GRANITE FORMING EVENTS AND THEIR ROLE IN CRUST FORMATION OF THE INDIAN SHIELD

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ABSTRACT Continental crustal evolution in the Indian shield appears to have started around the middle Archaean and completed by the early Proterozoic. In this time span of around 700 - 800 Ma, the primordial gneissic crust has evolved, recycled and stabilized. The earliest phase of the granitoid activity, from the middle-to late Archaean consists predominantly of a tonalite-trondhjemite-granodiorite (TTG) suite, while the second phase of the Archaean - Proterozoic transition (APT) period consists predominantly of granodiorite-adamellite suite. Minor granite forming events have occurred in the middle-to late Proterozoic. The compositional changes in the granites from the Archaean to the Proterozoic appear to have been mainly controlled by the tectonics and the source compositions at each stage and contribution from the mantle appears to be negligible. Increasing of some large ion lithophile (LIL) elements and decreasing of compatible trace elements in the APT granites compared to the earlier gneissic phase and the overall compositions of the latter (the gneisses) suggest that the middle- to late Archaean polyphase gneisses are the partial melts of the mafic rocks from greenstones and the various phases of the tonalite-trondhjemite-granodiorite (TTG), viz., the hornblende-biotite- and feldspathic gneisses (younging in the same order) are the successive fractionate of similar or same source. The tectonic setting at the time of formation of the TTG gneisses is more of a compressive regime and crustal thickening appears to have played a role in the initiation of partial melting of the source. The appearance of extensive K-rich batholithic granites throughout the shield in a limited time span of 200-300 Ma during the early Proterozoic, increase of LIL elements and high Th, Rb and Sr variations in these batholithic granites suggest that these granites are anatectic in nature and have formed due to the release of compressional forces and initiation of an extensional regime in the shield area. Though sporadic important alkalic granite bodies have formed in the middle to late Proterozoic, they are mostly restricted to the orogenic belts like the Aravalli, the Delhi, the Satpura and the Eastern Ghats. Many of these post-tectonic granites (mostly A-type) give evidence for crust-mantle interaction in their formation and their emplacement in a stable continental crust setting.

Keywords: Granite, Crust, Polyphase gneisses, Archaean granitoids, Tonalite-Trondhjemite

INTRODUCTION The process of transformation of the Indian continental crust from the early thin unstable stage (Naqvi *et al.* 1978) in which the greenstone belts had formed, to the present day continental crust, in which the greenstones occur as enclaves is not well understood. While there is direct evidence for the nature of the middle crust beneath the granite-greenstone terranes (the southern and Eastern that granulite belts), the mode of formation and the process of stabilization of the 10-15 km upper crust, consisting of the tonalite-trondhjemite-granodiorite suite, are still debated. The debate stems mostly because of the controversies persistent in understanding the evolution of the granite-greenstone terranes, especially the granites and their genetic classification. Opinions divide on the mode of formation of continental crust, either as a continuous process throughout the geological past or as an 'episodic' event in the early history of the earth. The apparent persistence of some Precambrian structures throughout the crust in several shield areas implies that the present day crust has remained coherent through subsequent time since its formation.

Any attempt to model the evolution of the continental crust needs a detailed knowledge of the granite forming events and their time-space relation. Substantial geological and geophysical data exists on the Indian continental crust to suggest that the crust had evolved as a major 'episodic' event during middle to late Archaean (Ramakrishnan & Viswanatha 1981, Divakara Rao & Rama Rao 1982, Naqvi *et al.* 1983). Extensive studies have been carried out on the granite-greenstone terranes of the Indian shield in the last three decades. Based on the available geological, geochemical, geophysical and geochronological data on the granitoids of the Indian shield (Fig. 1) a model for the evolution of the Indian continental crust and its cratonization is presented.

GRANITE FORMING EVENT IN THE INDIAN SHIELD

Two major granite forming events can be identified in the Indian shield that are of regional extent, the Middle-to late Archaean tonalite-trondhjemite-granodiorite (TTG) formation (Fig. 2) and late Archaean-early Proterozoic (Archaean-Proterozoic Transition, APT) granite-adamellite-monzonite formation (Fig. 3), both of which show time-space and compositional continuity to a large extent. Both the events i.e. the crust formation by TTG suite and crust-stabilization by the APT granites appears to have been completed in a short time span of 800-900Ma, between 3200 Ma and 2300 Ma, the period after which the Indian continental crust has not been effected much on regional scale. However, important but less extensive granite forming event occurred in Middle-Proterozoic (~1000-1400 Ma), which was limited in occurrence, restricted mostly to the Delhi-Aravalli, Eastern Ghat orogenic events.

EARLY CRUST FORMING EVENT Tonalites (and trondhjemite rocks) form the major part of Archaean granite-greenstone terranes all over the world (Stroh *et al.* 1983, Monrad *et al.* 1983, Naqvi *et al.* 1983). The Indian shield contains complex gneiss-migmatite with a regional NNW-SSE to N-S fabric covering major part of the craton. The metamorphism in this terrain varies from amphibolite facies in the

north to granulite facies in the south, with a transitional zone in between (Pichamuthu 1961, Rameshwara Rao *et al.* 1991). These gneisses also extend further north of the Dharwar craton, into central India (Amgaon gneiss, Divakara Rao *et al.* 1997), Bundelkhand craton (Sharma & Rahman 1996), Singhbhum craton (Saha 1966, older metamorphic group) and Aravalli and Delhi fold belts (the banded gneissic complex, Roy *et al.* 1988) where they form the basement.

The TTG suite commonly referred to as the Peninsular gneiss complex, shows both mineralogical and compositional heterogeneity on regional as well as local scale and predominantly consists of three phases, hornblende-gneiss (HG), biotite gneiss (BG) and feldspathic gneiss (FG) (Divakara Rao *et al.* 1983, Rama Rao & Divakara Rao 1994). The gneisses are inequigranular and fine to medium grained. Predominant mineral associations in hornblende gneiss are quartz, plagioclase, hornblende, biotite, chlorite, microcline and sphene, apatite and opaque are the accessories. The biotite-gneiss though broadly similar to hornblende-gneiss contains less hornblende and more biotite. The feldspathic gneiss is rich in quartz, plagioclase, interstitial potash feldspar (mostly microcline) and has very low contents of biotite and hornblende.

Time-space relationships between these different phases is quite clear in the field as the biotite-and feldspathic-gneisses cross-cut the hornblende gneiss, which in turn exhibits clear cross-cut relationship with the greenstone sequences of the Dharwar craton (Naqvi *et al.* 1983, Divakara Rao *et al.* 1974, 1983). Apart from the major three phases, there are minor banded and migmatite-gneiss phases but they are of local importance. The tonalite-gneisses associated with the greenstone belts of Tirthahalli, Aladahalli, Holenarsipur (Hussain 1980), Shigegudda (Rama Rao *et al.* 1991), KR Pet (Rama Rao & Divakara Rao 1994), gneisses flanking the Chitradurga schist belt; occurring as dome upwarps in Shimoga schist belt (Seshadri *et al.* 1982), and the Madekere gneisses, constitute a part of the polyphase Peninsular gneissic complex, forming a part of the gneisses as shown in Fig. 1. All these gneisses show remarkable chemical and chronological similarity, suggesting their formation from similar source in probably same event.

The gneisses that extend further north into parts of Central India, as well as in parts of the lower Himalaya (Rohtang gneiss, Divakara Rao *et al.* 1978), and Aravalli-Bundelkhand and Singhbhum cratons moderately differ, both in mineralogy and chemistry, from the type Peninsular gneissic complex of the southern Indian shield, as the former have been partly reworked in later orogenic movements (Divakara Rao *et al.* 1997). Overall major element characteristics of the southern polyphase gneisses are broadly similar though the large ion lithophile elements and rare-earth elemental abundance differ in different phases (Table I). Chronological data on these gneisses (Table II) form a cluster around ~3 Ga (Jayaram *et al.* 1983) suggesting their formation in a short time span; the oldest gneiss so far dated has an age of 3.36 Ga (Hassan gneiss, Beckinsale *et al.* 1980).

Evidence for the existence of gneisses older than Hassan gneiss may exist in the conglomerate pebbles from the greenstones (some of which

Figure 1 - Map showing the location of gneisses and granites under study.

Figure 2 - Diagrams showing the predominant tonalitic character of the Archaean gneisses (after Harpun, 1963).

Figure 3 - Diagram showing the quartz-monzonite character of the APT granite (after Harpun, 1963).

ations, especially in K/Rb ratios, can also result from post formational K-enrichment, for which sufficient evidence exists in this part of the craton. The overall picture suggests that the source for these tonalitic gneisses could be dominantly amphibolite with little garnet (or no garnet), which under high pH_2O anatexis (10-30%) can produce tonalitic melts (Green & Ringwood 1968). Variation in the REE abundance in these different phases of gneisses, their LREE/HREE fractionation and nature of the Eu anomalies (Fig. 4) suggest that the degree of partial melting and hornblende, biotite or plagioclase phases in the source have controlled the overall chemistry.

Geochronological data available on these gneisses demonstrate that this partial melting of the greenstones and formation of the present day gneissic crust in the shield occurred in short time span (~500 m.y.) during middle to late Archaean. The average composition of the Archaean crust thus has high $Fe_2O_3^{(T)}$, CaO, Na_2O , P_2O_5 , Sr and Zr low Rb, Ba compared to the Proterozoic crust (Table VII).

PROTEROZOIC CRUST The tonalitic crust evolved in the middle-to late Archaean has remained stable during the latter geological period till present though during late Archaean-Early Proterozoic Transition (APT), parts of it has been reworked due to anatexis, resulting in the formation of batholithic K-rich granitoids of adamellite-monzonite character (Table V, Fig. 3). These granites of porphyritic pink and grey type are distributed all over the shield (Fig. 1) starting with the Ghingee, Closepet, Hyderabad, Lepakshi, Perur, Hampi granites in South and Bundelkhand, Dongargarh, Singhbhum, Jabalpur granites in the central and northern India.

Mineralogically these APT granites differ substantially from the Archaean gneisses, and consist predominantly of orthoclase, quartz and hornblende, while plagioclase and biotite are subordinate. Microcline is abundant in some of these K-rich granites and the majority of these granites show replacement of plagioclase by orthoclase (orthoclase often contain corroded, partly digested plagioclase); apatite and zircon are the main accessories. Chemically these granites are not much different from the gneisses and have similar silica values (in average 71.98 in gneisses and 71.93 in granites) slightly higher Al_2O_3 , lower $Fe_2O_3^{(T)}$, CaO and MgO (Table IV) with substantial increase in K_2O . They are rich in Rb, Ba and occasionally in total REE (Fig. 5A, Table V). Overall chemical compositions suggest that the Archaean tonalitic gneisses have been recycled in mostly what appears

Table 3 - Chemical composition of hornblende gneisses (HG), biotite gneisses and feldspathic gneisses (FG)

	HG (N=7)	BG (N=7)	FG (N=5)
SiO_2	69.20	72.30	74.11
TiO_2	0.36	0.26	0.17
Al_2O_3	14.84	14.29	13.64
Fe_2O_3	4.11	2.68	2.48
MgO	0.92	0.52	0.30
MnO	0.16	0.13	0.16
CaO	2.89	1.56	0.73
Na_2O	4.72	3.75	3.60
K_2O	1.38	4.08	4.58
P_2O_5	0.11	0.10	0.06
Pb	79	107	155
Sr	234	138	89
Zr	178	167	100
Cr	35	28	27
Ni	52	46	35
Zn	32	22	17
La	35.77	68.96	31.8
Ce	78.87	55.98	75.56
Pr	8.65	16.66	7.27
Nd	30.19	55.12	25.62
Sm	6.33	9.46	5.51
Eu	1.06	1.81	1.12
Gd	6.38	9.57	5.41
Tb	0.87	1.31	0.80
Dy	3.72	6.14	2.64
Ho	0.57	1.05	0.51
Er	1.43	2.53	1.40
Tm	0.25	0.34	0.24
Yb	1.98	2.63	1.77
Lu	0.45	0.42	0.40

to be a closed system (through crustal remelting process) to give rise to these granites. A remarkable feature about these APT granites is their chemical homogeneity (especially in major elements), their K-rich nature with the pink and grey feldspar, and their similar ages (Table II). Detailed study of these granites (Divakara Rao *et al.* 1995, Subba Rao *et al.* 1992, Narayana *et al.* 1996) show that while these APT granites are similar major element compositions, their trace and REE concentrations vary.

MIDDLE AND LATE PROTEROZOIC GRANITES The middle-to late-Proterozoic granite forming event of the Indian shield has much relevance to understand the granitoid formation in middle Proterozoic orogenic movements. These granites mostly occurring as bosses and lenses and occasionally as large massifs Jalor, Sivana, Erinpura granites of Rajasthan, the megacrystic granites of Eastern Ghats, the alkali granites Kanigiri, Darsi, Vinukonda and chemically differ from the Archaean gneisses as well as APT granites (Table VI).

Granites, mostly syntectonic or post-to late tectonic in nature. Important granites of this group are (Fig. 1) the Jalor, Sivana, Erinpura, Malani, Berach granites of Aravalli (Srivastava 1988) and Delhi (Roy & Das 1985) fold belts, the Vinukonda, Kadiri, Darsi, Kanigiri, Podili granites on the east of Eastern Ghat and west of Cuddapah (Ratnakar & Leelanandam 1989) the megacrystic granites of the Eastern Ghats granulite belt (Narayana 1996).

These granites are rich in SiO_2 and poor in CaO, MgO, FeO. They are alkaline granites and contain ~9% alkalis ($K_2O > Na_2O$, Table V). They contain A-type and I-type granites (Divakara Rao *et al.* 1993) and have higher Rb and low Sr and Ba unlike the Archaean gneisses or APT granites. They are coarse grained to porphyritic, contain orthoclase (microcline), plagioclase and quartz with variable amounts of biotite and hornblende. Apatite, zircon are the common accessories. The high alkali, low CaO, MgO, Sr in the above granites indicate their A-type nature (Loiselle & Wones 1979). Some of these granites however have high SiO_2 , alkalis, CaO, MgO, Sr, Ba and low Rb and fall in I-type granites (Chappel & White 1974). Alkali granites are also referred to as anorogenic granites (Anderson 1983) and generally have low Al, Ca, Mg, Ba and Sr and high Fe, Na and K (Collins *et al.* 1982, Whalen *et al.* 1987). The REE distribution in these granites (Fig. 5B) have low to medium LREE/HREE ratios (~15) while some of them show very high ratios (19 to 41).

Several processes, partial melting, fractional crystallization, metasomatism, liquid immiscibility, crustal assimilation and thermo-gravitational diffusion (Clemens *et al.* 1986) have been suggested for the origin of alkali granites. However, these granites in the Indian shield consist of alkali granites that exhibit both S-type and I-type characteristics, some being post-orogenic (Ba, Sr rich granites) and some being late orogenic (low Ba, Sr and high Fe minerals). It is possible, as in a mobile belt during the last stages of orogenic episodes, that there

Figure 4 - Rare earth element distribution in the Archaean gneisses (normalized to chondrite, Haskin, 1968).

exists a very sharp and fast transition from subduction related calc-alkaline suites through collision related anatectic and/or high K-calc-alkaline suites to post-orogenic alkaline-silica-saturated suites (Bonin 1990). These alkali granites with enrichment of Zr, REE, Fe in Vinukonda, Kanigiri, Darsi, fairly uniform trace and REE abundance in Velatur and the variation present in CaO, MgO, Fe₂O₃⁽¹⁾, Rb, Sr and Ba indicate their formation both from crustal and mantle sources (Divakara Rao *et al.* 1993) have both crustal and mantle contribution for their genesis unlike the anorogenic granitoids of late Archaean and APT.

DISCUSSION Two contrasting evolutionary models are in vogue for crustal development, one postulating that the present day crust developed very early in the earth's history, almost synchronous with the episode of major differentiation of the core-mantle (Ringwood 1975), and the other proposing that the present-day crust derived mainly from the mantle, by successive igneous differentiation processes extending throughout the geological time.

Oldest rocks known on the continental crust are the 3.96 Ga Acasta gneiss from Canada (Bowring *et al.* 1989), the 3.9 Ga granulite grade orthogneiss from Enderby Land, Antarctica (Black *et al.* 1986) and the 3700 Ma orthogneisses of western Greenland (Moorbath 1975), but detrital zircon dates of 4100-4200 Ma (Fraude *et al.* 1983) indicate the existence of still earlier crust. In the Indian shield, the oldest gneiss dated is the Hassan gneiss (3300 Ma) and so far, no evidence for crust earlier than this has been recorded. The 'state of art' knowledge on the

Indian crust suggests that in all probability the present day crust dates back to middle Archaean (3.2 to 3.3 Ga). The younger greenstone sequences of the Dharwar (Naqvi *et al.* 1974), contain polymictic conglomerates in which tonalitic pebbles are present. However, this tonalite pebbles may perhaps have been derived from the first phase of the polyphase gneisses, the mafic rich hornblende-gneiss as compositionally these pebbles are similar to the 3.2 Ga hornblende-gneiss.

The middle- to late-Archaean gneisses, that grade from the hornblende-gneiss through biotite gneiss to the younger feldspathic gneiss show gradual increase in SiO₂, K₂O and Rb from the earliest to the late phase while TiO₂, Fe₂O₃, MgO, CaO, Na₂O, Sr, Zr, Cr and Ni decrease. The hornblende-gneiss is predominantly tonalitic while the biotite and feldspathic gneisses tend to granodiorite with Na₂O/K₂O > 2 in the hornblende-gneiss and < 2 in biotite and feldspathic gneisses. This gradual chemical variation with mineralogical variation, between different phases of gneisses is a common feature in the gneissic terrain not only in Dharwar, but also the central and northern Indian cratons, suggesting that the entire gneissic phase of the shield must have evolved through a common process from a similar source. These gneissic rocks can thus, be broadly divided into tonalitic and granodiorite suites, a characteristic lithological associations in the Archaean greenstone belts elsewhere (Glikson 1972). The REE abundance and their distribution patterns with variable low to strong negative Eu anomalies (Fig. 4) suggest this mode of origin. Gradual variation (increase or decrease) in major, trace and REE abundance from hornblende-gneiss to feldspathic gneiss suggest that all the phases are the successive partial melts of the same source. In studies at higher pressures on dehydration melting of amphibolite at 10 kbar (Wolf & Wyllie 1989) and on hydrous melting of basalt at 5-30 kbar (Winther & Newton 1992), tonalitic to trondhjemitic melts were derived. Winther & Newton (1992) observed that the chemical composition of partial melts is not very sensitive to the degree of melting pressure, temperature and amount of water in the charge at conditions between 5-30 kbar and 750-1100°C. Low water contents of 1-5 wt.% in the charge yield trondhjemitic melts and high water contents of 15 wt.% produced tonalite melts. The former represent low degrees of melting while the latter represent melt fractions of >55%.

The observed compositional differences between the TTG gneisses of the shield support multi-stage evolution that involve remelting of TTG. Such a multistage origin was proposed for TTG crust in Finland (Jahn *et al.* 1984, Kroner & Compston 1990).

Initial Sr and Nd ratios argue for either primitive mantle source for TTG's or a source with unfractionated radiogenic isotopes or a short

Table 4 - Average chemical compositions of the hornblende gneisses, biotite gneisses and feldspathic gneisses

	Hornblende gneiss	Biotite gneiss	Feldspathic gneiss
	Avg. Range	Avg. Range	Avg. Range
K%	2.05 (0.11-4.2)	2.43 (0.76-3.9)	2.8 (0.26-4.0)
Rb(ppm)	1.30 (30-2.6)	39 (43-246)	155 (44-250)
Sr	234 (36-429)	156 (Tr-256)	179 (50-413)
Zr	187 (70-586)	264 (58-750)	137 (24-251)
K/Rb	140 (38-226)	180 (61-312)	177 (59-270)
Ca/Sr	120 (49-406)	102 (35-349)	41 (0.5-27)
Tr/Zr	130 (7-39)	10 (3-26)	11 (0.5-27)

Table 5 - Chemical composition of the Archean-Early Proterozoic transition granites in the studied area. 1 -Closepet; 2 - Hampi; 3 - Hyderabad; 4 - Mahboobnagar; 5 -Karimnagar; 6 - Warangal; 7 -Lepakshi; 8 - Kadiri; 9 -Perur; 10 - Dongargarh (Porphyritic); WA - Dongargarh (Equigranular); 11 - Bundelkhand; 12 - Singhbhum; 13 -Tanakallu

Wt. %	1	2	3	4	5	6	7	8	9	10	10A	11	12	13	14	Average
SiO ₂	70.21	71.98	73.17	72.71	69.59	68.87	72.80	72.32	71.12	72.71	73.88	71.36	71.60	71.90	74.81	71.93
TiO ₂	0.31	0.28	0.25	0.17	0.56	0.36	0.24	0.26	0.20	0.12	0.19	0.41	0.12	0.19	0.15	0.25
Al ₂ O ₃	15.86	14.42	13.91	14.31	14.42	14.86	14.08	13.69	13.85	15.80	13.90	13.39	14.90	15.02	13.67	14.40
Fe ₂ O ₃	0.84	0.90	1.05	0.98	1.91	1.54	1.67	1.92	1.82	1.24	2.26	1.52	1.00	1.89	1.44	1.46
FeO	1.28	1.23	0.78	0.54	1.52	1.18	-	-	1.27	-	-	1.39	1.60	-	-	1.20
MgO	1.08	0.31	0.37	0.57	0.80	1.03	0.29	0.34	1.85	0.21	0.20	1.58	0.90	1.63	-	0.79
CaO	1.82	1.57	0.96	1.15	2.30	2.21	1.32	1.17	1.58	1.23	0.81	1.11	2.80	0.93	1.09	1.47
Na ₂ O	3.82	3.93	3.75	3.37	3.31	3.08	3.81	2.75	3.40	5.32	4.61	2.30	4.60	3.32	2.93	3.62
K ₂ O	4.46	4.47	5.27	5.29	4.90	4.69	4.39	5.26	4.31	4.27	4.87	5.10	2.50	3.82	5.06	4.57
P ₂ O ₅	0.11	0.10	0.05	0.04	0.17	0.13	0.05	0.05	0.09	0.03	0.02	Tr	-	0.05	0.02	0.07
LOI (ppm)	0.59	0.50	-	0.54	-	-	-	-	-	-	-	-	-	-	-	-
Rb	117	221	285	280	145	137	167	253	191	172	137	300	560	138	0.75	0.57
Sr	305	151	100	166	263	385	140	152	292	267	64	-	378	582	-	221
Ba	769	571	294	425	726	1586	532	474	412	1229	924	800	-	82	-	229
Zr	237	175	190	156	139	132	162	194	154	123	173	-	-	-	-	717
EREE	180	297	355	161	398	324	160	350	205	-	-	-	-	179	-	159
CeN/Yb N	22	20	25	27	20	26	11	18	12	-	-	-	-	18	-	258

Figure 5A - Rare earth elemental distribution in APT granites (normalized to chondrite, Haskin, 1968).

crustal residence time of an isotopically fractionated source (De Paolo 1988). Major element chemistry and experimental phase relation studies preclude a direct mantle origin of TTG through partial melting of peridotite (Moorbath 1977). It is now well accepted that the Archaean polyphase gneisses are the partial melting products of mafic amphibolites from the greenstones or mafic rocks (Martin 1987). Evidence for the evolution of tonalitic gneisses from mafic schists of the greenstones is abundant from many shield areas (Windley 1977, Harter *et al.* 1978, Barker 1979, Monrad 1983, Bhaskar Rao *et al.* 1983, Divakara Rao *et al.* 1983). Generation of tonalite and granodiorite, usually, is facilitated by partial melting of the thick lower crust with dominant mafic component (Helz 1973, Johnston & Wyllie 1988).

Evidence from experimental work on partial melting of tholeiites and trondhjemites suggest that tonalite magmas are formed by partial melting of hydrous mafic rocks at 15 kb pressure and 800-900°C temperature. Major part of the tonalitic gneisses of the Indian shield are suggested to be the partial melts of such hydrous mafic rocks (Naqvi & Rogers 1983). The late stage granodiorite gneisses may represent the partial melts of the tonalitic-gneisses. Different phases of gneisses present in the Indian shield thus can be partial melts of similar source and represent successive fractionates of source or the final feldspathic phase can be a partial melt of the earlier formed HG phase. Especially the variation in K, Rb, Ca, Sr, Ti, Zr and REE in the later gneissic phases suggest that the feldspathic and biotite gneisses probably are not the partial melts of hornblende-gneiss and may represent separate melt fraction of the source from which the hornblende-gneiss has evolved.

It is also possible that the HG a partial melt of mafic-hydrous source formed at greater depths has in turn fractionated at shallower depths to form BG and FG. Available geochronological data and the field relationships between the gneisses suggest that the total process was completed in a short time span of the order of 300-400 m.y. resulting in an 'episodic' gneiss-forming event in the middle-to late Archaean.

The gneissic crust thus formed by an 'episodic' event, however, appears to have partly undergone a recycling process, during late-Archaean-early Proterozoic transition (APT) resulting in the formation of huge batholithic granites of Adamellite-quartz monzonite nature. The APT granites are K-feldspar rich, coarse grained to porphyritic and are different compositionally from the earlier tonalite phase. They are rich in LIL elements LREE, K, Rb, Ba and poor in Sr, Zr, CaO, MgO, FeO compared to the above gneiss. The REE distribution patterns (Fig. 5A) in these granites also differ from place to place suggesting that the overall composition of a particular granite batholith is controlled more by the nature of the gneissic source at that particular place.

Figure 5B - Rare earth elemental distribution in Middle-Proterozoic A-type granites (normalized to chondrite, Haskin, 1968).

Table 6 - Chemical composition of Middle to Late Proterozoic granites of the studied area.

	Kanigiri	Vinukonda	Chamundi	Dindigal	Songsak
SiO ₂	76.00	74.28	71.14	74.17	71.65
TiO ₂	0.21	0.11	0.26	0.12	0.15
Al ₂ O ₃	12.61	13.82	15.28	14.31	14.30
Fe ₂ O ₃	2.69	2.26	2.01	0.67	1.44
FeO	-	1.80	-	0.76	-
MnO	0.05	0.03	0.04	0.03	0.29
MgO	0.04	0.04	0.42	0.05	1.09
CaO	0.72	1.02	1.50	0.86	0.88
Na ₂ O	4.10	3.15	3.94	3.40	3.43
K ₂ O	5.30	5.54	4.31	5.37	5.72
Rb	-	-	134	170	-
Sr	-	-	524	235	-
Ba	-	-	1032	-	-
Zr	-	-	137	163	-
ΣREE	-	-	180	162	-

The high SiO₂, peraluminous nature of some of these granites, their low CaO content random distribution of Sr, Ba and Rb in them, suggest that these granites are the anatectic remelts of the earlier formed polyphase gneisses with the mineral and chemical characteristics of the source gneiss, have substantially contributed to the similar variations present in the granite compositions. The overall compositional similarity present in these APT granites support their formation from the same or similar source, the polyphase gneiss. The higher K, Th contents in some of these granites however, are contributed both from the source, as well as by post formational metasomatic activity a process for which substantial evidence exists in the terrain. The APT granites both by their mode of field association and chemical composition support their evolution from a crustal source (mostly tonalitic-trondhjemitic gneisses) rather than from a mantle source. Recent

Table 7 - Overall compositional change from Archaean to Proterozoic in the studied region.

	Average Archaean crustal composition	Average Proterozoic crustal composition	Overall change
SiO ₂	71.98	71.93	No change
TiO ₂	0.30	0.25	Decrease
Al ₂ O ₃	13.99	14.40	Slight increase
Fe ₂ O ₃	1.83	1.40	Decrease
FeO	2.37	1.20	Decrease
MnO	0.10	-	-
MgO	0.97	0.79	Decrease
CaO	2.31	1.47	Decrease
Na ₂ O	4.43	3.62	Slight decrease
K ₂ O	2.05	4.57	Increase
P ₂ O ₅	0.32	0.07	Decrease
Rb (ppm)	54	221	Increase
Sr	304	229	Decrease
Ba	235	717	Increase
Zr	398	159	Decrease
ΣREE	-	258	-

studies on the granites from Closepet (Divakara Rao *et al.* 1995), Tanakallu (Subba Rao *et al.* 1992), Hyderabad (Rama Rao *et al.* 1997), Dongargarh (Narayana *et al.* 1996), Perur (Divakara Rao *et al.* 1994) and other areas clearly support a crustal remelting origin for these granites. A significant character in these granites is their coeval age apart from their overall chemical similarity (Table II) all having formed around 2.5-2.2 Ga (Archaean-Proterozoic transition).

Genesis of the TTG suite is significant to early continental development and the relevant genetic hypothesis broadly fall under four categories (a) partial melting of eclogitic or mafic garnet granulite source composition (O'Nions & Pankhurst 1974, Condie & Hunter 1976, Compston 1978, Glikson 1979), (b) partial melting of amphibolite (Barker & Arth 1976, Hunter *et al.* 1976); (c) fractional crystallization of basaltic magma (Arth *et al.* 1978) and d) high degrees of remelting of earlier sialic crust of suitable composition. The (La/Yb)_n REE profiles of the many of the Indian gneisses (Bhaskar Rao *et al.*

1983, Naqvi *et al.* 1983) suggest their formation from a source of basaltic composition in the form of amphibolite.

The mean age of continental crust, as inferred from Nd isotopic data for sediments is ~2.0 Ga (Miller *et al.* 1986), but it is unclear from Nd, Sr and Pb isotopic data in mantle derived rocks whether the age is the result of successive crustal addition through time (Moorbath, 1978) or continental crust formation in the early Archaean and its continuous recycling through mantle since then (Armstrong 1991).

Age data on the Indian granitoids do not give evidence for a crust older than 3.4 Ga, though it is possible that the earlier crust, if any, might have been completely recycled. It requires more single zircon dates to confirm this. The Archaean TTG suites from the shield, as well as from other Archaean terranes are not direct mantle products (Jahn *et al.* 1981) and are most likely derived by partial melting of basaltic sources.

The majority of the granites are associated with major faults, rifts or strike slip faults which extends through the entire crust. Faults of these dimensions are envisaged as reaching such depths where the melting of crustal rocks is triggered by adiabatic decompression (Cobbing 1996). Similarly generation of abundant tonalite to granodiorite intrusives in the Archaean crust by partial melting may require a thick lower crust with an average mafic composition (Wedepohl *et al.* 1991). Formation of the TTG suite and APT granites in a time span of 0.9 Ga (3.3 to 2.4 Ga) with gneisses and the extension of the TTG of middle to late Archaean throughout the shield without any significant evidence for an older crust, supports that the bulk of the present day continental crust has evolved only during that period in a compressional tectonic regime (thickened crust). Reversal of the tectonic compression to adiabatic decompression has resulted in the formation of the ademet-lite-quartz-monzonite APT granites around 2.4 to 2.3 Ga. The crust thus formed in middle Archaean and stabilized in early Proterozoic has remained stable thereafter.

The only other minor granite forming event was in middle Proterozoic along the orogenic movements like Delhi, Aravalli, Eastern Ghats. These granites are small bodies and are insignificant as far as the crust forming events in the Indian shield are concerned. The compositional changes in the Indian continental crust from the Archaean to Proterozoic shows that there was not much change except for the reequilibration of the Archaean crust in the Proterozoic.

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