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Basalts of the northeastern Deccan Traps, India: Isotopic and elemental geochemistry and relation to southwestern Deccan stratigraphy

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Abstract. The northeastern Deccan Traps include flows with strong isotopic and elemental affinities to lavas in the southwest as far as 900 km away. However, many of the northeastern flows show a negative correlation of $^{206}Pb/^{204}Pb$ with $\varepsilon_{Nd}(t)$ and positive correlation of $^{206}Pb/^{204}Pb$ with $(^{87}Sr/^{86}Sr)_t$, distinct from any of the isotopic fields for the southwestern formations; this array (from $\varepsilon_{Nd}(t) = +5$, $(^{87}Sr/^{86}Sr)_t = 0.7041$, $^{206}Pb/^{204}Pb = 17.9$ to $\varepsilon_{Nd}(t) = 0$, $(^{87}Sr/^{86}Sr)_t = 0.7068$, $^{206}Pb/^{204}Pb = 20.5$) overlaps the Ambenali Formation (Fm.) field and runs toward that of the "common signature" [*Peng et al.*, 1994] that appears to have been an important magma type in several of the lower formations of the southwest. This array appears to represent mixing between an Ambenali-type and (1) a common-signature end-member or (2) an end-member with even higher $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ and lower ε_{Nd} than the common signature; such mixing has been postulated, but not documented previously, for the Deccan. Lavas isotopically and chemically indistinguishable from the Ambenali Fm. form the tops of sections near Jabalpur and Chikaldara. Beneath them are flows that chemically resemble the Poladpur Fm. (which sits immediately below the Ambenali in the southwest) and several lavas similar to the Khandala Fm. (beneath the Poladpur and intervening Bushe Fm. in the southwest). Given the general stratigraphic correspondence with the southwestern sequence, many of these northeastern flows may be petrogenetically related to the respective southwestern formations. Lavas with broadly Poladpur- and Khandala-like elemental compositions are also abundant in a thick section south of Mhow; several other Mhow-area flows resemble the distinctive Bushe Fm. However, nearly all of the Poladpur- and Khandala-like northeastern Deccan lavas analyzed have higher $^{206}Pb/^{204}Pb$ than any southwestern Poladpur or Khandala Fm. basalts. If they indeed are related petrogenetically to these formations, many of the northeastern magmas interacted less with low-$^{206}Pb/^{204}Pb$ continental material and thus must have erupted from different feeder systems.

1. Introduction

The Deccan Traps (Figure 1) are a 500,000 km^2 flood basalt sequence in west-central India, the bulk of which was erupted in a geologically short period of time around 66 Ma [e.g., *Duncan and Pyle*, 1988; *Courtillot et al.*, 1988; *Venkatesan et al.*, 1993; *Baksi*, 1994; *Sheth et al.*, 1997]. Previous detailed geochemical studies have focused primarily on the southwestern part of the province (boxed area in Figure 1), where the thickest exposures (> 1 km thick) are located [e.g., *Najafi et al.*, 1981; *Mahoney et al.*, 1982; *Cox and Hawkesworth*, 1984, 1985; *Beane et al.*, 1986; *Subbarao et al.*, 1988; *Khadri et al.*, 1988; *Lightfoot and Hawkesworth*, 1988; *Lightfoot et al.*, 1990; *Peng et al.*, 1994]. Combined Pb-Nd-Sr isotopic and chemical investigations of the northeastern region of the Deccan are lacking, and the relationship of lavas in the northeast to those as far as 900 km away in the southwest has not been established. In this paper, we report the results of our study of basalts from three major sections in the northeastern Deccan.

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Based on geochemical characteristics and field markers, the southwestern Deccan stratigraphy has been classified into three subgroups and 11 formations (see Table 1) [e.g., *Cox and Hawkesworth*, 1984; *Beane et al.*, 1986; *Lightfoot and Hawkesworth*, 1988]. The Kalsubai Subgroup includes the lower five formations: from bottom up, the Jawhar, Igatpuri, Neral, Thakurvadi, and Bhimashankar. The overlying Lonavala Subgroup is composed of the Khandala and Bushe formations. Above the Bushe lie the Poladpur, Ambenali, Mahabaleshwar, and Panhala formations, which make up the Wai Subgroup. The southwestern Deccan basalts are nearly flat-lying with <0.5° average dip to the south [*Devey and Lightfoot*, 1986; *Beane et al.*, 1986]. Most of the lava pile in this region has been attributed to fissure eruptions from apparent feeder dikes in a broad area around Igatpuri [e.g., *Hooper*, 1990].

Recent and ongoing work in the central part of the province east of Igatpuri reveals eastward continuations, again at very low average dip angles, of the Thakurvadi, Bhimashankar, Khandala, and Poladpur formations, the Khandala appearing for at least 250 km and the Poladpur some 340 km east of Igatpuri [*Subbarao et al.*, 1994, 1998; *Peng*, 1998]. Likewise, in the southeastern Deccan, *Mitchell and Widdowson* [1991] showed that lavas chemically similar to those of the Poladpur and Ambenali formations extend for as much as 350 km from the type-sections in the southwest. Even farther to the southeast, *Baksi* [1994] suggested that flow remnants near the east coast in the Rajahmundry area might correlate over a distance of more than 800 km with the Kohlapur member of the Mahabaleshwar Formation (Fm.). Thus available evidence indicates that the

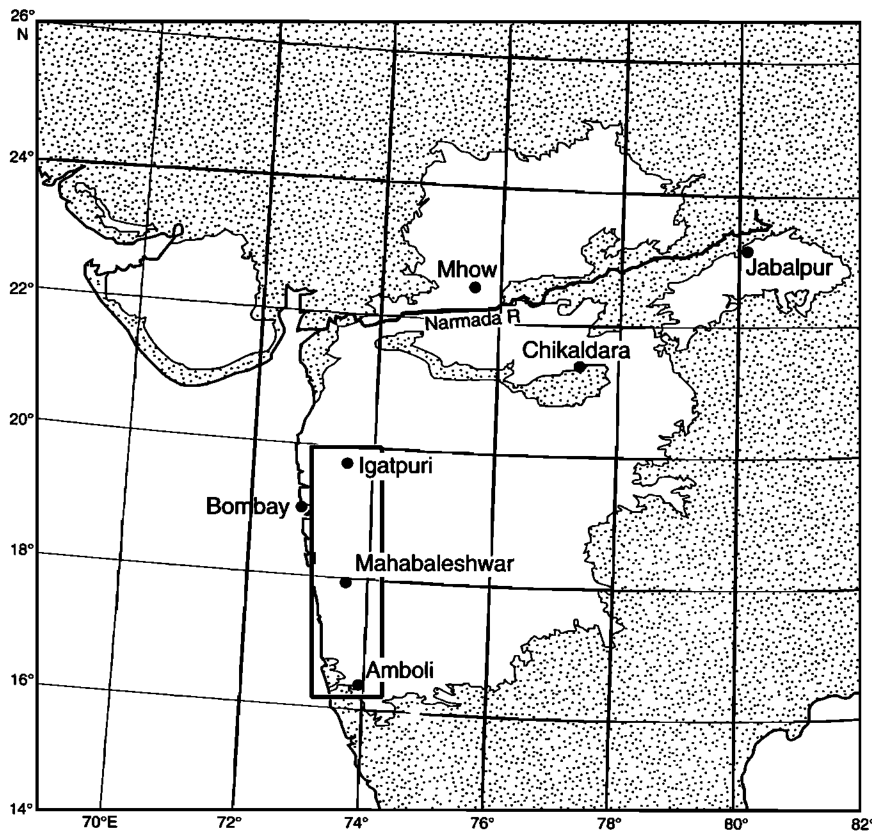


Figure 1. Map of western India showing Deccan Traps (white) and adjacent areas. Box represents the well-studied southwestern region of the Deccan. Modified from *Peng et al* [1994] with permission from Elsevier Science.

Khandala, Poladpur, Ambenali, and perhaps Mahabaleshwar formations may extend over considerable distances in some directions. For comparison, some individual flows in the Columbia River Basalt province of the western United States have been traced for more than 600 km [e.g., *Hooper*, 1997, and references therein]. On the other hand, marked isotopic and chemical differences have been documented between flows of the northwestern Deccan and those of the southwest [*Krishnamurthy and Cox*, 1977; *Mahoney et al.*, 1985; *Melluso et al.*, 1995; *Peng and Mahoney*, 1995]; unlike the tholeiitic basalts of the southwestern formations, many of the northwestern lavas are relatively alkalic and may correspond to a stratigraphically lower part of the overall volcanic succession (i.e., below the Jawhar Fm. stratigraphically) [*Peng and Mahoney*, 1995].

Geochemical knowledge of the northeastern Deccan is limited. *Sreenivasa Rao et al.* [1985] reported major element, Ba, Zr, and Sr abundances for lavas from two sections southwest of Mhow. These authors divided the sequence into tentative stratigraphic formations but did not attempt correlation with the southwestern Deccan stratigraphy. However, they noted that the lowermost flows were normally magnetized and covered by a series of reversely magnetized lavas. Because all formations of the southwestern Deccan below the Mahabaleshwar Fm. are reversely magnetized, Sreenivasa Rao et al. argued that the lower levels of their study area were older than those exposed in the southwest. On the other hand, from preliminary Nd-Sr isotopic and chemical data, *Mahoney* [1984, 1988] concluded that some lavas in the far northeastern Deccan have strong affinities with the Ambenali and Poladpur formations. *Sen and Cohen* [1994] noted that the chemical composition of a flow west of Jabalpur indicated that it could be related to the Mahabaleshwar Fm., which overlies the Ambenali in the southwest. Recently, *Yedekar et al.* [1996], *Deshmukh et al.* [1996], and *Bhattacharji et al.* [1996] have also observed that close chemical similarities exist between some northeastern and southwestern basalts. However, in addition to being abundant in the western part of the Deccan, dikes (and sills) are common in the north within a long-lived zone of tectonism paralleling the Narmada River and known as the Narmada-Tapti Lineament [e.g., *Deshmukh and Sehgal*, 1988, and references therein]. Most are hypabyssal, but *Subbarao et al.* [1988] and *Bhattacharji et. al.* [1996] noted elemental similarities between several Narmada-area dikes and flows, whereas *Crookshank* [1936] and *Sen and Cohen* [1994] documented one case of a large sill passing into a flow. Also, seismic and field studies indicate a local thickening of the basalt sequence in the Jabalpur area to more than 900 m [*Kaila*, 1988; *Pattanayak and Shrivastava*, 1998]. *Sen and Cohen* [1994] suggested that one or more Deccan magma chambers underlie this region and could have supplied some local flows, although they also considered long-distance lateral transport of magmas from the west, either on the surface or in dikes, to be highly likely.

2. Samples and Analytical Methods

We collected samples of 15 flows from the easternmost lobe of the Deccan (Figure 1), sometimes called the Mandla lobe or Mandla plateau, on traverses south and southwest of Jabalpur. Farther west, we sampled 32 flows and one dike in a 620-m-thick section north of Chikaldara, and 29 flows and one dike in a 690-m-thick section north of the Narmada River, south of Mhow

Table 1. Stratigraphic Summary of the Western Deccan Formations

Subgroup	Formation (Maximum Thickness)	Member or Chemical Type
Wai	Panhala (>175 m)	
	Mahabaleshwar (280 m)	
	Ambenali (500 m)	Ambenali CT
	Poladpur (375 m)	Upper
		Lower
		Sambarkada
		Valvhan
		Ambavne
Lonavala	Bushe (325 m)	Pingalvadi
		Bushe CT
		Shingi Hill
		Hari.
		Karla Picrite
		Bhaja
	Khandala (140 m)	Rajmachi
		Khandala Phyric CT
		KA3
		Madh
		Boyhare
		KA2
		Khandala Phyric CT
		KA1
		Dhak Dongar
		KCG
		Monkey Hill
		Giravli
Kalsubai	Bhimashankar (140 m)	Bhimashankar CT
		Manchar
	Thakurvadi (650 m)	Thakurvadi CT
		Water Pipe Member
		Paten Basalt
		Thakurvadi CT
		Ashane
		Thakurvadi CT
		Jammu Patti Member (Upper, Middle, Lower)
	Neral (100 m)	Tunnel Five
		Tembre Basalt
		Neral CT
		Ambivli Picrite
	Igatpuri –	Kashele
		Mg-Rich Igatpuri
		Igatpuri Phyric
	Jawhar (>700 m)	Thal Ghat
		High-Field-Strength-Poor Jawhar
		Plagioclase Phyric
		Mg-Rich Jawhar
		Kasara Phyric

CT, chemical type; KCG, Khandala Coarse Grained; KA, Khandala Aphyric. Simplified from Table 1 of *Peng et al.* [1994] with permission from Elsevier Science.

(details available from J. Mahoney). As in the southwestern Deccan, even in outcrops with locally advanced weathering, relatively fresh samples (perhaps showing some bleaching or Fe-oxide staining but hard and largely free of veins and amygdules) could usually be found in the cores of jointed blocks or the interiors of spheroidally weathered boulders. In hand specimen and petrographically, the northeastern lavas are closely similar to flows in the southwestern Deccan [cf. *Fermor*, 1934; *Crookshank*, 1936; *Deshmukh*, 1977; *Sethna and Sethna*, 1988; *Yedekar et al.*, 1996; *Pattanayak and Shrivastava*, 1998].

Whole-rock powders of the samples were prepared from amygdule-free chips and analyzed for major and trace elements by X ray fluorescence (XRF) spectrometry, the results of which are presented in Table 2. Analyses of the Chikaldara and Mhow samples were made at Washington State University in the same laboratory as the extensive collection that *Beane et al.* [1986], *Beane* [1988], *Khadri et al.* [1988], and coworkers used to define many of the southwestern Deccan formations, whereas measurements of the Jabalpur-area samples were made at the Scripps Institution of Oceanography. A subset of samples from each section was analyzed for Nd, Sr, and Pb isotopic ratios and Nd, Sm, Sr, Rb, and Pb abundances by isotope dilution (Table 3). As in our previous studies, isotopic work was generally carried out on small, hand-picked and acid-cleaned rock chips to avoid alteration and possible Pb contamination [e.g., see *Peng and Mahoney*, 1995]. Abundances of Sr and Rb obtained by isotope dilution generally agree to within a few ppm with the whole-rock XRF values; nevertheless, because most do not strictly represent whole rock abundances, the isotope-dilution values are used here only for age-correcting Sr and Nd isotopic ratios and (for Pb, Nd, and Sm) for constructing primitive-mantle-normalized element diagrams.

3. Chemical Characteristics and Comparison With Southwestern Deccan Chemical Stratigraphy

The northeastern Deccan basalts are tholeiitic, as are those in the southwest. In each of the three northeastern areas studied, significant variations in chemical composition with relative stratigraphic position are present, particularly for trace and minor elements (Figure 2). Both the major and trace element characteristics of the northeastern lavas generally resemble those of the southwestern formations, indicative of broad similarities in petrogenesis and posteruptive history. They contrast with the trend toward relatively alkalic compositions displayed by lavas in the northwestern part of the province (e.g., Figure 3a). In bivariate plots of element abundances and interelement ratios, the northeastern Deccan data as a group overlap considerably with fields for the southwestern formations (e.g., Figure 3), notably with fields for the Ambenali and Poladpur [cf. *Mahoney*, 1988; *Yedekar et al.*, 1996; *Deshmukh et al.*, 1996], Khandala and, for a few samples, Bushe formations. It is important to note that significant overlap also typically exists in such diagrams between two or more of the southwestern formation fields as well, in part reflecting the petrogenetically transitional nature of some formations (such as the upper Poladpur), the presence of some members in several formations with broadly similar chemical composition (e.g., the Poladpur's Ambavne-a and Khandala's Rajmachi members) and, for some samples, effects of alteration, crystal accumulation or intra-flow differentiation on some elements [e.g., *Cox and Hawkesworth*, 1985; *Beane*, 1988; *Beane and Hooper*, 1988; *Lightfoot and Hawkesworth*, 1988; *Peng et al.*, 1994].

The northeastern Deccan lavas do not differ significantly as a group from those in the southwest in either phenocryst mineralogy or range of abundances, or in their level or type of alteration [e.g., *Sethna and Sethna*, 1988; *Deshmukh et al.*, 1996; *Pattanayak and Shrivastava*, 1998]. A few of our northeastern samples appear to contain excess phenocrysts, particularly Jabalpur-area samples SA82-21a and 21b (taken from different parts of the same flow), which have abundant clinopyroxene phenocrysts and high CaO/Al_2O_3 (1.0-1.1); *Beane and Hooper* [1988] discussed similar examples in the southwestern Deccan. Among the commonly analyzed elements, the main effect of the slight to moderate low-temperature alteration that has affected many Deccan samples is on K and Rb; at higher than usual levels of alteration, Ba is

Table 2a. Major and Trace Element Abundances of Northeastern Deccan Lavas of Chikaldara Section

	CH83-1	CH83-2	CH83-3	CH83-4	CH83-5	CH83-6	CH83-7	CH83-8	CH83-33	CH83-9	CH83-10	CH83-32	CH83-11
SiO_2	49.89	50.58	50.34	50.87	52.26	53.66	50.18	49.16	49.08	49.65	50.28	50.28	50.66
Al_2O_3	13.96	14.21	14.17	14.03	15.26	15.56	14.25	14.12	14.90	14.09	14.36	14.01	14.75
TiO_2	2.68	2.38	2.28	2.45	1.37	1.37	2.47	2.48	2.00	2.21	2.27	1.93	2.23
FeO*	13.22	12.61	13.04	13.19	11.91	11.09	14.00	13.98	12.47	13.85	13.37	12.17	12.53
MnO	0.21	0.21	0.22	0.23	0.19	0.20	0.22	0.22	0.18	0.21	0.21	0.19	0.197
CaO	10.91	11.54	11.38	11.15	10.34	10.92	11.11	11.03	11.92	10.87	10.90	11.84	11.28
MgO	6.57	6.68	6.75	5.90	5.70	5.51	6.82	6.92	6.77	6.92	6.66	8.11	6.42
K_2O	0.16	0.18	0.19	0.20	1.02	0.36	0.12	0.13	0.13	0.19	0.20	0.11	0.32
Na_2O	2.28	2.23	2.34	2.23	2.14	2.46	2.09	2.13	2.01	2.32	2.38	1.97	2.33
P_2O_5	0.24	0.21	0.21	0.23	0.14	0.15	0.21	0.22	0.17	0.20	0.20	0.17	0.23
Ni	83	78	82	77	39	44	96	93	70	89	92	159	75
Cr	104	155	144	137	90	108	195	203	103	150	148	379	120
Sc	38	44	39	39	40	36	38	36	41	38	40	38	36
V	385	394	384	375	322	310	419	390	382	398	394	355	390
Ba	38	47	22	44	185	138	26	44	37	38	35	15	92
Rb	2	4	5	7	18	19	0	0	2	5	7	0	3
Sr	240	225	222	225	281	136	207	206	156	199	194	194	222
Zr	149	133	133	141	113	110	132	136	117	128	126	111	143
Y	30	29	29	31	33	32	30	31	27	31	29	26	30
Nb	14	11	13	11	6	9	11	11	9	10	9	7	12
Ga	23	23	21	24	15	20	20	23	22	21	24	19	20
Cu	212	214	220	226	137	174	246	231	169	222	234	193	228
Zn	116	110	105	110	90	90	113	114	91	106	111	95	103

Table 2a. (continued)

	CH83-12	CH83-13	CH83-30	CH83-14	CH83-15	CH83-16	CH83-17	CH83-18	CH83-19	CH83-20	CH83-21	CH83-22	CH83-23
SiO_2	51.48	52.00	50.32	50.27	50.60	51.51	50.91	52.05	51.80	51.13	52.46	51.25	51.41
Al_2O_3	13.56	12.01	13.72	13.74	13.58	13.67	12.76	13.62	13.48	12.96	13.47	13.31	13.45
TiO_2	2.33	2.42	2.40	2.39	2.53	2.29	3.04	2.66	2.67	3.44	2.99	3.10	2.66
FeO*	14.78	14.32	14.19	14.26	14.57	14.10	15.55	14.60	14.60	14.90	14.27	14.62	14.01
MnO	0.22	0.20	0.22	0.22	0.21	0.24	0.23	0.24	0.23	0.19	0.21	0.23	0.21
CaO	10.00	9.98	10.76	10.38	10.38	10.91	10.01	10.12	10.04	9.01	9.52	9.70	9.92
MgO	5.72	5.70	5.79	5.86	5.81	5.76	4.99	5.22	5.17	4.79	5.08	5.16	5.14
K_2O	0.48	0.24	0.13	0.45	0.42	0.29	0.14	0.29	0.50	1.19	0.73	0.46	0.36
Na_2O	2.18	1.76	2.18	2.60	2.42	2.28	2.09	2.33	2.34	2.26	2.39	2.27	2.48
P_2O_5	0.21	0.21	0.22	0.22	0.23	0.22	0.29	0.26	0.26	0.37	0.31	0.30	0.28
Ni	45	48	52	58	50	54	32	38	40	26	45	42	48
Cr	71	69	91	85	76	100	39	53	44	41	82	79	71
Sc	38	35	35	35	36	39	36	37	35	34	33	37	34
V	436	421	409	400	416	406	427	410	406	442	415	422	380
Ba	54	75	57	108	80	97	47	97	111	279	136	123	221
Rb	10	3	2	4	2	11	0	10	20	19	16	9	13
Sr	190	156	327	190	192	205	231	221	218	231	217	204	283
Zr	139	139	151	151	153	142	190	172	171	247	202	200	184
Y	33	32	33	35	35	31	40	36	36	45	39	40	38
Nb	11	10	13	11	11	12	16	14	13	20	16	16	13
Ga	21	21	21	24	23	22	24	21	25	26	22	20	24
Cu	245	216	156	236	253	211	260	233	239	267	302	286	221
Zn	117	125	111	117	118	108	135	124	127	140	125	132	115

Table 2a. (continued)

	CH83-24	CH83-25	CH83-26	CH83-27	CH83-28	CH83-29	CH83-31
SiO_2	51.02	50.62	50.61	51.36	52.10	51.69	49.42
Al_2O_3	13.95	14.69	14.54	14.00	13.39	12.89	13.57
TiO_2	2.96	2.01	2.13	2.55	3.11	2.70	3.27
FeO*	13.73	12.51	13.34	13.73	14.24	15.08	14.45
MnO	0.20	0.20	0.20	0.17	0.21	0.24	0.23
CaO	9.50	11.67	10.28	10.23	9.57	9.92	10.89
MgO	4.63	6.72	6.03	5.48	5.02	5.48	5.52
K_2O	1.01	0.26	0.27	0.31	0.67	0.43	0.33
Na_2O	2.40	2.15	2.50	2.14	2.50	2.49	2.20
P_2O_5	0.33	0.17	0.20	0.27	0.34	0.26	0.33
Ni	53	79	56	48	53	48	84
Cr	117	245	131	67	122	57	180
Sc	29	38	37	32	32	35	39
V	381	376	380	364	394	411	416
Ba	236	25	124	199	201	101	112
Rb	13	6	9	3	22	18	5
Sr	268	205	393	279	272	207	218
Zr	215	111	151	180	216	174	186
Y	39	26	31	35	39	36	35
Nb	17	9	12	15	15	15	21
Ga	24	22	17	24	25	22	22
Cu	268	186	206	189	266	236	305
Zn	116	95	109	119	129	121	127

For each section, samples are listed in stratigraphic order with top first; dike samples MH83-21A and CH83-31 are listed at ends of their respective groups. Major element abundances are in weight percent and trace element abundances are in parts per million. FeO* is total Fe as FeO. For comparison of major element data to each other or to other data sets, values should be normalized to 100 wt % totals, as deviations from 100 wt % largely reflect differences between samples and standards in volatile content and oxidation state. CH and MH samples were analyzed at Washington State University; SA samples were analyzed at the Scripps Institution of Oceanography and the data adjusted for generally small interlaboratory biases based upon results for southwestern Deccan samples measured in both labs. For several SA samples, Rb and Sr abundances were determined on whole rock powders by isotope dilution. See *Knaack et al.* [1991] and *Peng et al.* [1994] for information on methods, precision, and comparison to standards.

sometimes affected as well, although to a smaller relative extent [e.g., *Cox and Hawkesworth*, 1985; *Mahoney et al.*, 1985; *Beane et al.*, 1986; *Lightfoot and Hawkesworth*, 1988]. A rather typical example of the chemical difference between samples from relatively fresh and more weathered portions of the same outcrop is given by MH83-16A and 16B (Table 2b), the latter being visibly more altered (slightly punky, with rust-colored patches): although Rb is essentially the same in this case, K_2O is lower by nearly a factor of 2 in MH83-16B (0.33 versus 0.63 wt %). Despite their susceptibility to alteration, K and Rb previously have proven useful in evaluating first-order differences among different groups of Deccan basalts because the differences between some members or chemical types significantly exceed most observed intraflow variations attributable to alteration; however, these elements clearly must be used cautiously and in concert with other elements.

The southwestern Deccan lava stratigraphy was originally classified, within the framework of observed field relationships, into formations and their component members or chemical types by employing multielement cluster analysis for an extensive data set of more than 1200 samples [*Beane et al.*, 1986; *Beane*, 1988; *Khadri et al.*, 1988], as well as selected elemental and isotopic criteria deemed to be diagnostic of a given packet of flows (e.g., Zr/Nb, Ba/Y, TiO_2, $^{87}Sr/^{86}Sr$) [e.g., *Cox and Hawkesworth*, 1984; *Devey*, 1986; *Beane et al.*, 1986; *Lightfoot et al.*, 1990]. To evaluate possible relationships of the northeastern Deccan basalts to those in the southwest, we compared our data to the southwestern data set in several ways: (1) with bivariate plots of element abundances and ratios such as those in Figure 3, (2) with mantle-normalized multielement patterns, (3) through discriminant function analysis of the chemical data, (4) by checking for general stratigraphic similarities and differences between the geochemical variation in the northeastern sections and that in the southwest, and (5) with Nd-Pb-Sr isotopic data for a subset of the samples.

Table 4 summarizes the results of discriminant function analysis (using the SPSS 7.5 for Windows software, SPSS, Inc.) comparing the northeastern Deccan data with the southwestern chemical groupings defined by Beane and coworkers (full data set available via e-mail from prhooper@mail.wsu.edu), supplemented by data from *Lightfoot* [1985] and *Devey* [1986] (some of which were published by *Cox and Hawkesworth* [1985], *Lightfoot and Hawkesworth* [1988], and *Lightfoot et al.* [1990]). For this exercise, no derived variables (e.g., Zr/Y, Mg-number) were used, and we excluded Cr because there are contamination problems with some of the southwestern Deccan Cr analyses [*Beane*, 1988]. Mn also was not used because it is not always analyzed and many of the existing measurements are of low precision relative to the very limited range of variation observed. Nb has not been measured for some samples, and data for Sc, V, Ga, Cu, and Zn measurements, when available, suffer from lack of interlaboratory calibration and variable quality.

First, both the southwestern and northeastern Deccan data were transformed to standardized values via the Z-score method [e.g., *Klecka*, 1975]. Then, for the southwestern Deccan data set the program calculated the F-statistic (essentially the ratio of between-groups variability to within-groups variability) for each variable. The program then selects variables successively, beginning with the variable having the highest F-to-enter value above a threshold value (chosen by the program). In subsequent steps, F-to-enter values are recalculated for the remaining variables, and the one with the highest value exceeding the threshold is added to the

Table 2b. Major and Trace Element Abundances of Northeastern Deccan Lavas of Mhow Section

	MH83-22	MH83-23	MH83-24	MH83-25	MH83-26	MH83-27	MH83-28	MH83-5	MH83-4	MH83-3	MH83-2	MH83-1	MH83-6
SiO_2	52.76	52.76	52.69	51.42	51.94	50.96	53.22	52.14	52.97	52.69	53.01	52.77	51.65
Al_2O_3	15.25	15.00	14.84	13.74	13.37	13.52	14.67	13.00	14.87	14.18	13.89	14.04	13.28
TiO_2	1.30	1.35	0.99	2.35	3.00	2.36	2.21	3.01	2.15	2.30	2.40	2.35	3.11
FeO*	11.56	11.84	11.07	13.95	14.05	13.68	12.69	14.41	12.62	13.01	13.15	13.01	14.27
MnO	0.20	0.19	0.23	0.19	0.22	0.22	0.20	0.22	0.18	0.21	0.20	0.20	0.22
CaO	10.88	10.72	11.49	10.84	9.67	10.74	9.96	9.41	10.02	9.88	9.54	9.76	9.36
MgO	5.91	5.78	6.89	5.78	5.12	6.05	5.03	5.12	5.08	5.29	5.34	5.58	4.81
K_2O	0.46	0.56	0.33	0.29	0.53	0.41	0.59	0.78	0.53	0.61	0.66	0.77	0.86
Na_2O	2.48	2.44	2.22	2.62	2.51	2.40	2.59	2.51	2.54	2.55	2.47	2.69	2.61
P_2O_5	0.13	0.14	0.11	0.22	0.30	0.22	0.23	0.31	0.22	0.23	1.26	0.24	0.34
Ni	53	42	70	58	47	60	47	46	46	49	58	60	51
Cr	106	104	165	90	85	93	60	79	61	63	85	94	123
Sc	41	38	43	37	35	35	35	34	32	32	33	33	33
V	320	328	311	389	414	389	350	419	341	358	354	347	421
Ba	126	145	118	49	95	162	211	114	201	232	218	212	253
Rb	18	14	15	7	21	6	19	13	20	21	26	14	27
Sr	135	133	112	206	210	212	250	202	249	248	243	242	249
Zr	105	109	83	148	197	152	161	201	158	164	180	165	219
Y	31	32	28	32	40	33	32	41	33	32	35	34	41
Nb	7	7	7	13	16	11	11	16	11	12	12	12	18
Ga	20	20	16	21	19	21	18	24	25	22	23	20	25
Cu	141	176	158	219	239	223	166	268	165	159	163	185	251
Zn	90	93	81	112	124	112	111	125	106	109	115	117	122

Table 2b. (continued)

	MH83-7	MH83-30	MH83-29	MH83-8	MH83-9	MH83-10	MH83-11	MH83-12	MH83-13	MH83-14	MH83-15	MH83-16A	MH83-16B
SiO_2	50.88	52.51	52.39	51.54	51.60	50.25	51.57	51.32	50.47	51.04	50.99	51.64	52.22
Al_2O_3	13.70	14.30	13.57	14.18	14.03	16.57	15.19	13.71	13.73	14.48	14.00	14.08	14.34
TiO_2	3.36	2.29	2.23	1.94	2.06	1.65	1.36	2.62	2.53	2.54	3.08	2.09	2.08
FeO*	14.74	13.09	14.10	14.22	14.62	11.54	12.75	14.61	13.24	12.73	13.96	13.86	14.14
MnO	0.19	0.20	0.24	0.24	0.23	0.17	0.21	0.24	0.20	0.20	0.20	0.23	0.22
CaO	8.17	9.82	10.26	10.63	10.31	10.00	11.58	10.06	11.29	10.79	9.70	9.97	10.29
MgO	4.52	5.34	4.93	5.59	5.38	6.92	6.10	4.83	6.48	5.54	4.49	5.41	5.24
K_2O	1.53	0.79	0.61	0.26	0.31	1.12	0.23	0.38	0.31	0.53	0.90	0.63	0.33
Na_2O	2.34	2.56	2.32	2.33	2.32	2.72	2.04	2.58	2.24	2.39	2.40	2.28	2.32
P_2O_5	0.38	0.24	0.25	0.19	0.21	0.21	0.13	0.26	0.23	0.25	0.33	0.21	0.21
Ni	50	49	40	38	46	63	50	40	68	50	41	45	40
Cr	108	59	57	43	68	83	74	82	140	63	49	59	61
Sc	31	37	37	40	35	30	40	38	36	35	35	40	38
V	427	337	413	409	414	232	359	395	383	367	374	431	425
Ba	254	209	147	116	110	251	92	137	87	138	197	131	118
Rb	53	15	24	9	15	29	2	16	3	9	22	18	17
Sr	251	246	179	158	157	196	153	243	268	296	312	155	166
Zr	236	164	154	123	134	135	91	165	151	164	207	135	135
Y	45	32	36	31	34	28	27	35	28	30	36	34	33
Nb	19	12	16	10	13	10	9	18	17	21	30	12	13
Ga	26	20	24	19	22	20	21	22	21	22	25	21	22
Cu	290	177	270	233	228	43	151	232	223	154	219	250	262
Zn	124	110	118	107	119	90	94	122	102	104	120	110	114

Table 2b. (continued)

	MH83-17	MH83-18	MH83-19	MH83-20	MH83-21A
SiO_2	50.53	51.28	50.37	51.19	52.50
Al_2O_3	14.18	14.33	14.14	14.09	13.15
TiO_2	2.57	2.53	2.25	2.57	2.23
FeO*	13.34	13.18	12.34	13.12	15.44
MnO	0.21	0.21	0.19	0.24	0.23
CaO	10.30	10.46	11.76	10.83	8.81
MgO	5.76	5.61	6.84	5.55	4.66
K_2O	0.80	0.80	0.36	0.41	1.00
Na_2O	2.36	2.47	2.18	2.40	2.45
P_2O_5	0.26	0.26	0.20	0.26	0.28
Ni	51	49	84	44	24
Cr	65	66	168	74	49
Sc	38	36	39	37	36
V	365	347	366	403	456
Ba	154	167	76	136	263
Rb	20	23	7	13	25
Sr	282	287	265	276	158
Zr	166	166	137	165	165
Y	32	31	27	33	39
Nb	22	21	16	18	19
Ga	21	21	21	24	21
Cu	199	205	165	197	320
Zn	104	109	98	116	130

See Table 2a footnotes.

model in each step. An F-to-reject value is also calculated for each variable included previously; those with values below an F-to-reject threshold (also chosen by the program) are excluded. When all variables have been considered, the program calculates discriminant functions, group centroids, and the Mahalanobis distance for each sample to the nearest formation centroid. For the southwestern data set, eight canonical discriminant functions involving eleven elements with the largest F-values (SiO_2, Al_2O_3, TiO_2, CaO, K_2O, P_2O_5, Ba, Ni, Sr, Zr, and Y) were obtained; note that iron and magnesium, in particular, were excluded, reflecting their relatively strong correlations with some of the other variables in the discriminant functions. The results showed that 82% of the southwestern Deccan samples were correctly identified; that is, matched with their correct formations as known from combined field relationships, cluster analysis, and other evaluations of chemical and isotopic data. Most misidentifications corresponded to lavas from members known to have chemical compositions similar to those of members in overlying or underlying formations (see above), although some appear to reflect excess phenocrysts or high levels of alteration in individual samples (judging from the data and descriptions of *Beane* [1988]).

Next, the standardized data for the northeastern Deccan basalts were added as unknowns and evaluated with the same discriminant functions. As Table 4 (second column from left) shows, most of the northeastern basalts can be matched with southwestern counterparts of the Ambenali, Poladpur, Khandala, Bushe or, rarely, Bhimashankar formations at Mahalanobis distances similar to those pertaining among the southwestern lavas. Samples for which the Mahalanobis distance from any southwestern formation centroid was greater than 20 (corresponding to a conditional probability approaching zero) are shown with question marks. Figure 4 compares values (listed in Table 4) of the first two discriminant functions for the northeastern Deccan samples with the fields defined by the relevant southwestern formations. The first two functions, which account for 73% of the overall variation in the southwestern data set, effectively separate the Khandala, Bushe, and Ambenali Fm. fields; the Poladpur field is also largely separated from the Bushe and Khandala Fm. fields. However, the Poladpur and Ambenali Fm. fields overlap significantly (reflecting the chemically transitional nature of lavas in the upper Poladpur Fm.), and the Bhimashankar Fm. field overlaps with both these fields and that of the Khandala Fm.

Among the northeastern Deccan basalts, both the Chikaldara and Jabalpur sections are capped by several flows (samples CH83-1 to 4 and 7 to 10; SA82-25 to 28) whose closest resemblance is to the Ambenali chemical type of the southwestern Deccan. Figure 5a illustrates the close correspondence in incompatible elements between these lavas and the distinctive Ambenali pattern, and Table 5 includes a comparison of compositions of three of these lavas with the Ambenali chemical-type average. In both the Jabalpur and Chikaldara areas, the volcanic pile beneath the Ambenali-like carapace is dominated by flows with chemical compositions generally similar to those of the Poladpur Fm.; interspersed at lower levels are several flows in the Chikaldara section and one in the Jabalpur section whose closest southwestern Deccan matches are with the Khandala Fm. (see some specific examples in Table 5 and Figures 5d and 5e). This overall stratigraphic order is roughly like that in the southwestern part of the province except that Bushe Fm. equivalents are conspicuously absent in the lower Chikaldara and Jabalpur sections, whereas in the southwestern Deccan the Bushe Fm. separates the Poladpur from the Khandala. Interestingly, however, two flows with Bushe-like chemical composition do lie within the upper, Ambenali-like part of the Chikaldara sequence (samples CH83-5 and 6), well out of the stratigraphic order seen in the southwest. The Chikaldara dike (CH83-31), which cuts through the upper, Ambenali-like part of the sequence, has a Mahabaleshwar-like chemical composition; in the southwestern Deccan, the Mahabaleshwar Fm. overlies the Ambenali.

No Ambenali-like lavas were sampled in the Mhow section, but flows with Poladpur- and Khandala-like chemical compositions are common. Several Bushe-like flows, represented by samples MH83-22, 23, and 24, and MH83-10 and 11, are present at the top and middle of the section. Note that MH83-10, which has a large Mahalanobis distance from the Bushe Fm. centroid, is similar to

Table 2c. Major and Trace Element Abundances of Northeastern Deccan Lavas of Jabalpur Area

	SA82-25	SA82-26	SA82-27	SA82-28	SA82-23	SA82-21b	SA82-21a	SA82-22	SA82-24	SA82-19	SA82-20
SiO_2	48.88	48.61	49.37	49.86	49.50	49.67	49.34	51.95	50.17	50.04	49.19
Al_2O_3	13.46	13.39	13.21	14.63	13.12	11.04	11.95	13.26	14.09	12.50	14.19
TiO_2	2.71	2.86	2.80	2.35	2.78	1.62	1.95	2.15	2.11	3.50	2.68
FeO*	14.30	15.10	14.82	13.55	14.97	12.12	13.20	13.34	12.67	15.87	13.69
CaO	11.11	10.82	10.76	11.69	10.36	12.18	11.99	10.82	11.51	8.96	11.18
MgO	5.97	6.54	5.62	6.72	5.45	9.95	8.54	5.38	6.21	4.57	5.50
K_2O	0.20	0.19	0.20	0.10	0.21	0.11	0.12	0.20	0.18	0.60	0.30
Na_2O	2.25	2.09	2.24	1.86	2.28	2.13	1.78	2.30	2.33	2.47	2.15
P_2O_5	0.26	0.27	0.33	0.26	0.28	0.19	0.20	0.23	0.25	0.39	0.27
Ni	117	99	82	92	75	220	196	65	118	51	79
V	397	413	427	416	435	384	381	433	406	452	366
Ba	43	57	67	16	90	62	68	65	73	159	178
Rb	2	3	3	<1	5	3	4	2	3	30	8
Sr	236	229	227	200	238	156	161	186	201	219	300
Zr	173	169	183	128	187	117	119	144	141	297	175
Y	39	36	37	34	42	34	33	36	34	57	35
Nb	12		14				8				

Table 2c. (continued)

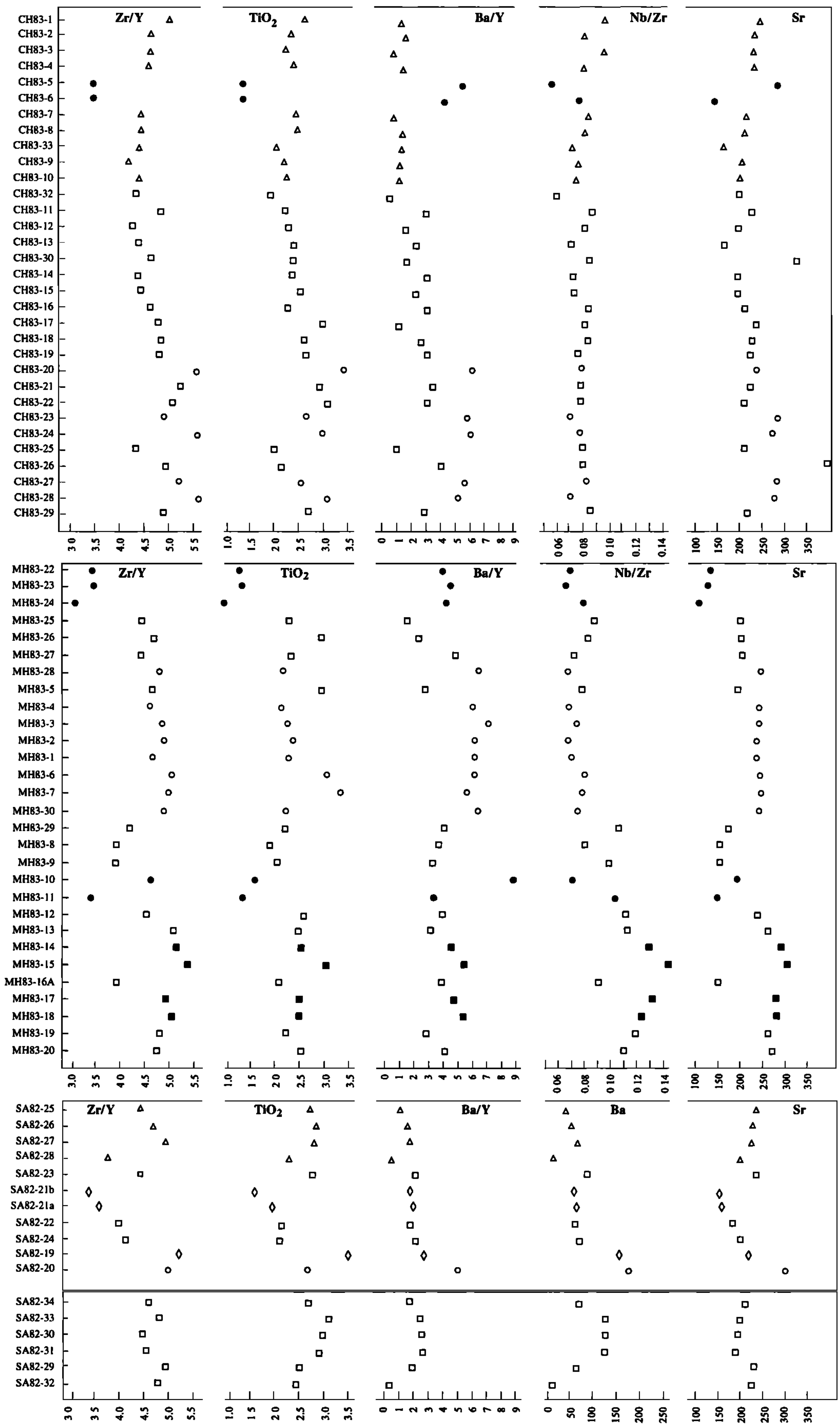
	SA82-34	SA82-33	SA82-30	SA82-31	SA82-29	SA82-32
SiO_2	49.62	50.29	50.13	49.87	48.50	48.96
Al_2O_3	12.94	12.89	12.06	12.15	13.38	13.14
TiO_2	2.69	3.14	3.03	2.95	2.52	2.49
FeO*	15.05	15.63	16.10	15.78	14.76	15.09
CaO	10.67	9.99	10.15	9.87	11.30	11.41
MgO	6.02	5.10	5.95	6.23	6.16	6.29
K_2O	0.30	0.81	0.75	0.80	0.16	0.10
Na_2O	2.13	2.29	2.11	2.53	2.29	1.98
P_2O_5	0.29	0.34	0.32	0.34	0.25	0.25
Ni	63	64	65	77	81	75
V	442	412	416	407	426	438
Ba	72	128	129	127	66	15
Rb	9	22	22	22	4	1
Sr	211	200	195	192	233	225
Zr	189	241	229	219	168	172
Y	41	50	51	48	34	36
Nb						

See Table 2a footnotes.

Table 3. Nd-Sr-Pb Isotope Ratios and Isotope-Dilution Elemental Abundances of Northeastern Deccan Lavas

Sample	Pb, ppm	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Nd, ppm	Sm, ppm	$\varepsilon_{Nd}(t)$	Sr, ppm	Rb, ppm	$(^{87}Sr/^{86}Sr)_t$
					Jabalpur					
SA82-25	0.940	18.135	15.480	38.549	21.91	6.020	+4.9	236.4	2.36	0.70413
SA82-28	0.900	18.524	15.576	39.085	16.67	4.850	+3.6	200.6	0.37	0.70486
SA82-21a					15.39	4.430	+1.5	161.2	3.94	0.70599
SA82-20	1.92	19.434	15.772	39.974	26.16	6.290	+3.5	300.4	7.92	0.70523
SA82-34	1.77	19.840	15.732	40.000	22.59	6.030	+2.2	210.0	8.92	0.70578
SA82-30	2.21	20.458	15.834	40.390	27.30	7.170	+0.5	194.7	21.60	0.70683
SA82-31	2.31	20.454	15.826	40.401	26.77	7.132	+0.3	187.2	23.01	0.70686
SA82-32					20.54	5.590	+2.1	224.9	1.17	0.70621
					Chikaldara					
CH83-1	0.749	18.415	15.458	38.849	14.06	4.184	+4.5	229.0	0.17	0.70421
CH83-3	1.49	17.875	15.453	38.501	13.80	4.030	+2.6	226.9	5.40	0.70456
CH83-5	2.48	19.501	15.797	40.299	11.18	3.159	-9.6	220.8	17.25	0.70984
CH83-7	1.18	18.347	15.526	38.709	15.41	4.534	+5.1	205.7	0.77	0.70429
CH83-14	2.00	19.181	15.675	39.599	16.00	4.588	+1.0	193.1	6.33	0.70595
CH83-17	2.35	19.883	15.731	39.992	14.08	4.194	+1.3	229.2	0.59	0.70613
CH83-18	1.74	19.770	15.752	40.024	16.96	4.903	+0.8	207.8	6.93	0.70614
CH83-20	3.85	19.694	15.739	40.118	28.48	7.372	-3.0	183.5	21.73	0.70805
CH83-24	3.21	18.436	15.550	39.181	30.54	7.642	-3.5	269.0	8.85	0.70720
CH83-28	3.14	18.421	15.548	39.160	22.30	6.265	-3.6	256.9	24.37	0.70736
					Mhow					
MH83-22	2.82	19.507	15.811	40.350	10.28	2.869	-9.6	130.1	20.38	0.71286
MH83-24	2.55	19.497	15.816	40.397	10.27	2.753	-11.2	107.4	13.36	0.71192
MH83-25	1.44	19.679	15.771	40.034	14.35	4.100	+1.1	209.4	7.92	0.70585
MH83-28	3.50	18.300	15.601	39.746	13.74	3.803	-7.0	242.2	21.84	0.71008
MH83-3	3.72	18.235	15.587	39.610	14.77	4.314	-6.8	278.4	21.43	0.70941
MH83-8	2.01	19.478	15.846	40.257	15.34	4.354	+0.1	136.3	9.81	0.70628
MH83-10	2.36	20.886	16.019	42.729	14.89	3.704	-13.2	202.5	34.44	0.71610
MH83-15	3.17	19.636	15.789	40.260	35.65	8.219	+1.2	306.1	21.98	0.70590
MH83-16A	2.40	19.484	15.845	40.259	13.95	3.981	-0.3	155.8	19.20	0.70673
MH83-18	2.80	19.509	15.854	40.171	20.52	5.116	+1.2	297.1	21.70	0.70623
MH83-20	2.22	19.627	15.782	40.145	16.02	4.240	-0.4	280.6	10.11	0.70652

The ratios $(^{87}Sr/^{86}Sr)_t$ and $\varepsilon_{Nd}(t)$ have been age-corrected to 66 Ma; Pb isotope ratios are present-day values, as in earlier Deccan studies. Data are reported relative to standard values and total measured ranges (over several years) of $^{143}Nd/^{144}Nd = 0.511855 \pm 0.000010$ (0.2 ε_{Nd} units) for La Jolla Nd; $^{87}Sr/^{86}Sr = 0.71024 \pm 0.00002$ for NBS 987 Sr; and the Pb isotope ratios of *Todt et al.* [1996] for NBS 981 Pb (for which our total measured ranges are ±0.010 for $^{206}Pb/^{204}Pb$, ±0.010 for $^{207}Pb/^{204}Pb$, and ±0.32 for $^{208}Pb/^{204}Pb$). Uncertainties on individual sample measurements are less than or equal to the above total ranges for standards. Uncertainties on isotope-dilution data are 0.2% (Sm, Nd), 0.4% (Sr), and 1% (Pb and Rb). See *Peng et al.* [1994] for fractionation corrections and total procedural blanks (which are negligible). Note that $\varepsilon_{Nd}(0) = 0$ corresponds to $^{143}Nd/^{144}Nd = 0.51264$ today, and $\varepsilon_{Nd}(t) = 0$ at 66 Ma corresponds to $^{143}Nd/^{144}Nd = 0.512555$ for $^{147}Sm/^{144}Nd = 0.1967$.


Zr/Y
TiO2
Ba/Y
Nb/Zr
Sr
Ba
CH83-1
CH83-2
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0.06 0.08 0.10 0.12 0.14
0 50 100 150 200 250
100 150 200 250 300 350

lavas of the Shingi Hill member of the Bushe Fm. (Figure 4). Figures 5b and 5c show the correspondence of three of the Bushe-like Mhow lavas with the Bushe Fm. in incompatible elements (see also Table 5); in particular, they have the distinctive, large Pb peak, low relative Nb, high Ba, Rb and K, and low concentrations of Sr, P, and Ti typical of the Bushe chemical type and Shingi Hill member. In the lower part of the section four Bhimashankar-like flows are interspersed with the chemically Poladpur-like lavas. Unfortunately, stratigraphic interpretation of the geochemical picture at Mhow is complicated by the likelihood that part of the stratigraphy in this region has been repeated by normal faulting [*Dhandapani and Subbarao*, 1992]. We also attempted a comparison of our results with those published by *Sreenivasa Rao et al.* [1985] for 11 samples from a section north of the Narmada River some 20 km west of our section. Despite the limited number of elements available for comparison (major elements, Ba, Zr, Sr) and possible interlaboratory biases in the data, several of their lavas are chemically similar to those we sampled and appear likely to be from the same flows. The lower four flows we sampled are similar to those in the normally magnetized interval at the base of their section. Recall, however, that all formations from the Ambenali downward in the southwestern Deccan are reversely magnetized.

4. Isotopic Data and Implications

Are any of the northeastern Deccan basalts correlatable with the southwestern stratigraphy? The chemical data indicate similarities between many northeastern Deccan lavas and the Ambenali, Poladpur, Khandala, and Bushe formations, and the overall superposition of chemically Ambenali-like lavas above Poladpur-like ones in the Chikaldara and Jabalpur areas is consistent with the southwestern stratigraphic succession. The existence of strong combined Nd-Pb-Sr isotopic similarities complementing the chemical similarities would greatly increase the likelihood that basalts in the two regions are closely related; in particular, isotopic ratios are not affected by (postcontamination) fractionation processes in magma chambers or during flow emplacement, which can modify elemental characteristics. (Nor, incidentally, are they affected appreciably by the type or levels of alteration present in the Deccan [e.g., *Lightfoot and Hawkesworth*, 1988].) On the other hand, the presence of significant and systematic isotopic differences would indicate that the northeastern lavas are not simply distant representatives of the southwestern flows even though they may have had broadly similar petrogenetic histories.

Nd-Pb-Sr isotopic measurements are far fewer in number than chemical analyses, but isotopic data for the different formations of the southwestern Deccan define divergent fields with only limited overlap (see Figure 6). These fields have been interpreted to reflect the effects of different types and amounts of lithospheric influence on magmas derived from convecting mantle associated with the Réunion plume head [e.g., *Mahoney et al.*, 1982; *Cox and Hawkesworth*, 1985; *Lightfoot and Hawkesworth*, 1988; *Lightfoot et al.*, 1990; *Peng et al.*, 1994; *Peng and Mahoney*, 1995]. Thus, in principle, combined isotopic characteristics should be a powerful index for stratigraphic classification. A caveat is that the isotopic fields for several of the southwestern formations are defined by relatively few analyses; for example, the field for the thick Thakurvadi Fm. by combined Nd-Sr isotopic data for ten samples but Pb-Nd-Sr isotopic data for only five samples. Further analyses would almost certainly broaden some of these fields. Also, some overlap is present, particularly for several of the lower-formation fields (e.g., Neral and Thakurvadi arrays at high $^{206}Pb/^{204}Pb$ in Figure 6b, or among several arrays at $\varepsilon_{Nd}(t)$ = -1 to -4 in Figure 6c). Other fields, however, such as those of the high-$\varepsilon_{Nd}(t)$ Ambenali Fm., the very low-$\varepsilon_{Nd}(t)$, very high-$(^{87}Sr/^{86}Sr)_t$ Bushe Fm., and the narrow, strongly curved Khandala Fm. field, are both distinctive and reasonably well-defined.

Our isotopic results confirm the presence of Ambenali-type flows in the upper parts of both the Jabalpur and Chikaldara sections, but reveal important differences as well. As Figures 6a and 6b show, the Jabalpur-area data form an array unlike any for the southwestern Deccan, extending from the Ambenali field (sample SA82-25 plots within the Ambenali field in all isotope-ratio diagrams) out to the right or high-$^{206}Pb/^{204}Pb$ side of the Poladpur field and approaching that of the Bhimashankar Fm. More generally, this array points toward the "common-signature" region of isotopic space [*Peng et al.*, 1994], indicated by shading in Figure 6, where several of the lower-formation arrays (i.e., the Thakurvadi, Khandala, Neral, and Bhimashankar) broadly approach or converge. The absence of overlap of the Jabalpur-area isotopic data with the Poladpur field in Figures 6a and 6b contrasts with the chemical affinities of many of these lavas. However, note that in Figure 6c, the data for samples SA82-21a, 30, 31, 32, and 34 do fall on or very close to the narrow Poladpur field.

Three of the chemically Ambenali-type flows of the upper Chikaldara section were analyzed isotopically (CH83-1, 3, and 7). Their isotopic ratios lie within the Ambenali field in Figure 7, the only exception being that CH83-3 has slightly lower $\varepsilon_{Nd}(t)$ (at +2.6) than those Ambenali Fm. lavas which have been analyzed for Pb isotopes (however, note that Ambenali basalts with $\varepsilon_{Nd}(t)$ as low as +2.5 exist but have not been analyzed for Pb isotopes [*Lightfoot*, 1985]). These basalts undoubtedly would be classified as Ambenali Fm. if found in the southwestern Deccan. In contrast, CH83-5, representing one of the two chemically Bushe-like flows in the Chikaldara section, has $(^{87}Sr/^{86}Sr)_t$ = 0.7098, much too low for it to be classified as Bushe Fm. (characterized by $(^{87}Sr/^{86}Sr)_t$ = 0.7135-0.7202; Figure 7c). Together with the fact that the two Bushe-like flows are stratigraphically out of place, situated within the Ambenali-type part of the section and not beneath the chemically Poladpur-like portion, this isotopic difference indicates that these flows are not true Bushe lavas but represent a type of basalt not (yet) seen in the southwestern Deccan.

We also measured isotopic ratios for three of the chemically Poladpur-like (CH83-14, 17, 18) and three of the Khandala-like

Figure 2. (opposite) Selected compositional variations with stratigraphic position in the Chikaldara, Mhow and Jabalpur areas. Analytical errors on data are small relative to the observed variations in each section: on Zr/Y = 0.20, TiO_2 = 0.01, Ba/Y = 0.64, Nb/Zr = 0.007, Ba = 4, Sr = 1 [see *Peng et al.*, 1994]. Symbols indicate closest chemical affinity with southwestern formations as determined by discriminant function analysis (Table 4): triangle, Ambenali-like; open square, Poladpur-like; solid circle, Bushe-like; open circle, Khandala-like; solid square, Bhimashankar-like; diamond, no close match. Note that there are probably several flows (unsampled) in the break shown for the Jabalpur area.

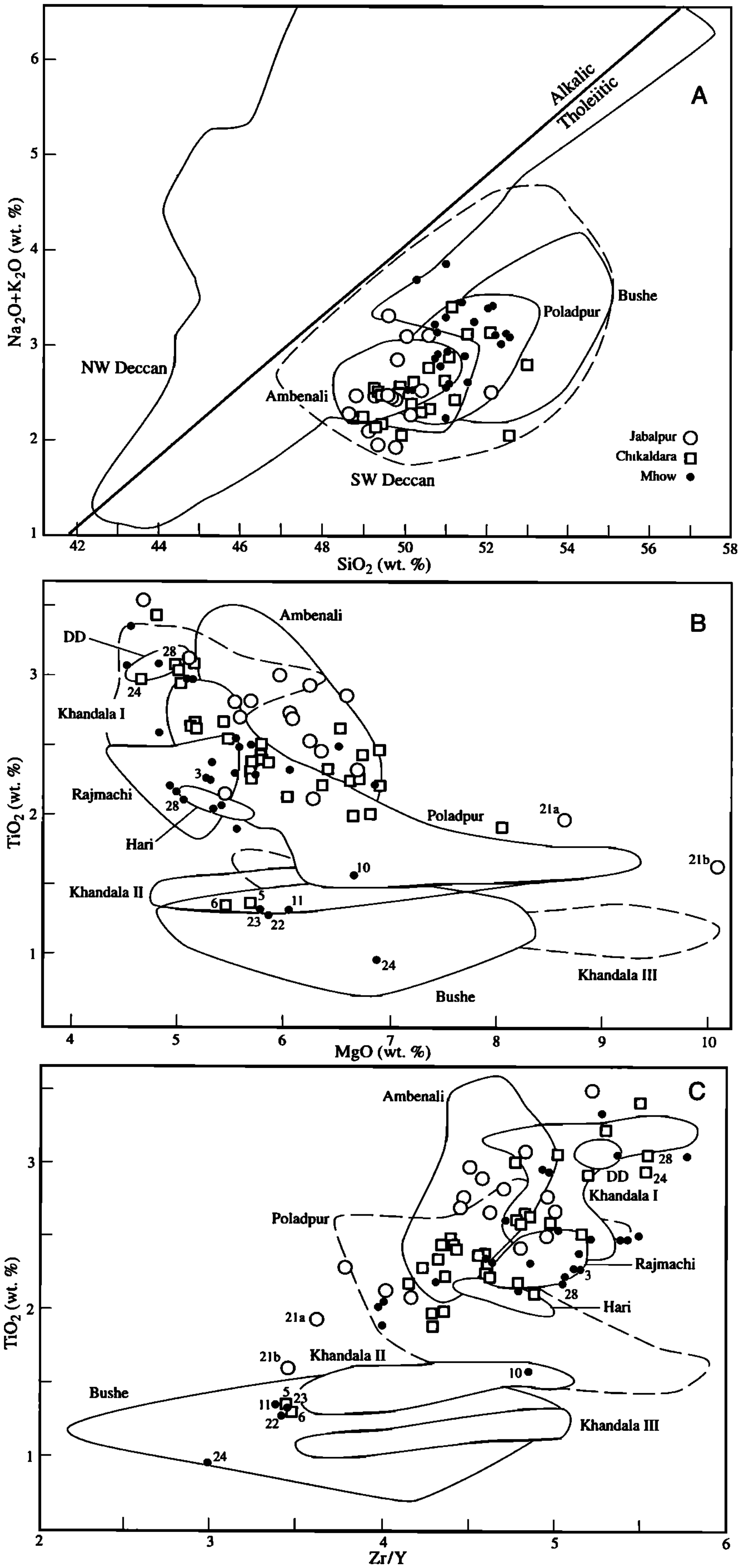

A
Alkalic
Tholeiitic
NW Deccan
SW Deccan
Ambenali
Poladpur
Bushe
Jabalpur
Chikaldara
Mhow
Na_2O+K_2O (wt. %)
SiO_2 (wt. %)
B
Ambenali
DD
Khandala I
Rajmachi
Hari
Poladpur
Khandala II
Khandala III
Bushe
TiO_2 (wt. %)
MgO (wt. %)
C
Ambenali
Poladpur
DD
Khandala I
Rajmachi
Hari
Khandala II
Khandala III
Bushe
TiO_2 (wt. %)
Zr/Y

Table 4. Summary of Discriminant Function Analysis

Sample	SW Formation Match	M-Distance	Function 1	Function 2
		Jabalpur Area		
SA82-25*	Ambenali	10.20	0.492	-1.531
SA82-26	Ambenali	2.77	1.979	-1.213
SA82-27	Ambenali	11.03	2.232	-0.636
SA82-28*	Ambenali	17.45	1.740	-1.547
SA82-23	Poladpur	5.73	-0.136	-0.566
SA82-21b	?			
SA82-21a*	?			
SA82-22	Poladpur	11.08	-1.621	-0.768
SA82-24	Poladpur	14.03	0.302	-0.443
SA82-19	?			
SA82-20*	Khandala	11.13	2.252	0.690
SA82-34*	Poladpur	4.43	-0.260	-0.818
SA82-33	Poladpur	15.57	-1.749	0.077
SA82-30*	Poladpur	19.68	-1.934	-0.067
SA82-31*	Poladpur	7.33	-0.606	0.170
SA82-29	Poladpur	5.22	1.029	-1.110
SA82-32*	Poladpur	8.28	-0.168	-2.016
		Chikaldara		
CH83-1*	Ambenali	2.43	1.964	-1.613
CH83-2	Ambenali	2.02	1.194	-1.495
CH83-3*	Ambenali	3.12	0.605	-1.910
CH83-4	Ambenali	2.55	0.877	-1.443
CH83-5*	Bushe	12.94	-2.978	0.585
CH83-6	Bushe	8.62	-4.526	0.935
CH83-7*	Ambenali	0.33	1.229	-1.665
CH83-8	Ambenali	0.48	1.511	-1.312
CH83-33	Ambenali	3.72	0.122	-1.318
CH83-9	Ambenali	2.44	0.226	-1.407
CH83-10	Ambenali	1.01	0.584	-1.388
CH83-32	Poladpur	4.09	0.206	-1.810
CH83-11	Poladpur	1.58	0.536	-0.455
CH83-12	Poladpur	5.85	-0.911	-1.273
CH83-13	Poladpur	7.79	-0.918	-0.792
CH83-30	Poladpur	9.86	0.480	-1.783
CH83-14*	Poladpur	4.19	-0.366	-0.219
CH83-15	Poladpur	3.83	-0.209	-0.815
CH83-16	Poladpur	0.08	0.127	-0.430
CH83-17*	Poladpur	5.99	-0.047	-1.433
CH83-18*	Poladpur	2.49	-0.556	-0.382
CH83-19	Poladpur	1.49	-0.217	-0.251
CH83-20*	Khandala	10.53	1.058	2.667
CH83-21	Poladpur	5.15	-0.162	0.323
CH83-22	Poladpur	5.53	0.112	0.134
CH83-23	Khandala	5.42	0.425	1.700
CH83-24*	Khandala	4.84	1.158	1.943
CH83-25	Poladpur	4.24	0.243	-1.882
CH83-26	Poladpur	19.89	0.250	-0.660
CH83-27	Khandala	3.79	0.565	1.426
CH83-28*	Khandala	7.20	1.097	1.380
CH83-29	Poladpur	3.37	-0.260	-0.372
CH83-31#	Mahabaleshwar	6.40	3.915	-0.096
		Mhow		
MH83-22*	Bushe	4.85	-4.282	0.585
MH83-23	Bushe	6.02	-4.263	0.855
MH83-24*	Bushe	8.77	-4.317	0.506
MH83-25*	Poladpur	1.57	-0.494	-1.340
MH83-26	Poladpur	4.12	-0.554	-0.412
MH83-27	Poladpur	4.91	0.151	0.638
MH83-28*	Khandala	4.23	-1.180	1.662
MH83-5	Poladpur	3.40	-0.403	-0.103
MH83-4	Khandala	6.10	-1.647	1.507

Figure 3. (opposite) (a) Total alkalies versus SiO_2, (b) TiO_2 versus MgO, and (c) TiO_2 versus Zr/Y for northeastern Deccan basalts (see symbol legend). Fields for the southwestern Deccan formations are from *Beane et al.* [1986] and *Beane* [1988]. DD, Dhak Dongar member, Khandala Fm.; Khandala I, Khandala Phyric, Monkey Hill, and Giravli types; Khandala II, KCG and Madh types; and Khandala III, Boyhare and KA1-3 types. Northwest (NW) Deccan field is from data of *Krishnamurthy* [1974], *Mahoney et al.* [1985], and *Melluso et al.* [1995]. Line separating alkalic and tholeiitic compositions in Figure 3a is for Hawaii [from *MacDonald and Katsura,* 1964]. Data points with numbers are for several samples discussed in text.

Table 4. (continued)

Sample	SW Formation Match	M-Distance	Function 1	Function 2
		Mhow		
MH83-3*	Khandala	2.22	-0.472	2.004
MH83-2	Khandala	5.18	-1.002	1.910
MH83-1	Khandala	1.92	-0.639	1.573
MH83-6	Khandala	4.67	1.022	2.354
MH83-7	Khandala	3.71	1.381	2.257
MH83-30	Khandala	2.53	-0.454	1.504
MH83-29	Poladpur	7.84	-1.193	0.678
MH83-8*	Poladpur	10.37	-1.252	0.275
MH83-9	Poladpur	11.59	-1.458	0.254
MH83-10*	Bushe ?	22.07	-0.863	2.853
MH83-11	Bushe	7.28	-2.335	-0.198
MH83-12	Poladpur	3.77	0.650	0.268
MH83-13	Poladpur	8.95	1.831	-1.102
MH83-14	Bhimashankar	3.27	1.644	-0.120
MH83-15*	Bhimashankar	7.73	2.355	0.908
MH83-16A*	Poladpur	10.74	-1.449	0.479
MH83-16B	Poladpur	9.66	-1.500	0.376
MH83-17	Bhimashankar	3.15	1.725	0.140
MH83-18*	Bhimashankar	3.99	1.536	0.348
MH83-19	Poladpur	7.92	1.306	-1.333
MH83-20*	Poladpur	3.59	1.245	-0.028
MH83-21A#	?			

Flow samples from each area are listed in stratigraphic order. M-distance is the Mahalanobis distance; function 1 and function 2 columns list scores of the first two canonical discriminant functions, plotted in Figure 4. Question marks indicate an M-distance >20 to closest southwestern formation centroid.

*Samples analyzed for isotopes.

#Dike samples are shown at bottom of their group.

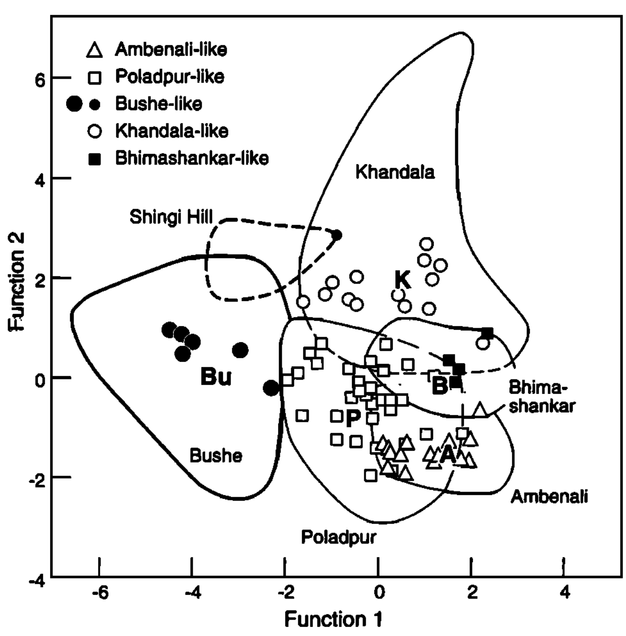


Figure 4. Plot of values (see Table 4) of the first two canonical discriminant functions for the northeastern Deccan basalts. Fields for relevant southwestern formations are shown, with bold letters denoting formation centroids. Dashed outline is for lavas of the Shingi Hill member of the Bushe Fm. Function 1 = $-0.409SiO_2 - 0.152Al_2O_3 + 1.293TiO_2 + 0.170CaO + 0.104K_2O + 1.293P_2O_5 + 0.333Ba + 0.380Ni + 0.338Sr - 1.554Zr - 0.790Y$. Function 2 = $-0.009SiO_2 + 0.124Al_2O_3 - 0.278TiO_2 - 0.153CaO - 0.230K_2O + 0.244P_2O_5 + 1.025Ba + 0.118Ni - 0.220Sr + 0.118Zr - 0.004Y$. Note that oxide and elemental abundances in these equations are Z-score-standardized values.

(CH83-20, 24, 28) Chikaldara lavas. Data for all three Poladpur-like samples fall within the Nd-Sr isotopic field of the Poladpur Fm. in Figure 7c, but only CH83-14 plots within the Poladpur field in Figures 7a and 7b. Samples CH83-17 and CH83-18 have much higher $^{206}Pb/^{204}Pb$ and, with Pb isotopic ratios closely similar to those of Jabalpur sample SA82-34, lie on or very close to the high-$^{206}Pb/^{204}Pb$ trend defined by the Jabalpur-area data. Of the chemically Khandala-like samples, CH83-20 has a higher $^{206}Pb/^{204}Pb$ value than yet measured for any Khandala Fm. basalt, its data overlapping with the high-$^{206}Pb/^{204}Pb$ end of the Neral field. However, values for CH83-24 and CH83-28 are very similar to each other and fall on the narrow Khandala array in all isotope diagrams. Specifically, they have virtually identical isotopic ratios to those of the widespread Dhak Dongar member of the Khandala Fm. (triangle in Figure 7). Chemically, both of these lavas closely resemble the Dhak Dongar as well (see Table 5 and Figure 5d). Furthermore, lavas in three sections of the central Deccan some 150-200 km south and southwest of Chikaldara have been identified as Dhak Dongar [*Peng*, 1998; *Subbarao et al.*, 1998]. Thus, based on present evidence, it is possible that CH83-24 and 28 in fact represent Dhak Dongar flows.

For the Mhow section, we analyzed three of the chemically Bushe-like flows for isotopes (MH83-10, 22, and 24). Unlike Chikaldara lava CH83-5, data for MH83-10 fall within the Bushe field and those for MH83-22 lie very close to it in all isotope diagrams; both of these samples would be classified as Bushe Fm. if taken from the southwestern Deccan. Data for sample MH83-24 plot within the Bushe field in Figure 7a and outside of it in Figures 7b and 7c, but still much closer than do data for CH83-5. Presently, we cannot discount the possibility that these Mhow lavas may represent thin and locally faulted outliers of the Bushe Fm. (the type-sections of which are some 500 km distant), given the combination of distinctive chemical (see Figures 5b and 5c) and isotopic similarities.

Several Mhow-area samples from flows in the middle of the section are chemically similar to the Rajmachi member (e.g., Table 5) which divides the Khandala and Bushe formations in the southwestern Deccan. Chemically, this member is distinctive in resembling some Poladpur Fm. basalts [*Beane*, 1988]. It is also quite distinct isotopically from all other Khandala Fm. members, with values plotting well outside the Khandala array (Figure 7, star) [*Peng et al.*, 1994; *Peng*, 1998]. The two chemically Rajmachi-like samples we analyzed isotopically, MH83-3 and 28, have isotopic values closely similar to the Rajmachi, particularly MH83-28.

The remaining Mhow samples analyzed for isotopes (MH83-8, 15, 16A, 18, 20, 25) have Poladpur-like or Bhimashankar-like chemical signatures and exhibit a narrow range of $\varepsilon_{Nd}(t)$ (+1.2 to -0.4), $^{206}Pb/^{204}Pb$ (19.5-19.7), and $(^{87}Sr/^{86}Sr)_t$ (0.7059-0.7067) values. In the Nd-Sr isotope diagram (Figure 7c), they lie on the upper part of the Poladpur array; however, as with the chemically Poladpur-like Jabalpur and Chikaldara lavas, their $^{206}Pb/^{204}Pb$ ratios are elevated well above Poladpur Fm. values (Figures 7a and 7b). Indeed, data for MH83-15 and 25 fall close to or on the Jabalpur array.

5. Discussion

Our results demonstrate that many northeastern Deccan flows cannot be correlated straightforwardly with the well-established southwestern formational stratigraphy. Rather, isotopic data for many northeastern lavas define a trend indicative of mixing between Ambenali-type and high-$^{206}Pb/^{204}Pb$ end-members. Significantly, despite the apparent lack of an equivalent isotopic trend in the southwestern Deccan, such mixing previously has been inferred to have been a major process in the genesis of the southwestern formations. In order to reconcile the observed Nd-Sr isotopic characteristics with the subparallel Nd-Pb and Sr-Pb isotopic fields defined by many of these formations, *Peng et al.* [1994] concluded that two stages of mixing were required (schematically indicated by heavy arrows in Figures 6a and 6b). The first was postulated to be between Ambenali-type (presumably representing a major mantle source in the Réunion plume head) and high-$^{206}Pb/^{204}Pb$, low-ε_{Nd}, high-$^{87}Sr/^{86}Sr$ continental lithospheric end-members; in the second stage, the products of variable amounts of first-stage mixing were contaminated with several different low-$^{206}Pb/^{204}Pb$ continental crustal materials, giving the wide range of isotopic compositions seen for the southwestern Deccan formations. The comparatively limited isotopic range of the common signature toward which several of the lower-formation arrays converge was argued to either (1) reflect compositions within the high-$^{206}Pb/^{204}Pb$ continental lithospheric end-member itself or (2) represent a range of first-stage mixtures particularly favored by petrogenetic conditions prevailing throughout much of the period of lower-formation eruptions. Note that in the second case the high-$^{206}Pb/^{204}Pb$ first-stage end-member would have isotopic values even more extreme than for the high-$^{206}Pb/^{204}Pb$ end of the Bushe field, whereas in the first case, basalts with higher $^{206}Pb/^{204}Pb$ values than the common-signature lavas would require some other explanation. Although our new data provide strong evidence that mixing of Ambenali-type and high-$^{206}Pb/^{204}Pb$ end-members occurred, the isotopic values of the northeastern Deccan samples we analyzed do not extend beyond the common-signature range, thus leaving open the question of the high-$^{206}Pb/^{204}Pb$ end-member's precise composition and nature.

The combination of marked chemical and Pb-Nd-Sr isotopic similarities suggests that several flows of the Khandala Fm. (Dhak Dongar member, CH83-24 and 28; Rajmachi member, MH83-28 and 3) may be present in the Mhow and Chikaldara areas; moreover, the Bushe-like basalts in the Mhow section could possibly be Bushe Fm. flows. At Chikaldara, the isotopically Khandala-like flows are in the lower part of the section, stratigraphically broadly consistent with the Ambenali-type lavas being in the upper part and chemically Poladpur-like flows in between. Unfortunately, normal faulting in the Mhow area presently hinders assessment of the original stratigraphic relationship of the Bushe-type flows and other flows in the section. The new data do, however, extend the known limits of basalts with highly distinctive Bushe-like characteristics considerably to the northeast. Bushe Fm. (or Bushe-like) flows have not yet been found in the central Deccan very far east of Igatpuri [*Subbarao et al.*, 1998; *Peng*, 1998], but *Krishnamurthy et al.* [1988] reported a single Bushe-like flow from the extreme northwest corner of the Deccan [see also *Melluso et al.*, 1995], and *Devey and Stephens* [1991] showed that dikes with strongly Bushe-type chemical and Nd-Pb-Sr isotopic characteristics are present in the Seychelles Islands; prior to post-Deccan rifting of the Seychelles microcontinent from India, these dikes appear to have been located several hundred kilometers northwest of what is now Bombay. An important direction of future work will be to determine whether Bushe-type lavas exist in the region between the west coast and Mhow.

What does the presence of strongly Ambenali-like lavas in the upper levels of the Jabalpur and Chikaldara sections indicate about the original extent of the Ambenali Fm.? On the one hand, the Ambenali is thought to represent little-contaminated melts of Réunion plume-head mantle; in principle, stratigraphically unrelated magmas that formed in different parts of the large plume head and erupted at different times through different feeder vents could possess Ambenali-like isotopic ratios, so long as they escaped significant contamination by continental material in magma chambers or on their way to the surface. On the other hand, the elemental characteristics of such magmas generally would be expected to differ in some important ways from true Ambenali ones, because magmas formed in different regions of the plume head would tend to reflect somewhat different amounts of partial melting and liquid lines of descent. Indeed, an isotopically Ambenali-like mantle source was important in the northwestern Deccan Traps, but the major- and trace-element compositions of the northwestern flows are very distinct from those of the Ambenali Fm., reflecting lower degrees of partial melting and different magmatic histories [*Peng and Mahoney*, 1995]. In contrast, the northeastern Deccan lavas with Ambenali-type isotopic ratios have elemental characteristics within the range of the Ambenali Fm. basalts (e.g., Figure 5a and Table 5). Therefore, until dikes with both Ambenali-type isotopic and elemental characteristics are documented in the northeastern Deccan, the possibility that the Ambenali-like flows in the northeast represent a distal part of the southwestern Ambenali Fm. cannot be ruled out. If true, the Ambenali Fm. would be one of the most widespread of any Deccan formations (present in locations as far apart as 900 km).

However, the bulk of the Chikaldara, Mhow, and Jabalpur-area sections are made up of chemically Poladpur- and Khandala-like basalts; with a few notable exceptions (CH83-14, 24, 28, MH83-3 and 28), those analyzed isotopically are distinct from any of the Poladpur and Khandala Fm. lavas in the southwest Deccan. It is important to note that the isotopic difference is mainly in Pb isotopes; the Nd and Sr isotopic ratios of samples SA82-20, 21a, 30, 31, 32, and 34, CH83-14, 17, and 18, and MH83-8, 16A, 20,

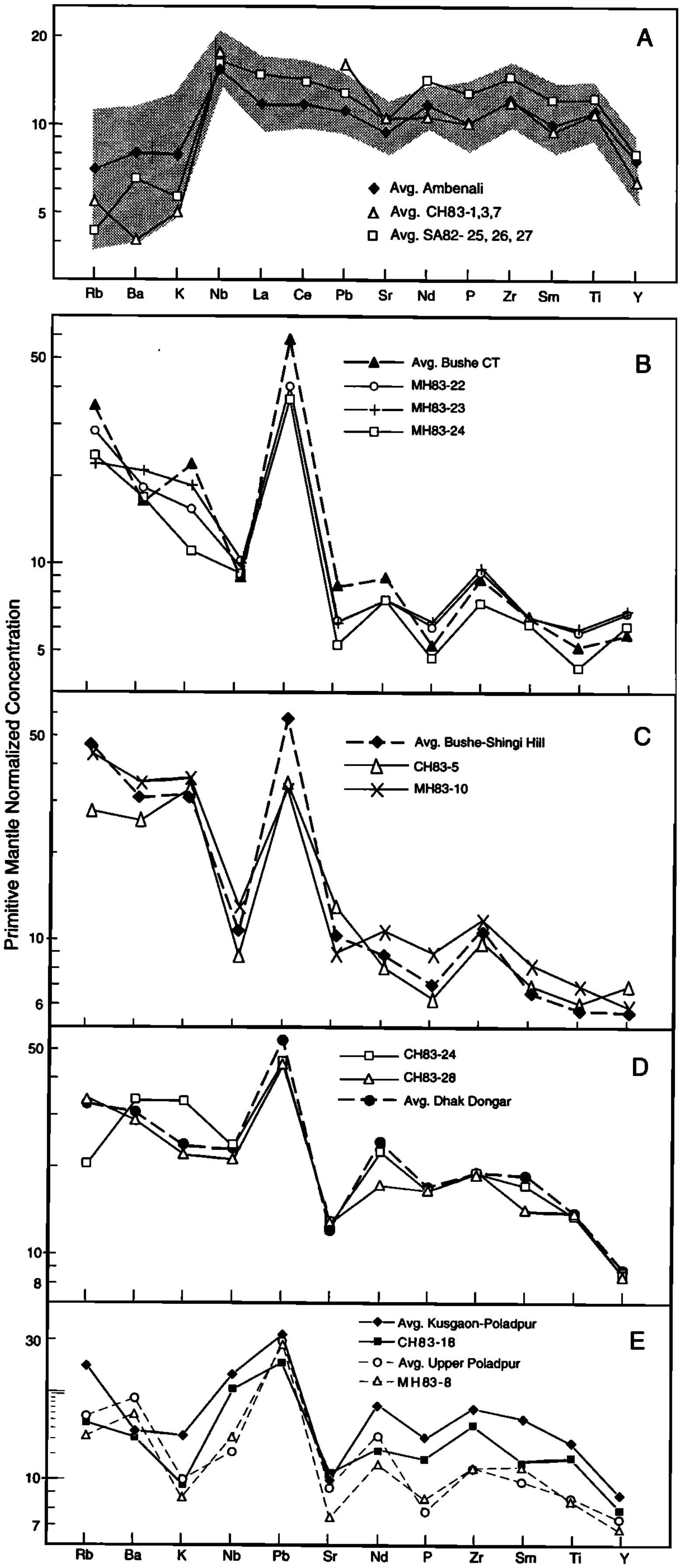

A
Avg. Ambenali
Avg. CH83-1,3,7
Avg. SA82- 25, 26, 27
20
10
5
Rb Ba K Nb La Ce Pb Sr Nd P Zr Sm Ti Y
B
Avg. Bushe CT
MH83-22
MH83-23
MH83-24
50
10
5
Primitive Mantle Normalized Concentration
C
Avg. Bushe-Shingi Hill
CH83-5
MH83-10
50
10
6
D
CH83-24
CH83-28
Avg. Dhak Dongar
50
10
8
E
Avg. Kusgaon-Poladpur
CH83-18
Avg. Upper Poladpur
MH83-8
30
10
7
Rb Ba K Nb Pb Sr Nd P Zr Sm Ti Y

Table 5. Comparison of Chemical Compositions of Selected Northeastern Deccan Basalts With Southwestern Formation Averages

	Ambenali CT		CH83-3	CH83-7	SA82-25	Poladpur (Kusgaon)		CH83-18	MH83-26
	n=60	(1 s.d.)				*n*=5	(1 s.d.)		
					Weight Percent				
SiO_2	49.34	(0.70)	49.88	49.45	49.30	51.05	(0.28)	51.34	51.58
Al_2O_3	14.20	(0.52)	14.04	14.04	13.58	13.09	(0.13)	13.43	13.28
TiO_2	2.53	(0.38)	2.26	2.44	2.73	2.84	(0.27)	2.62	2.97
FeO*	13.86	(0.80)	12.92	13.80	14.42	14.34	(0.40)	14.40	13.95
MnO	0.23	(0.05)	0.22	0.22		0.22	(0.01)	0.23	0.22
CaO	10.87	(0.57)	11.28	10.95	11.21	9.90	(0.43)	9.98	9.60
MgO	6.10	(0.40)	6.69	6.72	6.02	5.27	(0.25)	5.15	5.08
K_2O	0.23	(0.16)	0.19	0.12	0.20	0.41	(0 .12)	0.29	0.53
Na_2O	2.41	(0.14)	2.32	2.06	2.27	2.59	(0.08)	2.30	2.49
P_2O_5	0.23	(0.04)	0.20	0.21	0.26	0.28	(0.05)	0.25	0.30
					Parts per Million				
Ni	73	(14)	82	96	117	44	(5)	38	47
Sc	38	(2)	39	38		36	(3)	37	35
V	411	(44)	384	419	397	417	(13)	410	414
Ba	39	(28)	22	26	43	98	(23)	97	95
Rb	6	(5)	5	<1	2	15	(2)	10	21
Sr	220	(16)	222	207	236	210	(5)	221	210
Zr	141	(20)	133	132	173	186	(27)	172	197
Y	32	(6)	29	30	39	39	(4)	36	40
Nb	12	(3)	13	11	12	15	(2)	14	16
Ga	23	(2)	21	20		24	(1)	21	19
Cu	237	(40)	220	246		288	(57)	233	239
Zn	114	(10)	105	113		159	(24)	124	124

25, and 15 and 18 all fall within or lie very close to the high-ε_{Nd} portion of the narrow Poladpur field in the Nd-Sr isotope diagram (Figures 6c and 7c). Given (1) the generally good correspondence of the chemically Poladpur-like basalts with the Poladpur Fm. in Nd and Sr isotopes, and (2) the presence in the Jabalpur and Chikaldara areas of overlying Ambenali-type lavas (exactly as in the southwestern Deccan), the relevant northeastern Deccan lavas may well be petrogenetically related to the Poladpur Fm. but represent magmas that were not affected as strongly by the second stage of contamination (i.e., involving low-$^{206}Pb/^{204}Pb$, low-ε_{Nd} continental material). *Peng et al.* [1994] argued that the first stage of mixing for the southwestern Deccan occurred either in the upper lithospheric mantle or at the base of the crust, and that second-stage mixing took place in crustal conduits or magma chambers. Pb is highly enriched in most types of continental crust relative to elements of similar incompatibility in the oceanic mantle and is one of the elements affected most dramatically by small amounts of crustal contamination; for example, most types of continental crust have much lower Nd/Pb and Sr/Pb than magmas from the convecting mantle (e.g., Nd/Pb = 2.6 and 1.3 for average lower and upper crust, respectively [*Rudnick and Fountain*, 1995], whereas Nd/Pb = 24-30 for normal MORB and 12-15 for typical oceanic island basalts [e.g., *Sun and McDonough*, 1989]). Thus the differences in Pb-isotopic composition between most of these northeastern Deccan flows and the Poladpur Fm. field require systematic, but not necessarily large, differences in second-stage contamination.

Could these high-$^{206}Pb/^{204}Pb$ northeastern lavas simply represent Poladpur, possibly a few Khandala, Bhimashankar, and petrogenetically related flows that exist in the southwestern formations but previously have not been analyzed for Pb isotopes? Only two of the 12 members of the Khandala Fm. in the southwestern Deccan have not been analyzed for Pb isotopes; both members of the Bhimashankar Fm. have been analyzed [*Peng et al.*, 1994; *Peng*, 1998], and the Poladpur is one of the isotopically best-characterized formations, with at least 15 flows (out of 20 in the southwestern type sections) analyzed for Pb, Nd, and Sr isotopes [*Lightfoot and Hawkesworth*, 1988; *Lightfoot et al.*, 1990; and references therein]. Furthermore, data for the two chemically Poladpur-type lavas of the central Deccan that have been analyzed for Pb, Nd, and Sr isotopes fall well within the Poladpur isotopic field [*Peng*, 1998]. Thus, it seems highly

Figure 5. (opposite) Primitive-mantle-normalized [*Sun and McDonough*, 1989] incompatible element patterns. (a) Ambenali-like Chikaldara and Jabalpur-area basalts compared with the average pattern and range (shading) of Ambenali Fm. lavas; (b) MH83-22, 23, and 24 and average Bushe chemical type (CT); (c) MH83-10 and CH83-5 compared with the average for Shingi Hill member of the Bushe Fm.; (d) CH83-24 and 28 patterns compared with average for Dhak Dongar member, Khandala Fm.; and (e) MH83-8 compared with Upper Poladpur member and CH83-18 with Kusgaon member of Poladpur Fm. Data for southwestern basalts compiled from *Beane* [1988], *Mahoney* [1984], *Cox and Hawkesworth* [1985], *Lightfoot* [1985], *Devey* [1986], and Z. Peng (unpublished data, 1998). For the southwestern averages, there are fewer Pb abundance data available than for the other elements shown. Also, note that Pb, Nd, and Sm abundances for the northeastern Deccan samples were measured by isotope dilution on small chips of sample, rather than on whole rock powders, and may not always represent bulk rock composition (e.g., the relatively low Nd and Sm in CH83-28 pattern). La and Ce for SA pattern in Figure 5a are for sample SA82-25 only (A.V. Murali, unpublished neutron activation data, 1990).

Table 5. (continued)

	Bushe CT		MH83-22	MH83-24	CH83-6	Khandala (Dhak Dongar)		CH83-24	CH83-28	Khandala (Rajmachi)		MH83-28	MH83-3
	n=98	(1 s.d.)				*n*=6	(1 s.d.)			*n*=11	(1 s.d.)		
						Weight Percent							
SiO_2	52.67	(1.02)	52.27	52.24	52.99	51.17	(0.56)	51.16	51.51	52.38	(0.39)	52.49	52.19
Al_2O_3	15.06	(0.72)	15.11	14.71	15.36	13.41	(0.51)	13.99	13.24	13.94	(0.51)	14.47	14.05
TiO_2	1.21	(0.14)	1.29	0.98	1.35	3.07	(0.04)	2.97	3.08	2.32	(0.18)	2.18	2.28
FeO*	10.41	(0.40)	11.45	10.98	10.95	14.34	(0.20)	13.77	14.08	13.12	(0.42)	12.52	12.89
MnO	0.17	(0.02)	0.19	0.23	0.20	0.22	(0.02)	0.20	0.21	0.20	(0.02)	0.19	0.21
CaO	10.58	(0.56)	10.78	11.39	10.78	9.23	(0.20)	9.53	9.46	9.23	(0.42)	9.82	9.79
MgO	6.83	(1.14)	5.86	6.83	5.44	4.84	(0.17)	4.64	4.96	5.07	(0.68)	4.96	5.24
K_2O	0.65	(0.29)	0.46	0.33	0.36	0.71	(0.16)	1.01	0.66	0.90	(0.32)	0.58	0.60
Na_2O	2.30	(0.20)	2.46	2.20	2.43	2.66	(0.12)	2.41	2.47	2.59	(0.14)	2.55	2.53
P_2O_5	0.12	(0.02)	0.13	0.10	0.14	0.34	(0.01)	0.33	0.33	0.24	(0.02)	0.22	0.23
						Parts per Million							
Ni	97	(45)	53	70	44	58	(15)	53	53	56	(19)	47	49
Sc	34	(3)	41	43	36	34	(2)	29	32	32	(3)	35	32
V	277	(18)	320	311	310	410	(11)	381	394	354	(25)	350	358
Ba	111	(53)	126	118	138	214	(25)	236	201	195	(28)	211	232
Rb	21	(12)	18	15	19	21	(4)	13	22	27	(14)	19	21
Sr	179	(51)	135	112	136	258	(13)	268	272	243	(13)	250	248
Zr	102	(10)	105	83	110	215	(9)	215	516	165	(6)	161	164
Y	26	(3)	31	28	32	41	(2)	39	39	34	(2)	32	32
Nb	6	(1)	7	7	9	17	(1)	17	15	11	(1)	11	12
Ga	19	(2)	20	16	20	26	(2)	24	25	23	(1)	18	22
Cu	144	(47)	141	158	174	277	(60)	268	266	198	(36)	166	159
Zn	97	(21)	90	81	90	129	(8)	116	129	115	(9)	111	109

Southwestern Deccan averages are from data of *Beane* [1988]; *n* represents the number of samples and 1 s.d. is one standard deviation. Note that all major element data are normalized to 100 wt % totals.

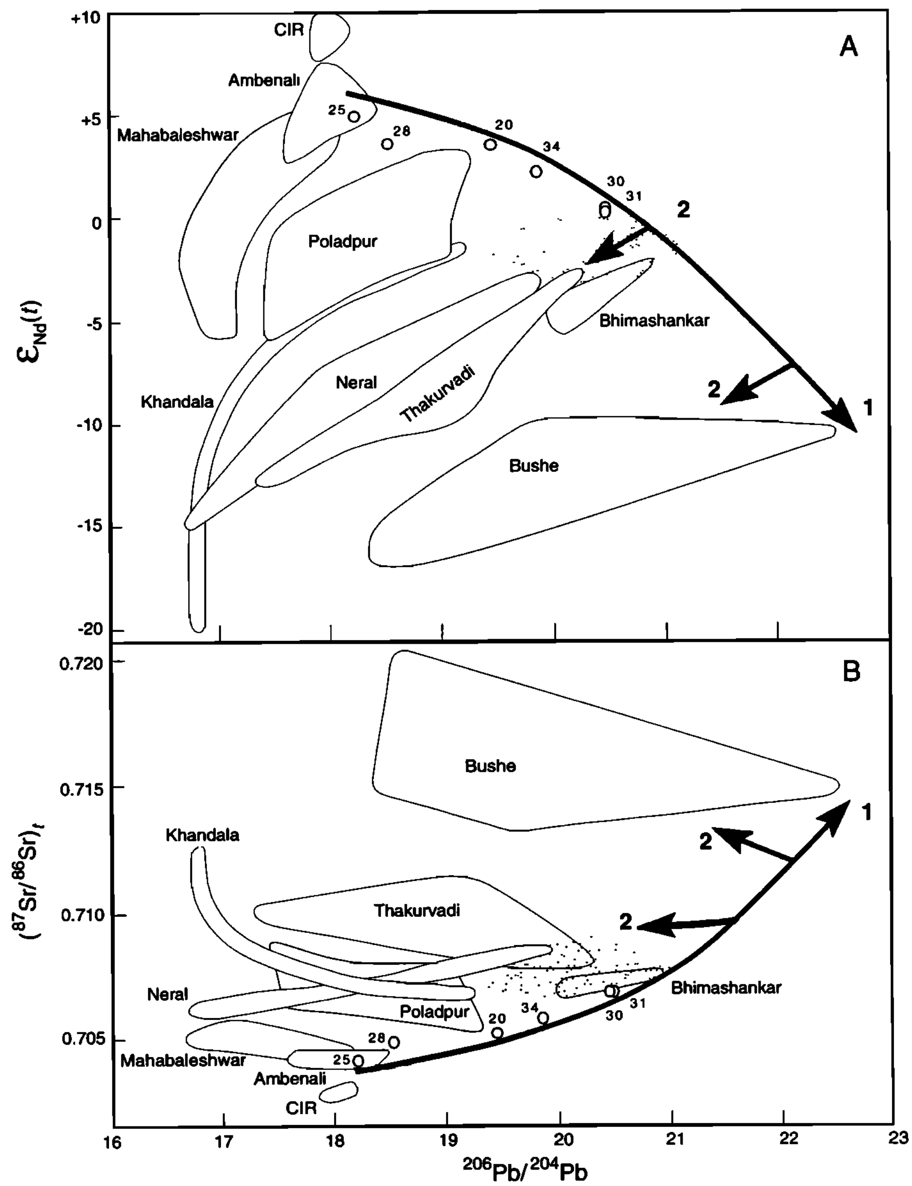


Figure 6. Relationships of (a) $\varepsilon_{Nd}(t)$ versus $^{206}Pb/^{204}Pb$, (b) $(^{87}Sr/^{86}Sr)_t$ versus $^{206}Pb/^{204}Pb$, and (c) $\varepsilon_{Nd}(t)$ versus $(^{87}Sr/^{86}Sr)_t$ for lavas of the Jabalpur area (circles; note SA82 prefix is left off sample numbers for clarity). Fields are shown for the southwestern Deccan formations and for Central Indian Ridge (CIR) normal-MORB [after *Peng et al.*, 1994]. The "common signature" defined by several lower formations of the southwestern Deccan is indicated by shading. Heavily lined arrows in Figures 6a and 6b illustrate schematically how the isotopic fields of most southwestern Deccan formations can be explained by two stages of mixing with continental lithospheric materials [*Peng et al.*, 1994], the first (labeled 1) involving Ambenali-like and high-$^{206}Pb/^{204}Pb$, low-ε_{Nd} end-members, and the second (labeled 2) entailing addition of low-$^{206}Pb/^{204}Pb$ continental material (qualitatively similar to Archean crust exposed elsewhere in India [e.g., *Peucat et al.*, 1989]) to the first-stage mixtures. Fields for the Igatpuri-Jawhar, Thakurvadi, and Panhala formations are left off one or more panels to avoid cluttering.

unlikely that the high-$^{206}Pb/^{204}Pb$ northeastern flows are present in the southwest but somehow happened to be overlooked in isotopic studies.

Because all of the southwestern Deccan formations from the Ambenali downward have reversed magnetic polarity, the normal polarity reported for the lower part of the sequence west of our Mhow section [*Sreenivasa Rao et al.*, 1985] appears to rule out any direct link between the lower lavas in the Mhow area and the Poladpur, Bhimashankar, or Khandala formations. However, paleomagnetic data do not rule out a close temporal (as well as

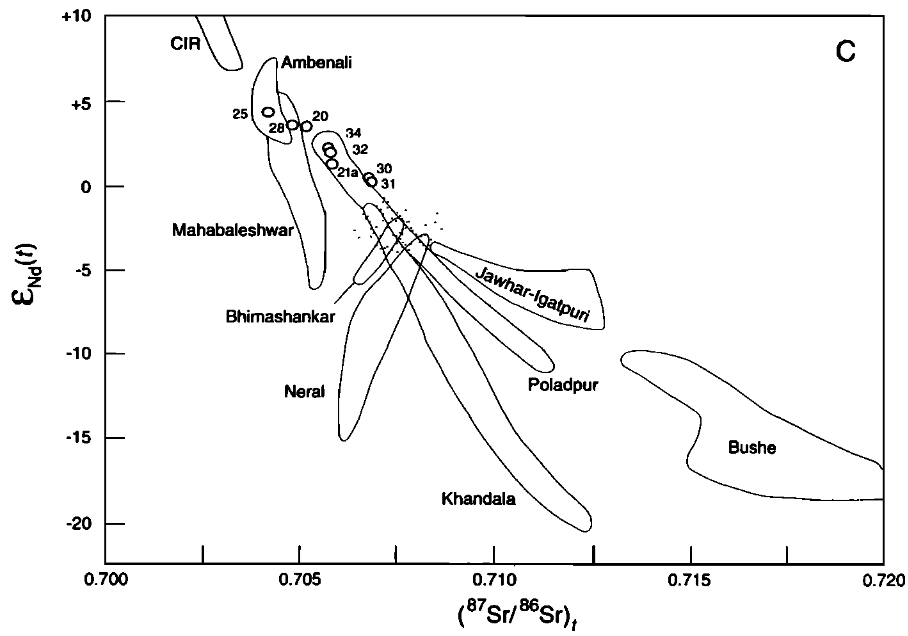


Figure 6. (continued)

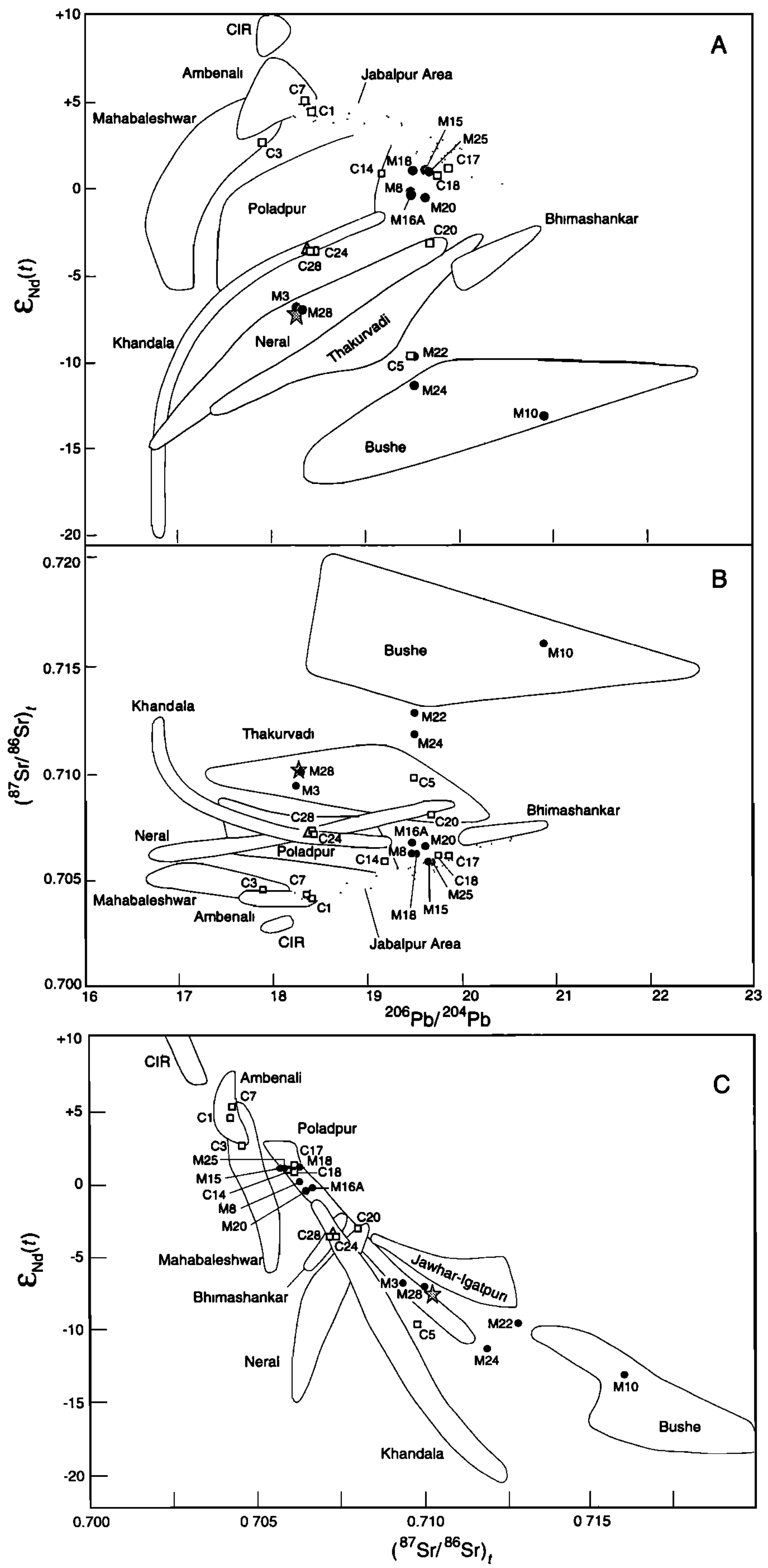
petrogenetic) connection of the upper parts of the Mhow section or of the Chikaldara and Jabalpur sequences to the relevant southwestern formations. The Chikaldara section consists exclusively of reversely magnetized lavas [*Wensink*, 1973]. Most published paleomagnetic data for the Mandla lobe are for sections well to the east (70-150 km) of those we sampled to the south and southwest of Jabalpur; regional interpretation of the data appears to be hampered somewhat by structural complications [*Vandamme and Courtillot*, 1992]. However, data for areas closest to our sections reveal reversed polarity [see *Vandamme and Courtillot*, 1992, and references therein]. Near the easternmost end of the Mandla lobe, a sequence of normally polarized lavas is present above reversely magnetized ones. Elevations there (up to 1100 m) are significantly higher than in our study area (<700 m), and it is likely that these flows lie stratigraphically above the Ambenali-type lavas we sampled. Interestingly, the Mahabaleshwar Fm., which sits above the Ambenali Fm. in the southwestern Deccan, is also normally magnetized, and it is possible that some Mahabaleshwar-like lavas exist in higher-elevation parts of the Mandla lobe [cf. *Yedekar et al.*, 1996]. Indeed, this possibility is supported by the chemically Mahabaleshwar-like lava (from ~1050 m elevation) at the western end of the lobe studied by *Sen and Cohen* [1994].

6. Conclusion

Although many northeastern Deccan lavas are different from any yet seen in the well-studied southwestern part of the province, close elemental and Nd-Pb-Sr isotopic similarities indicate that the Ambenali Fm. and perhaps a few Khandala and Bushe Fm. flows may be present in the northeastern Deccan. Ambenali-like basalts are present as far as 900 km from their southernmost exposures. Many northeastern lavas resemble the Poladpur or Khandala Fm. in chemical composition and the Poladpur in Nd and Sr isotopes, suggesting a petrogenetic relationship of some sort; however, their systematically higher Pb-isotope ratios, in particular, require that these lavas must have traversed different routes through the crust than the southwestern flows and thus issued from different feeder dikes. Much of the northeastern Deccan therefore appears not to conform to the model commonly assumed for flood basalts, based on work in the Columbia River Basalt Group, where many individual eruptions cross the entire province, in many cases having demonstrably issued from single eruptive centers or fissures [e.g., *Hooper*, 1997, and references therein; cf. *Peate*, 1997].

The feeder dikes of the Poladpur-like northeastern Deccan flows may or may not have been located at great distances from those feeding the southwestern flows. For example, paleotopography permitting [e.g., *Subbarao et al.*, 1994; *Widdowson and Cox*, 1996], most of the lavas of our study could presumably have flowed northeastward from feeders located at modest distances farther east or north of Igatpuri than the dikes supplying the lavas in the southwest. Alternatively, the feeders of many of the northeastern flows could have been along the Narmada-Tapti Lineament. Systematic study of the combined Pb-Nd-Sr isotopic and chemical characteristics of dikes along the lineament and in the region north and east of Igatpuri is required to resolve these possibilities. The answer is also critical for understanding the scale and nature of magma generation, storage, and transport in dikes and over the surface in the Deccan Traps.

Figure 7. (opposite) Isotopic variation diagrams as in Figure 6, except that data points are for Chikaldara (squares) and Mhow (dots) samples. CH83 and MH83 prefixes on sample numbers have been shortened to C and M for clarity. Shaded area in Figures 7a and 7b represents the data array defined by the Jabalpur-area lavas. Star is for Rajmachi member and triangle is for Dhak Dongar member of southwestern Deccan [*Peng et al.*, 1994; *Peng*, 1998].


A
CIR
Ambenali
Jabalpur Area
Mahabaleshwar
Poladpur
Bhimashankar
Khandala
Neral
Thakurvadi
Bushe
C7
C1
C3
C14
M18
M15
M25
C17
C18
M8
M20
M16A
C20
C24
C28
M3
M28
M22
C5
M24
M10
$\varepsilon_{Nd}(t)$
+10
+5
0
-5
-10
-15
-20
B
$(^{87}Sr/^{86}Sr)_t$
0.720
0.715
0.710
0.705
0.700
16
17
18
19
20
21
22
23
$^{206}Pb/^{204}Pb$
C
Jawhar-Igatpuri
0.700
0.705
0.710
0.715
$(^{87}Sr/^{86}Sr)_t$

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