^{10}Be and Al concentrations in an Arctic core: Implications to climate and sedimentation

B. L. K. Somayajulu, P. Sharma* and A. S. Naidu**

Physical Research Laboratory, Ahmedabad 380 009, India
*PRIME Lab, Physics Department, Purdue University, West Lafayette, IN47907, USA
**Institute of Marine Sciences, University of Alaska, Fairbanks, AK 99701, USA

The ^{10}Be/Al ratio in a gravity core from the Arctic ocean is shown to depend on the late Pleistocene palaeoclimate and its variation in turn can be used to obtain the sedimentation rate of the core. In meltwater-dominated regions of limited productivity of the world oceans, ^{10}Be/Al ratio in stratigraphic samples can serve, like δ^{18}O in productive areas, to decipher glacial–interglacial sequences.

THE Arctic is a particularly challenging deep ocean region for studying palaeoclimates and palaeoceanography[1–3]. It has a perennial ice cover which averages ~ 4 m in thickness with a present seasonal variation of ~ 10%. Palaeontological, sedimentological and stable oxygen isotope studies have identified time intervals when the Arctic was devoid of ice cap[4]. Since the presence of ice cover limits primary production (photosynthesis), biological processes are generally less intense in the Arctic, especially during glacial stages. This is reflected either by the absence or presence in small amounts of biological skeletal material, e.g. $CaCO_3$, opal and organic carbon. As such it is difficult to decipher in the Arctic the glacial/interglacial events using conventional palaeontological and stable isotope (δ^{18}O) stratigraphic data. Another problem concerning palaeogeographic investigations in the Arctic is related to the establishment of geochronology.

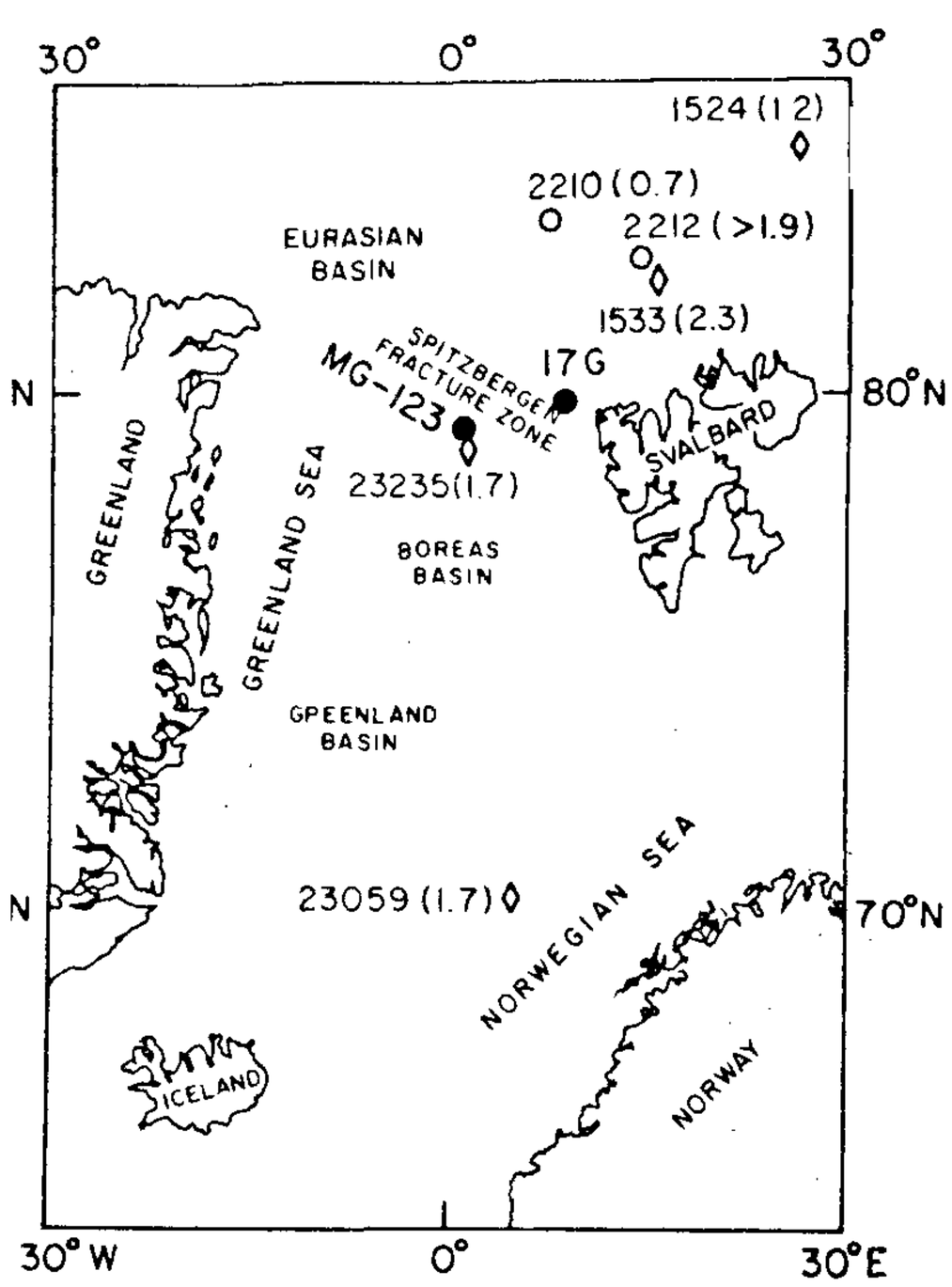
Since thorium-230 (half life = 75,200 yr) the granddaughter of primordial uranium-238 is present in relatively small concentrations in the Arctic sediments, it is difficult to establish geochronology using this nuclide which is commonly employed in other world ocean sediments[5–7]. Further, lack of substantial amounts of carbon (in inorganic or organic form) for conventional ^{14}C (half life = 5730 yr) dating has put serious constraints in developing the chronology of Arctic sediments until the recent development of the Accelerator Mass Spectrometry (AMS) technique to measure long lived cosmogenic radioisotopes (including ^{14}C) with very high sensitivity compared to the conventional techniques[8]. Attempts to use the technique of magnetic reversals[9] and the racemization of amino acid[10] have met with limited success; the data generated by the former technique in the Arctic was even questioned[11].

It has been suggested that cosmogenic ^{10}Be (half life = 1.5 m.y.) in sediments can be a proxy to detect meltwater spikes[12] and one way to confirm/establish the applicability of this method, would be to simultaneously measure ^{10}Be and δ^{18}O in planktonic foraminifera from the same sections of a sediment core[13]. It is implicit, in such a study, that other causes, viz. magnetic and cosmic ray intensity variations would not have contributed to ^{10}Be variation significantly[12]. A significant negative correlation was seen between ^{10}Be and δ^{18}O in a core collected in the Orca basin from the Gulf of Mexico[13], lending support to the contention that it could be useful in palaeoclimatic/palaeoceanographic studies. It appears likely that in marine sediments normalization of ^{10}Be to Al (rather than only ^{10}Be) will be preferable as the ratio is independent of any variations in the sedimentation rates and lithology of the core. Based on measurements of δ^{18}O and ^{10}Be in some Arctic sediments, it was shown recently that ^{10}Be contents of interglacial sediments are relatively higher than glacial ones[15]. We report here the results of ^{10}Be and Al measurements in six sections of gravity core 17G (~ 2.2 m long raised from 916 m water depth from eastern Arctic, north of Svalbard, location: 80°35′N; 10°04′E, Figure 1).

The $CaCO_3$ concentrations are very low (mostly < 5% in 17G – ref. 16), reflecting the presence of few calcareous fossils. Consequently, δ^{18}O stratigraphic measurements throughout the core were not possible. The magnetic reversal technique had only shown that the core deposition occurred during the late Pleistocene[9]. For comparing the ^{10}Be/Al with changing palaeoclimatic information, we have used, as proxy, the δ^{18}O data on core MG 123 (ref. 21) which was collected from a location adjacent to that of 17G (Figure 1).

Based on the available lithological and palaeontological information[16], six sections (from UNITS 1–5, Figure 2) from core 17G, representing glacial–interglacial stages with the late Pleistocene, were chosen for ^{10}Be studies. About 50 g dried (at 110°C) and powdered sediment from each section was brought into solution by HCl, HF and H_2SO_4 treatments in presence of stable Be carrier (equivalent to 25 mg BeO) and the radiochemically pure BeO was beta assayed in a sensitive low background flow-gas type GM counter[17]. The ^{10}Be beta counting rates were found to be small (few cph) to be accurately measured by this technique. Such low-counting rates were also observed by Finkel *et al.*[18] who first attempted ^{10}Be measurements on Arctic sediments. After eliminating boron by HF treatment, the BeO samples were sent to Zurich where the ^{10}Be/^{9}Be ratios were measured on the ETH-EN tendem accelerator[19]. A reagent blank was also run along with the samples. The Al in the same sections was measured by Atomic Absorption Spectrophotometry[20]. The measured ^{10}Be and Al concentrations along with the ^{10}Be/Al ratios are given in Table 1. Since the reagent blank has about three orders of mag-

de smaller ^{10}Be compared to the samples, no blank ection is required. The ^{10}Be/Al data are plotted as nction of depth in the core in Figure 2. Evidently, ^{10}Be/Al shows the expected variations when compared ı those of δ^{18}O as indicated by low values of ^{10}Be/Al sections corresponding to glacials (oxygen isotope es 2 and 5b) and higher values in interglacial sections



e 1. Map showing core locations in the Arctic Ocean. Core 17 ed in the present study and stable isotope data from core MG (ref. 21) are used for comparison (both cores are denoted by circles). Sedimentation rates (cm/10^3 yr) are given in parenthesis. data: open diamonds from ref. 15 and open circles from ref.

(isotope stages, 1, 3.3 and 5e) (Table 1, Figure 2). The ^{10}Be/Al during the Holocene (UNIT 1) is high and the value reaches a minimum, viz. 3.17×10^9 atom/g during LGM which corresponds to Unit II where no calcareous fossils are present. Most likely, the lack of fossils in the LGM section is due to depressed productivity because of more extensive ice cover in the Arctic. The ^{10}Be/Al then increases to 5.29×10^9 in UNIT 3 to 6.62×10^9 atoms/g in UNIT 4, both these increases correspond to the δ^{18}O decreases in core MG 123 (Figure 2). The UNIT 5 covers about 100 cm of core 17G which in principle should cover the various stages of the last major interglacial which peaked at 122 kyr BP (transition 5e). The ^{10}Be/Al ratio of 4.90×10^9 atoms/g may correspond to isotope stage 5b. Since the core is only ~2 m long, it could not have extended back to stage 5e which dates to 122 kyr BP but close to it as evidenced by the high ^{10}Be/Al ratio 9.84×10^9 atom/g in the bottommost sample.

To make this comparison, it is necessary to show that causes other than climate have not been responsible to a significant extent for the downcore ^{10}Be variations. The two important causes are the magnetic field intensity and cosmic ray intensity variations. From the available data[9,22], these are < 25% and climate (i.e. meltwater input during interglacials) appears to be the major cause in the study area (Figure 1). In a recent paper[23], it is shown that the ^{10}Be/^{9}Be ratio increased by ~55% only at 40–50 kyr BP when the magnetic field intensity was low. This core was collected from 38°N in the Atlantic. At polar latitudes, such increases will be lower. Sample No. 3 of core 17G represents this period and some of the high ^{10}Be can be attributed to such an effect.

Since the ^{10}Be/Al variations correspond to the isotopic stages 2, 3 and 5 which in turn act as proxy to palaeoclimate, it is possible to deduce 'ages' for the different levels in core 17G and estimate temporal changes in its sedimentation rate [from ^{10}Be data of core 17G in conjunction with the δ^{18}O stratigraphy of the nieghbouring core MG 123 (Figure 1), it ranges

Table 1. ^{10}Be and Al in Arctic core 17G

Sample No.	Sample depth (cm)	Al* (%)	Measured ^{10}Be/^{9}Be ($\times 10^{-11}$)	^{10}Be (10^8 atoms/g.sed)	^{10}Be/Al (10^9 atoms/g)
1	19–25	7.64	3.99 ± 0.08	5.07 ± 0.10	6.64 ± 0.36
2	39–42	7.76	1.13 ± 0.03	2.46 ± 0.07	3.17 ± 0.18
3	74–79	7.67	3.47 ± 0.05	4.06 ± 0.06	5.29 ± 0.27
4	94–98.5	7.67	4.21 ± 0.07	5.08 ± 0.08	6.62 × 0.34
5	147–152	7.67	3.49 ± 0.07	3.76 ± 0.08	4.92 ± 0.26
6	203–211	7.46	9.48 ± 0.10	7.34 ± 0.08	9.84 ± 0.50
	Blank	–	$(5.94 \pm 0.45) \times 10^{-14}$	–	–

*Uncertainties in Al measurements are ± 5%.

Table 2. Glacial–interglacial stages and sedimentation rates deduced for core 17G using $\delta^{18}O$, $^{10}Be/Al$ and lithostratigraphy*

Isotopic stage using $\delta^{18}O$†	Litho-stratigraphic unit**	$^{10}Be/Al$ (10^9 atoms/g)	Mean sample depth (cm)	Assigned age‡ (10^3 yr)	Sedimentation rate (cm/10^3 yr)
2	2	3.17	40	19	2.1
3.3	3/4	6.62	96	53	1.8
5.2	5	4.92	150	87	1.7
5.5(?)	5	9.84	207	122	1.7

*See Table 1 and Figure 2 for details.
†Data from neighbouring core MG 123. Stages are assigned using stack data[25].
**ref. 16.
‡ref. 21.
(?) Since this is the near-bottom sample, the deduced sedimentation rate is a lower limit.

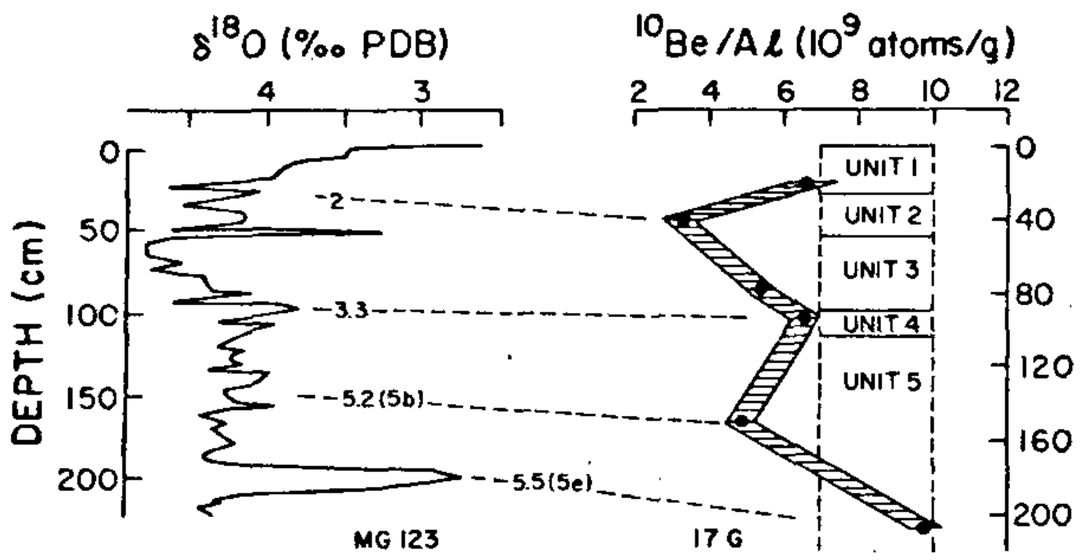


Figure 2. $^{10}Be/Al$ ratio as a function of depth in core 17G (for details on lithological units, see ref. 16) and its comparison with $\delta^{18}O$ curve of core MG 123 (ref. 21). Isotope stages 2–5.5 are based on stack data[24].

from 1.7 to 2.1 cm/10^3 yr (Table 2)]. The sedimentation rate remained almost uniform at 1.7 to 1.8 cm/10^3 yr until the last LGM, i.e. 19×10^3 yr BP and increased to 2.1 cm/10^3 yr since then. These rates fall in the range 0.35 to 4.3 cm/10^3 yr, recently reported for the Nordic seas and the eastern Arctic[15,24] (Figure 1) using ^{14}C, $\delta^{18}O$ and ^{230}Th excess techniques. In this connection, it should be noted that there is a controversy on the deposition rates in the deep Arctic basins. Earlier studies that were mostly confined to the western Arctic yielded sedimentation rates which are a factor of 5–10 slower[3,6,7]. It thus appears that $^{10}Be/Al$ ratio depends on the climate in the Arctic sediments and it can be used to derive sedimentation rates like for example $\delta^{18}O$. It should be emphasized, however, that this is only a preliminary study. More cores from meltwater-affected areas would have to be analysed for $^{10}Be/Al$ and $\delta^{18}O$. In oceanic areas like in the Arctic where biological productivity is generally low in many parts, the $^{10}Be/Al$ profile will be promising in ascertaining the sedimentation rates.

The present study has indicated that both ^{10}Be and $^{10}Be/Al$ are equally sensitive to distinguish glacial–interglacial stages in the Arctic based on which sedimentation rates can be derived. In areas where significant variations in the clay contents (as indicated by Al concentrations) occur $^{10}Be/Al$ ratio is more sensitive[14].

1. Hunkins, K., Be, A. W. H., Opdyke, N. D. and Mathieu, G., in *Late Cenozoic Glacial Ages* (ed. Turekian, K. K.), Yale Univ. Press, 1971, pp. 215–237.
2. Herman, Y. (ed.), *The Arctic Seas, Climatology, Oceanography, Geology and Biology*, Van Nostrand Reinhold, New York, 1989.
3. Clark, D. L., *Can. Soc. Pet. Geol. Memoir*, 1975, **41**, 501–524.
4. Worsley, T. K. and Herman, Y., *Science*, 1980, **210**, 323–325.
5. Goldberg, E. D. and Koide, M., *Geochim. Cosmochim. Acta*, 1962, **26**, 417–450.
6. Ku, T. L. and Broecker, W. S., in *Progress in Oceanography* (ed. Sears, M.), Pergamon Press, London, vol. 4, pp. 95–103.
7. Somayajulu, B. L. K., Sharma, P. and Herman, Y., in *The Arctic Seas* (ed. Herman, Y.), Van Nostrand Reinhold, New York, 1989, pp. 571–579.
8. Clark, D. L., Andree, M., Broecker, W. S., Mix, A. C., Hofman, H. J., Morenzoni, E., Nessi, M., Suter, M. and Wolfli, W., *Geophys. Res. Lett.*, 1986, **13**, 319–321.
9. Lovlie, R., Markussen, B., Sejrup, H. P. and Thiede, J., *Phys. Earth Planet. Interiors*, 1986, **43**, 173–184.
10. Sejrup, H. P., Miller, G. H., Brigham-Grette, J., Lovile, R. and Hopkins, D., *Nature*, 1984, **310**, 772–775.
11. Darby, D. A., Naidu, A. S., Mowatt, T. C. and Jones, G., in *The Arctic Seas* (ed. Herman, Y.), Van Nostrand Reinhold, New York, 1989, pp. 657–720.
12. Somayajulu, B. L. K., *Geochim. Cosmochim. Acta*, 1977, **41**, 909–913.
13. Somayajulu, B. L. K., Sharma, P., Klein, J., Middleton, R., Williams, D. F. and Moore, W. S., *Chem. Geol. (Isotope Geosci. Sec.)*, 1991, **107**, 253–258.
14. Somayajulu, B. L. K., Paleoceanographic Studies, Abstract, 5th International Conference on Paleoceanography, Oct. 10–14, Halifax, Canada, 1995, p. 70.
15. Eisenhauer, A., Spielhagen, R. F., Frank, M., Hentzschel, G., Mangini, A., Kubik, P. W., Dittrich-Hannen, B. and Billen, T., *Earth Planet. Sci. Lett.*, 1994, **124**, 171–184.
16. Markussen, B., Late Quaternary sedimentation and paleoceanography in the eastern Arctic Ocean, Ph D thesis, University of Oslo, Norway, 1986, pp. 175.
17. Sharma,. P., Implications of beryllium-10 measurements in marine sediments and ferromanganese nodules, Ph D thesis, Gujarat Univ., 1982, pp. 196.

18. Finkel, R., Krishnaswami, S. and Clark, D. L., *Earth Planet. Sci. Lett.*, 1977, **35**, 199–200.
19. Wolfli, W., Bonani, G., Suter, M., Balzer, R., Nessi, M., Stoller, Ch., Beer, J., Oeschger, H. and Andre, M., *Radiocarbon*, 1983, **25**, 745–753.
20. Sarin, M. M., Borole, D. V. and Krishnaswami, S., *Proc. Indian Acad. Sci.*, 1979, **A88**, 131–154.
21. Marquard, R. S. and Clark, D. L., *Mar. Micropaleonol.*, 1987, **12**, 325–341.
22. Sharma, P., Bhattacharya, S. K. and Somayajulu, B. L. K., Proceedings of the 18th International Conference (Bangalore, India), 1983, vol. 2, pp. 337–340.
23. Robinson, C., Raisbeck, G. M., Yiou, F., Lehman, B. and Laj, C., *Earth Planet. Sci. Lett.*, 1995, **136**, 551–557.
24. Imbrie, J., Hays, J. D., Martinson, D. G., McIntyre, A., Mix, A., Morley, J. J., Pisias, N. G., Prell, W. L. and Shackleton, N. J., in *Milankovich and Climate* (ed. Berger, A. L.), D. Reidel Publishing Co., 1984, Part-II, pp. 269–305.
25. Stein, R., Schubert, C., Vogt, C. and Futterer, D., *Mar. Geol.*, 1994, **119**, 333–355.

ACKNOWLEDGEMENTS. We thank Dr Berit Markussen and Prof. J. Thiede of the University of Oslo, Norway (presently at University of Kiel, Germany) for providing us the samples from the Arctic core 17G and Dr W. Wolfli of the Institut fur Mittelenergrephysik, Zurich, Switzerland and his associates for the AMS measurements.

Received 11 March 1996; revised accepted 6 April 1996

CO_2-rich fluid inclusions in granulites from Bandanwara area, Rajasthan

R. L. Somani and Pankaj K. Srivastava

Department of Geology, University of Rajasthan, Jaipur 302 004, India

Fluid inclusion studies in acid granulite from Bandanwara area indicate densities from 0.96 to 1.04 gm/cc for the primary and 0.81 to 0.87 gm/cc for the secondary CO_2 inclusions. The CO_2 isochores for the primary inclusions are passing through the mineralogical P–T box, suggesting synmetamorphic nature of the fluid trapped. The secondary inclusions are trapped during the later phase of metamorphism.

GRANULITE facies rocks in Western Indian Shield are a part of Banded Gneissic Complex (BGC)[1]. These rocks reported from Bhim-Karera[2], Bandanwara[3], Chinwali[4] and Sandmata[5] areas form discontinuous exposures (Figure 1, inset map). The rocks of granulite facies in Bandanwara area are exposed around Bandanwara village (26°8′:74°42′), 43 km south of Ajmer in Central Rajasthan.

Medium to high density CO_2-rich fluid inclusions in different minerals are characteristics of the granulite terrain all over the world[6–9]. It is suggested that the dehydration processes in the deeper continental crust were largely controlled by the action of carbonic fluids as implied by the terms 'metamorphism en milieu carbonique'[6] and 'carbonic metamorphism'[7]. This observation is consistent with the low-water activities predicted by the mineral phase equilibria in the granulite facies rocks. In most of the cases, the densities of the trapped CO_2 indicate close correspondence with respect to P–T conditions estimated from mineral phase equilibria. However the origin of this fluid and its role in the genesis of granulite is still debated.

In India, fluid inclusion studies for understanding the genesis of granulitic rocks have been extensively applied in granulites of Southern India[9,10], but no such attempts have yet been made on the granulite terrain of Rajasthan. Here we report the preliminary results of fluid inclusion study in the granulite terrain of Bandanwara area.

The high-grade metamorphic rocks exposed in the Bandanwara region belong to Banded Gneissic Complex[11] (Figure 1). The area forms a part of North-Eastern limb of the 'V'-shaped outcrop of BGC in the east of NE–SW trending axis of Delhi synclinorium[3]. The rocks in the area constitute migmatite gneiss, migmatite, granulite, enderbite, amphibolite, pelitic schist and calc-silicate rocks.

The granulite present in the area may be broadly divided into acid granulite, basic granulite and migmatized granulite. The acid granulites are exposed in vast area, forming continuous hills and are mainly quartz-feldspathic. The basic granulites occur in limited area as low-lying thin horizons. At places basic granulites

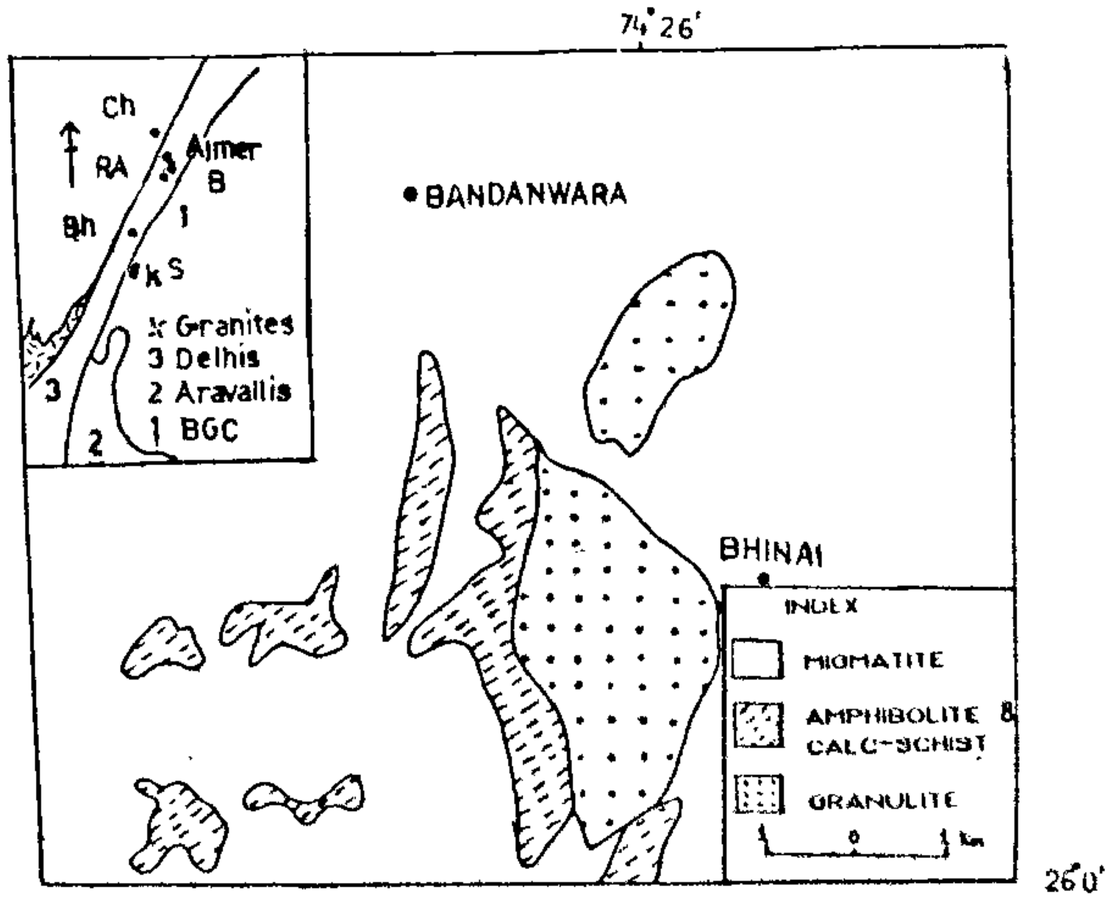


Figure 1. Geological map of the Bandanwara area (modified after Gyani[3]). The inset map, simplified after Heron[11], shows various granulite occurrences in the region (B, Bandanwara; Bh, Bhim; Ch, Chinwali; K, Karera; RA, Rampura Agucha; S, Sandmata).