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Occurrence and petrogenesis of Loda Pahar trondhjemitic gneiss from Bundelkhand craton, central India: Remnant of an early crust

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The occurrence and the geochemistry of the typical high-Al trondhjemitic gneiss intruding into the highly deformed basic host rocks from Loda Pahar, Kabrai area, northeastern part of the Bundelkhand massif is reported. This large relict of the early crust is intruded by various phases of Proterozoic calc-alkaline granitoids. The highly fractionated REE pattern with HREE depletion and concave upward shape at the HREE end of the Loda Pahar trondhjemitic gneiss (LPTG), besides the major and trace element chemistry, is typical of Archaean TTG suites reported from shield areas of other continents. The evolution of such trondhjemitic magma is considered to have played a significant role during early crustal growth and the LPTG provides the first convincing evidence to qualify the Bundelkhand craton as a typical Archaean terrain.

In recent years considerable work has been done to understand the nature and evolutionary trends in the formation of early crustal rocks, the relicts of which are exposed in shield areas of all the continents. The Archaean crust in general is comprised of granitoid gneisses, massive granitoids and greenstones in proportion of 6 : 3 : 1[1]. The evolutionary trends recognized in the granitoid rocks of the Precambrian terrains of the world contain two main associations, an older Na-rich tonalite–trondhjemite–granodiorite (TTG) suite and younger K-rich granodiorite–monzonite–adamellite–granite (GMAG) suite. The former predominates throughout the Archaean, but subsequently, the latter becomes significant. The chemical and isotopic characters of the two suites are distinct and provide a major temporal demarcation in continental evolution at the Archaean–Proterozoic boundary[1].

In India, evidence to reconstruct different stages of early crustal evolution have so far come from the cratonic nucleii of Dharwar, Singhbhum and very recently from Bastar. Though the Bundelkhand craton is being considered unique for representing an early crust, unaffected by Proterozoic and subsequent deformational events[2], there is no convincing geochemical or geochronological data to indicate the presence of an early crust from Bundelkhand craton except for the geochemical data of early Proterozoic Bundelkhand granitoids[3].

The authors initiated detailed petrochemical studies of the Bundelkhand craton and have identified different components (metabasic and metasediments with banded iron intruded by various phases of TTG) of the early crust into which the Proterozoic calc-alkaline granitoid suite intrudes. The present paper reports the occurrence of a large relict block of trondhjemitic gneiss in deformed Archaean crust intruded by undeformed early Proterozoic calc-alkaline granitoids from Loda Pahar, Kabrai area. It also discusses the geochemistry, petrogenesis and its implication to the evolution of the Archaean crust in the Bundelkhand craton of the Central Indian Shield.

Semicircular to triangular outcrop of Bundelkhand granite massif in the northern part of the Indian Shield is known to be comprised dominantly of granitoid plutons of various phases, younger basic dykes and quartz reefs, mainly the early Proterozoic magmatic events. The information on the nature of the Archaean crust into which the younger Proterozoic granitoids intruded is very much limited to the reported occurrences of numerous enclaves of schists, gneisses, banded iron, calc-silicates, mafic and ultramafic rock suites only[4].

Recently, Rahman and Zainuddin[3] identified five phases within the Bundelkhand massif and provided geochemical data to characterize their source rock from Mahoba area. The earliest phase of the hornblende-bearing granodiorite having metaluminous composition and Y depletion has been attributed to hydrous partial melting of hornblende- and/or garnet-bearing mafic source. The porphyritic varieties of the biotite granite which intrude into the hornblende granodiorite are Y-undepleted, I-type, monzo-granites and were generated from the melting of the felsic crust. The subsequent intrusion of two phases of younger leucogranites (coarse and fine-grained varieties) are peraluminous monzo- to syno-granite and show marked enrichment with Y, Zr, Th, K and Rb and depletion of P, Sr, Ti and Ba. The magma for these leucogranite phases corresponds to the highly fractionated calc-alkaline to alkaline composition and felsic I-type granite characteristics. Following the preliminary geochronological age of 2550 Ma (based on Rb–Sr whole-rock isochron of seven samples collected from widely separated areas from the massif) for the Bundelkhand granite by Crawford[5], Sarkar *et al.*[6] carried out detailed Rb–Sr whole-rock dating of various plutons exposed in the northwestern part (Jhansi–Babina track). Six whole-rock samples of grey granodiorite–granite suite from a quarry define a Rb–Sr isochron age of 2359 ± 53 Ma with initial Sr ratio Sr_i of 0.7082 ± 0.0036. Another set of five whole-rock samples of pink-coloured coarse-grained granite–granite porphyry–aplite suite from Babina–Talbehat yielded a Rb–Sr isochron age of 2246 ± 78 Ma with Sr_i ratio of 0.7125 ± 0.0045. Four whole-rock samples of Badera gneissic migmatites (southeast of Babina) yielded a Rb–Sr isochron age of 2130 ± 102 Ma, possibly reflecting a strong thermal imprint due to large-scale emplacement of younger (pink) granite phase rather than the true age of the formation of the gneissic component of the older crust. However, the Geological Survey of India has dated 3.5-Ga-old gneissic rock from Babina–Talbehat area[7].

The authors during their initial field studies recognized numerous xenoliths of highly folded gneissic rocks within

Table 1. Geochemical composition of trondhjemitic gneiss from Bundelkhand Craton, Central Indian shield

	G-21	G-22	G-23	G-24	G-25	G-26	G-27
SiO_2	70 69	70.01	70 39	69 94	69.45	70.12	69 96
TiO_2	0.27	0.27	0.26	0.28	0.27	0.28	0.27
Al_2O_3	15.89	16.02	15.99	16.21	16.50	16 18	16.02
Fe_2O_3 (T)	1.55	1.58	1.57	1.77	1 77	1.64	1.61
MnO	0.041	0.033	0.038	0 043	0 062	0 039	0.049
MgO	0 81	0 82	0 77	0.77	0.72	0 82	0 66
CaO	1.83	2.17	2.16	1 97	2.06	2.18	2 17
Na_2O	5 62	5.67	5.56	5.87	6 08	5.75	5.55
K_2O	2.71	2.70	2.32	2.46	2.51	2 48	2.75
P_2O_5	0.10	0.12	0.11	0.11	0 11	0.12	0.12
Total	99.51	99.40	99.17	99 42	99.54	99.62	99.16
K_2O/Na_2O	0 48	0 47	0.41	0.42	0 41	0.43	0.49
ACNK	1.03	0.99	1.03	1.02	1.00	1 01	0.99
Trace elements							
Sc	1.4	1.5	—	2	2	—	2
V	15	15	—	15	14	—	13
Cr	11	21	—	12	9	—	18
Ni	2	1	3	1	—	3	—
Cu	—	4	5	10	14	7	10
Zn	43	66	55	49	44	59	51
Ga	19	18	19	20	19	19	18
Rb	107	86	106	117	195	136	153
Sr	647	910	836	722	759	881	653
Y	10	13	—	10	10	—	11
Zr	171	160	167	199	190	162	180
Nb	14	10	11	13	11	10	10
Ba	657	643	—	581	562	—	709
U	9	6	6	6	6	5	4
Th	25	17	17	21	21	13	4
La	52	—	—	59	—	—	—
Ce	81			87			
Nd	29			33			
Sm	5 2			6			
Eu	1.1			1 2			
Gd	3			3.4			
Dy	1.9			2			
Er	0 9			0.9			
Yb	0 8			0 8			
Lu	0.11			0.12			

the undeformed hornblende granodiorite phase exposed on the hillocks west of Mahoba railway station. Following these occurrences of older gneissic relicts in early Proterozioc intrusive granite phases, large exposures of older gneissic rocks (representing the Archaean crust) were delineated along Mahoba–Charkhari and Mahoba–Kabrai roads. One such large gneissic block (1 km long and 500 m wide) with associated metabasics is exposed around the Loda Pahar hillock, east of Kabrai, near the junction of Kabrai–Kanpur and Mahoba–Banda road, and is surrounded by intrusive biotite-bearing porphyritic granite phase. This hillock is 50 m high, the southern face of which has been extensively quarried for road construction material. On the northern slope of the Lodha Pahar, 1 m wide sulphide mineralized shear zone has been observed in the gneissic rocks which runs parallel to its northern contact with the biotite granite. Highly deformed and altered peridotites, and mafic schistose rocks are the host into which the trondhjemitic gneiss intrudes. Clear contact relationships among the various rock units in this area are masked by subsequent granitic activity and soil cover.

The Loda Pahar trondhjemitic gneiss (LPTG) is grey to pink, medium- to fine-grained gneiss with occasional phenocrysts of feldspar having a uniform mineral composition. The rock consists of quartz and plagioclase as dominant mineral with rare presence of K feldspar. Biotite altered to green chlorite is ferromagnesian mineral phase and is aligned parallel to the foliation of the rock. Accessory minerals include small euhedral crystals of Fe–Ti oxides, epidotes, apatite and zircon. All the samples exhibit typical granoblastic fabric modified by cataclastic deformation as evidenced by mortar texture, deformed and rapidly tapering lamellae in feldspars with locally developed myrmekites. The quartz, occurring as linear bands, shows undulose wavy extinction, recrystallized sutured grain contacts, with occasional granulated and polycrystallized fine-grained streaks parallel to the gneissosity.

Seven fresh and representative samples of Loda Pahar trondhjemitic gneiss were selected for geochemistry. All the major and trace elements were determined by XRF (Siemens SRS-3000 sequential X-ray spectrometer) and the rare-earth elements (REE) by AES-ICP at WIHG. The analytical methods for determining REE are similar to those proposed by Walsh[8]. The geochemical data of the LPTG are given in Table 1.

The chemical composition of the LPTG is quite uniform. The rock contains a restricted range of SiO_2 (69.45–70.69%), Al_2O_3 (15.89–16.5%), MgO (0.66–0.82%), CaO (1.83–2.18%), Na_2O (5.55–6.08%) and K_2O (2.32–2.75%). The rock is poor in ferromagnesian elements ($Fe_2O_3 + MgO + TiO_2 < 5\%$) and has high Na_2O values relative to CaO and K_2O with consistent low K_2O/Na_2O (< 0.5) ratio. The sodic character of the LPTG is indicated by the K–Ca–Na triangular diagram (Figure 1), thus clearly reflecting trondhjemitic trend confirming to the definition of trondhjemite[9]. Further, the LPTG is classified as high-Al trondhjemites in view of its high Al_2O_3 content (> 15%) at 70% SiO_2 (refs 10–12). Its high-Al nature is also substantiated by lower ratio of K/Rb (106–260, av. 176) and Rb/Sr (av. 0.17), low Y (10–13 ppm), Cr (9–21 ppm, av. 14 ppm) and Nb (10–14 ppm), and high Sr (647–910 ppm) content. Similar values have been reported for Archaean high-Al TTG rocks from various continents[11]. Being uniform in major and trace element composition, two samples of LPTG were selected for REE analysis. The consistency of REE data and the highly fractionated $(La/Yb)_N$ (43, 49.6) with depleted Yb_N content (3.83) and concave upward shape at heavy REE (HREE) end without any significant Eu anomaly in the LPTG is remarkably similar to the typical high-Al TTG suite reported from the Archaean[11,13].

As mentioned earlier, the Archaean TTG at 70% SiO_2 level have been divided into geochemically distinct low-Al and high-Al types. This subdivision emphasizes the significant role of hornblende and its retention as a refractory phase in the source rock during partial melting, thereby increasing the Al_2O_3 content in the melt[14]. Various models for the origins of TTG parental magmas have been proposed by the earlier workers; however, the recent geochemical and experimental studies on the Archaean rocks convincingly support the idea of partial melting of garnet-bearing amphibolites[13].

The strongly fractionated REE pattern and HREE depletion in the LPTG magma (Figure 2) suggest that

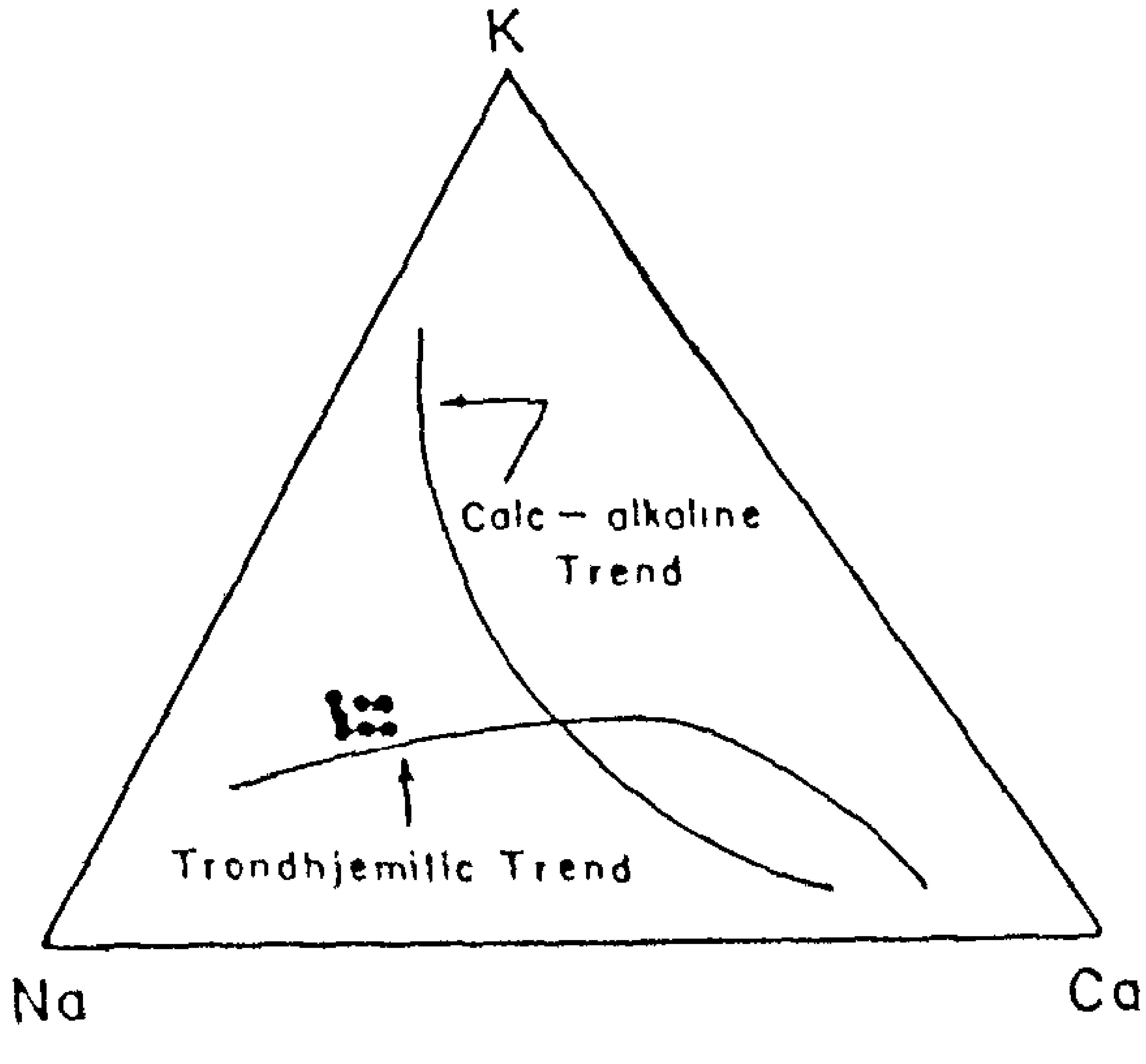

Figure 1. Ternary K–Na–Ca plot for the LPTG samples lying on the trondhjemite trend (from ref. 10).

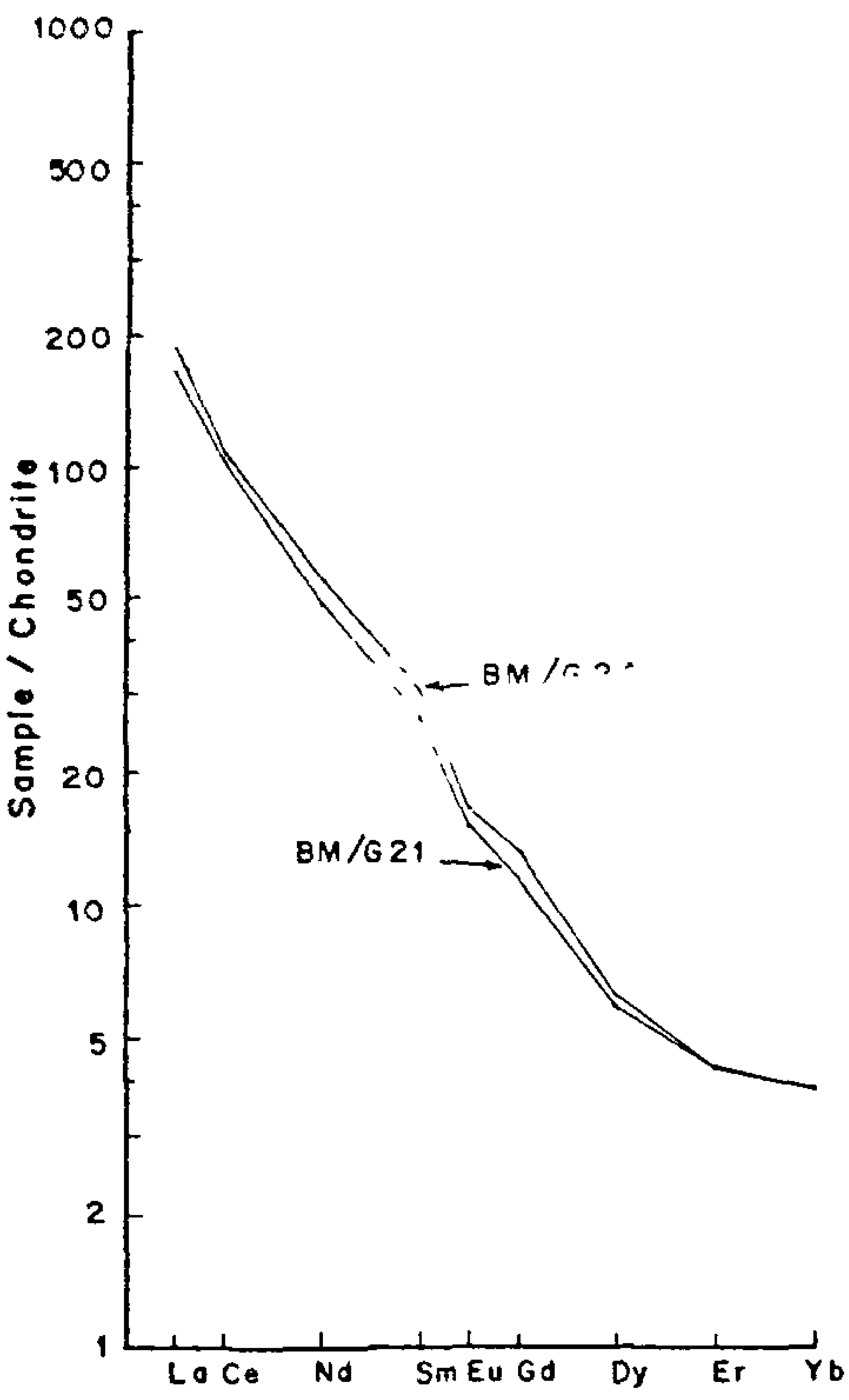

Figure 2. Chondrite normalized REE pattern of LPTG.

hornblende and/or garnet may be the residual phase in the source. Further, the presence of garnet in the hornblende-rich source is implied by the metaluminous composition and the low normative corundum average values of 0.36%. The plots of the LPTG samples on $(La/Yb)_N$ vs Yb_N and Sr/Y vs Y diagram (Figure 3) fall in the Archaean TTG field and suggest the generation of magma by partial melting of the source rock comprised of 10% garnet amphibolite. Such a derivation of trondhjemitic magma is now well constrained by experimental and geochemical data by Martin[12,13], who suggested a three-stage process for their genesis: (i) initial production of a large volume of tholeiitic magma by partial melting of mantle; (ii) metamorphic transformation of this tholeiite into garnet amphibolite and their subsequent partial melting to give rise to the parental magmas of TTG, leaving hornblende + garnet + clinopyroxene + minor plagioclase; and (iii) fractional crystallization mainly of hornblende + plagioclase to produce the differentiated TTG suite. The highly fractionated REE pattern of the LPTG compares closely with the high-Al older metamorphic tonalitic gneiss (OMTG), Champua area of Singhbhum–Orissa craton (3.6 Ga)[15,16]; Markampara trondhjemite from Bastar craton (3.5 Ga)[17]; trondhjemitic gneiss from Satnur–

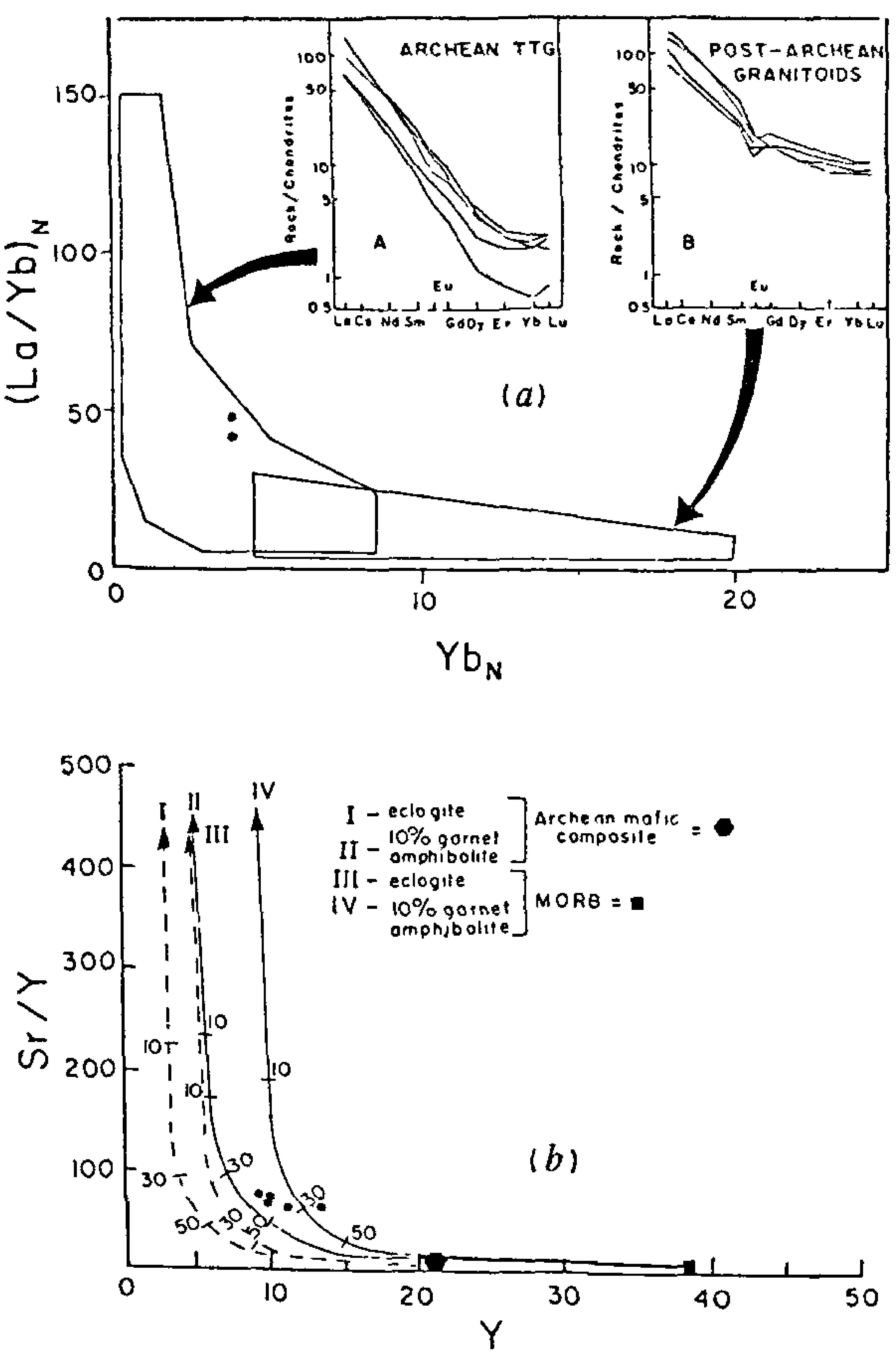

Figure 3. ***a***, $(La/Yb)_N$ versus (Yb_N) diagram showing changes in REE contents with time (from ref. 13), the LPTG data plot in the Archean TTG field, ***b***, Sr/Y versus Y diagram showing that the LPTG samples have an affinity with 10% garnet amphibolite source (from ref. 11).

Halagur–Sivasamudram area, Dharwar craton (2.9 Ga)[18] of the Indian Shield; trondhjemitic gneiss from Mount Edger batholith, Pilbara, Australian Shield (3.3 Ga)[19]; Ancient Gneissic Complex, Swaziland (3.0 Ga)[20,21] and Kivijarvi trondhjemitic gneiss from eastern Finland (2.8 Ga)[12]. In view of the remarkable geochemical similarity between the LPTG and other trondhjemitic rocks from different Archaean terrains, it is evident that the likely process of their formation may be the same.

To summarize, the presence of the typical high-Al trondhjemitic gneiss in association with other crustal components as relicts from the Kabrai area provides the first convincing evidence to qualify the Bundelkhand craton as a typical Archaean terrain similar to Singhbhum–Orissa, Bastar and Dharwar cratons of the Indian Shield.

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Hypothalamic γ-glutamyl transpeptidase activity in rats following morphine and naloxone treatment

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Hypothalamic γ-glutamyl (γ-GT) transpeptidase activity was measured in pubertal and sexually mature male rats. Rats were given subcutaneous injection of morphine and naloxone and the enzyme activity was measured at different time intervals. Morphine had an inhibitory effect on the enzyme activity in both the age groups. Naloxone, an opioid receptor antagonist, had a stimulatory effect on γ-GT activity in pubertal rats while it had no effect in sexually mature rats. This suggests that opiates exert an inhibitory effect on glutathione utilization through γ-GT cycle. Physiological significance of this finding with reference to pituitary function appears to be the suppression of gonadotropin secretion.

GAMMA-glutamyl transpeptidase (γ-GT) is a widely distributed enzyme that functions in the utilization of glutathione by transferring the γ-GT moiety of the tripeptide to amino acid or peptide acceptors. This enzyme together with others plays a major role in the synthesis and degradation of glutathione via the γ-GT cycle[1]. Gamma-GT is a membrane-bound enzyme present in abundance in epithelia of many organs[2,3]. The substrates for the enzyme are glutathione (GSH), oxidized glutathione (GSSG), S-substituted glutathione and other γ-GT compounds. Glutathione's function is to maintain protein thiol groups which may be required for catalysis and is involved in protein assembly and degradation. Glutathione also helps in protecting protein and cell membranes against peroxides and free radicals. Glutathione has also been reported to play a modulatory role on anterior pituitary hormone release[4]. It is probable that glutathione interacts with neuropeptides such as GnRH, opioid peptides and other regulatory elements at the hypothalamic level to elicit an endocrine response. The present study was designed to evaluate whether hypothalamic γ-GT transpeptidase activity responds to treatment with morphine sulphate – an opiate agonist – and naloxone – an opioid receptor antagonist – and thereby affects glutathione metabolism in pubertal and sexually mature rats.

All the experiments were done in colony-bred rats, derived from Wistar strain, purchased from the Animal Facility of Jawaharlal Institute of Postgraduate Medical Education and Research (JIPMER), Pondicherry, and Kind Institute of Preventive Medicine, Madras. Forty (pubertal) and 60 (sexually mature) days old male rats were used in this study. They were maintained under controlled conditions of light (14 h light and 10 h dark) and temperature with free access to drinking water and standard rat pellets.

Morphine sulphate, γ-GT paranitroanilide, glycyl–glycine and naloxone were obtained from Sigma Chemical Co., St Louis, USA. Naloxone (2 mg/kg body weight, dissolved in 0.9% saline), morphine sulphate (2 mg/kg body weight dissolved in 0.9% saline) were injected subcutaneously. All the doses employed are known to produce physiological responses[5,6]. Rats were sacrificed at 1 and 4 h after injection and hypothalamus was quickly dissected out and processed for estimation of γ-GT transpeptidase. The enzyme activity was estimated according to the method of Tate and Meister[7] as standardized by Pasha and Sadasivudu[8]. This method has been widely used to measure the enzyme activity in