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SEDIMENT AND WATER MOVEMENT IN COASTAL EMBAYMENTS.

*COLLINS M.**

Embayments are shallow water inner continental shelf environments which include deltas, estuaries and intertidal flats; they are located within a coastal zone where frictionally-dominated flows are predominant (Gorsline & Swift, 1977)(Fig. 1). The energy inputs to such systems is highly variable and, consequently, some of the sedimentary processes which take place are more understandable and predictable than others.

In terms of attempts to generalise the characteristics of such environments analyses have been carried out which classify deltas in terms of climate, tectonics, fluvial regime, sediment input, and receiving basin characteristics (Elliot, 1978). In contrast, embayments vary considerably in their physical characteristics and in the way in which energy inputs combine to transport sediment. Transport processes which take place in embayments are the result of tidally- and wave-induced currents, river inputs, and relative changes in sea level in response to eustatic or isostatic movement; these characteristics can be used to define the *regime* of an embayment. Tidal influence can be classified in terms of its' spring tidal range or as microtidal (<2m), mesotidal (2-4m) or macrotidal (>4m)(Davies, 1964). Regions of high tidal range are characterised by broad intertidal coastal zones, with the associated dissipation of wave energy. In areas of low tidal range, there is less dissipation of wave

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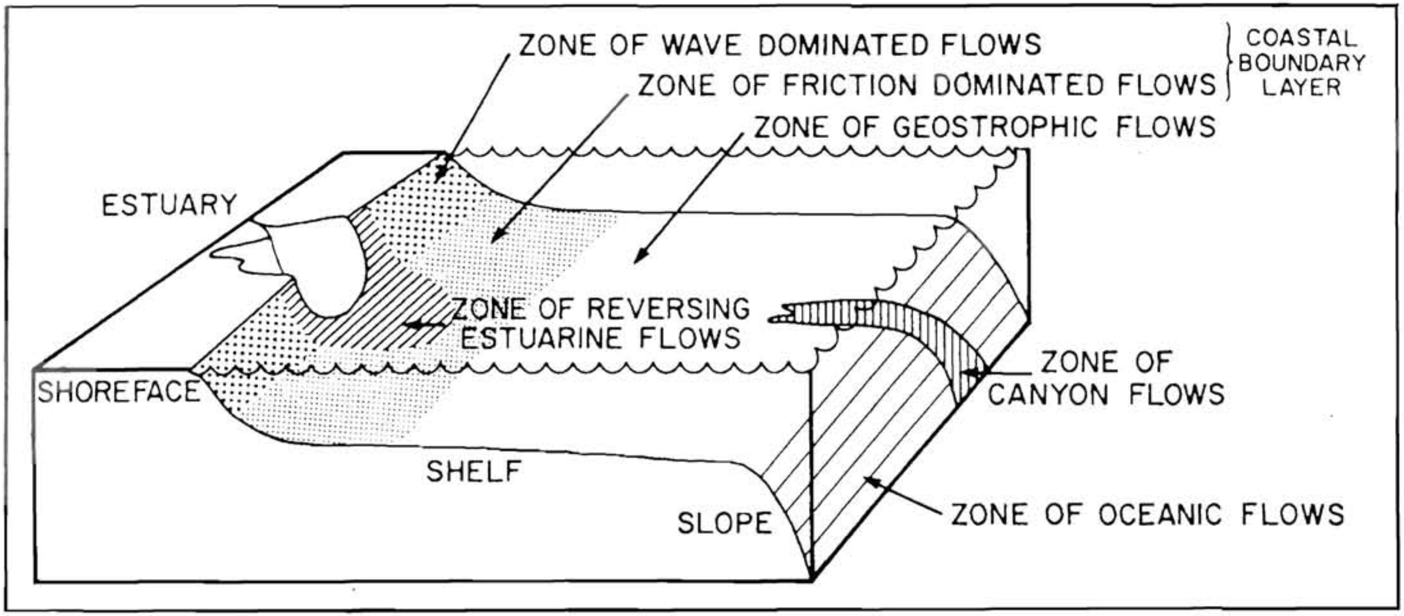


Figure 1. **Geomorphic units of the continental shelf and associated hydrodynamic zones (from Gorsline and Swift (Eds.).** *Shelf Sediment Dynamics: A National Overview*, **1977).**

energy and its' concentration results in the erosion of any cliffed coastline.

Wave action at a coastline. within an embayment, is a more difficult variable to quantify, than the tidal characteristics. 'Typical' wave conditions for the design of coastal engineering works are taken sometimes as the 'significant wave' height ($H1/_3$), which represents the mean height of the highest $1/_3$ of the wave height spectra. Even this does not represent, however, the extreme storm events which can drastically influence the movement of sedimentary material in coastal waters. In addition to the effects of wave heights and their breaking characteristics on the shoreline, the obliqueness of wave approach to the coastline generates longshore currents within the nearshore zone. Mass movement of water towards the coastline, caused by waves, can be associated with rip currents. Such currents return the water in an offshore direction as a concentrated flow (Mackenzie, 1958).

In an attempt to understand the broad pattern of wave/current interactions on the inner shelf, it has been suggested that currents are more effective in shaping the sea floor, than in developing the coastal configuration. The configuration is considered to be the result of refracted wave patterns (Bird, 1983). Currents are the mechanism, therefore, by which sediments are removed from a coastal zone which has been eroded by waves. In terms of research commitment, the superimposed effect of waves on currents has received less attention than research on currents and waves as independent sediment transporting mechanisms. Nevertheless, their combined influence can create considerable variability in the predicted transport paths for material moving as bedload (see below); this could be an important factor in understanding long-term patterns of accumulation or erosion of sedimentary material (Pattiaratchi & Collins, 1984).

Fluvial discharge and its seasonal variability also influences sedimentary processes in embayments. Rivers need act not only as the source of supply of fine- or coarse-grained sediments to the shallow marine environment, but can create plumes of low salinity surface waters which extend over large areas of the adjacent sea bed: these waters overlie the more saline waters originating from offshore. Such surface layers can influence mixing processes within the near-surface waters and also inhibit the transfer of energy, from the air/sea boundary and through the water column, to the sea bed (Sultan *et al.*, 1984).

The energy inputs to embayments, described above, vary in temporal and spatial intensity; this is reflected in suspended sediment and bed load transport paths and rates. Although interdisciplinary and detailed studies have been carried out on specific embayments (Collins *et al.*, 1980; Conomos, 1979), such as the Baie de Seine, some research has concentrated upon the transport processes themselves. Hence, the Gulf du Lion (southwestern France) and the Gulf de Gascogne (Atlantic seaboard of France) are considered to be embayments which are dominated by wave action, on the basis of the onshore/offshore gradients in the texture of the sediments and the superimposed wave power. Conversely, and on the same comparative basis, Carmarthen Bay (southwestern British Isles) and the North Yorkshire (U.K.) Shelf of the North Sea are considered to be tidally-dominated areas in terms of sediment transport (Jago & Barusseau, 1981, 1983). In spite of these attempts to subdivide the inner continental shelf areas into dynamic categories, however, there is still a considerable amount of debate on the subject of the geological implications of the dominance of wave- over tidally-induced processes at the coastline (Davis & Hayes, 1984).

Against a background of their response to tidal and wave energy inputs, embayments can also be areas of transient sediment storage and through which material passes either from offshore to onshore or in the opposite direction. In the case of transfer towards the coastline, waves can provide the energy to move material from an adjacent sea bed to the nearshore zone. In the case of movement in an offshore direction, river-borne sediments are supplied to the coastline and transported subsequently offshore. Embayments will now be described here to illustrate these contrasting sets of sedimentological conditions and demonstrate how embayments, such as the Baie de Seine, form part of a much larger sedimentary system. A range of scientific approaches and expertise have been incorporated into the investigations which will be described. The techniques include: numerical and physical modelling; the measurement of currents, using direct reading or self-recording current meters; the deployment and recovery of drogues and drifters; dye tracing, to examine surface water movement and dispersion processes; sedimentological analyses, including those for grain size and heavy mineral concentration; geophysical investigations; and the application of spaceborne and airborne remote sensing. Details of the way in which these approaches have been adapted for use in the research of embayments are contained within the various publications cited.

The first area to be considered is *Swansea Bay*, which is a highly industrialised embayment situated along the northern coastline of the Bristol Channel, southwestern British Isles (Fig. 2). The region is one of high tidal and wave energy. Spring tidal ranges are of the order of 10m,

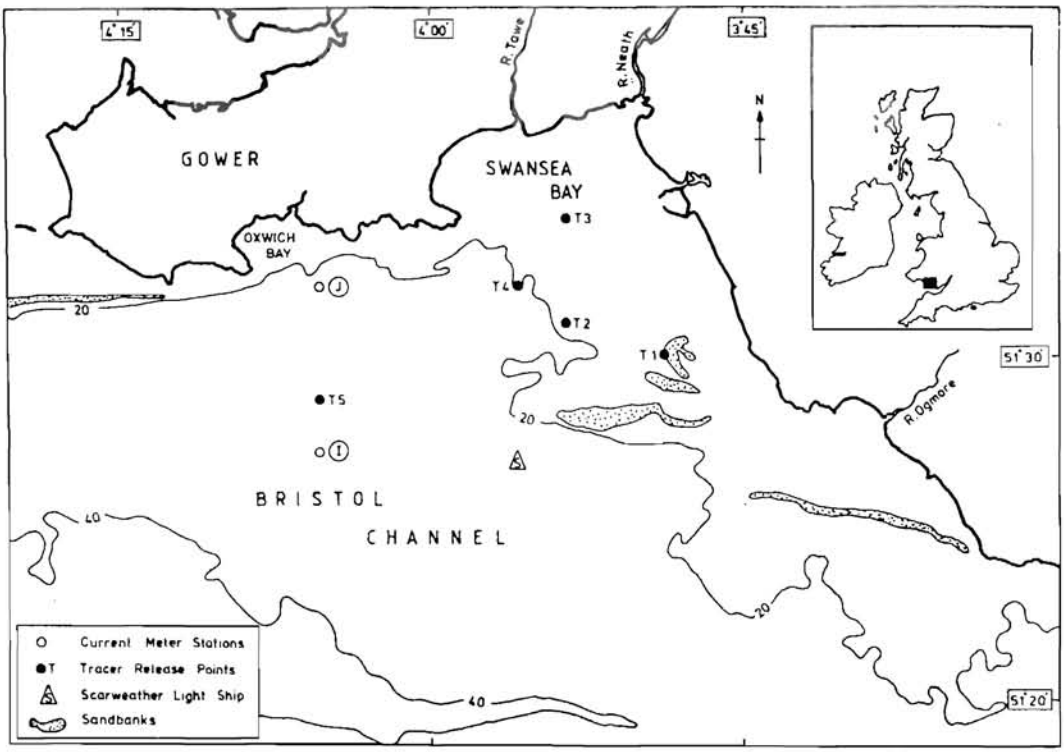


Figure 2. Swansea Bay and the adjacent northern Bristol Channel showing rivers and oceanographic monitoring stations.
Key: tracer release points (T_1 to T_5); self-recording current meter stations (I and J); (Scarweather) Light Vessel (S); and sandbanks (shaded). T_1 is the release position for Scandium^{46} tracer, with a mean grain size of 170μm; T_5 the position of release of fluorescent sand (400μm). Bathymetry is in metres above Chart Datum.

with maximum observed wave heights of the same order of magnitude and with their origin out in the Atlantic Ocean. Minor low freshwater discharges enter the area, with annual sediment inputs only of the order of 75,000 tonnes. It has been estimated that such an input of material would increase the suspended sediment concentration in the waters of the embayment by only 0.25mg/l at any one instant in time (Collins, Ferentinos & Banner, 1979).

Sediment transport processes within Swansea Bay and the adjacent Bristol Channel have been examined by various investigators often resulting in contradictory interpretations of transport paths (Harris & Collins, 1985). Foraminiferal and sedimentological evidence has inferred, for example, that material has been transported, on a long-term basis, from offshore to onshore (Culver, 1980). In contrast, the orientation of large-scale bedforms (Culver *op.cit.*) and bed-load sediment transport paths predicted from recent self-recording current meter data show transport is in the opposite direction (Heathershaw, 1981). These apparently contradictory inferred directions of transport emphasise the need to examine the influence of 'extreme' or 'storm' events, caused by the superimposition of wave activity upon that of currents, on embayments.

Similar tracer studies carried out in the Swansea Bay area indicate changes in sediment transport paths and rates which can take place under the influence of extreme wave action. In 1975 and 1976 material of size ? was treated with Scandium^{46} and released on to the sea bed; its movement was monitored then over a 12-month period (Heathershaw and Carr, 1977). The results of this investigation showed two long-term trends in the transport paths (Fig. 4). One direction of transport was related to the orientation of the main tidal flow; the other to the direction of approach of

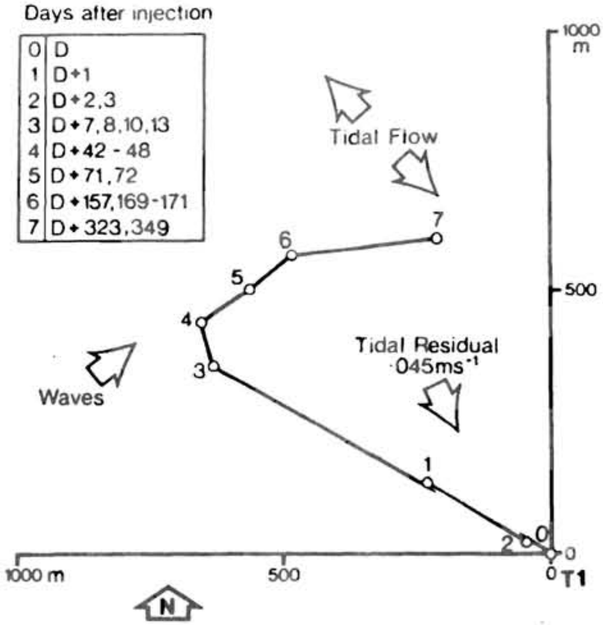


Figure 3. Movement of the tracer at Site T_1 (for location, see Fig. 2), over a 349-day period (from Heathershaw and Carr, 1977).

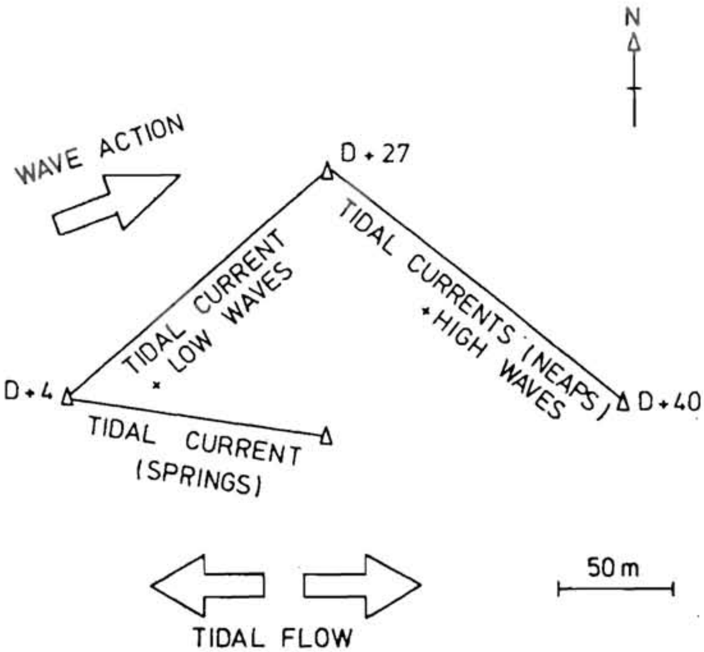


Figure 4. Movement of the tracer at Site T_5 (for location, see Fig. 2), over a 40-day period (from Pattiaratchi and Collins, *Marine Geology*, 1984).

southwesterly swell waves from the Atlantic (Fig. 3). A similar study was carried out in 1976, but involved the release of 1 tonne of fluorescent sand onto the sea bed. Subsequent monitoring of the movement of the centroid of the deposit took place over a 40-day period. The results demonstrated the immediate response of loosely-consolidated material on the sea bed, to wave action. During the first part of the monitoring period, over the first 4 days (up to D+4), movement of the tracer follows the spring tidal current direction. From D+4 to D+27, movement is in response to the combined action of current and waves. Similarly, between D+27 and D+40, the tracer responds to high wave energy input superimposed upon neap tidal currents. It should be noted that there is almost complete opposition between bed load transport directions under spring tidal conditions, in the absence of waves, and neap tides under the influence of waves (Fig. 4). The varying transport directions identified during the fluorescent tracer study were confirmed subsequently by using self-recording current meter data (for location see Fig. 2) for the application of bed load transport formulae for movement of sediment under the combined influence of waves and currents (Pattiaratchi & Collins, 1984; 1985). At a current meter station located within 30m of water (Fig. 2), the predicted transport was towards the west under spring tidal conditions alone, but towards the east when waves were superimposed upon neap tides (Fig. 5). Measured and predicted transport paths can be used, in this way, to understand regional sediment transport pathways (Fig. 6). These data emphasise the important concept that directions of sediment movement can change in the presence of waves. The embayment itself (*Swansea Bay*) is representative of a coastal zone where net long-term sediment transport is to landward.

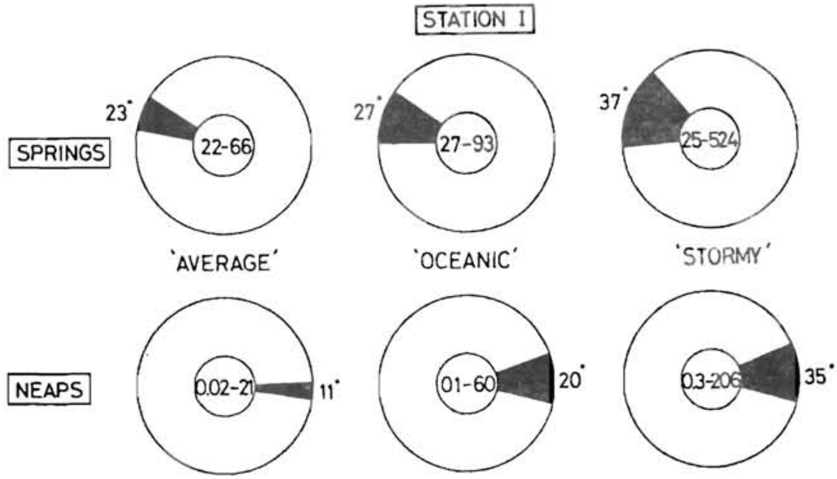


Figure 5. Station I (see Fig. 2): Summary of predicted bedload transport vectors under the combined influence of waves and currents, based upon the formulae of Bagnold, Bijker and Madsen and Grant (from Pattiaratchi and Collins, *Marine Geology*, 1984).

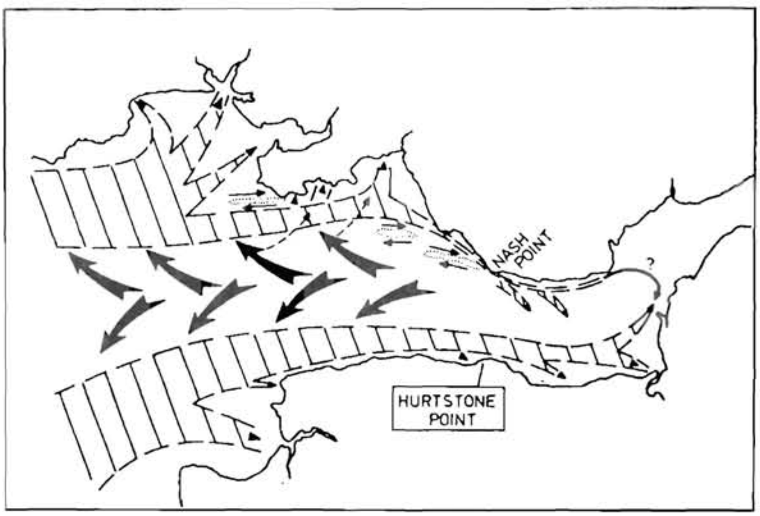


Figure 6. Conjectural near-bottom drift in the Bristol Channel, as indicated by sea bed drifter patterns. Ebb-dominated flow is located within the central part of the Channel. Flood-dominated zones are present along the northern and southern coastlines; these are created by the combined influence of tidal currents and waves (from Collins and Ferentinos *Oceanologica Acta*, 1984).

Another area for consideration is *Thermaicos Bay* (*Gulf*) in the northwestern part of the Aegean Sea, eastern Mediterranean. A series of shallow water embayments or gulfs receive fine-grained sediment input from two major river systems (Axios and Aliakmon). The rivers have formed, through deposition of sediment at their mouths, bird-foot type delta systems, (Fig. 7). The catchment area of the River Axios extends to the mountainous regions of Yugoslavia and, in response to snowmelt on the mountains, the maximum sediment/water discharge occurs in April. In contrast, the River Aliakmon is smaller and has a catchment area which is more confined to the coastal zone; this responds to localised rainfall, with peak discharges occurring in February/March (Fig. 8)(Robles *et al.*, 1983).

The Aegean region is one in which the influence of river sediment inputs can be identified to as far back as 500 B.C. (Conispoliatis, 1979) and, during certain seasons of the year, the complete embayment is overlain by low salinity and highly turbid waters originating from the river systems (see Fig. 9, representing surface water salinities in February). Such plumes from the river systems vary in their areal extent, both seasonally and in direct and relatively immediate response to local wind conditions (Collins, 1983; Balopoulos *et al.*, 1985). Fluvial sediments have been and are being deposited over the beds of the adjacent inner and outer embayments (Conispoliatis, 1983); they have been identified, on the basis of the clay mineral distributions, further offshore in water depths of around 1500m (Lykousis *et al.*, 1981). The embayments form, therefore, an area for the temporary storage of fine-grained sediments; these are eventually transported offshore.

Offshore transport of sediments is effected by turbidity currents, in a tectonically-active region of the eastern Mediterranean Sea (Ferentinos

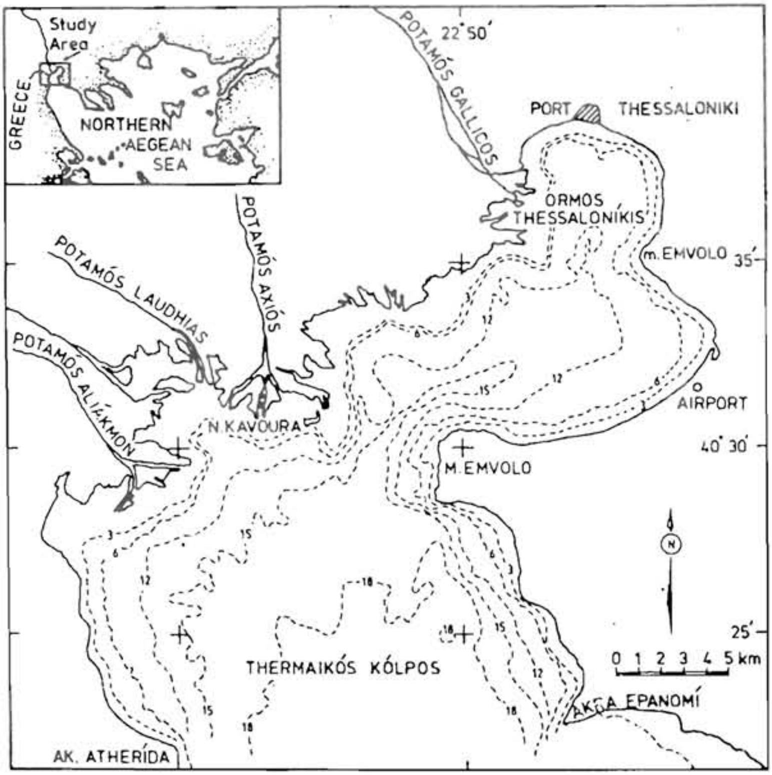


Figure 7. The location and bathymetry of Thermaicos Bay, northwestern Aegean Sea. Bathymetry in fathoms, abstracted from Greek Government Hydrographic Chart, 1959. The river systems (Gallicos, Axios, Laudhias and Aliakmon) and their associated deltas are shown.

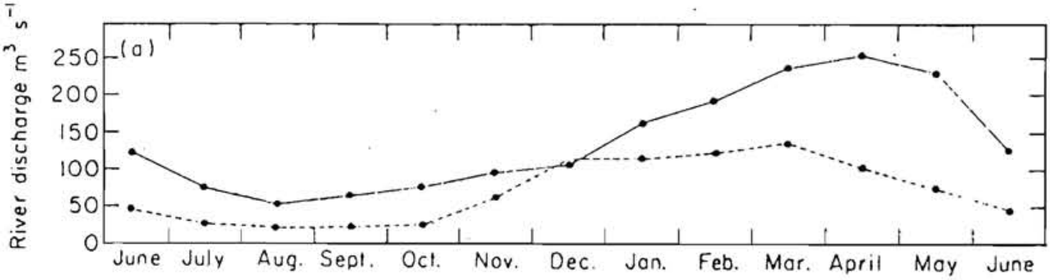


Figure 8. Mean monthly discharge information ($m^3 s^{-1}$) from the rivers Axios (——) and Aliakmon (- - -), 1962/63 - 1970/71 (from Robles *et al.*, *Estuarine Coastal and Shelf Science*, 1983).

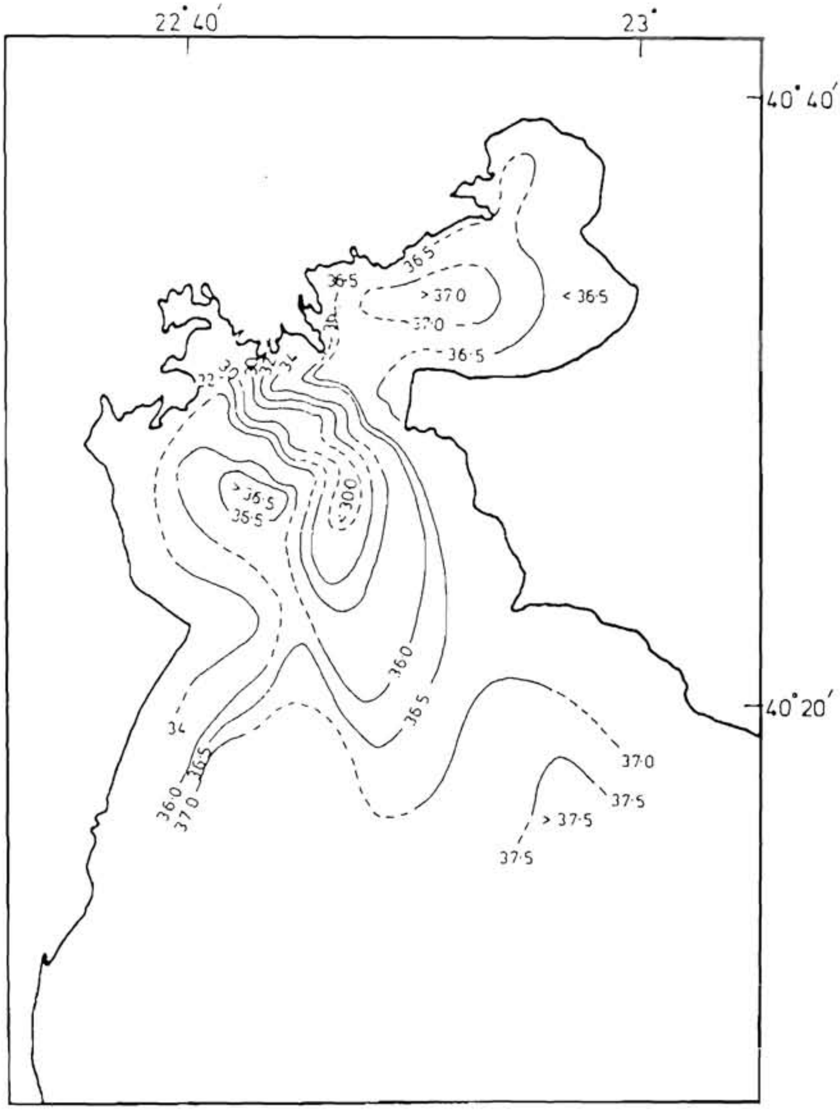


Figure 9. Surface water salinities in the Thermaicos Bay (Gulf), in °/oo, showing the extent of the low salinity 'plume' from the mouth of the R. Axios, February 1976(from Robles *et al.*, *Estuarine, Coastal and Shelf Science*, 1983).

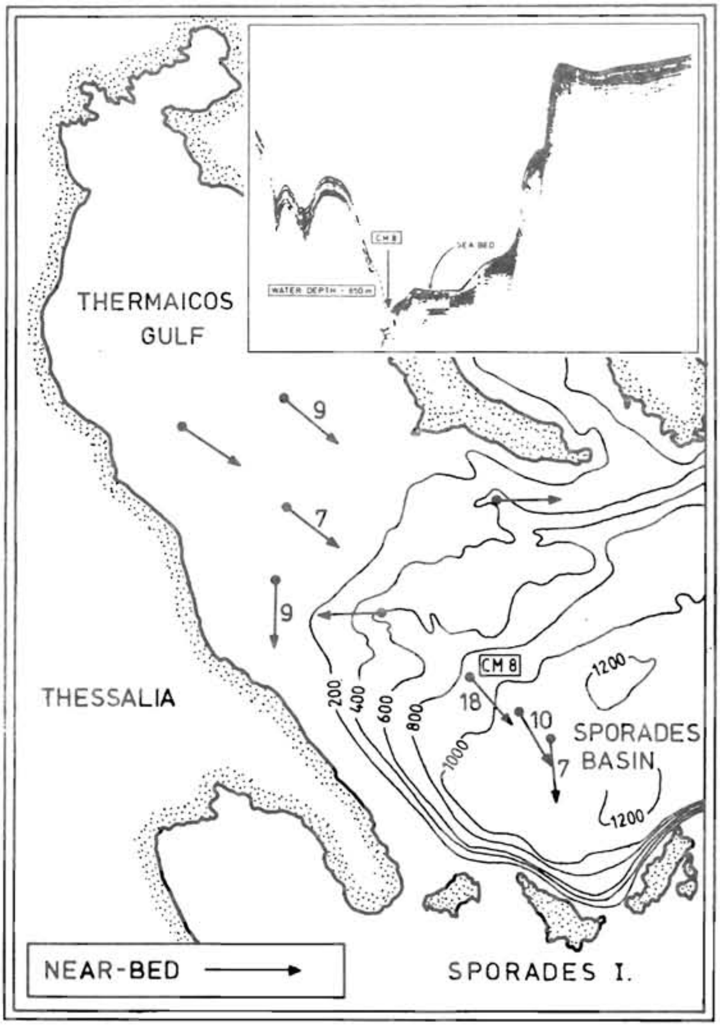


Figure 10. Near-bed residual currents in the N.W. Aegean Sea, obtained from self-recording current meters. Arrows show directions of the residuals; associated arrows the magnitude of the residual speed, in cms^{-1}. Inset to the Figure shows the submarine canyon bathymetry in the vicinity of current meter (CM) 8, from shallow seismic (3.5kHz) survey data. Bathymetry is in metres. (Current meter data supplied by C.B. Pattiaratchi, based upon observations made during RRS *Discovery* Cruise 137).

et al., 1981), and within near-bed water movements, self-recording current meter observations from the area have shown there to be residual water movement in an offshore direction, extending along the axis of a submarine canyon (Fig. 10). A similar mechanism for the transfer of fine-grained material from the continental shelf to an adjacent perched deep-water basin (1800m in depth) has been identified for the Zakynthos Valley/Canyon system in the eastern Ionian Sea, western Greece (Ferentinos *et al.*, 1985).

The transport of fine-grained material, of fluvial origin, across the continental shelf/ slope and through the submarine canyons of the Aegean Sea constitutes a regional pattern of sediment movement (Fog. 11). Within this pattern, the embayments are areas through which transport takes place, from landward to seaward.

Transport systems along the western coastline of the United States are similar to those in the Aegean Sea and are where littoral cells are formed. Each cell consists of: input of sediment from longshore transport within the littoral zone, sometimes associated with an embayed coastline; and offshore movement through a submarine canyon system (Fig. 12). The canyons in this latter area, in contrast to those in the Aegean, act as conduits for coarse-grained material. Another example of the investigation of a complete sedimentary system is the study of benthic biological activity in Suruga and Sagami Bays, central Japan; this is providing information to establish the basic framework for the understanding of sediment movement within the adjacent troughs and basins (Okada & Ohta, 1983).

The detailed investigations described above, relating to *Swansea Bay* and *Thermaicos Bays* demonstrate that processes which take place in embayments, particularly those concerned with water and sediment movement, represent only a constituent part of a much larger transport system.

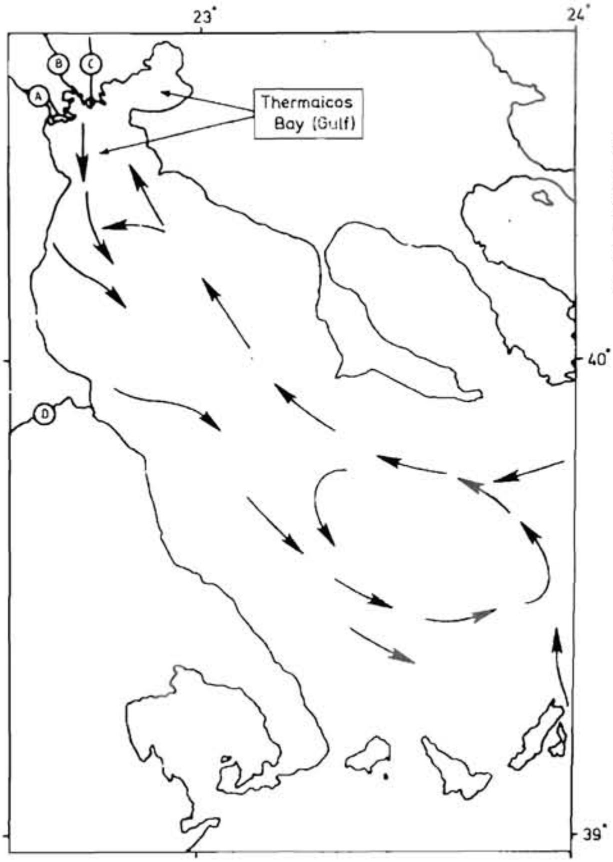


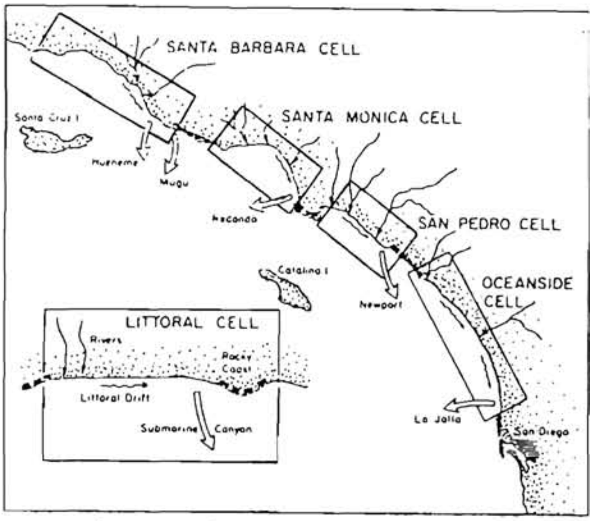
Figure 11

Pattern of surface residual water movement over the northwestern Aegean Sea, inferred from the mineralogy of the fine-grained bottom sediments.

Key : A = R. Gallicos; B = R. Axios; C = R. Aliakmon; D = R. Pinios

Figure 12

The southern California coast divided into a series of cells, each cell being a system where rivers add sand to the beaches and the sand moves south as littoral drift to be trapped within submarine canyons and lost offshore to deep water (from Komar, 1976).



Transport of sediment can take place from onshore to offshore, through embayments within the coastal zones, where there are major river inputs. From an offshore source of supply, material can move in the opposite direction, to create coastal environments of net deposition.

CONCLUSION

(i) that the superimposed effect of waves should be considered, in inner continental shelf areas which are dominated apparently by tidal currents, to establish the long-term effects of storm activity;

and (ii) that embayments form part of much larger sediment transport systems and, consequently, require understanding within their regional setting.

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Balopoulos, E.Th., Collins, M.B. & James, A.E. 1985. Satellite images and their use in the numerical modelling of coastal processes. Int. Jnl. Remote Sensing (in press).

Bird, C.F. 1983. Coasts: An Introduction to Coastal Geomorphology, (3rd Edition), Blackwell, Oxford, 320pp.

Collins, M. 1983. The application of satellite imagery to sedimentological investigations on the continental shelf. In: Sedimentation on the Continental Shelf with Special Reference to the East China Sea, China Ocean Press (Beijing)/Springer Verlag (Berlin), 893-919.

Collins, M.B., Banner, F.T., Tyler, P.A., Wakefield, S.J. &James, A.E. (Eds.). 1980. Industrialised Embayments and their Environmental Problems: A Case Study of Swansea Bay. Pergamon Press, Oxford, 616pp.

Collins, M.B., Ferentinos, G. & Banner, F.T. 1979. The hydrodynamics of a high (tidal and wave) energy embayment (Swansea Bay, northern Bristol Channel), U.K. Estuarine & Coast. Mar. Sci., 8, 49-74.

Conispoliatis, N. 1979. Sedimentology and Mineralogy of Thermaicos Bay, N.W. Aegean Sea. Unpub. M.Sc. Thesis, University of Wales, 133pp.

Conispoliatis, N.K. 1983. The distribution of clay minerals in the recent surface sediments of the Thermaicos Bay. OPYKTO OYTO, 22, 37-46.

Conomos, T.J. (Ed.). 1979. San Francisco Bay: The Urbanised Estuary. American Association for the Advancement of Science, 493pp.

Culver, S.J. 1980. Differential two-way sediment transport in the Bristol Channel and Severn Estuary, U.K. Marine Geology, 34, M39-M43.

Davies, J.L. 1964. A morphogenetic approach to world shorelines. Zeits. Geomorph., 8,(Sp. No.), 127-142.

Davis, R.A. Jr. & Hayes, M.O. 1984. What is a wave-dominated coast? Marine Geology, 60, 313-329.

Elliot, T. 1978. Deltas. In: Reading, H.G. (Ed.). Sedimentary Environments and Facies. Blackwell Scientific Publications, 97-142.

Ferentinos, G., Brooks, M. & Collins, M.B. 1981. Gravity-induced deformation on the north flank and floor of the Sporhades Basin of the North Aegean Trough. Marine Geology, 44, 289-302.

Ferentinos, G., Collins, M.B., Pattiaratchi, C.B. & Taylor, P. 1985. Mechanisms of sediment transport and dispersion in a tectonically active submarine/valley canyon system: Zakynthos Straits, N.W. Hellenic Trench. Marine Geology, 65, 243-269.

Gorsline, D.S. & Swift, D.J.P. (Eds.). 1977. Continental Shelf Dynamics: A National Overview, Report of a Workshop, Colorado, NSF, U.S.A., 134pp.

Harris, P.T. & Collins, M.B. 1985. Bedform distributions and sediment transport paths in the Bristol Channel and Severn Estuary, U.K., Marine Geology, 62, 153-166.

Heathershaw, A.D. 1981. Comparisons of measured and predicted sediment transport rates in tidal currents. In: Nittrouer, C.A. (Ed.). Sedimentary Dynamics of Continental Shelves, Elsevier, Amsterdam, 75-104.

Heathershaw, A.D. & Carr, A.P. 1977. Measurements of sediment transport rates using radioactive tracers. Coastal Sediments '77, ASCE/Charleston, S. Carolina, Nov. 2-4, 1977, 399-416.

Jago, C.F. & Barusseau, J.P. 1981. Sediment entrainment on a wave-graded shelf. In: Nittrouer, C.A. (Ed.). Sedimentary Dynamics of Continental Shelves, Elsevier, Amsterdam, 279-299.

Jago, C.F. & Barusseau, J.P. 1983. Shore-normal textural gradients of inner continental shelves. In: Sedimentation on the Continental Shelf, With Special Reference to the East China Sea. China Ocean Press (Beijing)/Springer Verlag (Berlin), 877-892.

Komar, P.D. 1976. Beach processes and Sedimentation, Prentice-Hall, New Jersey, 429pp.

Lykousis, V., Collins, M.B. & Ferentinos, G. 1981. Modern sedimentation in the N.W. Aegean Sea. Marine Geology, 43, 111-130.

Mackenzie, J.D. 1958. Rip Current Systems, J. Geol., 66(2), 103-113.

Okada, H. & Ohta, S. 1983. Benthic biological activity. In: Sedimentation on the Continental Shelf, with Special Reference to the East China Sea. China Ocean Press (Beijing)/Springer Verlag (Berlin), 93-105.

Pattiaratchi, C.B. & Collins, M.B. 1984. Sediment transport under waves and currents: a case study from the northern Bristol Channel, U.K. Marine Geology, 56, 27-40.

Pattiaratchi, C.B. & Collins, M.B. 1985. Sand transport under the combined influence of waves and tidal currents: an assessment of available formulae. Marine Geology, 67, 83-100.

Robles, F.L.E., Collins, M.B. & Ferentinos, G. 1983. Water masses in Salonica Bay and Thermaicos Bay (northwestern Aegean Sea), Estuarine Coast. & Shelf Sci., 16, 363-378.

Sultan, S.A.R., James, A.E. & Collins, M.B. 1984. A note on processes influencing the mixed layer depth in the northwestern Aegean Sea. Thalassografica, 7, 5-18.