J. geol. Soc. London, Vol. **139,** 1982, pp. 605–614, 5 figs, 2 tables. Printed in Northern Ireland.

Late Cretaceous and early Miocene Andean-type plutonic activity in northern Makran and Central Iran

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SUMMARY: Two calc-alkaline plutonic complexes, Bazman and Natanz, intruded through the south-eastern active and south-western ancient continental margins of Central Iran, Have been dated by the Rb-Sr whole-rock isochron method at 74 ± 2 and 24 ±4.5 Ma, respectively. Detailed trace element studies together with low $^{87}Sr/^{86}Sr$ initial ratios (<0.706) indicate that these complexes represent parts of an Andean-type magmatic arc formed in response to subduction of Tethyan oceanic crust beneath Central Iran. Geochemical data on the igneous rocks at Bazman suggest that subduction of the Oman oceanic crust was well established by the late Cretaceous. On the evidence of the Natanz rocks, the Arabian–Central Iranian collision did not occur during the late Cretaceous, but took place during late Paleogene or early Neogene time. The Natanz low-Rb diorites and gabbros cannot be comagmatic with the more salic rocks, for they have distinctly lower $^{87}Sr/^{86}Sr$ ratios and the gabbros, at least, were intruded some 10 Ma earlier.

Recently there has been considerable controversy concerning the nature and dating of the final closure of the Tethyan ocean and of the Arabian–Central Iranian continental collision. Although the geosuture between these continental fragments is along the Main Zagros reverse fault line (Fig. 1), Alavi (1980) suggested that it lies about 130 km further NE. Sabzehei (1974), Nabavi (1976), Hushmandzadeh (1977) and Haghipour (1980) have discussed tectonic features in the region but their interpretations take no account of plate tectonics and argue against the existence of a substantial amount of oceanic crust to participate in subduction-related processes. Obduction of ophiolites and pelagic sediments along the active Central Iranian and the passive Zagros continental margins in the Late Cretaceous–Palaeocene (Fig. 1), with change of sedimentary regime from oceanic to shallow marine and continental, has led some workers to propose a Late Cretaceous–Palaeocene intercontinent collision along the Zagros suture line (Takin 1972; Stocklin 1974, 1977; Hallam 1976; Welland & Mitchell 1977; Desmons 1980; Adamia *et al.* 1980; Berberian & King 1981). If this assumption is correct, then the well-developed Tertiary plutonic activity in the region must be considered as post-collisional magmatism that is not related to subduction. Other workers argue against the Late Cretaceous–Palaeocene closure of the Tethyan ocean and believe that intercontinent collision took place during Miocene time (Dewey *et al.* 1973; Smith 1973; Forster 1974; Krumsiek 1976; Kanasewich *et al.* 1978; Klootwijk 1979; Sengor 1979; Sengor & Kidd 1979; Powell 1979). In the course of petrological investigations of two calc-alkaline complexes (Bazman and Natanz) in southeastern and southwestern Central Iran (Berberian 1981*a*), geochemical and geochronological studies have been used to throw new light on this problem.

The Bazman calc-alkaline intrusive complex (mela-diorite to alkali granite) is situated in the southeastern margin of the Central Iranian tectonic unit. Its position along the southeastern extremity of the Karkas-Jebel Barez Oligo-Miocene plutonic belt (Fig. 1) would appear to imply that it belonged to the same episode. On the other hand, it is also located in the northern part of the coastal-Makran subduction zone (White & Klitgord 1976) which has been active at least since the Cretaceous (Farhaudi & Karig 1977; Berberian & King 1981) and may be related to its magmatic-arc activity. Stratigraphically, the age of the Bazman complex can be shown to be post-Triassic–pre-Neogene, since the intrusive rocks cut Permian and Triassic limestones and are overlain by Neogene continental red beds (Berberian 1974).

The Natanz intrusive complex forms a part of a long volcanic-plutonic belt (the Karkas–Jebal Barez belt; Fig. 1) running parallel to the Zagros–Central Iranian convergent plate boundary. It is situated above the established Mesozoic subduction zone of Tethyan oceanic crust. The complex is composed of a typical calc-alkaline intrusive sequence (gabbro to granite) intruded into folded Eocene volcanic rocks during Oligocene–Miocene time.

Petrology of the Bazman and Natanz complexes

The Bazman intrusive complex in SE Iran shows the characteristics of a zoned pluton with a dominance of granitic intrusions. Rock types in this complex range from basic (mela-diorite) to extreme granitic compositions (alkali granite). As with other typical zoned plutons (Cobbing & Pitcher 1972; Bateman & Nokleberg 1978; Bateman & Chappell 1979; Perfit *et al.*

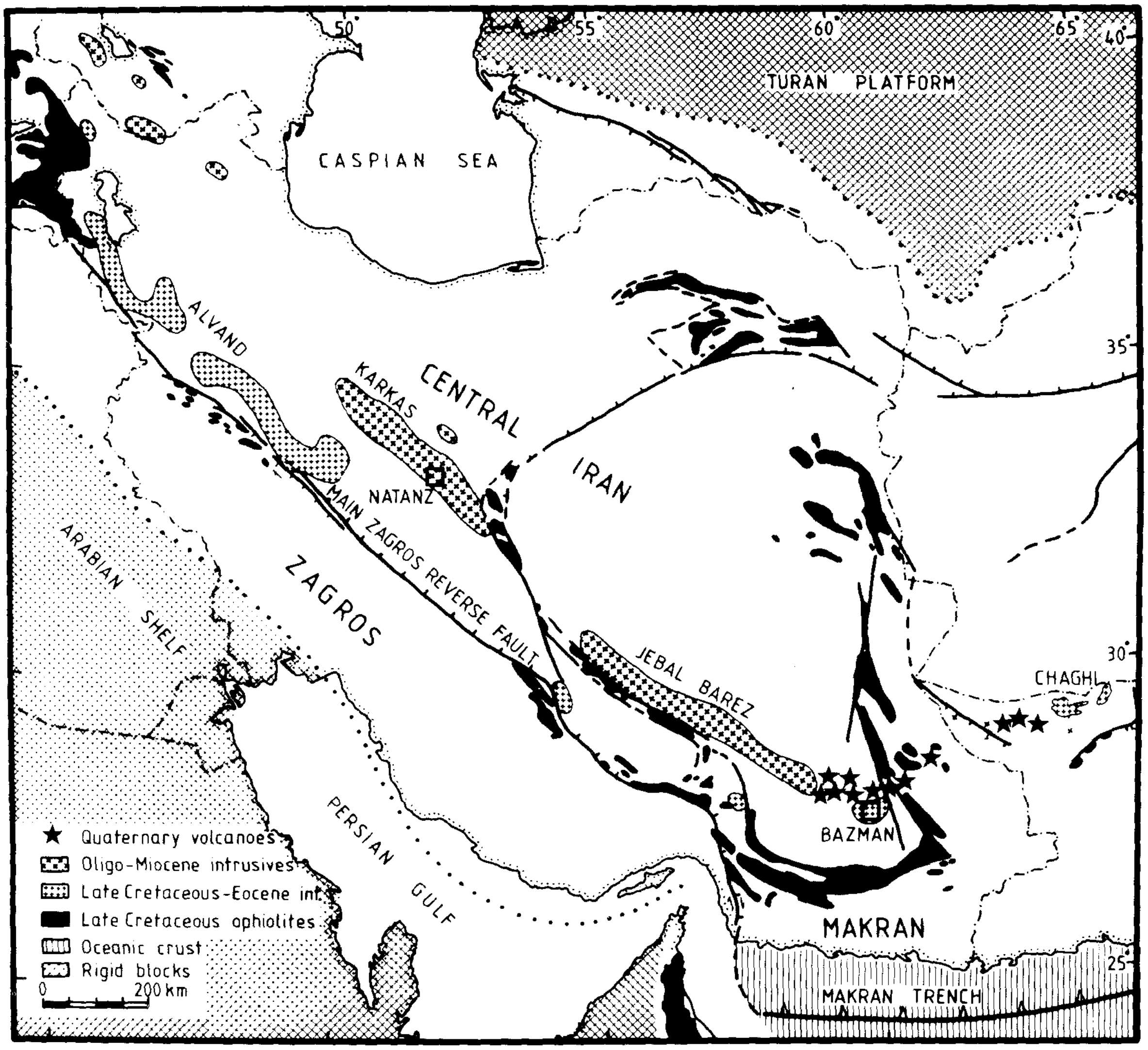

FIG 1. Map showing position and trend of the late Cretaceous ophiolites, the late Cretaceous–Palaeocene Alvand–Bazman and the Oligocene–Miocene Karkas–Jebal Barez calc-alkaline plutonic belts in Central Iran. Position of the late Cretaceous Bazman and the Oligocene–Miocene Natanz intrusive complexes are shown by squares. Based on Berberian (1981*a*) and Berberian & Berberian (1981). Lambert Conformal Conic Projection.

1980; Vennum 1980), the basic rocks occur in minor amount at the margins and there is a progressive increase in silica values towards the centre, where alkali granites occur. It is not clear whether the marginal mafic rocks, which are composed of higher temperature mineral assemblages, belong to a separate intrusive phase with a slightly greater age, or whether the whole mass is the result of a single intrusive event. Lower temperature mineral assemblages, such as K-feldspars and quartz, increase inwards, while mafic minerals, such as hornblende, increase towards the margin of the main body. This may be interpreted as a result of crystal fractionation during inward solidification and displacement of the melt-volatile phase with falling temperature (Vance 1961). Since the complex is dominated by granitic rocks and the marginal basic zone (diorite) is narrow, there is a possibility that as with the Thorr pluton (Pitcher & Berger 1972) the basic periphery may have formed as a result of contamination of granitoid rocks by carbonate country rocks. On the basis of petrography and geochemical characteristics five groups of rocks (meladiorite, diorite, granodiorite, granite and alkali granite) have been recognized in this complex. All display

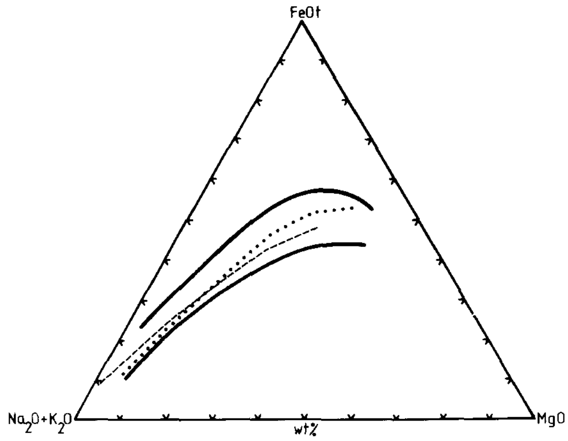

FIG. 2. AFM variation diagram showing chemical trends of the Bazman and the Natanz intrusive complexes. Thick lines: boundary lines of Kuno (1968) for the Hakone hypersthenic rocks. Dashed line: trend of the Bazman intrusive complex. Dotted line: trend of the Natanz intrusive complex.

similar petrographic features in their textures, mineralogy, and types of zoning to suggest that they formed under a limited range of P/T, P_{H_2O} and activity of O_2. When their chemical compositions are plotted on variation diagrams (Berberian 1981*a*) a continuous variation is displayed that suggests that all types are comagmatic and may have been derived from a common parent. In Fig. 2 the trends are shown on an AFM plot.

The Natanz complex in Central Iran shows a wider range of rock types occurring as discrete units which range from gabbro to granite. Emplacement began with the basic intrusives and ended with the granitoid rocks. Inclusions of basic rocks are frequently found in the granitoid rocks and the latter cut the former. No evidence of *in situ* differentiation or of inward zoning is observed. As with other typical calc-alkaline Andean-type intrusives (Roddick & Hutchinson 1974; Pitcher 1974; Gastil 1975), the Natanz complex represents a typical low-K calc-alkaline series with a dominance of intermediate types. Six different rock types exist in this complex (gabbro, diorite, tonalite, granodiorite, adamellite and granite), which show very close relationships in their chemical and mineralogical compositions (Fig. 2). All intrusive rocks have undergone post-emplacement deformation and have developed a low to medium grade of thermal metamorphism in the adjacent country rocks and xenoliths.

Highly calcic plagioclases and amphiboles are the main felsic and mafic minerals. Extreme zoning and the presence of calcic cores to the plagioclase (up to An_{47} in granites and An_{92} in gabbros) were observed. These calcic cores may indicate a shallow depth of intrusion, a high water vapour pressure, or point to the existence of restite material in the magma. Petrographic features as well as major and trace element geochemistry appear to suggest a common dioritic parental magma for all rock types (Berberian 1981*a*) in this complex.

The chemical compositions of representative rock types of both complexes (major, minor and trace elements; and norms) and their chemical variation as plotted on an AFM diagram are shown in Table 1 and Fig. 2, respectively. Except for the Bazman alkali granite, all the analysed rocks from both complexes prove to be distinctly calc-alkaline types. In their relatively high Na_2O/K_2O ratios, metaluminous chemistry, relatively high normative diopside and low corundum, they are typical members of the I-type granitoids of Chappell & White (1974). These characteristics are also shown by the trace elements, particularly by the high field strength group of incompatible elements of which Zr and Nb are easily determined and distinctive members. The rising and then falling Zr values with SiO_2 are clearly shown in Table 1 (Tarney & Saunders 1979).

Geochronology

In order to identify possible petrogenetic relations between these plutonic complexes and the recognized subduction zones in SE and SW Central Iran, 23 rocks and 3 separated minerals (biotite and muscovite) from the Bazman and the Natanz complexes were analysed.

Analytical Methods

For whole-rocks, Rb and Sr were determined by X-ray fluorescence spectrometry on pressed powder pellets made with a minimum quantity of 5% Moviol solution as a binder. Concentrations are accurate to ±5% and the Rb/Sr ratio to ±1% except where Rb concentrations are less than 50 ppm. Errors based on counting statistics are indicated in Table 2. $^{87}Sr/^{86}Sr$ ratios were measured after standard ion exchange separation of Sr on a VG Micromass 30B mass-spectrometer controlled by a Hewlett-Packard 9845A calculator. The precision of each result is ±0.01% and the value obtained for the NBS 987 $SrCO_3$ by this method is 0.71027 ± 0.00001.

For the mineral separates (biotite and muscovite) Rb and Sr were determined by mass-spectrometric isotope dilution with enriched ^{87}Rb and ^{84}Sr spikes, using triple Ta filament loading for Rb. Full results are given in Table 2. All errors are quoted as 2-sigma. The decay constants and other physical parameters used throughout are those recommended by IUGS Subcommission of Geochronology (Steiger & Jäger 1977).

Discussion

Bazman

The 10 whole-rock data points for this complex do not define an isochron (Fig. 3), but the 3 most

TABLE 1: *Rock analyses and norms of Bazman and Natanz complexes*

Locality	*Bazman*						*Natanz*					
Anal. no.	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Rock no.	*231*	*239*	*232*	*237*	*238*	*234*	*164*	*178*	*109*	*220*	*144*	*91*
SiO_2	73.89	71.51	67.96	56.93	48.59	53.77	73.29	67.72	67.57	63.56	53.05	49.90
TiO_2	00.09	00.14	00.28	00.73	00.77	00.64	00.22	00.53	00.46	00.59	00.98	01.03
Al_2O_3	14.94	15.26	16.72	17.89	21.35	20.44	14.12	15.61	15.40	16.13	17.81	20.63
Fe_2O_3	00.47	00.49	01.05	02.07	00.81	01.77	00.80	02.15	01.52	02.41	03.95	00.76
FeO	00.38	00.98	01.41	04.79	06.28	04.78	01.05	01.96	02.63	03.43	04.73	03.03
MnO	00.11	00.03	00.08	00.17	00.13	00.14	00.03	00.01	00.07	00.10	00.16	00.13
MgO	00.17	00.42	00.85	04.14	03.81	04.54	00.49	01.38	01.77	02.45	04.48	05.96
CaO	00.40	01.55	03.59	07.44	12.17	09.86	02.05	03.15	03.90	05.46	08.37	14.43
Na_2O	04.29	03.80	04.39	03.22	02.56	03.09	03.86	03.77	03.92	03.57	03.39	02.34
K_2O	04.49	05.03	02.70	01.35	00.83	00.76	03.40	03.13	02.45	01.26	00.77	00.16
P_2O_5	00.07	00.06	00.13	00.37	00.65	00.27	00.05	00.08	00.06	00.09	00.12	00.02
H_2O^+	00.69	00.50	00.61	00.99	01.47	00.68	00.58	00.58	00.59	01.20	01.17	01.32
H_2O^-	00.02	00.22	00.03	—	—	—	00.10	00.07	00.06	00.07	00.07	00.08
Total	100.01	99.99	99.80	100.09	99.42	100.74	100.04	100.14	100.40	100.32	99.05	99.79
Trace elements												
Nb	61	21	19	9	10	5	12	10	12	5	10	trace
Zr	55	70	143	65	70	27	87	297	128	107	28	18
Y	26	17	16	17	16	9	17	42	25	40	30	18
Sr	135	291	549	458	920	618	142	240	252	263	381	389
Rb	289	135	93	50	20	5	106	98	102	26	22	4
Norms												
Qz	30.67	25.82	22.86	10.03	00.00	04.40	32.41	24.79	23.61	21.75	06.32	00.00
Co	02.46	00.89	00.36	00.00	00.00	00.00	00.48	00.48	00.00	00.00	00.00	00.00
Or	26.53	29.72	15.96	07.98	04.90	04.49	20.09	18.50	14.48	07.45	04.55	00.95
Ab	36.30	32.15	37.15	27.25	21.66	26.15	32.66	31.90	33.17	30.21	28.69	19.80
An	01.53	07.30	16.96	30.37	44.31	39.66	09.84	15.10	17.19	24.27	31.11	45.31
Di	00.00	00.00	00.00	03.35	09.79	06.09	00.00	00.00	01.44	01.82	07.74	20.80
Hy	00.79	02.27	03.53	14.87	09.42	14.86	02.18	04.40	06.65	08.74	11.54	08.41
Ol	00.00	00.00	00.00	00.00	03.72	00.00	00.00	00.00	00.00	00.00	00.00	00.02
Mt	00.68	00.71	01.52	03.00	01.17	02.57	01.16	03.12	02.20	03.49	05.73	01.10
Il	00.17	00.27	00.53	01.39	01.46	01.22	00.42	01.01	00.87	01.12	01.86	01.96
Ap	00.17	00.14	00.31	00.88	01.54	00.64	00.12	00.19	00.14	00.21	00.28	00.05
Total	99.30	99.27	99.17	99.12	97.99	100.08	99.36	99.49	99.75	99.06	97.82	98.39

1, alkali granite; 2, granite; 3, granodiorite; 4, 5, diorite; 6, mela-diorite; 7, granite; 8, adamellite; 9, granodiorite; 10, tonalite; 11, diorite; 12, gabbro.

Analyses 1–3 & 7 by J. H. Scoon, the rest by F. Berberian.

radiogenic samples (two granites and a granodiorite) are precisely collinear (mean square weighted deviates; MSWD = 0.0), with a slope corresponding to an apparent age of 74 ± 2 Ma and an intercept of 0.7056 ± 0.0001. The muscovite separate from an alkali granite gives an age of 64 ± 1 Ma. This rock shows some evidence of a later hydrothermal event. The plagioclase crystals are partly sericitized but are mostly homogeneous with cores as calcic as An_{28} but they have narrow rims as sodic as An_{15}. An unusual feature of this primary plagioclase is the presence of fine multiple twinning on the Albite-Ala B law. In some cases this early plagioclase is sharply mantled or replaced by almost pure albite. The evidence of albitization, together with the patchy development of muscovite, seems to suggest a later hydrothermal event that may be responsible for the younger age obtained for the muscovite separate of this rock. No other age data are known for the Bazman rocks and intrusion during latest Cretaceous or early Palaeocene times seems probable.

The calculated initial $^{87}Sr/^{86}Sr$ ratios of the remaining granodiorites and diorites range from 0.7043 to 0.7053 (Table 2) and are insensitive to assumed age in the interval 64–74 Ma. This degree of source rock heterogeneity is not unusual in calc-alkaline magmatic arcs. It appears to rule out very close direct links via fractional crystallization unless contamination has

TABLE 2: *Rb-Sr analytical data for Bazman and Natanz complexes*

Nos	*Rock type*	*Rb(ppm)*	*Sr(ppm)*	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_0$	*Age (Ma)*
Bazman							
231	Alkali granite	274	122	6.489	0.71249	0.70564	
239	Granite	131	268	1.419	0.70714	0.70564	74.2 ± 2.0
232	Granodiorite	91	514	0.516	0.70619	0.70565	
230	Granodiorite	90	616	0.422	0.70527	0.70482	
235	Granodiorite	70	524	0.385	0.70524	0.70483	
236	Granodiorite	99	461	0.622	0.70530	0.70464	
237	Diorite	53	459	0.333	0.70464	0.70429	
233	Diorite	40	526	0.219 (0.8)	0.70487	0.70464	
238	Diorite	25	939	0.076 (1.2)	0.70535	0.70527	
234	Mela Diorite	7	619	0.032 (3.8)	0.70470	0.70467	
231	Misc. separate	951	7.87	360.7	1.0326 (0.3)		63.6 ± 1.4
Natanz							
148	Granite	95	141	1.959	0.70641	0.70574	
149	Granite	93	107	2.528	0.70660	0.70574	
151	Granite	112	105	3.089	0.70672	0.70567	
164	Granite	106	135	2.284	0.70639	0.70561	
205	Granite	107	140	2.225	0.70634	0.70558	24.0 ± 4.5
134	Adamellite	98	216	1.310	0.70608	0.70563	
224	Adamellite	82	219	1.086	0.70600	0.70563	
109	Granodiorite	104	233	1.294	0.70617	0.70573	
201	Tonalite	76	258	0.859	0.70597	0.70568	
220	Tonalite	26	255	0.298 (1.0)	0.70541	0.70530	
152	Diorite	27	356	0.217 (1.0)	0.70522	0.70514	
87	Gabbro	14	445	0.088 (2.0)	0.70528	0.70525	
91	Gabbro	2.6	375	0.020 (9.4)	0.70529	0.70528	
205	Bi. separate	625	28.1	64.45	0.72397 (0.02)	—	20.0 ± 0.4
		620	28.5	63.67	0.72395	—	20.2 ± 0.3
109	Bi. separate	714	36.1	57.29	0.72369	—	22.0 ± 0.3
152	Bi. separate	268	26.9	28.88	0.71527	—	24.0 ± 0.5
87	Bi. separate	269	131	5.94	0.70806	—	33.5 ± 1.8
		291	126	6.70	0.70850	—	34.3 ± 1.6

One-sigma errors are 0.5% on $^{87}Rb/^{86}Sr$ and 0.01% on $^{87}Sr/^{86}Sr$ except where shown otherwise. Errors on calculated ages are 2-sigma. Initial $^{87}Sr/^{86}Sr$ ratios are calculated assuming ages of 74 Ma for the Bazman rocks and 24 Ma for the Natanz rocks.

Ages for mica separates are WR-mineral isochrons.

occurred at a very late stage, or through a selective mechanism that is not reflected in major element chemistry.

Natanz

Whole-rock data points for the Natanz complex (13 samples) scatter outside analytical error (MSWD = 3.02) about a line of much lower slope than those for Bazman. Inspection of the isochron plot (Fig. 4) suggests two groupings. The gabbros and two low-Rb diorite samples fall significantly below the best-fit line for the remaining rocks (see Fig. 4 caption). The latter group defines a good isochron age (MSWD = 0.79) of 24 ± 4.5 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7057 ± 0.0001.

This subdivision is also in part supported by analyses of biotites separated from a selection of the rocks: the results suggest that not all members of the complex are coeval. Ages determined for biotite–whole-rock pairs for granite and granodiorites are 20 and 22 Ma, respectively, with analytical uncertainty much less than 1 Ma. Both are within the error of the whole-rock isochron with its much larger error. Biotite from diorite sample 152 also gives an age compatible with the whole-rock isochron although, at 24.0 ± 0.5 Ma, this is significantly older than the biotite ages of the more acid rocks. The range from 24 to 20 Ma could be related to prolonged cooling or to resetting during hydrothermal activity during and after intrusion. A $^{40}Ar/^{39}Ar$ age of *c.* 20 Ma is also obtained for the granitoid rocks of the complex (J. A. Miller, pers, comm., 1980). However, a much older age of 34 Ma (duplicated) is given by Rb-Sr analysis of the biotite

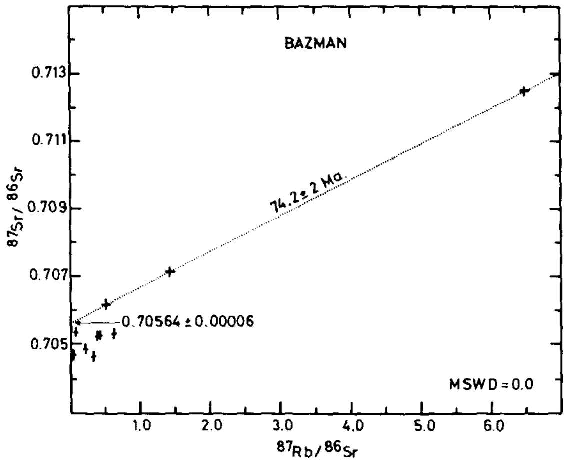

FIG. 3. Rb-Sr isochron diagram for the Bazman intrusive complex. The line shown refers to the 3 samples with $^{87}Sr/^{86}Sr$ above 0.706 (two granites and one granodiorite).

from gabbro sample 87. This suggests that the basic igneous rocks were emplaced at least 10 Ma earlier than the acid rocks, in late Oligocene times. Although this is also compatible with observed field relationships, there is no other evidence for such a long interval in the igneous activity at Natanz. It is possible that the low-Rb diorites (e.g. 152) were emplaced during this interval and that the isotope systems in their biotites were reset during the intrusion of the granites. The initial $^{87}Sr/^{86}Sr$ ratios of all the Natanz rocks have been calculated for the time of granite emplacement at 24 Ma, (i.e. very close to the Oligocene–Miocene boundary) since very little radiogenic ^{87}Sr would have accumulated in the basic rocks during the previous 10 Ma.

Petrogenesis

As shown in Table 2, initial $^{87}Sr/^{86}Sr$ ratios for all the samples analysed range from 0.7043 to 0.7057. This variation falls within, though towards the top of, the range of values associated with magmas produced at destructive plate margins such as the Andes (Faure & Powell 1972; McNutt *et al.* 1975; Noble *et al.* 1975; Francis *et al.* 1977; Hawkesworth 1979). The observed increase in this ratio compared to that of mid-ocean ridge basalts (typically ~0.7030) is usually ascribed either to a lithospheric mantle with higher Rb/Sr ratios over a geologically long period (Brooks *et al.* 1976) or else to introduction of more radiogenic Sr from altered basalts in the subducted oceanic slab (Hawkesworth *et al.* 1977, 1979). Where ratios above 0.706 are prevalent, contamination of the magmas by continental material (through partial melting, assimilation or a selective process) is often postulated (e.g. Francis *et al.* 1977), since this situation usually only arises for magmas intruded through very thick continental crust. The present data do not enable resolution of these various hypotheses. A tendency to increasing initial $^{87}Sr/^{86}Sr$ ratios both with increasing silica saturation within each of the complexes and also with time, implies a progressive process of some complexity, such as recurrent remelting of previously-formed underplated material at the base of the continental lithosphere. Nevertheless, the overall conclusion must be that the magmas are primarily of I-type affinity.

Conclusion

The combination of geological, petrochemical and geochronological evidence from two separate calc-alkaline intrusive complexes above an active and an ancient subduction zone in SE and SW Central Iran, have produced a new explanation for the tectonomagmatic evolution of Iranian continental crust along the Alpine–Himalayan active fold-thrust mountain belt. Despite the great distance (about 1000 km) and considerable age difference established between the Bazman (74–64 Ma) and Natanz (33–20 Ma) complexes, both have very close and relatively low $^{87}Sr/^{86}Sr$ initial ratios and are otherwise chemically comparable.

The low initial ratios together with the location of the calc-alkaline rocks of the Bazman complex above the Makran subduction zone (Fig. 1), the coincidence of trace element plots with the fields of the island-arc rocks (Berberian 1981*a*) and the late Cretaceous–early Palaeocene radiometric age, all suggest that the complex was related to the subduction of Arabian oceanic crust (Gulf of Oman) beneath south-eastern Central

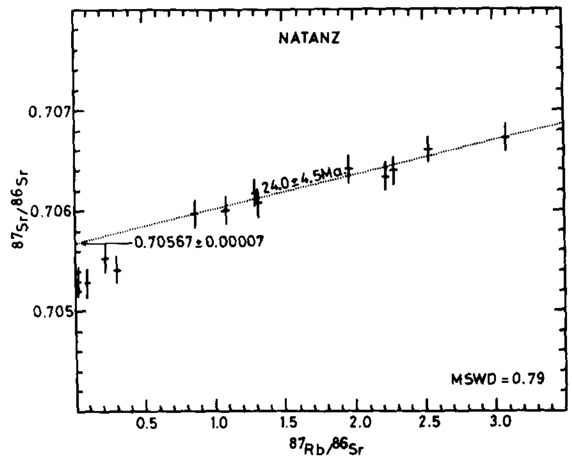

FIG. 4. Rb-Sr isochron diagram for the Natanz intrusive complex. The line shown refers to the samples with $^{87}Rb/^{86}Sr$ above 0.5 (5 granites, 2 adamellites, 1 granodiorite and 1 tonalite).

Iran. The emplacement of the Bazman alkali granite (the youngest phase) during the late Cretaceous presumably reveals that northward subduction of Arabian (Oman) oceanic crust beneath the south-eastern boundary of the Central Iranian continental margin was well established by late Cretaceous time. This implies that the oceanic crust of the Gulf of Oman was formed prior to the Cretaceous.

The Bazman complex is not the only evidence of magmatic arc activity above the Makran subduction zone. A widespread series of E–W trending calc-alkaline intrusive and volcanic rocks (Sirjrani volcanics) of late Cretaceous–Palaeogene age (Jones 1960; Abu-Bakr & Jackson 1964; Vikhter *et al.* 1978; Arthurton *et al.* 1979) are exposed in the Chaghi area NE of the Bazman complex in western Pakistan (Fig. 1) and all lie above the Makran active subduction zone. Apparently the Cretaceous magmatic arc continues still further NE and appears as the Bazai Ghar volcanics and Khwaja Amran intrusive rocks W of the Chaman fault in Pakistan (Lawrence *et al.* 1981), as the Arghandab batholith and Kandahar volcanics in Afghanistan (Bellon *et al.* 1979; Afzali *et al.* 1979), and as the Kohistan volcanic-arc sequence in the Karakorum (Tahirkheli *et al.* 1979). Towards W Bazman, the Cretaceous–Palaeocene magmatic arc appears as the Alvand plutonic belt in western Iran (Fig. 1).

The Bazman–Chaghi late Cretaceous calc-alkaline activity in SE Iran and W Pakistan is succeeded by Quaternary calc-alkaline volcanism in the same region (Fig. 1). This coincidence may indicate that, despite the southward retrogression of the Makran trench and the accretionary sediment wedge during the Cenozoic, the present geometry of the subduction zone beyond

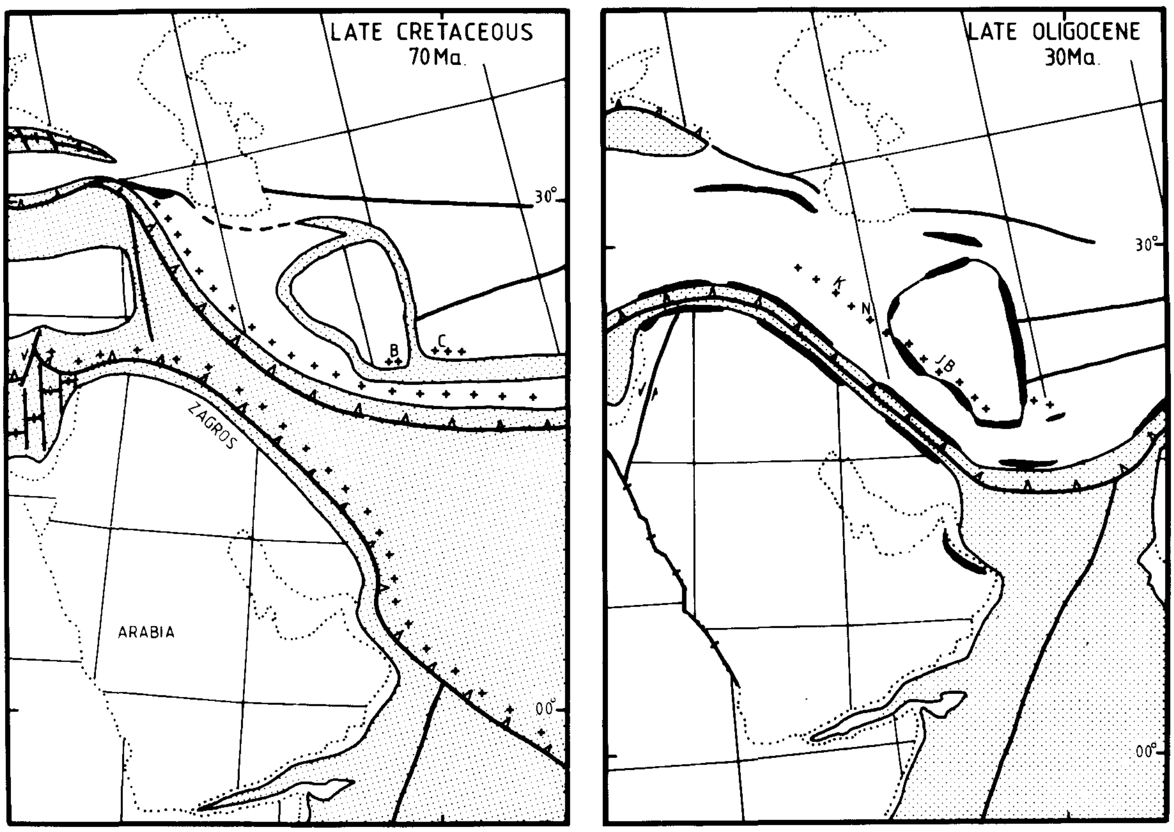

FIG. 5. Palaeo-reconstruction sketch maps of Iran during late Cretaceous (70 Ma) and late Oligocene (30 Ma) showing the northeastward drift of Arabia with respect to Eurasia, narrowing of the Tethyan ocean (stippled) and evolution of the magmatic arcs. Subduction zones are shown by heavy lines with triangles, spreading ridges by heavy lines with small vertical bars, and the present shorelines by dotted lines. Black patches indicate the emplaced late Cretaceous ophiolites and the magmatic arcs are shown by +. B: Bazman; C: Chaghi (on the left map); K: Karkas; N: Natanz; JB: Jebal Barez (on the right map). Modified after Smith & Briden (1977; for the palaeocontinental maps), Robertson & Woodcock (1980; for the Mediterranean section of the left map) and Berberian & King (1981). Mercator Conformal Projection.

the hinge line is similar to that of the late Cretaceous. This observation is important, since studies of modern plate boundaries clearly indicate that plate motions and plate-boundary geometries can change rapidly.

In this study the Bazman complex has been related to the Makran active subduction zone; its similarity with the Natanz complex seems to indicate that the latter was also subduction-related. It is reasonable to assume that the calc-alkaline magmas of both the Bazman and Natanz complexes were generated in association with the consumption of oceanic crust along the southeastern (Makran) and the southwestern (Zagros) subduction zones, respectively (Fig. 5). The Natanz complex is a part of the Karkas–Jebal Barez plutonic belt which follows closely the trend of the south-western Central Iranian continental margin and the Zagros suture line (Figs 1 and 5). The development of major porphyry copper deposits (Waterman & Hamilton 1975) in the southern segment of this belt is typical of I-type subduction-related granites (Gustafson 1979) and this adds further support to the argument that this is an Andean-type magmatic belt. There is no evidence in the petrography, geochemistry or isotope characteristics of the Natanz complex samples analysed here to suggest the formation of significant amounts of S-type magma such as appears to have resulted from continent–continent collision in SE Asia during the mid-Cretaceous (Beckinsale 1979). Rather, the present study suggests continued subduction of oceanic crust (perhaps as a marginal basin) beneath Central Iran until Miocene times, with final continent–continent closure not occurring until after this time (Fig. 5). In this case the late Cretaceous–Palaeocene ophiolites (emplaced along the Zagros passive and the Central Iranian and Makran active continental margins) could have formed as arc-basin complexes. The geometry of reconstructions during Late Cretaceous ophiolite obduction would then require the existence of at least two separate subduction systems (Fig. 5). Emplacement of large masses of ophiolites during Late Cretaceous–Palaeocene times in Iran marks the beginning of an important convergent regime but their accretion to the continental margins does not indicate an inter-continent collision.

The Andean-type magmatic arc along the active continental margin of Central Iran began to develop in Triassic time (the oldest date available). Magmatic activity continued throughout most of Mesozoic time, but the degree of continuity of activity is not clear at this stage (Berberian & Berberian 1981). Existing data suggest at least three Mesozoic intrusive episodes: late Triassic, late Jurassic and late Cretaceous (Berberian 1981*a*). Through most of Mesozoic time the magmatic arc activity was confined to a relatively narrow region close to the active margin of the Central Iranian plate (Fig. 1; Berberian & Berberian 1981). The present study shows that the latest Andean-type magmatic activity took place during the Oligocene–Miocene and that the magmatic arc migrated inland (Figs 1 and 5). This shift in magmatic activity may be due to changes in convergence rate and in dip of the subduction system (a relatively steeply-dipping subduction system for the Mesozoic and a lower angle descending slab for the Cenozoic activity). At present it is not clear whether any such changes in the dip of the subduction system resulted from changes in convergence rates of a single plate, or from detachment of a down-going slab with the formation of a new subduction system. Apparently, during late Miocene and Pliocene times an Alpine-type continental tectonic regime was superimposed on the Mesozoic–Palaeogene Andean-type margin. Convergence of the Arabian and Eurasian plates would then have resulted in a thickening and shortening of the continental crust by folding, reverse faulting and elevation of the Iranian plateau (Berberian 1981*b*). Despite the lack of younger pelagic sediments or of ophiolite mélange emplacements, the results of this study indicate a Miocene closure of the Tethyan ocean and define more closely the geometry and nature of the past plate interactions in a region where the sea-floor record is missing (Fig. 5). Data in hand are not yet complete and some elements of the explanation are necessarily speculative, but they fit together with some internal consistency.

A final comment on relations between the basic and granitoid rocks of Natanz is in order. Although major element data as plotted on variation diagrams suggest a continuous comagmatic relationship between the mafic and salic rocks (Berberian 1981*a*), this appears to be ruled out by the distinct age and isotope differences established between the two groups. Similar associations of calc-alkaline mafic and granitoid rocks with distinct age, geochemical and isotopic differences have been reported from the Peru batholith (Pitcher 1978; Atherton *et al.* 1979). Analogous considerations may apply also to the associations of mafic and granitoid rocks in the Andean Intrusive Suite of the Antarctic Peninsula (Adie 1955) where detailed radiometric studies are currently in progress.

It is conceivable that at Natanz and in the examples just mentioned, two groups of independently-generated magmas were produced at different times to form parts of what is now ostensibly a single complex. This may be due either to an underplating effect or to the reactivation of the same temperature and/or pressure anomaly. On the other hand, the emplacement of successive magmas with contrasted compositions may be related by structural controls along a well-developed lineament that allowed the uprise at different times of non-cognate magmas from sites where deep faults intersect (Depuis 1976).

ACKNOWLEDGMENTS. Helpful discussions with R. K. O'Nions are gratefully acknowledged; we are grateful also to A. G. Smith for his comments on the manuscript. The Geological Survey of Iran provided all the field facilities for sampling, mapping the investigated areas, and shipping the samples to Cambridge. Isotopic analyses were carried out at the Isotope Geology Unit, Institute of Geological Sciences, London. We thank J. H. Scoon for analysing 4 rock samples. Cambridge Earth Sciences Contribution No. ES. 162.

References

ABU-BAKR, A. M. & JACKSON, R. C. 1964. *Geological map of Pakistan,* 1:2,000,000. Geol. Surv. Pakistan, Quetta.

ADAMIA, SH., LORDKIPARIDZE, M. & ZAKARIADZE, G. 1980. The Caucasus. *In:* ADAMIA, SH. *et al.* (eds). *The Alpine Middle East between the Aegean and the Oman traverses.* Colloque C5, 26 IGC., *Mémoire BRGM,* **115,** 131–2.

ADIE, R. J. 1955. The Petrology of Graham Land: II. The Andean Granite-Gabbro Intrusive Suite. *Falkland Islands Dependencies Survey, Sci. Rep.* **12,** 39 pp.

AFZALI, H., DEBON, F., LEFORT, P. & SONET, J. 1979. Le massif monzosyénitique de Zankachan (Afghanistan central): caractères, âge Rb-Sr et implications tectonoorogénique. *C.r. Acad. Sci. Paris,* **288 D,** 287–90.

ALAVI, M. 1980. Tectonostratigraphic evolution of the Zagrosides of Iran. *Geology,* **8,** 144–9.

ARTHURTON, R. S., SARWAR ALAM, G., ARISUDDIN-AHMAD, S. & IQBAL, S. 1979. Geological history of the Alamreg–Mashki Chah area, Chagai district, Baluchestan. *In:* FARAH, A. & DEJONG, K. A. (eds). *Geodynamics of Pakistan.* Geol. Surv. Pakistan, Quetta, 325–31.

ATHERTON, M. P., MCCOURT, W. J., SANDERSON, L. M. & TAYLOR, W. P. 1979. The geochemical character of the segmented Peruvian Coastal Batholith and associated volcanics. *In:* ATHERTON, M. P. & TARNEY, J. (eds). *Origin of Granite Batholiths.* Shiva Publishing Ltd., Orpington, 45–64.

BATEMAN, P. C. & CHAPPELL, B. W. 1979. Crystallization, fractionation, and solidification of the Tuolumne intrusive series, Yosemite National Park, California. *Bull. geol. Soc. Am.* **90,** 465–82.

—— & NOCKLEBERG, J. 1978. Solidification of the Mount Givens granodiorite, Sierra Nevada, California, *J. Geol. Chicago,* **86,** 563–79.

BECKINSALE, R. D. 1979. Granite magmatism in the tin belt of South East Asia. *In:* ATHERTON, M. P. & TARNEY J. (eds). *Origin of Granite Batholiths.* Shiva, Orpington, 34–44.

BELLON, H., BORDET, P. & MONTENANT, C. 1979. Histoire magmatigue de l'Afghanistan Central: nouvelles donees chronometrique K-Ar. *C.r. Acad. Sci. Paris,* **289 D,** 1113–6.

BERBERIAN, F. 1981*a*. *Petrogenesis of Iranian plutons: a study of the Natanz and Bazman intrusive complexes.* Thesis, PhD, Univ. Cambridge.

—— & BERBERIAN, M. 1981. *Tectono-plutonic episodes in Iran.* Geodynamics Series, **3,** WG-6, American Geophysical Union, 5–32.

BERBERIAN, M. 1974. *Structural history of the Southern Lut Zone (northern highlands of Jaz Murian Depression, Baluchestan), a preliminary field note.* Geol. Surv. Iran. Int. Rep., 21 pp.

—— 1981 (in press). *Active faulting and tectonics of Iran.* Geodynamics Series, **3,** WG-6, American Geophysical Union, 33–69.

—— & KING, G. C. P. 1981. Towards a paleogeography and tectonic evolution of Iran. *Can. J. Earth Sci.* **18,** 210–65.

BROOKS, C., JAMES, D. E. & HART, S. R. 1976. Ancient lithosphere: its role in young continental volcanism. *Science,* **1933,** 1086–94.

CHAPPELL, B. W. & WHITE, A. J. R. 1974. Two contrasting granite types. *Pacific Geology,* **8,** 173–4.

COBBING, E. J. & PITCHER, W. S. 1972. The coastal batholith of Central Peru. *J. geol. Soc. London,* **128,** 421–60.

DEPUIS, L. 1976. Le massif granitique de Ploumanac'h: association du diapirisme de la subsidence souterraine a l'intersection de grandes failles du Tregor (Cotes du Nord). *C.r. Seances Acad. Sci. Paris,* **283,** 311–4.

DESMONS, J. 1980. Iran: correlation of the phases of deformation, metamorphism and magmatism. Collogue C5, 26 I.G.C., *Memoire BRGM* **115,** 308.

DEWEY, J. F., PITMAN, W. C., RYAN, W. B. F. & BONIN, J. 1973. Plate tectonics and the evolution of the Alpine system. *Bull. geol. Soc. Am.* **84,** 3137–80.

FARHOUDI, G. & KARIG, D. E. 1977. Makran of Iran and Pakistan as an active arc system. *Geology,* **5,** 664–8.

FAURE, G. & POWELL, J. L. 1972. *Strontium Isotope Geology.* Springer-Verlag, 188 pp.

FORSTER, H. 1974. Magmentypen und erzlagerstatten in Iran. *Geol. Rdsch.* **63,** 276–92.

FRANCIS, P. W., MOORBATH, S. & THORPE, R. S. 1977. Strontium isotope data for recent andesites in Equador and north Chile. *Earth planet. Sci. Lett.* **37,** 197–202.

GASTIL, R. C. 1975. Plutonic zones in the Peninsular Ranges of Southern California and northern Baja California. *Geology,* **3,** 361–3.

GUSTAFSON, L. B. 1979. Porphyry copper deposits and calc-alkaline volcanism. *In:* MCELHINNY, M. W. (ed.). *The Earth: Its Origin, Structure and Evolution.* Academic Press, 427–68.

HAGHIPOUR, A. 1980. North and Central Iran. In: ADAMIA, SH. *et al.* (eds). *The Alpine Middle East between the Aegean and the Oman traverses.* Colloque C5 26 I.G.C. *Memoire BRGM,* **115,** 133–4.

HALLAM, A. 1976. Geology and plate tectonics interpretation of the sediments of the Mesozoic radiolarite-ophiolite complex in the Neyriz region, southern Iran. *Bull. geol. Soc.Aa.* **87,** 47–52.

HAWKESWORTH, C. J. 1979. $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$ and trace element characteristics of magmas along destructive plate margins. *In:* ATHERTON, M. P. & TARNEY, J. (eds). *Origin of Granite Batholiths: geochemical evidence.* Shiva Publishing Ltd., Orpington, 76–87.

——, NORRY, M. J., RODDICK, J. C., BAKES, P. E., FRANCIS, P. W. & THORPE, R. S. 1979. $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$, and incompatible elements variations in calc-alkaline andesites and plateau lavas from South America. *Earth planet. Sci. Lett.* **42,** 45-57.

——, O'NIONS, R. K., PANKHURST, R. J. HAMILTON, P. J. & EVENSEN, N. M. 1977. A geochemical study of island-arc and back-arc tholeiites from the Scotia Sea. *Earth planet. Sci. Lett.* **36,** 253–62.

HUSHMANDZADEH, A. 1977. *Ophiolites of south Iran and their genetic problems.* Geol. Surv. Iran, Int. Rep., 89 pp.

JONES, A. G. (ed.). 1960. *Reconnaissance geology of part of West Pakistan, a Columbo Plan Cooperative Project.* Ottawa, Government of Pakistan, 550 pp (Hunting Survey Report).

KANASEWICH, E. R., HAVSKOV, J. & EVANS, M. E. 1978. Plate tectonics in the Phanerozoic. *Can. J. Earth Sci.* **15,** 919–55.

KLOOTWIJK, C. T. 1979. India's and Australia's pole path since the late Mesozoic and The India–Asia collision. *Nature, London,* **286,** 605–7.

KRUMSIEK, 1976. Zur bewegung der Iranisch–Afghanischen plate (palaeomagnetisch ergebnisse). *Geol. Rdsch.* **65,** 909–29.

KUNO, H. 1968. Differentiation of basalt magmas. *In*: HESS, H. H. & POLDERVAART, A. (eds). *Basalts,* **2,** J. Wiley & Sons, 623–88.

LAWRENCE, R. D., YEATS, R. S., KHAN, S. H., SUBBANI, A. M. & BONNELLI, D. (in press) Crystalline rocks of the Spinatizha area, *Pakistan. J. Struct. Geol.*

NABAVI, M. H. 1976. *An introduction to Iranian geology* Spec. Pub. geol. Surv. Iran, 110 pp (in Farsi).

MCNUTT, R. H., CROCKET, J. H., CLARK, A. H., CAELLES, J. C., FARRAR, E., HAYNES, S. J. & ZENTILLI, M. 1975. Initial $^{87}Sr/^{86}Sr$ ratio of plutonic and volcanic rocks of the Central Andes between latitudes 26 and 29 south. *Earth planet. Sci. Lett.* **27,** 305–13.

NOBLE, D. N., BOWMAN, H. R., HERBERT, A. L., SILBERMAN, M. L., HEROPOULOS, C. E., FABBI, B. P. & HEDGE, C. E. 1975. Chemical and isotopic constraints on the origin of low-silica latite and andesite from the Andes of Central Peru. *Geology,* **3,** 501–4.

PERFIT, M. R., BRUECKNER, H. & LAWRENCE, J. R. 1980. Trace element and isotopic variations in a zoned pluton and associated volcanic rocks, Unalaska Island, Alaska: a model for fractionation in the Aleutian calc-alkaline suite. *Contrib. Mineral. Petrol.* **73,** 69–87.

PITCHER, W. S. 1974. The Mesozoic and Cenozoic batholith of Peru. *Pacific Geol.* **8,** 51–62.

—— 1978. The anatomy of a batholith. *J. geol. Soc. London,* **135,** 157–82.

—— & BERGER, A. R. 1972. *The geology of Donegal: a study of granite emplacement and unroofing.* Wiley Interscience, London, 435 pp.

POWELL, C. MCA. 1979. A speculative tectonic history of Pakistan and surroundings: Some constraints from the Indian Ocean. *In*: FARAH A. & DEJONG, K. A. (eds). *Geodynamics of Pakistan.* Geol. Surv. Pakistan, Quetta, 5–24.

ROBERTSON, A. H. F. & WOODCOCK, N. H. 1980. Tectonic setting of the Troodos massif in the east Mediterranean. Ophiolites, *Proc. Int. Ophiolite Symp., Cyprus,* Geol. Surv. Dep. 36–45.

RODDICK, J. A. & HUTCHINSON, W. W. 1974. Setting of the coast plutonic complex, British Columbia. *Pacific Geol.* **8,** 91–108.

SABZEHEI, M. 1974. *Les melange ophiolitiques de la region de Esfandagheh.* These d'etate, Universite de Grenoble, France.

SENGOR, A. M. C. 1979. Mid-Mesozoic closure of Permo–Triassic Tethys and its implications. *Nature, London,* **279,** 590–3.

—— & KIDD, W. S. F. 1979. Post-collisional tectonics of the Turkish–Iranian plateau and a comparison with Tibet. *Tectonophysics,* **55,** 361–76.

SMITH, A. G. 1973. The so-called Tethyan ophiolites. *In:* TARLING, D. H. & RUNCORN, S. K. (eds). *Implication of Continental Drift to the Earth Sciences.* Academic Press, London, **2,** 977–86.

—— & BRIDEN, J. C. 1977. *Mesozoic and Cenozoic paleocontinental maps.* Cambridge Univ. Press, 63 pp.

STEIGER, R. H. & JÄGER, E. 1977. Subcomission on geochronology: Convention on the use of decay constants in Geo- and Cosmochronology. *Earth planet. Sci. Lett.* **36,** 359–62.

STOCKLIN, J. 1974. Possible ancient continental margins in Iran. *In:* BURK, C. A. & DRAKE, C. L. (eds). *The Geology of Continental Margins.* Springer Verlag, New York, 873–87.

——, 1977. Structural correlation of the Alpine ranges between Iran and Central Asia. *Mem. h. ser. Soc. Geol. France,* **8,** 333–53.

TAHIRKHELI, R. A. K., MATTAUER, M., PROUST, F. & TAPPONNIER, P. 1979. The India–Eurasia suture zone in northern Pakistan: synthesis and interpretation of recent data at plate scale. *In:* FARAH, A. & DEJONG, K. A. (eds). *Geodynamics of Pakistan.* Geol. Surv. Pakistan, Quetta, 125–30.

TAKIN, M. 1972. Iranian geology and continental drift in Middle East. *Nature, London,* **235,** 147–50.

TARNEY, J. & SAUNDERS, A. D. 1979. Trace element constraints on the origin of Cordilleran Batholiths. *In:* ATHERTON, M. P. & TARNEY, J. (eds). *Origin of Granite Batholiths.* Shiva, Orpington, pp. 90–105.

VANCE, J. A. 1961. Zoned granitic intrusions—an alternative hypothesis of origin. *Bull. geol. Soc. Am.* **72,** 1723–27.

VENNUM, W. R. 1980. Petrology of the Castle Crags pluton, Klamath Mountains, California. *Summ. Bull. geol. Soc. Am.* **91,** 255–8.

VIKHTER, B. YA., YEREMENKO, G. K., CHMVREV, V. M. & ABDULLA, D. 1978. Pliocene–Quaternary volcanism of Afghanistan. *Internat. Geology Rev.* **20,** 525–36.

WATERMAN, G. C. & HAMILTON, R. L. 1975. The Sar Cheshmeh porphyry copper deposit. *Econ. Geol.* **70,** 568–76.

WELLAND, M. J. P. & MITCHELL, A. H. G. 1977. Emplacement of the Oman ophiolite: a mechanism related to subduction and collision. *Bull. geol. Soc. Am.* **88,** 1081–8.

WHITE, R. S. & KLITGORD, K. 1976. Sediment deformation and plate tectonics in the Gulf of Oman. *Earth planet. Sci. Lett.* **32,** 199–209.

Received 3 July 1981; revised typescript received 30 January 1982.

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