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^{14}C DATING OF RECENT CRUSTAL MOVEMENTS IN THE PERSIAN GULF AND IRANIAN MAKRAN

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ABSTRACT. Radiocarbon dating of mollusks and barnacles from fossil shoreline deposits in the Persian Gulf and on the coast of Iranian Makran is being used to assess the extent and rate of recent crustal deformation in the area. Samples are selected with the help of x-ray diffraction and of light and scanning electron microscopy; whenever possible, two or more ages are determined for each locality on monospecific samples. Age/height values have been used to compute local uplift rates by allowing for sea-level fluctuations, but eustatic controversy can be avoided by limiting the analysis to fault chronology and to relative vertical movements between dated sections. Short counting times on large, carefully pretreated samples would supply the numerous, cheap, low-resolution ages required to follow up the preliminary results obtained by the survey.

INTRODUCTION

Crustal models of the Persian Gulf and the Makran (fig 1) cannot be tested and refined without information on Late Cainozoic earth movements. Marine platforms and beaches now above sea level have been cited for over a century as evidence of recent coastal uplift in many parts of the region (Blanford, 1872), but until their chronology is established they will remain of little more than curiosity value (see, for example, Farhoudi and Karig, 1977).

An attempt is accordingly being made to supplement the few radiometric ages available for the beaches with ^{14}C determinations on carefully selected mollusks and barnacles. This paper summarizes the procedures by which samples are selected and shows how the results are being used to trace local and regional earth movements.

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Sample selection and pretreatment

In the course of reconnaissance surveys in Iran and Qatar (Vita-Finzi, 1975; 1978), beach or shallow-water deposits above high water were selected for dating if they promised to throw light on individual structures or on the regional pattern of deformation. Whenever possible, two or more samples composed of one mollusk species or barnacles were collected from the horizon to be dated. Aragonitic bivalves and gastropods were favored because their shells lend themselves to simple tests for gross recrystallization (Grant-Taylor, 1972).

Pretreatment was delegated wholly to the radiocarbon laboratory, until the presence on a date report of phrases such as 'some surrounding material could not be separated' and 'sample from lump containing shell-like material' brought to life the dictum that 'the true limit of

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the radiocarbon method may lie as much in the cleaning of the materials as in the measurement of the radiocarbon radiation' (Libby, 1970). Thereafter, the following course of action was taken. A representative specimen from each sample was freed of encrusting material with the help of dental drills and burrs, the chambers of gastropods being exposed for the purpose by cutting with a diamond saw cooled with de-ionized water. Acetate peels of sectioned shells and plates were compared under the light microscope with modern specimens or published descriptions of the species in question. Besides permitting the rejection of samples showing clear signs of recrystallization, the peels showed whether additional mechanical cleaning was advisable (pl 1-C).

Samples displaying no obvious recrystallization were analyzed by x-ray diffraction. A fragment taken right across the valve or chamber wall or from the cleaned exterior was used, with either halite or aragonite providing an internal standard for calcitic specimens. To avoid inversion and maximize peak intensity, it was ground in a mortar for 3 to 4 minutes (*cf* Milliman, 1974); the powder was applied to glass slides with Durofix diluted with acetone, and analyzed on a Philips PW 1010 diffractometer using a CuKα source with an Ni filter. A slow scan speed of ½°/min and a chart speed of 40mm/min were adopted; reproducibility was never worse than $\pm$ 0.07°2θ, comfortably within the requirements of most lattice constant curves.

Unless it could be eliminated by further abrasion (pl 1-A,-B), calcite in aragonitic mollusks led to their rejection, but <1 percent calcite was provisionally condoned if it was associated merely with subtle coarsening (Chappell and Polach, 1972) of the shell structure. Oysters and barnacles with an $MgCO_3$ content similar to that found in their modern counterparts were passed, although the limitations of this test are clear. Further checks for alteration were made on fracture surfaces with the SEM

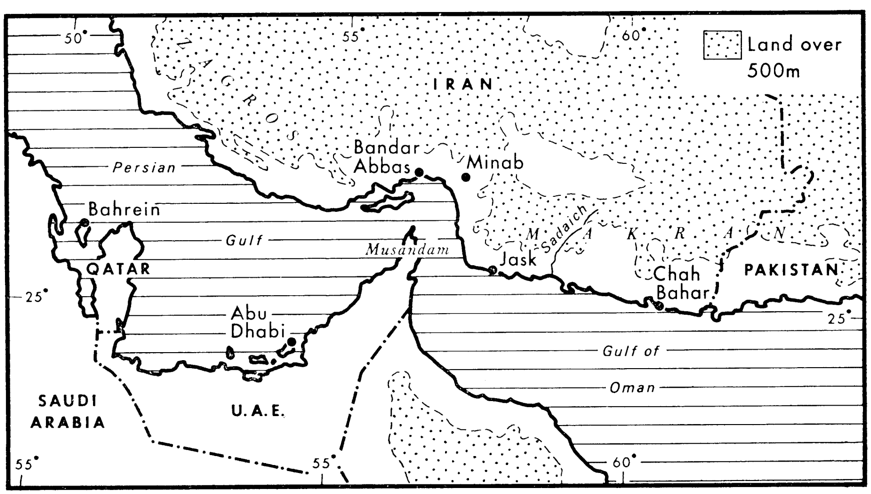

Fig 1. Location map.

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(Walker, 1979). Provided there was no evidence of calcite precipitation, any dissolution or borings thus revealed were deemed innocuous (pl 1-D).

The use of stable isotopes for detecting contamination is hampered above all by variations in analytical procedure. The $\delta^{13}C$ readings obtained for age normalization by the dating laboratories (and not all of them are equipped for the task) have to be supplemented with independent determinations on selected portions of the specimen, and allowance needs to be made for oceanic composition and terrestrial runoff when comparing the isotopic composition of samples of different age. Similar problems arise in the interpretation of trace elements even if one does not aspire to the statistical analysis of sizeable populations (Curtis and Krinsley, 1965). This is not to disparage the reassurance to be gained from Sr/Mg values that lay within the modern range of variability for that species, and from isotopic readings that fell inside the $\delta^{13}C/\delta^{18}O$ envelope characteristic of barnacles and shallow-water mollusks in areas not affected by significant freshwater influx or by maverick salinity and circulation patterns.

Unfortunately, only some of the arcids and oysters were large and massive enough for a single individual to supply all the carbonate required for age determination as well as for the above tests. Samples composed of several specimens were checked by additional x-ray analyses; thorough inspection and mechanical cleaning meant that leaching, and hence the number of shells or barnacle plates, could be kept to a minimum and the need for duplicate dates on inner and outer (or middle) fractions obviated.

Cross-checks

Granted that it could be the accidental product of undetected contamination, reasonable agreement between the ages obtained on two or more monospecific samples from the same beach inspired some confidence in the result. In the sequence of fossil intertidal platforms at Tujak (pl 2), 55km NW of Jask, this undoubtedly applies to Terrace III (table 1). The ages obtained for the other two terraces are far less consistent, but a possible solution is to accept those that have been determined on mollusks in place or with their valves still articulated. Where all the specimens in a beach are redeposited, however, the youngest age must presumably prevail.

The ages were also checked for their consistency with stratigraphic history provided this was not in any way contingent on tectonic factors. Alluvial deposits that could be equated with dated sequences inland have proved useful for this purpose. For example, beds of Minab Alluvium, a fill dated by ^{14}C determinations on charcoal to ca 1250 to 100 years BP (Vita-Finzi, 1979a), overlie a beach east of Jask dated to 4870 $\pm$ 100 years BP (UM-1151) and also occupy a channel cut by the Zengali River through the Tujak terraces discussed above.

No radiometric technique other than ^{14}C was accessible to the author. In accordance with the widespread view that ^{14}C ages on shell carbonate of more than 20,000 years should be treated as minima, Page

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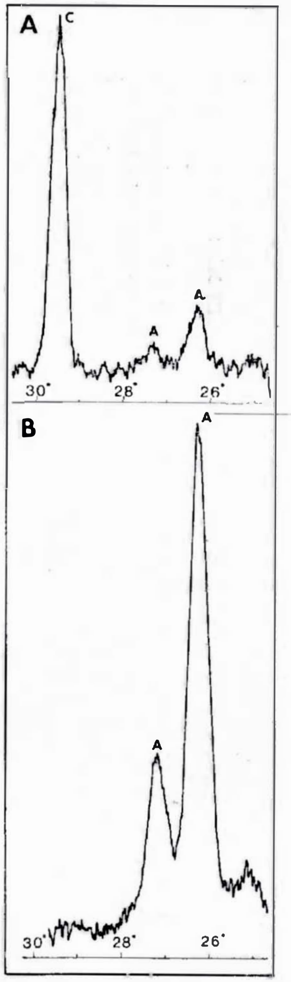
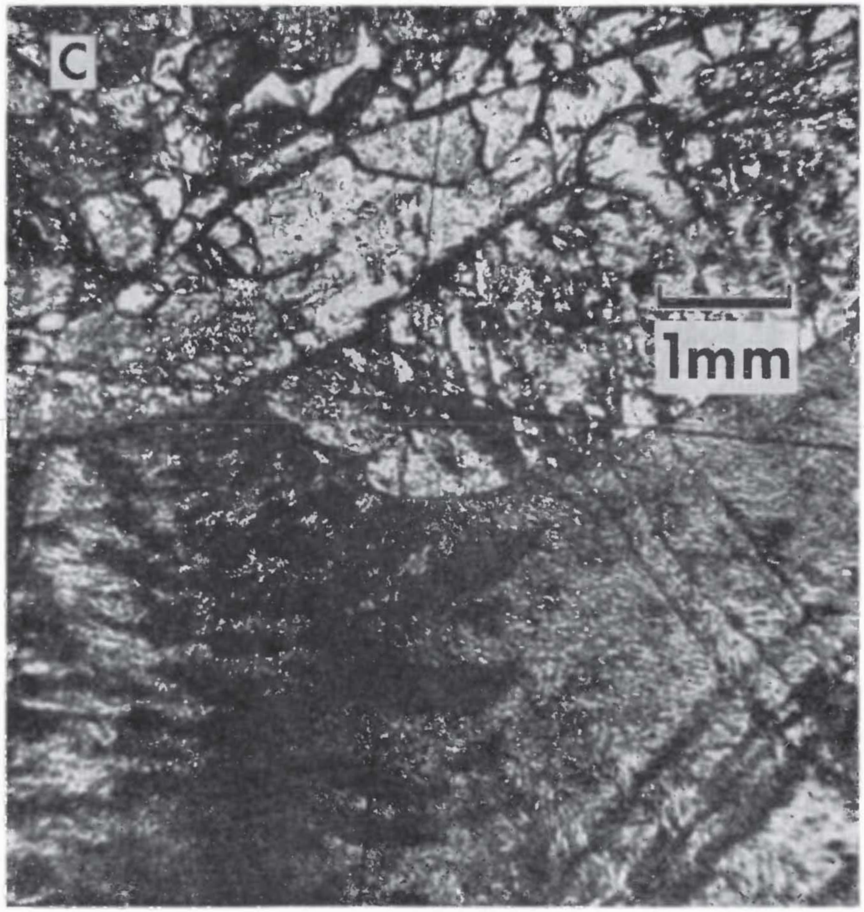
PLATE 1





X-ray diffractographs of outer margin of Oliva *sp* (A) before and (B) after mechanical cleaning. Note elimination of calcite. (C) Acetate peel and (D) scanning electron micrograph of same specimen showing boundary between original shell aragonite and replacement calcite. Note dissolution of aragonite lamellae in (D).

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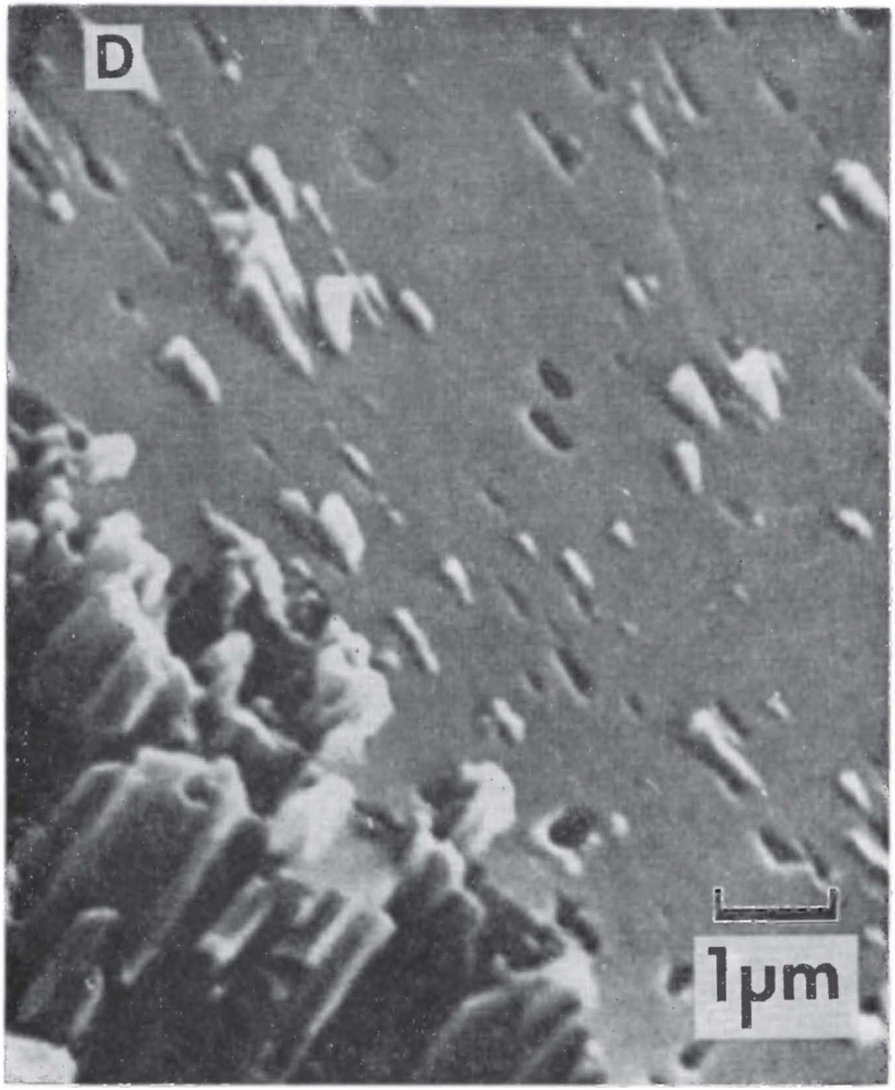

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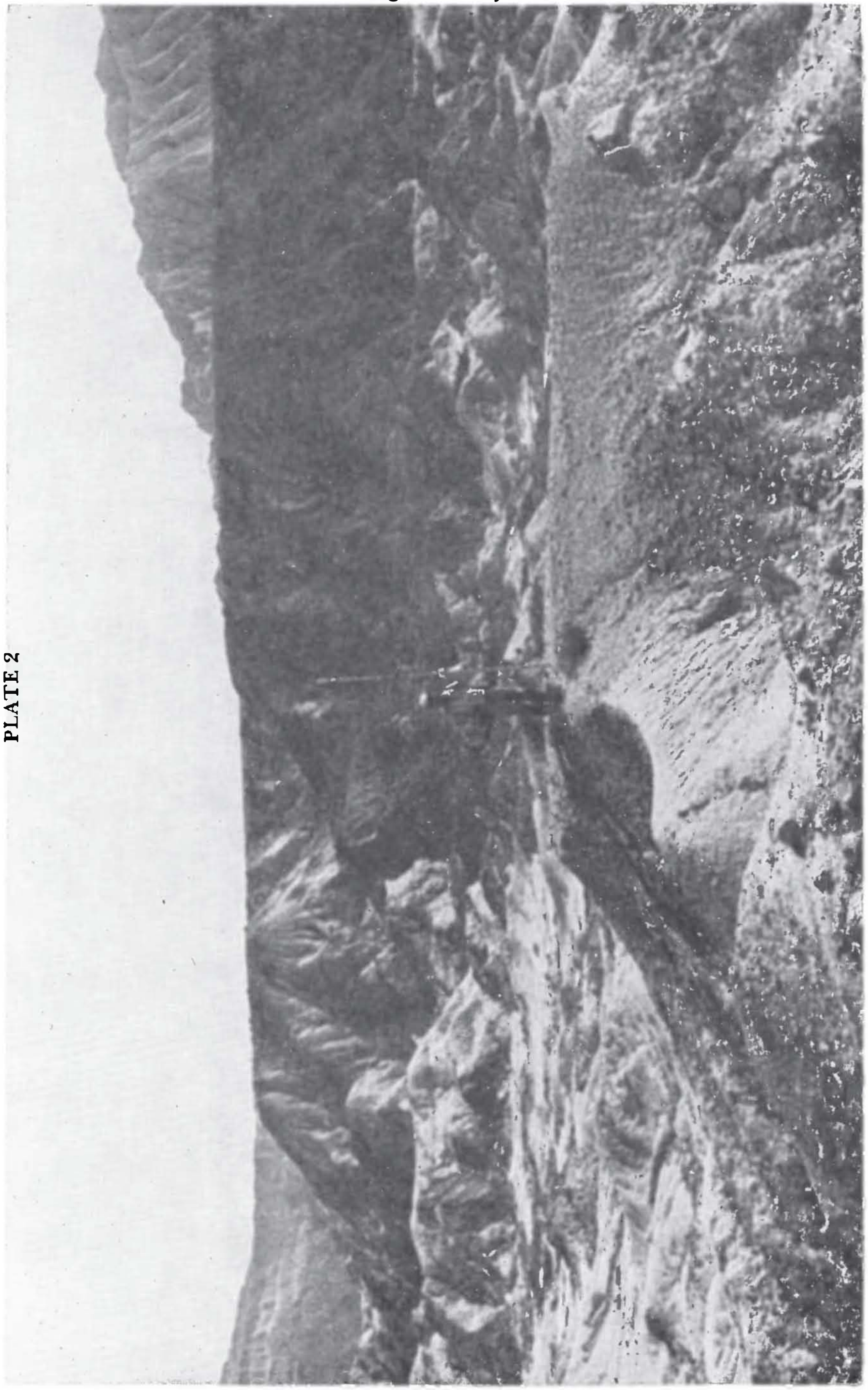
PLATE 2



Beaches II and III at Tujak

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TABLE 1

^{14}C ages for Tujak

Sample no.	Height above high water (m)	Species	Lab no.	Age (yr BP)*	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)‡	X-ray¶
ET I a	2.0	*Scapharca inaequivalvis*	SRR-1258	1530 ± 45	+0.40	−0.27	A
I b	"	*Crassostrea* cf *cucullata***	QC-549	1700 ± 105	+1.81	−0.50	C
I c	"	*Asaphis deflorata*	SRR-1309	2910 ± 50†	+1.40	−0.84	A
ET II o	11.8	*C* cf *cucullata****	SRR-1313	2330 ± 50	0.00	−2.76	C
II b	"	*S inaequivalvis*	UM-1268	3325 ± 85	+0.79	−0.60	A
II c	"	*A deflorata****	SRR-1257	2510 ± 40	+1.90	+0.11	A
ET III E	28.6	*Estonia rugosa****	SRR-1312	6535 ± 80	+2.20	−1.14	A
III x	"	*A deflorata*	UM-1255	6170 ± 155	+0.83	−0.78	A
III b	"	*S inaequivalvis*	UM-1269	6110 ± 95	+0.46	−1.02	A tr C

* Ages normalized to $\delta^{13}C = 0‰$ using $\delta^{13}C$ values supplied by dating laboratory and listed here.
** Shells in growth position.
*** Shells with valves still articulated.
† Ascribed to both Terrace I and Terrace II in figure 3B.
‡ Measurements by P A R Ireland.
¶ A = aragonite, C = calcite with 1-2% $MgCO_3$, tr C = <1% calcite.

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and others (1979) rejected many of the older ages they obtained for beaches at Jask and Konarak in favor of uranium series determinations. The results, which in every case exceeded 110,000 years, appeared to justify their action. But there is at present no evidence that uranium series dates on shell are any more dependable than ^{14}C dates, and until the technique is applied to associated corals (and backed by adequate documentation of the samples) the ^{14}C ages would seem to deserve provisional acceptance.

Local uplift rates

In order to convert a series of age/height values into a measure of vertical displacement we must allow for sea-level fluctuations during the corresponding period. An attempt was made to do this for the last 7000 years at Tujak and two other sections on the Zagros coast of Iran where dated beach deposits are found on the flanks of anticlinal structures bordering the coast (Vita-Finzi, 1979b). In view of the lack of agreement over eustatic history, two contrasting sets of corrections were employed of which one assumed progressive submergence and the other progressive emergence over the period. The resulting uplift rates were converted to rates of crustal shortening as a first step towards elucidating the mechanisms responsible for fold development. As the Gulf record favors the transgressive model (Sarnthein, 1972), discussion here is confined to values corrected after Flint (1971).

The original graphs for Tujak were based on a total of five ^{14}C dates for the three platforms. Four additional dates are incorporated in table 1 and fig 2B. If, as in the original study, all the dates are used to calculate graphs by least squares, the additional values change the resulting uplift rate from 7.4 to 7.3mm/yr; if the manifestly redeposited samples

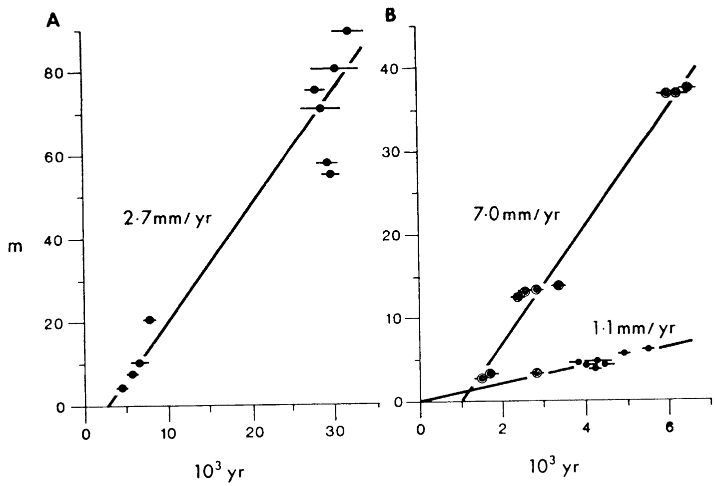

Fig 2. Age-height values and uplift rates calculated by least-squares for (A) sections of Makran coast not affected by major faulting and (B) Tujak (◉) and Qatar (●). Data sources and details of eustatic correction are given in text.

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are ignored, the calculated rate is 6.6mm/yr. In short, the increased confidence that stems from additional age determinations has not been matched by a corresponding gain in information.

The presence of discrete beaches suggests movement was not continuous, and this tallies with the widespread faulting associated with the anticline at Tujak. The least-squares plot is intended to evaluate cumulative displacement, and, unlike a graph taken axiomatically through the origin, it could conceivably reveal halts in uplift. The graph suggests movement stopped about 1000 years ago. The Sadaich Alluvium of south Iran has a terminal age of ca 7300 years BP, which was derived from ^{14}C dating of shell from a midden on its surface. Near Minab and elsewhere (Ghorashi, ms), it has been faulted whereas adjoining exposures of the Minab Alluvium have not, the implication being that movement occurred between 7300 and 1250 years BP (Vita-Finzi and Ghorashi, 1978). In view of its potential value for the study of seismic risk the apparent tectonic hiatus after 1000 years BP needs to be explored from independent sources.

Eustatic correction of the scanty data available for Qatar and Abu Dhabi (Vita-Finzi, 1978; Evans and others, 1969; Taylor and Illing, 1969) gives an uplift rate of 1.1mm/yr, with the least-squares line going through the origin (fig 2B). The field evidence is compatible with continuing, slow uplift at the margins of the Qatar anticline. In an attempt to differentiate between localized fault movement and regional uplift in the Makran, a similar approach was extended to sections on that coast located in zones apparently free of large-scale faulting using data from Page and others (1978) and Vita-Finzi (1979a). For the period between 15,000 and 30,000 years BP the eustatic curves of Flint (1971) were supplemented with that of Chappell and Veeh (1978). An uplift rate of 2.7mm/yr was obtained (fig 2A) but, in view of the strong contribution to the rate made by the eustatic factor and the ample evidence for differential movements along the coast, this result is little more than exploratory.

An intriguing corollary of prolonged and uniform uplift is that shorelines that formed at different times and elevations could thereby be brought together. A beachrock deposit west of Bandar Abbas has yielded ^{14}C dates of 4625 ± 115 years BP (MC-1099) on aragonitic bivalves and 25,685 ± 270 years BP (SRR-1310) on oysters. Redeposition of the oysters (*cf* Macintyre, Pilkey, and Stuckenrath, 1978) could conceivably account for the gross discrepancy between the two ages. An alternative explanation is that two shorelines are represented, one of which formed 4600 years ago at −3m and the other 26,000 years ago at −33m, and that they were both uplifted at the rate of 1.4mm/yr previously calculated for the section (Vita-Finzi, 1979b).

Fault chronology and regional patterns

The drawback to using eustatic corrections is that they are destined to remain controversial. One tectonic application of age/height values

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that evades the the problem is the analysis of fault history. There is disagreement over the extent to which fault action, and in particular block faulting, has helped to fashion the Makran coast, and even where faulting is admitted its chronology is uncertain. Whether apparently faulted surfaces were formerly continuous and when movement took place can be established by dating beaches that are cut by faults or that postdate them.

The 29m marine terrace at Gavatre, about 5km west of the Pakistan/Iran border, invites this kind of treatment as it is cut by two north-south wrench faults, one about 2km and the other about 3km long (Ghorashi, 1978). Samples of *Oliva bulbosa* taken at the north and south margins of the terrace deposits on opposite sides of the western fault have given dates of 27,130 $^{+515}_{-485}$ and 27,140 ± 310 years BP (SRR-1315, 1327) respectively; the fault is presumably younger. The peninsula of Konarak, 25km west of Chah Bahar, displays a normal fault in Tertiary beds which is capped by a beach deposit. The dates so far obtained for this deposit are 34,180 $^{+1610}_{-1340}$ (SRR-1321) on barnacles and >44,300 years BP (QC-537) on oysters. By the rules of redeposition the lower one provides the maximum age for the beach and, *ipso facto*, the minimum age for the fault. Although such limiting values leave much to be desired, they are a first step towards linking the coastal record of faulting with that obtained inland.

In addition, comparison of the heights attained by coeval beach deposits at the locations used for plotting figure 3A gives some impression of the regional pattern of deformation. East of the Zendan Fault, which separates the Makran from the Zagros Belt to its west, the 4000 to 6000 years 'waterline' is represented by a beach 1.3m above high water east of Jask (UM-1151), and by shell samples about 5 to 6m above high water from the tombolo that links Konarak to the mainland (Page and others, 1979). A similar trend characterizes the 30,000 to 35,000 year band, with heights of 5.9m at Jask and 18m some 3.5km east of Chah Bahar (Vita-Finzi, 1979a). Page and others (1979) have already suggested that late Quaternary rates of uplift on the Makran coast show an eastward increase. Some prospect now exists of disentangling the component due to regional tilting from local fault displacements.

The need for numerous, reliable ages in this kind of study is obvious. The high cost of each ^{14}C determination to users of commercial laboratories could be reduced by limiting counting time to that required for results to be expressed in multiples of 10^3 years, and the disproportionate time required for sample preparation by delegating the pretreatment of suitably large samples to the client. The choice is not between rapier and cutlass (or rifle and sawed-off shotgun) but between too few values that are unduly precise and an adequate number of values whose resolution matches the needs of the investigation.

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