CHAPTER 7
SUMMARY AND CONCLUSION

The investigated area is a north easterly extension of the Assam Meghalaya Plateau, situated at a distance of 20 km from the heart of the metropolis of Guwahati of Kamrup district, Assam, the only premier city of the NE region of the Indian subcontinent. The area is confined within the 26°11' - 26°14' N latitudes and 91°50' - 91°55' E longitudes.

Geologically the area is a part of the basement gneissic complex composed of varied lithologies of acidic to basic, to calcareous composition resulting the development of quartzofeldspathic gneiss as the most dominant rock. Amphibolite, hornblende biotite schist, biotite schist, calc silicate rock, basalt, dolerite, pegmatite and other vein rocks are enclaved within, and maintain an interlayering relationships either as discontinuous lenses or impersistent layers of varied thickness. All the different rock types occur as layers of different orthogonal thicknesses found within the quartzofeldspathic gneissic host, and specifically the most persistent and relatively thinly layered amphibolite acts as the marker horizon which helps in working out the regional structural configuration of the area. Hornblende biotite schist, although almost indistinguishable in the field from amphibolite, is intimately associated with other dark and light coloured rock associations and form a broad banded gneissic look of the gneissic terrain. Such dark coloured rocks are designated as metabasites irrespective of their genetic aspects. Calc silicate rocks exhibit bandings of varied composition and they are intricately deformed. Biotite concentration in the form of lenses at the contact between quartzofeldspathic gneiss and amphibolite, and rarely between quartzofeldspathic gneiss and calc silicate rock might be indicative of metasomatic product and not a true representation of the pre-existing pelitic remnant.

Instability prevails over the entire lithosetting of the area resulting restructuring and recrystallisation of the parental composition and display evidences of greater crustal instability or mobility leading to the formation of folds, foliations, lineations, joints, fractures and faults of both extensional and contractional tectonism. The vein rocks also play an important role in
deducing the structural history of the area. The emplacement of these vein rocks are structure controlled and may belong to different generations rather than their emplacement in the structural weak locales of different generation of folds towards a late phase of brittle deformation.

The rocks of the area suffered from polydeformational events and associated poly metamorphism resulting folds, foliation and lineation under a dominant ductile field which merged into brittle stage and developed large scale fracturing and faults. Four deformatonal events resulting three generations of folding (F, to F3), foliation (S, to S3) and lineation (L, to L3) are observed in the field.

The earliest deformatonal imprint is marked in the form of intrafolial, rootless folds, found within the most ductile quartzofeldspathic gneissic host and are usually marked by the competent rocks. The sheared out lenses and boudins are also the resultant fabrics of this deformation. Such F1 folds are invariably associated with axial planar foliation (S1) which cuts the hinges of F1 folds at maximum angle and gradually decreases away from the hinges and finally made parallelism with the tectonically attenuated limbs of the folds. S1 foliation is highly penetrative irrespective of rock associations excepting vein rocks and later intrusives in the form of sills and dykes and clearly predate other deformatonal events. On the regional scale S1 is parallel to lithological layering (S0) and hence considered as a form surface for identification of the superposition of later deformations. Thorough recrystallisation and / or crystallisation under metamorphic environment took place syngenetic to first phase deformation. The original attitudes of the layerings could not be ascertained due to intensive shearing but it is apparent that the original bedding was horizontal or nearing so and layer parallel shear couple results the development of transposition of bedding cum layerings. Thus the initial layerings suffered more and more shortening and entered in the field of extension, ultimately transposing into a new planar fabric S1 (= S0). Hence the pervasive foliation (S1) is the resultant of tectonic and metamorphic restructuring under ductile environment and promoted the growth of different set of minerals and their preferential alignment along the axial surfaces of F1 folds of first generation.

The D2 deformation largely controlled the regional configuration of the lithological layerings (S0) and regional foliation (S1) and is marked by a km sized antiform and a synform around
Forest gate and Narengi Patthar quarry areas in the south western sector and Tatimara and Chandrapur in the north eastern sector. Minor folds of $D_2$ deformation show varied geometry showing asymmetric to overturned types and they are, in most of the cases, coaxial with $F_1$ fold geometry. The penetrative $S_2$ plane acts as a diagnostic tool to differentiate $F_2$ folds from $F_1$ folds. Most of the $F_2$ folds suggest that they are upright in nature showing nearly sub-vertical axial plane and subhorizontal plunge of the fold axes. The trend of the $F_2$ folds change from E-W to NE-SW. The curvature of the axial traces of the major $F_2$ folds is the resultant of superposed $F_3$ folds. The $F_2$ are parasites to the major folding, and the sense of asymmetry acts as a good indicator of shear, showing flexural slip mechanism. This deformation largely results the crustal shortening and neither large scale shearing nor change over shortening mechanism to extension took place during this deformation, and is, probably, the cause of no major recrystallisation or readjustment in the transposed composition of the rocks. The deflection of $L_1$ lineation from the $F_2$ fold axes indicates shortening during $D_3$ deformation along the axial direction of the $F_2$ folds. The present up and down facing folds of different dimensions show non cylindricity and non planar habit and it is apparently due to the influence of later deformational impacts over the initial NE-SW trending cylindrical folds of near horizontal plunge.

The $D_3$ deformational impact was relatively of mild type and developed NW-SE trending asymmetric folds. Such folds show characteristic short and long limb, short limbs dip north easterly while the long limbs dip south westerly at a lower angle than the other. Interference of $F_3$ is the sole cause of axial curvature of the $F_2$ major fold.

The $D_4$ deformation has reached the brittle stage and the resulting structures are the faults, large scale fractures and joints of the area. Minor shear zones were observed in surface outcrops and such shearing are related to the emplacement of pegmatitic veins almost across the lithological layering. The increasing complexity in the geometry of the faults to the south western part of the area is largely due to influence of emplacement of porphyritic granite further south west of the study area (not included in the area of study).

From the morphological study of folds (using dip isogon method), it has been found that most of the folds in nature are buckle folds and they are often modified by varying
degree of flattening. The intensity of flattening and shearing with attendant cleavage is more pronounced in case of $F_1$ folds and such state of strain is weak in the subsequent $F_2$ folding. Although in a gneissic-migmatitic terrain, fold morphology is usually complex and the viscosity co-efficients are highly variable, the folds behave independently showing certain amount of disorder in the layer thickness from limb to the hinges. Such variation leads to the formation of a series of fold morphology belonging to $1B-1C-2; 1C-2-3$. Analyses of the $F_2$ folds of asymmetric pattern indicate that incompetent layers are showing class $1C-2-3$ types while competent layers are reflecting $1B$ to $1C$ and in a few cases Class $1A$ nearness to Class $1B$ (such $1A$ folds are classed as $1A_3$ type while Class $3$ types are categorised mostly under Class $3A-3B$ of Zagorcev, 1993). Such wide variation in geometric fold classification is largely a function of non linear phenomena in an inhomogeneous state of strain which is essentially controlled by several independent variables like (a) competency contrast of the layered sequences, (b) their rheological variation, (c) the strain intensity, (d) initial layer thickness, (e) layer parallel / oblique compression leading to initial shortening and their final transformation in the field of extensional mechanism.

The study of boudin structures has been incorporated and relationships with other deformational structures are established. They are the resultant of tensile stress due to application of strong compression transverse to the beds (Sen and Mukherjee, 1975), or formed by longitudinal compression (Gzovskii, 1975 from Janoszewski, 1984). This is opposite to boudin’s mechanism, being swelling and constriction of a ductile bed in a less ductile environment (Mukhopadhyaya, 1972). Layer parallel extensional tectonism under layer normal / parallel compressive stress leads to the development of continuous and discontinuous boudinages. Pinch and swell structures, barrel, rectangular, parallelogram, tile like imbricate and lenticular types are some of the structures which indicate tectonic attenuation and fragmentation of the initial layering in the continuum of $D_1$ deformational phase. Tile like imbricate behaviour of boudin is the resultant of layer shortening. Such layer shortening during $D_2$ deformation produces $F_2$ folds which occasionally maintain coaxiality with $F_1$ folds - (type $3$ interference pattern). Layer oblique $D_2$ dextral shear effects the lenticular boudin but when the aspect ratio ($W:T$) is $3:2$ or more, boudins are rotated by simple shear ($\psi = 20^\circ$ to $50^\circ$). The $D_1$ boudins are
further boudinaged during D$_2$ deformation when the right limbs of the F$_1$ folds rotated more than 120° resulting local extensional field and the earlier boudins are further fragmented. Such boudins are mostly enclosed within the D$_2$ synkinematically emplaced pegmatitic and/or migmatitic materials and showing both sinistral and dextral shear. Shear fractures indicating sinistral rotation and neck fold hint post D$_1$ boudinage phenomena and such variation of their left and right vergence may be the effect of post D$_2$ deformation. The deformed shapes and attitudes of the boudins are largely controlled by F$_2$ and F$_3$ and are subsequently shortened by low angle reverse faults, fault plane being roughly E-W dipping north.

The different rock types collected from the field were confirmed by their petrographic and mineralogic study. The petrography reveals that the major rock type is the quartzofeldspathic gneiss composed dominantly of quartz, microcline, plagioclase, biotite, muscovite and rarely hornblende. The presence of hornblende, muscovite/biotite in the quartzofeldspathic gneiss is one of the conspicuous features relating to the original parental source. The presence of hornblende and muscovite/biotite in quartzofeldspathic gneiss is a clear indicative of bimodal character i.e. both I and S-types.

Petrographic study further reveals the existence of amphibolite, hornblende biotite schist, calc-silicate rock, biotite schist, basalt, dolerite, pegmatites and other vein rocks. Quartzofeldspathic gneiss is constituted dominantly by quartz and feldspar, feldspars being microcline and plagioclase of albite composition. The mafic minerals biotite and hornblende are present where the former exceeds the latter. Effect of sericitization, myrmekitization are some of the other features. Replacement of plagioclase by microcline, shearing effect shown by marginal grain boundary granulation are some of the very notable features of the rock.

Amphibolite is relatively medium grained and composed essentially of hornblende, plagioclase, quartz, cordierite and biotite. Biotisation of hornblende is observed, epidote is developing out of hornblende as a retrograde product. Cordierite is characterised by sector twinning with lots of iron particles as inclusions. The amount of quartz in modal composition is more in case of sheared amphibolite and the stretching ribbon quartz shows effect of subsequent folding.

Hornblende biotite schist show maximum similarity with amphibolites but does not have
plagioclase or wherever present it hardly exceeds 3% in modal composition. Schistose and lepidoblastic texture is observed.

Calc-silicate rock is dominantly composed of diopside, hornblende, plagioclase, quartz, garnet and epidote. Even under microscope banding characters are observed and dark bands are marked by mafic minerals like pyroxene and amphibole, while the light colour bands are formed by quartz, feldspar and garnet. Epidote is developing out of plagioclase while some hornblende also show disintegration resulting epidote. Pyroxene is also partially altered to hornblende. Grain size and shape of garnet are partially granular to skeletal and well developed euhedralisation character is rare. The rock invariably shows granoblastic texture.

Biotite schist is essentially composed of biotite, plagioclase and quartz. It shows characters of almost no strain of the constituent minerals which indicates that the biotite rich rock may be a late transformed metasomatic product after some metabasic rocks. Biotisation of amphibolite may have led to the development of this rock.

Basalts and dolerites are post metamorphic rocks and petrographically constituted essentially by plagioclase and pyroxene with subordinate amount of honblende, biotite. They occur as small sills and dykes of probable Jurassic period (= Sylhet trap)

Pegmatite is constituted by megascopically visible quartz, feldspar and micas and no thin sections are prepared due to its extreme coarseness

Petrochemistry (both major and trace elements) of a few selected samples of quartzofeldspathic gneisses and metabasics, the latter is constituted by amphibolites and related hornblende biotite schist, of the present area was done. From the analysed major element oxides the CIPW norm, Niggli and ACF values of the samples were also worked out using some computer based programmes and presented in various diagrams. Based on petrochemistry, field and petrographic evidences, the quartzofeldspathic gneiss may be suggested as both igneous and sedimentary origin. Limited trace element geochemistry is taken into consideration while delineating the bimodal petrogenetic histories of the most dominant quartzofeldspathic gneiss of the area. A series of replacement relationships between the grains of different minerals are observed which indicate the presence of metasomatic influx.
of minor amount of soda, potash and silicate metasomatism. Partial melting resulting the
development of migmatite is another aspect associated with the multi transformation system
and thus on the regional scale, quartzofeldspathic gneiss developed as the host rock of the
area. The plots of major oxides and traces of metabasites in the different diagrams, their field
and petrographic evidences indicate the varied nature of their parental source with strong
affinity towards its ortho and para types showing mostly tholeiitic to calc-alkaline type affinity
and are comparable to tholeiitic basalt.

Biotite schist is not related to any metamorphosed products of argillaceous sediments
rather they are the metasomatic alteration of amphibolite as a site selective product generally
confined at the border zone of amphibolites and quartzofeldspathic gneiss.

On the other hand calc-silicate rocks are genetically related as a metamorphic product
of impure calcareous sediments with clayey and probably sandy impurities.

Basalts and dolerites are undoubted basic igneous bodies either in the form of sills or
dykes of post metamorphic stage and their emplacement into the country rock is in no way
related to any contact effects. They may be genetically related to Jurassic-Cretaceous volcanic
activities in the southern fringe of the Assam Meghalaya plateau although separated in space
Of the vein rocks, pegmatite plays a vital role not related to any significant storehouse of
mineralisation rather their emplacement into the country rock is structure controlled and follow
the weak locales of the different phases of deformation. Pegmatites which carry large amount
of k-feldspar can be best utilised for high tension insulator, and act as good aquifer for ground
water potential zone.

The different rock units of the gneissic terrain have repeatedly suffered from restructuring
and readjustment since Precambrian time, and whether they can be considered to represent a
tectonic slice of the lower continental crust or upper part of the mantle is a matter to ponder?
The over all nature of structures and composition of the lower part of the crust is still not
crystal clear although tremendous volume of research has been conducted from both medium
and high grade gneissic complexes. The present area forms an integral part of the gneissic
terrain characterised by high grade granulite facies condition of metamorphism located in the
Goalpara area of Assam (A C Mazumder, personal communication) and west Khasi Hills
district of Meghalaya, while the present and the adjacent areas belong to medium grade gneissic terrain and is a continuation of the former belt. The amphibolite facies condition (= medium grade) prevailed in the metasedimentary and metavolcanic rock units of the present area may be interpreted to have formed during the initial geosynclinal sedimentation and subsequently metamorphosed during regional metamorphism. This aspect is supported by low k values relative to silica and high Na$_2$O / K$_2$O ratio (Baragar, 1968). Thus these bimodal derivatives may be either the result of collision tectonics (?), source of sediments being derived by erosion of older continental crust and profusely intruded by basic igneous activity in the form of sills and dykes, which were tectonically transposed into the present form of lithosetting. Most of the granitoid rocks of the Assam Meghalaya Plateau might be the resultant of intracrustal melting. The presence of hornblende in some of the quartzofeldspathic gneiss and biotite and / or muscovite in some others may be taken into consideration in support of their I and S-type of genetic histories. Complexities thus arose inspite of tremendous works in recent years. Passchier et al. (1990) noted that the continental crust appears to have been extensively sliced up by horizontal tectonic movements and the gneissic terrain represent a relatively thin slab of the crust during earliest deformation by extensional tectonism. Homogeneous crustal shortening in the subsequent periods may lead to the thickening of the gneissic skin of the earth by tectonic stacking (Myers, 1976). The generalised NE-SW trending linearity, with a few exceptions towards E-W, bearing the signatures of high grade gneissic terrain in the south-west to western part of the Assam Meghalaya plateau and medium grade towards north-eastern part may be a product of such tectonic stacking and probably indicate active continental margin as proposed by Kay and Kay, 1981 in many Proterozoic terrains of the globe.

On going collision of India and Eurasia may have some impacts over the problem. The north of north eastern Indian continental margin constituted by older metamorphics and supracrustal rocks continued to have been thrusted under the Eurasian plate during last 40 MA and about 1500 km of the Indian continental plate has now disappeared below the Eurasian plate (Mattauer, 1986) and probably transformed into an high to medium grade terrain. Unless otherwise dated, this aspect does not bear any potential value.

The geochemical characteristics of the metasedimentaries and metavolcanics leading to
the formation of the gneissic craton are inadequately explained due to lack or meagre preservation of geochemical data excluding REE study. Some of the geochemical diagrams (listed in chapter 5) indicate the presence of tectonic setting and can be correlated with the recent advancements in the field of geochemistry. This is one of the reasons why the nature of the primitive crust or the old sediments of the supracrustal block cannot be ascertained with full satisfaction whether they were enriched in mafic constituents and represent a partially melted simatic encrustation of or remobilised upper most part of the mantle in a protooceanic or continental environments.

Detailed structural reconstruction of the whole Assam Meghalaya plateau along with systematic petrological interpretations, geochemical and isotope study including detailed whole-rocks and metamorphic minerals dating and high resolution seismology may reflect some valuable insights into this complex problem provided a good inter-disciplinary collaborative mission could be built up.

However with enormous limitations and constraints and based upon the field and stratigraphic relationships of the different lithounits, a simplified tectonostratigraphic succession is proposed.

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