Isotopic evidence of Middle Proterozoic magmatism from Bombay High Field: Implications to crustal evolution of western offshore of India

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Precambrian granitic basement rocks obtained from well BH-36 of Bombay High Field, western offshore of India has been studied both by Rb-Sr and K-Ar dating methods. Seven basement samples chosen from two cores have yielded whole rock Rb-Sr isochron age of 1446 ± 67 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7062 ± 0.0012. This age has been interpreted as the formation/emplacement time of the granite. Two biotite fractions of different grain size separated from a sample CC6B2T have yielded Rb-Sr mineral isochron age of 1385 ± 21 Ma. However, these fractions when studied by K-Ar dating method have yielded slightly higher but mutually consistent ages of 1458 ± 43 Ma and 1465 ± 43 Ma, respectively.

Further, two biotites separated from additional samples CC5B9T and CC6B3B have yielded K-Ar ages of 1452 ± 42 Ma and 1425 ± 40 Ma with an overall mean age of 1438 ± 19 Ma. This mean K-Ar age is indistinguishable from whole rock Rb-Sr isochron as well as mineral isochron age within experimental error. The similarity in the whole rock and biotite ages obtained by different isotopic methods suggests that no thermal disturbance has occurred in these rocks after their emplacement/formation around 1450 Ma ago. The present study provides the evidence for the existence of an important Middle Proterozoic magmatic event around 1400–1450 Ma on the western offshore of India which, hitherto, was thought to be mainly confined to the eastern Ghats, Satpura and Delhi fold belt of India. This finding may have an important bearing on the reconstruction of Proterozoic crustal evolution of western Indian shield.

1. Introduction

The evolution of any sedimentary basin is closely interlinked with global tectonics. The rifting and collision of the lithospheric plates in the geological past have carved the outlines of the tectonic framework and basinal architecture of most of the prolific basins. Basin formation and evolution are generally associated with mantle related geothermal phenomena, which also control the process of generation of hydrocarbons. Since geochemical and isotopic characteristics of the basement rocks provide the finger prints of various paleogeological processes associated with basin formation and evolution, it is necessary to carry out in detail the multi-isotopic studies of the basement rocks.

This paper deals with geochronological studies undertaken on the granitic basement of the Bombay High Field, with a view to understand the Precambrian basement evolution of the western offshore of India. The granulitic basement from well HBM-1 belonging to Heera field of western offshore

Keywords. Rb-Sr/K-Ar dating; basement rocks; granite; Bombay High Field, Mumbai Offshore Basin.

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of India has earlier been dated by Rb-Sr method and found that it has the age of 502 ± 25 Ma (Rathore *et al* 2000). This age has been interpreted as the time of secondary mobilization coinciding with the Pan-African thermal event. The results of Rb-Sr and K-Ar isotopic studies on the basement rocks (whole rocks as well as biotite minerals) of well BH-36, which was drilled on the eastern periphery of the Bombay High near the fault zone, are presented in this paper.

2. Geological setting

The Mumbai Offshore Basin (MOB) covers an area of about 1,20,000 sq. km and is limited to its north by the Saurashtra Arch and to south by the Vengurla Arch (figure 1). The tectonic framework, stratigraphy, structural features and the depositional history of the MOB have been studied in detail by various authors (Rao and Talukdar 1980; Basu *et al* 1982; Biswas 1982; Biswas

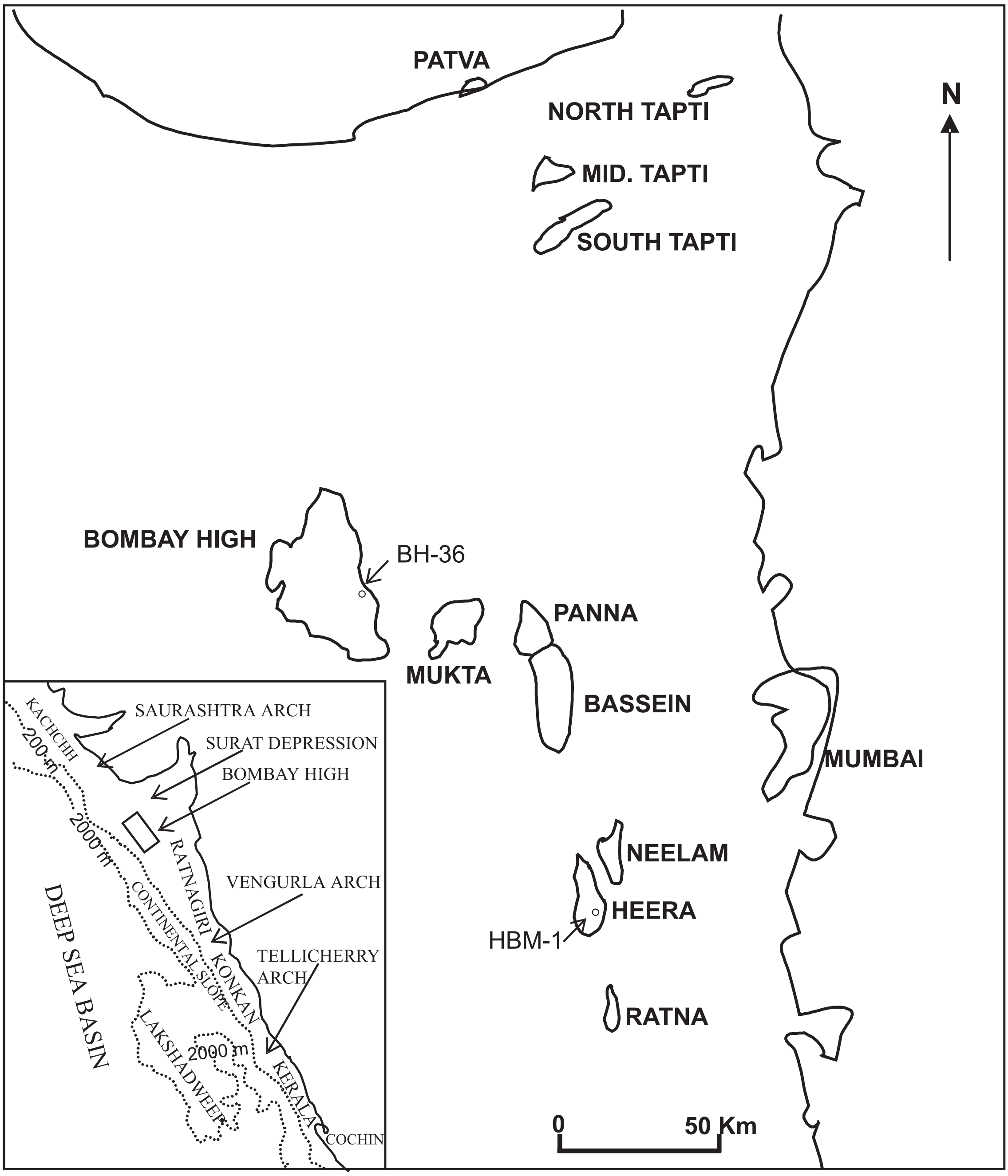

Figure 1. Location map of Mumbai Offshore Basin. Inset shows important features of western offshore along with location of Bombay High which is shown in greater detail in figure 2.

and Deshpande 1983; Biswas 1987). However, little information is available about the nature and age of the basement, which plays an important role in the evolution of structures like horsts, grabens, rifts and regional faults and, therefore, controls the pattern of sedimentation and also at times the thickness of the formation within the basin.

The basement of Bombay High in MOB consists of basalts (Deccan traps) as well as Precambrian rocks. A broad distribution of different basement rock types in the Bombay High is shown in figure 2 (Leviant *et al* 1997). The Precambrian rocks in different parts of the basin are of varied lithology, comprising generally of biotite gneiss, chlorite gneiss, syenite and granodiorite and other schistose rocks. The basaltic basement from wells B-121-1, B-57-10, B-126-10 of the Bombay High Field was dated earlier by Rathore *et al* (1997).

3. Sample details and methodology

Two successive basement cores viz., CC-5 (1890.0–1899.0 m) and CC-6 (1899.0–1901.5 m) were chosen from the well BH-36 for isotopic and chemical studies (figure 2). Major and trace elemental analyses

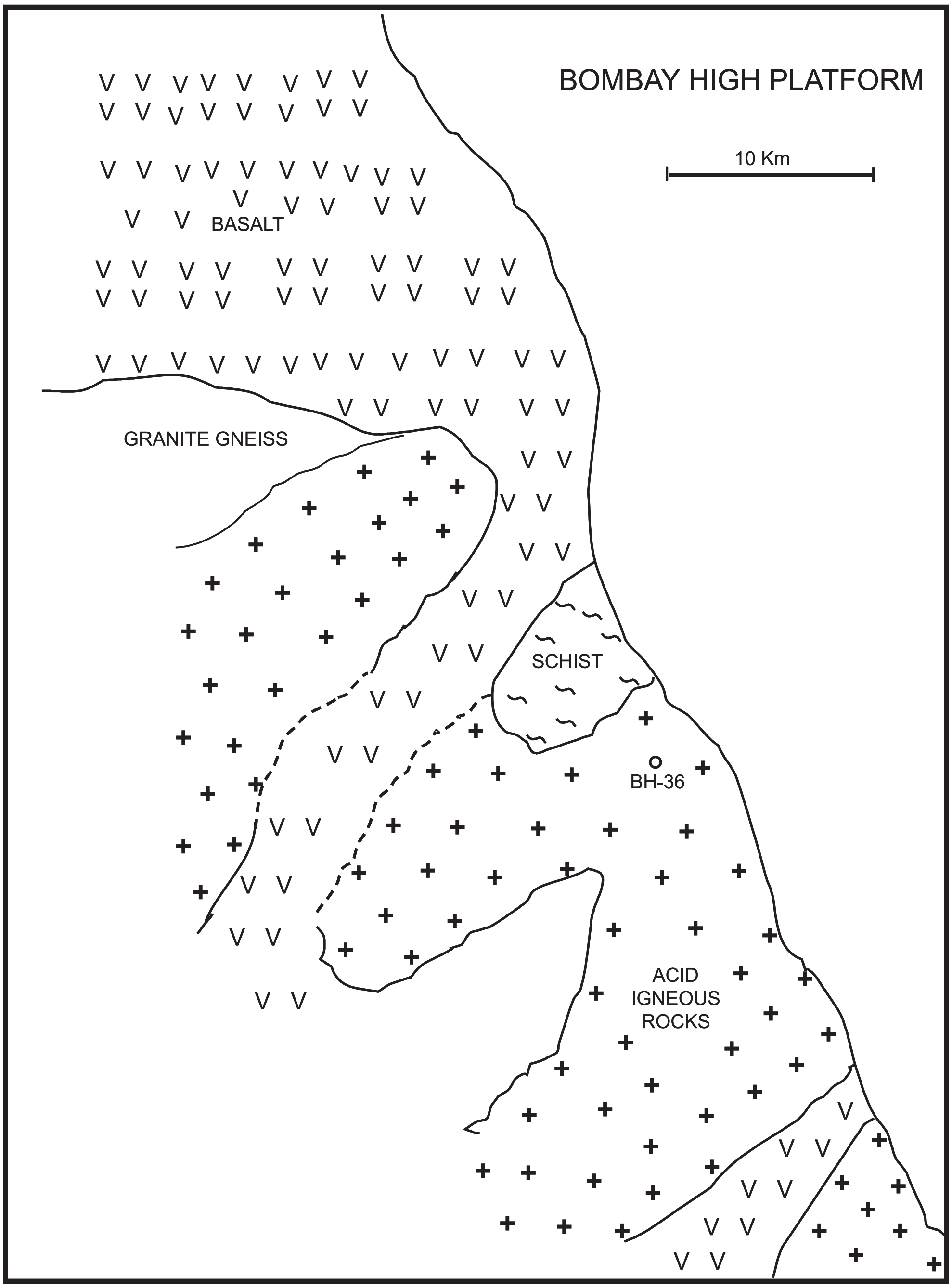

Figure 2. Location of well BH-36 and distribution of basement rock types of Bombay High.

were done on an energy dispersive XRF system at the Wadia Institute of Himalayan Geology (WIHG), Dehradun. The accuracy of major elements was about 3% while that of trace elements was better than 5%.

For Rb-Sr isotopic studies, fresh whole rock samples were processed following the procedures described in detail by Rathore *et al* (1999). Maximum care was taken to prevent any cross contamination. Biotites were separated by crushing and sieving the samples in the range of 40–50 mesh. One sample was sieved into two fractions i.e., 40–50 and 50–70 mesh and were washed and dried at around 50°C in an oven. The clean mineral fractions were then fed into a magnetic barrier separator first at 0.1 A current to remove all the high magnetic materials i.e., magnetite and haematite etc. and then at 0.35 A current to separate the biotite. The biotite fractions, collected from the barrier separator, were further purified using the gravity separation method and were repeatedly washed with acetone to remove the bromoform stains. They were then washed with distilled water followed by acetone in an ultrasonic bath, to remove adsorbed and unwanted chemicals, if any, from the surface of the minerals. The cleaned fractions were then dried at low temperature (50°C). The final purification step involved hand picking of the impurities under microscope to get around 99% pure biotite fraction.

Two sets of about 150–200 mg each of the powdered samples (one unspiked and the other spiked with ^{84}Sr and ^{87}Rb) were weighed and dissolved using a mixture of acids ($HF + HNO_3 + HClO_4$) in pressure digestion bombs at 150°C. The enriched tracers (spike solutions) were added by weight (typically 150–200 mg) before digestion of the samples to ensure complete mixing. Rb and Sr from whole rocks as well as biotite fractions were separated using ion exchange chromatography and their isotopic analyses were carried out on a VG 354 thermal ionization mass spectrometer by peak jumping routine on single collector. The data were processed on an on-line HP 9836 computer. In general, 200 and 60 scans were done for measurement of Sr and Rb isotopic abundances, respectively. The measured $^{87}Sr/^{86}Sr$ ratios were corrected for mass fractionation assuming $^{86}Sr/^{88}Sr = 0.1194$. The mean $^{87}Sr/^{86}Sr$ value of NBS 987 Sr standard measured during this work was 0.710219 ± 0.000058 (2σ).

K-Ar analyses were carried out only on biotite minerals. One aliquot from the biotite fraction was used for K measurement and the other for Ar measurement. K measurements were done by flame photometry. The accuracy of K-measurement was monitored using a glauconite (GL-O) standard (Odin *et al* 1982), and was found to be better than ±1.5%. The amount of ^{40}K was calculated from the known isotopic abundance of K, i.e., $^{40}K/K = 0.0001167$. Argon isotopic analyses were performed on Micromass 1200 noble gas mass spectrometer following the procedure detailed by Rathore *et al* (1993).

4. Results and discussion

4.1 *Petrography*

The basement rock from well BH-36 is coarse-grained, euhedral to sub-hedral and mesocratic. It is predominantly composed of quartz followed by feldspars and biotite. The minor minerals include iron oxides, sphene and zircons etc. Quartz is euhedral to anhedral and occupies the interstitial spaces between feldspars. The feldspars constitute both alkali and plagioclase feldspars. Both microcline and orthoclase feldspars are present. The microcline crystals show well-developed polysynthetic twinning. Perthite (orthoclase and microcline intergrowths) feldspars are also observed. Myrmekite intergrowths are also observed. Most of the plagioclase feldspars are of the oligoclase type with well-developed twinning. The extinction angle on the albite twin law is about 10°. Pronounced bending of the twin lamellae are also observed. At places, the feldspars have been converted into sericite. The quartz grains show at places mild strain effect. The biotite is in tabular and flaky form and shows light green to light brown pleochroism. The biotite grains do not show any preferred orientation indicating that the rock has not been subjected to any later deformation. The biotite grains show sharp edges but in some places show corroded boundary. These grains show perfect cleavages and parallel extinction. In one or two grains, there is a development of phengitic mica along the cleavage planes of biotite. Titanite grains perching over some biotite flakes are also seen. These grains may have developed from the exsolved or liberated titanium from the biotite and may be giving more greenish colour to the biotite. Iron oxides, titanite, zoicite, apatite and zircon etc. are present as accessory minerals and are sparsely distributed throughout the rock. The rock type can in general be defined as granitic.

4.2 *Chemical analysis*

Chemical analysis of a set of representative samples is presented in table 1. Petrographic studies of these samples have suggested granitic nomenclature, which, however, has not convincingly been corroborated by their chemical composition. Silica contents in these rocks are relatively lower than

Table 1. *Major and trace elemental composition of granitic basement from well BH-36.*

Core No. Sample detail	CC-5 B7/9M	CC-5 B9/9T	CC-5 B9/9B	CC-6 B2/3T	CC-6 B3/3T	CC-6 B3/3M	CC-6 B3/3B
SiO_2(%)	60.90	58.74	59.36	57.49	50.82	58.70	57.80
TiO_2	1.42	1.12	1.18	1.35	1.04	0.94	1.40
Al_2O_3	17.16	16.02	16.08	15.64	15.46	15.28	16.13
Fe_2O_3	5.39	5.33	5.30	6.45	7.76	6.13	6.61
CaO	1.72	2.04	1.46	1.25	6.83	1.85	1.73
K_2O	3.12	2.09	2.44	2.74	2.95	1.77	2.41
MgO	1.77	2.63	2.80	4.78	5.68	3.19	3.80
MnO	0.04	0.06	0.06	0.08	0.11	0.07	0.07
Na_2O	5.07	6.71	6.19	6.30	5.81	7.22	6.71
P_2O_5	0.48	0.43	0.42	0.45	0.46	0.36	0.55
Ba (ppm)	1504	843	959	881	674	683	915
Cr	21	37	26	28	30	36	19
Ni	10	13	11	14	14	14	10
Cu	4	11	4	12	5	5	5
Zn	54	64	146	90	84	57	88
Ga	27	24	26	27	27	25	26
Pb	4	4	4	4	6	5	8
Th	18	17	17	18	13	11	21
U	2.5	2.8	2.1	1.4	0.9	1.5	2.0
Rb	72	52	59	79	80	49	68
Sr	194	182	116	101	213	119	164
Y	34	32	27	27	40	29	39
Zr	561	546	430	512	483	463	563
Nb	36	33	32	34	32	29	39
Total (%)	97.06	95.16	95.28	96.54	96.95	95.50	97.20

those expected for the rocks of granitic composition but when the data points are plotted on a Rb-Ba-Sr ternary diagram (Matheis *et al* 1982), they fall within the field of *true granites* (figure 3).

4.3 *Isotopic data*

4.3a *Rb-Sr studies*

Eight whole rock samples collected from two basement cores (CC-5 and CC-6) of well BH-36 were analyzed for Rb-Sr studies. Analytical data are given in table 2. The studied samples are relatively enriched in Sr content (101–213 ppm) compared to Rb which ranges from 51–88 ppm. The dispersion in Rb/Sr ratio among the samples is good ranging from 0.32 to 0.79. All the errors have been quoted at 2σ level and the errors on $^{87}Rb/^{86}Sr$ ratios have been taken as 2%. The analytical data were regressed as per the scheme of Provost (1990). These data points were plotted on an Sr evolution diagram, then they defined the best fit line corresponding to an age of 1461 ± 79 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7062 ± 0.0014 and MSWD of 3.1, suggesting a slight scatter of these points. In the absence of sample CC6B3M in calculation, the other seven samples define an isochron with an age 1446 ± 67 Ma (figure 4) with an initial Sr ratio of 0.7062 ± 0.0012. The age and initial Sr ratio, thus obtained, are not different from the earlier regression, when the sample CC6B3M was included, except that MSWD in the latter case reduces to 2.27 from 3.1, thereby, suggesting closer fitting of the data points. This exercise, thus suggests that the basement rocks of well BH-36 were emplaced around 1450 Ma ago. The initial Sr ratio of the studied samples suggests crustal derivation of the magma.

Two biotite fractions, viz., 40–50 mesh and 50–70 mesh, separated from whole rock sample

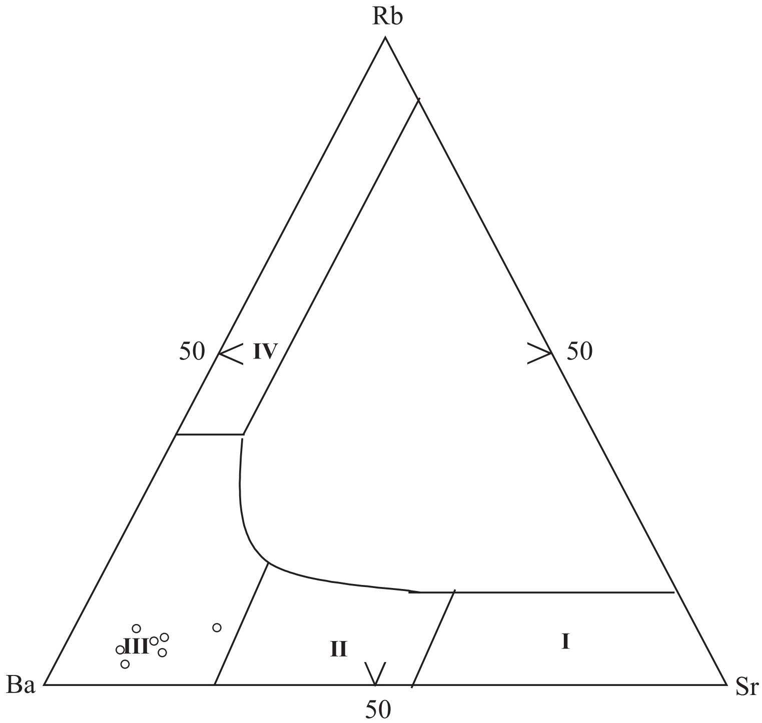

Figure 3. Rb-Sr-Ba triangular diagram; **I**–Diorites, **II**–Diorites and granodiorites, **III**–Normal granites, **IV**–Strongly differentiated granites (after Matheis *et al* 1982).

Table 2. *Rb/Sr analytical data of basement rocks (whole rock and biotite) of well BH-36.*

Sl. No	Sample no.	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$ (atomic)	$^{87}Sr/^{86}Sr \pm 2\sigma$
1	CC6B3T (538)	79.78	213.16	1.085	0.728639 ± 44
2	CC6B2T (535)	79.57	100.75	2.295	0.752677 ± 45
3	CC5B9T (512)	51.55	161.65	0.925	0.725061 ± 44
4	CC5B9B (511)	59.38	115.98	1.486	0.737741 ± 74
5	CC5B7T (510)	88.72	198.05	1.299	0.734017 ± 44
6	CC6B3B (536)	70.16	142.61	1.428	0.736596 ± 103
7	CC5B7M (509)	70.56	190.94	1.072	0.728177 ± 64
8	CC6B3M^x (537)	50.89	120.41	1.226	0.733106 ± 132
9	Biotite-A	504.28	31.94	45.765	1.609736 ± 128
10	Biotite-B	520.92	53.28	29.939	1.30388 ± 104

Note: Biotites separated from whole rock sample CC6B2T and are of different size A: 40–50 mesh and B: 50–70 mesh.
^{x}Not included in calculation.

CC6B2T were also analyzed for Rb-Sr isotopic studies (table 2). The highly radiogenic biotite fractions along with their whole rock yields an isochron age of 1385 ± 21 Ma (figure 5) with an initial Sr ratio of 0.7061 ± 0.0012. MSWD of the fit is excellent at 0.16. The isochron age obtained from whole rock-biotite pair is apparently lower than the whole rock isochron age but within 2σ uncertainty both the ages are indistinguishable. The concordance of these ages can be taken as an evidence for the existence of a common starting isotopic composition both on whole rock and mineral scale close to 1450 Ma ago. We can, therefore, combine the seven whole rocks and two biotite fractions in the regression and when this is done, a precise internal isochron, corresponding to an age of 1394 ± 25 Ma (figure 6), Sr_i of 0.70712 ± 0.00051 and MSWD of 1.9, is obtained.

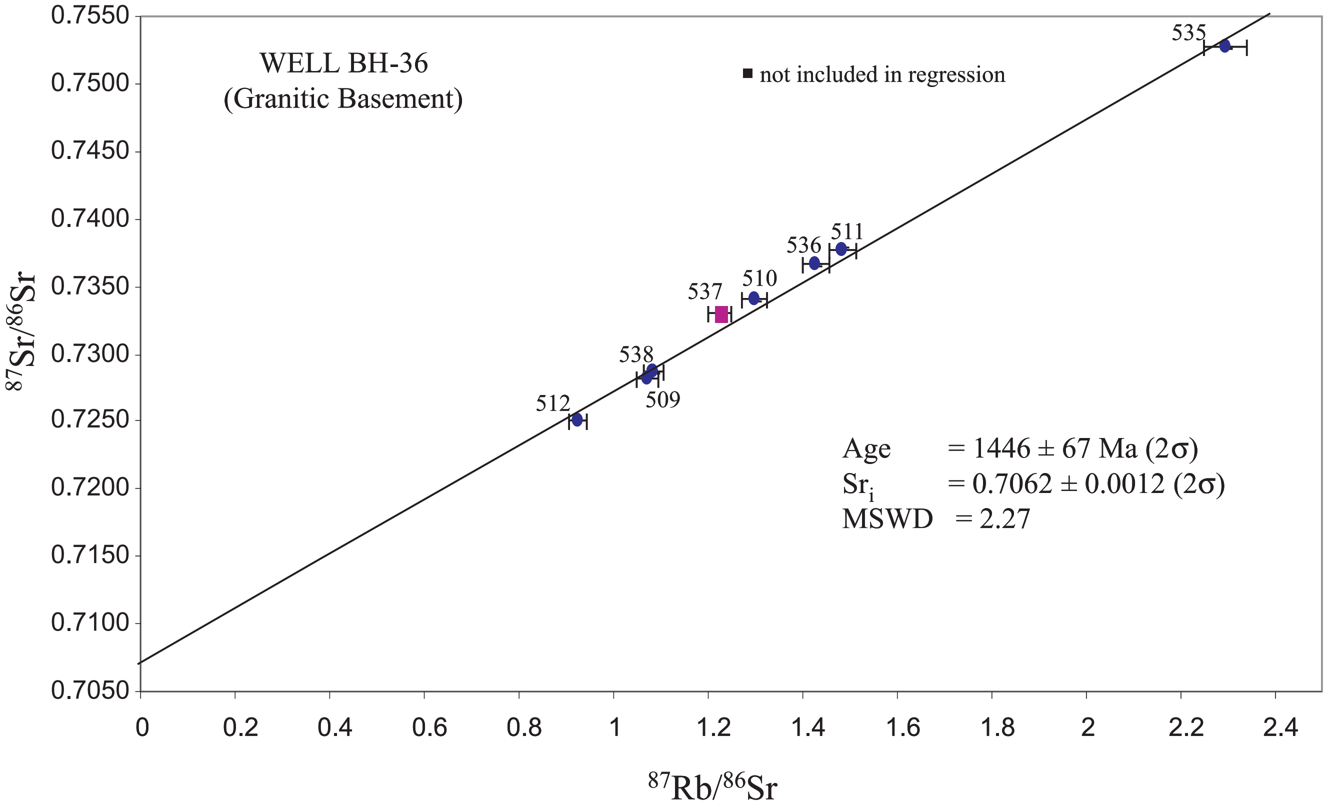

Figure 4. Rb-Sr whole rock isochron diagram of granitic basement from well BH-36.

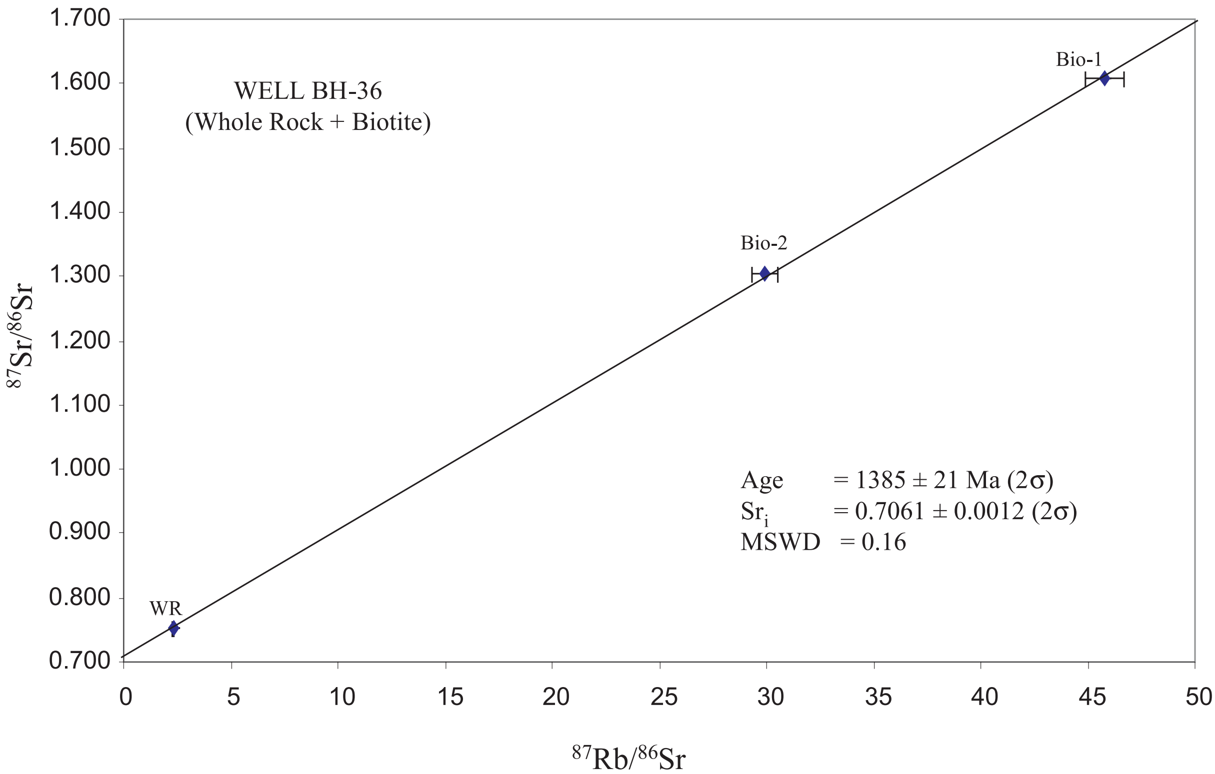

Figure 5. Rb-Sr mineral isochron of well BH-36.

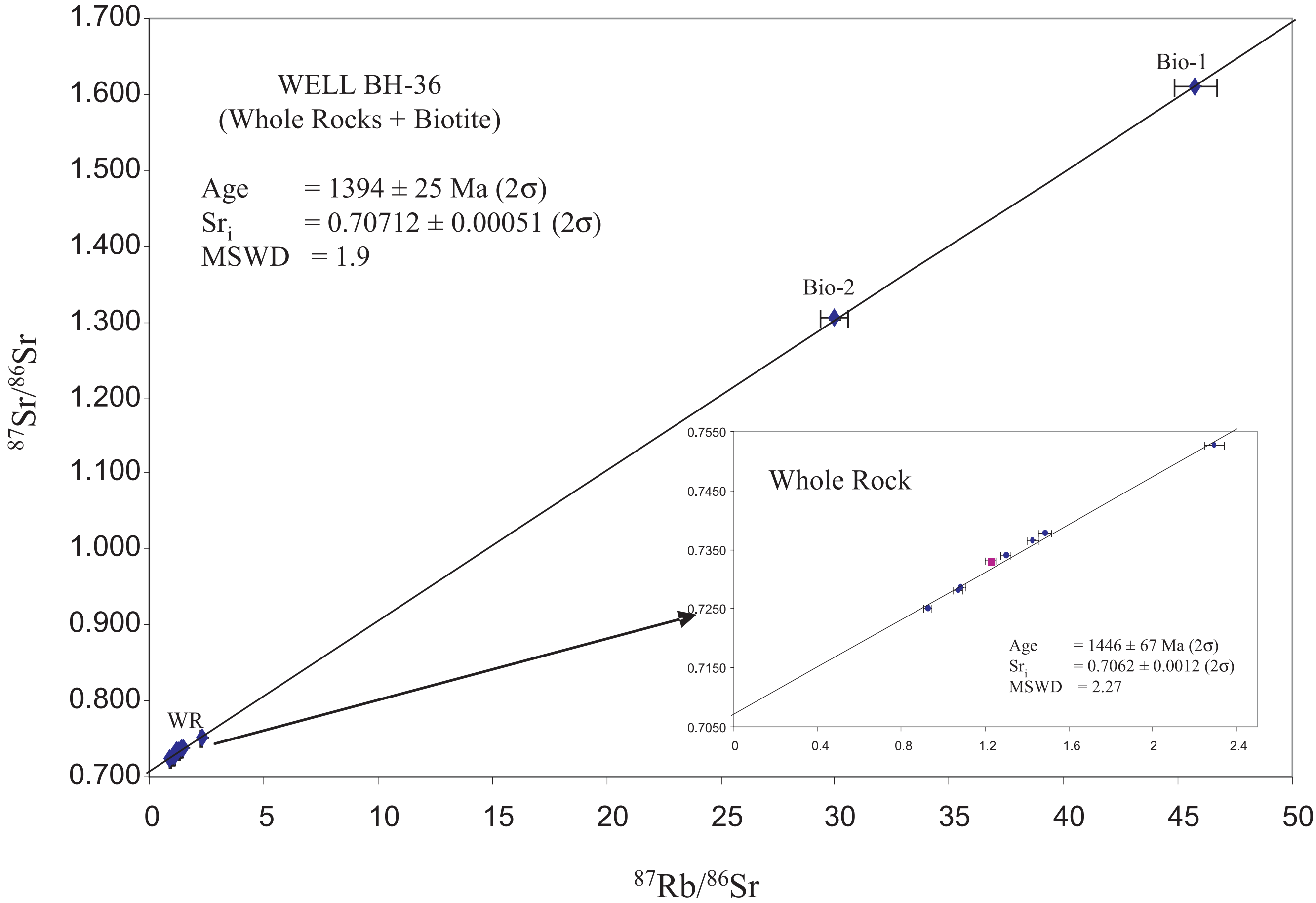

Figure 6. Rb-Sr isochron of whole rocks–biotites of well BH-36.

Table 3. *Analytical data and calculated K–Ar ages of biotite separates from basement rocks of well BH-36.*

Sl. No.	Sample details	K (wt. %)	Total^{40}Ar (x 10^{-6} cc STP. g^{-1})	Rad^{40}Ar (x 10^{-6} cc STP. g^{-1})	Age($\pm 2\sigma$) Ma
1	CC5B9T	6.80	603.858	589.671	1452 ± 42
2	CC6B2T (40–50 mesh)	7.94	735.794	692.654	1458 ± 43
3	CC6B2T (40–50 mesh)[d]	7.94	665.735	647.496	1392 ± 40
4	CC6B2T (50–70 mesh)	7.68	682.939	674.381	1465 ± 43
5	CC6B3B	7.90	699.833	666.597	1425 ± 40
6	GL-O[#]	6.46	31.419	24.679	95.71 ± 2.91

[#]Glauconite standard with a reported age of 95.03 ± 1.11 Ma (Odin *et al* 1982).
[d]Duplicate analysis.

4.3b *K-Ar studies*

K-Ar studies were carried out on biotite minerals separated from different rock samples to see the effect of thermal heating on K-Ar systematics subsequent to their formation. The biotites were separated from three samples viz., CC5B9T, CC6B2T and CC6B3B. Out of these, from one of the samples i.e., CC6B2T, two size fractions (40–50 mesh and 50–70 mesh) were separated to check the effect of grain size on K content as well as its age. The analytical data are given in table 3. The study indicates that the coarser fraction, i.e., 40–50 mesh, is relatively enriched in K content (7.94%) compared to the finer fraction (50–70 mesh), which has K content of 7.68% (table 3). However, it is very interesting to note that both the fractions have yielded mutually consistent K-Ar ages of 1458 ± 43 Ma and

1465 ± 43 Ma, respectively, which indicates that there is no effect of grain size on age determination. Two other biotites, separated from the samples CC5B9T and CC6B3B, have given K-Ar ages of 1452 ± 42 Ma and 1425 ± 40 Ma (table 3), respectively. K-Ar age standard (GL-O) was also analyzed along with the samples to check accuracy of the measurements. The age standard has yielded a K-Ar age of 95.71 ± 2.91 Ma as against its reported age of 95.03 ± 1.11 Ma (Odin *et al* 1982).

The present study suggests that the biotites separated from different samples have yielded concordant ages within 2σ errors, with a mean age of 1438 ± 19 Ma. This mean biotite K-Ar age is indistinguishable from that obtained by whole rock Rb-Sr isochron method (1446 ± 67 Ma) within the experimental error. The similarity in the whole rock and biotite ages obtained by different isotopic methods as well as whole rock-biotite pair by Rb-Sr method suggests that no thermal disturbance has occurred in these rocks after their emplacement/formation around 1450 Ma ago.

Isotopic ages around ca.1400–1500 Ma of rock samples obtained from the Indian subcontinent are very scanty. The middle Proterozoic alkaline magmatic event in Rajasthan has been represented by nepheline-syenites from Kishangarh which have been dated at 1480 ± 50 Ma (Crawford 1970). Sinha Roy (1984) attributed emplacement of these syenites to initiation of continental rifting leading to formation of north Delhi trough. Balasubrahmanyam and Chandy (1976) have obtained mineralization age of 1440 ± 70 Ma for galena from the Zawar mines in southern Rajasthan. Choudhary *et al* (1984) have obtained formation ages of syntectonic granites from Alwar basin of northern part of Rajasthan in the time band of 1500–1600 Ma. Sarkar *et al* (1981) reported an isochron age of 1404 ± 89 Ma with an initial Sr ratio of 0.70661 ± 0.00022 for anorthosites belonging to Chilka Lake Igneous Complex of Orissa. The initial Sr ratio of 0.70661 implies limited hybridization of the parent magma prior to emplacement. Pandey *et al* (1986) have obtained Rb-Sr isochron age of 1420 ± 17 Ma with an initial Sr ratio of 0.7393 ± 0.0011 for the soda granites from Singhbhum shear zone of Bihar. The high initial ratio indicates substantial involvement of older sialic material suggesting formation of soda granites through remobilization of the preexisting crust most probably through the metasomatic processes. Recently Chalapathi Rao *et al* (1999) have suggested an episode of mafic potassic magmatic activity in the Cuddapah basin at ca. 1400 Ma based on precise Ar-Ar age determination on Kimberlite and Chelima Lamproite.

With increasing availability of data, the 1400 ± 100 Ma magmatic event is becoming widespread and significant. The present study provides the first indication of existence of this important magmatic event around 1400–1450 Ma from the western offshore of India. The Rb-Sr isotopic studies (Rathore *et al* 2000) on granulitic basement from well HBM-1 of Heera field, which is more akin to Dharwarian protocontinent, has indicated the presence of secondary thermal event around 500 Ma in this part of the basin. This ca. 500 Ma, thermal event has been interpreted as the time of secondary isotopic mobilization which has coincided with the wide spread Pan-African thermo tectonic event spreading from the Arabian peninsula to eastern Africa covering Madagascar, southern India, Sri Lanka and east Antarctica (Key *et al* 1989; Burton and O'Nions 1990; Stern 1994; Shiraishi *et al* 1994).

However, such thermal disturbance has not been observed in the basement rocks of the region further northwest in Bombay high (figure 1) as evidenced by multi-isotopic (Rb-Sr and K-Ar) studies on whole rocks as well as mineral separates of well BH-36. This change in isotopic behavior of basement rocks from these regions coupled with possible linkage of Bombay high with Middle Proterozoic Mobile Belt of Delhi, Satpura and eastern Ghats suggests that these fields may in all probability be representing different entities, with different geological histories, which might have got juxtaposed together to form the western offshore. However, this enunciation, based on isotopic studies alone on limited wells/samples, may be far fetched and needs to be substantiated by further isotopic studies from a few more wells of different fields of western offshore of India as well as by other geophysical studies.

5. Conclusions

The granitic basement from well BH-36 of Bombay high field has given a well-defined Middle Proterozoic whole rock Rb-Sr isochron age of 1446 ± 67 Ma. Concordant mineral Rb-Sr age, obtained from biotite fractions of different mesh size, indicates a common starting isotopic composition both on whole rock and mineral scale close to 1450 Ma ago.

K-Ar studies carried out on biotites separated from different samples, including different mesh size fractions used in Rb-Sr studies, have yielded mutually consistent ages with a mean of 1438 ± 19 Ma. This average K-Ar biotite age is indistinguishable from that obtained by whole rock Rb-Sr isochron method (1446 ± 67 Ma) within the experimental error. The similarity in the whole rock and biotite ages obtained by different isotopic methods as well as whole rock-biotite pair by Rb-Sr method suggests that no thermal disturbance has occurred in these rocks after their emplacement/formation around 1450 Ma ago. The present study provides the first indication of existence of an important Middle Proterozoic magmatic event around 1400–1450 Ma from the basement encountered in the Bombay High Field, similar to those evidenced in the Middle Proterozoic Mobile Belts (MPMB) of eastern Ghats, Satpura and Delhi. This finding extends the limit of the MPMB to the western offshore and may have an important bearing on the reconstruction of Proterozoic crustal evolution of western Indian shield.

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