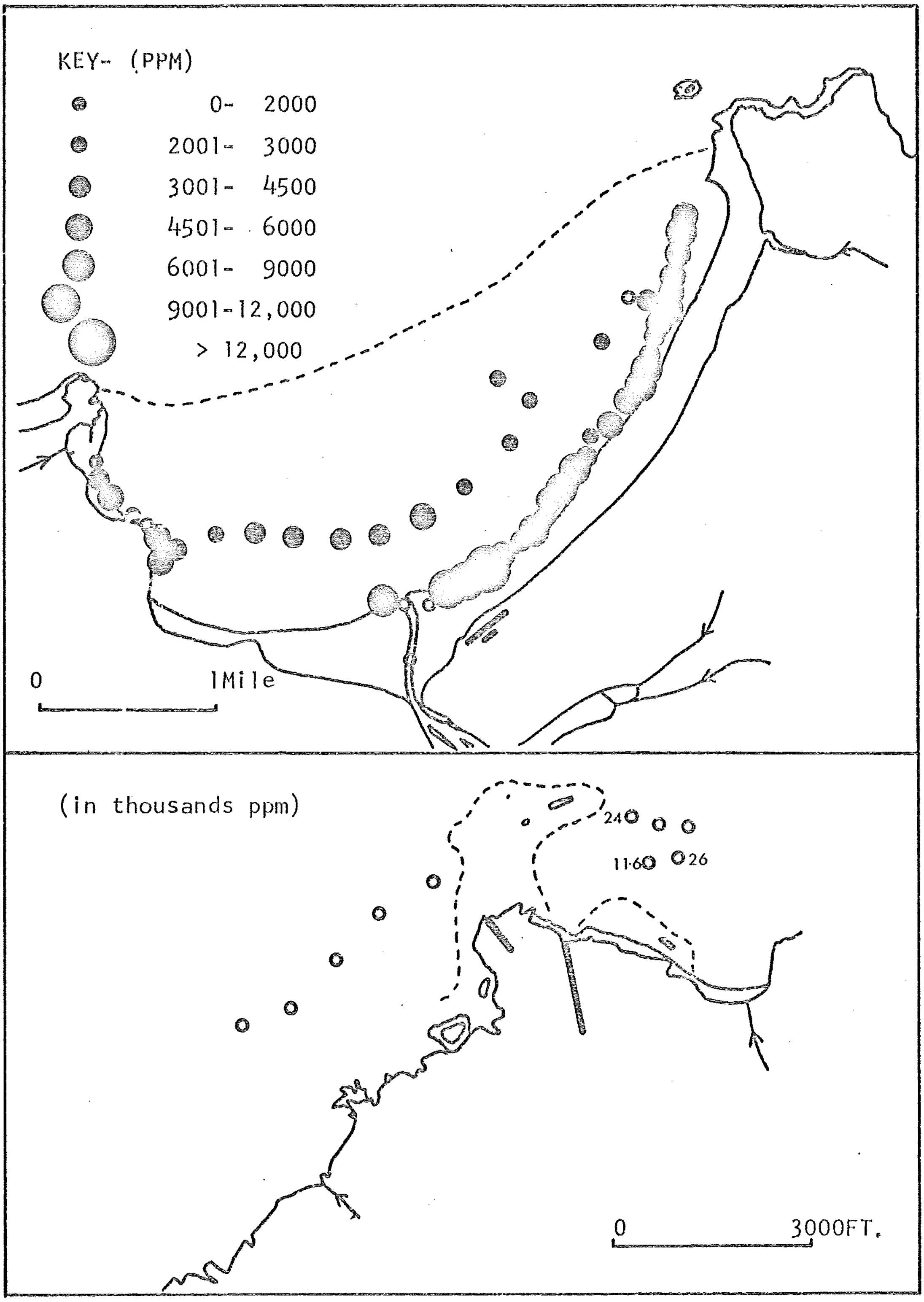


Fig. 6.5D. Distribution of 90-124 micron tin in St. Ives Bay and Pendeen.

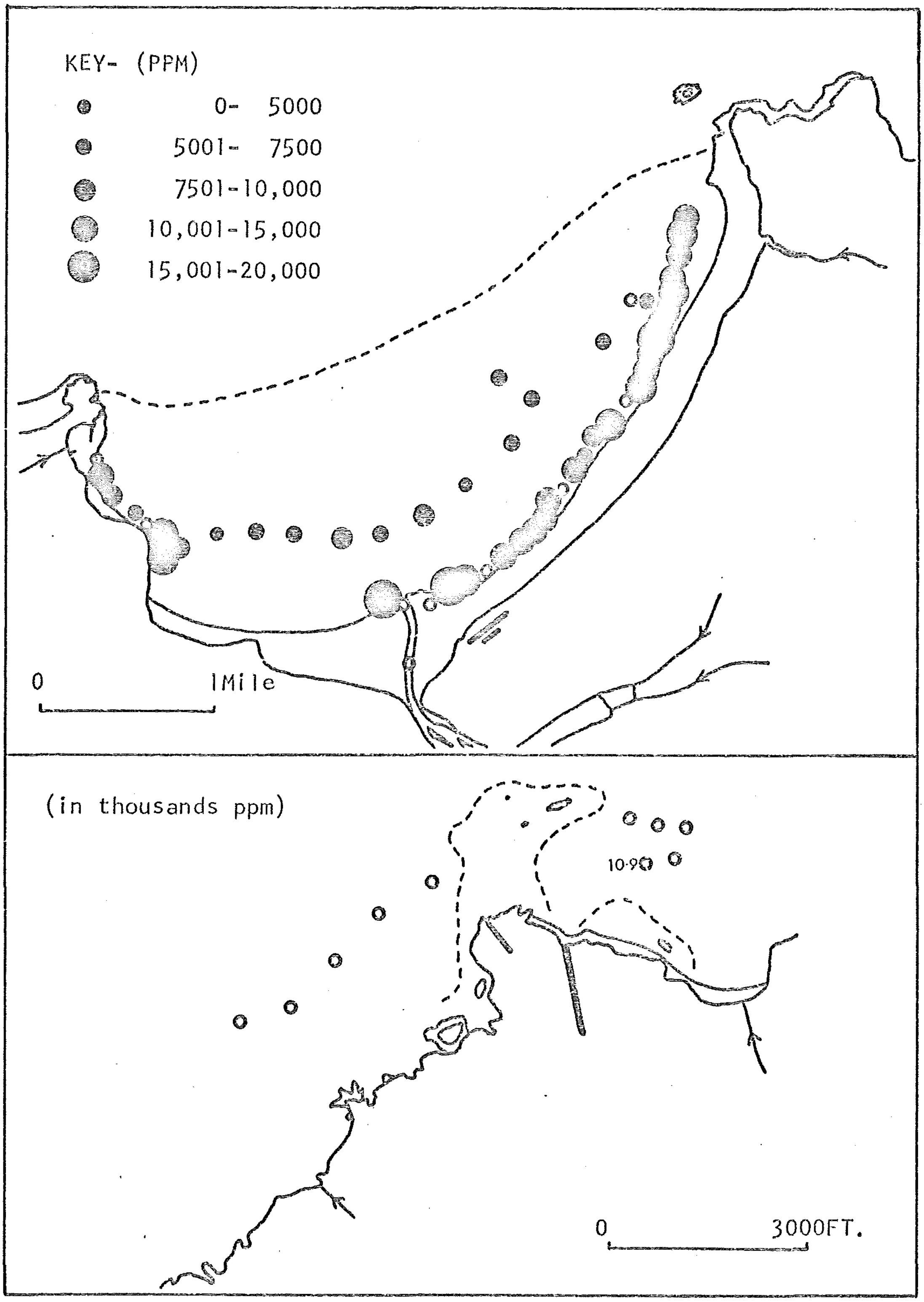


Fig. 6.5E. Distribution of under 90 micron tin in the St. Ives Bay and Pendeen.

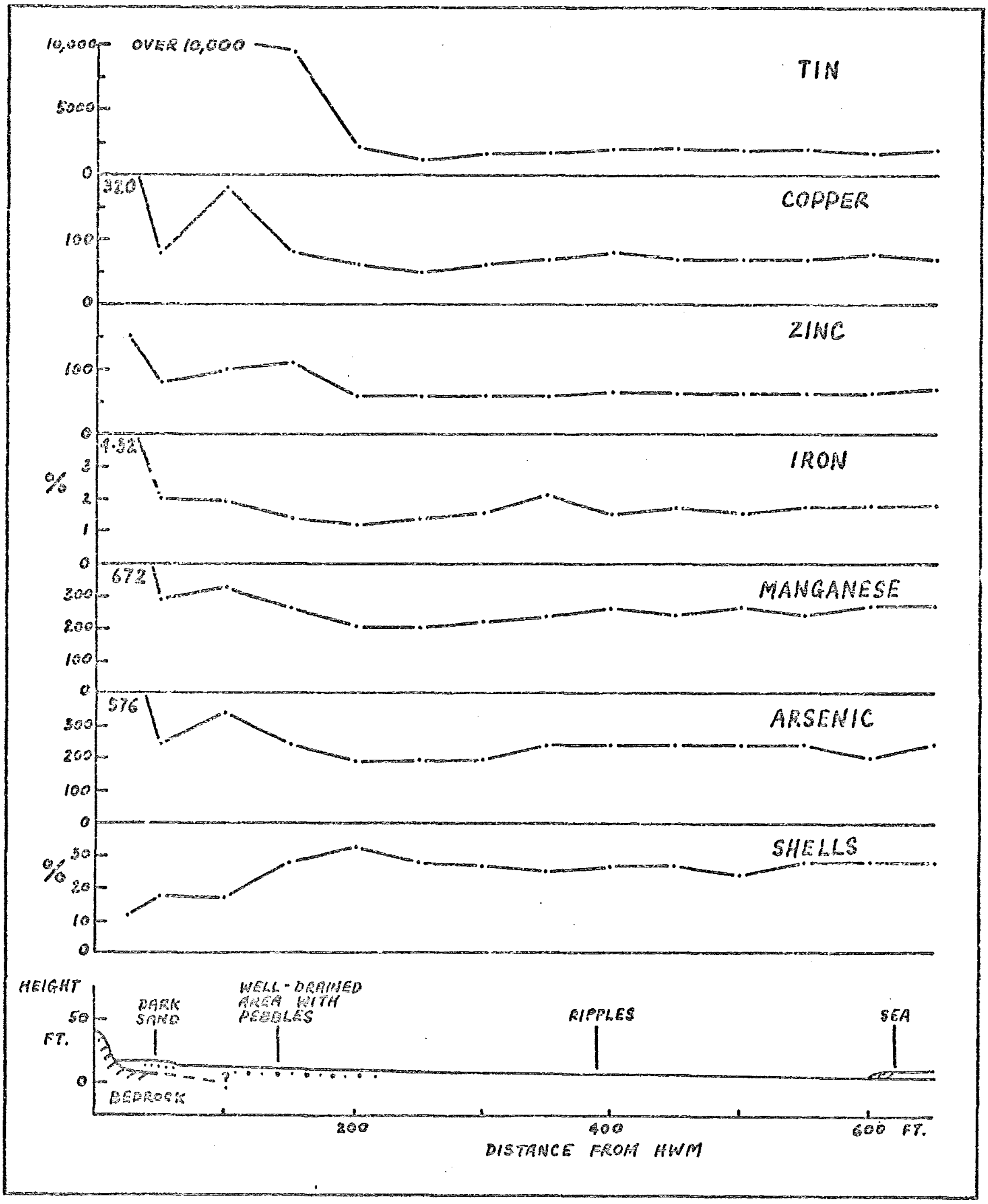


Fig. 6.6A. Distribution of tin, other elements and shells along beach traverse 1. (in ppm unless specified)

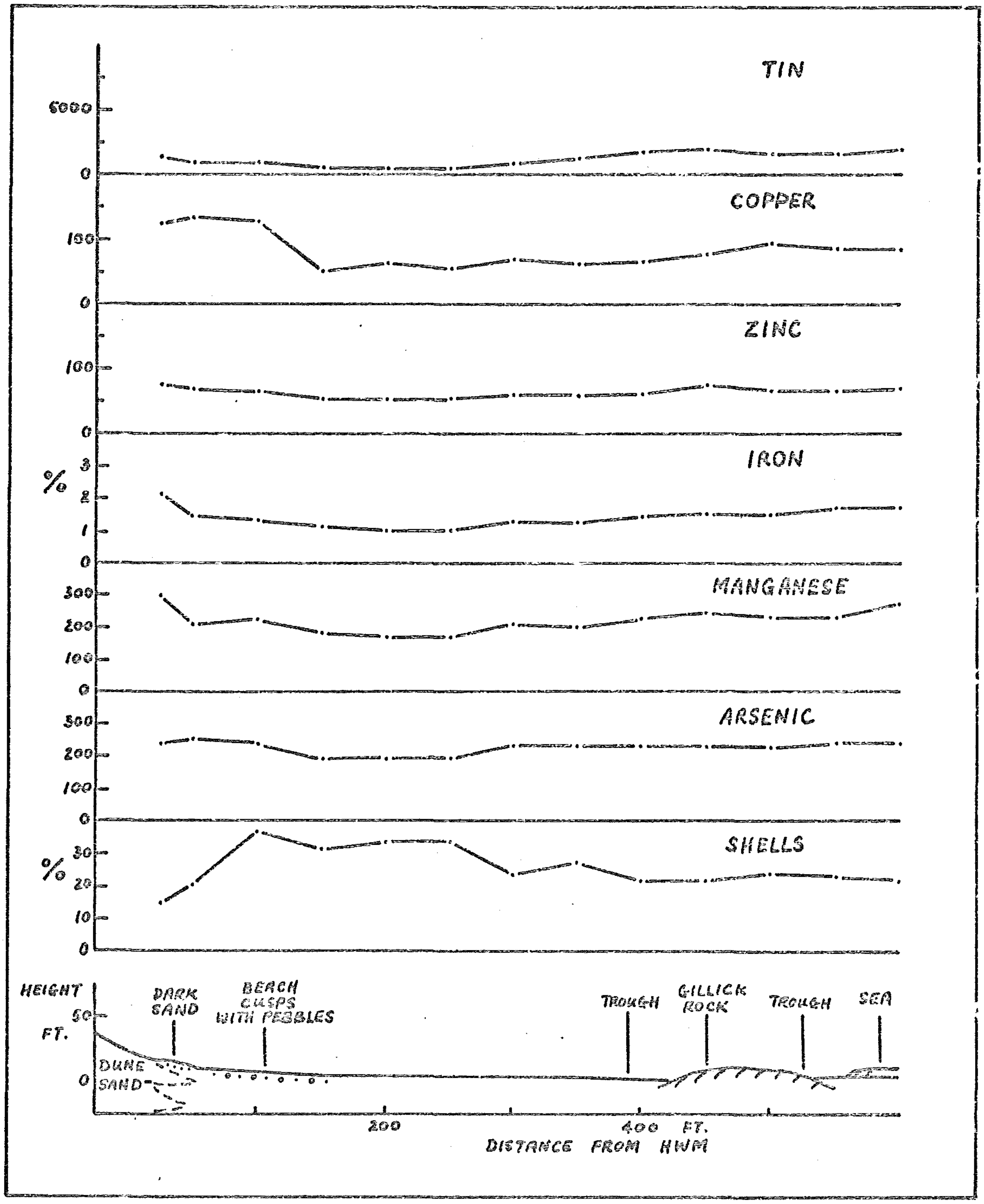


Fig. 6.6B. Distribution of tin, other elements and shells along beach traverse 2. (in ppm unless specified)

sand dunes and is partially protected by Bessack Rock, a killas reef occurring half a mile west of the traverse (Fig. 3.3B.). During periods of offshore winds or calm weather with dominantly constructive waves as was encountered during this sampling period, there is a net movement of sediment towards the High Water Mark. Land derived detritus containing mine tailings transported into the Bay through the Red River is therefore able to mix with the beach sediment and may subsequently be reworked and sorted by wave and tidal action. Both traverses show varying degrees of enrichment of all the elements towards the High Water Mark which are accompanied by decreases in shell content; this is particularly clearly shown in traverse 1 where the concentration of all the elements increases in the surficial beach sediment within a zone of 200 ft. from the High Water Mark, although variations can also be found within this zone. Away from the High Water Mark, the distribution of elements becomes generally more regular, even though minor variations can still be found.

In traverse 2, the trough area around Gillick Rock (Fig. 6.6B.) was found to be marginally enriched in all the elements. This may be explained by land detritus enriched in mine tailings being deposited on the beach zone reworked and concentrated in the trough. The association of all these elements whose concentration is liable to dilution by shells indicates that these elements are present in the same mineral, or associated detrital phases. The concentration of heavy minerals in beach placers is well known. Mineral grains bearing these metals have high specific gravity and tend to accumulate in areas of high energy, particularly along the High Water Mark. The heavy minerals are selectively concentrated through a jigging process by the swash and backwash of waves.

Traverse 1 was subsequently resampled using a closer spacing during a period of strong onshore wind, in order to determine their part in the offshore dispersion of land derived detritus deposited on the beach zone. The results are shown in Fig. 6.7. The beach during this period was found to have diminished to a stretch of sand less than 150 ft. in width from the High Water Mark and beyond the limit of the sand, a wave-cut platform with boulders and pebbles was exposed. The concentrations of all the elements again show good agreement in their distribution. However, they are also generally significantly higher than the old traverse and this may again be correlated with the variation in shell content of the sediment. In conclusion, during periods with strong onshore winds in the exposed areas, the beach sediment containing land derived detritus may be reworked and dispersed offshore. This dispersion of beach sediment is shown by the high concentration of heavy minerals in the remaining sediment, and suggests a very selective sorting process leading to heavy minerals remaining behind and being concentrated in depressional areas.

6.5.1B. Portheras Cove beach sediment

Portheras Cove lies immediately east of Pendeen on the north coast of the Land's End Peninsula and is partially protected from the west by Pendeen Head and the nortn-west by reefs running from the Head to the Wra (Fig. 3.3C.). The beach sediment was sampled randomly at an interval of approximately 50 ft. during a period of strong westerly winds leading to beach degradation and the exposure of numerous boulders of granite near the High Water Mark. The total minus-8-mesh fraction of the beach sediment was analysed for copper, zinc, iron, manganese, arsenic and tungsten as well as for tin, and the results are presented in Fig. 6.8A-H.

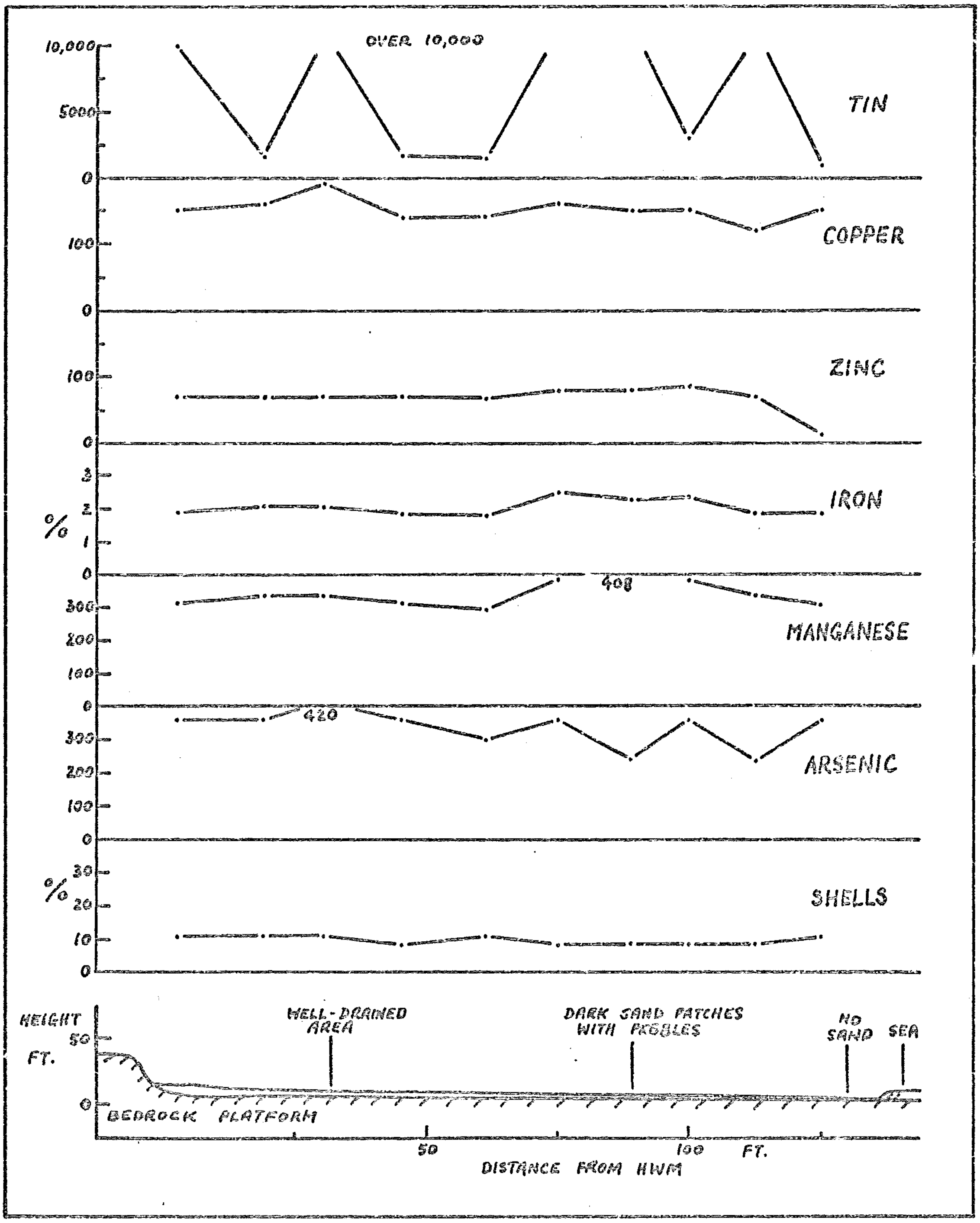
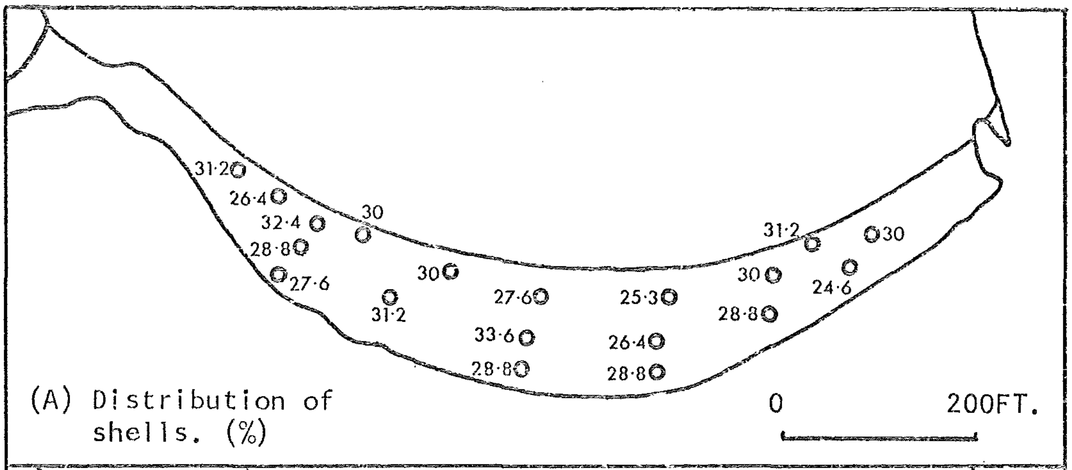
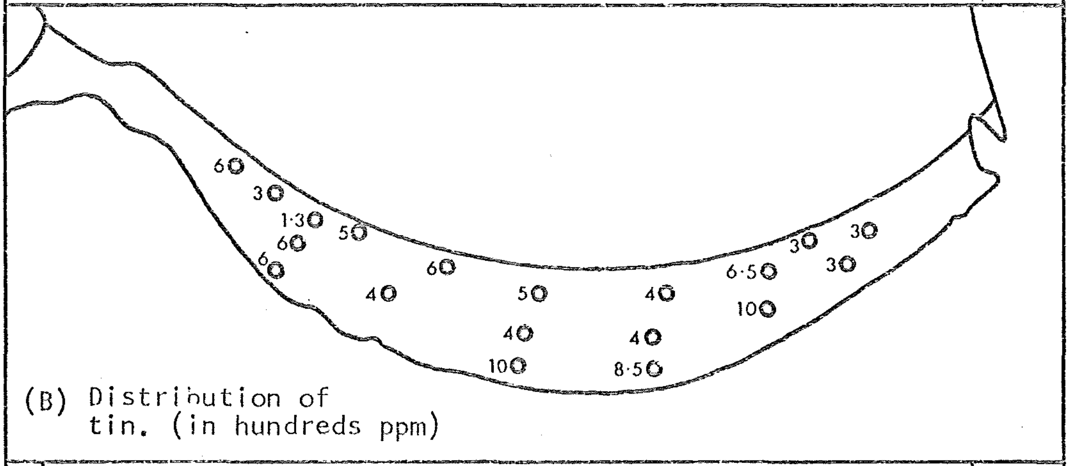


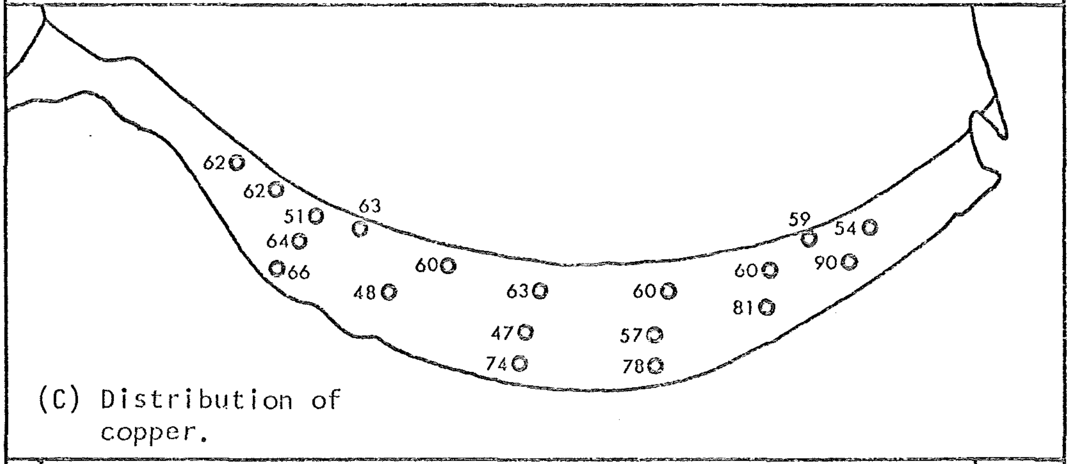
Fig. 6.7. Distribution of tin, other elements and shells along beach traverse 1, resampled during a period of beach degradation. (in ppm unless specified)



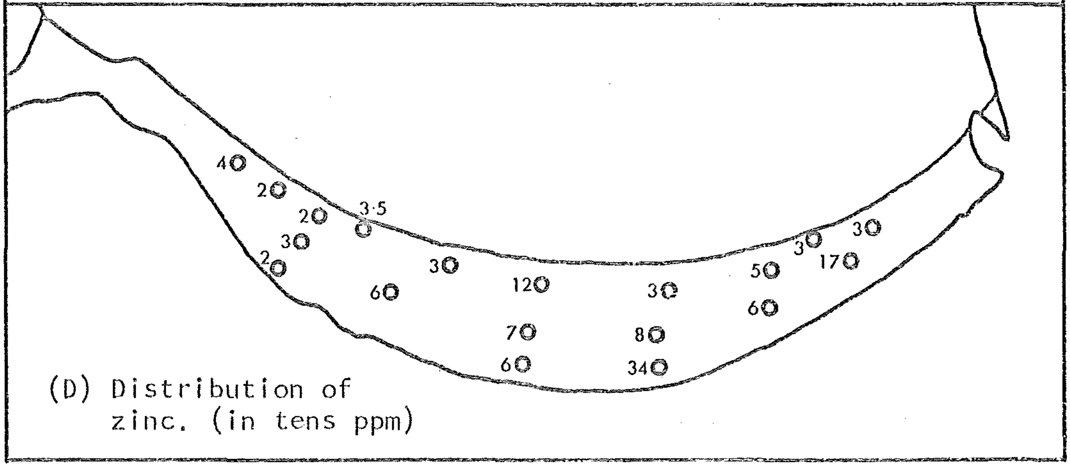
(A) Distribution of shells. (%)



(B) Distribution of tin. (in hundreds ppm)

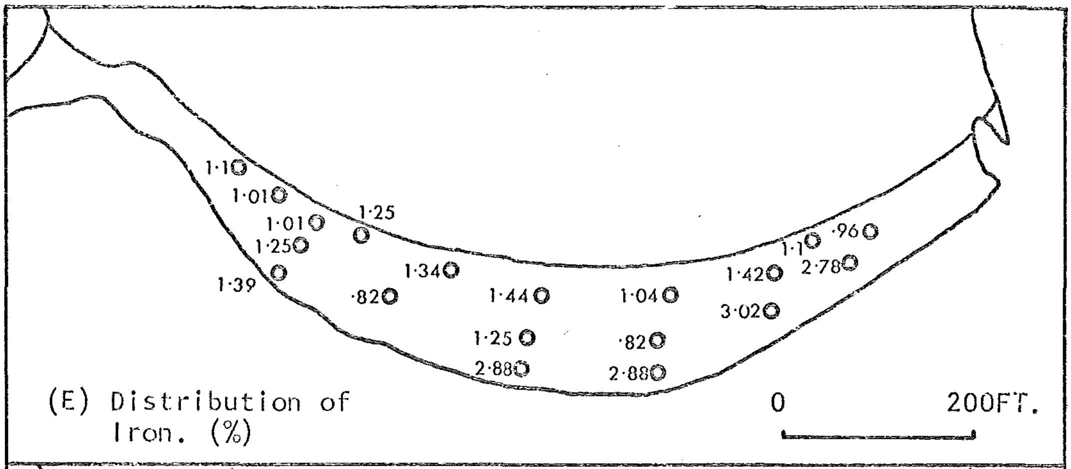


(C) Distribution of copper.

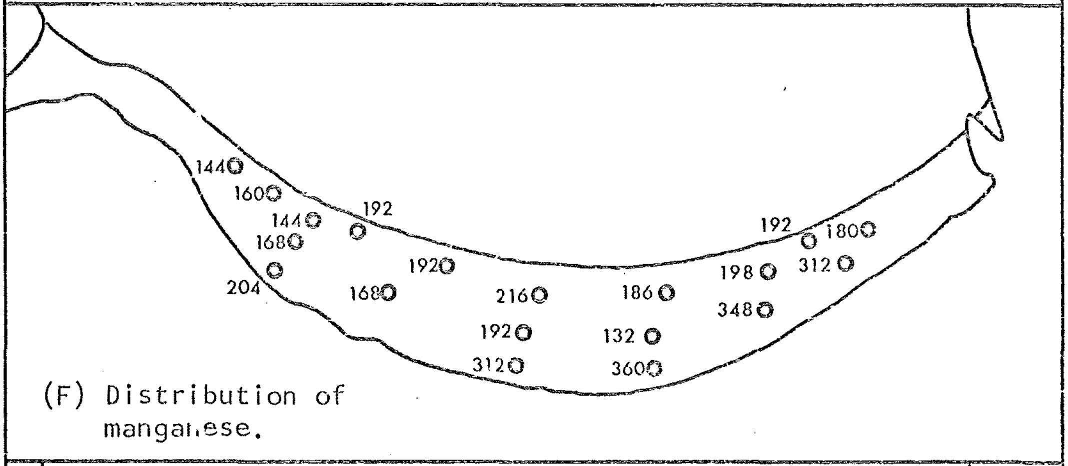


(D) Distribution of zinc. (in tens ppm)

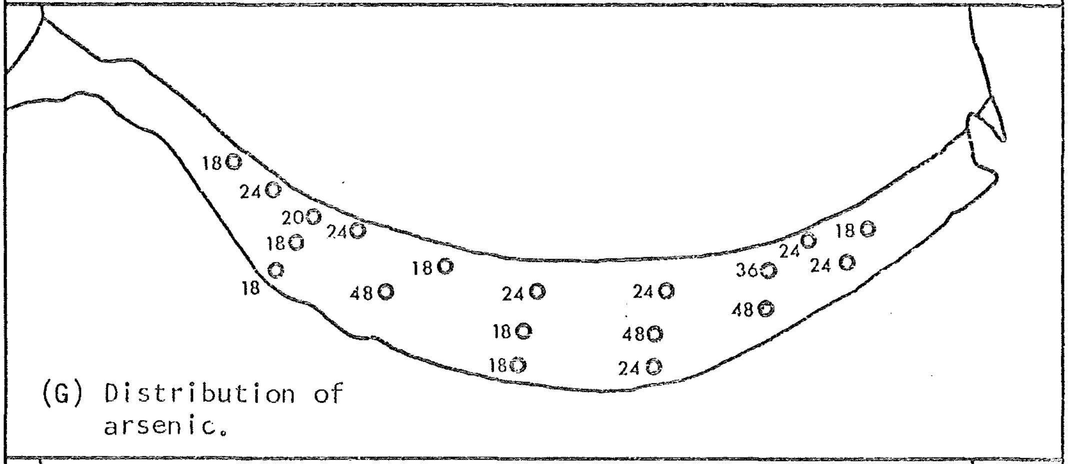
Fig. 6.8A-D. Portheras Cove beach sediment. (in ppm unless specified)



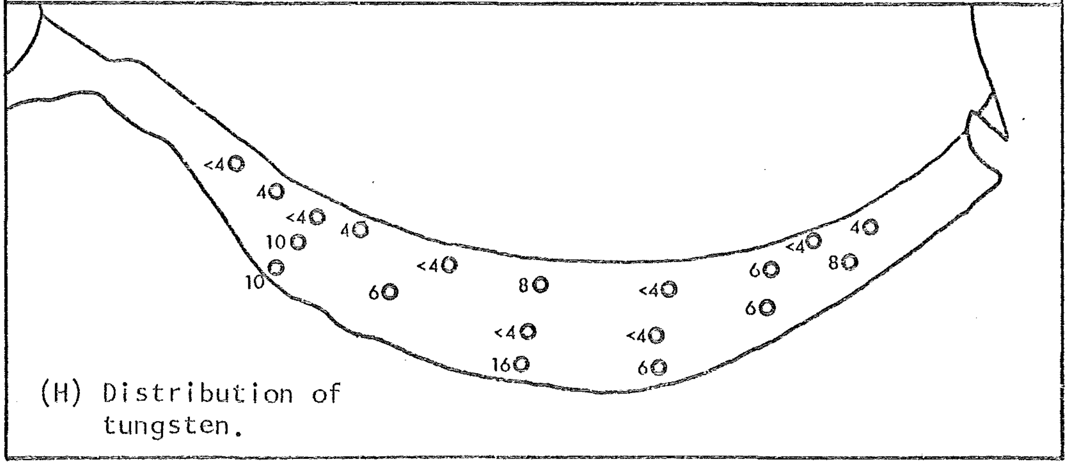
(E) Distribution of Iron. (%)



(F) Distribution of manganese.



(G) Distribution of arsenic.



(H) Distribution of tungsten.

Fig. 6.8E-H. Portheras Cove beach sediment. (in ppm unless specified)

As in the beach sediment traverses in St. Ives Bay, the distribution of elements with the exception of zinc and arsenic all show good agreement. Again the distribution of elements can be correlated with the shell distribution, and the elements are enriched in the zone nearest to the High Water Mark. The more irregular distribution of zinc and arsenic may be explained by the fact that the cliffs round the Cove are of granite and both zinc and arsenic bearing minerals are normally associated with the metamorphic aureole zone which occurs offshore from the granite. In comparison with the concentration of tin and other elements off the mouth of the Red River, the much lower concentrations here indicate that they may be related to natural conditions rather than mining contamination. Although extensive mining activity comparable in scale to that of the Camborne-Redruth mining districts can be found west of Pendeen Head, due to the relative protected situation of the Cove than in the Gwithian Beach, the beach sediment is less contaminated by mine tailings.

6.5.2. Distribution of tin in the offshore surficial sediment of St. Ives Bay

The distribution of tin in the minus-8-mesh fraction (Fig. 6.5A.) indicates tin enrichment off the mouth of the Red River and the Hayle Estuary. While the tin enrichment in the former may be explained by tailings from the Camborne-Redruth mining districts, the enrichment off the latter may be explained by the sluicing system described in section 6.4.0. which has caused the estuarine sediment rich in tin to find their way into the Bay at low tide. Towards the middle portion of the Bay, the sediment which is appreciably finer, better sorted and poorer in shells than sediment nearer to the shore also shows a marginal increase in tin enrichment reflects the smaller scale mining activity on the adjacent land.

The size distribution of tin shows that the bulk of the tin in sediment off the Red River and the Hayle Estuary occur in the finest (under 90 micron) fraction. In the western end of the Bay near St. Ives, the high tin concentration found in the 124-170 micron fraction may be explained by old mine and alluvial workings in the vicinity of the coast as well as by submarine bedrock mineralisation. Due to the short distance from the source and the steep gradient of the streams, coarse tin can be transported downstream into this part of the Bay. In the middle of the Bay, the sediment was found to contain the lowest tin concentrations in the fine size fractions. However, as these fine fractions are more abundant than in the near-shore sediments, the total tin in the middle of the Bay is higher than near-shore. This confirms the physical influences of sedimentation on the relationship between energy level, sediment type and mineralogical composition. In terms of distance from a land source, one would expect to find coarse tin nearest to the shore. Fine tin from mine tailings because of its hydraulic properties is able to travel furthest offshore before deposition.

6.5.3. Distribution of tin and other elements off Pendeen

As a result of the coarse grain size of the sediment, there was insufficient material for analysis for many of the fine fractions. The minus-8-mesh total tin and the tin size distribution show that the sediment west of Pendeen Head, is an area with numerous tin mines along the coast and also with known submarine tin lode outcrops, is more enriched in tin compared with sediment to the east which is in a less intensively mineralised area. The tin concentrations found in the coarse size fractions are found to be appreciably higher than those in the St. Agnes Head/Portreath area, and may be related to the high energy environment due to the exposed nature of the coast.

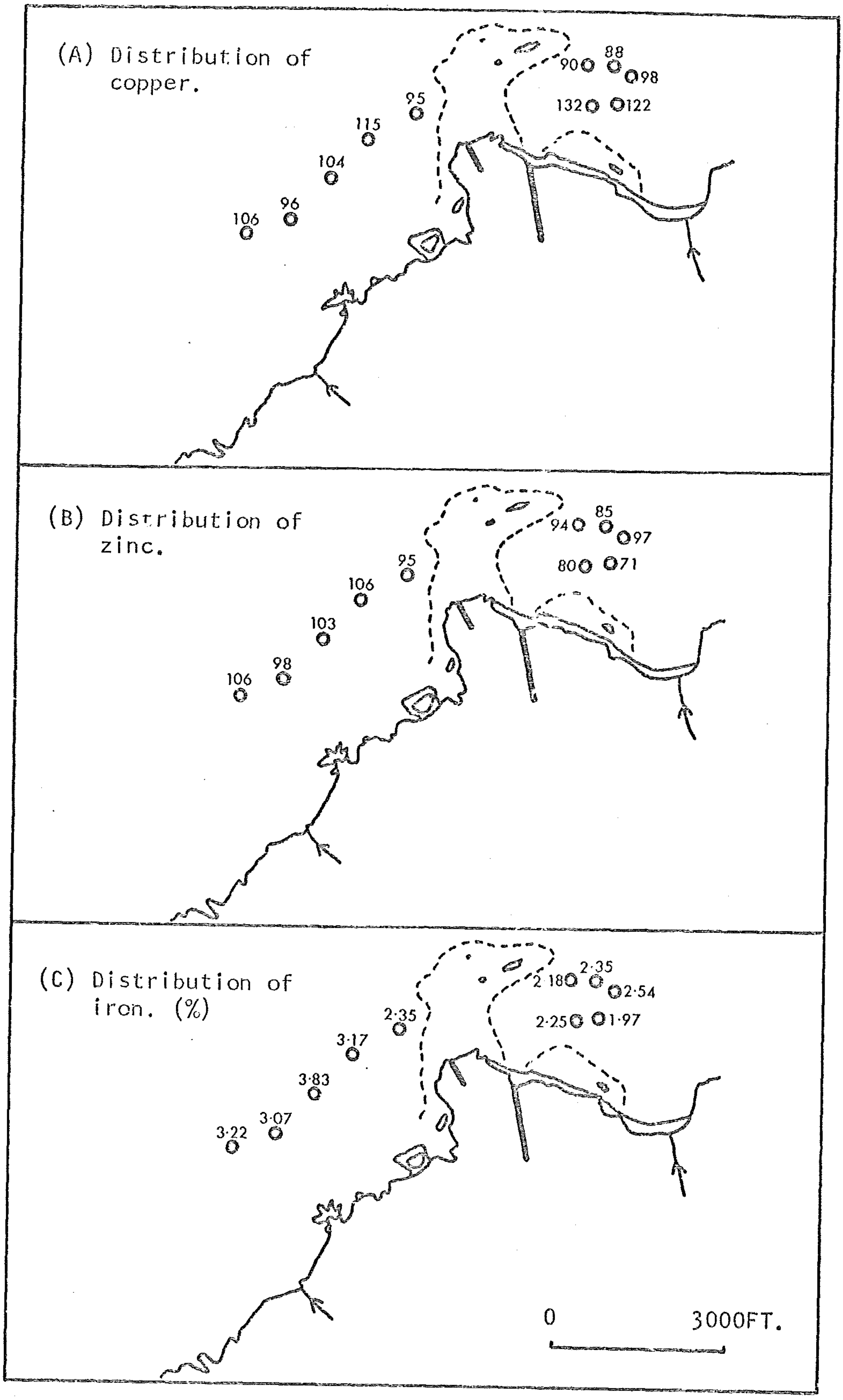
The distribution of other elements in the minus-8-mesh shell-free fraction are shown in Fig. 6.9A-F. With the exception of iron, all the elements show only minor variations in their concentration ranges. However, all the elements show distribution patterns similar to that of tin. This suggests that under the prevailing high energy level and oxidising conditions, the metals in the form of sulphide minerals are unstable and weather easily leading to uniformly low concentrations and small concentration ranges. Towards the Wra reef, all the elements including tin decrease. This is in agreement with the hypothesis that they derive from mining contamination. If these elements have a submarine mineralised bedrock source in the vicinity, they would be expected to show increases in their concentrations in the marginal sediment.

6.6.0. Summary of conclusions

The main conclusions in this chapter are:-

(1) The tin distribution in the surficial beach sediment between St. Agnes Head and Chapel Porth has been found to be influenced by selective sorting and concentration processes.

(2) The distribution of tin in the minus-80-mesh stream sediment reflects areas of known mineralisation, and of past mining contamination. The stream sediment of the Red River main channel which is affected by the discharge of present day mine tailings is lower in tin concentration than many of the streams draining from old tin mining



(A) Distribution of copper.

(B) Distribution of zinc.

(C) Distribution of iron. (%)

Fig. 6.9A-C. Distribution of other elements in Pendeen sediments. (in ppm unless specified)

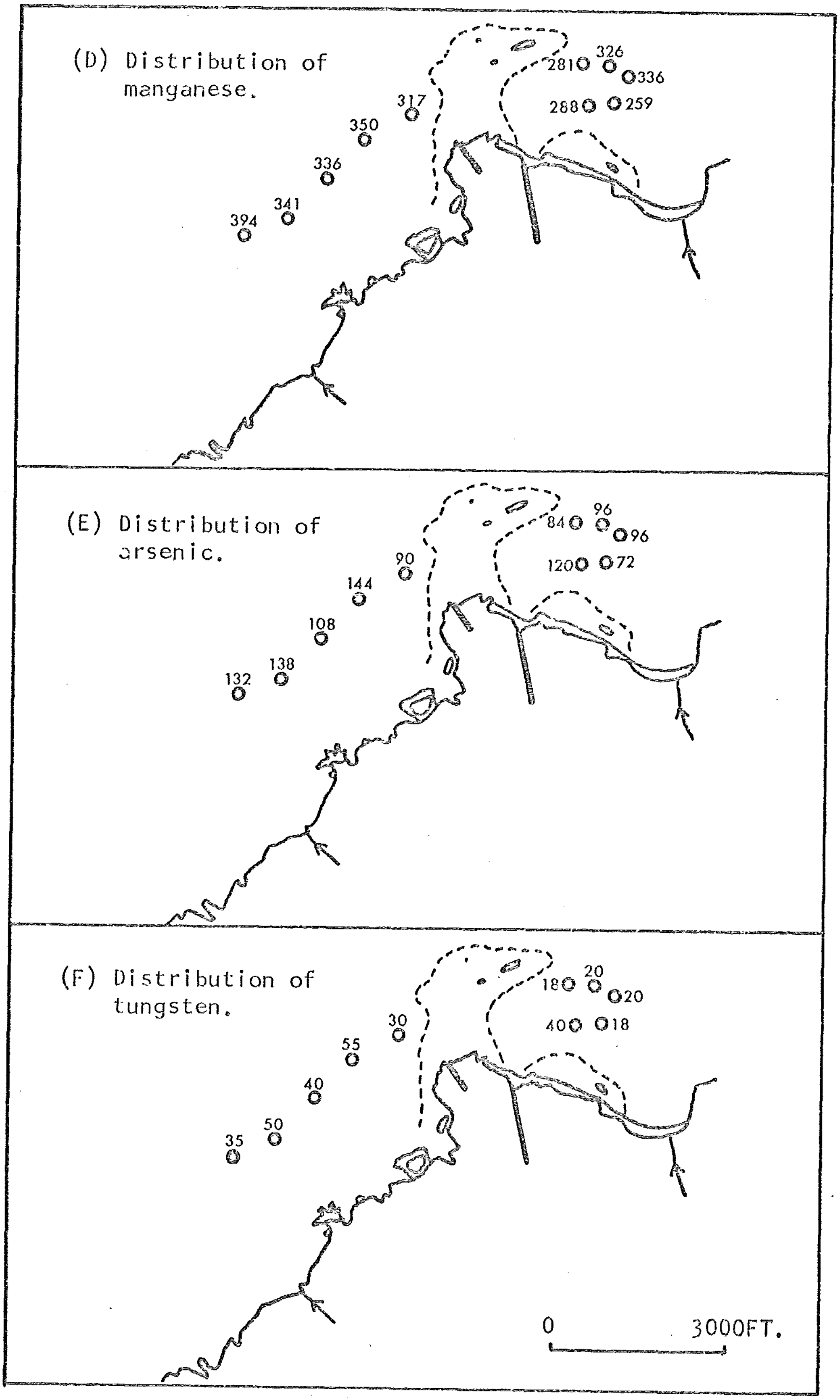


Fig. 6.9D-F. Distribution of other elements in Pendeen sediments. (in ppm)

districts.

(3) Studies on the Red River have demonstrated that appreciable quantities of very fine sand to silt and clay grade size tin are transported downstream in suspension when mine tailings are discharged into the River.

(4) Copper and arsenic associated with tin in the mineralised source rock present as sulphide minerals are unlikely to be as abundant as tin in marine sediments due to their chemical instability under 'normal' weathering and erosion.

(5) High concentrations of tin and other elements in the Hayle Estuary sediments confirm the efficiency of estuaries in trapping land derived sediment rich in heavy minerals. Variations in the composition of the sediment at depth show good correlation with past mining activity.

(6) Investigations on beach sediment has confirmed the existence of sediment enriched in tin and other elements near the High Water Mark. Under changing wind conditions, considerable amounts of beach sediment is transported offshore and alongshore, thus causing a redistribution of detrital tin and other elements.

(7) In St. Ives Bay and off Pendeen, the tin size distribution has been found to be controlled primarily by distance from source. In the former, which receives mine tailings via the Red River from a source about 5 miles upstream, tin in the sediment off the mouth of the River is appreciably finer than off Pendeen where the mine tailings are from coastally situated mines.

CHAPTER 7. FURTHER DISCUSSION

7.1.0. Introduction

In this chapter, conclusions reached in chapters 4 and 5 are examined further on account of findings in Chapter 6. Attention has been focused on the origin of tin in the surficial sediment, and characteristics used in differentiating between tin of an eluvial or alluvial source which may be of significance in mineral exploration have been discussed.

7.2.0. Sources of tin in marine sediments

The possible sources of tin in marine sediments are (a) derived from the weathering and erosion of submarine mineralised bedrock, and (b) derived from the weathering and erosion of mineralised bedrock on land followed by transport into the sea by fluvial action.

In (a), the extent of tin dispersion is unlikely to be very great due to the high specific gravity and chemical stability of cassiterite which renders it immobile. As a result tin has a strong tendency to concentrate in sediment filling bedrock depressions through elutriation. However, the weathering of submarine bedrock proceeds very slowly and it is doubtful whether much tin can be liberated from the source rock. Even along the High Water Mark, wave action on the resistant bedrock cliffs in the St. Agnes Head/Portreath area proceeds very slowly and only very little sediment can be derived in this way. Cliff detritus from this process is likely to be very fine because cliff erosion is achieved almost entirely by abrasion, grinding and impact. Hosking (1960) found further evidence to support this conclusion. In Cornish mineral lodes which outcrop at sea level, the sulphides and other minerals which tend to decompose fairly rapidly under 'normal' subaerial conditions show virtually no chemical decomposition when they are washed daily by the sea, although beyond the littoral zone they are often seen to be actively decomposing. Therefore, the weathering and erosion of submarine mineralised bedrock, which is often concealed and protected by sediment cover is unlikely to be a major source of tin supply to marine sediments.

The weathering and erosion of mineralised bedrock on land together with the reworking of mine tailings, followed by transport to the sea by rivers and streams can account for the bulk of the tin in the surficial sediment off Cornwall. The main evidences are:-

(1) The decrease in tin and associated elements away from the mouth of the rivers and streams draining from known mineralised areas.

(2) The enrichment in tin and associated elements in surface sediments as contrasted with its lower levels in the underlying sediments.

In addition to these two features, detailed studies in St. Ives Bay and Pendeen have confirmed that the enrichment in tin and associated elements in surficial sediments is the result of mining contamination from the land. Submarine bedrock mineralisation could not account for the element concentrations found in the surficial sediment, whereas the supply of mine tailings to the Bay has been demonstrated in the stream sediment investigations. Similar conditions must have existed in the St. Agnes Head/Portreath area when mines were operating on the land in the vicinity, and were using the streams for the discharge of tailings. Furthermore, the high concentration of copper, zinc, iron and arsenic present as sulphide minerals in the source rock could not follow the tin through the normal cycle of erosion because they tend to decompose rapidly under subaerial conditions. Their association with tin in the surficial sediments must therefore be indicative of a mining contamination origin.

7.3.0. Dispersion of tin

There is good evidence to support the findings of Ong (1966) and Hazelhoff Roelfzema (1968) on the dispersion of tin, in that fine tin is invariably found associated with coarser-grained sediment, which may be due to the hydraulic properties of the sediment particles which is largely a result of their different specific gravities. Ref. This may however, also be accounted for in part by the trapping of fine cassiterite grains within the intergranular spaces of the larger mineral grains, and this has been indicated by well-sorted fine sands enriched in tin being found with poorly sorted gravels in stream sediments. Hydraulic equivalence may, at best, therefore only apply to well-sorted sediments.

As an alternative to the theory of hydraulic equivalence applying in the format used by Hazelhoff Roelfzema (1968), which suffers from numerous defects, a sedimentological study on sorting and grain size distribution of tin in the sediment in the shell-free basis is a better guide in faciliating interpretation of multiple tin sources. The best sorted samples in stream, beach and marine sediments show the highest tin concentrations. Therefore high tin concentration in all grain size fractions accompanied by poor sorting in the sediment should be a good guide to submarine bedrock mineralisation, while the opposite coupled with good sorting suggests selective concentration processes in operation.

Investigation on the Red River has demonstrated that fine tin in the fine sand to silt and clay size range is transported downstream into St. Ives Bay in suspension under normal flow conditions. Transport of coarse grain size tin on the other hand, is largely by saltation and rolling and is much more strongly influenced by the stream velocity due to the stream gradient and/or periods with high surface run-off (Hazelhoff Roelfzema 1968).

Although the streams draining off the St. Agnes Head/Portreath coast appear only to contribute small quantities of detritus to the offshore sediments at the present day, because of their steep stream bed gradients, they are potentially capable of transporting sediment when available. This must have been the case when mines and smelting houses were operating in the vicinity of the coast and were using the streams for the disposal of tailings. Contamination, although not on the same scale as the Red River because the mining activity here was not as intensive, is likely to have been responsible for supplying vast quantities of mine tailings offshore. Off the mouth of the existing streams, the sediment channels enriched in tin and other elements in the surficial horizon indicate former extensions of drainage systems, a feature also found by Ong (1966) in Mount's Bay. These sediments are however generally well-sorted which is uncharacteristic of sediment with a fluvial origin. Therefore, they must have been reworked. However, despite the reworking processes, enrichment in tin and other elements can still be found, which suggests that heavy minerals can become immobile once deposited.

The offshore dispersion of beach sediment enriched in mine tailings deposited at the mouth of the Red River has been demonstrated. Marine processes have been shown to be selective and are responsible for the concentration and grain size distribution of tin in marine sediments extending into the foreshore zone. Conditions favourable for beach aggradation and degradation depend primarily on the wind strength and direction and it has been shown that under favourable conditions, vast quantities of beach sediment containing mine tailings can be dispersed offshore.

7.4.0. Differentiation between eluvial and alluvial sources of tin

The analysis of tin in surficial marine sediment in order to locate submarine bedrock mineralisation is of little use unless the sediment cover is very thin. The difficulty arises because of the immobility of cassiterite. In the southern part of the main sediment body in the St. Agnes Head/Portreath area, where the sediment thins out to nothing, the marginal sediment shows decreases in tin concentration in all grain size fractions. Therefore, the anomalous concentrations found within the sediment body and away from the marginal sediment is likely to have an alluvial rather than an eluvial origin.

The use of pathfinder elements associated with tin in the source rock is also dependant on an understanding of mining contamination in determining element distribution. The association of copper, iron, arsenic and tungsten with tin in the surficial sediment is indicative of an alluvial source. Zinc and manganese, both enriched in killas as well as in mine tailings, show a similar pattern to tin, copper, iron, arsenic and tungsten close inshore, but increases further offshore, which suggests that they may be better pathfinders for tin of eluvial origin. Therefore, high zinc and manganese concentrations accompanying high tin but low in copper, iron and arsenic in poorly sorted sediment could theoretically indicate an eluvial source due to the availability of locally derived tin bearing killas.

The grain size distribution of tin remains the most valuable means of differentiating between eluvial and alluvial sources of tin. Although the size of availability of cassiterite in the source rock governs the grain size distribution of tin, at increasing distances away from the source rock, the tin can be expected to decrease in all grain size fractions particularly in the coarsest. Therefore, using this criterion, it should be possible to differentiate between the two sources of tin because coarse-grained tin originating from an eluvial source will distort the alluvial grain size distribution of tin. However, when dealing with reworked near-shore surficial sediments in the St. Agnes Head/Portreath area, differentiation between eluvial and alluvial tin is very difficult due to sediment mixing. Towards the St. Agnes Beacon Granite, the tin enrichment in the coarse size fractions of sediments is likely to be both eluvial and alluvial in origin and related to local sources both onshore and offshore.

In St. Ives Bay, the bulk of the tin in the sediment off the Red River which has originated from mine tailings has been shown by mineralogical studies to be present largely in the form of fine cassiterite inclusions with quartz-tourmaline and quartz-chlorite intergrowths (Warren Spring 1962, unpub. rep.). These grains make up the bulk of the tin present in mine tailings and because of their low specific gravity compared to mono-mineralic cassiterite grains are much more liable to loss in mineral recovery processes and transport by fluvial processes to the sea.

CHAPTER 8. MAIN CONCLUSIONS AND RECOMMENDATIONS

8.1.0. Main conclusions

8.1.1. Field techniques

(1) The Shipek grab provides a rapid means of sampling surficial marine sediments. The sediment samples obtained were found to be satisfactory for the purpose of marine geochemical reconnaissance in areas with sand.

(2) The Decca Navigator provides a rapid means of position fixing offshore. However due to the inaccuracy of the method in near-shore areas, the sextant is recommended in future work.

(3) The Hydrowerkstatten Vibrocorer was found to be suitable for taking sediment cores in medium to fine sand but further improvements are necessary for its use in exposed areas with strong currents. A more powerful vibrocorer would be necessary for taking basal sediment samples adjacent to the bedrock.

(4) The bucket auger provides a rapid means of sampling the vertical sections of alluvial and estuarine sediments. Although the samples obtained are often disturbed, when sufficient care is taken contamination due to sediment mixing is insignificant.

8.1.2. Laboratory techniques

(1) The importance of sampling reproducibility for tin-bearing sediment has been stressed. In order to minimise sampling error, the samples should be split down representatively and ground.

(2) A rapid method for the determination of tin by atomic absorption using a nitrous oxide/acetylene flame based on the method of Bowman (1968) has been modified and applied to sediments, and the results show agreement with the volumetric technique.

(3) The preliminary removal of shells from beach and offshore

sediments is found to be highly desirable in tin determination. This firstly upgrades tin in the sediments and reduces sampling error; secondly, gives a clearer picture of the distribution of tin in detrital sediments, and thirdly, removes shell interferences in tin determination.

(4) To save time and cost, the leach solution from a nitric acid/perchloric acid attack on the sample prepared for the atomic absorption analysis of other elements can be adopted for the colorimetric determination of arsenic following the procedure of Stanton (1966). The results using this technique are comparable with those obtained by potassium bisulphate fusion.

8.1.3. Application of hydraulic equivalence

(1) The hydraulic equivalence theory based on Stokes Law used to distinquish the source of tin by Hazelhoff Roelfzema and Tooms (1969) may apply only to silt size particles. For coarser size particles there is only a rough approximation.

(2) Because the sediment off the North Cornish coast consists largely of medium to fine sand, which yields very little silt size fraction, hydraulic equivalence cannot be applied here.

(3) Grinding has been shown to be essential to minimise sampling error, therefore the present tin results take account of both mono-mineralic and composite cassiterite grains. Since composite cassiterite grains may be present in abundance in sediment, and do not fulfill the conditions required by Stokes Law, the relative availability of tin determined on the basis of these grains using hydraulic equivalence, may be totally misleading.

(4) In order to apply hydraulic equivalence satisfactorily, it is necessary to adopt time consuming grain counting techniques to

determine the abundance of mono-mineralic cassiterite grains and their equivalent size mineral grains. However, as an alternative to this very slow process, the mean size and sorting coefficient of the sediment, used in conjunction with the tin grain size distribution, is a far more rapid and reliable method than hydraulic equivalence in distinquishing between different sources of tin.

8.1.4. Physical and environmental features in the offshore areas

(1) There is no evidence to suggest that the submarine rocks in the areas investigated are composed of rocks other than killas.

(2) The environmental conditions found in the St. Agnes Head/Portreath area are thought to be intermediate between the exposed high energy Pendeen area and the more shethered lower energy bay environment in St. Ives Bay. This is reflected in the mean size of the surficial sediments. In the Pendeen area the sediment is dominated by coarse sand, in the St. Agnes Head/Portreath area by medium sand and in the St. Ives Bay by fine sand.

(3) Off the mouth of present day rivers and streams, there are sediment filled bedrock channels similar to those in Mount's Bay (Ong 1966), and may be extensions of former river valleys.

(4) Bathymetry suggests that the marine erosion platform in the Cligga Head/St. Agnes Head area at about 10 fathoms (Garnett 1962) may occur in other parts of the North Cornish coast. There is also evidence for other platforms at greater depths.

(5) In all areas, the majority of the surficial sediments are well-sorted to moderately sorted, which suggests reworking processes have taken place.

(6) Sediment thickness is reflected in mean size, sorting coefficient and shell content in the surficial sediment.

(7) Towards the shore, the sediment generally increases in mean size as well as becoming progressively better sorted. This is in agreement with the expected increase in energy level conditions found within the breaker zone.

(8) Mean size versus sorting on the very well-sorted sand half a mile west of St. Agnes Head suggests the existence of strong bottom currents off the headland.

(9) In St. Ives Bay, the shell content in the surficial sediment increases towards the western part of the Bay and decreases gradually towards the mouth of the Red River. Towards the central part of the Bay which contains fine silty sand, there is also a decrease in shell content compared to the coarser sediment found at shallower depths.

(10) With the exception of St. Ives Bay, there is a general increase in shell content away from the shore and with increasing water depth in the surficial sediments. Superimposed on this general distribution pattern, sediments from near the margin of the sediment body are enriched in shells, and sediments off the mouth of present day rivers and streams are poor in shells.

(11) Wind strength and direction is primarily responsible for the direction of sediment movement in the foreshore zone.

8.1.5. Distribution of tin in stream sediments

(1) The minus-80-mesh tin distribution in stream sediments reflects the known tin mineralisation areas as well as giving an indication of the intensity of mining activity in these areas. In some areas where tin is not the main ore element, the high concentration of tin may be related to contamination from smelting houses using ore from other areas.

(2) Investigations on the Red River have shown that large quantities

of fine tin in the very fine sand to silt and clay size range travel downstream in suspension under normal flow conditions, and eventually reach the sea. The bulk of the tin lost through present day mine tailings is below 20 microns in grain size and these tailings find their way downstream into the sea without any difficulty.

(3) The Red River shows a general decrease in tin concentration downstream away from the mineralised area.

✓(4) The association of copper, iron, arsenic and tungsten, and less clearly zinc and manganese with tin, is the result of mining rocks containing minerals bearing these elements. The distribution pattern of elements present as sulphide minerals found associated with tin in the source rock including copper, zinc, iron and arsenic, are related to their relative transportational resistance. These sulphide minerals are likely to be much less abundant than tin in stream sediments during 'normal' weathering and erosion, because they are more easily broken down than cassiterite.

Bell sed.

(5) The presence of primary alluvial tin placers is indicated by high tin concentrations in coarse size fractions.

(6) Zinc and manganese are poor pathfinder elements for tin in killas areas, because they occur in abundance in barren killas.

8.1.6. Distribution of tin in estuarine sediments

(1) The Hayle Estuary acts as an excellent trap for land detritus which has included past mine tailings.

(2) Examination made on the elemental composition in the vertical section of sediment correlates well with past mining records and recent geological events. On this basis, the effect and nature of past mining contamination on marine sediments can be

evaluated.

8.1.7. Distribution of tin in beach sediments

(1) There is a zone of enrichment in heavy minerals including cassiterite near the High Water Mark in the surficial sediments.

(2) Sediment enriched in mine tailings deposited on the beach by rivers and streams can be dispersed offshore during periods of strong onshore winds. The offshore dispersion of sediment is however selective, coarse-grained heavy minerals are the least mobile and have a tendency to remain on the beach.

(3) In the St. Agnes Head/Chapel Porth beach, variations in tin concentration in the sediment may be accounted for by the influence of reworking processes including running water down the beach slope, as well as wave action influencing the formation of beach cusps.

(4) The highest tin concentrations are generally found to be associated with well-sorted sediments. This suggests that selective sorting and concentration is primarily responsible for local enrichment in cassiterite, while distance from source is only of secondary importance.

8.1.8. Distribution of tin in marine sediments

(1) In the St. Agnes Head/Portreath area, the surficial sediment is enriched in tin which suggests a recent origin. This enrichment is accompanied by copper, iron, arsenic and tungsten, and less clearly by zinc and manganese. The latter two elements are enriched in killas, therefore their distribution in sediments may serve as a guide to bedrock source and sediment thickness.

(2) Off the mouth of rivers and streams draining from old disused mining districts, the surficial sediment is enriched in tin and other elements in the foreshore zone. This indicates that

alluvial placers may be present.

(3) Tin is invariably found concentrated in the fine size fraction of sediments. In the coarser size fractions, the tin present is almost entirely in the form of composite grains.

(4) The grain size distribution of tin in sediments partly reflects the distance from the source. Coarse tin is found near to the source rock as well as near to the shore, while fine tin travels greater distances and is found furthest away.

(5) The grain size distribution of tin in sediments using the distance from source criteria, can give an indication of its origin. For example, anomalous concentrations of fine tin not accompanied by coarse tin, as is the case off the mouth of the Red River, shows a mining contamination origin.

(6) Enrichment in tin and associated elements in the basal sediments may be indicative of submarine bedrock mineralisation.

(7) The enrichment in sediments of elements associated with tin in source rocks is the result of mining contamination. Mining operations are responsible for the liberation of minerals bearing these elements in a fresh state, and since these minerals have not been subjected to the long process of 'normal' weathering and erosion, they may be enriched in surficial sediments.

(8) The very well-sorted sand half a mile west of St. Agnes Head which is enriched in coarse tin compared to adjacent sediments is likely to be the result of reworking processes due to strong bottom currents. The high concentrations of elements associated with tin in the sand suggest that the sediments are unlikely to be those of a fossil beach, because mining activity responsible for the concentrations is a geologically very recent event.

8.2.0. Recommendations for future work

(1) The vertical distribution of tin and its associated elements in sediments off the North Cornish coast should be further investigated by detailed coring, especially in the anomalous area between Porthowan and Portreath, and the area off the Towanwrath Lode.

(2) There is a need for a detailed Sparker and echosounder survey in the St. Agnes Head/Portreath area, to aid interpretation of the tin distribution.

(3) Mineralogical studies should be carried out to determine the grain size and characteristics of mono-mineralic cassiterite grains, and the abundance of composite tin grains.

(4) The part played by tidal currents and wind-induced currents in sediment movement should be further investigated.

(5) The method of tin determination proposed should be tested for soils to determine its further application.

(6) The sediment at about 10 fathoms and the sediment channels off the mouth of present day rivers and streams should be cored and studied to verify the existence of tin-bearing fossil beach and alluvial placer deposits.

(7) In order to evaluate the mineral potential of the sediments, heavy media separations should be carried out to determine the liberation characteristics of tin in the sediments particularly in the anomalous areas.

(8) The sampling problem of heavy minerals present as discrete mineral grains warrants more attention in mineral exploration.

PLATES

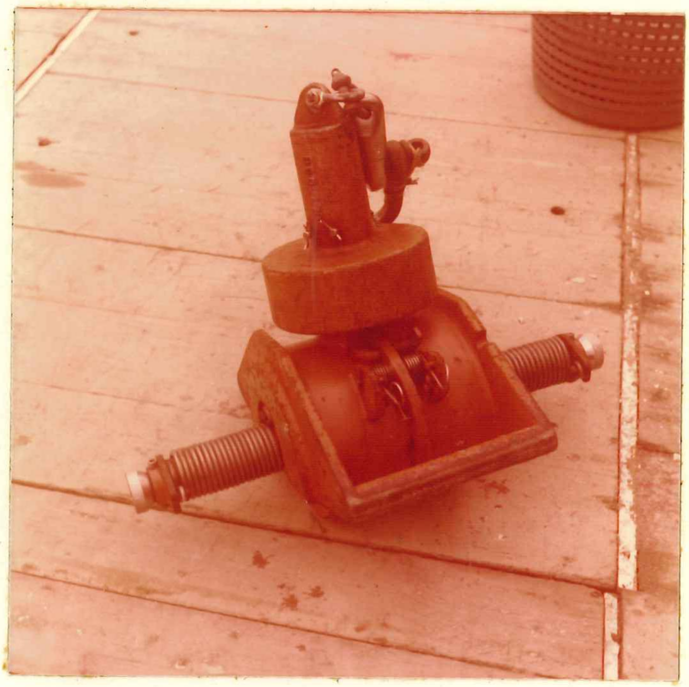


Plate I. The Shipek grab.

Plate II. Photograph taken 2 minutes after a pit was dug in the foreshore zone of the Gwithian Beach.

APPENDIX

WIND STRENGTH AND DIRECTION DATA FOR THE SAMPLING PERIODS RECORDED AT THE KEHELLAND METEOROLOGICAL STATION.
(Time in G.M.T., direction to the nearest 10° and strength in knots).

(A) Gwithian Beach Traverse 1 and 2, 5th January, 1972.

1/ 1	0015	060	10	2/ 1	0015	050	05	3/ 1	0015	calm	-
	0615	060	10		0615	060	11		0615	calm	-
	1215	070	12		1215	060	02		1215	260	03
	1815	080	12		1815	calm	-		1815	calm	-
4/ 1	0015	calm	-	5/ 1	0015	110	02				
	0615	calm	-		0615	100	05				
	1215	030	05		1215	190	03				
	1815	100	05		1815	120	05				

(B) Gwithian Beach Traverse 1 resampled and Portheras Cove Beach, 7-10th April, 1972.

2/ 4	0015	250	15	3/ 4	0015	260	20	4/ 4	0015	190	16
	0615	240	22		0615	290	04		0615	200	20
	1215	220	20		1215	280	05		1215	250	30
	1815	250	24		1815	200	10		1815	250	32
5/ 4	0015	280	38	6/ 4	0015	270	20	7/ 4	0015	230	25
	0615	280	25		0615	270	22		0615	220	30
	1215	270	24		1215	260	15		1215	270	30
	1815	230	22		1815	220	16		1815	250	32
8/ 4	0015	260	30	9/ 4	0015	260	02	10/ 4	0015	240	18
	0615	280	27		0615	360	13		0615	280	12
	1215	270	25		1215	360	15		1215	280	28
	1815	270	05		1815	300	10		1815	280	27

(C) Grab and St. Agnes Head/Chapel Porth beach sampling, 28th June - 4th July, 1972.

14/ 6	0015	080	08	15/ 6	0015	020	08	16/ 6	0015	360	06
	0615	070	08		0615	010	05		0615	340	05
	1215	030	15		1215	340	09		1215	350	05
	1815	020	15		1815	340	10		1815	340	04
17/ 6	0015	calm	-	18/ 6	0015	230	18	19/ 6	0015	290	12
	0615	190	03		0615	220	22		0615	290	10
	1215	200	14		1215	220	15		1215	270	17
	1815	210	15		1815	320	15		1815	280	16
20/ 6	0015	210	05	21/ 6	0015	240	12	22/ 6	0015	270	18
	0615	220	06		0615	240	18		0615	270	14
	1215	210	16		1215	260	18		1215	280	15
	1815	230	20		1815	270	22		1815	280	17
23/ 6	0015	310	15	24/ 6	0015	280	20	25/ 6	0015	230	12
	0615	280	06		0615	250	12		0615	220	15
	1215	270	10		1215	230	12		1215	210	15
	1815	260	15		1815	230	10		1815	220	14

26/ 6	0015	220	12	27/ 6	0015	180	14	28/ 6	0015	290	14
	0615	230	10		0615	220	15		0615	240	06
	1215	260	04		1215	320	15		1215	230	10
	1815	220	04		1815	280	15		1815	230	09
29/ 6	0015	230	04	30/ 6	0015	160	04	1/ 7	0015	270	05
	0615	230	02		0615	210	05		0615	290	10
	1215	360	02		1215	180	22		1215	310	18
	1815	270	05		1815	220	15		1815	290	18
2/ 7	0015	270	14	3/ 7	0015	290	22	4/ 7	0015	240	10
	0615	240	13		0615	300	14		0615	220	15
	1215	270	23		1215	240	15		1215	220	18
	1815	270	22		1815	260	13		1815	220	15

(D) Vibrocoring, 10th October, 1972.

4/10	0015	050	10	5/10	0015	070	08	6/10	0015	060	02
	0615	060	11		0615	060	04		0615	030	02
	1215	080	15		1215	010	05		1215	360	03
	1815	030	08		1815	030	08		1815	320	06
7/10	0015	calm	-	8/10	0015	260	02	9/10	0015	210	25
	0615	220	06		0615	100	02		0615	010	25
	1215	270	15		1215	200	10		1215	020	25
	1815	290	11		1815	170	12		1815	360	18
10/10	0015	360	08								
	0615	350	13								
	1215	330	14								
	1815	310	12								

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OFFSHORE SAMPLE LOCATIONS AND SAMPLE CHARACTERISTICS
KEY-
   + - SAMPLES WITHOUT GRANULOMETRIC ANALYSIS ARE DESCRIBED
   * - PERCENT SHELLS = 100 - PERCENT DETRITAL FRACTION
   S - SAND
  LS - LITTLE SAND
   G - GRAVEL
   R - ROCK
  BG - BAD GRAB
  CS - CLEAN SAND
  CR - COUNTRY ROCK GRAVEL PRESENT
 COLOUR-
  PY - PALE YELLOW
 PYG - PALE YELLOW-GREY
  YG - YELLOW-GREY
 DYG - DARK YELLOW-GREY
  YB - YELLOW-BLACK
   G - GREY
 SORTING-
   M - MODERATELY SORTED 0.5-1.0
   P - POORLY SORTED 1.0-2.0
  VP - VERY POORLY SORTED 2.0-4.0
  EP - EXTREMELY POORLY SORTED OVER 4.0
SAMPLE     LOCATION                                PERCENT
 NO.        (DECCA)                  MEAN SORTING DETRITAL     OBSERVATIONS
        GREEN  PURPLE TYPE  COLOUR   SIZE  COEFF+  FRAC*
 ST. AGNES HEAD / PORTREATH GRABS
   1     31.11  71.12    S     PYG    1.75  0.651    22.50      CR
   2     31.32  71.30   BG
   3     31.60  71.21   BG
   4     31.55  71.27   BG
   5     31.77  71.25   BG
   6     32.16  71.00   BG
   7     32.39  70.75   BG
   8     32.68  70.60   BG
   9     33.03  70.29   BG
  10     33.16  69.90   BG
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11	33.33	69.70	RG					
12	33.56	69.55	RG					
13	33.71	69.35	S	DYG	2.43	0.658	30.07	
14	33.90	69.16	S	DYG	2.25	0.518	24.51	
15	34.23	68.99	S	DYG	2.60	0.666	35.97	
16	34.59	68.86	S	DYG	2.59	0.649	36.37	
17	34.81	68.80	S	DYG	2.54	0.627	36.75	
18	35.16	68.88	S	DYG	2.58	0.594	34.66	
19	35.45	68.88	S	PYG	2.23	0.621	21.15	
20	35.77	68.94	S	YG	2.48	0.578	29.66	
21	36.08	68.99	S	PYG	2.30	0.598	23.76	
22	36.55	69.00	S	YG	2.40	0.568	28.36	
23	36.64	68.96	S	PYG	1.91	0.600	15.02	
24	36.93	68.96	S	PYG	1.97	0.570	15.39	
25	37.29	68.99	S	PY	1.80	0.599	7.88	
26	37.57	69.14	S	PYG	-	P	11.80	
27	37.87	69.16	S	PY	-	M	8.22	
28	38.18	69.18	S	PY	1.39	0.707	8.43	
29	38.16	69.27	S	PY	1.78	0.553	7.32	
30	38.83	69.23	S	PY	-	M	8.31	
31	29.27	69.17	S	PY	1.30	0.747	7.89	
32	39.47	69.06	S	PY	1.68	0.559	9.32	
33	31.60	71.30	S	PY	-	P	20.55	CR
34	31.80	71.16	S	PY	1.74	0.621	11.00	
35	32.21	71.06	S	PY	1.97	0.666	14.87	
36	32.46	70.79	S	PY	2.04	0.521	12.25	
37	32.77	70.57	S	PYG	2.25	0.497	18.87	
38	33.00	70.36	S	PYG	2.21	0.481	19.32	
39	33.29	69.75	S	YG	2.47	0.522	36.56	
40	33.42	69.50	S	DYG	2.47	0.599	36.73	
41	30.28	70.09	S	DYG	1.93	0.357	48.58	
42	30.34	69.74	S	DYG	1.58	0.544	52.09	
43	30.49	69.48	S	DYG	1.57	0.447	51.83	
44	30.60	69.15	S	YG	1.64	0.478	50.23	
45	30.75	69.05	S	DYG	1.79	0.378	50.27	
46	30.84	68.80	S	YG	1.55	0.340	51.98	
47	30.93	68.60	S	YG	1.51	0.607	53.99	

48	30.99	68.71	S	YG	1.40	0.592	54.91	
49	31.12	68.57	S	YG	1.49	0.582	53.58	
50	31.27	68.39	S	DYG	1.57	0.478	52.37	
51	31.42	68.28	S	YG	1.54	0.460	52.88	CR- QUARTZ
52	31.64	68.19	S	YG	1.34	0.586	56.48	
53	31.72	68.10	S	YG	1.56	0.468	52.49	
54	31.84	67.85	S	DYG	1.77	0.461	50.14	
55	32.02	67.79	S	YG	1.37	0.624	54.62	CR- QUARTZ
56	32.15	67.67	S	YG	1.55	0.484	52.81	
57	32.27	67.59	S	YG	1.59	0.507	52.46	
58	32.36	67.44	S	PYG	1.56	0.525	53.12	
59	32.50	67.31	S	YG	1.67	0.474	51.51	
60	32.63	67.22	S	YG	1.68	0.448	51.04	
61	32.75	67.12	S	YG	1.69	0.458	50.95	
62	62.84	67.00	S	DYG	1.87	0.398	48.68	
63	33.00	66.85	S	DYG	1.88	0.386	50.03	CR- RED SLATE
64	33.08	66.82	S	YG	1.77	0.435	50.57	
65	33.21	66.79	S	DYG	1.93	0.379	49.86	
66	33.31	66.72	S	YG	1.91	0.399	48.47	
67	33.45	66.68	S	YG	1.71	0.470	49.92	
68	33.60	66.65	S	DYG	1.75	0.475	49.52	
69	33.71	66.65	S	YG	1.84	0.516	48.89	
70	33.84	66.65	S	YG	1.95	0.416	48.32	
71	33.95	66.66	S	DYG	2.09	0.405	50.81	
72	34.05	66.68	S	YG	2.02	0.453	51.25	
73	34.20	66.63	S	YG	2.01	0.446	49.70	
74	34.29	66.55	S	YG	1.85	0.678	50.90	
75	34.45	66.50	S	DYG	1.70	0.628	50.46	
76	34.59	66.49	R					
77	34.59	66.33	S	PYG	1.89	0.478	50.54	
78	34.55	66.25	R					
79	34.55	66.20	S	DYG	1.78	0.427	48.68	
80	34.51	66.15	R					
81	34.60	66.19	R					
82	34.62	66.21	S	DYG	1.94	0.463	39.84	
83	34.68	66.26	R					
84	34.80	66.32	S	DYG	1.81	0.589	52.73	

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 85    34.95  66.33   S    DYG    2.30  0.409   54.97
 86    35.05  66.25   R
 87    35.05  66.25  LS
 88    35.00  66.15   S     YG    2.12  0.478   51.62
 89    34.90  66.10   R
 90    34.95  66.10   R
 91    35.16  66.18   R
 92    35.24  66.22   R
 93    35.38  66.22   R
 94    37.18  66.10   S    DYG    2.10  0.528   50.95
 95    37.30  66.05   S    DYG    2.17  0.482   55.18
 96    37.94  65.65   R
 97    37.96  65.66   S     YG    1.97  0.477   46.57
 98    37.82  65.66   S     YG    1.57  0.722   52.79
 99    37.93  65.70   S     YG    1.90  0.406   44.47
100    38.38  65.70   R
101    38.40  65.71   G     PY      -      EP   55.60     CR
102    38.63  65.63   R
103    38.60  65.45  LS
104    38.63  65.55   S    DYG    1.94  0.809   45.23
105    39.16  65.71   R
106    39.22  65.70  LS
107    39.38  65.58   S    DYG    2.19  0.540   51.06     CR- SLATE
108    39.80  65.89   G             -      VP   52.35
109    32.10  71.98   R
110    33.05  72.05  LS
111    33.52  71.72   S     YG    2.39  0.853   28.43     WITH SILT
112    33.63  71.41  LS                                  CR- QUARTZ
113    33.76  71.20  LS                                  CR
114    33.93  70.95   S     PY    1.77  0.658    8.25
115    34.12  70.80   S     PY    1.75  0.603    9.57
116    34.30  70.70   S     PY    2.03  0.497   12.70
117    34.45  70.60   S    PYG    2.24  0.444   20.50
118    34.55  70.50   S    PYG    2.28  0.418   21.99
119    34.65  70.42   S    PYG    1.98  0.461   14.99
120    34.75  70.30   S    PYG    1.83  0.6[illegible]1   12.95
121    34.85  70.22   S     PY    2.35  0.456   27.20
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122	34.98	70.10	S	PYG	2.23	0.459	22.71	
123	35.12	69.95	S	PYG	1.96	0.519	19.35	
124	35.22	69.79	S	PYG	1.95	0.505	15.87	
125	35.32	69.70	S	PYG	2.01	0.533	17.09	
126	35.42	69.65	S	DYG	2.32	0.480	25.26	
127	35.58	69.55	S	PYG	2.21	0.536	20.60	
128	35.75	69.65	S	PYG	2.21	0.548	20.55	ORGANIC MATTER RICH
129	35.89	69.62	S	PYG	2.27	0.513	25.59	
130	36.05	69.61	S	YG	2.40	0.454	25.42	ORGANIC MATTER RICH
131	36.20	69.60	S	PYG	2.27	0.503	24.73	
132	36.32	69.62	S	PY	1.72	0.662	12.93	
133	36.46	69.61	S	PY	1.91	0.790	15.61	
134	36.55	69.60	G	PY	-	VP	9.40	
135	36.64	69.62	S	PY	2.12	0.518	20.07	
136	36.80	69.64	S	PY	1.99	0.755	17.70	
137	37.00	69.65	S	DYG	2.30	0.572	22.62	
138	37.09	69.69	S	PY	1.87	0.591	13.36	
139	37.19	69.70	S	PY	-	M	7.94	
140	37.30	69.70	S	PY	-	P	7.37	
141	37.40	69.73	LS					
142	37.52	69.72	S	PY	1.43	0.734	8.86	
143	37.60	69.76	S	PY	1.60	0.735	9.83	
144	37.71	69.75	S	PY	2.02	0.518	14.51	
145	37.81	69.75	S	PY	-	M	7.82	
146	37.92	69.75	S	PY	-	M	8.10	
147	38.02	69.70	S	PY	-	M	7.75	
148	38.10	69.71	S	PY	1.83	0.665	12.67	
149	38.16	69.66	S	PY	1.85	0.597	12.64	
150	38.30	69.72	S	PY	-	M	7.60	
151	38.40	69.78	S	PY	-	M	7.81	
152	38.50	69.70	S	PY	2.00	0.533	13.47	
153	38.61	69.69	S	PY	1.65	0.653	11.79	
154	38.72	69.73	S	PY	-	M	8.20	
155	38.81	69.69	S	PY	-	P	8.27	
156	38.90	69.65	S	PY	-	P	8.32	
157	39.00	69.58	S	PY	-	M	7.98	
158	39.12	69.53	S	PY	-	P	8.62	

159	39.22	69.51	S	PY	-	P	7.72	
160	39.31	69.42	S	PY	1.53	0.685	8.86	
161	39.42	69.32	S	PYG	2.02	0.692	13.52	
162	39.51	69.25	LS					
163	39.60	69.15	LS					
164	39.70	69.10	LS					
165	30.88	70.50	S	YG	2.02	0.445	45.97	
166	31.00	70.52	S	YG	2.00	0.403	42.94	
167	31.10	70.51	S	DYG	2.05	0.502	38.50	SOME CLAY
168	31.20	70.50	S	YG	2.21	0.417	38.60	
169	31.30	70.45	S	YG	2.33	0.423	36.80	
170	31.40	70.39	S	YG	2.37	0.348	37.09	
171	31.51	70.32	S	YG	2.41	0.326	38.13	
172	31.60	70.29	S	YG	2.38	0.336	36.33	
173	31.70	70.29	S	YG	2.48	0.356	34.27	
174	31.80	70.20	S	YG	2.40	0.325	34.84	
175	31.90	70.15	S	YG	2.41	0.338	33.24	
176	32.00	70.10	S	YG	2.38	0.361	32.71	
177	32.10	70.00	S	YG	2.44	0.362	34.11	
178	32.22	69.91	S	YG	2.45	0.414	34.17	
179	32.33	69.90	S	YG	2.44	0.4[illegible]9	30.46	
180	32.45	69.90	S	YG	2.39	0.443	30.88	
181	32.53	69.95	S	YG	2.42	0.438	29.88	
182	32.65	69.90	S	YG	2.38	0.455	23.62	
183	32.72	69.94	S	YG	2.37	0.452	27.28	
184	32.82	69.85	S	YG	2.43	0.481	31.34	
185	32.92	69.75	S	DYG	2.44	0.517	31.99	
186	33.02	69.65	S	DYG	2.52	0.518	35.26	
187	33.11	69.55	S	YG	2.54	0.540	38.27	
188	33.21	69.51	S	DYG	2.49	0.559	36.61	
189	33.30	69.41	S	YG	2.47	0.580	40.44	
190	33.40	69.35	S	YG	2.51	0.547	38.28	
191	33.50	69.29	S	YG	2.45	0.575	35.22	
192	33.60	69.25	S	DYG	2.47	0.651	36.00	
193	33.71	69.20	S	YG	2.40	0.586	32.37	
194	33.85	69.20	S	PYG	1.89	0.732	17.32	
195	33.95	69.15	S	YG	2.51	0.594	35.25	

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196    34.05   69.15   S    YG    2.29   0.521   27.04
197    34.15   69.15   S    YG    2.57   0.570   36.12
198    34.22   69.19   S    YG    2.31   0.721   29.62
199    34.32   69.09   S   PYG    1.77   0.576   13.85
200    34.40   69.03   S   PYG    1.93   0.512   16.47
201    34.51   68.95   S    YG    2.63   0.638   37.16
202    34.61   68.85   S    YG    2.58   0.673   35.90
203    34.71   68.80   S    YG    2.55   0.632   35.56
204    34.81   68.74   S   DYG    2.54   0.647   35.16
205    34.91   68.72   S    YG    2.45   0.647   34.44
206    35.03   68.69   S   DYG    2.54   0.550   33.89
207    35.14   68.65   S    YG    2.52   0.508   35.37
208    35.24   68.62   S    YG    2.48   0.664   34.07
209    35.34   68.64   S    PY    1.73   0.579   12.46
210    35.45   68.56  LS
211    35.55   68.52   S   DYG    2.26   0.608   26.32
212    35.64   68.40   S    PY    1.85   0.543   12.20
213    35.75   68.39   S    PY    2.12   0.571   11.80
214    35.86   68.36  LS
215    35.95   68.36   S    PY    1.65   3.471    8.79
216    36.06   68.34   S    PY     . -       M   12.46
217    36.14   68.23   G    PY      -       VP   10.38
218    36.30   68.09   G    PY      -       VP   17.07      CR
219    36.45   68.00   S    YG    2.55   0.581   34.19
220    36.60   67.94   S   DYG    2.46   0.650   31.56      WITH SILT
221    36.71   67.93   S   PYG    2.15   0.536   22.80
222    36.84   67.92  LS
223    36.96   67.90  LS
224    37.06   67.85  LS
225    37.20   67.93   G    PY      -       VP   23.34
226    37.40   67.80   R
227    37.53   67.82   R
228    37.68   67.72   R
229    37.75   67.59   R
230    37.89   67.54   R
231    38.01   67.50   R
232    38.12   67.45   R
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233	38.25	67.35	R					
234	38.27	67.30	R					
235	38.50	67.25	R					
236	38.63	67.15	G	PY	-	VP	19.01	CR- SLATE, QUARTZ
237	38.72	67.09	LS					
238	38.88	66.90	R					
239	38.98	66.82	R					
240	39.10	66.74	LS					
241	39.22	66.60	LS					
242	39.32	66.45	R					
243	39.46	66.40	R					
294	31.10	70.05	S	YB	2.64	0.485	56.35	
295	31.23	69.55	S	YB	2.52	0.548	56.45	
296	31.35	69.44	S	YB	2.60	0.534	57.43	
297	31.45	69.27	BG		.	.	.	
298	31.58	69.00	S	YB	2.48	0.616	57.65	
299	31.73	68.80	S	YB	2.59	0.599	60.63	
300	31.86	68.75	S	YB	2.67	0.593	63.48	
301	31.98	68.60	S	YB	2.54	0.647	60.49	CR- QUARTZ
302	32.10	68.53	S	YB	2.55	0.667	61.38	
303	32.23	68.45	S	YB	2.51	0.660	59.30	
304	32.34	68.35	S	YB	2.53	0.590	59.76	
305	32.48	68.20	S	YB	2.48	0.601	56.95	
306	32.60	68.10	S	YB	2.53	0.605	59.07	
307	32.72	67.95	S	YB	2.55	0.609	58.96	
308	32.83	67.75	S	YB	2.56	0.594	56.17	CR- QUARTZ
309	32.96	67.60	S	YB	2.58	0.586	61.96	CR- QUARTZ
310	33.10	67.55	S	YB	2.73	0.547	62.48	CR- QUARTZ
311	33.22	67.45	S	YB	2.56	0.541	60.28	
312	33.33	67.43	S	YB	2.61	0.530	62.69	
313	33.45	67.40	S	YB	2.57	0.544	62.06	
314	33.58	67.35	S	YB	2.49	0.532	60.43	
315	33.70	67.30	S	YB	2.54	0.585	60.94	
316	33.82	67.30	S	YB	2.49	0.523	57.47	
317	33.95	67.30	S	YB	2.52	0.552	58.81	
318	34.10	67.32	S	YB	2.40	0.482	55.00	
319	34.22	67.30	S	YB	2.39	0.512	54.65	

320	34.36	67.25	S	YB	2.28	0.597	52.67	
321	34.50	67.24	S	YB	2.25	0.590	51.63	
322	34.63	67.22	G	PY	-	VP	26.99	
323	34.75	67.18	R					
324	34.95	67.10	R					
325	35.55	67.00	S	YB	~~1.73~~ 2.62	0.483	60.97	
326	35.70	67.00	S	YB	2.63	0.529	59.60	
327	35.82	66.98	S	YB	2.58	0.527	59.02	
328	35.98	66.90	S	YB	2.55	0.513	56.41	
329	36.10	66.85	S	YB	2.58	0.524	58.98	
330	36.22	66.78	S	YB	2.55	0.485	61.10	
331	36.40	66.72	S	YB	2.54	0.546	61.02	SOME CLAY
332	36.52	66.70	S	YB	2.47	0.531	56.41	
333	36.65	66.68	S	YB	2.32	0.515	46.76	
334	36.80	66.65	G	PY	-	VP	21.86	CR
335	36.95	66.58	R					
336	37.06	66.55	R					
337	37.24	66.48	R					
338	37.55	66.45	G	PY	-	VP	17.56	CR
339	37.70	66.35	G	PY	-	VP	25.05	CR
340	37.82	66.30	G	PY	-	VP	27.75	CR
341	37.98	66.20	G					
342	38.15	66.15	R					
343	38.35	66.15	R					
344	38.75	66.05	R					
345	36.50	68.50	S	PY	-	P	11.25	
346	36.60	68.50	S	PY	1.72	0.540	10.48	
347	36.70	68.50	S	PY	1.82	0.537	11.20	
348	36.80	68.50	S	PY	1.38	0.892	12.10	
349	36.90	68.51	S	PY	1.72	0.551	10.39	
350	37.00	68.50	S	PY	-	P	8.83	
351	37.10	68.50	LS					
352	37.20	68.49	LS					
353	37.30	68.45	LS					
354	37.40	68.53	G		-	P	10.62	
355	37.52	68.50	LS					
356	37.60	68.49	LS					

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357     37.70  68.50   LS
358     37.80  68.49    R
359     37.90  68.45   LS
360     38.10  68.55   LS
361     38.22  68.53    R
362     38.43  68.54   LS
363     38.52  68.49    G      PY          -        VP    16.37
364     38.62  68.53    R
365     38.82  68.46   LS
366     38.92  68.50    R
367     39.10  68.48   LS
368     39.23  68.40   LS
369     39.30  68.40    R
370     39.52  68.44    G      PY          -        VP    26.58
371     39.62  68.40    R
044     31.49  70.95    S       YG      1.91   0.468    26.00
045     31.61  70.59    S       YG      2.27   0.331    30.89
046     31.76  70.26    S       YG      2.44   0.346    38.68
047     31.76  70.18    S       YG      2.49   0.358    42.09
ST. AGNES HEAD./ PORTREATH CORE SPLITS
CORE 045 31.61  70.59
   1                    S      PYG      2.35   0.376    35.18
   2                    S        G      2.38   0.363    32.55
   3                    S        G      2.38   0.360    31.29
   4                    S        G      2.28   0.373    25.04
   5                    S        G      3.43   0.399    32.62
   6                    S        G      2.68   0.416    48.82
   7                    S        G      2.82   0.424    57.43
   8                    S        G      2.85   0.457    54.02
   9                    S        G      2.84   0.445    53.83
  10                    S        G      2.88   0.457    51.51
  11                    S        G      2.86   0.453    53.01
CORE 046 31.76  70.26
   1                    S      PYG      2.50   0.346    41.02
   2                    S       YG      2.57   0.383    44.05
   3                    S        G      2.58   0.326    46.23
   4                    S        G      2.59   0.345    40.45
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  5                     S      G     2.49  0.404    34.99
  6                     S      G     2.51  0.417    34.59
  7                     S      G     2.54  0.376    36.84
  8                     S      G     2.61  0.490    37.05
  9                     S      G     2.68  0.486    39.46
ST. IVES BAY GRABS
244     36.95  64.62    R
245     35.67  64.54    S     YG     2.60  0.539    64.10
246     36.30  64.35    S    DYG     2.96  0.478    70.33
247     37.90  64.22    S    DYG     2.88  0.522    65.03
248     37.40  63.90    S    DYG     2.68  0.559    56.54
249     37.75  63.65    S    DYG     2.72  0.464    63.50
250     38.40  63.53    S     YG     2.66  0.455    61.79
251     39.00  63.40    S    DYG     2.46  0.511    53.36
252     39.70  63.49    S    DYG     2.57  0.488    57.38
253     40.20  63.55    S     YG     2.62  0.516    52.76
254     41.07  63.80    S    DYG     2.52  0.543    47.17
255     41.55  64.00    S    DYG     2.45  0.547    46.66
256     42.05  64.10    S    DYG     2.45  0.547    36.69
257     42.82  63.80    S    DYG     1.85  0.354    26.36
258     43.12  63.83    S    PYG     2.05  0.597    24.13
259     43.05  64.96    S     PY     1.49  0.541    20.85
260     42.85  65.15    S     PY     1.59  0.457    21.49
261     42.91  65.45    S     PY     1.68  0.452    22.78
262     43.39  65.80    S     PY     1.73  0.532    21.22
263     43.24  66.00    S    PYG     1.95  0.580    27.05
264     43.40  66.20   BG
265     34.36  65.00    S     YG     2.61  0.492    67.34
266     34.55  64.85    S    DYG     2.60  0.479    67.74      WATER SLIGHTLY RED
267     34.75  64.75    S    DYG     2.44  0.517    55.69      WATER SLIGHTLY RED
268     34.98  64.60    S     YG     2.25  0.464    47.25
269     35.00  64.45    S    PYG     1.68  0.741    47.31
270     35.20  64.30    S    PYG     2.04  0.542    43.57
271     35.42  64.20    S     YG     2.33  0.455    58.27      WATER SLIGHLY RED
272     35.55  64.05    S     YG     1.85  0.634    47.90      CR
273     35.65  63.90    S     YG     1.96  0.662    53.92
274     35.70  63.75    S    DYG     2.03  0.691    48.31
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275	35.90	63.69	S	DYG	2.20	0.502	57.44	
276	36.10	63.55	S	YG	1.61	0.726	47.56	
277	36.35	63.52	S	DYG	2.09	0.560	55.61	
278	36.52	63.45	S	DYG	2.21	0.461	56.96	WATER SLIGHTLY RED
279	36.72	63.40	S	YG	2.05	0.547	50.38	
280	37.00	63.35	S	YG	1.92	0.636	49.46	
281	37.30	63.35	S	YG	1.69	0.749	44.94	
282	37.50	63.20	S	YG	2.01	0.632	46.15	
283	37.60	63.15	S	DYG	2.00	0.627	43.72	
284	37.80	63.15	S	YG	2.08	0.588	45.73	
285	37.96	63.12	S	DYG	2.15	0.520	45.24	
286	38.19	63.05	S	DYG	2.18	0.485	47.31	
287	38.40	63.10	S	YG	2.21	0.396	52.83	
288	38.65	63.10	S	YG	1.87	0.765	39.72	
289	38.85	63.03	S	YG	2.16	0.584	50.68	WATER SLIGHTLY RED
290	39.20	62.99	S	PY	1.25	0.666	31.31	CR- FELDSPAR
291	39.80	62.30	S	PY	1.44	0.631	27.55	
292	39.55	63.15	S	PY	–	M	30.33	
293	39.60	63.20	S	PY	1.58	0.670	34.74	
PENDEEN GRABS								
372	30.90	66.40	S	CS	1.57	0.604	53.69	
373	31.10	66.50	S	CS	–	M	38.58	
374	31.19	66.42	S	CS	1.48	0.753	49.03	
375	30.95	66.25	S	CS	–	M	44.44	
376	31.20	66.26	S	CS	–	M	52.67	WATER SLIGHTLY RED
377	32.65	66.50	S	CS	1.45	0.603	49.33	
378	33.10	66.45	S	CS	1.57	0.481	69.72	
379	33.60	66.35	S	CS	1.48	0.468	54.34	
380	33.90	66.32	S	CS	1.41	0.571	50.89	
381	34.05	66.35	S	CS	1.40	0.495	50.83	

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RESULTS OF GRANULOMETRIC ANALYSIS
GRAIN SIZE IN MICRONS
WEIGHT PERCENT OF TOTAL MINUS-8-MESH SEDIMENT GIVEN
PHI INTERVALS AND NEAREST B.S.S. MESH SIZE
 2057 MICRON - -1.041 PHI -   8 MESH
  500 MICRON -  1.000 PHI -  30 MESH
  350 MICRON -  1.515 PHI -  44 MESH
  250 MICRON -  2.000 PHI -  60 MESH
  170 MICRON -  2.557 PHI -  85 MESH
  124 MICRON -  3.011 PHI - 120 MESH
    -2057  -500  -350  -250  -170
NO.  +500  +350  +250  +170  +124  -124
ST. AGNES HEAD / PORTREATH GRABS
  1 13.10 11.91 41.66 29.22  2.83  1.28
 13  2.80  4.46 17.16 32.04 26.76 16.78
 14  2.42  5.42 25.69 38.39 19.46  8.62
 15  2.01  4.06 14.73 20.83 28.69 29.68
 16  2.56  3.34 12.34 25.45 31.54 24.76
 17  3.01  3.72 13.45 24.75 31.98 23.10
 18  1.00  3.07 11.48 26.52 34.45 22.59
 19  4.19  7.12 25.57 33.47 19.51 10.14
 20  2.55  3.83 14.07 29.99 32.87 16.68
 21  3.36  3.83 21.82 32.50 25.53 10.55
 22  3.04  6.24 15.55 35.20 29.49 12.27
 23  6.75  4.45 38.52 26.20  9.62  3.93
 24  4.42 14.97 37.50 29.25 10.92  4.58
 25  8.42 13.32 40.44 23.17  7.34  2.70
 26 44.08 17.92 18.29  6.16  1.76  0.77
 27 34.22 28.04 25.78  9.75  2.50  0.77
 28 22.90 29.37 32.25 12.31  2.44  0.73
 29 22.98 22.82 33.49 16.73  3.20  0.77
 30 35.20 25.42 28.28  9.84  1.02  0.25
 31 27.39 24.82 35.68 10.44  1.18  0.49
 32 11.78 22.91 41.24 20.07  3.28  0.72
 33 12.88 15.98 38.44 28.01  3.41  1.28
 34 55.13 12.99 19.51  9.95  1.29  1.12
 35  9.50  9.36 29.82 38.68  8.82  3.81
 36  4.16  9.24 33.48 38.45 10.84  3.84
 37  2.28  3.83 22.59 45.55 18.35  7.41
 38  2.19  4.67 26.17 44.79 16.62  5.56
 39  1.88  2.94 13.37 35.40 32.48 16.94
 40  1.55  3.32 14.26 30.43 30.57 19.88
 41  1.80  8.97 47.03 37.08  4.76  0.37
 42 14.52 20.57 45.45 17.16  2.05  0.24
 43 10.28 27.48 47.77 13.78  0.61  0.08
 44  9.24 23.75 48.47 17.01  1.36  0.18
 45  4.34 15.22 50.65 26.89  2.72  0.19
 46  7.54 30.05 53.77  8.12  0.43  0.09
 47 17.45 26.28 43.80 11.67  0.73  0.07
 48 19.95 29.97 40.10  9.26  0.65  0.07
 49 17.38 26.31 43.99 11.37  0.82  0.13
 50 11.96 26.86 46.84 13.15  1.07  0.13
 51 12.73 27.02 47.57 11.79  0.85  0.04
 52 23.29 29.89 39.01  7.37  0.42  0.04
 53 12.60 25.32 47.47 13.14  1.33  0.15
 54  6.86 16.17 45.22 27.73  3.68  0.34
 55 20.48 31.09 39.63  8.12  0.60  0.08
 56 13.88 27.54 45.12 12.39  0.97  0.09
 57 13.05 24.10 44.72 15.59  2.21  0.33
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58	14.57	25.29	43.45	14.79	1.75	0.16
59	9.61	20.71	47.03	19.54	2.76	0.34
60	8.78	21.31	47.55	19.72	2.36	0.28
61	8.64	19.83	47.90	20.34	2.96	0.33
62	3.34	12.62	48.29	31.18	4.07	0.51
63	2.89	12.64	49.01	30.80	4.24	0.43
64	5.79	16.72	45.89	27.83	3.43	0.34
65	2.19	9.55	47.70	34.80	5.25	0.52
66	2.33	9.79	42.31	38.70	6.15	0.71
67	8.35	19.68	47.17	21.09	3.24	0.46
68	7.28	18.02	46.58	23.74	3.76	0.62
69	7.27	13.78	42.47	29.34	6.25	0.89
70	2.97	10.18	42.72	34.94	7.92	1.27
71	1.36	5.27	36.39	44.05	11.22	1.70
72	2.68	8.45	38.31	38.45	10.56	1.55
73	3.23	8.27	38.29	38.85	9.82	1.54
74	10.80	12.44	36.17	32.08	7.53	0.98
75	13.02	14.67	41.15	26.78	3.18	0.30
77	6.05	12.68	40.06	34.73	5.91	0.58
79	6.68	15.81	48.66	25.95	2.56	0.33
82	4.29	11.09	38.82	37.75	6.80	1.25
84	10.30	13.45	38.34	30.76	6.29	0.86
85	0.51	2.19	20.03	50.00	22.90	4.38
88	2.47	7.05	31.61	40.89	14.34	3.64
94	3.98	9.81	32.23	37.67	13.93	2.39
95	2.10	6.30	27.50	40.63	19.61	3.85
97	2.74	11.89	39.02	34.60	10.06	1.68
98	19.22	21.83	33.69	18.86	5.34	1.07
99	2.22	12.82	46.20	33.23	4.91	0.63
101	97.26	0.68	1.03	0.68	0.23	0.11
104	4.82	13.72	40.73	31.82	7.30	1.61
107	2.82	7.11	26.58	35.97	21.88	5.64
108	79.19	14.01	5.99	0.71	0.05	0.05
111	11.79	4.31	16.33	27.44	17.46	22.68
114	12.85	12.59	38.66	28.46	5.29	2.14
115	12.75	13.17	39.24	28.61	4.82	1.42
116	5.48	8.41	30.72	43.44	9.59	2.35
117	1.85	4.24	20.85	50.37	18.82	3.87
118	1.35	3.70	19.70	50.51	21.21	3.54
119	3.98	9.57	39.25	36.89	8.82	1.49
120	9.65	16.88	35.21	27.81	8.36	2.09
121	1.29	3.38	16.43	44.93	28.02	5.96
122	1.75	5.09	23.16	45.09	21.23	3.68
123	5.45	11.55	36.30	33.99	10.23	2.48
124	5.21	11.24	36.97	34.85	8.79	2.93
125	5.66	8.71	35.12	37.74	9.58	3.19
126	1.30	2.97	20.04	44.90	21.89	8.91
127	3.02	5.73	26.24	39.22	18.25	7.54
128	3.44	5.55	27.81	42.97	14.92	5.31
129	2.73	4.44	21.86	40.51	22.88	7.58
130	2.06	3.48	19.78	41.93	24.53	8.23
131	3.00	4.16	21.05	40.60	23.79	7.40
132	14.33	15.01	37.77	25.55	5.56	1.77
133	7.34	11.51	39.20	31.36	8.42	2.17
134	70.06	12.39	9.94	4.77	2.06	0.77
135	3.90	6.80	30.77	38.51	15.98	4.03
136	12.26	6.98	23.32	37.45	16.68	3.32
137	4.77	3.94	18.55	39.59	26.74	6.42
138	8.70	14.49	36.68	28.57	9.44	2.13

139	36.73	23.35	27.21	9.89	2.16	0.67
140	52.45	20.59	19.14	6.06	1.27	0.48
142	24.42	22.08	33.77	15.20	3.65	0.88
143	18.28	18.34	36.81	20.33	4.95	1.29
144	4.46	9.64	35.36	35.98	12.05	2.50
145	33.21	23.88	28.37	11.55	2.42	0.57
146	45.72	21.98	22.50	7.43	1.86	0.52
147	37.55	25.18	25.87	8.85	1.99	0.57
148	11.94	14.56	34.56	27.63	9.19	2.12
149	8.10	14.11	37.10	29.78	8.95	1.96
150	32.48	24.65	29.98	10.34	2.04	0.51
151	38.11	25.31	25.41	8.81	1.84	0.51
152	5.12	10.42	35.50	35.12	11.12	2.72
153	15.41	18.69	38.71	21.91	4.25	1.03
154	32.27	19.69	31.01	14.36	2.22	0.44
155	57.47	18.59	17.21	5.63	0.88	0.22
156	60.03	17.97	16.33	4.80	0.71	0.15
157	36.52	24.00	26.97	10.00	2.06	0.45
158	62.46	19.45	13.68	3.50	0.76	0.15
159	49.97	24.29	18.18	5.91	1.39	0.27
160	19.73	23.18	35.00	18.24	3.31	0.54
161	7.14	10.23	28.08	40.26	11.69	2.60
165	0.88	6.08	49.60	29.96	10.13	3.35
166	1.99	4.41	51.39	31.32	7.69	3.20
167	2.31	8.42	40.46	32.26	11.99	4.56
168	0.72	2.88	27.88	47.66	17.45	3.42
169	0.60	1.90	20.19	54.36	18.21	4.75
170	0.61	1.21	11.63	60.52	21.65	4.37
171	0.59	0.91	8.49	60.23	25.29	4.48
172	0.55	1.05	8.77	62.42	22.67	4.54
173	0.53	0.96	8.61	63.96	21.80	4.15
174	0.50	1.01	8.01	63.18	21.97	5.34
175	0.57	1.21	8.32	60.32	23.82	5.75
176	0.63	1.29	10.38	60.58	20.97	6.17
177	0.53	1.06	8.22	54.38	28.04	7.77
178	0.79	1.69	10.38	50.16	28.49	8.49
179	1.55	2.19	11.61	46.60	29.76	8.28
180	1.21	2.40	13.71	47.67	26.31	8.70
181	0.89	2.00	12.76	46.33	28.94	9.08
182	1.85	4.30	20.61	44.01	20.80	8.43
183	1.11	2.75	15.75	46.13	26.10	8.17
184	1.13	2.61	13.38	42.98	28.32	11.59
185	2.23	3.25	13.75	37.76	30.65	12.35
186	1.23	2.39	11.33	34.98	34.03	16.04
187	1.55	2.72	11.54	30.95	35.35	17.89
188	1.84	3.32	13.89	31.83	31.56	17.56
189	1.50	3.07	14.12	30.32	32.45	18.55
190	1.08	2.67	14.37	32.45	30.82	18.61
191	1.54	3.51	17.43	32.20	28.59	16.73
192	2.45	4.91	17.48	27.70	27.56	19.91
193	1.98	3.99	19.79	31.96	26.61	15.67
194	10.55	16.32	33.61	21.65	11.08	6.79
195	2.12	3.61	14.33	28.37	32.32	19.24
196	1.23	4.47	25.13	39.37	20.30	9.41
197	2.35	3.75	12.52	25.77	31.69	23.92
198	5.48	7.44	20.16	27.15	23.88	15.89
199	9.62	21.28	43.88	18.42	4.00	2.81
200	2.84	12.67	46.58	25.69	6.81	5.41
201	2.07	3.46	12.07	22.11	31.15	29.15

202	2.59	4.03	13.48	24.55	29.37	25.98
203	2.47	3.84	13.56	25.30	31.81	23.02
204	2.41	4.18	14.44	25.66	30.44	22.87
205	3.19	5.00	16.42	26.82	30.28	18.29
206	1.18	3.18	14.07	32.46	31.55	16.93
207	2.00	3.50	13.85	28.10	32.43	20.13
208	3.17	5.24	15.37	26.44	29.16	20.62
209	10.32	18.66	43.82	20.36	4.50	2.33
211	2.42	7.25	25.60	31.21	21.84	11.69
212	7.81	16.69	43.13	22.23	7.36	2.78
213	8.02	19.21	41.51	21.14	7.10	2.97
215	11.13	23.76	46.26	14.73	2.98	1.13
216	38.14	19.18	26.24	10.13	3.35	2.97
217	66.45	17.49	12.16	2.05	0.67	1.17
218	64.00	12.64	13.42	6.21	1.58	1.26
219	1.98	3.12	12.71	29.89	30.39	21.90
220	3.10	3.57	16.22	31.42	25.67	20.03
221	3.26	6.34	26.24	36.29	19.13	8.74
225	79.53	6.86	6.28	3.05	1.64	2.63
236	87.70	4.61	5.80	3.52	0.96	0.41
294	0.40	1.43	9.78	23.98	43.42	20.98
295	0.33	2.46	16.64	24.24	37.33	19.00
296	0.35	1.59	12.60	26.09	37.60	21.77
298	0.56	3.68	22.28	24.39	27.93	21.15
299	0.41	2.25	15.93	25.03	30.50	25.87
300	0.35	1.60	12.52	23.15	32.89	29.50
301	0.49	3.52	19.81	23.49	27.03	25.66
302	0.41	2.96	19.13	23.79	27.74	25.97
303	0.45	3.62	21.87	25.18	25.01	23.87
304	0.44	3.10	18.64	25.30	28.77	23.74
305	0.77	3.81	20.40	28.16	26.36	20.51
306	0.73	2.98	18.19	27.50	28.38	22.22
307	0.41	2.76	17.71	29.84	26.50	22.79
308	0.73	2.20	14.49	29.11	31.20	22.29
309	0.61	2.32	14.14	29.58	30.39	22.96
310	0.73	1.97	12.16	28.06	33.64	23.44
311	0.51	1.86	13.35	31.48	32.25	20.55
312	0.48	1.64	13.16	31.35	32.32	21.06
313	0.42	1.62	13.45	32.28	31.30	20.94
314	0.69	2.17	16.50	33.76	29.09	17.80
315	1.34	2.29	14.86	32.16	28.18	21.18
316	1.14	1.97	17.17	37.63	27.36	14.72
317	2.36	1.75	13.09	36.83	28.06	17.90
318	1.66	2.06	16.30	42.45	26.92	10.61
319	2.14	2.20	17.13	41.74	24.60	12.20
320	4.67	3.95	21.34	38.69	22.07	9.27
321	5.04	4.27	20.93	41.56	20.47	7.73
322	72.88	7.29	9.60	7.75	1.80	0.68
325	1.31	1.64	8.23	28.97	40.38	19.46
326	2.00	2.26	8.29	25.36	41.06	21.04
327	1.66	2.63	9.75	27.63	38.43	19.91
328	1.27	2.58	10.45	29.83	39.03	16.85
329	1.33	2.53	10.05	30.75	37.32	18.02
330	1.42	1.76	9.36	32.90	38.80	15.76
331	2.62	2.66	10.59	32.08	34.24	17.81
332	2.57	2.68	11.75	35.72	34.07	13.21
333	2.12	4.51	22.99	44.18	18.85	7.36
334	77.34	10.24	6.82	3.20	1.68	0.72
338	64.69	11.36	14.06	8.03	1.47	0.38

339	75.45	7.75	8.29	5.54	2.17	0.81
340	89.68	4.04	2.73	1.56	1.10	0.88
345	47.01	23.80	20.82	4.10	2.00	1.38
346	9.06	19.66	44.13	20.18	4.89	2.08
347	7.28	16.34	44.00	23.38	6.69	2.31
348	29.62	20.85	29.20	11.44	4.88	4.01
349	10.11	19.50	44.26	18.90	5.04	2.19
350	54.13	24.26	17.26	3.10	0.45	0.80
354	61.54	19.70	14.17	2.63	0.70	1.26
363	72.49	13.31	10.53	2.45	0.58	0.64
370	88.75	4.46	3.30	1.76	0.80	0.93
044	6.53	8.14	44.59	34.84	3.83	2.06
045	0.64	1.52	14.50	66.11	14.74	2.48
046	0.54	1.07	7.36	57.07	28.78	5.18
047	0.70	1.19	7.13	48.07	36.17	6.73
ST. IVES BAY GRABS						
245	1.38	2.11	9.84	31.09	35.56	20.01
246	0.58	0.64	2.38	14.32	38.81	43.25
247	0.58	0.64	3.68	20.39	36.38	38.34
248	2.55	2.55	6.41	25.49	38.87	24.12
249	0.60	0.82	4.97	29.18	40.18	24.25
250	0.57	1.09	6.07	32.85	39.56	19.85
251	2.53	3.20	11.32	39.71	31.63	11.61
252	0.73	1.36	8.95	37.40	34.78	16.78
253	0.92	1.53	8.25	33.95	34.23	21.12
254	2.15	2.94	10.31	35.29	33.19	16.11
255	2.90	3.87	11.78	37.45	30.86	13.14
256	2.96	3.74	11.58	37.07	32.23	12.42
257	3.64	12.22	51.58	31.07	1.14	0.34
258	6.19	9.87	29.72	35.30	15.18	3.73
259	20.74	27.04	33.69	13.97	3.26	1.31
260	11.73	23.90	49.42	14.36	0.47	0.13
261	8.66	20.85	46.68	22.23	1.39	0.18
262	10.60	16.34	42.49	28.85	1.48	0.25
263	7.66	11.44	31.00	37.94	8.43	3.54
265	1.12	2.10	8.78	28.56	39.70	19.75
266	0.66	1.87	8.94	29.80	41.09	17.64
267	1.72	3.87	14.18	34.72	35.22	10.28
268	1.37	4.72	22.42	45.52	21.69	4.28
269	17.79	16.08	30.48	27.11	7.75	0.78
270	5.22	10.44	29.56	38.86	13.93	1.99
271	1.24	3.90	17.57	43.58	28.77	4.94
272	10.11	16.71	31.86	28.78	10.56	1.98
273	9.18	11.26	25.46	36.63	15.78	1.69
274	8.63	11.21	26.37	35.69	15.75	2.35
275	3.25	6.58	23.41	41.80	22.17	2.79
276	17.98	20.26	34.73	22.15	4.41	0.47
277	5.19	8.87	27.34	38.81	17.64	2.15
278	1.96	5.73	23.72	45.02	20.87	2.69
279	5.13	9.73	29.93	38.15	15.44	1.61
280	9.17	13.12	30.70	33.24	12.22	1.56
281	17.83	16.73	30.61	25.58	8.40	0.85
282	8.08	10.87	25.65	37.99	15.45	1.95
283	9.19	10.11	24.27	38.27	16.45	1.71
284	6.85	8.30	23.52	43.25	16.24	1.83
285	4.79	6.29	23.33	46.32	17.57	1.70
286	3.82	6.09	22.20	46.57	19.53	1.79
287	1.78	3.59	20.67	56.26	16.90	0.80
288	14.01	11.40	25.34	35.06	12.58	1.61

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289   6.11   6.55 20.47 40.58 22.86   3.44
290  39.49  24.05 26.07  9.46  0.85   0.07
291  29.34  23.73 33.29 12.73  0.82   0.09
292  31.67  23.49 30.18 13.62  0.94   0.10
293   7.58  13.25 34.53 33.74  9.37   1.54
PENDEEN GRABS
372  17.37  21.86 37.16 21.68  1.72   0.21
373  38.37  21.95 29.07  9.83  0.67   0.11
374  24.30  21.93 27.38 23.32  2.78   0.29
375  50.17  21.91 18.93  7.52  1.31   0.16
376  33.86  23.27 26.37 12.61  3.17   0.73
377  21.89  34.27 36.60  6.42  0.64   0.18
378   9.09  23.72 50.31 15.59  1.11   0.18
379  15.19  30.82 44.15  9.10  0.60   0.13
380  20.73  32.41 36.71  9.15  0.84   0.17
381  19.94  35.15 37.38  6.95  0.49   0.08
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