CHAPTER-VI

Discussion and Summary

In this chapter, all the results obtained from the present study have been summarized and discussed. An attempt has been made to understanding the evolution of the rock types from Namakkal-Mohanur Corridor (NMC), possible equivalents of the oceanic remnants within the Cauvery Suture Zone (CSZ) considering the field geological settings, structural architecture and laboratory studies. A geological and structural map has been prepared for the first time for the NMC with particular emphasis on the newly constructed Rail cutting section. This is possible because of the fresh geological cross section exposed along the Rail cutting section with a strike length of about 6km between Namakkal and Mohanur, located in the south central part of the CSZ.

The chapter I deals with the introduction to the present work highlighting the significance in understanding the mafic-ultramafic rock association in the CSZ, in general, and the Namakkal-Mohanur corridor in particular. Features like significance of regional granulite facies rocks, brief review on Precambrian granulite terranes, scope, principal objectives of the proposed study, methodologies adopted, hypothesis to be tested, and a brief outline of the thesis are detailed.

The chapter II on the geology of Southern Granulite Terrane (SGT) provides details of different lithological units and some broad aspects of the tectonics. The important lithologies of Archaean and Proterozoic age groups include Sathyamangalam Group (>3200 Ma), layered mafic and ultramafic complexes, Bhavani Group (~3000 Ma), Kolar Group (~2900 Ma), Khondalite Group, Charnockite Group (~2600 Ma) and Migmatitic complex (2200-2250Ma) etc. The Proterozoic rocks include younger granulites/charnockies, granites,
alkali syenites, carbonatites, mafic and ultramafic intrusives mostly occurring in and around the Cauvery suture/ shear zone.

*The Sathyamangalam Group* consists of quartzite ±fuchsite ± kyanite ± sillimanite and banded iron formation, sillimanite schist ± garnet, kyanite- schist, corundum bearing mica schist and talc-tremolite schist; calc granulite, crystalline limestone/marble, ortho-and para amphibolites. The layered mafic and ultramafic complexes comprise dunite, peridotite, websterite, garnetiferous gabbro, gabbroic anorthosite occurs near Mettupalayam dominantly in the western part of the CSZ. They generally occur as enclaves within the migmatitic gneisses as a part of the dismembered sequence. Large volume of garnetiferous gabbro and hornblendeic anorthosite with chromitite layers as well as small lenses of eclogitic rocks are the characteristic features of this suite. *Bhavani Group* of rocks occurs mostly around Bhavani town in the form of typical exposures of peninsular gneissic group of rocks. Khondalite and Charnockite group of rocks and their reworked equivalents are the dominant variety of rocks in the SGT. *Khondalite Group* essentially consists of rocks of sedimentary parentage such as quartzite and garnet-sillimanite gneiss ± graphite ± cordierite (metapelites) and occur mostly to the south of Palghat-Cauvery Shear Zone (PCSZ). *The Charnockite group*, comprising charnockite (hypersthene bearing granite), two-pyroxene granulite, banded quartz-magnetite granulite/banded magnetite quartzite and thin pink quartzo-feldspathic granulite, are extensively developed in the north-eastern sector of the SGT.

The SGT has witnessed two major periods of granitic activity resulting in the development of migmatites, initially during Neoarchaean to Palaeoproterozoic and another during Neoproterozoic period. The Alkaline magmatism has also witnessed two events of alkaline magmatism, during Paleoproterozoic period as well as Neoproterozic periods. A number of mafic dyke swarms traverse the northern part of the SGT and intrude the charnockite and migmatite group of rocks with varying trends. The anorthosites and
ultramafic rocks occur in the southern part of the terrane (Oddanchatram, Kadavur and Tirunelveli), south of the PCSZ indicating that they were possibly emplaced within a Palaeoproterozoic crust. The SGT broadly witnessed two granulite facies metamorphic events: Neoarchaean (ca. 2.5 Ga) and Neoproterozoic (ca 1.0–0.55 Ga). Ultra high temperature metamorphism at T=900-1150°C and P=7-13 Kbar and eclogite facies rocks are also recorded in the SGT.

Three important Precambrian ophiolite complexes are recently reported from the CSZ that include: Manamedu (MOC), Devanur (DOC) and Agali (AOC) complexes. Their lithologies, structural styles, geochemical signatures and geochronological data are described in the chapter. The zircons in the two plagiogranites samples of MOC yielded ~780Ma. Devanur ophiolitic complex (DOC) has yielded SHRIMP zircon 238U-206Pb ages of 2528±61 and 2545±56Ma. The U–Pb concordia ages of zircons in the metagabbro and trondhjemite of AOC yielded ~2.5Ga, which are correlatable with similar age data reported recently from DOC. A tectonic model was also proposed envisaging accretion of oceanic arcs and micro-continents onto the margin of the Dharwar Craton during Neoarchean.

The field observations and the geochemical signatures of all the three ophiolite complexes suggest the magma derivation in a suprasubduction setting. The lithological distribution in the area has been interpreted to represent a typical ‘Ocean Plate Stratigraphy’ sequence with arc and exhumed sub-arc mantle material. They also represent the remnants of the Mozambique Ocean crust developed during Rodinia breakup and which was destroyed during Cambrian period at the time of Gondwana amalgamation.

Different tectonic blocks are recognized in the SGT and are separated by two major shear zones namely the Cauvery Suture/ Shear Zone (CSZ) and Achankovil Shear Zone (AKSZ). The CSZ has been variously described attributing its tectonic significance as detailed in the chapter. Importantly, the CSZ is considered as the trace of the Cambrian suture.
zone of Gondwana. The CSZ trends E-W and constitutes a set of parallel pervasive shear zones that include: (1) the Moyar-Attur Shear Zone, (2) the Bhavani Shear Zone, (3) the Palghat-Cauvery Shear Zone (PCSZ), and (4) the Achankovil Shear Zone. The disposition, regional geometry, dramatic variations in foliation fabrics, persistent dextral kinematic indicators on all scales of observation, the apparent contemporaneous development of mylonitic fabrics based on Rb–Sr mica ages and the presence of possible convex upward reversed or thrust faults suggest that the CSZ could reflect a crustal-scale ‘flower structure’. The Madurai Granulite Block is the largest crustal block in southern India. The AKSZ holds a key position in juxtaposing the member terranes in the East Gondwana supercontinent. The AKSZ has been correlated with the sinistral Ranotsara shear zone of Madagascar.

The Chapter III summarizes the detailed geological and structural mapping of ~6km long recently constructed Rail cutting section in the Namakkal-Mohanur corridor (NMC), located in the south central part of the CSZ. The section provided unique opportunity to study excellently exposed geological cross sections. Regionally, many large-scale structural features such as shear zones, fold patterns, elliptical closed structural forms and the regional orientations of structural trends are interpreted from the Satellite images, in general, correspond to the gneissic foliations (S1).

The study area of rail cutting section orthogonally cuts across the eastern part of the E-W trending PCSZ. The fold structures within the shear zone show tight-isoclinal folds, often exposing the fold hinges parallel to the shear zone boundaries. The important rock units are: mafic-ultramafic assemblages, amphibolites, hornblende gneisses, charnockites, granitoids and pegmatites. Pyroxenites, gabbros, peridotites, hornblendites, serpentinites form mafic-ultramafic assemblages and occur in the form of bands, lenses and pods. These are intercalated with minor thin bands of chert and Plagiogranite/trondhjemite. All these rocks trend WNW-ESE and are isoclinally folded with gentle to moderate dipping axial planes to
north. Based on the field observations, a series of north dipping thrust/shear zones, associated with imbricate thrusting are inferred from the section.

The analysis of deformational history of the region reveals two events: The D1 structures consist of at least two events of progressive deformation that produced near coaxially refolded isoclinal folds (F1–F1a) that trend WNW-ESE. The resultant axial planar foliation is referred to here as S1, which corresponds to the metamorphic gneissic foliation. The D1 fabrics described here are well preserved, as evident field observations, showing low D2 strain at several places, particularly east of Namakkal. Regional E-W trending refolded isoclinal fold structures (F1–F1a) are well defined by two -pyroxene granulites and banded magnetite quartzites. Shallow dipping S1-fabrics and down-dip lineations are often recorded in the hinge regions of F2 folds. Mineral lineations (L1) as well as other concomitant structures such as boudinages along the competent layers such as pyroxenites, hornblendites, websterites, peridotites which could be related to D1, are also recognisable on mesoscopic scale outcrops. The D1 event included a dominant north south shortening with a possible component of vertical shortening.

The regional pattern of finite strain is quite heterogeneous with most strain concentrated along the shear zones. The S1 plane is reworked and/or transposed in to a new penetrative, steep mylonitic foliation (S2). The L1 stretching lineations are progressively reoriented and replaced by the pronounced L2 shallow plunging lineations consistent with the development of S–L tectonites. The L2 lineations are mostly north or north east plunging. The D2 event is manifest in refolding of F1 isoclinal folds leading to kilometer scale elliptical (F2) folds. The F2 folds are mostly non-cylindrical with gentle to moderate easterly plunges. All the evidence described above suggests that D2 deformation is a combination of (i) pure shear associated with north–south shortening and (ii) simple shear together with dextral strike
slip shearing, which can be described as transpressional tectonics, similar to modern collisional zones.

The Rail cutting section has been divided into 6 zones based on distinct lithological assemblages and the presence of important shear zones. Each zone is characterized by the predominance of distinct lithological association and are classified as follows: Hornblende gneiss-Pegmatite association (Zone I), Charnockite-Pegmatite association (Zone II), Charnockite-Pyroxenite association (Zone III), Granulite (Felsic & Mafic)-Amphibolite-Pyroxenite association (Zone IV) and Metagabbro-Amphibolite-Pegmatite association (Zone V). The lithological and structural details of each zone are described separately in the chapter.

Zone I represents the northern most segment with a width of about 1km striking WNW-ENE. The poles to the foliation show dips on either side with moderate values suggesting that the rocks strike nearly east west and are isoclinally folded. The rocks often show recumbent fold structures exhibiting highly weathered gneissic rock intruded by pyroxenites, which are further intruded by 30-50 cm wide horizontal pegmatite veins. The interpreted structural cross section shows south verging thrust planes associated with northerly dipping refolded folds. Large recumbent fold structures with near horizontal axial planes are common. A few southerly dips are also recorded which may represent hinge zones of broader recumbent folds emerging from north.

The interesting feature in Zone-II is its association with the intrusives of plagiogranite/trondhjemite/ and pegmatites occurring both across and parallel to the foliation fabrics. All the foliation poles suggest that the dips are mostly to south west with moderate to steep values. All the lineations are clustered showing moderate plunges to south. The structural cross section shows refolded folds often showing sheath fold geometries. Thrust planes dipping to north are also inferred which are associated with serpentine outcrops.
The Zone III comprises major rock units such as mafic and felsic granulites, pyroxenites, hornblendites, charnockites and metagabbros. The rocks trend WNW-ENE with a dominant northerly dips. The lineations show moderate to steep plunges to north and north east. The structural cross section shows broad thrust related refolded fold structure indicating its emergence from north. The lensoid bodies of hornblendite and pyroxenites occur in the core of the broad aniformal fold.

The major rock units in Zone IV include mafic and felsic granulites, metagabbros, pyroxenites, hornblendites, hornblende gneisses, amphibolites and plagiogranite/trondhjemite which trend WNW-ENE with dominant northerly dips. The foliation poles show their maxima in the southern sector suggesting the predominant moderate to steep dips to north. The lineations also show moderate to steep plunges to north and north east. Field observations show that the development of foliations within the mafic ultramafic rocks indicates the intensity of deformation. At several places, steeply dipping foliated mafic ultramafic rocks are also recorded. The structural cross section shows isoclinal folds dipping mostly to north. Two important south verging thrust planes are inferred and are associated with mostly hornblendite and hornblende gneisses.

Zone V is an important segment representing the southern most part of the rail section with the presence of a major shear zone at the southern contact with an E-W trending chain of Neoproterozoic granite plutons. The other important rock units are amphibolites, mafic and felsic granulites, metagabbros, pyroxenites, hornblendites, hornblende gneisses, peridotites and plagiogranite/trondhjemite, trending WNW-ENE with a dominant northerly dips. The foliation poles suggest predominant moderate to steep dips to north. The lineations also show moderate to steep plunges to north and north east indicating the tectonic transport from north to south.
A variety of structural features are well brought out with large scale sketches displaying mutual relationship of distinct rock types and different structural styles. The presences of sheath folds of different sizes are also well exposed in this section and with gently and southerly dipping thrusts are recorded. Thin veins of plagiograni te/trondhjemite occur along the foliation planes. Well defined north dipping shear zones, relict horizontal foliations and deformed sheath fold structures are well preserved in association with south verging thrusts. The presence of tectonic mélanges is also a striking feature displaying the chaotic assemblage of fragments of pyroxenites, websterites, amphibolites and syenitic gneisses.

A regional structural cross section presents a range of structural features such as foliation fabrics, fold styles, stretching lineations, shear zones and interpreted thrust planes and associated imbricate structures. From north to south, the dominant structural features are inferred as recumbent structures in Zone I, folded curvilinear axial planes in Zone II, tight isoclinal fold structures in Zone III, very tight isoclinal folds in Zone IV and folded axial planes with near recumbency in Zone V. All the zones are separated by south verging imbricate thrust zones marked by mylonitic fabrics. It is also possible that all these imbricate thrusts are linked to roof and floor thrusts suggesting that they could be duplex structures emerging from north. This kind of structural pattern is similar to the structures described between Mahadevi and Manamedu Ophiolite complex, 25 km east of the present study area. The NMC and MOC form a typical part of the south verging back thrust in the framework of the crustal scale ‘Flower structure’, defined by (Chetty and Bhaskar Rao, 2006), implying that the rocks witnessed transpressional tectonic regime and collisional processes.

Petrographic details of all important rock units are provided in Chapter IV. Peridotites are generally medium- to coarse-grained, comprising mineral assemblages such as olivine (40-50%) and orthopyroxene (40-50%) with accessory amphibole, spinel and opaque
mineral. Clinopyroxene is absent. There are also rare amphiboles which are medium-grained (0.3-0.6mm) and xenoblastic, and occur along the grain boundaries of pyroxenes indicating its retrograded nature. The rock shows cumulate texture with spinels occurring along the grain boundaries of orthopyroxene and olivine.

*Hornblendites* are composed mostly of amphibole (~80%), orthopyroxene (10-20%), and accessory plagioclase, quartz, biotite, chlorite, rutile, and calcite with cumulate texture in some samples. Fine to medium-grained (up to 0.5 mm) quartz and plagioclase are present along the grain boundaries of amphiboles and show xenoblastic texture. Fine- to coarse-grained biotite (0.1-1.4 mm) is partly replaced by retrograde chlorite and calcite fills grain boundary of most amphibole grains. Some orthopyroxene grains are transformed into hornblende and biotite is seen within the amphiboles. Plagioclase is fine-grained (up to 0.1mm) and is seen as inclusion within coarse-grained orthopyroxene as a relict and this texture suggests amphibole was probably formed by the following decompression/hydration reaction: Orthopyroxene + Pl + H2O => Amph.

*Pyroxenites* consist of clinopyroxene (50-60%), orthopyroxene (30-40%), and amphibole (10-20%) with accessory opaque minerals and show primary magmatic cumulus texture under the microscope. Clinopyroxene contains inclusions of quartz, while orthopyroxene contains biotite possibly as primary minerals. Although, the rocks are tectonically highly disturbed but are free from foliation fabrics. Some of the phenocrysts of clinopyroxenes show orthopyroxenes as relict granulations suggesting their derivation from the later. Typical igneous textures are characteristic features of these rocks implying equilibrium of crystallization. Garnet and secondary hornblendes are present. Garnet is surrounded by hornblende, which shows wavy extinction. Reaction rims of hornblende are also present. Secondary epidotes are also common and the opaque minerals represent magnetites.
Garnet-clinopyroxene rock (ultramafic rock) is characterized by the association of garnet (30-40%), clinopyroxene (30-40%), amphibole (10-15%) and orthopyroxene (5-10%) with accessory rutile and other opaque minerals. As the amphibole fills the matrix of pyroxenes and garnets, and is regarded as a retrograde mineral. Rutile and opaque minerals occur together with amphibole and therefore, they could also be retrograde minerals.

Metagabbro is composed of clinopyroxene (40-50%), garnet (20-30%), orthopyroxene (10-20%), amphibole (10-20%), and plagioclase (5%), with accessory zircon (Zr) Rutile, and ilmenite. Amphiboles are formed along grain boundaries of pyroxenes as retrograde minerals. Garnet is subidioblastic and contains the inclusions of clinopyroxene and plagioclase. Garnet and ortho/clinopyroxenes are separated by symplectites of plagioclase + amphibole, probably suggesting the progress of the following retrograde reaction:

\[ \text{Grt} + \text{clinopyroxene (Orthopyroxene)} + \text{Qtz} + \text{H}_2\text{O} \rightarrow \text{Amph} + \text{Pl} \]

\[ \text{Grt} + \text{Orthopyroxene} + \text{Qtz} + \text{H}_2\text{O} \rightarrow \text{Amph} + \text{Pl} \]

Amphibolites are composed of amphibole (40-50%), plagioclase (20-30%), and quartz (20-30%), with accessory garnet, apatite, biotite, calcite, rutile and opaque minerals. Some amphiboles also show inclusions of vermicular quartz and plagioclase. Rare fine-grained garnets (up to 0.1 mm) are also seen within plagioclase, but most of the garnets were probably completely changed to other minerals.

Quartz occurs along the grain boundaries of amphibole and orthopyroxene probably as a recrystallized mineral. Some fine-grained (less than 0.2 mm) biotite grains occur as inclusions in amphiboles indicating that they represent retrograde minerals. Orthopyroxene is partly transformed to amphibole. Amphibole, plagioclase and orthopyroxene are also present along cracks within the garnet. All these features suggest that the rock is retrogressed and recrystallized. Plagioclase fills the grain boundaries of amphibole or occurs as thin film around garnet. Garnet is often surrounded by plagioclase + fine-grained amphibole and shows
symplectite texture, suggesting that the progress of the following retrograde reaction: Grt + Qtz + H2O => Amph + Pl

Banded Iron formation (BIF) shows mylonitic texture with alternate bands of quartz and magnetite-rich layers. Plagiogranites show granular texture as an igneous rock and comprise dominantly of quartz (50-60%) and plagioclase (30-40%) with accessory biotite, muscovite, chlorite and calcite. Calcite grains are seen within the plagioclase. Quartz and plagioclase are mostly present along the grain boundaries of quartz and feldspars, or along secondary cracks in plagioclase and quartz.

Quartzo-feldspathic gneiss is composed of plagioclase (35-45%), quartz (35-45%), garnet (10-15%), clinopyroxene (5-10%), and orthopyroxene (1-3%) with accessory amphibole, biotite, apatite, muscovite, opaque mineral and zircon. All minerals are stretched along the foliation planes of the rock defining mylonitic fabrics. Quartz also shows ribbon texture. Opaque mineral and zircons are generally scattered in the rock. Microscopic studies suggest that the rock is retrogressed and mylonitized.

The chapter V summarises the geochemical characteristics of different rock units from the NMC. The ultramafic rocks (peridotites) show high Mg# (82.65-85.72) and high Ni contents with primitive magma characteristics. The depletion of Nb, Rb and Sr and enrichment of Ba might be products of the subsequent granulite facies metamorphism witnessed by these rocks. The geochemical data of amphibolites obtained suggest that their protoliths consist of basaltic rocks with calc-alkaline differentiation trends. The standard tectonic discrimination plots (Y vs Cr, Zr vs Ti, Vs Ti) of these amphibolites show Island Arc Tholeiitic signatures; Normalized MORB spider plots reveal the enrichment of LILE and depletion of HFSE with clear negative Nb anomalies. These characteristics are typical of ophiolitic rocks formed in a suprasubduction zone environment similar to many SSZ ophiolites world wide. The geochemical characteristics of mafic dykes/amphibolites form
MOC and DOC in the adjacent region of NMC also show similar characteristics implying suprasubduction zone tectonics. The existence of SSZ-type tholeiites with strong geochemical signatures are indicative of pre-melting subduction influence, which provide evidence for the development of arc-like crust by melting of a mantle source above the subduction zone.

The amphibolites from NMC show slight LREE enrichment and HREE flat patterns with positive Eu anomalies. The Lu/Hf vs La/Sm ratio plot represents the protoliths were derived from spinel-lherzolite mantle composition. The plagiogranite intrusions within the NMC are leucocratic trondhjemitic in nature characterized by low potassium (< 1wt% K2O; except one sample) and high sodium (4.9–7.1 wt% Na2O) contents. The very low potassium content has been suggested as a diagnostic feature of oceanic and ophiolitic plagiogranites. The rare earth elements (REE) show relatively low absolute concentrations and flat chondrite normalized patterns (3-30 × chondrite) with distinct, but variable, +ve Eu anomalies represent the feldspar involvement during fractionation of magma. The geochemical features described above are consistent with the hypothesis that the arc-related calc-alkalic and tholeiitic basalts typically show moderate degrees of light rare-earth-element (LREE) enrichment, and flat heavy rare-earth-element (HREE) profiles, indicating an origin in a shallow (spinel-lherzolite) mantle and more evolved magmas exhibiting positive Eu anomalies, consistent with low pressure plagioclase fractionation.

The tectonic setting of Proterozoic ophiolites from different geological terranes has been described by several workers. The CSZ in southern India has been recently interpreted as the zone of closure of the Neoproterozoic Mozambique Ocean. The supercontinent Rodinia assembled in the Mesoproterozoic ~1300 Ma and broke up during the Neoproterozoic at ~800 Ma. The Mozambique Ocean formed during the breakup of Rodinia (although some authors represent its coexistence with Rodinia as one of its flanking marginal oceans) and closed with the assembly of the Gondwana supercontinent at ~550 Ma. It has
been postulated that the Mozambique Ocean has contracted by subduction beneath either or both of the India-Madagascar and east African margins while the Palaeo-Pacific Ocean grew between Australia-Antarctica and Laurentia during mid-Neoproterozoic along with the break-up of Rodinia. The final closure of the Mozambique Ocean is thought to have occurred during the late Neoproterozoic at the end of Precambrian along with the formation of Gondwana. Magmatic cores of zircons from the plagiogranites and gabbros in Manamedu Ophiolite Complex yielded U-Pb age of 800 Ma which correlates well with the Wilson Cycle of the Mozambique Ocean following Rodinia breakup at around 800-750Ma. The U-Pb Zircon ages of metagabbro from NMC yielded 769 Ma age (Koizumi et al., 2012) which suggests the same age of evolution history of the complex along with Manamedu Ophiolite Complex and might represent the continuation of the MOC.

The Proterozoic mosaic of southern India is believed to be a collage of crustal blocks divided by Neoproterozoic-Cambrian crust-scale shear/suture zones. The CSZ has been considered as the trace of a Cambrian suture and continuation of Betsimisaraka suture zone from Madagascar and represents the Mozambique Ocean closure during the final phase of amalgamation of the Gondwana supercontinent (Collins and Pisarevsky, 2005). The reported occurrences of MOC, DOC, AOC and the newly reported NMC (the present study) represent oceanic remnants within the CSZ and provide a unique opportunity to unravel the different stages of Wilson cycle of the Mozambique Ocean as well as the tectonics. Further, these rocks, together with the occurrence of eclogite facies rocks with garnet+omphacite+quartz and diagnostic ultrahigh-temperature assemblages with sapphirine+quartz, spinel+quartz and high alumina orthopyroxene+ sillimanite+quartz (indicating extreme metamorphism), suggest that the rocks of the CSZ witnessed the subduction-collision processes during Neoarchean as well as Cambrian-collisional orogenies in the SGT at the southern margin of India. However, the formation of the Cambrian suture, the trace of which is marked in the southern margin of
the CSZ in the SGT, southern India, is well depicted in the tectonic model (Fig. 6.1) given below (Santosh et al., 2009).

Fig. 6.1: Cartoon illustration showing a composite plate tectonic model for southern India from North (Archaean Dharwar Craton) to South (Pacific-type orogen) with two major collisional orogens in between. The PCSZ/CSZ represents the main suture developed through Mozambique Ocean closure. The cross section also covers ACSZ + KKB/Trivandrum Block up to the Nagercoil Block at the southern tip. The Madurai Block represents a wide magmatic arc in between (after Santosh et al., 2009).
LIST OF PUBLICATIONS


ABSTRACTS


