CHAPTER II

GEOLOGICAL SETTING
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The chapter deals with the geological setting of the Bondla mafic-ultramafic complex. An outline of the regional geological framework is followed by a concise account of the geology of Goa. Lastly, the geology of the area is described.

Regional Geological Framework

The area under study forms a part of the Karnataka Craton of Peninsular India. The craton is predominantly occupied by granitic gneisses, granites, and schistose supracrustal rocks. The former constitute the Peninsular Gneissic Complex whereas, the schistose rocks have been included by Foote (1876) under the Dharwar System. The gneisses and the schists together constitute the Archaean of Peninsular India.
Fermor (1936) was amongst the earlier workers who first divided the Archaean province of India into two sub-divisions. The charnockitic region to the south and the non-charnockitic region to the north. This early idea was later developed by Radhakrishna (1983) who recognised two types of metamorphic terrains in south India: (i) the southern high-grade Granulite terrain and (ii) the northern low-grade Granite-Greenstone terrain. Within the latter two types of provinces are recognised - the western and the eastern. These are separated by the N-S running Closepet Granite batholith. The western province is referred to as the iron-manganese Shimoga province and the eastern as the Kolar Gold Field province (Radhakrishna, 1983). These two provinces are also referred to as the western Dharwar Craton and the eastern Dharwar Craton respectively (Naqvi and Rogers, 1987). The area under study forms a part of the western Dharwar Craton.

The western Dharwar Craton is constituted of schistose supracrustal rocks consisting of a volcano-sedimentary assemblage. The rocks occur as bands of greenstone which are separated from one another by intervening gneissic and granitic rocks. Number of such bands have been
described from the craton. They are considered to be the remnants of the Dharwar metavolcanics and metasediments which formerly covered a large part of the craton and which have escaped denudation as they formed synclinal strips folded-in with the gneisses (Krishnan, 1968).

The schists and the gneisses exhibit a complicated interrelation with each other. In some areas, the schists appear to rest on the gneisses whereas in others a reverse relationship is observed. Opinions differ among various workers as regards the basement cover relationship which has led to a major debate on the Archaean rocks of peninsular India. Hence, different workers have proposed various schemes of classification for the Dharwars of south India (Smeeth, 1916; Rama Rao, 1940; 1962; Nautiyal, 1967; Pichamuthu, 1968; Radhakrishna, 1974; 1983; Swami Nath et al., 1976).

Three views on the classification of Dharwars are widely prevalent: (i) the Dharwar greenstone suite is younger than the Peninsular Gneiss (ii) the Dharwar schistose rocks belong to one stratigraphic suite which is older than the Peninsular Gneiss and (iii) the Dharwar
supracrustals belong to a number of different suites whose ages overlap those of gneissic rocks.

Various attempts have been made to resolve the schist-gneiss controversy by radiometrically dating the components of the Peninsular Gneiss. The latter includes a complex suite of tonalite-trondhjemite gneiss with a wide variety of screens and inclusions of other rock types. Some of these enclaves are engulfed remnants of older schists, whereas, others may be metasedimentary and/or metavolcanic rocks formed on the gneisses and not connected to the schists. The gneiss suite includes former sedimentary, volcanic and intrusive rocks, metamorphosed and emplaced granite. These various components are so closely and finely intermixed that their discrimination is not possible.

The radiometric ages of the Peninsular Gneiss suite therefore, vary greatly between 3400 and 3000 Ma (Naqvi and Rogers, 1987). Some of the oldest ages are provided by the Gorur Gneiss - 3358 ± 60 Ma (Beckinsale, et al., 1980) and Anmod Ghat Trondhjemitic Gneiss - 3400± 140 Ma (Dhoundiyal, et al., 1987). By and large it is agreed
that the 3000 Ma period represents the time of emplacement of trondhjemitic gneiss and corresponds to the cratonisation of the western Dharwar Craton (Naqvi and Rogers, 1987). Towards the eastern part of the craton a suite of potassic granite known as the Closepet Granite occurs whose ages vary between 2500 and 2300 Ma. e.g. Chitradurga Granite and Arsikeri Granite.

In recent years, Radhakrishna (1974) and Swami Nath et al., (1976) suggested that the Peninsular Gneiss formation is an event separating two Archaean greenstone sequences. The older sequence is included under the Sargur Group (Swami Nath and Ramakrishnan, 1981) whereas, the younger one constitutes the Dharwar Supergroup (Swami Nath and Ramakrishnan, 1981). The general stratigraphic scheme for the western Dharwar Craton is as follows (after Swami Nath and Ramakrishnan, 1981):
Middle to Late Proterozoic (Helikian & Hadrynian) Kaladgi, Badami and Bhima Groups.

----- UNCONFORMITY-----

Late Archaean (Kenoran)

to Early Proterozoic (Aphebian) Dharwar Group
(2400 - 2600 Ma) SuperGroup --- Unconformity ---
| Bababudan
| Group

----- UNCONFORMITY -----

Middle Archaean (2900 - 3000 Ma) Peninsular Gneiss granitoids
Migmatites, gneisses,

Early to Middle (Sargur) several unclassified associations
Archaean of supra-
(> 3000 Ma) crustal rocks

Basement not seen

(3400 Ma gneisses)
Geology of Goa

Major portion of Goa is occupied by the rocks of the Dharwar System (Foote, 1876). Maclaren (1904) described the rocks from Castle Rock along the eastern border of Goa and assigned them to "Castle Rock Band" which occupies a major portion of Goa and extends northwards into the Konkan region of Maharashtra. Towards the south it extends into North Canara district of Karnataka. The "Castle Rock Band" comprises magnetite-, haematite-quartzite, biotite-quartz-schist, phyllites, grey limestones, basic igneous rocks and granitic gneisses. A summary of information available till 1950 is found in Pascoe (1965). He has referred to the Goa rocks as northward extensions of the Upper Chloritic Division of Dharwar System (Smeeth, 1916). Oertal (1958) carried out systematic mapping of Goa and published the first geological map of the region. He divided the Dharwarian rocks into: (i) Lower Intra-conglomerate group and (ii) Upper Metalliferous group of schistose rocks. The granitic rocks were considered by him to be intrusive into the schist.
During the post-liberation period, the Geological Survey of India carried out systematic geological mapping and a revised geological map was published (Gokulam, 1972). Except for a small area in the northeast which is covered by Deccan Traps (late Cretaceous to Eocene), the rest of the state is occupied by greenstones of Archaean to Proterozoic age. The rocks in general trend NW-SE conforming to the regional Dharwarian trend in Peninsular India. Gokul et al., (1985) assigned these rocks to the Goa Group which in their opinion, is broadly comparable and correlatable to the Chitradurga Group of the Dharwar Supergroup. The Goa Group consists of four formations. The detailed stratigraphic succession is as follows (after Gokul et al., 1985):

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Formation</th>
<th>Rock Type</th>
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<tbody>
<tr>
<td>Sub-Recent</td>
<td></td>
<td>Sea sand and</td>
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<tr>
<td>To Recent</td>
<td></td>
<td>Laterite</td>
</tr>
<tr>
<td>Upper Cretaceous</td>
<td>Deccan Trap</td>
<td>Basalt</td>
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<tr>
<td>To Lower Eocene</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proterozoic ?</td>
<td>Basic Intrusives</td>
<td>Dolerite, Gabbro</td>
</tr>
</tbody>
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PROTEROZOIC

Pegmatite, Vein quartz, Porphyritic ACID granite, Hornblende Intrusives granite, Felspathic gneiss, Granite gneiss

INTRUSIVES

Metabasalt formation

Manganiferous chert breccia

Banded ferruginous quartzite

Manganiferous chert breccia
<p>| ARCHAEAN GROUP | Formation | Bicholim | with pink ferruginous phyllite Limestone Pink ferruginous phyllite Quartzite chlorite-amphibole schist | Argillite Quartzite Tilloid Metagreywacke Metagabbro Peridotite Talc-chlorite-schist Variegated phyllite |</p>
<table>
<thead>
<tr>
<th>U</th>
<th>Barcem</th>
<th>Quartz-formation</th>
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<tbody>
<tr>
<td>P</td>
<td>Formation</td>
<td>chlorite-schist</td>
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<td>Quartz-sericite-</td>
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<td>schist</td>
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<td></td>
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<td>Red phyllite</td>
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<td></td>
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<td>Massive,</td>
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<td></td>
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<td>Schistose,</td>
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<td>Vesicular</td>
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<td>_metabasalt</td>
</tr>
</tbody>
</table>

The Barcem Formation is predominantly constituted of metabasalts which are schistose, vesicular and massive. These are intercalated with metasediments. Argillites and metagreywackes dominate the Sanvordem Formation whereas pink ferruginous phyllites with banded-haematite-quartzites predominate in the Bicholim Formation. The youngest Vagheri Formation comprises metagreywacke and metabasalt. This volcano-sedimentary sequence is intruded by granitic gneisses which are exposed in three differ-

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ent areas of the state. Dhoundiyal et al., (1987) carried out Rb-Sr whole rock radiometric dating of the granitic gneisses from Goa. The Anmod Ghat Trondhjemitic Gneiss which outcrops in the eastern part of the state has yielded a Rb-Sr whole rock isochron age of 3400 ± 140 Ma (Dhoundiyal et al., 1987). This gneiss is analogous to the Gorur Gneiss of Karnataka which has also provided some of the oldest ages (3358 ± 67 Ma; Beckinsale et al., 1980) so far recorded in south India. The Anmod Ghat Trondhjemitic Gneiss therefore, could represent the basement for the Goa Group of rocks (Dhoundiyal et al., 1987). The other granitic gneisses from Goa such as the syntectonic Chadranath Granite from central Goa has been dated to 2650 ±100 Ma and the post-tectonic Canacona Granite Porphyry from south Goa has given Rb-Sr whole rock age of 2395 ± 390 Ma (Dhoundiyal et al., 1987).

A number of basic intrusives represented by gabbroic plutons and dolerite dykes intrude the schistose rocks. The mafic-ultramafic complex at Bondla near Usgaon is one such intrusive complex in central Goa (Jena, 1985; Balakrishnan et al., 1992). All rocks in general except the granitic gneisses and the intrusive mafic-ultramafic
complexes exhibit a thick laterite cover which varies in thickness from a couple of metres to over 25 metres.

Structurally, the area is complex and exhibits at least three cycles of deformation during which the rocks have been subjected to folding and faulting. During the first phase of deformation the rocks were folded along an E-W axis with folds plunging due west. Such folds are seen in the southern part of Goa. The Chandranath Granitic Gneiss occupies the core of an antiformal structure related to this fold movement (Gokul, 1985).

The above deformational episode was followed by the second fold movement which was the strongest phase of deformation along a NE-SW compression. The resulting folds trend NW-SE and are best exposed in the central and northern parts of Goa. The folds are tightly appressed, isoclinal to overturned to the SW and doubly plunging by 20 to 40° due NW and SE (Gokul, 1985). A number of NW-SE and NE-SW trending faults and shear zones traverse the rocks. One of the NW-SE trending shear zones traverses the rocks of the western part of the area under investigation.
Geology of the Area

The area under study where the mafic-ultramafic complex is exposed, exhibits a thick laterite and soil cover which supports dense vegetation (Plate I Photo 1). This has hindered field observations to a considerable extent. It was observed that the metasediments exhibit the thickest laterite cover followed in decreasing order by the peridotites. The gabbroic rocks in particular are least lateritised.

Mapping of lithological units and delineating their boundaries had to be done on the basis of the detached remnant outcrops. Hence, the boundaries of the different lithological units are inferred. Fresh outcrops were available along road cuttings, stream cuttings, quarry and mining pits and unlateritised remnants. Help was also taken of black and white aerial photographs on 1:60,000 scale to demarcate the boundaries of the lithological units and to study the structure of the area.
Aerialphoto interpretation followed by ground truth collection showed that the metasediments are folded into a NW-SE trending anticline. It is overturned towards SW and is plunging due NW (Dessai and Peshwa, 1982). A prominent shear zone traverses the western limb of the fold. The shear zone extends over a length of 15 km from Kusumwada in NW to Gurkhem in SE. Its maximum width is about 2 km (Balakrishnan et al., 1992). The shear zone can be examined to the east of Usgaon-Tisk road (Plate I Photo 2). The rocks are crushed and mylonitised. This is related to the second episode of folding (Gokul, 1985). Along the shear zone, the rocks of the mafic-ultramafic complex have been fractured. Away from the shear zone, the effects of shearing are subdued. It appears therefore, that the shearing may have been synchronous with the emplacement of the complex.

The metasediments are foliated parallel to the direction of shearing. The foliation trends N305° and dips 35-40° due N45°. The shear zones are often conjugated with dextral and sinistral displacement on sub-vertical shear surfaces. The metasediments are traversed by four sets of fractures. They trend (i) N335° and dip 40-

These fractures are filled by quartz-calcite veins which belong to three episodes. The quartz veins of the first episode trend N335° and N275°. They are cut by veins trending N255 to 265° which belong to the second episode. The veins of both these episodes are very thin (5 mm - 1 cm in thickness). The veins of the second episode are lenticular. The lenticles exhibit sinistral en echelon pattern. At places, gash veins of quartz trending N-S are seen. They vary between 2 and 10 cm in length and less than 1 cm across and have tapering ends. These veins are traversed by a very prominent set of quartz veins trending N230°. They vary in width from 5-30 cm. The veins pinch and swell both along the strike and dip (Plate II Photo 1). The intersections of these veins with those of the second generation are invariably occupied by sulphides. At places, along intersections of veins crescent shaped, unsupported country rock fragments are seen within milky quartz. At places, augen shaped fragments of country rock are found enclosed in loops of
vein quartz. Along the contacts of the veins the country rocks are discoloured in comparison with the unaltered rock which is dark grey to pale greyish in colour. The width of discoloured zone varies depending upon the thickness of the quartz vein. In general, vein with an average width of about 2 cm shows a discolouration zone of the same width. The veins also exhibit a thin zone of sericite and propylite along the contact. In the immediate vicinity of the veins the proportion of sericite increases. Away from the vein contact the wall rock alteration assemblage is represented by epidote, sphene and calcite. The thicker veins of quartz (4-6) cm show banding and crustification which is marked by alternate bands of calcite and quartz. The quartz-rich bands are generally thicker than those of calcite. At places, vugs and cavities are lined by idiomorphic crystals of quartz and calcite. The veins also show well developed crystals of quartz grown from opposite side of the vein wall.

The area is predominantly covered by metasediments with interlayered metavolcanics which belong to the Barcem Formation. The various lithological units exposed in the area are shown in the geological sketch map (Fig. 2.1)
Fig. 2.1 Geological sketch map of the Bondla mafic-ultramafic complex (modified after Gokul, et al., 1985 and Balakrishnan et al., 1992)
which is compiled based on field observations, study of
the aerial photographs and information from the litera-
ture. The metasediments consist of quartz - chlorite-
sericite-schists and phyllites with banded iron-formations
which outcrop mainly to the north of the area. The quartz-
chlorite-sericite-schists are exposed to the west of
Usgaon-Tisk (Mollem) road. They are extensively lateri-
tised. Isolated exposures are found along the road cut-
tings. The rocks are well foliated. The foliation is
marked by parallel arrangement of flaky chlorite and
sericite. The foliation strikes N3050 and dips 35-
40° due N45°. At places, intercalations of pink- ferrugi-
nous phyllite can be seen. The chlorite schists along the
strike are gradational into sericite schists. The
quartz-chlorite-sericite-schists are underlain by
phyllites. The latter constitute the most dominant hori-
zon in the stratigraphic sequence. Isolated exposures of
phyllite are found from Usgaon in the north to Durgini in
the south, however, rarely they are fresh. The phyl-
lites are extensively and almost completely lateritised
except in places where they are more arenaceous. Along
the strike, the phyllites which are normally pale grey in
colour, become ferruginous and grade into pink phyllites.
They have intercalations of haematite-quartzite. The phyllites strike N10° and dip 40-50° due N50°. To the north of Usgaon, they are intercalated with metabasalts which are exposed in the Madai river. The metabasalts are non-vesicular and exhibit weak schistosity.

The metasediments are intruded by an almost elliptical N-S trending mafic-ultramafic complex. A composite schematic stratigraphic section (not to scale) is shown in Fig. 2.2. The complex occupies the core of the NW-SE trending fold (Dessai, 1985a; Dessai and Peshwa, 1982) discernable on aerial photograph. The western contact of the complex is sheared and mylonitised. The shear zone trends NW-SE. The complex comprises mafic and ultramafic rocks. The latter are represented by dunites and peridotites which are exposed towards the northern and central part of the area. Those towards the north are exposed at Ganje about 2.5 km east of Usgaon. In the central part the exposures are found about 2 km east of Tisk. Good exposures of peridotites are also found to the east of the Usgaon-Bondla road. The ultramafites are represented by serpentinised and talcose peridotites and dunites. They are pale greyish green in colour when fresh. Along the
Fig. 2.2  A schematic stratigraphic column (not to scale) of the Bondla mafic-ultramafic complex.
shear zone they exhibit a foliation parallel to that of the enclosing metasediments. The ultramafites in general extend over a length of 6 km. The width of the outcrop is more than 3 km. Along the shear zone they exhibit fracturing, crushing and development of slickensided surfaces. The fractures trend N100° and dip 25° towards N350°, and N65° and dip 55° towards N335°. Along the fractures, veins of amphibole asbestos and chlorite are seen. The veins vary in width from 3 cm to over 40 cm and they are mainly of cross-fibre type.

The peridotites are also exposed at Kusumwada. The contact of the peridotites with metasediments is sheared. Along the shear zone, the peridotites are rendered talcose. They pinch out laterally. The ultramafites at lower levels are coarse grained. The grain size decreases at higher elevation. This variation is best seen along the road from Usgaon to Bondla. The peridotites in the field show banded appearance due to alternating light and dark coloured layers. The dark bands are made up predominantly of coarse grained chromite. These layers stand out (Plate II Photo 2) and alternate with those of greyish green coloured olivine. The latter vary in thickness.
from 3 to 10 cm. This type of banding was originally described as pseudo stratification (Hall, 1932 in Wager and Brown, 1967). Such-sheet like structures were later described as layering in the Bay of Island intrusion, Newfoundland (Ingerson, 1935 in Wager and Brown, 1967) and the Stillwater Complex, Montanna (Peoples, 1936 in Wager and Brown, 1967). The term layering was also adopted by Wager and Brown (1967) for similar features in Skaergaard intrusion, East Greenland. Following Wager and Brown (1967) the banding shown by the ultramafic rocks of Bondla has been referred to as 'layering'. This type of layering which is due to variation in proportion of chief minerals was referred to as rhythmic layering (Wager and Deer, 1939). Buddington (1936) refers to this type of layering as gravity stratification. For the thickness of layered rocks developed while a specific cumulus mineral or assemblage of cumulus minerals was forming, the term 'Zone' is used (Wager and Brown, 1967). The same terminology is followed in this work.

The chromite layers vary in thickness from 1 cm to more than 10 cm. The layers thicken and thin and pinch out laterally. The layers trend N50° and dip 30 to 35°
towards N1300. Along the shear fractures the chromites are remobilised and they give an appearance of a thin network of chromite veins which occur at an angle to the layering. Such veins vary in thickness from 1 to 3 cm. The layering and the remobilised chromite veins thus give an appearance of a network of chromite. Along the remobilised chromite veins, fibrous green chlorite is invariably developed perpendicular to the vein wall.

A thick chromitite layer occurs at the top of the ultramafic zone and is exposed to the west of Poikul. It extends laterally over a distance of 1 to 1.5 km and has a width of outcrop of about 300 m. The rock is massive, dark grey in colour and very fine grained.

The troctolites are exposed at the Bondla recreation park. These are underlain by a thin horizon of pyroxenites.

Gabbroic rocks are exposed along the Madai river 2 km NE of Ganje. The contacts of the gabbros with the metasediments are fine grained due to shearing. Quartz veins are intruded along the shear zone. Veins of epidote
have developed along the shear fractures. They can be traced intermittently up to Bondla along the eastern slopes of the Bondla ridge. Those in the Madai river are coarse grained and exhibit uniform layering (Wager, 1968). The bottom of the layers is generally coarse grained than the top which is gradational. The layers are generally distinguishable by virtue of their texture and grain size. The grain size at the bottom of the layer varies between 1 and 2 cm and it decreases towards the top.

Excellent exposures of gabbro are found to the east of Durgini along the Mollem-Panaji highway. The gabbro rise to a height of 396 m above M.S.L. The western contact is fine grained, sheared and fractured. The contact zone is more melanocratic than the rest of the body. The gabbros exhibit uniform layering (Wager, 1968). The bottom of the layer is coarser and more melanocratic than the top. The top of the layer is gradational due to increasing proportion of plagioclase.