

The existence of oceanic islands in the Neotethys: Evidence from Ladakh Himalaya, India

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Highly tectonized and disrupted ophiolitic melange is exposed as a linear belt along the Indus suture zone in the western Ladakh Himalaya. The tectonic blocks of volcanics and gabbro imbricated with turbidites (interpreted as trench fill sediments) along the melange zone represent the relicts of oceanic island(s) that contributed to the rugged topography of the Neotethys ocean floor during the Late Cretaceous period. The geochemical data indicate an active participation of oceanic island(s) in the tectonics of the suture zone. The elevated bathymetric features like oceanic islands are buoyant compared to the oceanic crust and offer resistance at the trench, as observed in the modern analogues. Therefore, when the oceanic island(s) resting on the Neotethyan oceanic crust arrived at the inferred trench, it subsequently underwent collision and selective subduction. The ocean-island-trench collision, perhaps also initiated the precollision T1 thrusting during 75–60 Ma and, consequently, obduction of Spongtang ophiolite klippe. The final obduction of Spongtang during Post Lower Eocene was coeval with the collision of Indian and Eurasian plates¹.

HIGHLY tectonized and disrupted melange outcrops as a linear belt along the Indus suture zone in the western Ladakh Himalaya² (Figure 1). The blocks within the melange zone are of diverse parentage and are imbricately arranged in the turbiditic matrix (trench fill sediments). The entire zone has undergone intense deformation and stratal disruption due to subduction and offscraping^{3–6}. On the basis of the available geological, geochemical and geochronological data of the rock types from the melange zone of the Indus suture zone, an attempt has been made to reconstruct the palaeogeography of the Neotethys and the possible cause for the obduction of the Spongtang ophiolite.

Petrographic and geochemical characters

The blocks imbricated with the turbiditic matrix consist of basalt (pillow lava), diabase and gabbro. These lithologies are closely associated with shallow marine carbonates, i.e. oolitic limestone, debris flow deposits,

pyroclastics, agglomerates and volcanoclastics. Macroscopically, these volcanics are greyish green and red in colour and possess vesicular and amygdular structures. Amygdules are filled with calcite, chlorite, epidote, chalcedony and, occasionally, pumpeyllite. The volcanics exhibit a variety of textures, e.g. trachytic, porphyritic, phenoclastic and microlitic. The bases are greyish green in colour, fine- to medium-grained, exhibiting ophitic to subophitic texture. Gabbros vary in composition from gabbroic norite to norite. Agglomerate blocks associated with the volcanics comprise clasts of porphyritic to amygdaloidal basalt lying in hyaloclastic matrix. The basalt and gabbro rocks have been chemically altered, as evidenced by the development of secondary phases such as carbonate, chlorite, titanite and oxidized opaques.

About 70 representative samples of basalts, diabase, gabbro and blueschist were analysed for major oxides, trace elements and 14 rare earth elements using X-ray fluorescence and ICP–AES (Inductively Coupled Plasma–Atomic Emission Spectrometer) techniques. The total area mapped and sampled extends from west of Shergol to Bodhkharbu in the western part of Ladakh². The samples presented in the table represent evenly the major traverses taken and the rock types exposed in the area. The lithologies along the melange zone have undergone intense deformation and metamorphism. The blueschist assemblage primarily includes glaucophane and lawsonite. Only the least altered samples, where primary minerals and textures are preserved in part, were selected for chemical analysis. The samples range from alkalic basalt to trachyandesite, based on the least mobile major and trace elements classification using P_2O_5 vs. TiO_2 (ref. 6), Nb/Y vs. Zr/P (ref. 7) and Zr/Ti vs. Nb/Y (ref. 8). Most of the samples showed a close affinity with within-plate alkalic basalt (WPA), using V–Ti (ref. 9), Ti–Zr (Figure 2), (Zr/Y)–Zr (ref. 10) and $2Nb-(Zr/4)-Y$ (ref. 11) discrimination diagrams.

Majority of the samples exhibit an enriched chemistry in terms of major, trace and rare earth elements. They are enriched in TiO_2 and Nb, with high Nb/Zr, Ti/Zr and Ti/Y ratios and possess high concentrations of other incompatible trace elements (Figure 2, Table 1). Their

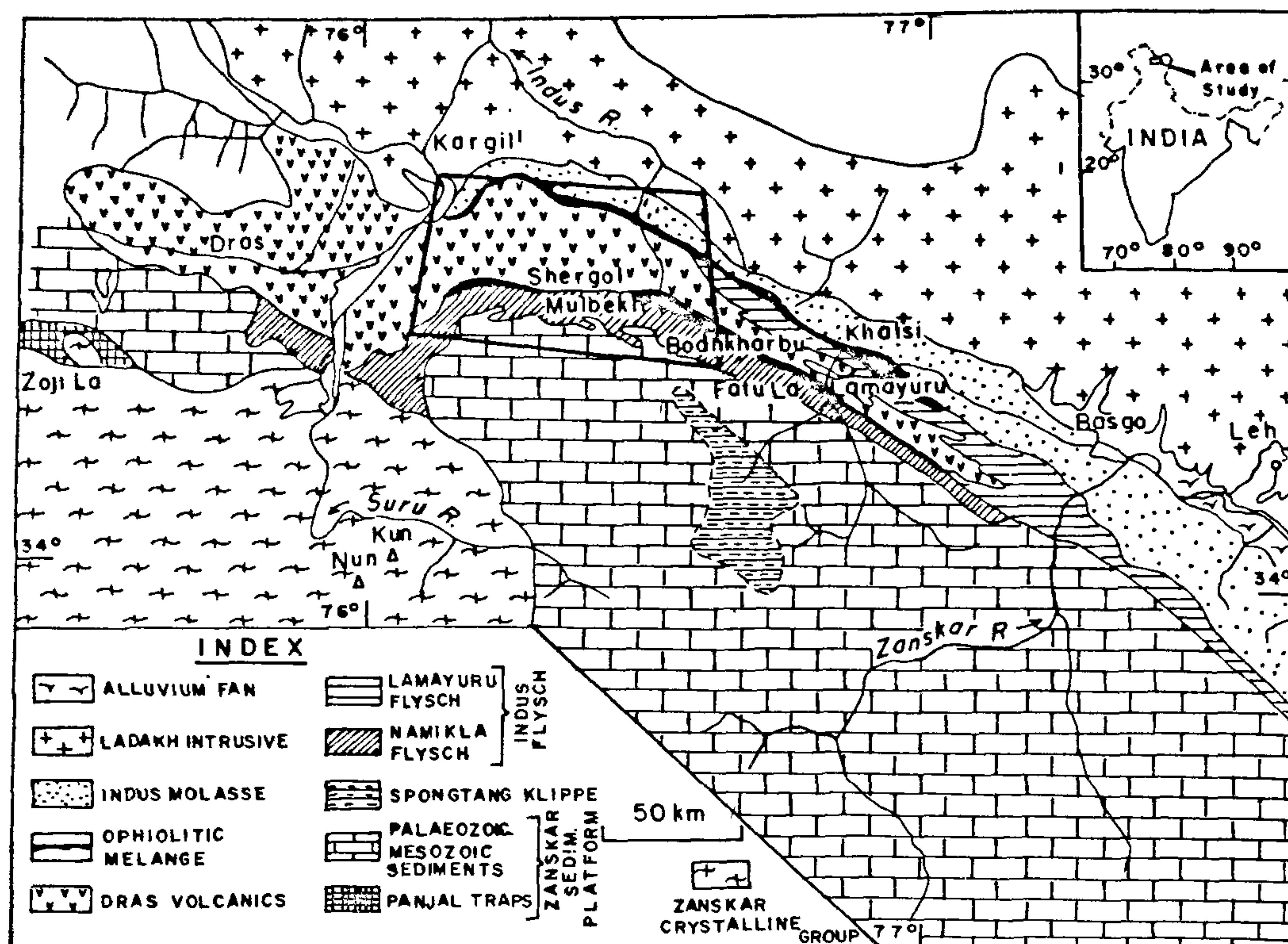


Figure 1. Geological map of the Indus Tsangpo suture zone between Kargil and Leh². Inset shows the area mapped.

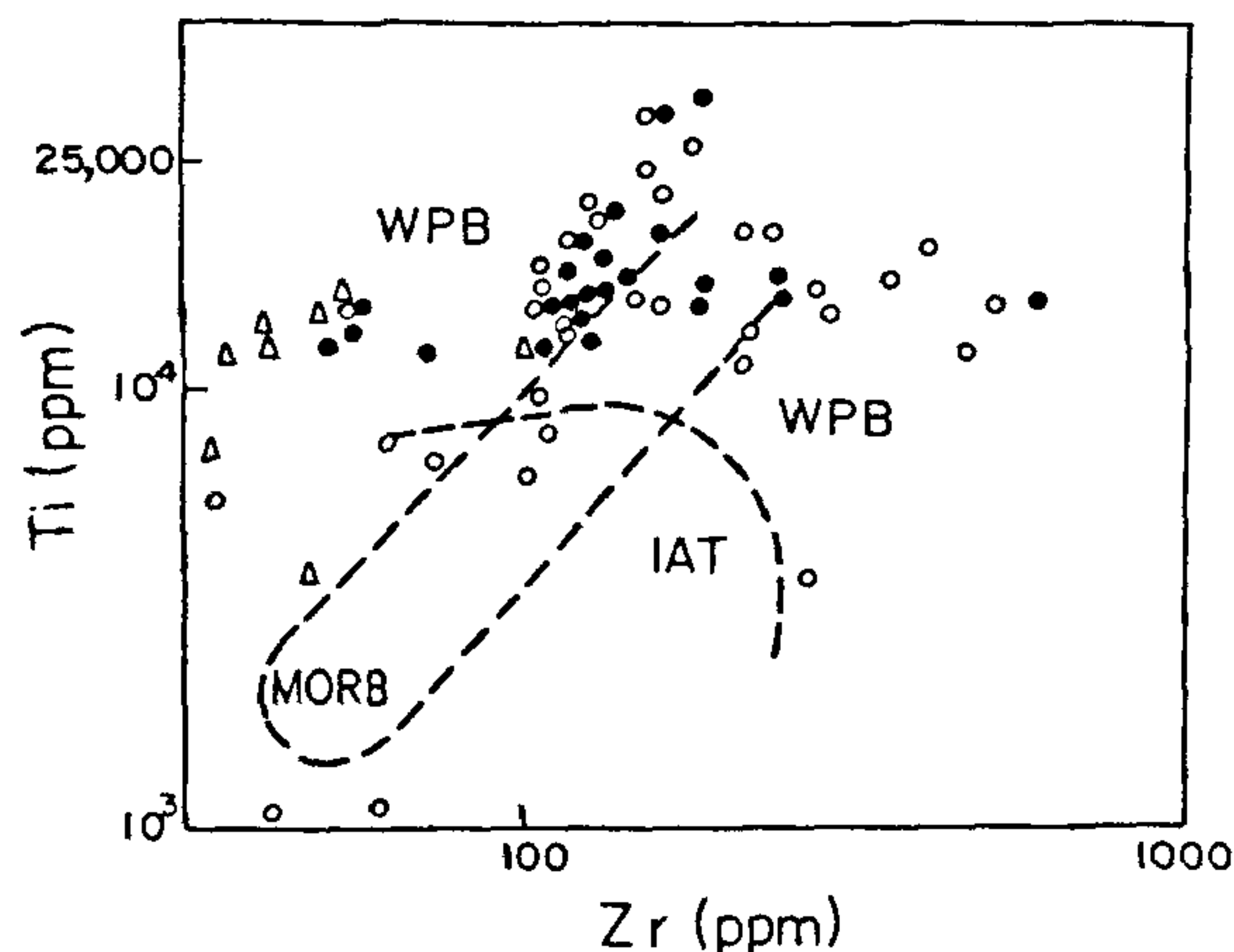


Figure 2. Ti-Zr tectonomagmatic discrimination diagram for volcanic and metavolcanic (blueschist) rocks from the ophiolitic melange zone; the various fields are after Pearce¹⁰. Open circles (○) are for volcanics, solid circles (●) are for gabbro and triangles (Δ) are for metavolcanics (blueschist). WPB, within plate basalt; IAT, Island arc tholeiite; MORB, Mid-oceanic ridge basalt.

mantle-normalized multi-element patterns (spider diagrams) are quite similar to those of ocean island basalt (OIB) (Figure 3). Average trace element ratios Nb/Zr

(0.29), Ti/Zr (78) and Ti/Y (411) are very close to those of OIB¹², viz. Nb/Zr (0.208), Ti/Zr (74) and Ti/Y (593), than to normal type of mid oceanic ridge basalt (N-MORB), with Nb/Zr (0.031), Ti/Zr (102) and Ti/Y (271). Similarly, the chondrite-normalized rare earth element patterns for all the samples selected from the ophiolitic melange zone (Figures 4 and 5 and Table 1) show a significant enrichment of light rare earth elements (LREE) and fractionation of heavy rare earth elements (HREE). They have high ratios of $(Ce/Yb)_N = 7.5$ and $(Gd/Yb)_N = 2.5$, comparable to OIB¹², which has $(Ce/Yb)_N = 9.8$ and $(Gd/Yb)_N = 2.8$, but much different from N-MORB¹², which has $(Ce/Yb)_N = 0.68$ and $(Gd/Yb)_N = 0.993$, from enriched type of MORB (E-MORB) (ref. 16), which has $(Ce/Yb)_N = 1.79$ and $(Gd/Yb)_N = 1.02$. Thus, the trace and REE geochemical signatures are comparable to modern-day OIBs typically erupted in within-plate tectonic environment. Within-plate or intra-plate volcanic rocks occur in two major tectonic settings – oceanic islands and continental rifts – in addition to minor within-plate igneous rocks in the cratons^{13–17}. Alkaline volcanics having these mineralogical and chemical characteristics occur either in the oceanic islands, e.g. Eastern Island^{16,18} and Austral Island, or in continental rifts ranging from extensive plateau to flood

Table 1. Representative analyses of volcanic and gabbro associated with the ophiolitic melange zone, Ladakh Himalaya

Sample no.	1 SC-17	2 PR-8	3 SC-18	4 698/8	5 B121/8	6 C-11	7 B75/5	8 TS-7	9 C-13	10 SK-4
Major oxide (wt%)										
SiO ₂	52.48	50.22	50.02	49.61	49.44	49.28	47.49	47.19	46.44	46.42
Al ₂ O ₃	18.48	14.65	16.79	12.07	14.75	14.35	9.52	13.53	15.49	13.84
FeO(T)	15.57	18.20	8.36	10.13	12.44	10.32	12.26	13.87	10.51	14.47
MnO	0.16	0.18	0.33	0.20	0.22	0.28	0.22	0.20	0.19	0.17
MgO	5.18	2.46	4.47	7.25	6.34	8.58	13.34	8.96	8.35	8.31
CaO	7.89	6.89	5.58	9.93	7.78	8.51	9.90	5.90	9.04	7.30
Na ₂ O	4.77	2.77	5.34	3.05	2.94	2.79	2.47	3.50	2.69	2.66
K ₂ O	1.97	0.75	2.03	1.02	0.64	2.72	1.07	0.45	2.24	1.24
TiO ₂	3.23	3.35	2.37	4.52	2.16	2.37	2.70	2.79	2.50	3.24
P ₂ O ₅	0.68	0.96	0.61	0.47	0.64	1.07	0.03	0.70	0.85	0.57
Total	97.83	98.93	96.64	98.25	97.35	99.25	99.00	97.92	98.30	98.22
Trace elements (ppm)										
Zr	647	401	501	286	117	283	53	265	376	272
Y	49	68	57	53	48	44	24	40	44	43
Sr	1228	301	1275	381	772	174	151	169	174	315
Ni	72	193	27	32	80	29	312	202	29	64
Cr	91	239	374	41	450	54	517	385	54	383
Z	75	269	193	412	107	247	286	332	247	371
Ba	172	160	170	442	310	208	102	165	208	145
Sc	nd	nd	nd	227	12	27	31	38	27	nd
Nb	200	17	187	28	57	51	24	90	51	10
Rb	121	7	123	30	32	112	35	17	120	29
Rare earth elements (ppm)										
La	93.54	40.34	59.24	20.19	58.14	43.42	22.42	32.59	54.44	30.14
Ce	145.50	97.27	114.80	47.29	128.70	93.35	49.26	58.16	108.20	69.32
Nd	51.65	49.36	61.40	29.29	68.73	43.46	26.90	38.87	43.92	40.62
Sm	13.46	13.95	13.72	8.93	16.42	10.32	7.23	10.20	11.26	9.86
Eu	3.23	3.11	3.40	2.42	4.35	2.51	1.74	2.76	2.63	2.57
Gd	8.62	12.14	8.29	7.26	10.88	8.07	5.85	8.73	9.43	8.59
Tb	1.08	1.80	0.94	0.79	1.34	11.38	0.86	1.35	1.41	1.47
Dy	5.99	9.42	6.54	7.22	9.04	6.83	4.73	6.88	7.13	7.62
Ho	1.07	1.98	1.09	1.27	1.42	1.24	0.79	1.32	1.41	1.44
Er	3.25	4.58	2.82	3.41	2.95	3.72	2.36	3.41	3.75	5.06
Yb	2.60	4.44	3.01	3.52	2.00	2.95	1.43	2.13	3.64	3.64
Lu	0.27	0.59	0.28	0.70	0.15	0.36	0.17	0.34	0.47	0.44
(Ce/Yb)	14.50	5.08	9.86	3.47	16.63	8.18	8.90	7.09	7.68	5.08
(Gd/Yb)	2.67	2.56	2.22	1.66	4.38	2.21	3.30	3.30	2.10	1.96
Nb/Zr	0.62	0.40	0.37	0.09	0.48	0.16	0.45	0.33	0.13	0.03
Ti/Zr	29.90	50.12	40.10	94.80	110.70	50.10	312.40	87.60	39.80	71.47
Ti/Y	217	295	352	511	270	405	690	58	340	452

Samples 2, 4, 10 are gabbro, samples 1, 3, 6, 8, 9 are volcanics and samples 5, 7 are blueschists.
nd – not determined.

basalts, e.g. Deccan Traps. However, as the REE data suggest, in the case of Himalayas there is a greater possibility of OIB having participated in the melange generation. Thus, with the help of the various data (not presented here) and diagrams it becomes evident that the magma(s) erupted in the ocean island type of primary geotectonic setting.

K–Ar ages for oceanic islands

Two samples of norite from different blocks of OIB affinity were dated using the K–Ar method (Table 2). For sample location and lithocolumn see Figures 6 and 7. Norite is greenish brown in colour, fine-to medium-grained, undeformed and holocrystalline. Andesine–

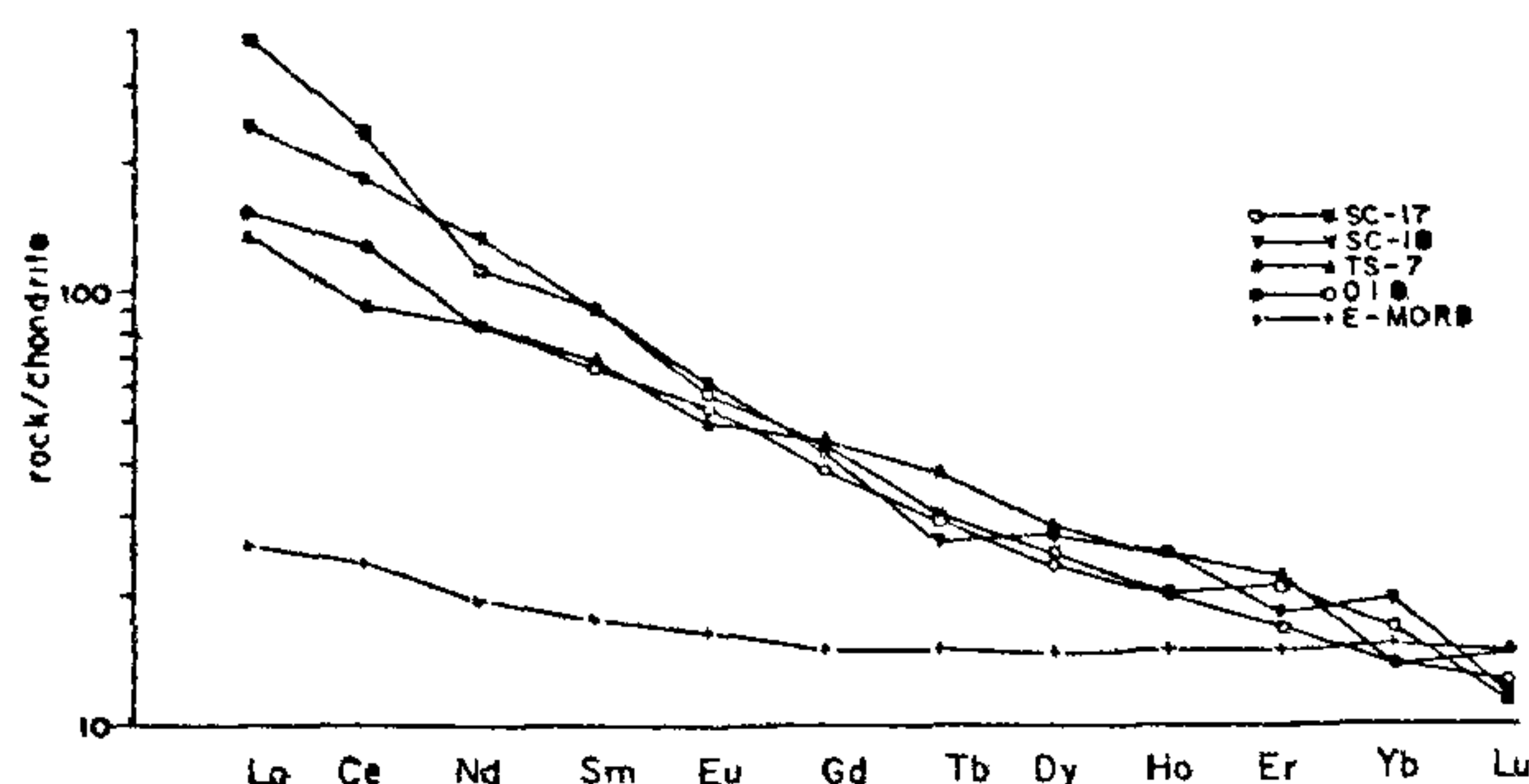


Figure 3. Chondrite-normalized rare earth element patterns for volcanics from the melange zone around Shergol village. For comparison patterns of E-MORB (enriched type of mid oceanic ridge basalt) and OIB (ocean island basalt) data are also given (after Sun and McDonough¹²).

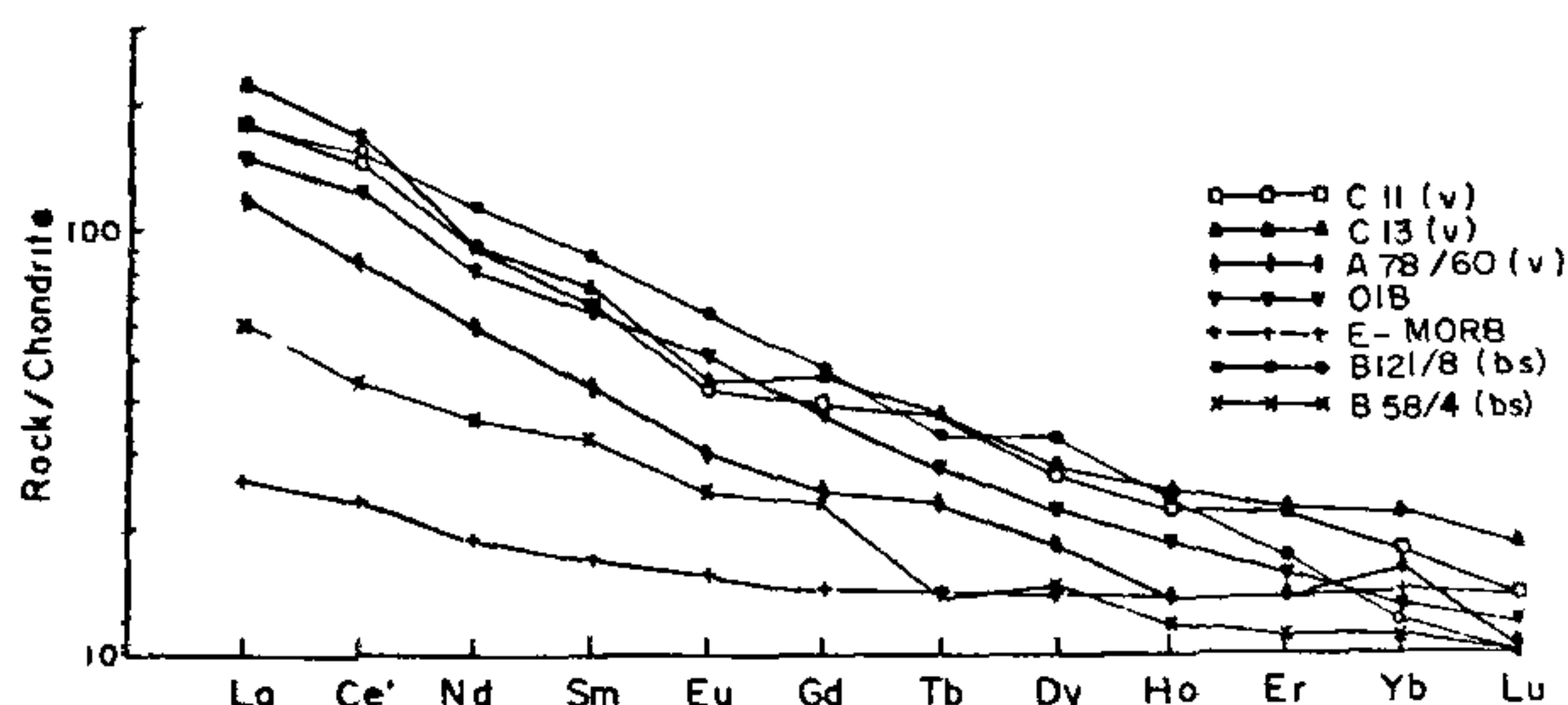


Figure 4. Chondrite-normalized rare earth element patterns for volcanic (v) and blueschist (bs) rocks from the ophiolitic melange zone. For comparison, patterns of OIB (ocean island basalt) and E-type MORB (enriched type of mid oceanic ridge basalt) data are also given (after Sun and McDonough¹²).

Oligoclase ($An_{10}-An_{30}$), hypersthene and subordinate augite form the principal constituents, while epidote, chlorite, apatite and iron oxide form the accessory minerals. Hypersthene and vermicular iron oxide exhibit symplectic texture (Figure 8). The ages obtained for the gabbro samples are 75 ± 3 Ma and 98 ± 3 Ma, in agreement with basalt dated as 77.5 ± 1 Ma, from the melange zone (near its thrust contact with the Lamayuru Formation) along the Chiktan nala section¹⁹, and with palaeontological data giving the Campanian–Maastrichtian age²⁰.

Discussion and conclusion

K–Ar ages (75 ± 3 and 98 ± 3 Ma) of oceanic island relicts preserved along the melange zone point to precollisional and postcollisional episodes. Neotethyan ocean floor witnessed the eruption of islands from time to time during the late Cretaceous period. These oceanic islands were younger (between 75–100 Ma) (ref. 5) to the surrounding oceanic ophiolitic substratum (aged 125–140 Ma) (ref. 21) in which they were embedded.

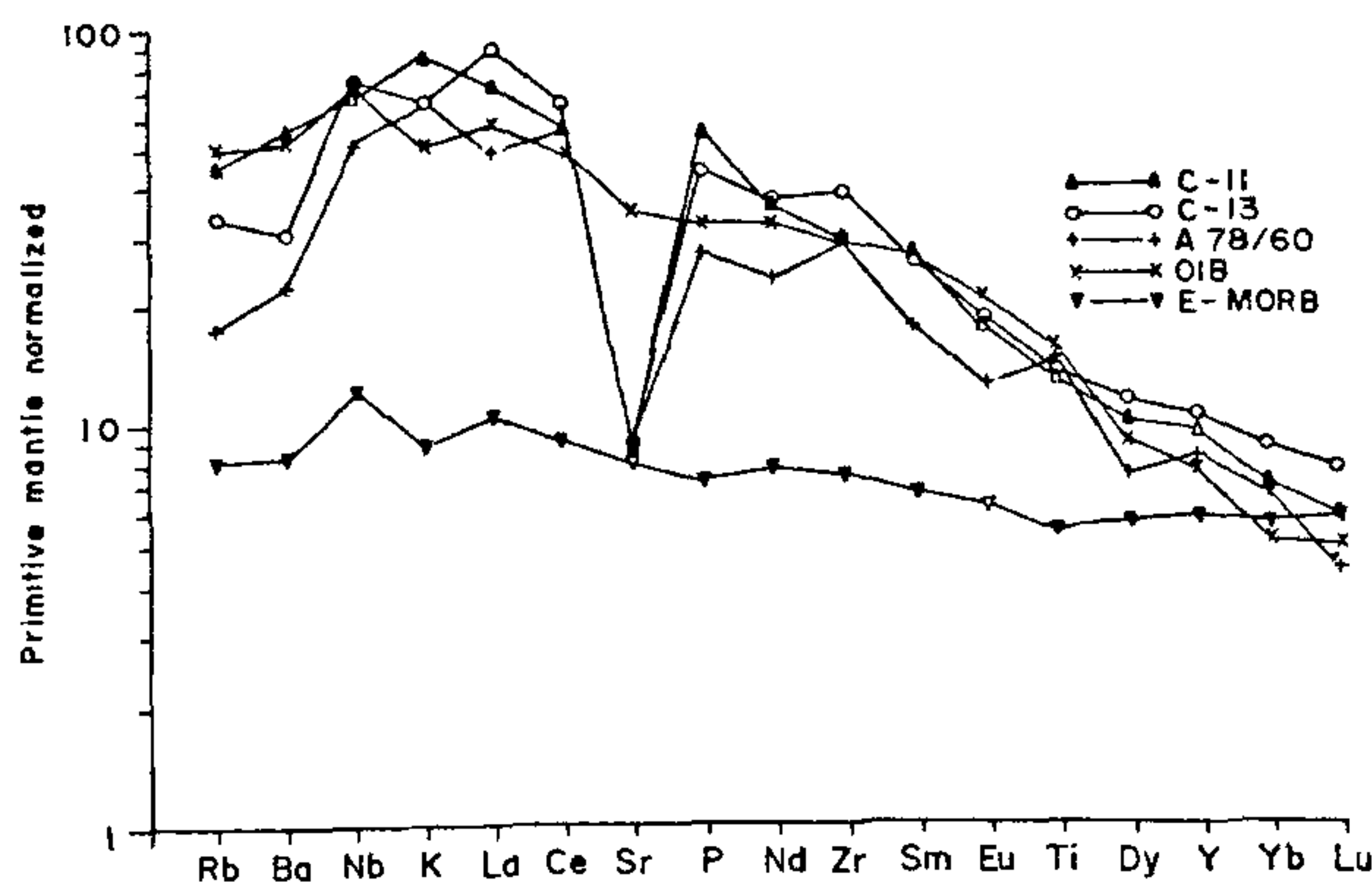


Figure 5. Mantle-normalized multi-element patterns of volcanics from melange zone along Chiktan nala. For comparison, patterns of OIB (ocean island basalt) and E-MORB (enriched type of mid oceanic ridge basalt) data are also given (after Sun and McDonough¹²).

Table 2. K–Ar age determination for the gabbro samples from ophiolitic melange of Ladakh Himalaya. Data obtained from Institute of Geochemistry and Physics of Minerals, Ukrainian Academy of Sciences, Kiev (courtesy Academician N. P. Shcherbak)

Sample number			Content		Age (Ma)
Laboratory	Author	Mineral	K, % radiogenic	Ar, ng/g	
134/1	PR-8	Rock	0.76	4.06	75± 3
134/2	PR-8A	Rock	0.74	5.2	98± 3

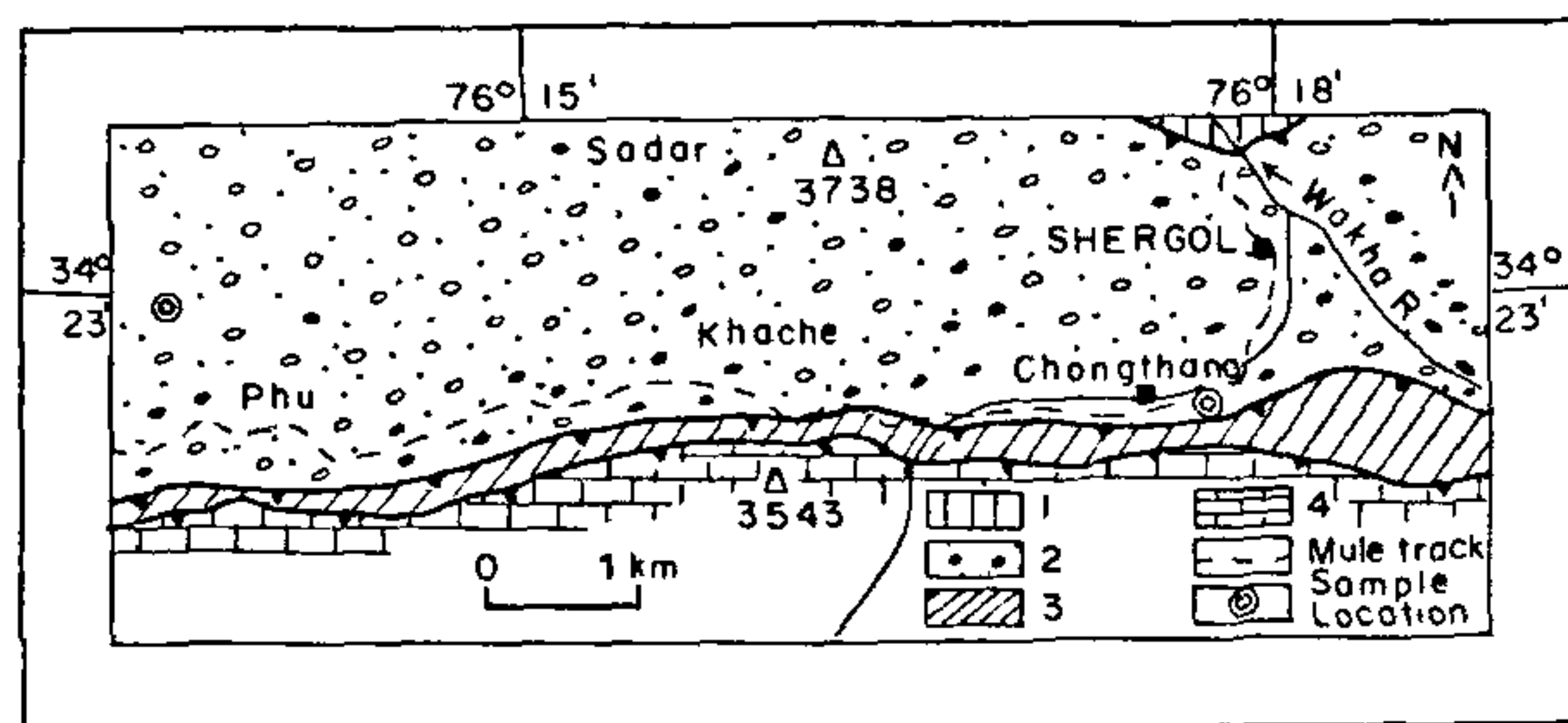


Figure 6. Geological map around Shergol village showing the sample locations for K–Ar age determinations: 1 – Nindam Formation; 2 – ophiolitic melange; 3 – Lamayuru Formation; 4 – Triassic Limestone.

The elevated bathymetric features like oceanic islands are buoyant compared to the oceanic crust and offer resistance at the trenches²². Therefore, when the oceanic island(s) resting on the Neotethyan oceanic crust arrived at the inferred trench, it subsequently underwent collision. As a consequence, it temporarily choked the throat of the subduction zone and obstructed the subduction process²³. The continued convergence of the oceanic floor enforced the removal of the barrier like ocean island by dismemberment, which probably aided its

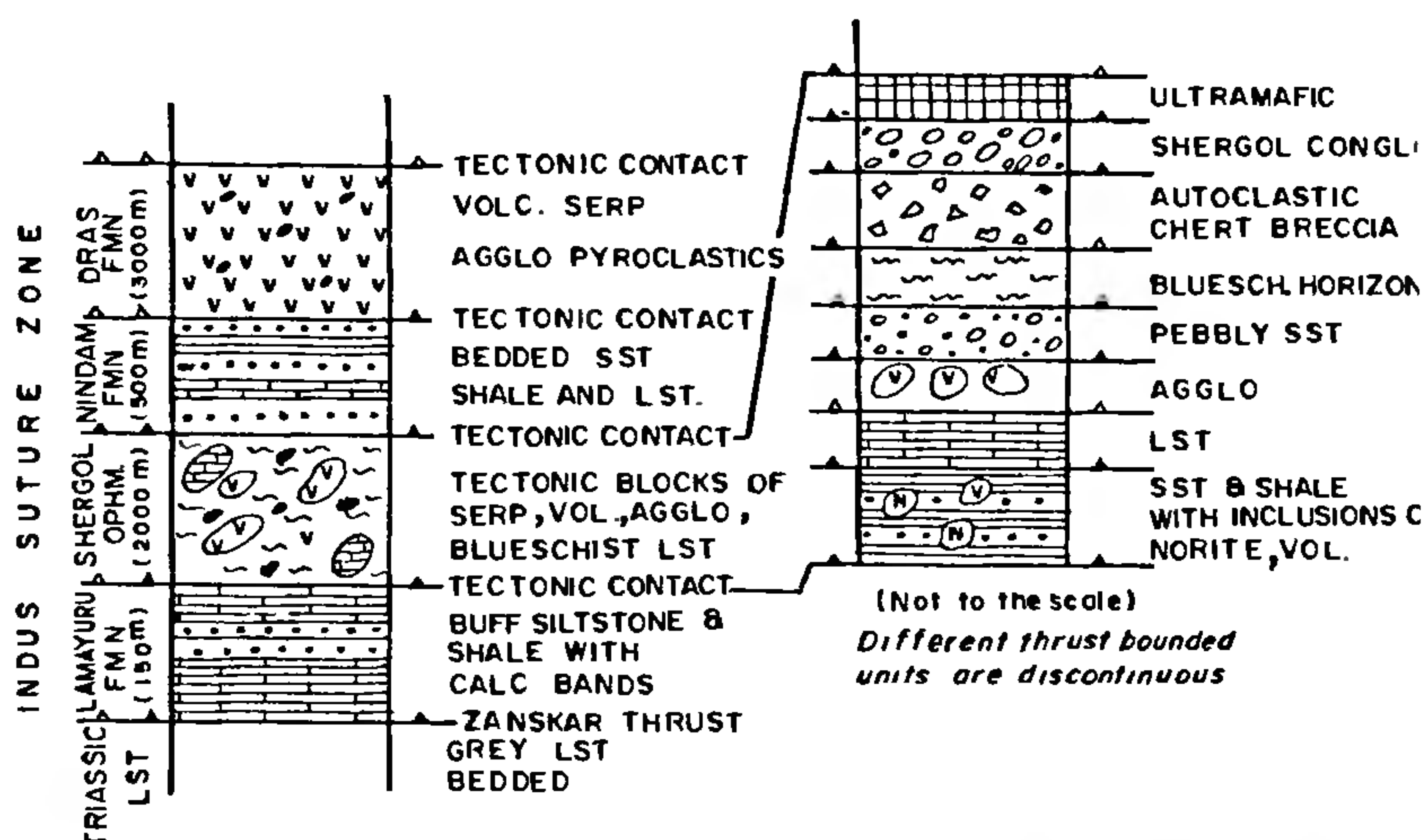


Figure 7. Generalized lithocolumn of the ophiolitic melange around Shergol village showing the sampled horizon.

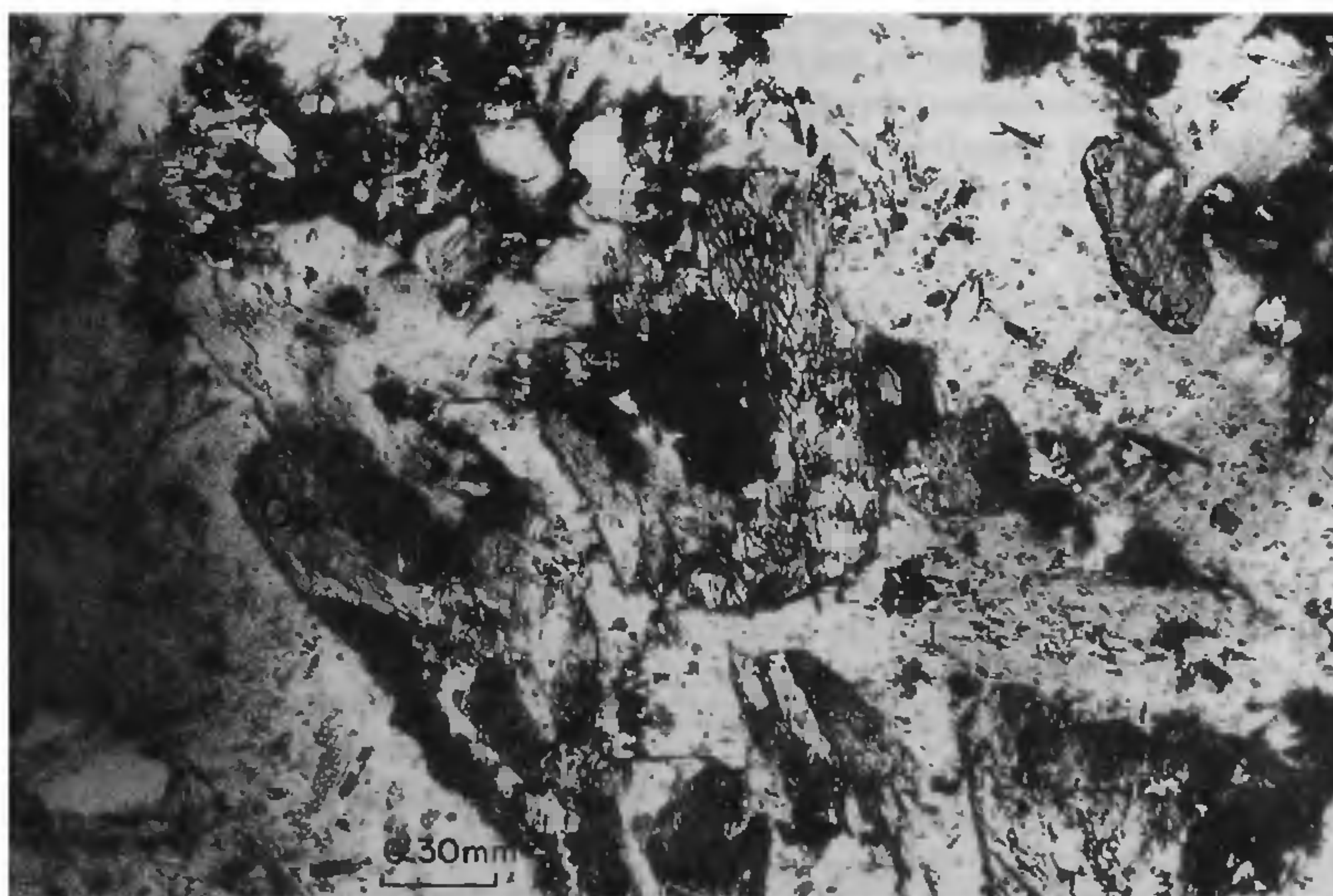


Figure 8. Photomicrograph of norite showing symplectic intergrowth between orthopyroxene (Opx) and iron oxide. On the right-hand side Cpx is seen altering to hornblende (Hb) (under plane-polarized light).

subduction. The episodic subduction and accretion, i.e. selective subduction²⁴ accompanied by the fragmentation of high-standing objects of oceanic floor, were possibly the major tectonic processes occurring at the inferred trench during India-Eurasia collision. The fragments of oceanic island are imbricated with the thick trench fill turbidites, indicating that the former were offscraped and accreted at the subduction front⁵.

The dismembered oceanic island is represented by blocks of volcanics, pillow lava, diabase, gabbro, norite,

oolitic limestone, chert and debris flow deposits. The volcanic, gabbroic and blueschist blocks are juxtaposed or closely associated with a relatively large portion of debris flow deposits, volcanoclastics and interbedded pelagic (often cherty) sediments. The debris flow deposits are characterized by lack of sorting and internal stratification, coarse texture, angularity, clast composition and rapid lateral and vertical changes in grain size. These features indicate that huge quantities of the epiclastic detritus (resembling those of talus deposit and landslide)

probably resulted from submarine debris flow deposited on a terrace-like depression²⁵. The debris flow probably originated from steep escarpments accumulated in small basins adjacent to the toe of the high-standing seamount.

Oceanic volcanism also witnessed carbonate deposition during intermittent periods of quiescence, as is evident from intercalated oolitic and pelletal limestone preserved in few volcanic blocks, with local chert bands observed in the field. Huge blocks of pyroclastics are also juxtaposed with the volcanic blocks. They consist of rounded to subrounded clasts of microporphyrific and vesicular basalt lying in hyaloclastic matrix. Their thick piles and association with the volcanics is indicative of the submarine volcanism at shallow levels. On the basis of the above field observations and interpretations (based on the researches carried out on the modern-day analogues) palaeoreconstruction of the inferred seamount has been suggested. Thus, the main body of the ocean island seems to be accreted as fragments to the melange and only a small portion is supposed to have been subducted and lost.

On the basis of the above discussion, a model for the ocean-island-trench collision, occurring as a consequence of the initiation of the obduction of Spong tang ophiolite and the emplacement of ophiolitic melange, has been proposed (Figure 7)^{26,27}. Such collisional events of ocean-island-trench are based on the comparative studies from modern analogues and present-day subductions zones, e.g. Circum Pacific belt^{22-24, 28, 29}.

The vast Neotethyan ocean floor that had opened during Permo-Triassic rifting approached the final closure during the Cretaceous-Tertiary times^{26, 30, 31}.

The obducted Spong tang klippe rests on allochthonous³² Lamayuru sediments and melange, similar to those along Indus suture zone about 30 km to its north. The statements of several authors about the Cretaceous compressive force³³ being responsible for the initiation of ophiolite obduction on to the passive margin^{1, 34} were not confirmed by field or petrographic evidences³⁵. India was too far from Eurasia at that time to have been affected by early collision forces³⁶. The present investigations have revealed that seamount collision at the trench was possibly responsible for the tectonic effect, viz. initiation of ophiolite obduction phase, in the light of their modern analogues^{29, 33, 35}.

The late Cretaceous oceanic island approached the subduction zone probably during Palaeocene and on its collision with the inferred trench temporarily slowed down the subduction process. Consequently, a strong compressive force developed which resulted in the initiation of the obduction phase of ophiolite (oceanic crust) between Late Maastrichtian to Late Palaeocene (Figure 9). The Spong tang zone in western Zaskar is the only area where precollisional ophiolite obduction structures can be distinguished. They have been described as

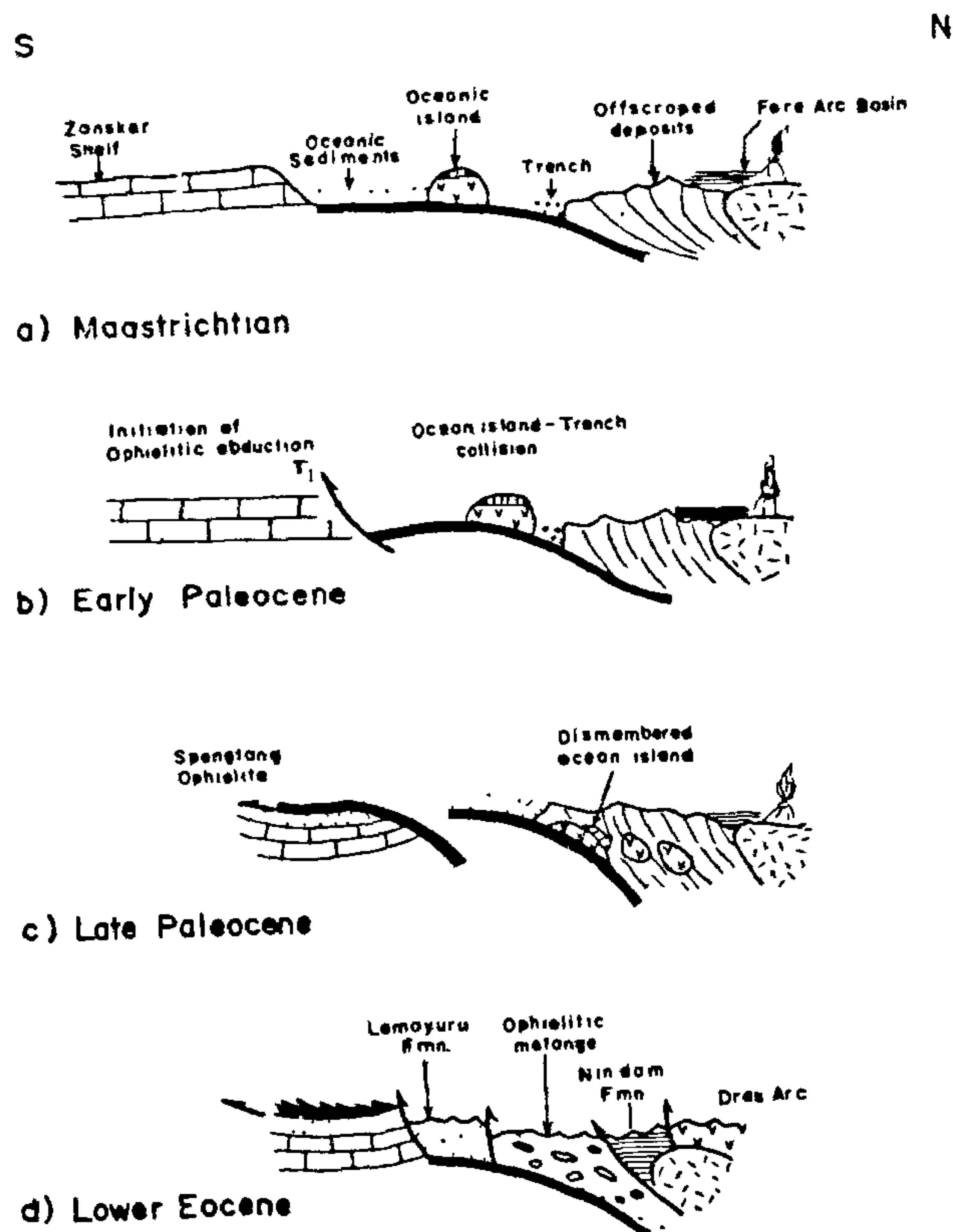


Figure 9. Chronological events of melange emplacement (based on the data of Searle *et al.*¹ and Reuber *et al.*²⁶).

precollisional ophiolite obduction phase T1: 75–60 Ma (ref. 1). The final obduction of Spong tang ophiolite from passive margin on to the Zaskar shelf during Post Lower Eocene was coeval with collision of Indian and Eurasian plates. Cretaceous oceanic volcanism and ophiolite obduction have also been reported from northern Oman mountains³⁷.

The oceanic island probably got dismembered and accreted during Late Palaeocene. Simultaneously with the gradual closing of the vast Neotethys, towards the Lower Eocene, the accreted melange kept on squeezing out due to compressive forces provided by the collision of the two continents. The emplacement of the linear belt of ophiolitic melange during Post Lower Eocene³² was coeval with India-Eurasia collision. The final collisional event of two continental blocks juxtaposes the different lithotectonic units within the remnant of tectonized lithosphere represented by this linear, ophiolitic melange zone in Ladakh Himalaya.

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