Geological, geochemical and Rb–Sr isotopic studies on tungsten mineralised Sewariya–Govindgarh granites of Delhi Fold Belt, Rajasthan, NW India

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Neoproterozoic granites are widespread in the Delhi Fold Belt of the Aravalli craton, some of which are associated with tungsten mineralisation. In one such instance, the volcano-sedimentary sequence of Barotiya Group in the South Delhi Fold Belt is intruded by a pluton of biotite granite gneiss known as Sewariya Granite (SG) and later by stocks and dyke swarm of tourmaline leucogranite known as Govindgarh Granite (GG). GG magmatism was associated with wolframite mineralisation in hydrothermal quartz veins occurring along the sheared contact between SG pluton and Barotiya mica schist. SG pluton shows the evidence of ductile and brittle deformations, whereas GG is by and large undeformed. Apart from quartz and feldspars, SG contains biotite and muscovite, and GG contains muscovite, tourmaline and garnet. Although both SG and GG are peraluminous, SG has a wide range of SiO₂ and narrow range of alkalis, and GG has a narrow range of SiO₂ and a wide range of alkalis. REE (rare Earth elements) modelling shows that the parent magma of SG and GG was derived from partial melting at different crustal levels. Rb–Sr isotope data of GG yield a mineral isochron age of 860 ± 7.4 Ma which represent the time of igneous crystallisation and cooling of the granite to less than 400°C.

Keywords. Aravalli craton; Delhi Supergroup; S-type granite; tungsten mineralisation; geochemistry; geochronology.

1. Introduction

Granites form a major component of the continental crust and the granitic melts are important media for the transport of lithophile and few other elements from lower to the upper continental crust. Hydrothermal activity associated with granite magmatism has produced the majority of the known greisen type and skarn hosted Sn–W deposits. During Neoproterozoic period, there was

widespread acid magmatism in the Aravalli craton, particularly within and to the west of the Delhi Fold Belt, some of which are associated with wolframite mineralisation in Degana, Balda and Sewariya areas (Pandian 1999). In the present study area, metamorphosed volcano-sedimentary formations of Barotiya Group (the western most basin of South Delhi Fold Belt (SDFB)) are flanked to the west by pre-Delhi marble and gneisses, and intruded by a large pluton

of Sewariya Granite (SG), which is a foliated, porphyritic to equigranular biotite granite gneiss. Geological Survey of India (GSI) discovered wolframite mineralisation in quartz–tourmaline veins occurring near Kalni, Motiya, Pipaliya, Richmaliyan and Kotariya, localised along the sheared intrusive contact between SG and Barotiya mica schist (Jain and Bhattacharjee 1992; Bhattacharjee *et al.* 1993; Chattopadhyay *et al.* 1995). Banerji and Pandit (1995) reported the occurrence of a leucogranite in the form of small pods and irregular bodies within meta-argillites of Barotiya Group along with an 18 km long NNE–SSW trending belt to the east of these tungsten prospects. Pegmatites associated with these leucogranite bodies were reported to contain Li-mineralisation in the form of lithium phosphate minerals ferrisicklerite and triphyllite (Bhattacharjee *et al.* 1993). Pandian and Dutta (2000) recognised and mapped larger exposures of a tourmaline leucogranite along Luni–Sagarmati river section near Govindgarh, about 15 km NE of Sewariya. In view of its distinct geological, petrographic and geochemical characteristics and relevance to tungsten mineralisation in Sewariya area, this granite body has been named as Govindgarh Granite (GG). Based on the geochemical characteristics of SG pluton and GG from Sagarmati River, Ray *et al.* (2015) have inferred a metasedimentary protolith for both these granites and that the anatexis conditions prevalent during their origin were disparate.

Geochronological data are available for several other granites of the Aravalli craton (Crawford and Compston 1970; GSI 1982; Choudhary *et al.* 1984; Tobisch *et al.* 1994; Srivastava and Sinha 1997; Torsvik *et al.* 2001; Pandit *et al.* 2003; Ashwal *et al.* 2013; Arif *et al.* 2017). In this paper, we present the petrographic, geochemical and Rb–Sr isotopic characteristics of the granites from Sewariya–Govindgarh areas in the background of their geological setting and relevance to tungsten mineralisation.

2. Geology of the study area

SG is one of the largest granite pluton occurring along the western margin of SDFB, exposed over a strike length of 35 km along NNE with an average width of about 6 km (Jain and Bhattacharjee 1992) (figure 1). SG is grey coloured, medium to very-coarse grained and generally shows a gneissic foliation trending N20–30°E with steep to near-vertical dip. It contains quartz, microcline,

plagioclase, biotite and muscovite as major phases and occasionally metasomatic tourmaline occurs as an accessory phase. SG is intruded by quartz veins, few 10s of centimetre thick and extending for few m, consisting only of grey quartz. These quartz veins follow different strike directions (e.g., N50°E in Kalni; N10°E in Kotariya) and often show evidence of brittle deformation along with the host SG.

The present study has revealed that GG is also a major litho unit occurring in the form of stock-like bodies and as dyke swarm intruding into the Barotiya rocks and SG in an NNE–SSW trending zone extending for about 20 km from Kalni in the north to Sewariya in the south, and about 8 km wide, limited to Govindgarh–Pisangan in the east and Sewariya–Kurki–Bijathal in the west. Two different varieties of GG are recognised: (i) an older medium-grained granite (MGG), which is either massive or layered with alternating tourmaline-rich and tourmaline-poor bands and (ii) a younger coarse-grained granite (CGG), which appears to be the product of pegmatitic stage (figure 2a and b). The two varieties of GG share a common mineral assemblage of quartz, sodic plagioclase, K-feldspar, tourmaline and muscovite with accessory garnet and apatite. Both types of GG are occasionally intruded by milky white quartz–tourmaline veins, many of which are observed along Sagarmati River near the Govindgarh village (figure 2a). There is a clear intrusive relationship between SG and GG, with the dykes of GG cutting across SG pluton at many places near Richmaliyan, Kotariya, Bijathal and Pipaliya (figure 2c).

There are few discrete shear zones in SG pluton showing brittle and ductile deformation trending NNE–SSW in the western margin of the study area. Along with its contact with mica schist, there are several instances where SG shows mylonite fabric with grain size reduction and evidence of dynamic recrystallisation (e.g., development of quartz ribbons) in a few metre wide zone (figure 2d). Apart from these ductile shear zones (DSZ) localised along the intrusive margin of SG, there are few DSZ occurring well within SG. In addition to the ductile shearing localised generally along or near to the intrusive contact of SG with Barotiya rocks, effects of brittle deformation are also observed in SG in three locations: (i) in the northern part of the study area, large outcrops of coarse-grained SG occur near Kalni with widespread development of thin bands of cataclasite in various orientations (trending N20°W, N50°W, N–S). Among these

Figure 1. Geological map of Sewariya–Govindgarh area (after [Bhattacharjee et al. 1993](#); [Pandian and Dutta 2000](#)). The inset shows tungsten deposits in Delhi Fold Belt.

cataclasite bands, early formed ones are displaced (up to few centimetres) by later ones indicating their progressive development during the brittle shearing event (figure 2e). Grey quartz veins occurring within SG are also displaced by these cataclasite bands by few centimetre to more than a metre; (ii) in a small ridge to the NE of Bijathal, ultramylonite band of SG is brecciated indicating a later brittle deformation within the DSZ; and (iii) veins of pseudotachylite, up to few centimetre thick and few metre long, traverse through mylonitised SG in Chhorola Bala river bank to the

east of Kotariya village (figure 2f), where these pseudotachylite veins are parallel-sub-parallel to the mylonite foliation of SG which trends N20°E; this is another instance of later brittle deformation within the DSZ.

Near to the NNE–SSW trending shear zones, Barotiya rocks and at few places GG have developed asymmetric folds whose axes are generally NNE–SSW trending (figure 2g). Apart from a few such instances, GG does not show any evidence of deformation. At places, dykes of GG intrude into the folded Barotiya rocks parallel to axial plane

Table 1. A stratigraphical succession of Sewariya–Govindgarh area.

	Milky white quartz veins with tungsten mineralisation
	Coarse-grained Govindgarh Granite
	Medium-grained Govindgarh Granite
	Intrusive contact.....
Post-Delhi magmatism	Ductile and brittle deformation of Barotiya rocks, SG and grey quartz veins
	Grey quartz veins in Sewariya Granite
	Sewariya Granite
	Sheared intrusive contact.....
Delhi Supergroup	Barotiya Group (mica schist, meta-volcanics)
	Structural hiatus.....
Pre-Delhi rocks	Ras marble, gneisses and amphibolite

of fold whose axis trends N45°E (figure 2h) and also oblique to fold axis trending N32°E (figure 2i). Angular xenoliths of Barotiya rocks are common in GG and at few places, Barotiya rocks have undergone brittle deformation due to the intrusion of GG.

We have found that although wolframite-bearing quartz veins are hosted by mica schist of Barotiya Group and adjoining marginal portions of SG pluton, dykes or larger intrusive of GG are invariably present in close proximity to these mineralised zones. Moreover, there is a striking similarity in the mineral assemblage of medium-grained layered GG (representing magmatic phase), coarse-grained GG (representing pegmatitic phase), wolframite-bearing quartz veins in the prospects and quartz veins occurring within GG (representing hydrothermal phase), characterised by the ubiquitous presence of tourmaline + muscovite ± apatite. From these geological characteristics, it is inferred that the younger leucogranite magmatism produced successively the medium-grained GG (MGG), coarse-grained GG (CGG) and milky white quartz veins some of which contain wolframite (figure 2j).

From the field relations, it is demonstrated that SG (biotite-bearing granitic gneiss) and GG (tourmaline-bearing leucogranite) were formed during two successive magmatic events, of which GG is a younger phase. The presence of NNE–SSW trending ductile and brittle shear zones in SG along the western margin of the study area indicate the upliftment of SG pluton from middle to upper crustal level. The succession of major geological events recorded in the study area is given in table 1.

3. Analytical methods

Petrographic study supplemented by X-ray diffraction (XRD) analysis was carried out on the granites. Major and trace element analysis of granites was carried out using X-ray fluorescence spectrometer and atomic absorption spectroscopy (for Li) at Wadia Institute of Himalayan Geology, Dehradun, electron probe micro analysis (EPMA) of selected mineral grains was done at Institute Instrumentation Centre, IIT-Roorkee. Selected granite and mica schist samples were analysed for REE and W using ICP-AES, respectively, at School of Environmental Sciences, Jawaharlal Nehru University, New Delhi and Department of Earth Sciences, Pondicherry University. The chemical composition of tourmaline and garnet analysed by EPMA is given in tables 2 and 3. Major, trace element and REE data of rocks are given in tables 4 and 5. For geochronology, whole rock samples of SG and GG, and pure mineral fractions of plagioclase, garnet and muscovite from GG were analysed. Pure mineral fractions were obtained from powdered rock samples by using bromoform, isodynamic separator and by hand picking under a binocular microscope. Precisely, weighed samples were taken in a 3 ml Savilax®

Figure 2. (a) Intrusive contact between medium-grained and coarse-grained GG. Younger quartz vein cuts through both (Sagarmati river); (b) magmatic layering in GG shown by tourmaline and garnet; (c) SG showing gneissic foliation, intruded by GG; (d) SG showing mylonite fabric (north of Sewariya); (e) brecciated ultramylonite in SG (NE of Bijathal); (f) veins of pseudotachylite in mylonitised SG (Chhorola Bala river east of Kotariya); (g) CGG folded along with Barotiya mica schist (near Govindgarh); (h) thin dyke of MGG occupying axial plane fracture in folded meta-basic rock of Barotiya Group (Sagarmati river); (i) dyke of CGG cuts oblique to axial plane of folded meta-basic rock of Barotiya Group (Sagarmati river); (j) tungsten mineralised quartz–tourmaline vein in mica schist (Motiya prospect).

Table 2. The chemical composition of tourmaline from different rock types in Sewariya–Govindgarh area.

Wt%	Layered MGG		MGG		CGG		Quartz vein		SG	
Points	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core
SiO ₂	35.12	36.55	36.98	37.74	33.56	36.33	36.08	36.25	33.85	34.28
TiO ₂	0.19	0.28	0.37	0.55	0.13	0.21	0.65	0.47	0.42	0.34
Al ₂ O ₃	31.27	31.00	32.09	33.21	28.79	30.71	29.94	29.46	31.8	31.71
FeO	11.23	11.01	11.28	8.62	10.47	14.61	9.71	8.97	14.47	14.56
MgO	2.32	2.25	3.10	4.91	0.84	0.68	4.04	4.42	0.67	0.87
MnO	0.02	0.18	0.11	0.04	0.14	0.10	0.02	0.06	0.20	0.16
CaO	0.14	0.15	0.20	0.34	0.09	0.08	0.01	0.04	0.27	0.25
Na ₂ O	1.91	1.72	1.93	1.87	1.69	1.54	2.13	2.01	2.02	1.94
Structural formula on the basis of 24.5 oxygen										
Si _(Total)	6.12	6.27	6.14	6.09	6.32	6.26	6.21	6.28	5.92	5.96
Al _(Total)	6.42	6.27	6.28	6.31	6.39	6.23	6.07	6.01	6.55	6.49
Al _(Z)	5.85	5.69	5.79	5.81	5.65	5.69	5.69	5.64	6.00	5.99
Ti	0.02	0.03	0.05	0.07	0.02	0.03	0.08	0.06	0.06	0.04
Si _(Z)	0.12	0.27	0.14	0.09	0.32	0.26	0.21	0.28	—	—
Al	0.57	0.58	0.49	0.5	0.74	0.54	0.38	0.37	0.55	0.50
Fe	1.63	1.58	1.56	1.16	1.65	2.10	1.39	1.29	2.12	2.12
Mg	0.60	0.58	0.77	1.18	0.24	0.17	1.03	1.14	0.17	0.23
Mn	—	0.03	0.02	0.01	0.02	0.02	—	0.01	0.03	0.02
Li _(Y)	0.19	0.23	0.16	0.14	0.35	0.17	0.20	0.19	0.13	0.13
Ca	0.03	0.03	0.03	0.06	0.02	0.01	—	0.01	0.05	0.05
Na	0.65	0.57	0.62	0.58	0.61	0.51	0.71	0.67	0.69	0.65
X _(vac)	0.32	0.40	0.35	0.36	0.37	0.48	0.29	0.32	0.26	0.30

Table 3. The chemical composition of garnet from medium-grained GG.

Wt%	1	2	3	4
SiO ₂	36.34	34.99	37.16	38.39
TiO ₂	—	0.01	0.01	0.01
Al ₂ O ₃	20.82	20.03	20.9	20.63
FeO	31.73	32.66	33.66	33.68
MgO	0.61	0.90	1.00	1.04
MnO	9.68	7.81	7.77	8.06
CaO	0.51	0.33	0.40	0.35
Based on 12 oxygen				
Si	2.99	2.98	3.01	3.07
Ti	—	—	—	—
Al	2.00	2.00	1.99	1.94
Fe	2.19	2.32	2.28	2.25
Mg	0.08	0.11	0.12	0.12
Mn	0.68	0.56	0.53	0.55
Ca	0.05	0.03	0.03	0.03

vial and digested in HF + HNO₃ + HCl (7:3:1) in steel-lined pressure digestion vessel (Parr®, USA). The solutions were passed through HCl columns to separate Rb, Sr and REE. The isotopic analysis was performed using thermal ionisation mass

spectrometer (Triton, Thermo-Finnigan) at Department of Earth Sciences, Pondicherry University. Details of isotope analysis followed in this study are given in [Anand and Balakrishnan \(2010\)](#).

4. Results

4.1 Petrography and mineral chemistry of granitic rocks

4.1.1 Sewariya granite

SG contains K-feldspar, sodic plagioclase and quartz, along with accessory biotite and muscovite. Fine-to-coarse flakes of biotite and muscovite are generally aligned along a plane, which define the gneissic foliation of the SG, and often show kink bands. Adjacent to wolframite mineralised quartz veins, SG has undergone hydrothermal alteration which has resulted in the replacement of K-feldspar by muscovite and quartz (figure 3a) and replacement of biotite by tourmaline (figure 3b). Hydrothermal tourmaline from SG contains inclusions of quartz and shows irregularly

distributed patches of blue and greenish yellow (figure 3b). These alterations indicate that the hydrothermal fluid was acidic and rich in boron. The hydrothermal tourmaline of SG is distinctly different from magmatic tourmaline of GG in having larger ‘a’ and ‘c’ cell dimensions (Sivasubramaniam 2005). The chemical analysis of this tourmaline shows the composition close to schorl (table 2).

SG from protomylonite is medium grained with few megacrysts (up to few centimetres) of microcline which appear to be porphyroblasts around

which micas swerve, and shows the development of quartz ribbons. SG from ultramylonite contains about 90% of fine- to very-fine-grained matrix in which porphyroblastic grains of quartz, K-feldspar and micas (in the size range of 4–20 mm) are disseminated. Thin quartz ribbons containing fine-grained quartz are also observed in ultramylonite (figure 3c). Cataclastic bands in SG, as small as less than an mm wide, show intense brecciation and size reduction of constituent minerals and whose effect also extends into the adjoining coarse mineral grains of SG (figure 3d). Thin sections of

Table 4. Major and trace element composition of SG and GG.

Sample	SG-115	SG-116	SG-138	SG-147	SG-150	SG-221	SG-251						
Sewariya granite													
SiO ₂	72.49	71.05	72.25	71.33	70.42	68.55	74.56						
TiO ₂	0.11	0.09	0.12	0.23	0.21	0.31	0.08						
Al ₂ O ₃	13.59	14.74	13.55	14.11	14.1	14.18	13.92						
Fe ₂ O ₃	1.91	1.62	1.85	2.35	2.34	3.01	1.63						
MnO	0.03	0.03	0.03	0.04	0.04	0.05	0.03						
MgO	0.24	0.26	0.25	0.51	0.76	0.66	0.19						
CaO	0.71	0.65	0.73	1.41	1.55	1.94	0.64						
Na ₂ O	2.81	2.7	2.92	2.11	2.53	2.87	3						
K ₂ O	5.01	5.49	4.92	5.06	3.99	4.56	5.43						
P ₂ O ₅	0.16	0.18	0.16	0.16	0.14	0.24	0.15						
Ba	22	–	14	456	159	670	20						
Rb	441	581	444	246	272	49	212						
Sr	27	30	25	72	46	139	100						
Y	28	28	28	37	29	4	37						
Zr	75	66	75	120	104	31	169						
Nb	10	12	12	9	11	2	14						
Li	<5	<5	25	36	40	<5	<5						
W					6	4							
Sample	G-101	G-105	G-127	G-130A	G-134	G-136A	G-141A	G-142	G-144	G-148	G-235	G-245	G-264
Medium-grained Govindgarh granite													
SiO ₂	74.09	71.57	70.7	72.27	72.97	73.43	73.36	70.29	71.63	74.87	71.75	71.21	72.79
TiO ₂	0.01	–	0.01	0.01	0.01	–	0.01	–	0.01	–	–	0.06	0.03
Al ₂ O ₃	14.85	15.12	15.26	15.13	14.99	14.62	14.57	14.15	14.82	14.75	14.89	14.56	14.8
Fe ₂ O ₃	0.7	0.55	0.45	0.35	0.44	0.64	0.24	0.39	0.86	0.68	0.72	0.81	0.75
MnO	0.04	0.02	0.03	0.03	0.02	0.04	0.02	0.01	0.07	0.02	0.02	0.02	0.02
MgO	0.16	0.12	0.12	0.18	0.16	0.09	0.14	0.1	0.15	0.1	0.13	0.18	0.28
CaO	0.55	0.49	0.54	1.11	0.51	0.52	1.18	0.47	0.46	0.5	0.87	0.67	1.16
Na ₂ O	3.59	6.07	6.3	6.03	4.03	5.71	3.74	5.78	4.14	7.04	6.8	4.73	4.43
K ₂ O	5.29	2.71	2.51	1.95	4.97	3.53	4.58	2.99	5.85	1.39	2.73	4.37	4.42
P ₂ O ₅	0.12	0.2	0.36	0.07	0.15	0.1	0.07	0.21	0.39	0.2	0.08	0.29	0.14
Ba	206	17	–	–	125	–	57	11	172	–	20	153	20
Rb	174	143	156	96	169	185	205	177	155	70	49	487	183
Sr	85	36	22	45	69	20	63	54	65	29	109	18	90
Y	5	5	2	7	7	7	15	3	0	5	7	31	17
Zr	47	42	39	24	35	43	21	35	32	40	45	68	39
Nb	5	5	6	4	4	3	3	4	2	5	3	12	2
Li	6	19	<5	6	10	15	<5	<5	6	19	<5	40	6
W	5	7				6	2			3			1

Table 4. (Continued.)

Sample	G-124	G-128A	G-130B	G-133	G-145	G-232	G-237A	G-241B	G-253	G-259
Coarse-grained GG										
SiO ₂	71.6	73.2	71.41	72.11	73.42	71.71	73.44	73.95	74.66	72.31
TiO ₂	—	0.02	—	0.02	0.01	0.01	0.01	0.03	—	—
Al ₂ O ₃	15.84	15.2	14.24	14.73	14.82	14.48	13.7	14.8	13.87	15.95
Fe ₂ O ₃	—	0.14	0.34	0.9	0.36	0.39	1.04	0.87	0.4	0.05
MnO	0.03	0.01	0.01	0.07	0.03	0.01	0.02	0.02	0.02	—
MgO	0.1	0.19	0.14	0.18	0.15	0.18	0.17	0.33	0.11	0.13
CaO	0.45	1.59	0.94	0.96	0.87	1.01	0.94	0.52	0.64	0.36
Na ₂ O	9.02	5.97	5.43	6.08	4.63	6.32	6.02	4.95	6.31	2.09
K ₂ O	1.14	1.68	2.36	1.59	3.95	1.93	1.62	3.15	2.21	10.37
P ₂ O ₅	0.46	0.12	0.06	0.12	0.12	0.11	0.09	0.23	0.22	0.08
Ba	6	27	—	20	183	83	20	20	20	422
Rb	66	79	71	62	157	159	167	328	94	304
Sr	35	44	88	72	118	48	40	197	33	168
Y	35	44	88	72	118	48	40	197	33	168
Zr	29	30	21	54	25	56	29	50	25	26
Nb	<5	<5	<5	9	<5	5	8	8	7	<5
Li	<5	<5	<5	9	<5	5	8	8	7	<5
W	11							2		3

Table 5. REE abundances (in ppm) in granites and mica schist of Sewariya–Govindgarh area.

REE	MGG				CGG		SG			Barotiya mica schist		
	G-101	G-105	G-141A	G-245	G-241B	G-259	SG-138	SG-150	SG-221	G-210	G-313	G-119
La	2.13	2.07	4.45	8.86	1.55	1.32	9.15	19.48	39.56	44.38	45.74	38.84
Ce	4.3	4.21	7.99	15.11	3.16	2.43	20.79	41.6	83.85	83.55	91.21	78.95
Nd	1.58	0.99	2.46	5.14	1.28	0.69	8.46	16.73	35.75	35.46	36.5	31.83
Sm	0.36	0.32	0.6	0.98	0.25	0.27	2.03	3.15	5.94	5.35	5.45	4.87
Eu	0.53	0.08	0.52	0.33	0.13	1.07	0.17	0.52	1.4	1.3	1.29	1.11
Gd	0.35	0.26	0.92	1.3	0.21	0.18	3.6	4.87	8.21	6.87	6.68	6.3
Dy	0.79	0.69	2.06	1.6	0.59	0.55	4.48	4.63	6.66	5.74	6.08	5.17
Er	0.61	0.4	1.34	0.69	0.38	0.33	1.42	1.74	3.3	3.41	3.5	2.87
Yb	0.87	0.5	1.89	0.82	0.41	0.43	0.81	1.24	2.82	3.44	3.55	2.85
(Ce/Yb) _N	1.26	2.16	1.08	4.7	1.96	1.46	6.57	8.58	7.61	6.21	6.57	7.09
(Dy/Yb) _N	0.58	0.89	0.7	1.25	0.92	0.83	3.54	2.39	1.51	1.07	1.1	1.16
Eu/Eu*	4.5	0.83	2.16	0.92	1.71	14.14	0.19	0.41	0.62	0.66	0.66	0.62
(Sm + Gd) _N /2	1.63	1.34	3.35	5.06	1.07	1.05	12.24	17.6	31.32	27.19	27.09	24.84

pseudotachylite show a mixture of glassy matrix and very-fine-grained to fine-grained clasts mostly comprising quartz, with sharp contact with the medium- to coarse-grained SG (figure 3e).

4.1.2 Govindgarh granite

Both medium- and coarse-grained GG contain Na-plagioclase, microcline and quartz as essential minerals, and accessory muscovite, tourmaline, garnet and apatite. XRD analysis shows that the plagioclase is albite, and the composition of tourmaline lies close to schorl in schorl–dravite

series. Tourmaline shows dichorism in shades of blue, green, yellow and colourless with characteristic colour zoning in different intrusive phases: a small zone of blue core while rest of the grain is greenish yellow in early formed MGG (figure 3f); and a large zone of blue core surrounded by a narrow zone of yellowish green rim in CGG (figure 3g); yellow core and orange rim in the last formed hydrothermal tourmaline in wolframite mineralised quartz veins. The chemical composition of these tourmalines (table 2) generally corresponds with schorl (Fe-rich) variety except for few Mg-rich tourmalines from MGG and hydrothermal

quartz veins having a composition in the range of schorl–dravite. Reddish-brown garnet (figures 2b and 3h), and blue and green apatite are common accessories in MGG. The chemical composition of garnet (table 3) shows that it is dominantly of almandine composition with significant spessartite component ($\text{Py}_{3.7}\text{Alm}_{75.7}\text{Gro}_{1.2}\text{Sp}_{19.4}$).

Similar to SG, GG occurring close to W-mineralised quartz veins has undergone hydrothermal alteration (Pandian and Dutta 2000).

4.2 Geochemical characteristics of granites

4.2.1 Major and minor element geochemistry

In Harker variation, diagrams of major and minor elements (in oxide wt%) of SG and GG are given in figure 4. SG has a wide range of SiO_2 (68.55–74.56 wt%), narrow range of alkalis (mean K_2O 4.92 wt% and Na_2O 2.71 wt%), A/CNK ratio 1.51–1.74 and normative corundum 1.53–3.57 wt%. K_2O in SG is higher than that of GG and shows a slight increase with increasing SiO_2 . CaO content of SG (0.64–1.94 wt%) decreases with increasing silica content. Similarly, 1.62–3.01 wt% of Fe_2O_3 and MgO contents of SG also decrease with increasing silica content which could be related to *in-situ* crystal fractionation of biotite. The relative proportion of mafic components $\text{TiO}_2 + \text{Fe}_2\text{O}_3 + \text{MgO}$ is generally higher in SG (ranges from 1.9 to 3.98 wt% with a mean of 2.67 wt%). Higher total iron oxide and TiO_2 wt% in SG are due to the presence of biotite.

In contrast to SG, GG is characterised by narrow range of SiO_2 (70.29–74.87 and 71.41–74.66 wt% SiO_2 in MGG and CGG, respectively) and a wide range of alkalis (mean Na_2O 5.26, 5.68 wt% and K_2O 3.64, 3.00 wt%, respectively, in MGG and CGG). All samples of GG contain normative corundum (0.71–2.55 and 0.20–3.06 wt% in MGG and CGG, respectively) with A/CNK ratio of 1.41–1.66 in MGG and 1.24–1.71 in CGG. Na_2O and Al_2O_3 contents (14.15–15.26 wt% in MGG and 13.70–15.95 wt% in CGG) are higher and show a wide range in GG. The relative proportion of mafic components $\text{TiO}_2 + \text{Fe}_2\text{O}_3 + \text{MgO}$ is generally low in GG (0.39–1.06 wt% in MGG and 0.1–1.23 wt% in CGG).

Quartz–alkali feldspar–plagioclase ternary modal classification (Streckeisen 1974, 1976; Winter 2001) is widely used to determine the nature of the main magma series (Lameyre and Bowden 1982; Lameyre and Bonin 1991). Ternary minima and ternary eutectic composition of the water saturated

system at $P_{\text{H}_2\text{O}} = 0.5, 2, 4, 5$ kbar (figure 5) shows that SG falls close to the ternary minima (haplogranite field) in Qz–Or–Ab– H_2O diagram (Tuttle and Bowen 1958; Winkler 1979) corresponding to water pressures of 500–3000 bar. Some samples of GG lie close to ternary minima at relatively higher water pressures between 3000 and 5000 bar, while many samples of GG are scattered away from ternary minima for different water pressures. The displacement of some samples away from the minima is probably a result of melt segregation and therefore some of the samples do not represent the true bulk composition of the granitic melt. The relative positions of SG and GG in the same plot also indicate that the generation of SG melt took place at lower water pressures as compared to that of GG melt.

4.2.2 Trace element geochemistry

Bivariate plots of Rb, Nb, Zr and Y (figure 6) show a large difference between GG and SG in the concentration of these elements, with all these four elements enriched in SG as compared to GG. The range of concentration of Rb (212–581 ppm), Sr (18–100 ppm), Ba (14–670 ppm), Y (28–37 ppm), Nb (9–14 ppm) and Zr (66–69 ppm) is much wider in SG. In many bivariate plots of these trace elements, there is either positive correlation (Nb–Y, Y–Zr, Sr–Zr, Sr–Ba) or inverse relation (Rb–Sr) between pairs of trace elements. The composition of pseudotachylite (which occurs as irregular veins within SG) is comparable with SG in all elements, except for its relatively high Y and Nb content, and therefore it is inferred to have formed by near-complete flash melting of adjoining SG during the shearing event.

In the two varieties of GG, the range of concentration of trace elements is relatively narrow and no correlation is discernible in the bivariate plots. The concentration of W in GG (1–7 ppm in MGG and 2–11 ppm in CGG) is higher compared to normal granites (1.5 ppm) and closely match with metallogenetically specialised granite reported by Tischendorf (1977). SG and mica schist have average W concentration of 5 and 8 ppm, respectively, which is attributed to fluid–rock interaction accompanying GG magmatism and related hydrothermal W mineralisation. In figure 7, the concentration of Zr in SG and GG is compared with the proportion of Zr that can be dissolved in granite melts of various compositions at different temperatures (Watson and Harrison 1983). It

Figure 3. (a) Replacement of K-feldspar by muscovite and quartz in SG near W-mineralised quartz vein, XPL; (b) replacement of biotite in SG by tourmaline showing irregular colour zoning in patches of blue and greenish yellow, PPL; (c) ultramylonite in SG having thin quartz veins, XPL; (d) protomylonite in SG with few megacrysts of microcline, PPL; (e) pseudotachylite in SG showing a mixture of glassy matrix and very-fine-grained to fine-grained clasts mostly comprising quartz, XPL; (f) tourmaline in medium-grained GG shows colour zoning with a small zone of blue core and rest of the grain is greenish yellow, PPL; (g) tourmaline in coarse-grained GG shows colour zoning with a large zone of blue core and a thin greenish yellow rim, PPL; (h) garnet in medium-grained GG, XPL.

Figure 4. Harker variation diagrams of silica *vs.* other oxides (wt%) in GG and SG (triangle – MG; square – CG; circle – SG).

Figure 5. The plot of SG and GG in quartz–albite–orthoclase phase diagram (Winter 2001). Cotectic curves for water-saturated melt in equilibrium with quartz and alkali feldspar at different confining pressures (in bar) and the haplo granite field are marked (circle – MGG; square – CGG; inverted triangle – SG).

is observed that the samples of GG fall at lower temperatures ($<750^{\circ}\text{C}$) compared to those of SG ($>750^{\circ}\text{C}$). It also observed that there is a difference between early formed MGG (mostly above 700°C) and late formed CGG (many below 700°C) in this diagram. Low concentration of Zr in GG (<70 ppm) suggests relatively low temperatures of formation (Watson and Harrison 1983; Kalsbeek *et al.* 2001).

4.2.3 REE geochemistry

REE concentration of SG and GG is given in table 3. REE abundance of SG shows depleted negative slope pattern from LREE to HREE with strong negative Eu anomaly $[(\text{Eu}/\text{Eu}^*) < 1]$, ranges from 0.19 to 0.62. The high $(\text{Ce}/\text{Yb})_N$ value of 6.57–8.58 together with HREE depleted $(\text{Dy}/\text{Yb})_N$ value ranging from 1.51 to 3.54 in SG indicates a high degree of differentiation. The ΣREE is 50.91–187.49 ppm in SG with LREE 100 times and HREE 10 times greater than chondrite.

GG is enriched in LREE and HREE, and depleted in middle REE, showing bowl shape with very small negative or positive Eu anomalies $[(\text{Eu}/\text{Eu}^*) > 1]$ and ranges from 0.83 to 14.14 in normalised REE plot. $(\text{Ce}/\text{Yb})_N$ ranges from 1.08 to 4.70 in GG with HREE enrichment from Dy to Yb and $(\text{Dy}/\text{Yb})_N$ in the range 0.58–1.25. The ΣREE of GG is 7.26–34.84 ppm with only 5–40 times greater than chondrite values.

4.2.4 Rb–Sr isotope system

The whole rock samples of SG and GG do not define any isochron in Rb–Sr isotope evolution diagram. These granites must have assimilated country rocks resulting in inhomogeneous $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios. Such heterogeneities are expected from granite magmas derived by partial melting of continental crustal sources having an uneven distribution of biotite and muscovite. Hence, the $^{87}\text{Rb}/^{86}\text{Sr}$ initial ratio was brought down and the error on the isochron age is also high. When we consider only mineral isochron of MGG (G-134) for pure grains of muscovite, garnet, plagioclase (table 4), an age of 860.5 ± 7.4 Ma is obtained with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7533 ± 0.0050 (MSWD = 3.0) (figure 8a). In hydrothermally altered MGG (G-127), mineral isochron for pure muscovite, plagioclase and garnet defines an age of 847 ± 37 Ma with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.716 (MSWD = 64) (figure 8b). The hydrothermally altered granite (sample G-127) has yielded Rb–Sr mineral isochron age which is indistinguishable from the unaltered sample. However, the hydrothermal alteration has increased the scatter as reflected in the higher MSWD value and error on the age compared to the unaltered granite (sample G-134). Hence, the mineral isochron age for the sample G-134 represents the time of crystallisation and closure of muscovite, garnet and plagioclase for Rb–Sr isotopic system in the GG (table 6).

5. Discussion and conclusions

SG pluton is a biotite granite which has undergone extensive ductile and brittle deformation at different crustal levels. Contrary to this, GG is generally undeformed and occurs as stocks and dykes. SG and both varieties of GG are peraluminous with A/CNK ratio > 1 . However, GG has a wider range of A/CNK ratio, which is attributed to the presence of more number of aluminosilicate minerals (muscovite, tourmaline and garnet in addition to feldspars) and variation in their relative proportion. Garnet of GG is dominantly almandine with significant spessartite component which is typical of peraluminous granites (Clark 1981). The relative proportion of mafic components $\text{TiO}_2 + \text{Fe}_2\text{O}_3 + \text{MgO}$ higher in SG is due to the presence of biotite as an essential phase. The presence of euhedral tourmaline in GG reflects its early crystallisation from the parent magma which has

Figure 6. Trace element (in ppm) variation in GG and SG. Symbols are same as in figure 4.

minimised the formation of other ferromagnesian minerals and resulted in the absence of biotite. The relatively high Na_2O and Sr concentrations and positive Eu anomaly in MGG and CGG are due to the higher modal per cent of sodic plagioclase in these leucogranites. The positive Eu anomalies in the chondrite-normalised plot are invariably associated with the relatively high concentration of Sr (and in some cases Ba) and vice versa for the low concentration.

Chappell (2004) has observed that higher Zr and Y concentrations are characteristic features of high-temperature granites in which melting continued to higher temperatures before the magma could depart its source, and that high-temperature granites owe their origin to insufficient low-

temperature melt components (quartz, orthoclase, albite and water) in the source region. Higher concentration of Zr and Y is present in SG as compared to GG; therefore it indicates that SG melt was generated at a relatively higher temperature from a source rock which consisted of insufficient quartz, orthoclase, albite and water.

The multi-element primitive mantle-normalised spider diagram (figure 9) illustrates that SG is enriched in Rb, La and Ce and strongly depleted in terms of Sr, P and Ti. GG has a lower concentration of trace elements (e.g., Zr, Y, REE) that mainly reside in accessory minerals of the source rock, which indicates that a significant proportion of these elements remained in the restite during anatexis generation of the granitic

Figure 7. Zr concentration in the granites plotted against cation ratio $(\text{Na}+\text{K}+2\text{Ca})/(\text{Al}*\text{Si})$ (after [Watson and Harrison 1983](#)). The temperature lines marked in the diagram are from [Kalsbeek et al. \(2001\)](#) (for 700°C) and [Watson and Harrison \(1983\)](#) (for 750–800°C) with extrapolations of the temperature line at the lower end from cation ratio 0.5 to 0.8. Symbols are same as in figure 4.

magma ([Rapp and Watson 1988, 1995](#); [Kalsbeek et al. 2001](#)). The patterns produced by GG and SG in this diagram are comparable with upper continental crust values ([Taylor and McLennan 1981](#)).

5.1 Petrogenesis

The high concentration of boron in GG revealed by the ubiquitous presence of tourmaline, together with high A/CNK ratio of this rock shows that the source could be pelitic sediments ([Skjerlie and Johnston 1996](#); [Chappell and White 2001](#)). In the study area, GG is closely associated with mica schist of Barotiya Group. Therefore, it is possible that the parent magma of GG could have been generated by partial melting of meta-sedimentary rocks of Barotiya Group. The REE pattern of GG is complementary to that of amphiboles, which are enriched in middle REE than LREE and HREE. The HREE abundances in the GG sample show that accessory phases such as garnet, zircon, apatite, allanite with amphibole could have played a major role in the generation of GG magma.

Geochemical modelling is carried out using the least mobile elements, such as the REEs. For quantitative modelling of partial melting and fractional crystallisation processes, appropriate Kd values for different source and melt systems, as suggested by [Arth \(1976\)](#), [Hanson \(1980\)](#), [Nash and Crecraft \(1985\)](#), have been used. In all, 5–30% partial melting of a source similar to mica schist in the

Figure 8. Rb–Sr mineral isochron for plagioclase + garnet + muscovite in medium-grained GG: (a) unaltered sample, G-134 and (b) hydrothermally altered sample, G-127.

study area, leaving an amphibolite residue (90% hornblende +5% biotite +5% apatite) would produce a melt having LREE enriched REE pattern with a positive Eu anomaly (figure 10). The calculated pattern shows that garnet and allanite fractionation played a major role in the generation of the GG magma. The calculated mica schist sample has higher REE abundance than GG samples. However, in a heterogeneous meta-sedimentary rock such as mica schist, it is expected that the range in REE abundance may be large enough to be comparable with the REE abundance of GG. The positive Eu anomaly in the GG could not be due to plagioclase accumulation as it would have also increased the Sr abundance which is not supported by the Sr abundances observed. Hence, it suggests that REE abundances and modelling for GG show that partial melting of a heterogeneous source leaving amphibolite residue would satisfy the REE abundances of GG. REE modelling of SG

Table 6. *Rb–Sr isotopic composition of GG.*

Sample name	Minerals	$^{87}\text{Rb}/^{86}\text{Sr}$	Error (%)	$^{87}\text{Sr}/^{86}\text{Sr}$	Error (%)
G-134 (medium-grained granite)	Muscovite 1	1668.84	2	21.0806	0.1500
	Muscovite 2	1004.03	2	13.2260	0.1100
	Plagioclase	9.76	2	0.875142	0.0208
	Garnet	20.44	2	1.001800	0.0032
G-127 (medium-grained hydrothermally altered granite)	Muscovite 1	1401.05	1	17.5500	0.1120
	Muscovite 2	905.62	1	11.8000	0.0856
	Plagioclase	100.86	1	1.975600	0.0569
	Garnet	19.48	1	0.862400	0.0900

Figure 9. Primitive mantle-normalised spider diagram showing the granites from the study area (after Taylor and McLennan 1981): (a) medium-grained GG and (b) SG.

shows that 5–30% partial melting of mica schist source leaving a granulite residue (58% plag + 30% Cpx + 10% Ox + 2% garnet) could have produced the parental granitic magma (figure 11). Subsequently, 5–30% fractional crystallisation of 50% plag + 49.5% Hb + 0.4% zircon + 0.1% allanite from this parental magma could have produced the magma from which SG was formed (figure 12).

The Rb–Sr isochron age of 860.5 ± 7.4 Ma based on muscovite, garnet and plagioclase for the GG samples (G-134) represents the time of cooling of the granite body to $< 400^\circ\text{C}$. Several studies have

Figure 10. Calculated chondrite-normalised REE patterns for 5, 10, 15 and 20% partial melting of mica schist leaving residue 10% K-feldspar + 15% plagioclase + 48% hornblende + 20% biotite + 5% apatite + 2% allanite. Calculated patterns (dashed lines) are analogous with GG samples except for very small negative Eu anomaly in one sample (G-245). Symbols: a filled triangle with solid lines – MGG; a filled square with solid lines – CGG; plus with dotted lines – calculated melt; open circle – parent rock.

Figure 11. Calculated chondrite-normalised REE patterns for 5, 10, 20 and 30% partial melting of mica schist source leaving residue of 58% plagioclase + 30% CPX + 10% OPX + 2% garnet. Symbols: circle – SG; square – parent rock; plus – calculated melt.

Figure 12. Calculated chondrite-normalised REE patterns for 5, 10, 20 and 30% fractional crystallisation of 50% plagioclase + 49.5% biotite + 0.4% zircon + 0.1% allanite from parent SG-221. Calculated REE patterns are comparable with SG samples.

shown that igneous rocks that were not subjected to metamorphism or thermal disturbance exceeding a temperature of 400°C give Rb–Sr muscovite ages that match with U–Pb zircon ages within analytical uncertainties (Nebel *et al.* 2011). Thus, Rb–Sr muscovite–garnet–plagioclase isochron ages represent the time of cooling of these igneous bodies to <400°C. Since GG was emplaced as relatively small stocks and dyke swarms, it must have cooled to <400°C within a million year from the time of their intrusion. Hence, we consider that the Rb–Sr isochron age reported above is robust and date the time of igneous intrusion of the GG. Other two well-known granites associated with tungsten mineralisation along the western margin of the Delhi Fold Belt, at Balda and Degana have yielded Rb–Sr mineral isochron ages of 795 ± 11 and 827 ± 8 Ma, respectively (Vijay Anand *et al.* 2018).

5.2 Tungsten metallogeny in Delhi Fold Belt

In the Aravalli craton, tungsten mineralisation is mainly associated with Neoproterozoic granites occurring along the western margin of Delhi fold belt. The following observations are made by comparing the tungsten mineralisation in Govindgarh–Sewariya area with the other well-known tungsten deposits at Degana and Balda. There are few similarities among these three tungsten deposits: (i) Mid-Proterozoic metasediments (dominated by pelites) are intruded by an older biotite granite which has been deformed along with metasediments, and a younger geochemically specialised granite which is the source for W mineralisation

and (ii) ore mineralisation occurs in greisen-bordered quartz veins containing wolframite of ferberitic composition as the principal ore mineral. However, there are several dissimilarities among these tungsten deposits.

1. *Mineral assemblage of source granite:* Degana granite is F–Li-rich, contains topaz and zinnwaldite, and it is devoid of tourmaline (Pandian and Varma 2001). Balda granite is a muscovite–tourmaline-bearing leucogranite (Chattopadhyay *et al.* 1982).
2. *Nature of acid magmatism related to W mineralisation:* Degana granite is a complex of three porphyritic granitic intrusions, two generations of aplite dykes, greisen-bordered quartz veins, rare pegmatite and a multitude of greisen veinlets, all occurring within a small area (Pandian and Varma 2001). Relative proportion aplite dykes are significantly large in Degana pluton. Balda granite is a single, continuous and homogeneous textured pluton exposed over a length of about 20 km and having a maximum width of about 1 km. Quartz-rich veins and few pegmatites are present, whereas aplite dykes are not known in Balda area. In Sewariya area, GG is also a non-porphyritic granite, but occurs mostly as dyke swarm and few stocks emplaced within mica schist and older granite, and exposed over a zone 20 km long and few km wide. In the outcrop area, pegmatite component of GG (CGG) is more compared to MGG. Aplite dykes are not present in Sewariya–Govindgarh area.
3. *Nature of W mineralisation:* In Degana area, W mineralisation is essentially intrusion centred and marginally extends into adjoining phyllite. Two episodes of mineralisation are recognised, each preceded by emplacement of a porphyritic granite and aplite dykes (Pandian and Varma 2001). During each episode of W mineralisation, thick quartz lodes (up to 1 m) and a multitude of thin greisen veinlets have formed. Due to the preponderance of greisen veinlets in addition to quartz lodes within granite pluton and adjoining phyllite, the host rocks of orebody show stockwork character. Ore veins often show crustification, with zinnwaldite/muscovite lining the wall and quartz in the core; wolframite and fluorite are disseminated within quartz. The mica associated with the first episode of mineralisation is zinnwaldite, and the one associated with the second event of mineralisation is

muscovite. During the first episode of mineralisation, phyllite (of Phyllite Hill) is extensively brecciated, due to boiling of hydrothermal fluid. Such hydrothermal breccia is not known from the other two tungsten deposits.

In Balda area, wolframite-bearing quartz veins (few 10s of centimetre thick) are localised along the sheared intrusive contact of leucogranite against mica schist. Quartz makes up most of the veins, with tourmaline, beryl, fluorite, muscovite and wolframite (in decreasing order of abundance) disseminated within quartz. There are few fluorite-rich veins (containing relatively less proportion of quartz) occurring within the leucogranite. In Sewariya-Govindgarh areas, quartz-tourmaline veins containing wolframite occur exclusively along shear zones in mica schist and the older SG.

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