Chapter-9

Summary and Conclusions

Aravalli craton in the NW region of Indian subcontinent hosts the well known tungsten deposits at Balda, Degana and Govindgarh-Sewariya areas which are related to Neoproterozoic acidic magmatism in the region and occur along the western margin of NNE-SSW trending Mesoproterozoic Delhi fold belt. The tungsten deposits occur as greisen-bordered quartz veins (also as stockwork in Degana) with wolframite as the principal ore mineral.

Major rock types in Govindgarh-Sewariya area include metasediments and metavolcanics of Mesoproterozoic Barotiya Group belonging to Delhi Supergroup (the westernmost basin of South Delhi Fold Belt), a porphyritic to equigranular biotite bearing granitic gneiss known as Sewariya granite (SG), and medium and coarse grained tourmaline leucogranite called as Govindgarh granite (GG). Rocks of Delhi Supergroup extend towards east, and pre-Delhi gneisses and Ras marble occur to the west of study area. From field relations it is demonstrated that Sewariya granite (biotite-bearing granitic gneiss) and Govindgarh granite (biotite-free tourmaline leucogranite) formed during two successive magmatic events, of which GG is younger phase.

The present study has also revealed that Govindgarh granite is a major litho unit occurring in the form of dyke swarm and stock-like bodies intruding into the Barotiya rocks and Sewariya granite in a NNE-SSW trending zone along the western margin of South Delhi Fold Belt (SDFB). Presence of Govindgarh granite as stocks and dykes is recorded within a 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. Within this linear zone, there are some large areas where GG is either the dominant or exclusive rock, and this includes the north-south stretch of 5 km along Luni-Sagarmani river and the 4 km wide zone to the west of Luni-Sagarmani river up to Pipaliya.

There are two different varieties of Govindgarh granite: (1) an older medium grained granite, which is either massive or layered with alternating tourmaline-rich and tourmaline-poor bands, and (2) a younger coarse grained leucogranite which appears to be the product of pegmatitic stage. The two varieties of GG share a common mineral assemblage of quartz, sodic plagioclase, K-feldspar, tourmaline and muscovite; garnet and apatite are often found as
accessory minerals in medium grained GG. Both the types of GG are occasionally intruded by quartz-tourmaline veins, many of which are observed in Sagarmati river near Govindgarh village.

Geological Survey of India reported wolframite mineralization in quartz veins from Motiya, Pipaliya, Richmaliyan, Kotariya and Bijathal prospects where these tungsten-mineralised quartz veins trending N-S to NNE-SSW occur along the sheared contact between Barotiya mica schist and Sewariya granite (Jain and Bhattacharjee, 1992). Tungsten concentration in these quartz veins range from 0.1 to as high as 3.5 wt.% (Bhattacharjee et al. 1993). These veins consist of milky white quartz, tourmaline, muscovite and wolframite.

Apart from the tungsten-mineralised quartz veins localized along sheared contact between mica schist and Sewariya granite, the two granites (SG and GG varieties) are also intruded by quartz veins at several locations away from the tungsten prospects. SG is intruded by grey colored quartz veins which do not contain wolframite. These quartz veins show evidence of brittle deformation with displacement of few cm along a number of fault planes in different locations. Large number of these quartz veins is found near Kalni, and along Bhutiya Bala river section near Kotariya. These quartz veins have formed during late stage of the magmatic event which produced SG.

GG is intruded by quartz-tourmaline veins which contain milky white quartz, comparable with the quartz veins of tungsten prospect, but the presence of wolframite is not yet recorded in these quartz veins occurring within GG. Unlike the grey quartz veins in SG, these milky white quartz veins in GG are undeformed. These have formed during late stage of the magmatic activity which produced GG.

Contrary to previous observation, 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 intrusives of GG are invariably present in close proximity of 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 (both representing hydrothermal phase), characterized 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, coarse grained GG and milky white quartz veins some of which emplaced outside GG are proved to contain wolframite.

Presence of NNE-SSW trending brittle, brittle-ductile and ductile shear zones in SG along western margin of study area indicate upliftment of SG from middle to upper crustal level. These shear zones are part of a major NNE trending shear zone, called Phulad Shear Zone or Phulad Dislocation Zone, occurring all along the western margin of South Delhi Fold Belt. Near to the NNE-SSW trending shear zones, Barotiya rocks and at few places Govindgarh granite have developed asymmetric folds whose axes are generally NNE-SSW trending. Apart from few such instances, Govindgarh granite does not show any evidence of deformation. From these observations it is concluded that emplacement of Govindgarh granite in the form of dykes and stocks, and the development of W-mineralised quartz veins, both intruding into Barotiya rocks and SG is syn- to post-tectonic with reference to the shearing event whose imprints are abundantly present in SG.

Petrographic characteristics of SG and GG varieties are quite different. GG contains more sodic plagioclase than K-feldspar and tourmaline among essential minerals, and minor amount of garnet and apatite. Chemical composition of garnet from medium grained GG shows that it is essentially almandine with significant spessartite component. These mineralogical features show that the granitic melt from which GG crystallised was distinctly peraluminous and enriched in B and P. SG contains more K-feldspar than sodic plagioclase and biotite among essential minerals, occasional metasomatic tourmaline replacing biotite and no garnet or apatite. Biotite is ubiquitously present in SG, and totally absent in GG.

Primary tourmaline occurring in various phases of GG, and metasomatic tourmaline from SG and mica schist are all black coloured, but show distinct patterns of colour zoning in thin section which is unique to each of these lithologies. (1) pale blue core and dark greenish blue rim in layered medium grained GG (LGG), (2) a small zone of blue core surrounded by a wide zone of yellowish green rim in MGG; (3) a large zone of blue core surrounded by a narrow zone of yellowish green rim in CGG, (4) brownish grey core and orange rim in the quartz veins occurring in MGG and CGG; (5) yellow core and orange rim in quartz veins of tungsten prospects; (6) irregularly distributed patches of blue and greenish yellow in SG; and (7) irregular colour zoning in patches of orange to yellow in mica schist from zone of wall rock
alteration adjoining tungsten mineralised quartz veins, in which the tourmaline is studded with large number of quartz inclusions.

Wolframite mineralization is recorded in quartz veins trending N-S to NNE-SSW and occurring in Barotiya mica schist and Sewariya granite near Motiya, Pipaliya, Richmaliyan, Kotariya and Bijathal villages. These veins consist of milky white quartz, tourmaline, muscovite and wolframite. The X-ray diffraction and micro probe analysis show that wolframite is ferberitic in composition with average composition of \( \text{Fe}_{0.82} \text{Mn}_{0.30} \text{W}_{0.95} \text{O}_4 \). The excess at Fe-Mn site (>1) and deficiency (<1) at W site may be due to presence of some iron in Fe\(^{3+}\) state (Clark, 1970, Moore and Howie, 1978). Concentration of Fe is largest in the core of the wolframite samples, however, there is no systematic variation in huebnerite: ferberite (H/F) ratio from core to rim of these samples. Although we have not undertaken a detailed study on wolframite composition, the observed results suggest that wolframite of ferberitic composition could have precipitated from acidic hydrothermal solution, which was also responsible for alteration of alkali feldspars in the wall-rock to muscovite due to fluid-rock interaction.

The result of EPR study by Dhanya et al. (2005) on quartz samples from different quartz veins of Sewariya-Govindgarh area show that incidence of tungsten mineralization in a quartz vein can be recognized from EPR spectra of quartz. The EPR spectra of milky white quartz from the quartz veins occurring in tungsten prospects and within Govindgarh granite are comparable in all conditions, suggesting that these two belong to the same type. However, there is a clear distinction between the EPR spectra of these milky white quartz samples and the sample of grey quartz from barren quartz vein of Sewariya granite affinity, marked by contrasting trends in the relative intensity of \( E_1^- \) and peroxy centers after gamma irradiation.

From fluid inclusion study of quartz from tungsten-mineralised quartz veins of Sewariya-Govindgarh area, Sharma et al. (2003) have inferred that wolframite precipitated from a saline (32.49 to 43.34 wt.% NaCl equivalent) aqueous solution at temperature of 405 to 455°C and 250 to 300 bar pressure corresponding to depth of about 2500 m. Greisenisation of wallrock Sewariya granite and mica schist is prominent around mineralised veins, marked by introduction of muscovite, tourmaline and quartz.

Cell dimensions and c:a axial ratio of tourmaline from different rocks types, calculated from X-ray diffraction analysis, show that tourmaline from GG varieties and mineralised quartz veins have composition along schorl-dravite series and closer to schorl, whereas metasomatic
tourmaline from SG is distinctly different from others, having larger a and c dimensions. It is also observed that there is no systematic variation in cell dimension of tourmaline from the three litho-units which represent the magmatic (MGG), pegmatitic (CGG) and hydrothermal stages (mineralised quartz veins) of leucogranite magmatism. In case of tourmaline from CGG, there is little variation in cell dimensions from core to rim of single crystals, with cores tending to be closer to schorl along schorl-dravite line.

Chemical composition of tourmaline from various litho-units shows that these fall mostly within schorl field [in plot of Fe/(Fe+Mg) vs. Na/(Na+Mg)] with few tourmalines from MGG and quartz vein lying marginally in dravite field. Tourmaline from SG and CGG falls in the Fe rich portion of schorl field. The composition of tourmaline from different types of GG and the hydrothermal quartz veins is intermediate between end members schorl-dravite.

The variation in Na content in X-site of tourmaline is due to its substitution by vacancy and the resultant charge imbalance is compensated by Al$^{3+}$ substituting for divalent (Fe, Mg) in Y-site. Positive correlation between Al$^{3+}$ in Y site and vacancy in X site among the tourmaline samples from various litho-units shows that coupled substitution $(\text{Na}_X + (\text{Mg, Fe})_Y = \text{Al}_Y + \text{Vacancy}_X)$ has played a significant role in X and Y site occupancy of tourmaline. The X-site vacancy is smallest in SG tourmaline and largest in those from GG types. The significant values of vacancy in X site of tourmaline from GG phases shows that these alkali-deficient tourmaline crystallised from a melt depleted in alkalis as a consequence of albite fractionation.

The tourmaline from the study area shows optical zoning of different shades of blue and green, which could be related to another common substitution called dehydroxylation substitution involving $(\text{Fe}^{2+},\text{OH}^-) = (\text{Fe}^{3+},\text{O}_2)$. The dehydroxylation and alkali-defect substitution are common between schorl-dravite series.

The substitution of Mg in the Y-site of tourmaline is relatively higher in MGG and quartz vein tourmaline than that of CGG with inverse relation between Fe and Mg in all GG related phases (LGG, MGG, CGG and mineralised quartz vein). The difference in Mg content of tourmaline between MGG and CGG is attributed to scarcity of Mg in the late stage granitic melt from which CGG crystallised. Higher Fe/(Fe+Mg) values in tourmaline of CGG as compared to that of MGG indicates increasing Fe and decreasing Mg with progressive differentiation of the magma. Higher concentration of Mg in quartz vein tourmaline implies the effect of fluid-rock interaction which could have increased the Mg content of hydrothermal solution and
consequently more Mg is incorporated in Y site of tourmaline which precipitated from the hydrothermal solution. In contrast, Sewariya granite tourmaline shows an increase in Mg along with Fe in Y site. Tourmaline from SG shows inverse relationship between Al+Li and Fe in Y-site [plot of Al+Li in Y site against Fe in Y site], which indicates that coupled substitution Fe$^{2+} \rightarrow$ Al$^{3+}$ + Li$^+$ has played a significant role in Y site occupancy of metasomatic tourmaline in SG. Substitution of Si+Ti for Al in Z site is also noted in all the tourmalines. The extent of Si+Ti substituting for Al in Z site varies widely in MGG and SG, as compared to CGG and quartz vein tourmalines. Between CGG and quartz vein tourmalines, it is noted that the later shows greater substitution of Si +Ti in Z-site.

Core to rim variation in Y site cations and X site vacancy appears to be not systematic in general, though regular variation trends in some of the cations are observed. In MGG, Fe$^{2+}$ occupancy in Y site increases from core to rim accompanied by decrease in Mg$^{2+}$ and a small decrease in Al$^{3+}$+Li$^+$ in Y site, which may be responsible for a small zone of blue core surrounded by a wide zone of yellowish green rim. In CGG, Fe$^{2+}$ decreases from core to rim accompanied by a small increase in Al$^{3+}$+Li$^+$ in Y site. In quartz vein tourmaline, Fe$^{3+}$ in Y site increases slightly from core to rim and this is not accompanied by proportionate variation in other cations. From these variation trends, it is inferred that different types of colour zoning observed in the tourmalines from various litho-units is primarily due to variation in iron content from core to rim. The opposite trends observed in Fe$^{2+}$ variation in tourmalines of MGG and CGG, however, does not explain their comparable colour zoning pattern in thin section (blue core and yellowish green rim, with a difference in the extent of these colour zones). Dietrich (1985) has observed that blue colour of tourmaline can also be caused by Fe$^{2+} \rightarrow$ Fe$^{3+}$ charge transfer. Since in our analysis, Fe$^{3+}$ component of total iron is not determined and the total iron is expressed as Fe$^{2+}$, the effect of Fe$^{2+} \rightarrow$ Fe$^{3+}$ charge transfer on the colour variation of tourmaline in thin section could not be established. Core to rim compositional variation in the tourmaline from SG is irregular, and it corresponds well with patchy and irregular colour zoning observed in this type of tourmaline.

The Sewariya granite and both varieties of Govindgarh granite are peraluminous with A/CNK ratio >1. However, there is a wide range of A/CNK ratio in GG compared to SG, which is attributed to the presence of more number of alumino-silicate minerals (tourmaline and garnet, in addition to feldspars and muscovite) and minor variation in their relative proportion. The
major and trace element composition of medium grained GG and coarse grained GG are comparable, while these are different from SG in many elemental abundances. GG has a narrow range of SiO\textsubscript{2} and a wide range of alkalis, whereas SG has a wide range of SiO\textsubscript{2} and a narrow range of alkalis. GG is enriched in Na\textsubscript{2}O compared to K\textsubscript{2}O, whereas SG contains more K\textsubscript{2}O than Na\textsubscript{2}O. This is related to the abundance of sodic plagioclase over K-feldspar in GG, and vice-versa in SG. Characteristic variation trends of MgO, CaO and Fe\textsubscript{2}O\textsubscript{3} vs. SiO\textsubscript{2} are observed in SG with decreasing content of these oxides with increasing concentration of SiO\textsubscript{2}. Such variation trends are not observed in both the varieties of GG.

Large differences exist in concentration of Rb, Nb, Y between GG and SG, with all these 3 elements enriched in SG as compared to GG. The range of concentration of Rb, Sr, Ba, Y, Nb and Zr is much wider in SG, and in many bivariate plots of these trace elements there is either positive correlation (in Nb-Y, Y-Zr, Sr-Zr, Sr-Ba) or inverse relation (in Rb-Sr) between pairs of trace elements. In the two varieties of GG, the range of concentration of these trace elements is relatively narrow, and no correlation is discernible in the bivariate plots.

Sewariya granite falls close to the ternary minima (haplogranite filed) in Qz-Or-Ab diagram (Tuttle and Bowen, 1958), corresponding to water pressures of 500 to 3000 bars. Some samples of GG lie close to ternary minima at relatively higher water pressures between 3000 and 5000 bars, while many samples of GG are scattered away from ternary minima for different water pressures. Since the samples of GG do not show any definite differentiation trend in silica vs. other elements variation diagrams, it is inferred that the scattered disposition of GG in Qz-Or-Ab diagram indicates the variation inherited from heterogeneous source rock. The relative positions of SG and GG in the same plot also indicates that generation of SG melt took place at lower water pressures as compared to that of GG melt.

Multi-element variation diagram (spider diagram in Fig. 7.8) shows that Sewariya granite produces trough for Sr, P and Ti, whereas GG produces trough for P and Ti and not to Sr. The patterns produced by GG and SG are comparable with upper continental crust values. Higher concentration of Zr and Y present in SG as compared to GG, indicates that SG melt was generated at relatively higher temperature from a source rock which consisted of insufficient quartz, orthoclase, albite and water.

The W concentration in both GG and SG is abnormal compared to average granite value of 1.5 ppm (Krauskopf, 1979). The average composition of the metallogenetically specialized
granites reported by Tischendorf (1977) match closely with GG as well as SG for many elements including tungsten. Higher concentration of W in GGs compared to normal granites is inferred to reflect their metallogenetic specialization. However, SG and the mica schist are inferred to have acquired abnormal concentration of W during infiltration metasomatism accompanying the youngest event of leucogranite magmatism (which produced GGs) in the study area. This is also supported by the fact that SG and mica schist are not far from the tungsten prospects (whereas the analysed GGs are several km away from nearest tungsten prospect).

Trace element modeling using Rb, Sr and Ba indicates that partial melting of mica schist of Barotiya group at amphibolite facies could generate magma of GG composition, while dehydration melting of intermediate rocks (sanukitoid) leaving granulite residue could produce magma of SG composition.

In tectonic discrimination diagrams (Rb vs. Y+Nb and Nb vs. Y) both GG and SG fall within syn-collision granite and volcanic-arc granite fields, in which SG forms a small cluster clearly separated from GG and occurs more towards the boundary of WPG. The two varieties of GG have a large spread of values in Y and Nb as compared to SG. Since fractional crystallisation of plagioclase is significant in SG magma, it is possible that a shift could have influenced the occurrence of SG samples in VAG and VAG+ syn-COLG fields but close to WPG field in Nb vs. Y and in Y+Nb vs. Rb diagrams.

Govindgarh granite is enriched in LREE and HREE, and depleted in the middle REE concentration, showing bowl shaped pattern in chondrite normalized REE plot, with positive Eu anomaly for many samples. The ΣREE of GG is 7.26 to 34.84 ppm which is 5 to 40 times greater than chondrite values. The ΣREE value indicates that a significant proportion of these elements (REE) were retained in the source during anatectic generation of the granitic magma. The higher HREE abundances in the GG samples show that accessory phases such as garnet, zircon, apatite, allanite and amphibole in the source rock could have participated in the generation of GG magma.

Various possible REE models involving partial melting without and followed by fractional crystallisation were attempted to calculate the source rock composition from which the GG magma could be derived. It is inferred that 5 to 20% partial melting of a heterogeneous source similar to mica schist of Barotiya group in study area leaving an amphibolite residue (90%
honblende+5% biotite+5% apatite) would produce a melt whose REE abundance is comparable with that of GG.

In Sewariya granite, the $\Sigma$REE is 50.91 to 187.49 ppm with LREE and HREE about 100 and 10 times greater than chondrite respectively. Various possible REE models involving partial melting without and followed by fractional crystallisation were attempted to calculate the source rock composition from which the SG magma could be derived. It is inferred that 5 to 30 % partial melting of a source similar to sanuktoid in the BGC of Masuda area, leaving a granulite residue (58% Plagioclase + 30% CPX + 10% OPX + 2% Garnet) could have produced the initial granitic magma. Subsequently, 5 to 30% fractional crystallisation of 50% Plagioclase + 49.5% Hornblende + 0.4% Zircon + 0.1% Allanite from this initial magma could have produced the magma from which SG was formed.

It is concluded from REE modeling that the parent magma of the two types of granites (GG and SG) were derived from partial melting of different source rocks within the crust and at different crustal levels. GG formed by partial melting of a heterogeneous source similar to Mica schist of Barotiya group, leaving amphibolite residue in the mid crustal level, whereas SG formed by partial melting of a source similar to sanuktoid in the BGC of Masuda area, leaving granulite residue in the lower crustal level and followed by fractionation

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 which also occur along the western margin of Delhi fold belt in the Aravalli craton. There are few similarities among these three tungsten deposits.

1) They occur along the western margin of NNE-SSW trending Mid-Proterozoic Delhi fold belt.

2) In all these areas, Mid-Proterozoic metasediments (dominated by pelites) are intruded by a older biotite granite which has been deformed along with metasediments, and a younger geochemically specialized granite which is the source for W mineralisation.

3) 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. Balda granite is a biotite-muscovite-tourmaline leucogranite containing accessory fluorite. Tourmaline in the Balda granite is a schorl showing dichroism (brown to colourless) in thin section and no colour zoning. Govindgarh granite is also a tourmaline leucogranite containing muscovite as essential mineral, but it is devoid of magmatic biotite, and often contains magmatic garnet. Tourmalines from Govindgarh granite have composition along schorl-dravite series and closer to schorl, and invariably show characteristic colour zoning in thin section with blue core and yellowish green rim.

2) **Relative volume of source granite and its derivatives:** Degana granite is a complex of 3 porphyritic granitic intrusions, 2 generations of aplites, greisen-bordered quartz veins, rare pegmatite and multitude of greisen veinlets, all occurring within a small area. Total volume of aplite dykes is significantly large in Degana area.

   Balda granite is a single, continuous and homogenous textured pluton exposed over a length of about 20 km and having maximum width of about 1 km. Quartz rich veins and few pegmatites occur, whereas aplite is not known in Balda area.

   Govindgarh granite is also non-porphyritic, 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 outcrop area, pegmatite component of Govindgarh granite is more compared to medium grained granite. Aplite is not found in Govindgarh area.

3) **Nature of mineralisation:** W mineralisation in Degana area is centered around the granite pluton and marginally extends into adjoining phyllite. Two episodes of mineralisation are recognized, each preceded by emplacement of a porphyritic granite and aplitic dykes. During each episode of mineralisation, few thick quartz lodes (up to 1 m thick) and a multitude of thin greisen veinlets have formed. Due to preponderance of greisen veinlets in addition to quartz lodes within granite pluton and adjoining phyllite, the host rocks of orebody show stockwork character with 0.08 wt.% WO₃ in granites and 0.08 wt.% WO₃ in phyllite. 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 first episode of mineralisation is zinnwaldite, and the one associated with second event of mineralisation is muscovite. During
the first episode of mineralisation, phyllite (of Phyllite Hill) is extensively brecciated, possibly
due to effervescence and resultant volume expansion of fluid. Such brecciation of host rock is
not known from the other two tungsten deposits.

In Balda area, wolframite bearing quartz veins (few 10s of cm thick) are localized along the
intrusive contact of leucogranite against mica schist. Apparently there is no crustification (or
zoning) in these veins. 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 less quartz) occurring within the leucogranite.

In Sewariya-Govindgarh areas, quartz-tourmaline veins containing wolframite occur
exclusively within mica schist and the older granite, parallel to prominent foliation in these
rocks.