ESTABLISHMENT OF DEFORMATION PATTERN IN KANCHANKAYI EAST-HULKAL-HALBHAVI SECTOR OF KURLAGERE-GOGI-GUNDANAHALLI (KG) FAULT AND ITS IMPLICATIONS ON URANIUM MINERALISATION, YADGIR DISTRICT, KARNATAKA

by

DSOUZA VINOY AROCKIADAS

ENGG1G201801006

Bhabha Atomic Research Centre, Mumbai

A thesis submitted to the
Board of Studies in Engineering Sciences

In partial fulfillment of requirements

for the Degree of

MASTER OF TECHNOLOGY

of

HOMI BHABHA NATIONAL INSTITUTE

February, 2021

Homi Bhabha National Institute

Recommendations of the Thesis Examining Committee

As members of the Thesis examining Committee, we recommend that the thesis prepared by Dsouza Vinoy Arockiadas entitled "Establishment of deformation pattern in Kanchankayi East-Hulkal-Halbhavi sector of Kurlagere-Gogi-Gundanahalli (KG) fault and its implications on uranium mineralisation, Yadgir district, Karnataka" be accepted as fulfilling the thesis requirement for the Degree of Master of Technology.

	Name	Signature
Member-1	Dr. D. K. Sinha	DKSinha
Member-2	Dr. T. S. Sunil Kumar	TSKumar
Member-3	Dr. Navin Goyal	
Member-4	Dr. Pranesh Sengupta	P. Sengupta
Member-5	Dr. A. Rama Raju	A. R
Technical advisor	Siby K Varughese	
Examiner	Prof. M.S. Pandian	MSPandian
Guide & Convener	Dr. Chanchal Sarbajna	Chanchal Sarbajna
Chairman	Prof. Vivekanand Kain	VKain

Final approval and acceptance of this thesis is contingent upon the candidate's submission of the final copies of the thesis to HBNI.

I hereby certify that I have read this thesis prepared under my direction and recommend that it may be accepted as fulfilling the thesis requirement.

Date: 15-02-2021

Place: Hyderabad

Chanchal Sarbajna

(Dr. Chanchal Sarbajna)
Guide

DECLARATION

I, hereby declare that the investigation presented in the thesis has been carried out by me. The work is original and has not been submitted earlier as a whole or in part for a degree / diploma at this or any other Institution / University.

Vinoy Dsouza

(Dsouza Vinoy Arockiadas)

ACKNOWLEDGEMENTS

I express my sincere gratitude to my guide, Dr. Chanchal Sarbajna, Adjunct Professor, HBNI, for his valuable guidance, enriched suggestions, supervision and generous help to complete this project.

I would also like to thank my technology advisor Shri. Shri. S.K Varughese, SO-G for his support and guidance during the course of study. I am deeply indebted to Dr. D.K Sinha, Director, AMD, for providing all the facilities and the opportunity to pursue this M. Tech programme. I am thankful to Shri. S. Hamilton, Additional Director (Operations-I), Shri. B. Sarvanan, Additional Director (Operations-II), and Dr. T.S Sunil Kumar, Additional Director (R&D) for their encouragement and administrative support. I express my deep sense of gratitude to Shri D. K. Choudhury, SO-H, Regional Director, AMD, Southern Region, for providing the infrastructural facilities and co-operation extended throughout this project work. I thank Shri. Mayank Agarwal, Deputy Regional Director and Incharge, Bhima Basin Investigations, AMD, Southern Region as well for their co-operation and support.

I am also thankful to the competent authority of HBNI for providing the opportunity to pursue the M. Tech. degree. I am thankful to Head, BARC Training School, AMD Campus for his support.

I would like to acknowledge my seniors and colleagues, for their support during the field work and technical discussions.

I would like to extend my gratitude to Smt. Kusum Prakash, SO-F, Incharge, Petrology Lab and staff of Petrology Lab, AMD, SR for their generous support. Special thanks to Smt. Anubhooti Saxena, SO-E, AMD, WR for her technical support during fluid inclusion studies in Petrology Lab, AMD, WR. I would like to acknowledge the officers and Incharges of Chemistry and XRF laboratories of AMD, SR for their analytical support. I would like to thank my batch mates who were a source of inspirations to carry out this work.

Last but not the least, I want to thank my family for their support and encouragement throughout this research work. I would like to also thank everybody who has helped me either directly or indirectly throughout the tenure of the project.

Vinoy Dsouza

Dsouza Vinoy Arockiadas

CONTENTS

SYNOPSIS

Bhima basin is one of the smallest Meso-Neoproterozoic basins of Peninsular India, with an extent of 5,200 sq. km situated at the north-western fringe of Eastern Dharwar Craton (EDC). The basin is traversed by prominent E-W and NW–SE trending faults besides a number of smaller N-S and NE-SW trending faults. The present disposition of the basinal sediments is largely the result of the regional E-W and NW-SE trending faults. Bhima basin sediments are mostly undeformed except along the basin boundary and major faults, where faulting has caused intense brecciation, fracturing and folding within basement and sediments. The study area lies along east-west trending faults, Gogi-Kurlagere fault (KG fault) which is located on south central margin of Bhima basin and runs over 40 km from Kurlagere in the west to Gundahalli in the east. Important uranium occurrences like Gogi, Malla, Halbhavi, Darshanapur and Ukinal are located along the E-W trending Gogi-Kurlagere fault. Hence the KG fault has remained under extensive exploration since last two and half decades. The western and eastern extensions of Gogi-Kurlagere fault appear to be significantly promising with the main Gogi deposit lying at the central part of the fault. It has been noted that uranium mineralization in Gogi and adjoining Kanchankayi area is restricted within the brecciated limestone and basement granite along Gogi-Kurlagere Fault zone.

Detailed geological mapping (1:2000) undertaken as part of the present study from Kanchankayi East to Halbhavi sector along the KG fault zone, reveals zones of deformation which are manifested by brecciation and the variation in the dip of the beds. Mesoscopic study of carbonate rocks in the study area led to classify the limestones as massive limestone, bedded limestone, brecciated limestone, bedded cherty limestone and brecciated intraformational limestone on the basis of their structure and chert content.

Detailed structural mapping in the area shows 2 deformed zones which are associated with the 2 splayed arms of the KG fault. The southern splayed arm of the fault which is along the sediment basement contact is moderately deformed and is demarcated by moderate dips of the limestone beds. The northern splayed arm of the fault is intensely deformed and is within the Shahabad limestone, where vertical to steep dips of limestone beds are observed. Steep dip of the limestone beds are also observed in Halbhavi area which suggest that the fault has its eastern continuity till Halbhavi area. Two major fracture trends are observed in the study area, out of which the 130^0-310^0 fracture trend has formed from the tension stresses due to dextral strike slip movement along the KG fault.

Sub-surface borehole core sample studies reveal increase in deformation in the limestone with increasing depths upto the sediment basement contact. The zones of maximum deformation are brecciated and uranium mineralisation is hosted within the brecciated zones of limestone and granite. Brecciated zones in proximity to the granite wedge, which has pushed into the overlaying sediments has been observed to be more favourable for uranium mineralisation. Correlation of the surface and sub-surface data reveals a curvilinear deformed zone of the northern splayed arm of the fault.

Petromineralogical studies reveals that the undeformed limestone is fine grained composed of micritic calcite (<4μm). Disseminated fine pyrite is present in the limestone samples away from the fault zone too, which suggest that sedimentation of limestone may have been in slightly reducing conditions. The deformed limestones are brecciated to fractured with sparry calcite veins traversing along and across the fractures/brecciated zones. Pyrite is the primary ore mineral in the brecciated limestone present in the brecciated and fractured zones. Coffinite and pitchblende are the uranium bearing minerals and are associated with pyrite, calcite and carbonaceous matter. The basement granite contains quartz, plagioclase, microcline and K- feldspar as major minerals. Biotite and chlorite are present in minor amount whereas zircon, apatite occurs as accessory mineral phases. Microstructural studies of granite indicate brittle-ductile deformation in the area. Glauconitic shale and arenite fragments are observed in the brecciated granite suggesting brittle deformation, while deformed biotite and kinked plagioclase suggest ductile deformation. Microfracture of sparry calcite veins and offset of the calcite veins in the deformed limestone suggest brittle deformation.

Fluid inclusion studies on calcite veins associated with uranium mineralisation reveal that the primary inclusions in the calcite is mostly biphase (L+V) and are liquid dominated having degree of fill from 70 percent to 90 percent. The primary inclusions have temperatures of homogenisation from 117^0C to 144^0C and are found to be the first phase of fluid in the system. As homogenisation temperature is the minimum entrapment temperature of fluids, from the data of primary inclusions in calcite (associated with uranium minerals) it is inferred that the fluids responsible for the mineralisation of low temperature minerals like pitchblende and coffinite could be around 130^0C temperature.

Geochemical studies of the non-radioactive and radioactive limestone samples indicate that the non-radioactive limestones fall in low Mg limestone field while the radioactive limestone samples fall in dolomitic limestone field according to Grapes (2011) SiO2-MgO-CaO ternary plot. The high MgO content in the brecciated/deformed samples may be attributed to the fine chlorite and biotite present in the matrix of the brecciated zone and dolomite which is supported by petrographic studies. High SiO_2 is present in some of the limestone samples which is due to the chert and fine quartz present in the brecciated zone of the sample. The high values of Pb observed in the radioactive samples is mostly due to the radiogenic lead produced from the decay of uranium.

To understand the deformation pattern and its bearing on uranium mineralisation in Kanchankankayi area, a stacked section and 3D geological model of the study area has been prepared in the present work based on detailed geological and structural observations.

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 General

Meso-/Neoproterozoic basins in Canada and Australia constitute the major thrust areas for uranium exploration as they host low-cost, large tonnage, and medium to high grade unconformity related uranium deposits. In this context, the Meso-Neoproterozoic basins in India, and their basements, have become the first order targets for uranium exploration (Achar et. al. 1997). Active uranium exploration is being carried out in the Proterozoic basins of India since 1980. In Southern India, three Proterozoic basins are present viz., Cuddapah basin in Andhra Pradesh, Kaladgi-Badami and Bhima basins in Karnataka which have been identified as suitable host for uranium mineralisation.

Bhima basin sediments deposited over basement granitoids have a vast aerial extent of about 5200 sq km with limestone constituting more than 75% of the basin. Shale, arenite and conglomerate are the other litho-units which form part of the basin. Until the discovery of uranium in 1995-96 along Gogi-Kurlagere fault (AMD unpublished annual report, 1995-96), limestone was the only major deposit of economic significance. Shahabad limestone is used in flooring and roof material, while Wadi and Guntur limestone are extensively used for cement manufacturing. Barite occurs in nodular or discontinuous bands and is confined to the top horizon of Hulkal shale formation. The phosphate rich limestone recorded in patches within the Shahabad limestone at many places along the Gogi-Kurlagere fault and Wadi fault zone are not of any economic significance.

Discovery of uranium along Gogi-Kurlagere fault in Yadgir district opened up new avenue for economic potential of the Bhima Basin. Surface and sub-surface inputs till date in Gogi-Kurlagere fault by Atomic Minerals Directorate (AMD) with direct and indirect exploration methods has given a lot of information about the potentiality of the basin for uranium mineralisation. Exploration efforts led to establishment of a small sized medium grade uranium deposit in Gogi area (Achar, et. al 1997, Pandit, et. al 1999).

1.2 Uranium mineralisation at Kanchankayi area

The present study area is the north-eastern geological continuity of the country's one of the richest grade low tonnage uranium deposit established in Gogi area. Significant correlatable subsurface uranium mineralisation has also been established in Kanchankayi area and east of Kanchankayi. The uranium mineralisation in Gogi and Kanchankayi area is along the KG fault and is mainly associated with two lithounits viz., brecciated limestone and sheared granite and confined within a tectonised zone in the form of veins / veinlets (Dhana Raju et al., 2002).

In east of Kanchankayi area, the KG fault has undergone splay faulting where one of the arms of the splay fault follows the sediment basement contact while the other (northern arm) transgresses into the sediments. The uranium mineralisation is along one of the northern splayed arms of the fault where more deformation is observed. Few boreholes drilled along the major splay fault-the northern branch, has intercepted encouraging uranium mineralisation associated with brecciated zones in limestone. The mineralised zones are invariably associated with the carbonaceous matter and sulphides (predominantly pyrite). Pitchblende and coffinite are the main uranium-bearing mineral phases (Patnaik, et. al 2011). Structurally the uranium mineralisation is confined along the zone of reverse faulting, where the fault has created a series of minor fractures in limestone and basement granite that host the uranium mineralisation (Mahendra Kumar et al., 2014).

1.3 Location and accessibility of the study area

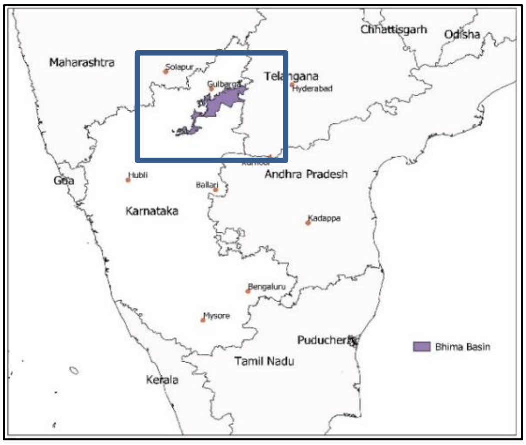
Kanchankayi-Hulkal-Halbhavi tract falls in the Survey of India Toposheet no. 56 D/10 and D/14 in Yadgir district of Karnataka (Figure 1.1). The area is bounded by $16^0$44' N-$16^0$45' N latitude and $76^0$45' E -$76^0$50' E longitude and is accessible by road which is 260km southwest of Hyderabad, 550 km north of Bangalore, 630 km southeast of Mumbai. Kanchankayi-Halbhavi village are part of Shahpur taluka. The study area is easily accessible as major roadways and railway routes are nearby. The nearest railway station is Yadgir about 40 km from the study area.

1.4 Climate

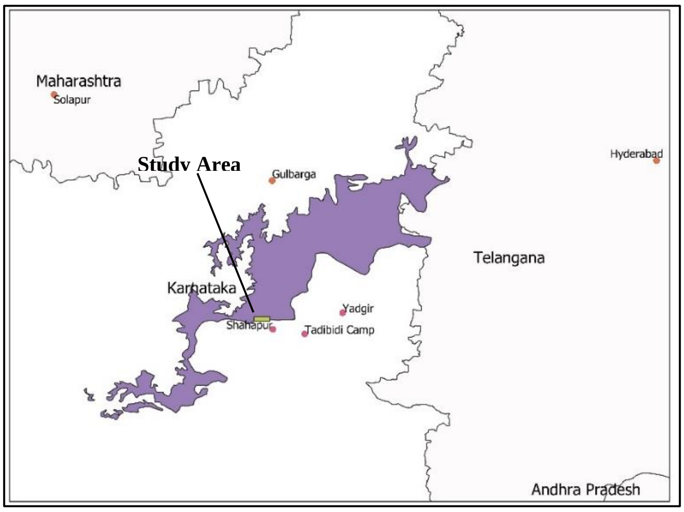
Kanchankayi-Halbhavi area is situated in the central part of the Southern Peninsular India, hence it mainly has a hot and dry climate with three seasons i.e., summer, rainy and winter. Summer months are from March to June during which the temperature may go beyond 43^0C at many places. Monsoon period is from mid-June to September. The annual rainfall in the area is around 600mm. Between November and February, the weather is cool and pleasant.

1.5 Physiography

The Kanchankayi-Halbhavi sector forms mainly flat land and there is no marked difference in topographic level except small hillocks near Kanchankayi and Halbhavi village. The area is mostly covered by thick soil and cultivated. Most of the land is covered with paddy field. Outcrops of the rocks of Bhima sediments and the Basement Granitoids are limited in the area. The elevation of the area varies from 430 m to 450m above mean sea level. The maximum elevation is 460m corresponding to the top of limestone hillock near Kanchankayi village.



(a)



(b)

(c)

Figure 1.1:(a) Location of Bhima basin in map of India (b) Location of Study Area (c) Google earth image of the study area

1.6 Previous work and origin of the problem

The uranium mineralisation in Kanchankayi is confined within the zone of deformation associated with reverse faulting. Air-borne geophysical surveys by M/s GEOTECH in 2008-09 and ground geophysical surveys by M/s Fugro Nexterra Pvt Ltd in 2009-10 revealed several low resistivity and high-chargeability zones and EM anomalies as promising drilling targets for uranium exploration at Kanchankayi. (AMD unpublished annual report, 2011). One of the EM anomaly was explored by reconnoitory drilling during 2010-11. Three boreholes (KNK-1 to 3) were drilled but no significant uranium mineralisation was intercepted and it was found that the causative rock for the EM anomalies was massive shale. Subsequently, after in depth study of both geological and geophysical data, borehole KNK-4 was drilled targeting the tectonised zone at the faulted basement-sediment contact. The borehole intercepted significant mineralisation (0.127% eU3O8 x 1.90m) for the first time in Kanchankayi area (AMD unpublished annual report, 2011). Subsequent detailed sub-surface exploration in the area along the basement-sediment contact established a medium grade U-deposit at Kanchankayi containing >2000 tonnes U_3O_8.

In Kanchankayi East-Hulkal- Halbhavi sector, preliminary geological mapping has shown that the KG fault gradually transgresses into the Bhima sediments forming splay faults (AMD unpublished annual report, 2015). Boreholes drilled along the major splay fault intercepted encouraging uranium mineralisation associated with brecciated zones in limestone, thus corroborating the presence of the fault in the sub-surface. The detailed geological and structural map in and around Kanchankayi East-Hulkal-Halbhavi sector of KG fault zone has not been done so far. As the mineralisation is structure controlled, a detailed structural understanding of Kanchankayi East-Hulkal- Halbhavi sector of KG fault zone is essential for planning of more boreholes in the area and understanding the structural setup of the area..

To fulfil the gap, the detailed field and subsurface structural studies of Shahabad limestone in Kanchankayi East-Hulkal- Halbhavi sector have been taken up in the present study to understand the nature of deformation associated with the fault zone vis-à-vis uranium mineralisation in the area.

1.7 Principal Objective

(i) Detail structural mapping over 5 sq km (1:2000) of Kanchankayi East-Hulkal-Halbhavi sector of KG fault.

(ii) Demarcating the zones of deformation associated with the splayed arm of the KG Fault and trace its eastern continuation within the Bhima sediments.

(iii) Micro-structural studies, to characterize the structure and associated uranium mineralisation.

(iv) Develop a geological model of Kanchankayi East-Hulkal- Halbhavi sector of KG fault, so as to identify potential zones for uranium mineralisation.

1.8 Research Plan/Methodology

(i) Detailed geological cum structural mapping over 5 sq km (1:2000) to demarcate the contacts of various lithounits and to trace the eastern continuity of KG fault.

(ii) Sampling of limestone for microstructural study.

(iii) Structural studies on borehole core samples from Kanchankayi area.

(iv) Microscopic studies to characterize different micro-structures and associated uranium mineralisation, supported by fluid inclusion studies.

(v) Geochemical studies of radioactive and non-radioactive limestone.

(vi) Integration of surface and sub-surface geological and structural data to generate a geological model of Kanchankayi East-Hulkal- Halbhavi sector of KG fault, which will help in identifying potential zones for uranium mineralisation.

1.9 Deliverables

(i) Detailed geological and structural map over 5 sq km (1:2000) of the study area.

(ii) Petro-mineralogical and microstructural interpretations focusing on the structural control on uranium mineralisation to develop a geological model.

CHAPTER 2

REGIONAL GEOLOGY

2.1 Geological Setting

The Meso-Neoproterozoic Bhima basin, is a NE-SW trending basin exposed on the northern margin of the Dharwar craton as reverse sigmoid. (Pandit et al, 2002**)**. A large part of the 5200 sq km area of the basin lies in the districts of Bagalkot, Bijapur and Gulbarga in the state of Karnataka with a small north-eastern part extending into the Rangareddy and Mahaboobnagar districts of Telangana state.

The unconformity contact between the Bhima sediments and basement granitic gneisses and younger granites of the Dharwar Craton is exposed along the southern and eastern margins of the basin. A number of basic dykes traverse the crystalline terrain. Limestone and shale are the predominant litho-units of the 300m thick Bhima group with subordinate arenite and a thin conglomerate at the base of the sequence at several places marking the unconformity with the basement. The northern and western extension of the basin is concealed under the Late Cretaceous-Paleocene Deccan traps

Geologically, the sediments of the Bhima basin are devoid of major imprints of metamorphism and tectonism as a result that most of the sediments are almost horizontally disposed with low dips retaining their original sedimentary fabric and giving rise to stratiplains, indicating conformity of the landforms with the sub-surface disposition of the rocks (Dhana Raju, et al., 2002). However, this scenario changes along the major fault zones that cut across the basin and in a few places, its basement granitoids too. The basin is dissected by prominent E-W and NW-SE trending fault. The major E-W faults are Tirth-Tintini fault and Wajhal fault in the southern part, Gogi-Kurlagere fault in the central part and Farhatabad fault in the northern part of the basin. The NW-SE trending Wadi fault is located in the north-eastern part of the basin. Besides these major faults, a number of minor N-S and NE-SW trending cross faults occur in the basin. Moderate to intense folding is observed in the vicinity of these faults, resulting in brecciation, dragging and, at places, isoclinal, overturned and recumbent folding. The width of the tectonised zones along these faults varies widely with a maximum of about 500m along the KG fault.

The east-west trending Gogi-Kurlagere - Gundahalli (KG) fault is located in south-central part of Bhima Basin and runs over 40 km from Kurlagere in the west to Gundahalli in the east and it takes a swerve to NW-SE direction from its regional E-W trend at west of Gogi. The area exposes basement granite, followed by Bhima sediments which consist predominantly of limestone with minor glauconitic shale and arenite. The deformed contact zone between basement granite and sediments is characterised by intense brecciation in both limestone and granite. Sub-surface drilling along the fault zone at Gogi, Darshanapur, Kanchanakayi areas revealed that the fault is of reverse nature with moderate dips forming "nose like" structure in the Gogi area and becomes sub-vertical to vertical towards west (Ukinal–Darshanapur area) and in the east (Halbhavi area).

2.2 Stratigraphy of Bhima Basin

The stratigraphic succession of Bhima Basin has been discussed by many workers since the time of Bruce Foote (1876). Jayaprakash A.V. (1999) of Geological Survey of India (GSI) proposed a lithostratigraphic succession which recognized three shale, two limestone formations and a paraconformity with a total thickness of Bhima sediments interpreted as about 297m. Kale's (1995) classification merges all the clastic and calcareous formations, thus reducing the total thickness of Bhima sediments almost to half as estimated by Jayaprakash. The stratigraphic successions proposed by both the authors are presented for comparison and the succession proposed by former are followed in the present work (Table 2.1)

Table 2.1: Stratigraphy of Bhima Basin

<table>
<tr><td colspan="4">Jayaprakash A.V. (1999)</td><td>Kale V.S (1995)</td></tr>
<tr><td>GROUP</td><td>FORMATION</td><td>MEMBER</td><td>LITHOLOGY (thickness in m)</td><td rowspan="14">B) Shahabad Limestone Formation

** Grey micritic impure limestone.

** Dark blue – grey massive limestone.

** Variegated, siliceous and cherty limestones

** Flaggy impure (cherty/argillaceous) limestones

-Gradational and transitional
----- Facies changes--
A) Rabanpalli Clastics Formation
B) Ekmai Shale Member (ferruginous & calcareous shales)
C) Kasturpalli Glauconitic Member
D) Kundrapalli Quatz-Arenite Member
a) Adki Hill Conglomerate Member.</td></tr>
<tr><td>DECCAN TRAP</td><td></td><td></td><td>Basic flows with intertrappean sediments</td></tr>
<tr><td rowspan="11">BHIMA GROUP

Total Aggregate Thickness 297m</td><td>Harwal</td><td></td><td>Brown, pink to vermellion shale (45)</td></tr>
<tr><td>Katama devarahalli</td><td></td><td>Deep grey, occasionally stylolitic flaggy limestone (40)</td></tr>
<tr><td>Hulkal</td><td></td><td>Grey, blackish buff, dull and pale pink shale, occasionally with fine grained thin silty beds at the base (30)</td></tr>
<tr><td rowspan="5">Shahabad</td><td>Mulkod Limestone</td><td>Deep grey to black flaggy limestone (100)</td></tr>
<tr><td>Gudur Limestone</td><td>Akin to Wadi limestone, yet slightly inferior in chemical composition (20)</td></tr>
<tr><td>Sedam Limestone</td><td>Variegated medium to thickly bedded siliceous limestone (60)</td></tr>
<tr><td>Wadi Limestone</td><td>Thickly bedded, stylolitic, relatively superior cement grade limestone (15)</td></tr>
<tr><td>Ravoor Limestone</td><td>Flaggy limestone with prominent fissility (Shahabad slabs) (10)</td></tr>
<tr><td rowspan="3">Rabanpalli</td><td>Korla shale</td><td>Fine silty base, grades into green shale, followed by chocolate brown shale with prominent parting (50)</td></tr>
<tr><td>Kundrapalle Sandstone</td><td>Fine grained quartz arenite, subfelspathic arenite, ferruginous cemented medium grained quartz arenite (15)</td></tr>
<tr><td>Muddebihal Conglomerate</td><td>Pebbly orthoconglomerate, locally or at the top matrix supported and also granular (2)</td></tr>
<tr><td colspan="4">-----------------------------Unconformity ----------------------------</td></tr>
<tr><td colspan="2" rowspan="2">BASEMENT CRYSTALLINES</td><td colspan="2">Younger Granites, Eastern Block Greenstone Belts,</td><td rowspan="2">Basement Crystallines</td></tr>
<tr><td colspan="2">Peninsular Gneisses.</td></tr>
</table>

2.2.1 Basement Crystallines

The crystalline, metamorphic and granitoid rocks comprising the basement to the sediments of the Bhima Group are traditionally clubbed as “Archean” (Krishnan, 1968). The Bhima sediments are overlaying on the basement crystallines with angular and erosional unconformity. The schist belts forming part of the basement complex are south-west to of the basin. These schist belts include Mangalur schist belt (West of Shahapur), Gurgunta schist belt and Hutti schist belt (south of Tintini). The gneissic rocks of Dharwar craton, clubbed loosely as the Peninsular Gneissic Complex include a variety of tonalitic and granodioritic gneisses, which have been generated in at least two separate phases (Kale, 1995). The intrusive granitic rocks are considered to be equivalents of the Clospet Granite and the Late Archean K-rich granite plutonic event occurring between 2500 Ma and 2000 Ma throughout the Dharwar craton. The basement terrain is intruded by a number of basic dykes southeast of the Bhima Basin. The basic intrusive activity seems to be comparable with the mafic dykes intruding the basement of the Cuddapah Basin and other parts of the Eastern Dharwar Craton (Dury, 1984). The late Archean granitoids are rich in accessory minerals such as sphene, allanite, apatite and zircon, and these accessories are the main source of uranium and thorium. In-situ gamma-ray spectrometric analysis reveals that these granitoids have higher abundances of Th, U, and K relative to granitoids occurring further away from the basin. Thus, they belong to the class of fertile granitoids from the point of uranium mineralization. The paucity of direct chronological data, and the dominance of true “Archean” rocks in the basement of the Bhima Group is noteworthy. Hence, the traditional name, “Archean Basement Complex” has been retained even though there are some post-Archean age constituents (Kale, 1995).

2.2.2 Bhima sediments

Rabanpalli Formation: Bhima sedimentation starts with the Muddebihal conglomerate. It is dominantly grey coloured conglomerate with a detrital matrix supported texture, poorly sorted and has clasts of pebbles and coarse sand. Rock fragments of banded ironstones, micaceous and chloritic schistose rocks, granitoids and gneisses make up the larger clast while sand sized clast are made up of feldspar and quartz. Feldspars are altered to kaolinitic clay which impart a white colour to the rock. The conglomerate grades upwards into coarse grained, sub-mature loosely packed sandstones. These sandstones have a gritty texture at places where they directly overlie the basement. Quartz is the largest component of the framework of sandstones, while fresh, unaltered feldspars, lithic fragments of granitoid and schistose rock together comprise almost half of the framework grains. A unit of sandstone having more petrological maturity with well-rounded quartz grains in siliceous matrix known as Kundraplle sandstone overlies the Muddebihal conglomerate. The quartz arenite is followed by a fining upward sequence of sandstone and siltstone which appear slightly greenish. Mathur (1977) reported the presence of glauconite from these horizons. The siltstone grades into a green colour glauconitic shale which is very fissile. The litho-unit comprises of alternating green glauconitic shale and purple shale.

Shahabad Formation: An interfingered gradation between the Rabanpalli and Shahabad Formation is commonly observed with calcareous and ferruginous shale beds alternating with thin laminae of impure micritic limestones (Kale,1995). This formation is the thickest formation of the Bhima group with thickness of about 100m. Mishra et.al. (1987) has divided the limestone formation into 5 members based on their physical characters, which are

(i) Flaggy, dark grey argillaceous limestone

(ii) Massive dark grey to bluish grey limestone

(iii) Variegated and siliceous limestone with chert bands

(iv) Slabby to blocky, light grey to bluish grey limestone

(v) Flaggy and slabby limestone.

Flaggy and slabby limestone member has decreasing flaggy layers and increasing massive beds towards the top. The limestone is extensively quarried for building construction and some horizons yield cement grade limestone. Flaggy limestones are followed by Thick slabby to blocky beds of limestone. The entire litho-unit is suitable for cement manufacture. Stylolites are also developed throughout the formation. Varigated and siliceous limestone overlies the massive light and grey limestone and is the thickest unit in Shahabad formation, with 80m thickness at some places. At the upper horizons of this unit thin chert bands are observed. The varigated siliceous limestone grades into dark grey to bluish grey limestone which is further overlain by flaggy argillaceous limestone.

Hulkal Formation: The limestone of Shahabad Formation is gradationally overlain by the siltstone-shale of Hulkal Formatiion. The transitional contact is exposed in the Bhima river section between Ferozabad and Kolkur, and is about 4 m thick. The lower part of the formation has thin phosphorite bands and the upper part has minor occurrence of arenite.

Katamadevarhalli Formation: The Hulkal shales grade into dark grey, well bedded limestones. These are siliceous limestones. The thickness varies from 10 to 40m. They are well exposed from near Jewargi to Maratgi and near Katamdevrahalli. Near Katamadevrahalli, the limestone beds attain a thickness of 40m.

Harwal Formation: This shale formation is represented by a fissile and friable purple shale lying above the Katamadevarhalli limestone with a gradational contact. The thickness of the unit varies from 5 to 10 m. Outcrops are seen near Gogi village, occurring under the Deccan traps. In some of the areas the unit overlaps the Katamdevrahalli Formation and directly overlies the Hulkal shales.

2.2.3 Deccan Traps

Deccan traps, essentially simple basaltic flows, are mostly fine-grained, compact but some of them are typically amygdaloidal. These traps, considered to be of Cretaceous to Eocene in age, are seen as outliers and are also present directly overlying the Archean basement complex much to the south of Bhima basin. This clearly indicates that the traps were far more extensive than their present limits. It may not be completely wrong, if it is said that the entire Bhima basin at one point of time in the geological history was concealed under Deccan traps.

2.3. Sedimentation and age of Bhima Basin

Detailed studies of sedimentary facies along with sequence stratigraphy is yet to be carried out in the Bhima basin. The Rabanpalli clastics consisting of conglomerate, arenite and shales with a fining upward sequence occur at the base of the basin are interpreted as products of deposition along beaches or deltaic zones grading laterally into a deeper tidal or sub-tidal environment (Kale & Peshwa, 1995). The REE and critical trace element ratios of the shales and sandstone of Rabanpalli formation indicate a felsic source like the basement Archean granitoids of the Dharwar craton (Dey, 2015). The presence of glauconite in shales and sandstone also indicate a shallow-marine environment. The overlying low Mg limestones of Shahabad Formation are products of shallow marine, carbonate flat depositional environments of an epicratonic platform (Kale, 1995) The wide-spread surface exposure of the carbonates in the basin suggest sustenance of a flat platform system, with very gentle slopes.

Pandey et al (2009) has reported a whole rock Pb/Pb isochron age of 1308 ± 49 Ma from the uranium mineralised Shahabad Limestone from Gogi. This implies a Mesoproterozoic age of the Bhima Group. Maithy & Babu (1996), Sharma et al. (2009) have reported a rich assemblage of carbonaceous macrofossils from shales of the Hulkal formation. These include *Sinosabellidites, Protoarenicola, Pararenicola, Protoarenicola, Chauria, Tawuvia, Beltina,* *Morania and Daltaenia.* On the basis of carbonaceous macrofossil assemblage, a Neoproterozoic (>740 Ma) age is assigned to the Hulkal Formation (Maithy & Babu 1996; Sharma & Shukla 2012). Dating the Bhima sequence, is difficult owing to the near absence of intrusive or extrusive igneous rocks, therefore a Meso-Neoproterozic age is assigned to the Bhima basin based on palaeontological evidence and dating of uranium mineralisation.

2.4. Structure of Bhima Basin

Sediments of the Bhima group generally display sub-horizontal bedding, except near faults, where steep dips, intense brecciation, isoclinal and recumbent folding and thrusting has been observed. The broad sub-horizontal disposition of the Bhima Group is evidence that the basin is unaffected by any major event of structural upheaval on a regional scale, post its lithification history (Kale,1995). Many of the major faults have affected not only the Bhima Group, but can also be traced through the basement terrain as zones of intense shearing, brecciation and silicification. Base metal mineralisation has been recorded from some of these faults (eg: Tintini copper deposits along the Tirth-Tintini fault (AMD unpublished annual report, 1998).

The major faults are the E-W Gogi-Kurlagere fault and the NW-SE Wadi fault and the minor faults are Tirth-Tintini fault, Wajhal fault and Farhatabad fault. The exposure pattern of the basin indicates that these faults have exercised control over the present configuration of the basin. Intense brecciation and at places isoclinal and recumbent folding is observed along narrow zones in the vicinity of the fault. The widest of such deformed zones is along the Wadi Fault with a width of around 500m, while this zone is approximately 300m at its widest along the Gogi fault.. Apart from folding and brecciation near the fault zones, some beds display small scale faulting and slump structures produced due to penecontemporaneous deformation of the semi-consolidated sediments prior to their total lithification. It was widely believed that the faults in the Bhima basin are strike-slip faults but the drilling done in Gogi and Kanchankayi area by AMD has established that some of the portions of the E-W trending KG fault have a reverse fault setup (AMD unpublished annual report, 1998-2016).

The evolution of Bhima basin is still unclear and seems to be different from that of the other Purana basins (Dey, 2015). Kale & Peshwa (1989, 1995) considered the dominant NW-SE trending fault as the main axial fault of the pull apart basin with dextral transtensional movement. This movement resulted in east-west trending second order faults. On the other hand, Jayaprakrash (2007) opined that the pull-apart originated from sinistral movement along the major NE-SW trending curved strike-slip fault. Later displacement along the east-west trending array of strike slip faults, caused by shear couple in a transtensional regime, brought the present configuration of the basin.

2.5. Uranium Mineralisation in Bhima Basin and work carried out by AMD

Bhima basin as such was considered least priority area for uranium exploration as limestone and shale constitute 80% by volume of the rock formations without any major tectonic activity (Kale, Phansalkar, 1991). Considering the basin being Proterozoic in age and the success of locating uranium deposits in the Proterozoic Cuddapah basin nearby, uranium exploration was taken up by AMD in the Bhima basin.

Reconnaitory radiometric traverses in the Bhima basin and its surrounding areas during the field season 1988-1989 bought a few radioactive anomalies during hydrogeochemical surveys near Wadi (with U upto 110 ppb) and a few low order U values in the basement granite near Ladlapur (AMD unpublished annual report, 1989). The encouraging U values in some of the hydrogeochemical samples led to the extensive exploration in the area, involving field techniques of ground radiometry, study of satellite imagery, jeep-borne and more hydrogeochemical surveys in the basin and the sediment -basement contact areas. This intergrated approach resulted in locating interesting surface uranium occurrences hosted in brecciated cherty phosphatic limestone near Ukinal along the tectonised zone of the Gogi-Kurlagere fault. A systematic radiometric survey was then undertaken along all the prominent fault zones which lead to the discovery of uranium mineralisation in various rock formations at a number of places. The uranium mineralisation in Bhima basin can be broadly classified into four categories: (i) hosted in phosphatic limestone/cherty limestone e.g., Ukinal, Darshanapur, Ramtirth (ii) hosted in non-phosphatic limestone e.g., Gogi, Halbhavi, (ii) hosted in granite e.g., Gogi and (iv) hosted in shale/siltstone e.g., Kasturpalli

(i)Mineralisation in phosphatic limestone: Uranium mineralisation hosted in phosphatic limestone has been located at Ukinal, Darshanapur and Madnal along the Gogi- Kurlagere fault zone and Ramtirth along the Wadi fault. The host rock has been identified as siliceous limestone, phosphatic chert and siliceous phosphorite. The major minerals are collophane and calcite admixed with silica, limonite, clay, glauconite and pyrolusite and other ore minerals present are specular hematite, anatase and pyrite as accessory. Uranium is mostly associated with collophane with minor amount in clay besides a little labile uranium along the grain boundaries.

(ii)Uranium in non-phosphatic limestone: Uranium mineralisation in non-phosphatic limestone is reported from Gogi, Halbhavi and Muktapur areas along the Gogi-Kurlagere fault. The mineralisation occurs in the form of veins cutting across bedding plane in brecciated grey Shahabad Limestone formation in the tectonised zone close to the sediment-basement contact. Surface samples contain 0.02% to 0.27% U_3O_8 and are free of thorium (Anjan Chaki et. al, 2005) Coffinite and pitchblende are the main uranium minerals which occur in intimate association with the carbonaceous matter and sulphides.

(iii)Mineralisation in granite: Uranium mineralisation in the basement granite close to the unconformity is reported at Gogi along the fault zone. In general, the uranium concentrations in the granites bordering the Bhima basin range from 10 to 110ppm. It occurs as fracture fillings and veinlets along the steeply dipping fractures developed in the granite thrusted over the sediments as well as horizonal fractures immediately below the unconformity contact.

(iv)Mineralisation in shale: Uranium mineralisation in glauconitic shale and siltstone has been identified near Kasturpalli intermittently over a strike length of 1 km (AMD unpublished report, 1998). The samples analysed upto 0.042% U_3O_8 but no distinct uranium mineral has been identified. The radioactivity is contributed by uranium adsorbed in limonite and U-Ti complex .

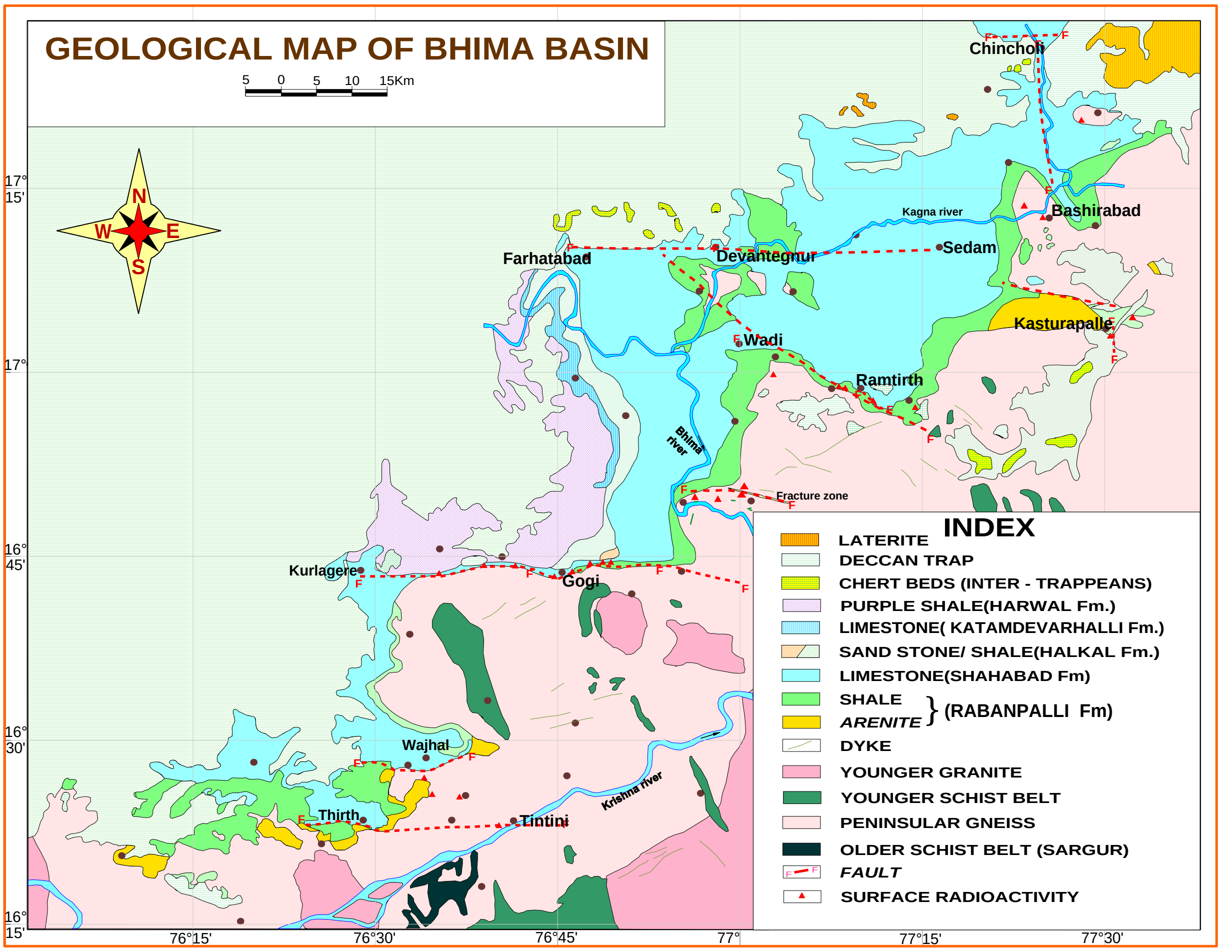


Figure 2.1 Geological map of Bhima basin (modified after Jayaprakash A.V 1999)

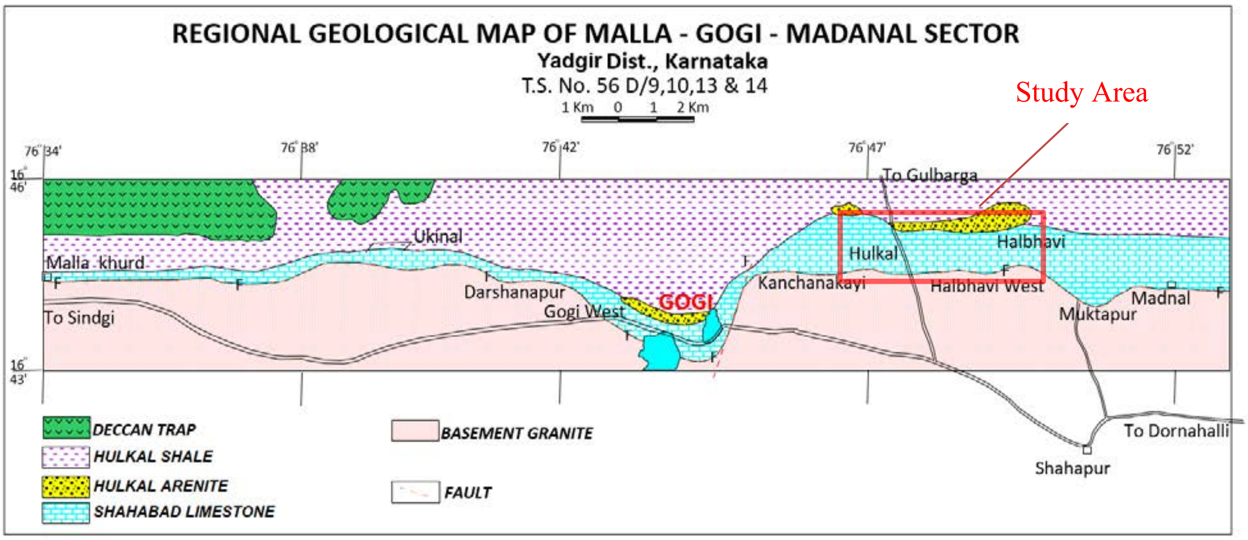


Figure 2.2 Regional geological map of Gogi-Kurlagere fault (after AMD,2004)

CHAPTER 3

GEOLOGICAL MAPPING

3.1. Introduction

A geologic map is a precisely oriented, scaled-down diagram of the earth's surface (Compton, 1985). Mapping is a means of discovering geological features, recording the field observations and visualizing the features in three dimensions. The observations made during the mapping of the area are the basis on which geological theories and models of an area are hypothesized.

3.2. Methodology

The toposheet was first studied to get an idea about the geomorphology, roads/routes and villages in the study area. Satellite data from Sentinel 2A (spatial resolution of 10m) was referred to identify any lineaments observed in the area. Based on the toposheet and satellite data, a reconnaitory traverse was planned with the aim to ground check the structural and lithological interpretations from the satellite data and to observe the disposition of the litho-units for planning of detailed traverses in the area. The geological traverses were taken along N-S direction, which is across to the general strike direction of the litho-units. Detailed geological observations and structural data were recorded at every 20m across and along the strike of the beds. The UTM co-ordinates of the locations were recorded using GPS (Garmin 78s model). Geological cum structural map was prepared based on the data recorded in the field traverses. The map was prepared on a GIS software - QGIS. The scale of mapping was 1:2000 and an area of 5 sq km was covered for the present study.

3.3 Description

Basement

Lithologically, the southern part of the study area exposes of basement crystallines comprising tonalite trondhjemite gneisses suite (Peninsular Gneissic Complex (PGC)) and Closepet equivalent granite. Scanty outcrops are found in south of Bheemarayagudi-Shahapur road. Due to the less exposures the granite is mainly studied from core samples of Kanchankayi area. On a mesoscopic scale, the Clospet Granite is medium to coarse grained, composed primarily of quartz and feldspar. In some zones it is moderately to highly altered, mainly chloritization is present. Alterations are particularly observed to occur along the grain boundaries as well as along the fracture planes. At places, calcite veins are present in fractured and brecciated granite. The granitoids are rich in accessory minerals like sphene, allanite, apatite and zircon which are probably source for uranium mineralisation in the area (Pandit er al 1999, Senthil Kumar et al 2002).

Basin sediment

Rabanpalli formation: The basement granite and gneiss are overlain by thin glauconitic shale or green shale (Rabanpalli formation). No exposures of this shale are found to occur on the surface within the study area but the shales are studied from the boreholes of Kanchankayi and Hulkal area. Due to lack of outcrop exposures, the contact between the basement and shale is inferred from studying rock chips in soil and observing the soil. Mesoscopically, it is very fine grained, laminated, green colour and composed of glauconite alternating with purple shale. Green colour glauconite mineral, which can form by diagenetic alteration of biotite under reducing conditions, is indicative of shallow marine environment of formation. Intercalation of oxidizing and reducing litho-units indicate frequent fluctuations in environment at the time of sedimentation. At places, fine grained arenaceous band are found to be alternating with the shale. The arenaceous bands dominantly composed of medium to fine grained quartz. The thickness of the arenaceous bands varies with minimum (<1cm) and maximum (5 cm).

Shahabad Limestone: Limestones of Shahabad Formation overlie the glauconitic shale. Megascopically, Shahabad limestone indicate variations in the composition and structure. To understand the variation in limestone unit, an attempt has been made during the present study to classify the limestone unit on the basis of structure and composition. On a mesoscopic scale, the lithounit can be divided into 2 categories i) Limestone without chert content and ii) Limestone with chert content. These two categories can be further subdivided on the basis of structure. The former is subdivided into three types a) Massive limestone b) Bedded limestone c) Brecciated limestone. The latter is divided into two types a) Bedded cherty limestone b) Brecciated intraformational limestone (Figure 3.1). Variations in the attitude of limestone unit are dealt in detail in coming chapter, “Structure and deformation”.

Bedded limestone is the dominant litho-unit in the study area. Brecciated limestone is observed near to the contact of Shahabad Limestone with Hulkal arenite. In most of the brecciated limestone outcrop exposures, moderate brecciation is observed. Limestone with chert content can be identified based on differential weathering of limestone and chert bands. Chert is more resistant to weathering than limestone. Also, chert in the study area has a light brown colour. Concretionary chert nodules in limestone are also observed near Kanchankayi and Halbhavi area (Figure 3.1 d). Brecciated Intraformational limestone is exposed near Kanchankayi Masjid hillock. The width of the intraformational limestone zone varies from 25m to 50m. Some slumping in the limestone beds can also be inferred from the localized change in dip of the beds in this area. The brecciated intraformational limestone and slumping of limestone beds are indicative of penecontemporaneous deformation in the area.

Hulkal Formation: Shahabad limestone in Kanchankayi-Hulkal-Halbhavi area is overlain by sandstone in the northern part. The rock is light coloured and is dominantly composed of silt and sand size grains of quartz and hence designated as quartz arenite. The quartz grains are sub-rounded to rounded with less than 10% matrix and are texturally as well as mineralogically mature. The contact between the limestone is mostly soil covered in Kanchankay-Hulkal area. Hillocks near Hulkal and Halbhavi area are mostly made up of arenite. The lithounit follows the general E-W strike with dip varying from horizontal to upto 15^0 towards north. In Halbhavi area, dip upto 35^0 is also observed (Figure 3.4). Quartz arenite is overlain by shale of Hulkal formation further northward towards the basin.

Thus, observations from field study reveals that the sediments of the Bhima Group exposed in the study area have mainly two cycles of sedimentation. First cycle is marked by thin arenaceous and argillaceous sediments of Rabanpalli Formation followed by thick calcareous sediments of Shahabad Formation. While, second cycle of Bhima sedimentation is marked by clastics of Hulkal Formation (Quartz arenite and Shale) followed by thick limestone of Katamdevarahalli Formation however this limestone unit is not exposed in the study area.

(a)

(b)

(c)

(d)

Figure 3.1 Different types of limestone observed in the study area (a) Bedded limestone (b) Brecciated intraformational limestone (c) Bedded cherty limestone (d) Limestone with chert nodules

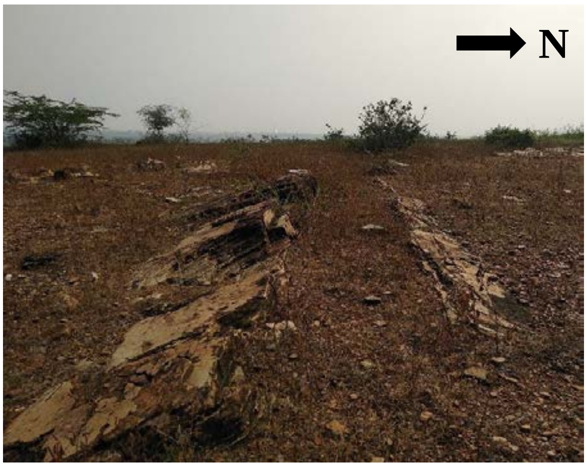


Figure 3.2 Field photograph of bedded limestone with localised opposite dip direction due to warping, Kanchankayi area

Figure 3.3 E-W trending bedded limestone exposed in Halbhavi area showing variation in dip towards N

Figure 3.4 Field photograph of Quartz arenite (Hulkal arenite) beds with localised slumping towards north, Halbhavi area

Figure 3.5 Field photograph of brecciated Limestone, Kanchankayi area

(a) (b) (c)

(d) (e) (f)

Figure 3.6 Borehole core samples of the different litho-units in the study area. (a) Bedded limestone with moderate dip (b) Brecciated limestone (c) Stylolite structure in limestone (d) Purple shale with intercalation of limestone beds (e) Brecciated Granite (f) Grey granite with zones rich in feldspathic content

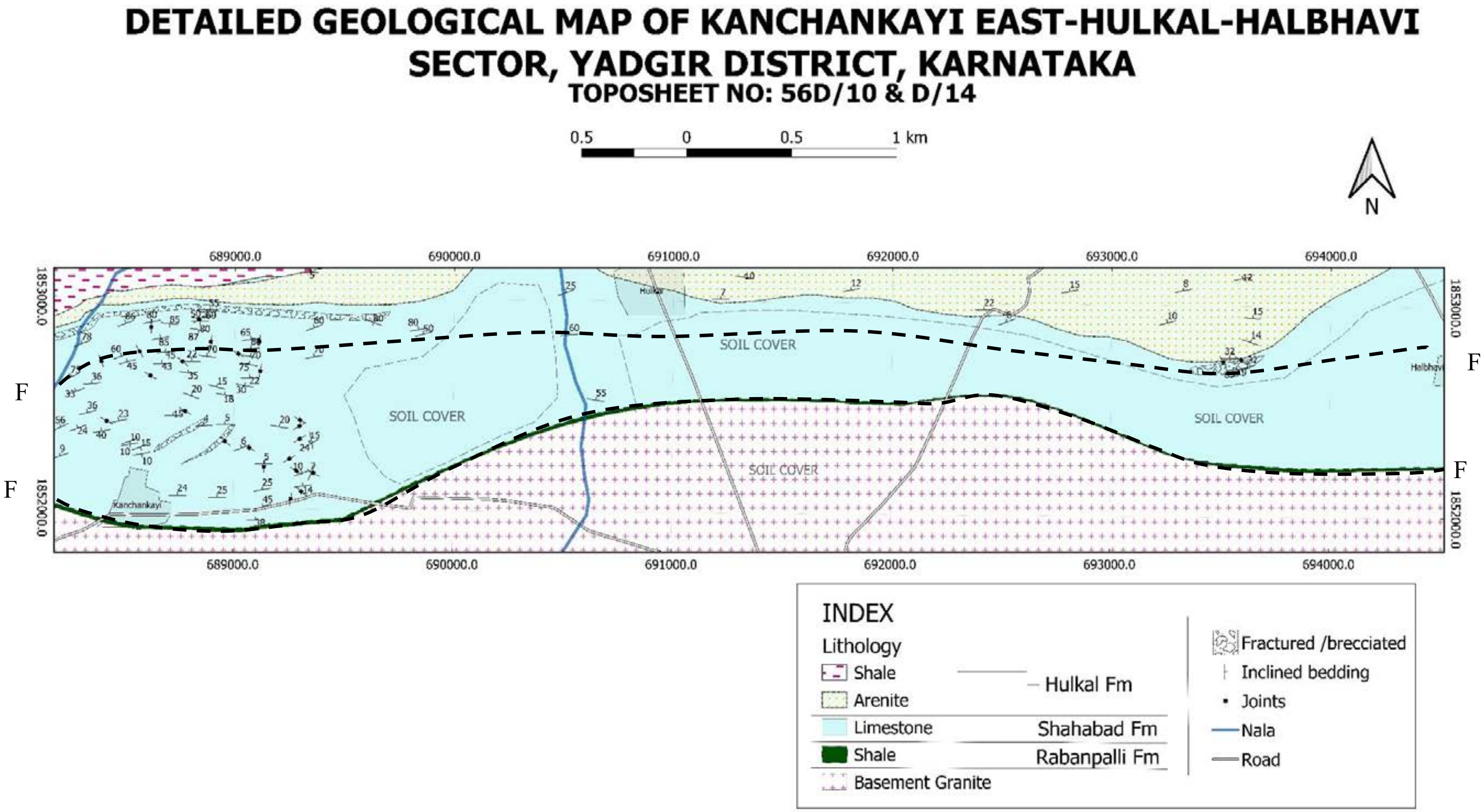


Figure 3.7. Detailed geological cum structural map (1:2000) of Kanchankayi East-Hulkal- Halbhavi sector, Yadgir District, Karnataka

CHAPTER 4

STRUCTURE AND DEFORMATION

4.1 Introduction

Structural geology is an essential tool in unraveling the geologic history of any given area or region within the earth, especially in areas affected by tectonic activities where deformational movements profoundly modify original arrangements of rocks and geologic contacts (Davis & Reynolds, 2012). The importance of studying deformational structures in structurally disturbed areas is that it represents the post-depositional history and deformational events of the area. In a sedimentary basin, the presence of bedding or stratification greatly facilitates the structural analysis of the area because the bedding and the interfaces of the beds provide set of marker surfaces which were more or less horizontal before the onset of deformation. Studying the deformed primary structures in the rock is the key to unfold post-depositional history of the area. The present chapter deals with the study of deformational structures in limestone of Shahabad formation in regional and mesoscopic scale. The study attempts to facilitate the understanding of deformation in the area and its variation in space and the implications of deformation on uranium mineralisation in the area.

4.2 Structural framework of Kanchankayi sector

On the regional scale, sediments of Bhima Group show horizontal disposition of bedding and can be considered as almost undisturbed and unaffected by any major tectonic events. The most prominent effect of deformation is restricted along the narrow tectonised zones- strike slip faults that affect the basin sediments and the basement granitoids of the Bhima Group. The width of the tectonised zones along these faults varies. Along the Gogi-Kurlagere (KG) fault the width varies from 50m to 500m. In general, the degree of deformation gradually diminishes and the beds attain sub-horizontal disposition as one approaches away from the fault zone towards the basin.

The E-W trending KG fault has reverse faulting in segments but not along the entire length of the fault. The KG fault has a NW-SE trend in Darshanpur - Gogi west sector while it has a NE-SW trend in Gogi-Kanchankayi sector. Drilling data around Gogi and Kanchankayi in the fault zones clearly confirms the presence of reverse fault giving rise to a nose like appearance in sections across strike. The reverse nature of the fault maybe attributed to the swerving nature of the KG fault which is a restraining bend in the Gogi-Kanchankayi sector. Bends in strike slip faults invite high concentration of strain (Crowell, 1974,). The deformed zones in the area are thus a result of the compressional regime formed at the restraining bend part of the KG fault. Further east of the Gogi-Kanchankayi sector, the fault takes a swerve to follow the regional E-W trend that has resulted in forming splay faults (Roy et.al., 2016). Splay faults form when the primary fault becomes critically misaligned with the principal stresses. In Kanchankayi area, two deformed zones have been demarcated from the geological mapping. These deformed zones are a manifestation of two arms of the splay fault. One arm of the splay fault follows the basement-sediment contact while the other arm transgresses into the sediments.

The study area displays lithounits which preserve primary and secondary structures. The dominant primary structure, the bedding planes, are defined by change in colour, composition and grain size within limestone unit of Shahabad Formation. In the present study, the primary focus is to understand the deformation of the primary structures. The major deformational structures in the study area include planar deformational structures like foliation, joint and fracture planes. In addition to these, fault zones are marked by brecciated zones.

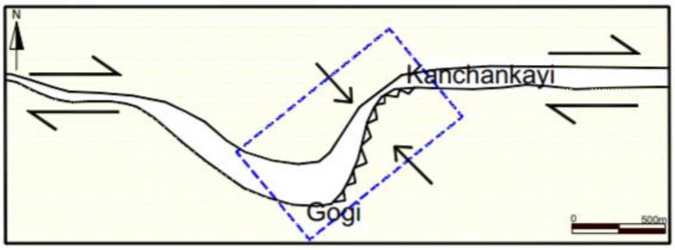


Figure 4.1 Schematic diagram showing development of transpressional zone at restraining bend of dextral slip fault near Gogi-Kanchankayi

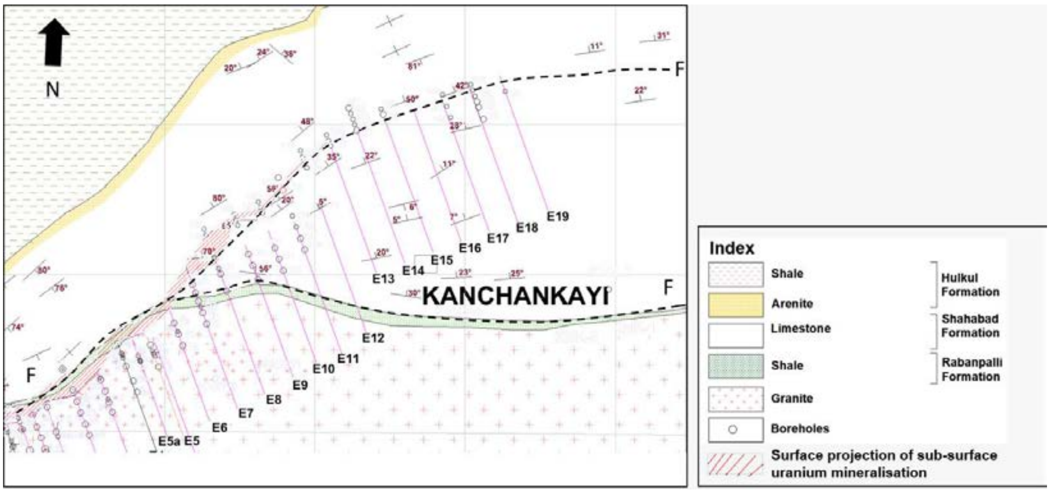


Figure 4.2 Schematic diagram of borehole plan of Kanchankayi sector showing splayed arms of the fault and surface projection of sub-surface uranium mineralisation

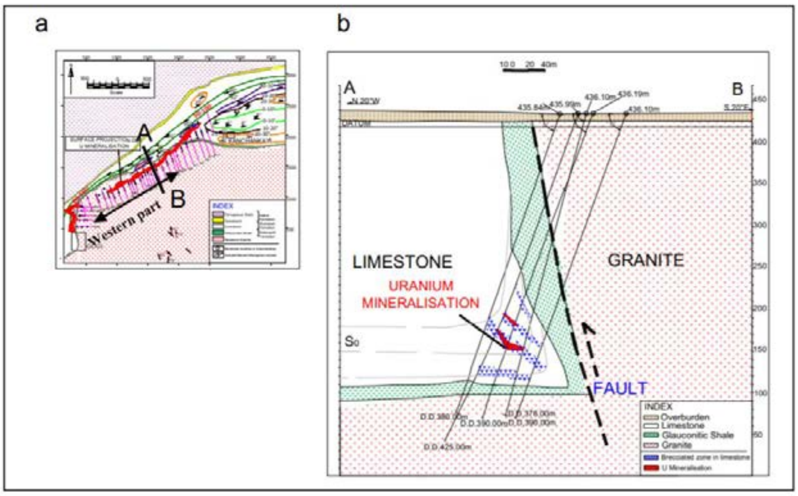


Figure 4.3 (a) Geological map showing location of transverse section line (b) Representative transverse section through boreholes in western part of Kanchankayi area depicting the structure and the uranium mineralisation zones in limestone (after AMD unpublished annual report, 2016)

4.3 Structural analysis

Structural analysis involves observing the deformed rocks in the field, acquisition of the structural data from the litho-units, plotting of the acquired data in a geological map and further analysis to understand the deformational history of an area. The acquisition of the structural data involved measurement of strike and dip of planar structures as well as trend and plotting them in the structural map produced. Based on the observations and data collected during mapping, the following structural studies were carried out in the Kanchankayi-East – Halbhavi sector.

(i) Stereo-analysis of bedding plane attitude of limestone to depict their variation along the fault zone.

(ii) Analysis of fracture trends using Rose diagram within limestone to understand their possible origin.

(iii) Preparation of geological cross sections to understand the structural setup of the study area.

(iv) Microstructural studies from thin sections of samples of limestone and granite which are discussed in the chapter-5—Petrography.

(v) Preparation of 3-dimensional model correlating the surface deformation and the sub-surface fault in Kanchankayi area.

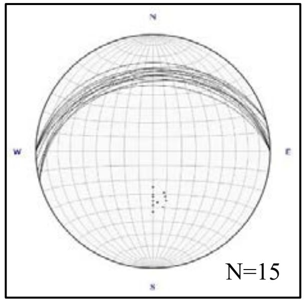
4.3.1 Stereo-analysis of bedding plane attitude of limestone

One of the most common method to analyse the geological structures in 3-dimension is the use of stereographic projection, where geometrical relationships between planes (bedding, foliations, joints, faults) and lines (mineral lineation, fold hinges, intersection lines between planes etc.) can be easily visualized (Phillips, 1961). The stereographic projection represents the equatorial circle of a sphere whose southern hemisphere contains the planar surface and linear structural elements. The intersections of these planar and linear structural elements are projected to the northern pole of the sphere and the locus of the intersection of those projection on the equatorial plane is depicted in stereo analysis. In other words, it is the projection of points from the surface of a sphere onto a horizontal plane passing through its centre.

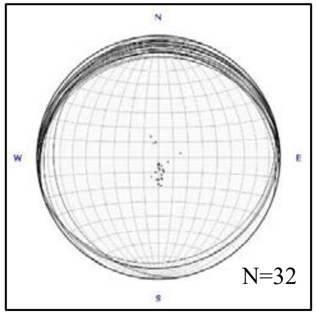
Results

The variation of dip of the beds is a very significant indicator of deformation in Bhima basin. Steeply dipping beds are observed along the major faults throughout the basin. In the study area, a wide variation of dip of beds are observed. The general strike of the beds in the area are N70 E- S70W with the dip towards the north. In some cases, reversal of dip direction of the bed is also noticed. Near the sediment basement contact (southern part of the basin), the dip of the limestone bed is around 25-45^0, suggesting moderate deformation in the area. Further north of the sediment basement contact, the limestone beds have shallow to sub-horizontal dips (10 to 20^0 dip) which is indicative of little or no deformation in the area. Further north of the less deformed zone, the dip of the beds increases gradually till a zone of high deformation is encountered where the dip of the beds varies from 45^0 to 85^0. The variations in the dip of the bed along the south to north profile is shown in the Figure 4.4. From the plots we can clearly see there are three zones in the study area, (i) Moderately deformed zone (ii) No deformation zone (iii) Highly deformed zone. The moderately deformed zone corresponds to the southern arm of the splayed KG fault which is along the sediment basement contact, while the highly deformed zone corresponds to the northern arm of the splay fault. The steep dips observed along the northern splayed arm of the fault also suggest that deformation is more in the northern arm than the southern arm of the fault where moderate dip of the beds are observed. Steeply dipping beds of cherty limestone are also observed near to the contact of Shahabad limestone and Hulkal arenite which suggest that the deformed zone extends till the contact of the two litho-units.

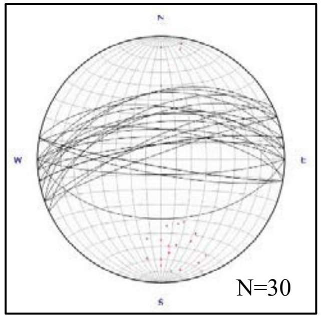
Variation of the bedding planes and structures of the rocks with depth was also studied to understand the sub-surface geometry and deformation in the rock. Figure 4.5 shows the variation of the bedding with depth from one of the borehole cores drilled in the northern arm of the splayed fault. At shallower depths, moderately dipping beds are observed, with increase in depth the beds become steep and around `130 – 140 m depth, brecciated limestone with multiple fractures is observed. At depths around 200m, steeply dipping beds are observed. The steep dips and brecciation in the sub-surface cores indicate intense deformation.



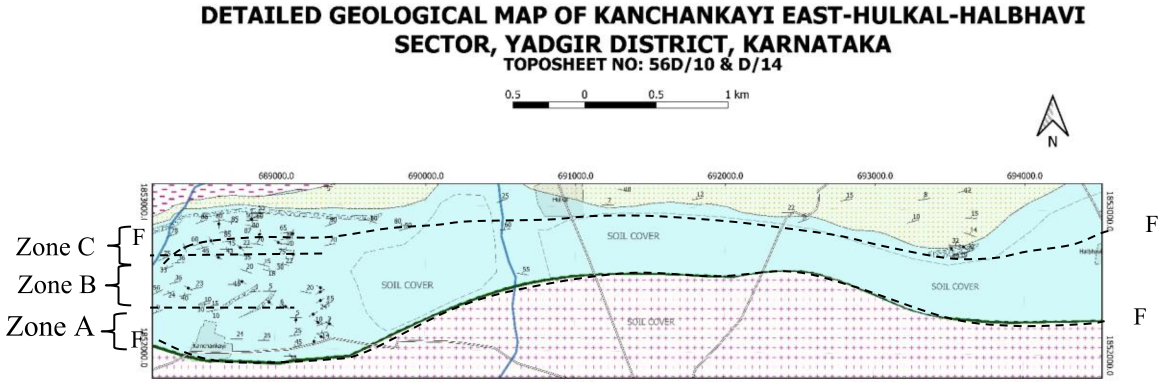
(a) Zone A: Moderate dip



(b) Zone B: Sub-horizontal dip



(c) Zone C: Steep dip



(d)

(e)

(f)

Figure 4.4 Variation in the dip of the beds along north-south profile in Kancahnakayi area (a) Stereographic projection of Zone A (b) Stereographic projection of Zone B (c) Stereographic projection of Zone C (d) Field photograph of Zone A (e) Field photograph of Zone B (f) Field photograph of Zone C

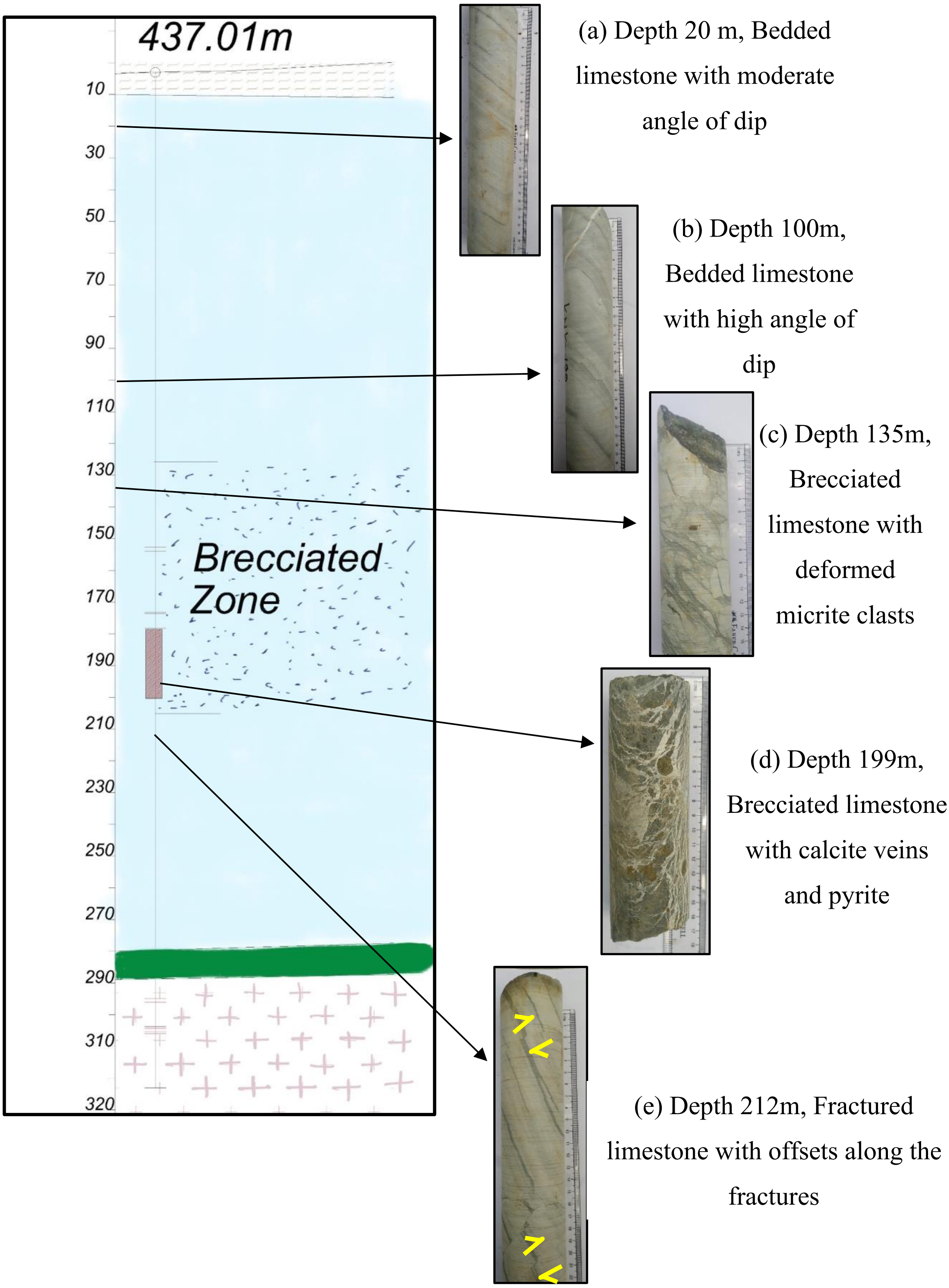


Figure 4.5 Deformation observed along the vertical borehole with increasing depth.

4.3.2 Analysis of fracture using Rose diagram (Azimuth frequency plot)

Mapping the location and orientation of fractures are essential for studying spatial patterns of fractures. In the study area orientation of the different fracture set present are noted and plotted using azimuth frequency rose diagram.

Rose diagram represents a histogram in which the orientation is transformed into circle to give a true angular plot. The interval is plotted as segment of the circle in their true orientation and the length of the orientation is frequency of the orientations. The objective of plotting the data of the study area in rose diagram is to bring out the general trend of surface fracture and also to demarcate the dominant fracture set for the proper understanding of stress responsible for development of these features.

Results:

Rose diagram plot of the fractures within limestone of Shahabad Formation show two distinct sets of fracture: a) 310 – 130 and b) 10 – 190. Most of the fractures in the study area are vertical. The 310 – 130 set of fracture is more prominent in the study area. Fracture trends in the granite, between Gogi and Kanchnakayi area also show similar fracture trend (Roy, 2016). This suggest that the 310 – 130 fracture set is developed on a regional scale and has affected both the sediments and the basement granite. In some of the outcrops, near Hulkal nala, the 310 -130 fracture set in massive limestone is filled with secondary calcite. In dextral strike slip setting, a tension fracture can be developed in the rock at an angle, due to the strike slip movement as illustrated in Figure 4.7. Small offsets in 10 – 190 fracture set is also observed in some outcrops. Offsets along 60 – 240 fracture trend is also observed in Halbhavi area but the fracture set is not prominent.

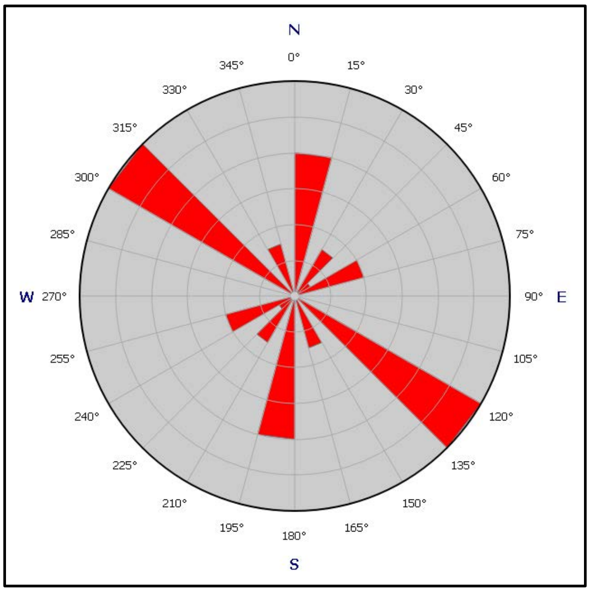


Figure 4.6 Azimuth frequency plot (Rose diagram) of the fracture data in the study area (n=100)

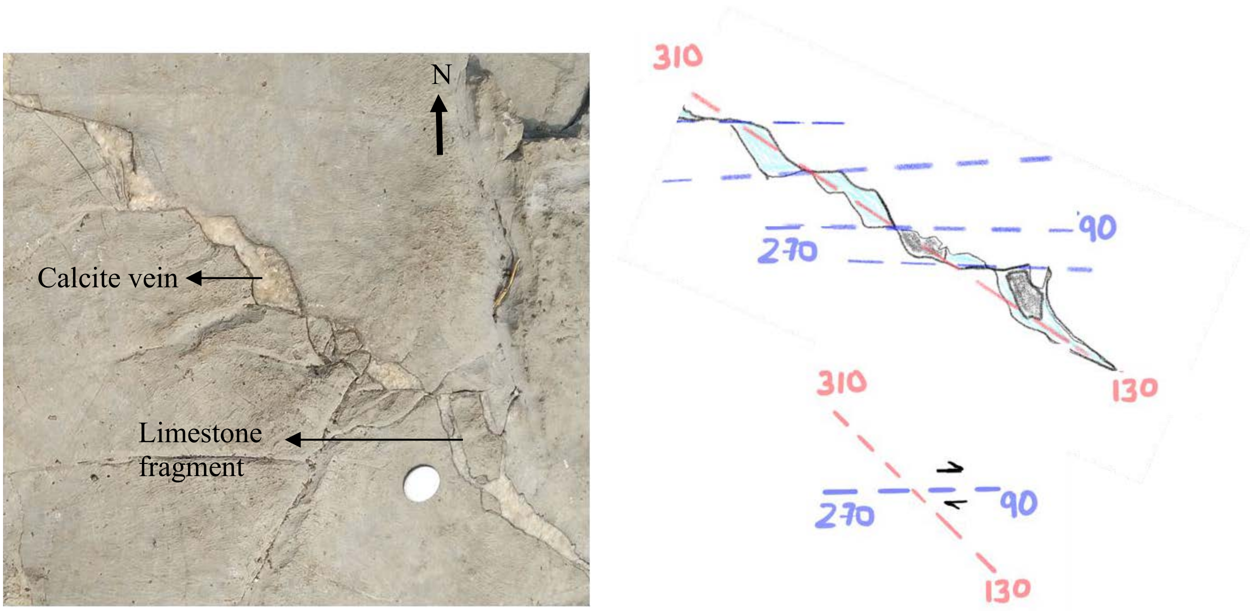


Figure 4.7 (a) Field photograph of calcite vein along 130-310 fracture (b) Schematic diagram of the field photo with fracture trend and direction of displacement inferred with the help of the pull-apart concept mentioned in Figure 4.8. The 310-130 fracture trend corresponds to the tension crack formed during strike-slip faulting

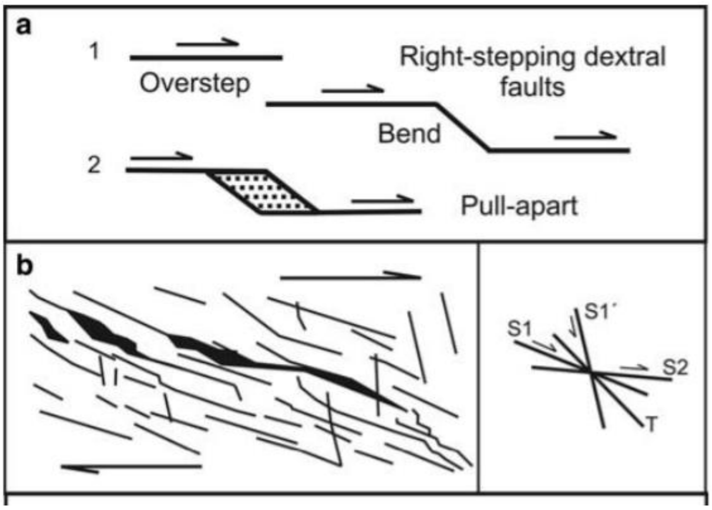


Figure 4.8 Three mechanisms for the development of pull-apart basins. An en echelon right-stepping dextral strike-slip faults. Pull-apart basins form at the overstep or bend (Mirror image for the left stepping sinistral faults). b Distributed shear. Pull-apart basins form during linking and coalescence of main faults. S_1 and S_1` are primary synthetic and antithetic strike-slip faults, respectively. T and S2 are tension and secondary synthetic strike-slip faults, respectively. (after Atmaoui, 2005)

4.3.3 Preparation of geological cross sections and 3-Dimensional geological model

Geological cross sections are graphical representation of vertical slices through earth to interpret the geological and structural relationship among different litho unit. The objective for preparation of geological section is to assemble geological information obtained from field studies, such as contact between different lithology and orientations of different structural features at individual outcrops so as to produce a geometrically accurate compilation of different lithology along a vertical plane in a section line and secondly, to extrapolate the information into a region (usually along depth) where there is no information. The accuracy by which we extrapolate the exact lithological contact and structural data to deeper level to predict the morphology of structure at depth plays a key role in understanding the deformation pattern and tectonic history of the area.

Two geological cross sections along line A-B and C-D in Kanchankayi and Halbhavi area respectively are shown in Figure 4.9. From the two sections we can see that the zone of deformation in the northern splayed arm of the fault is a curvilinear zone dipping south. We can see that the basement granite wedge has pushed into the overlaying limestone sediments causing brecciation and deformation in the shale, limestone and granite which is indicative of a reverse fault setup in the area. The reverse fault is a high angle reverse fault with a southerly dip and has a dip amount of around 70^0. The southern arm of the splay fault, on the other hand is a normal fault along the sediment -basement contact and has a $45\text{-}50^0$ dip towards the north.

Stacked transverse sections and 3 D model of a part of the study area were prepared for better geological understanding of the area and to correlate the geological sections in 3 dimensions. From the stacked section and the 3 D models we can observe that the uranium mineralisation is mostly confined to the brecciated zones near the granite wedge that has pushed into the overlaying sediments. As the brecciated zone is perpendicular to the granite wedge, the mineralised band in the brecciated limestone also forms a perpendicular to the granite wedge and is dipping towards north. The deformation in the overlying sediments is increasing from E-16 to E-19 section line i.e. from west to east. A lower uranium mineralised band is also intercepted from E-18 section line onwards.

4.4 Discussion

Geological and structural mapping in the area brings out the deformational pattern along the Gogi – Kurlagere fault zone in Kannchankayi-East – Hulkal – Halbhavi sector. The eastern continuation of the splayed arms of the fault are demarcated by the zones of deformation associated with the fault. Two zones of deformation are identified based on the variation in the dip of the beds. The two zones correspond to the two splayed arms of the KG fault. One in the southern portion of the geological map near to the sediment-basement contact where dip of the beds are around 25-45, which is indicative of moderate deformation. The deformed zone is the southern splayed arm of the KG fault. This fault is along the contact of the Bhima sediments and basement granite and is a normal fault which is confirmed from the drilling done in the area (KNK-1 & KNK-2). The other deformed zone is in the northern portion of the map and corresponds to the northern splayed arm of the main fault. The northern arm is more deformed as compared to the southern arm which is manifested by the steep dip of the beds observed in the deformed zone and the brecciation observed in the sub-surface bore hole cores.

Two major fracture trends – (i) 130-310 and (ii) 10-190 are observed in the study area. The 310-130 fracture set is more prominent in the study area and is also continuing in the basement granite. The 310-130 fracture set maybe formed due to the tensional fractures produced due to the dextral strike slip movement in the area.

Comparing the transverse sections of Gogi-Kanchankayi sector and Kanchankayi-Hulkal sector we can clearly see that the fault setup in both the areas are different. In Gogi-Kanchankayi sector, the sediment basement contact is a faulted contact and the fault is reverse in nature. On the contrary, the southern splayed arm of the fault in Kanchankayi area which is also along the sediment basement contact is a normal fault. The stress regimes in the area may have caused variation in the type of fault and the splaying of fault. Uranium mineralisation in Gogi-Kanchankayi sector is along the faulted contact, while in the Kanchankayi-Hulkal sector the mineralisation follows the northern splayed arm of the fault which transgresses into the Shahabad limestone. The northern splayed arm of the fault is reverse in nature, where the basement granite wedge is pushed into the overlaying Bhima sediments and has caused brecciation. Uranium mineralisation in the area is mostly confined to these reverse fault induced brecciated zones. The reverse fault setup in Gogi and Kanchankayi area are both high angle fault setups with the fault plane having a 60 dip towards the south.

The 3-Dimensional model and Stacked section (from E-16 to E-19 section line) of Kanchankayi area depicts a high angle curvilinear zone of deformation associated with the northern arm of the splayed fault.

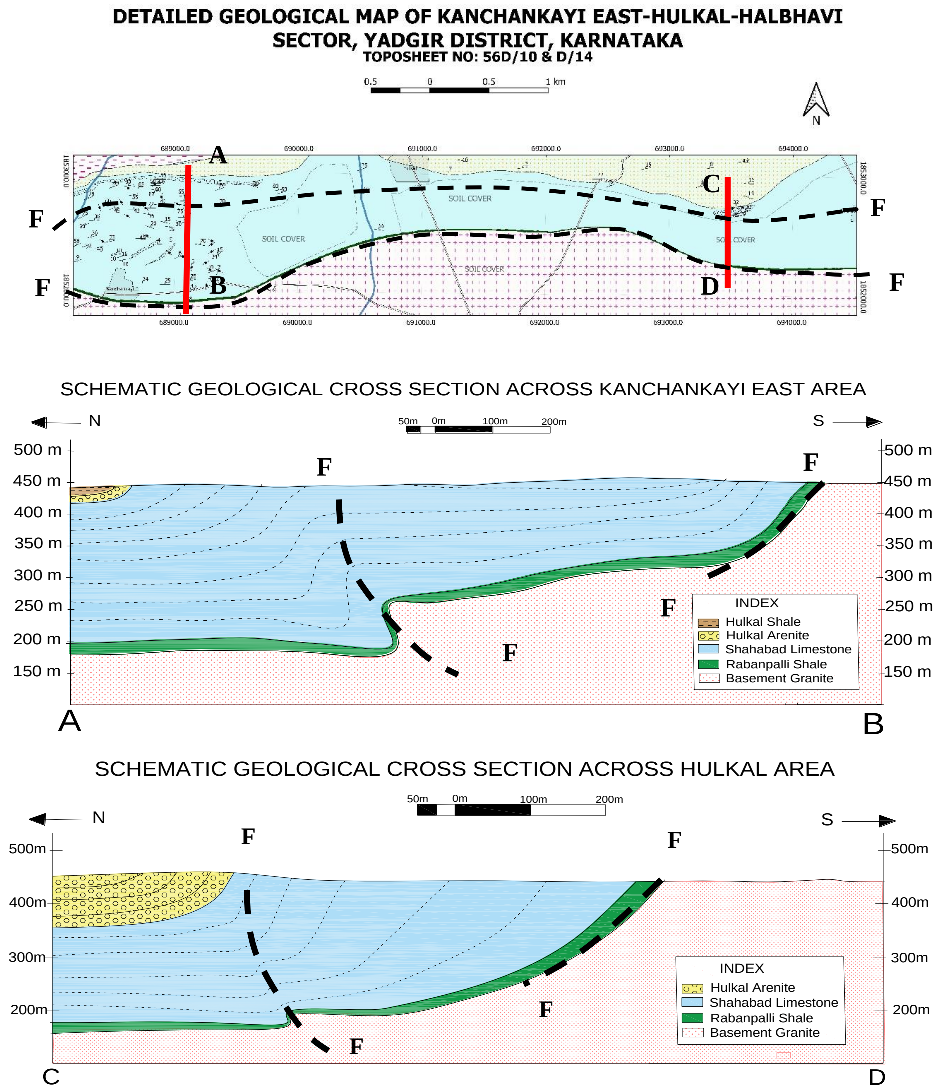


Figure 4.9 Geological cross sections along section AB and section CD

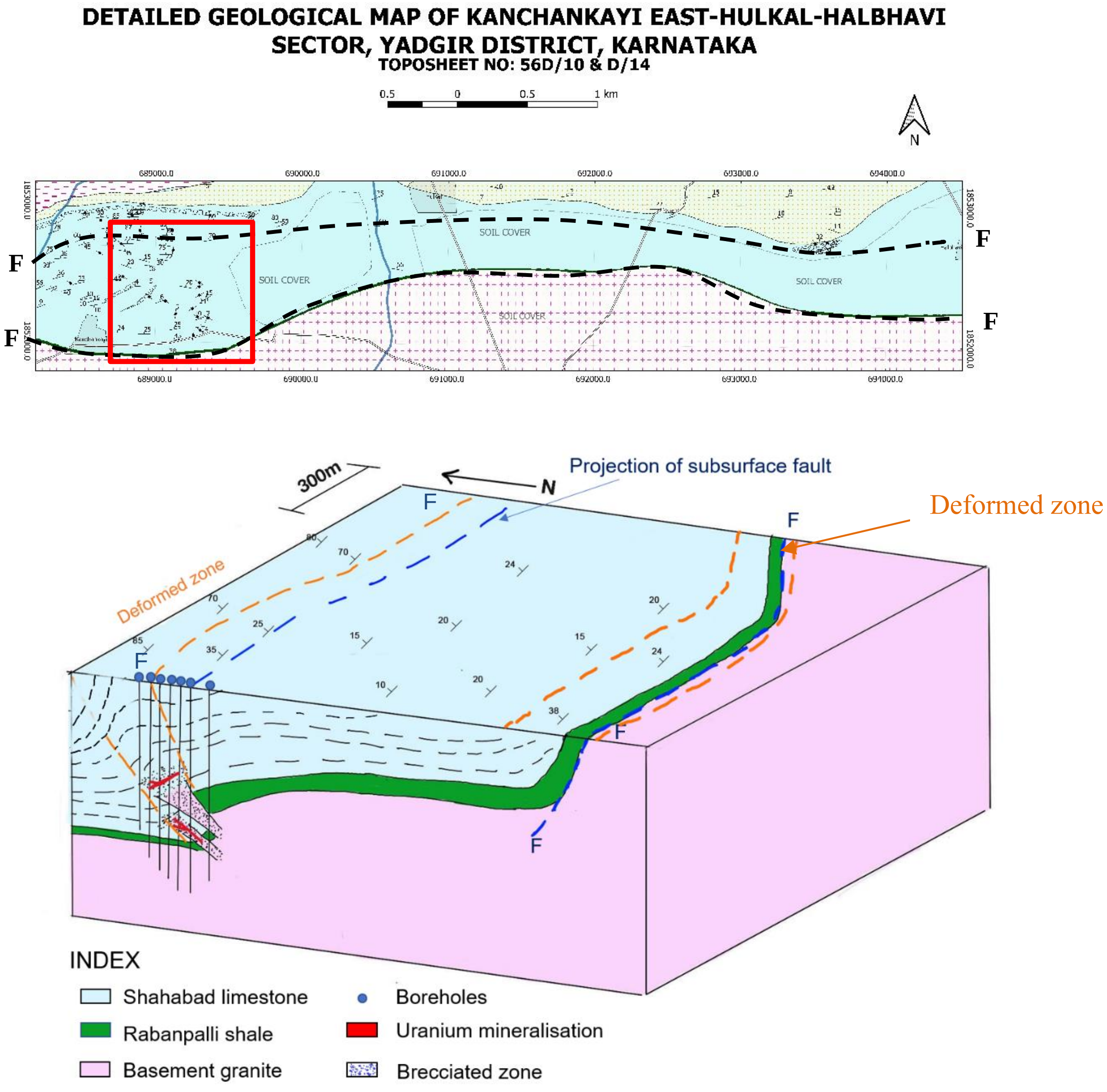


Figure 4.10 3 D Geological model of part of Kanchankayi area

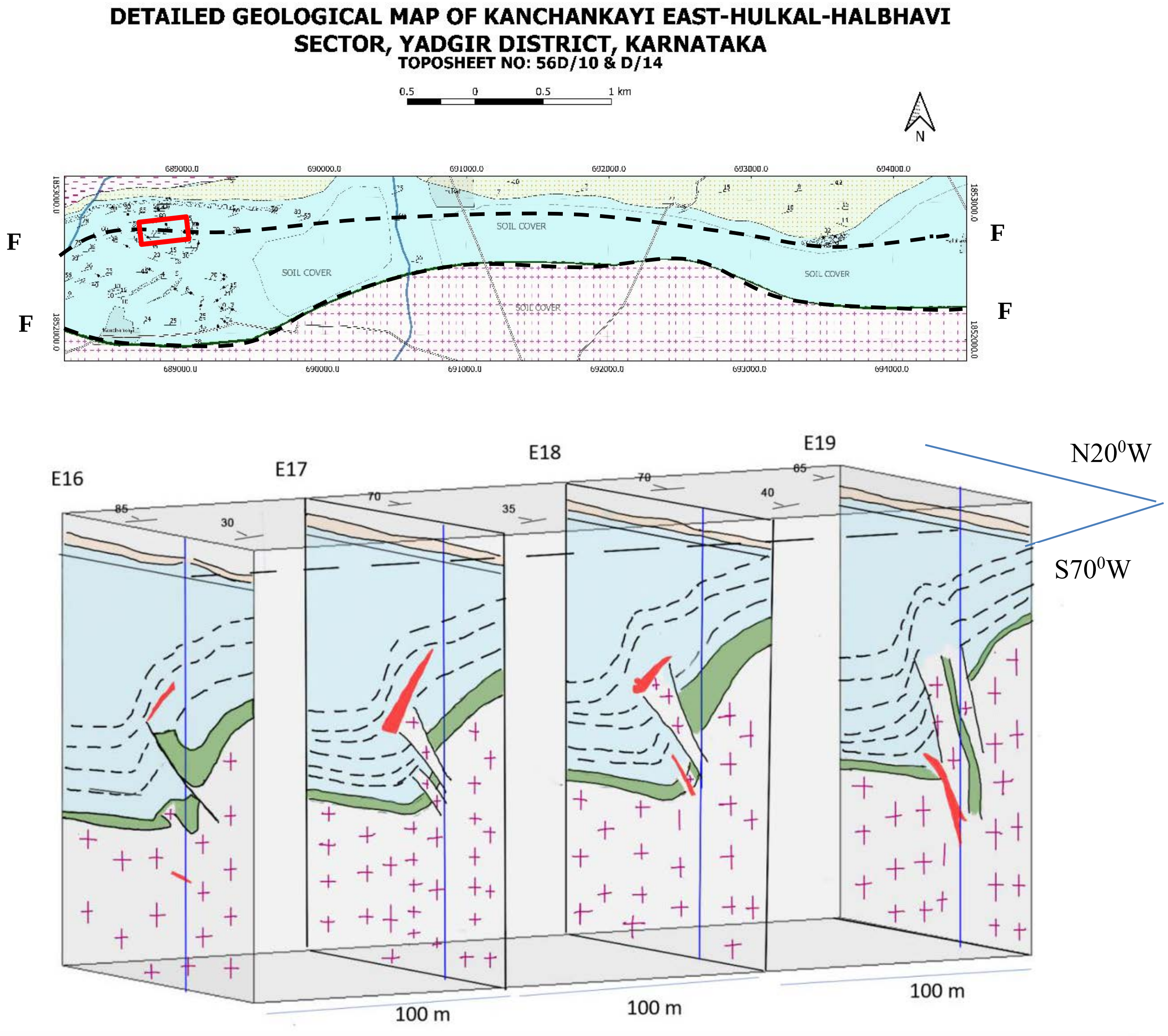


Figure 4.11 Stacked transverse sections of Kanchankayi area

CHAPTER 5

PETROGRAPHY

5.1 Introduction

The petrographic microscope provides one of the primary means of studying minerals and the rocks they comprise (Nesse, 2000). Petrographic studies of 20 samples (Limestone n=14, Granite n=6) from of the study area were carried out to find out the mineral assemblages, textures, and microstructures. The study not only identifies the mineralogical and microstructural parameters but also forms the basis for further geochemical studies.

5.2 Sampling and methodology

Samples have been collected from the litho units exposed in the study area as well as the borehole cores of Kanchankayi-Hulkal exploratory block. Sub-surface exploration in the Kanchankayi area is presently being done in Kanchankayi East-Hulkal block. Systematic sampling from borehole cores (KNK-191, KNK-192, KNK- 193, 199, HKL-1, HKL-2, HKL-3) has been carried out to study the mode of occurrence of radioactive phases, and other ore minerals. While taking a sample, the sample was carefully broken and then a picture of the sample was taken with brief description of the megascopic features observed in the sample. The samples were neatly labelled and placed in plastic bags to avoid breakage while transporting them to laboratory studies.

In the laboratory, the plane where the section needs to be cut is first marked on the sample. The samples are then cut, the saw cut face of the sample is first polished and attached to a glass slide using epoxy glue or Canada balsam. Further, the samples were polished till the thickness of 30 µm was obtained. This fine polishing was carried out by abrading the rocks against metal and glass plates using Silicone Carbide (SiC, also known a carborundum) powder of varying granule sizes of 220#, 400#, 600#, 800# and 1000# sieve mesh. This section was further polished by alumina (AlOH) solution and diamond paste to impart superfine polish and brilliant reflecting surface to the opaque metallic minerals. In addition to this, Cellulose Nitrate (CN) film study was also carried out for the identification of radioactive minerals. Steps involved is given in the following flow sheet.

Step 1 : Place indicators mixed with radioactive minerals/materials on four corners of the specimen on thin section/polished slab/bakelite or araldite moulds.

↓

Step 2: Cut the transparent CN – 85 alpha sensitive film of the thin section/mould and place the CN film on the top of the specimen. Make sure that the film has even and close contact with the specimen.

↓

Step 3: After 3 days of exposure through the contact, the exposed CN film is removed and 'etched' in 10% aqueous solution of sodium hydroxide (NaOH) for about 6 to 10 hours at room temperature.

↓

Step 4: The exposed and etched CN film now shows variable intensity of alpha tracks matching with concentration of radioelements in minerals and their size/shape.

Figure. 5.1 Flowchart of CN Film test

5.3 Basement granite

Mineralogy: As very few granite surface outcrops are present in the study area, most of the granite samples studied for petrography are from borehole core samples. Basement granite is medium to coarse grained often foliated grey to pink coloured in hand specimen. It has undergone brittle-ductile deformation leading to intense fracturing with partial to complete transformation into fine grained cataclasite and mylonite. Petro-mineralogical study reveals that the basement granite is comprised of quartz, plagioclase, microcline and K- feldspar as major minerals. Biotite and chlorite are present in minor amount whereas zircon, apatite occurs as accessory mineral phases. Texturally the rocks are medium to coarse grained, anhedral to subhedral, inequigranular and in equidimensional showing deformational texture. Rock have undergone lesser to moderate degree of alteration manifested in the form of sericitisation and chloritisation. Feldspar grains are showing alteration to form sericite.

Textures & Micro-structures: Microstructural studies of granitic samples bring out the evidences of brittle-ductile deformation. These evidences include some quartz grains showing undulose extinction, kinked plagioclase and deformed biotite. Granite near the tectonised contact zone in Kanchankayi area, shows intense brecciation and numerous fractures which are filled with secondary calcite veins. Grain size reduction as a result of brittle deformation has also been observed. Brecciated mixed rock having glauconite, arenite and granite clasts are also observed which indicates reverse faulting.

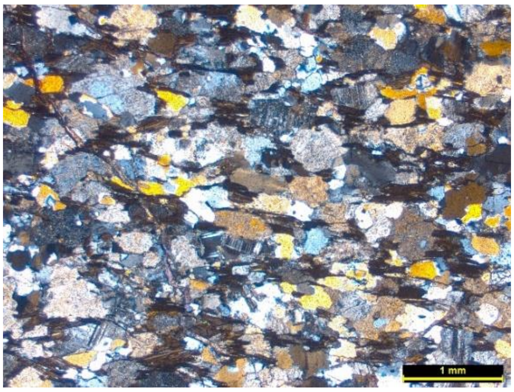


Figure 5.2 Photomicrograph showing crude foliation in basement granite. TL, XN

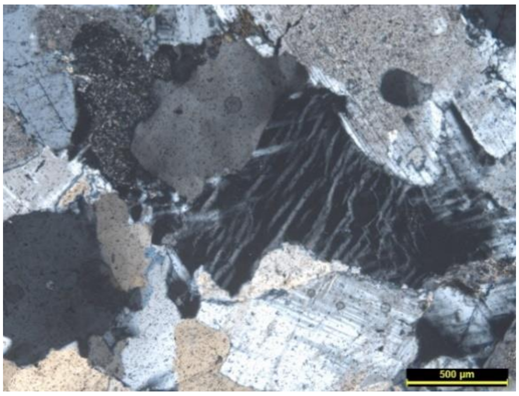


Figure 5.3 Photomicrograph showing perthitic texture in granite, TL, XN

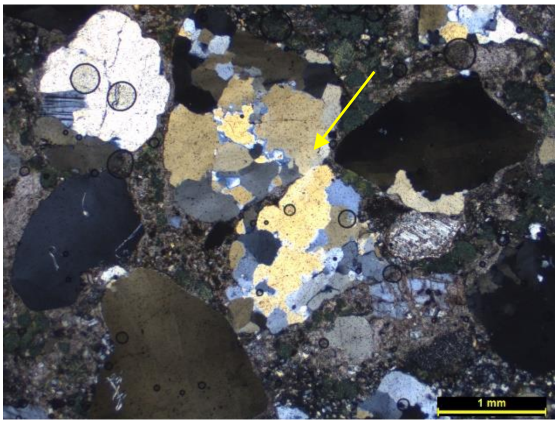


Figure 5.4 Photomicrograph showing crushed granite fragments in brecciated granite TL,XN

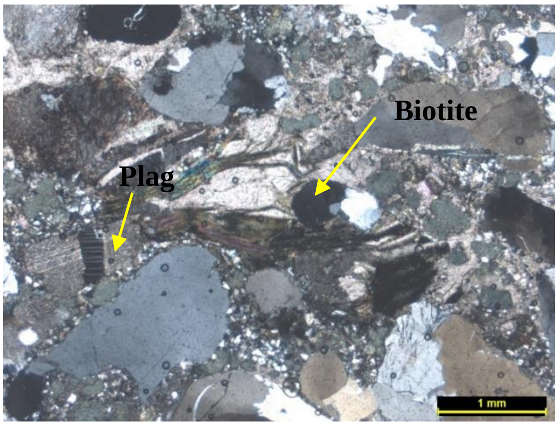


Figure 5.5 Photomicrograph showing deformed biotite and kinked plagioclase in granite. TL, XN

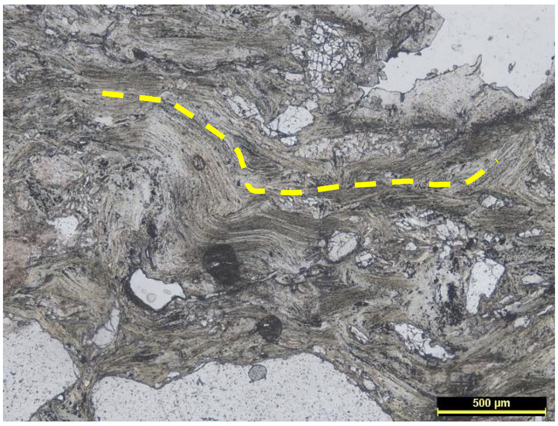


Figure 5.6 Photomicrograph showing deformed altered biotite. TL, 1N

5.4 Limestone

Undeformed limestone: Mesoscopically, limestone is fine grained, dark grey coloured and compact in nature. Under thin section the rock is fine grained and is composed of micritic calcite (<4μm). Sparry calcite is present as patches as a result of diagenesis. Few disseminated fine pyrite is also observed in some of the sections. Calcite grains are equant and anhedral. Stylolites are also noticed in some of the sections which are formed due to removal of mineral matter by pressure dissolution. Insoluble mineral like clay remain within the serrated surfaces of stylolites.

Deformed limestone: The rock is light grey in colour, fine grained and brecciated to fractured. In zones proximity to maximum brecciation, calcite veins traverse the brecciated rock. Under microscope the rock is brecciated and composed of micritic calcite (<4μm). Brecciated fragments of micritic and sparry calcite are mantled together. Primary micritic calcite is the major constituent of limestone which is fractured. Subordinate amount of sparry calcite which occurs as large anhedral and subhedral grains, is present as fracture filling of primary micritic calcite. Limestone is turbid due to presence of opaque impurities such as chert, chlorite, dolomite, limonite, clay and carbonaceous matter. Chert, clay including illite and smectite, chlorite and glauconite are present as impurities in limestone (Patnaik. et. al, 2011).

Texture and microstructure: Limestone samples collected away from brecciated/deformed zones are fine grained, thinly laminated. Evidences of brittle – ductile deformation are manifested in limestone of the study area near to the contact zone of basement granite. Brittle deformation in the limestone resulted in the development of numerous fractures which are later filled with secondary sparry calcite. In the petrographic studies, at least 2 sets of calcite veins are observed. The first set of veins are thin and are pre-brecciation/deformation event as they are later offset by the deformation. A second set of calcite vein is observed which is thicker and cuts across the brecciated zones. The contact of these veins with micritic matrix is sharp. The first set of calcite veins are also seen give a folded like appearance due to micro-fractures in some sections. Near to the contact zone of basement granite in Kanchankayi area, brecciated limestone contains angular to sub-angular clasts of micritic calcite, granite, shale and arenite.

Radioactive and other ore minerals: The ore minerals in limestone are dominantly pyrite and minor arsenopyrite, bravoite. Pyrite occurs in different forms and textural varieties viz. framboidal pyrite, euhedral pyrite and zoned pyrite. Based on occurrence, two types of pyrite can be identified. One type which is associated with micrite, where fine pyrite occurs in disseminated form in micrite. The second type of pyrite occurs as big euhedral pyrite crystals which is associated with brecciation or sparry calcite veins. Major uranium minerals identified in the limestone are coffinite and pitchblende. The radioactive minerals are identified with the help of CN films. Pitchblende is identified by irregular form, low reflectivity and high density of alpha tracks while coffinite is identified by moderate density alpha tracks and low reflectivity. These minerals are mainly present as veins and veinlets in association with calcite veins, sulphides and carbonaceous matter.

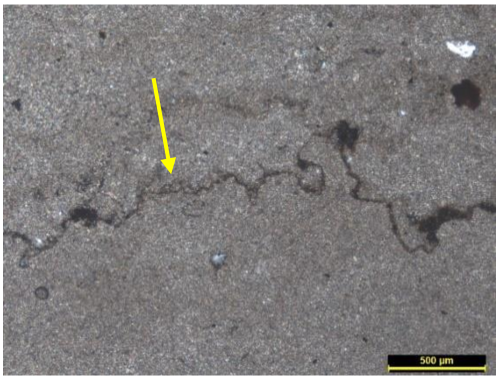


Figure 5.7 Photomicrograph showing stylolites in micritic limestone, TL, 1N

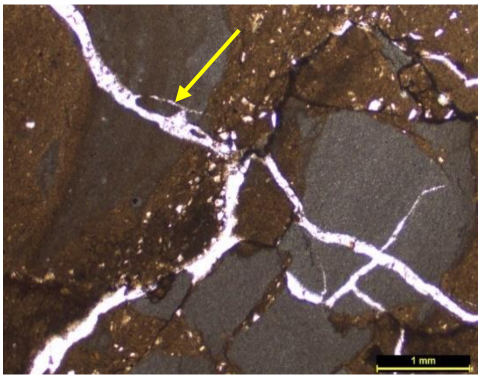


Figure 5.8 Photomicrograph showing sparry calcite veins cutting across the brecciated zones in brecciated limestone. TL, XN

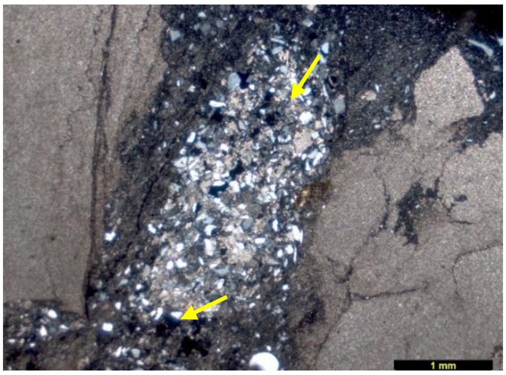


Figure 5.9 Photomicrograph showing small quartz and feldspar fragments in brecciated zones within brecciated limestone. TL, XN

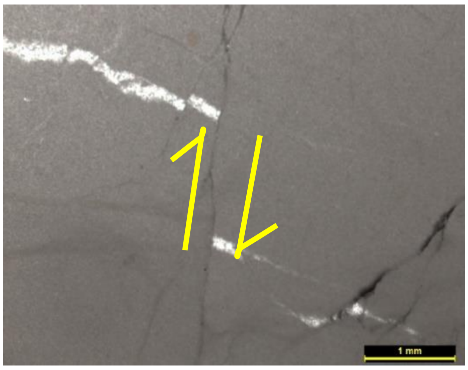


Figure 5.10 Photomicrograph showing offset of thin calcite veins in fractured limestone. TL,1N

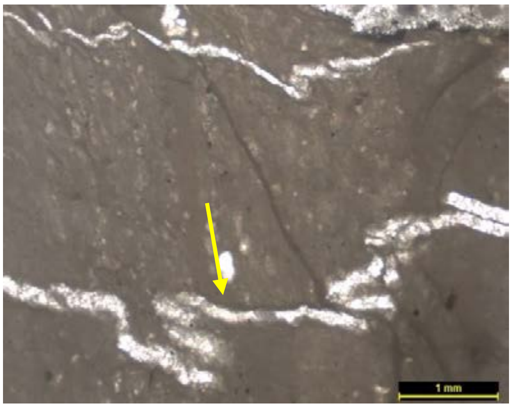


Figure 5.11 Photomicrograph showing calcite filled along microfractures which are interconnected giving a folded appearance in brecciated limestone.

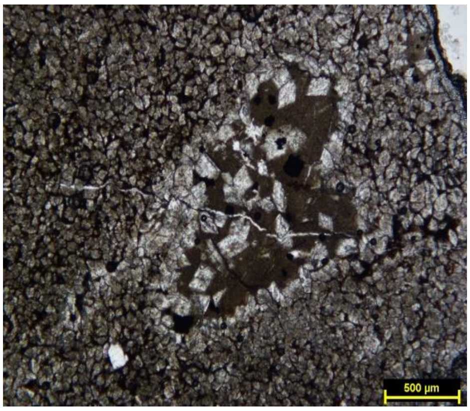


Figure 5.12 Photomicrograph showing cavity filled with coarser dolomite rhombs & micrite in microspar dolomite bearing

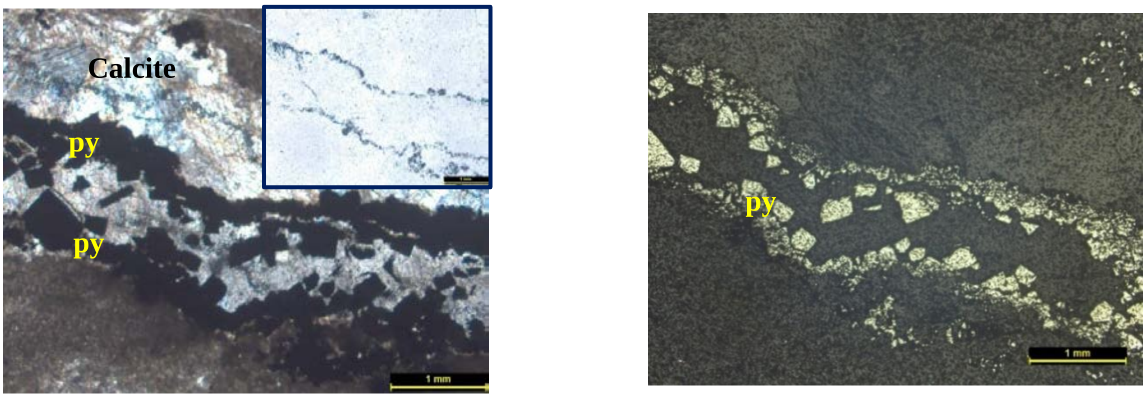


Figure 5.13 Photomicrograph showing pyrite (py) associated with sparry calcite vein, where fine pitchblende(pbl) is surrounding the pyrite grains in brecciated limestone,(a) TL,1N, inset: alpha tracks on CN film (b) RL, 1N

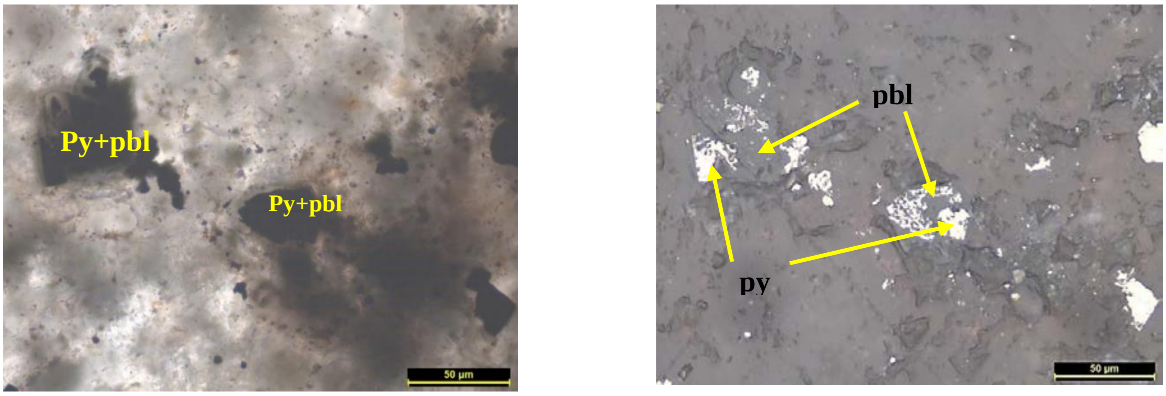


Figure 5.14 Photomicrograph showing pyrite(py) associated with pitchblende(pbl) in brecciated limestone (a) TL, 1N , (b) RL,1N

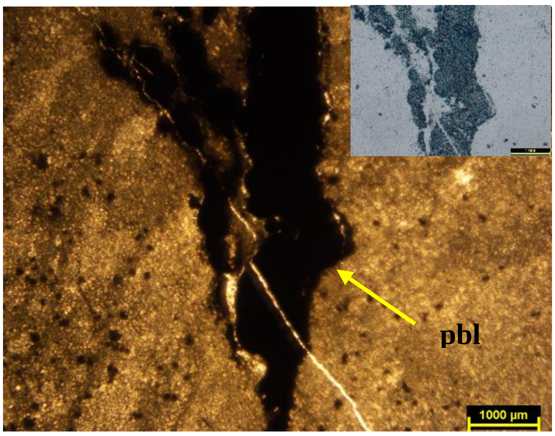


Figure 5.15 Photomicrograph showing a vein of pitchblende (pbl) in brecciated limestone, TL,1N inset: alpha tracks on CN

5.5 Fluid inclusion studies:

5.5.1 Introduction:

Primary fluid inclusions are original fluids trapped in minerals at the time of their crystallisation. In the present study, fluid inclusions were observed in calcite veins associated with uranium mineralisation in Kanchankayi area. In this area, uranium is hosted by brecciated limestone having veins of calcite+pyrite. Hence, these samples were collected for fluid thermometry and compositional investigations, using heating and freezing stage attached to a microscope. Such studies would help us to understand geological processes involved in uranium mineralisation.

Fluids under such geological setups could have played a role in migrating and mobilising uranium in the host rocks where precipitation could be possible because of presence of sulphides. The composition of the fluids varies depending upon the source of the fluid and interaction with the surrounding rocks before it gets trapped in the mineral. Fluid inclusions thus represent entrapped micro geochemical samples of mineralizing fluids – whose studies can provide important clues to an understanding of their nature and P-T-X conditions of mineralisation

5.5.2 Methodology:

Doubly polished thermometric wafers were prepared in Southern Region, AMD. Thermometric studies of the samples were carried out in Petrology lab, WR, AMD. The setup for carrying out fluid inclusion studies in Petrology Lab, AMD, WR consist of Nikon (Model-LV100N POL) petrological microscope mounted with a Linkam heating/freezing stage (MSDG600) on which controlled micro thermometry studies can be carried out. Thermometric studies in the range of -195^{0}C to 600^{0}C can be carried out on this instrument. For freezing studies, liquid nitrogen (LN2) is used while heating is done with the help of thermocouple.

5.5.3 Sampling/Optical examination:

1. Petrographically the samples which were connected spatially to the uranium mineralisation were selected. Petrographic observation is first done on the samples from the study area and a genetic sequence of these samples was established with the mineralisation.
2. Optical examination of the inclusions was done to locate the inclusions in the wafers, their distribution, size, degree of fill and association with each other were observed which helped to determine the type of inclusion (primary, secondary or pseudo-secondary).
3. Inclusions having larger size, isolated and better visible under the microscope were selected for heating studies. Heating studies were performed on such inclusions and temperature of homogenisation were noted to find the minimum temperature of formation of the host mineral (calcite).

Figure 5.16 Nikon petrological microscope mounted with Linkam cooling/freezing stage

5.5.4 Thermometric studies (Heating):

Table 5.1: Homogenisation temperature of fluid inclusions

Sr. no	Inclusion	Type	Homogenisation Temp(^{0}C)	Size (micron)	Degree of fill (%)
1	KS-433001	Biphase (L+V)	88	7	80
2	KS-433002	Biphase (L+V)	159	8	75
3	KS-434001	Biphase (L+V)	127	4	85
4	KS-434002	Biphase (L+V)	125	7	90
5	KS-438001	Biphase (L+V)	144	5	90
6	KS-438002	Biphase (L+V)	135	4	90
7	KS-438003	Biphase (L+V)	136	3	90
8	KS-435001	Biphase (L+V)	120	5	85
9	KS-435002	Biphase (L+V)	117	4	90
10	KS-435003	Biphase (L+V)	132	6	85
11	KS-435004	Biphase (L+V)	122	4	90
12	KS-433003	Biphase (L+V)	126	5	90
13	KS-433005	Biphase (L+V)	132	7	90
14	KS-433004	Biphase (L+V)	122	6	85
15	KS-433007	Biphase (L+V)	134	8	80
16	KS-433009	Biphase (L+V)	135	9	80
17	KS-433010	Biphase (L+V)	205	8	75
18	KS-433011	Biphase (L+V)	224	5	95
19	KS-433012	Biphase (L+V)	165	10	80

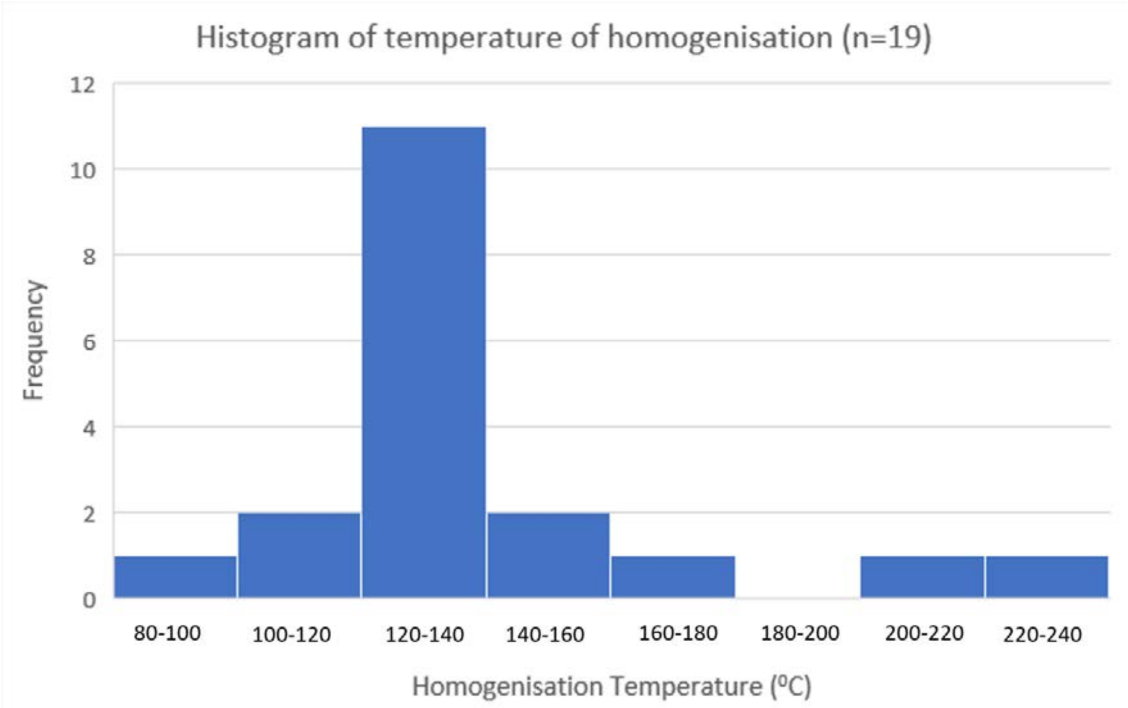


Figure 5.17 Histogram of temperature of homogenization

5.5.5 Discussion

Homogenisation temperature of the fluid inclusions is the minimum entrapment temperature of the fluid within a mineral. The primary inclusions within calcite in the present study, were found to have temperatures of homogenisation (Table 5.1) from 117^0C to 144^0C and were the first phase of fluid in the system. However, inclusions homogenising around 80-90^0C could be of second episode of the hydrothermal activity (secondary inclusions). As the uranium minerals like pitchblende and coffinite are hosted within the calcite veins, the fluids responsible for the precipitation of calcite and uranium minerals is same. Thus, based on the data of primary inclusions it is inferred that the fluids responsible for the mineralisation of pitchblende and coffinite could be of the range of around 130^0C temperature. Petrographically also low temperature minerals like pitchblende and coffinite occurring as veins are identified from the area. The study also indicates that hydrothermal activity is more than one episode. Primary inclusions indicate a higher temperature hydrothermal activity and the low temperature is indicated by the secondary inclusions having temperature of homogenisation around 80^0C (inclusions shown in Figure 5.21). Further freezing studies are to be carried out to ascertain the salinity of these fluid inclusions so that exact nature and composition of the mineralising fluids is known. Freezing studies were not carried out in the present study due to time constraint during the course of the project work. The primary inclusions are mostly bi-phase (L+V) and having degree of fill from 70 percent to 90 percent which indicates dominance of liquid phase over vapour phase.

The modal temperature of homogenisation of primary fluid inclusions is 130^{0}C as indicated in the histogram which means that the minimum temperature of formation of coffinite and pitchblende is around this temperature.

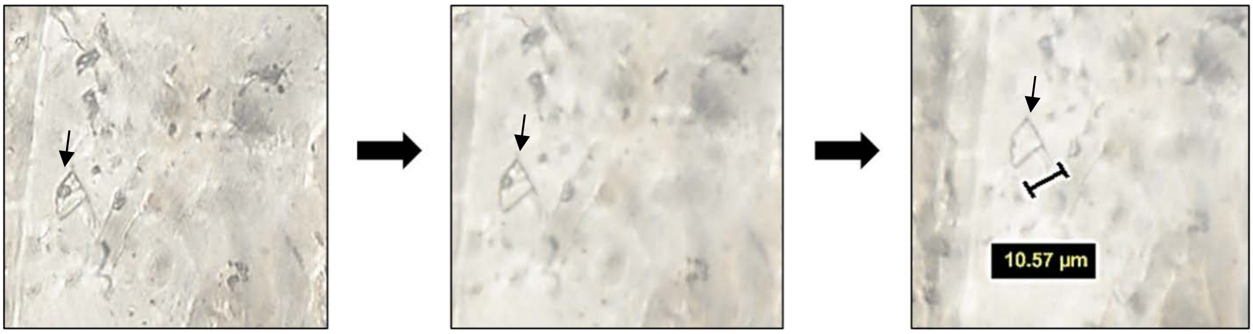


Figure 5.18 Homogenisation of bi-phase (vapour rich) fluid inclusion in calcite with increasing temperature (a) Temp: 40^{0}C, degree of fill 80 percent (b) Temp:96^{0}C, degree of fill: 85 percent (c) Temperature: 165^{0}C, degree of fill 100 percent

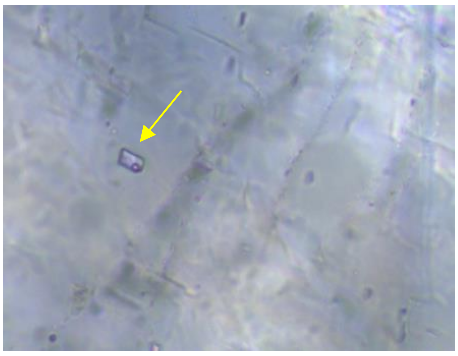


Figure 5.19 Primary inclusion in calcite

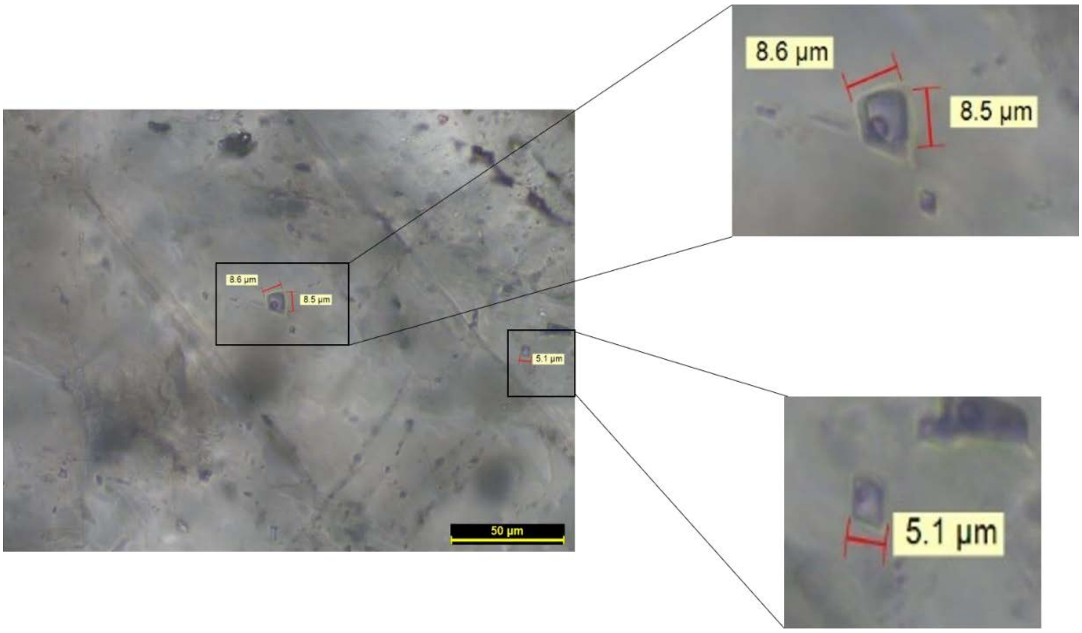


Figure 5.20 Primary inclusions in calcite

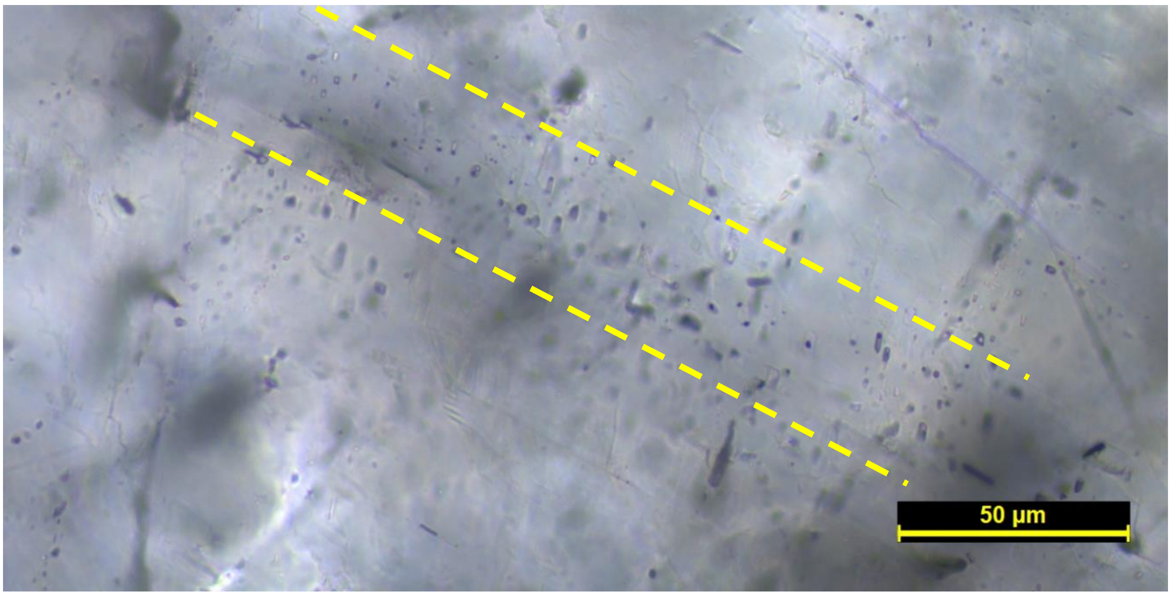


Figure 5.21 Secondary inclusions in calcite

CHAPTER 6

GEOCHEMSITRY

6.1 Introduction

Bulk chemical composition of sedimentary rock has been widely used to delineate units of clastic and carbonate strata (Primmer et al 1990). The study of major oxides along with the trace element data is also helpful in identifying any changes in the sedimentary rock after its deposition. Geochemical studies combined with petrography is an effective tool to understand the host rock characteristics and changes in rock due to diagenesis or deformation. The present chapter is mainly confined to study of major, minor and trace element data of Shahabad limestone from Kanchankayi-Hulkal area. to characterize the rock type, variations in the radioactive and non-radioactive samples and to support the petrographic observations of the samples.

6.2 Methodology

6.2.1 Wavelength dispersive X-ray fluorescence spectrometer (WDXRFS)

The representative rock samples (n=14) collected from the borehole core samples were analyzed for major and minor elements (in oxides; SiO_2, Al_2O_3, TiO_2, Fe_2O_3, MgO, MnO, CaO, K_2O, Na_2O, and P_2O_5) using Wavelength Dispersive X-Ray Fluorescence Spectrometer at XRF Laboratory, AMD, SR, Bengaluru.

Procedure: Major and minor elements were analysed using WDXRFS at the XRF Laboratory, AMD, SR, Bengaluru. An amount of ~ 200 g of sample was first crushed to 4 - 6 mesh size by a jaw crusher. Then a 10g sample was taken after sampling (using coning and quartering method) and further ground to –200 mesh using a laboratory-type disc mill and the powders were homogenized. One-gram representative sample (homogenized powder) was obtained by coning and quartering method. Further, the sample (1g) was spread uniformly over a 20g boric acid (pellet) bed in a cylindrical sample die, and finally pelletized in a semi-automatic pelletizer (Insmart, Hydraulic press) at a pressure of 20,000 kg/cm^2 resulting in a solid pellet 41 mm in diameter. Thus, flat and homogeneous pellets of both the sample and the CRMs (Certified Reference Materials) were obtained. Sequential ARL PERFORM'X 4200 (Thermo Fisher, Switzerland) with 4 kW Rh anode end window x-ray tube having ultrathin Be window (50 micron) WDXRFS with a single goniometer-based measuring channel covering the entire elemental range was used for the analyses of major and minor element oxides of representative rock samples (Sarbajna et al., 2009, 2017).

6.2.2 Wet chemical analyses

The representative rock samples sub-surface collected in the field were analyzed for trace elements (Cr, Ni, Zn, Rb, Sr, Zr, Ba, Mo, V), U and Th including REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc & Y) by wet chemical instrumental techniques at Chemistry Laboratory, AMD, Southern Region, Bengaluru.

Procedure: Representative samples were powdered (-200 mesh) as mentioned in previous section and the same were subsequently analysed by wet chemical instrumental techniques for major, minor and trace elements. About 0.5 gm of -200 mesh size fine powdered sample were taken for analysis. The samples were digested in acid media (1:1 HF – HNO3) to remove the silicate phases. The treated filtrate was then fused with Na_2CO_3 followed by pre-concentration and separation using HNO3. The separated solution was analysed in Inductive Couple Plasma – Optical Emission Spectrometer (ICP-OES) for the analysis of rare earth and other trace elements.

6.3 Geochemistry of limestone

Pre-Cambrian carbonate rocks are vulnerable to post sedimentary transformations in their structure and texture due to prolonged action of geological agents on the exposure. Hence any classification for such rock types based on the primary sedimentary structure or texture may be inadequate, since they undergo post sedimentary transformation related to diagenetic processes such as compaction, induration, cementation, recrystallisation, dissolution, pressure solution, metasomatism and/or very low-grade metamorphism etc. With this limitation in mind, alternative attempt was taken to classify the host rock based on the weight % concentration of major constituents of these carbonate rocks i.e., CaO and MgO and SiO2. The data were plotted on the triangular diagram (Figure 6.1) of Grapes (2011) in which carbonate nomenclature are adopted from Pettijohn (1949) in terms of mol% CaO-MgO-SiO2 –CO2. Though the triangular diagram of Grapes (2011) is for metamorphic rocks, for classification of limestone based on the geochemical basis, the diagram has been used. The data revealed most of the non-radioactive samples lie in the low Mg limestone field (except for sample H-4355, H-4357), while most of the radioactive samples lie in the dolomitic limestone field (except for sample H-4359). The high MgO content in the radioactive samples may be attributed to the fine chlorite and biotite present in the matrix of the brecciated zone and dolomite which is supported by petrographic studies.

CaO content in the limestone varies from 28.29 % to 51.50 %. The wide range of the CaO in limestones is due to the variability in SiO_2 content (3.04-38.84 %) in the rock. Large variation in SiO_2 is due to presence of chert in limestone and siliclastic components in variable proportion as impurity in brecciated limestone. Petrography also supports the observations as small quartz fragments are also seen in some brecciated zones of the limestone. Some of the samples also contain high Fe_2O_3 (upto 17.74 %) which is due to the fine pyrite disseminated in micrite and also pyrite veins traversing the brecciated limestone. Carbonate rocks are prone to alteration such as changes in texture and composition which lead to replacement by silica, phosphate and others. The replacement involves infiltration of xenocrysts or rearrangement of pre-existing sediments, as a result of diagenetic differentiation. The presence of siliceous impurity might be the result of post deformational influx from the granitic basement rocks. P_2O_5 content in the radioactive and non-radioactive limestone is almost similar in samples ranging from 0.03% to 0.35%.

From the 13 limestone samples studied, 6 samples from radioactive zone and 7 samples from the non-radioactive zones were collected. High Pb values are also observed in the radioactive samples and samples having high uranium concentrations are particularly high in Pb. The high values of Pb observed in the radioactive samples is due to the radiogenic lead produced from the decay of uranium. The concentration of Th in the samples is very less and also suggest that the uranium in the limestone is remobilized uranium. Thorium is a relatively immobile element compared to uranium in an oxidized state. Some of the radioactive samples also have high concentration of Mo and V. This suggest that the fluids responsible for mineralisation in the area might have increased concentration of Mo and V. Mo and V similar to uranium are immobile in reducing conditions (Rose & Wright,1980).

Studies done on carbonate rocks (Goldberg. et al., 1963; Tlig and M'Rabet, 1985) mention that carbonate rocks have generally low REE concentrations. The REE patterns in carbonate rocks are mainly influenced by depositional environment (Murray et al., 1990) and diagenetic processes (Armstrong. et al., 2003). The REE concentration in limestone samples from the study area is low (most of the REE have concentration less than the detectable limit of the instrument, except for La, Ce and Y), in agreement to the low REE concentration in limestone generally observed in limestones. It is difficult to study the REE patterns from the present analytical results due to the low concentration of the REE in the samples and the constraint of ICP-OES instrument which has a lower limit of detection around 1 ppm.

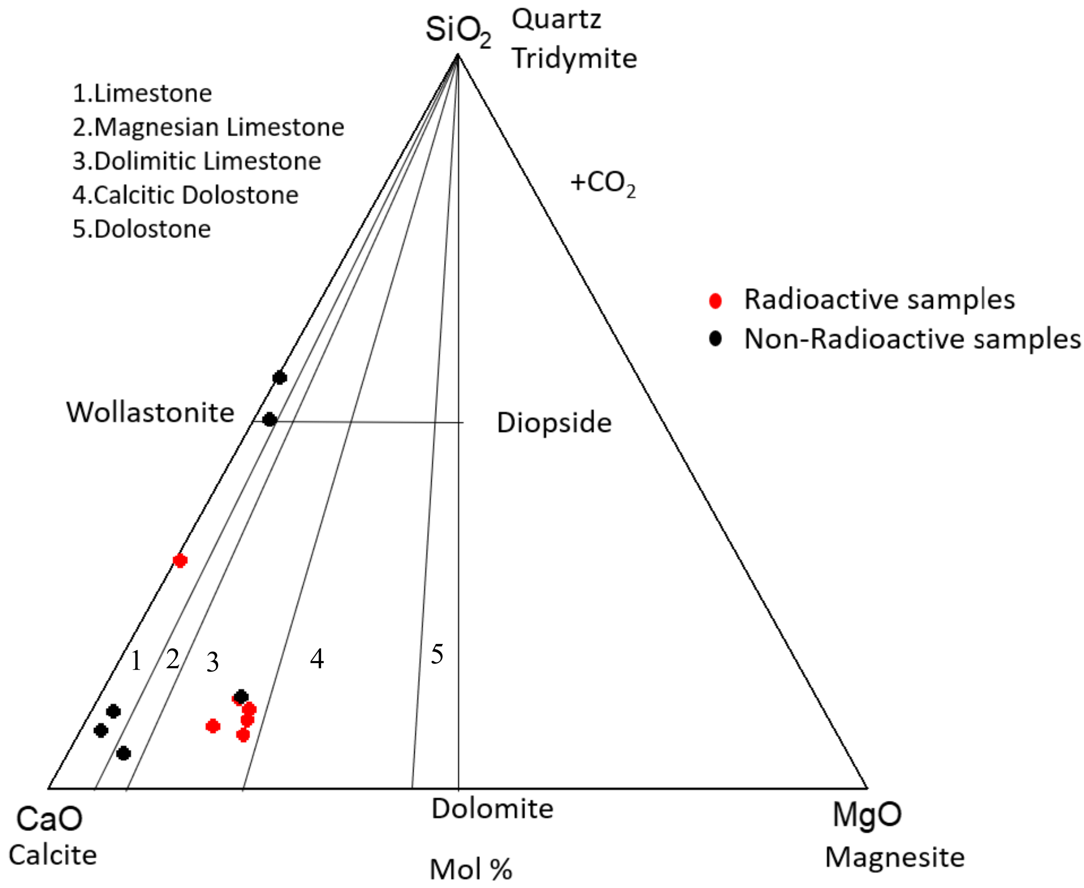


Figure 6.1 Ternary plot of limestone based on SiO_2, CaO and MgO composition (after Grapes, 2011)

Table 6.1 Major oxide and trace element data of limestone from Kanchankayi area, Yadgir District,

Sample	H-4352	H-4353	H-4354	H-4356	H-4358	H-4359	H-4350	H-4348	H-4355	H-4357	H-4360	H-4362	H-4363	H-4364
	Radioactive							Non-radioactive						
	Brecciated Limestone						Brecciated Limestone + Granite	Brecciated Limestone			Limestone			
	Major elements (% wt)													
SiO2	6.02	6.70	5.41	7.51	4.59	17.55	52.93	3.04	7.89	5.05	4.90	6.53	37.10	38.84
TiO2	0.04	0.08	0.04	0.08	0.04	0.04	0.16	0.02	0.05	0.05	0.03	0.03	0.11	0.03
Al2O3	0.98	1.88	1.28	1.86	0.95	1.37	10.74	0.61	1.75	1.20	0.90	0.94	2.84	0.86
Fe2O3(t)	0.71	0.84	0.75	2.10	0.83	2.81	1.53	0.46	0.91	0.60	0.48	0.39	0.61	17.74
MgO	8.30	7.73	6.40	7.00	8.35	0.11	0.08	2.76	7.14	6.50	0.96	1.06	0.83	0.01
MnO	0.13	0.13	0.15	0.14	0.14	7.43	1.96	0.05	0.07	0.08	0.02	0.03	0.05	0.29
CaO	42.00	39.80	43.50	40.20	41.95	35.71	13.27	51.50	40.75	44.53	50.80	50.20	32.80	28.29
Na2O	0.24	0.30	0.24	0.27	0.26	0.16	1.70	0.20	0.25	0.34	0.36	0.80	0.21	0.16
K2O	0.25	0.42	0.26	0.31	0.24	0.15	2.09	0.13	0.36	0.37	0.24	0.22	0.70	0.18
P2O5	0.15	0.16	0.13	0.03	0.13	0.05	0.06	0.08	0.19	0.13	0.03	0.04	0.35	0.13
LOI	40.81	40.50	41.22	39.10	42.40	33.06	12.38	40.85	39.52	41.14	40.30	39.40	24.50	12.19
	Trace elements (in ppm)													
Cr	56	225	250	27	19	135	104	37	22	20	8	15	116	38
Ni	273	72	13	<10	<10	15	23	<10	<10	<10	<10	<10	<10	36
Zn	18	40	22	91	13	34	33	12	16	11	<10	<10	21	25
Rb	13	28	<10	11	<10	11	111	<10	12	10	<10	<10	25	<10
Sr	86	83	87	99	84	105	65	64	92	106	86	89	48	44
Zr	28	25	22	23	16	<10	72	<10	27	13	18	12	24	<10
Ba	126	1268	434	306	87	111	354	65	634	3230	4286	875	107	770
Mo	<10	<10	<10	28	31	446	94	73	<10	<10	<10	<10	<10	42
V	87	398	188	83	58	464	231	96	181	55	<10	<10	10	<10
Pb	52	2095	470	325	105	4327	67	12	45	18	27	30	18	38
U3O8 (%)	0.030	0.735	0.271	0.219	0.017	1.810	0.014	0.003	0.005	0.003	<0.001	0.001	<0.001	0.002
Th	17	<10	11	13	19	45	18	20	22	16	<10	22	21	<10

Table 6.2 REE data of limestone from Kanchankayi area, Yadgir District, Karnataka.

Sample no:	H-4352	H-4353	H-4354	H-4356	H-4358	H-4359	H-4350	H-4348	H-4355	H-4357	H-4360	H-4362	H-4363	H-4364
	Radioactive							Non-Radioactive						
Rock Type	Brecciated Limestone						Brecciated Limestone + Granite	Brecciated Limestone			Limestone			
	Concentration in ppm													
La	7	8	22	22	10	22	15	9	13	13	6	8	18	6
Ce	15	16	34	43	23	54	38	12	23	26	12	15	39	16
Pr	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Nd	6	<5	10	19	<5	16	12	<5	<5	<5	<5	<5	9	<5
Sm	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Eu	1	<0.5	1.3	2.4	<0.5	1.4	1.1	<0.5	<0.5	1	<0.5	<0.5	1.3	<0.5
Gd	<5	<5	5	6	<5	5	<5	<5	<5	<5	<5	<5	<5	<5
Tb	<2	<2	4	3	<2	3	2	<2	<2	<2	<2	<2	<2	<2
Dy	<2	<2	4	4	<2	5	<2	<2	<2	<2	<2	<2	<2	<2
Ho	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Er	<2	<2	3	2	<2	2	<2	<2	<2	<2	<2	<2	<2	<2
Tm	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Yb	<1	2	2	2	<1	<1	2	<1	<1	<1	<1	<1	<1	<1
Lu	<0.5	<0.5	1	2.1	<0.5	1	2	1	<0.5	<0.5	<0.5	<0.5	<0.5	2
Sc	2	3	3	6	2	2	8	2	3	3	2	2	5	2
Y	23	11	55	61	10	67	19	10	11	16	6	12	22	8

CHAPTER 7

DISCUSSION

In the present chapter, data from detailed geological and structural mapping, petrography, fluid inclusion studies and whole rock geochemistry of the host rocks are discussed and evaluated. The regional geology of the area is briefly discussed at the start of the chapter, followed by the interpretation of the present work carried out.

7.1 Geological outline

The present study area lies in the between Kanchankayi and Halbhavi village, along E-W trending Gogi-Kurlagere fault zone which is located at the south-central part of the Bhima basin. Basement granites (Closepet equivalent) and Bhima sediments comprising of Rabanpalli shale, Shahabad Limestone and Hulkal arenite are the lithounits exposed in the study area.

Structurally, the basin is transacted by prominent E-W and NW–SE trending faults besides a number of smaller N-S and NE-SW trending faults (Kale and Peshwa, 1995). The major E-W trending faults are i) Kurlagere-Gogi-Gundanahalli (KG) ii) Farhatabad iii) Tirth-Tintini and iv) Wajhal-Hunsagi. Wadi Fault is a NW-SE trending and located in the northern part of the basin. The sediments of Bhima basin are devoid of major imprints of metamorphism and deformation except along the basin boundary, where faulting has caused intense brecciation, fracturing and folding both within basement and sediments (Achar et. al. 1997).

The 40 km long KG fault is a dextral strike slip fault, with reverse faulting in some of the segments along the fault (Roy, et.al 2016). Such reverse fault setup is observed in Gogi-Kanchankayi sector of the KG fault. In the present study, detailed geological mapping of the study area has led to categorization of limestone into 2 categories i) Limestone without chert and ii) Limestone with chert content. These two categories can be further subdivided on the basis of structure. The former is subdivided into three types a) Massive limestone b) Bedded limestone c) Brecciated limestone and the latter is divided into two types a) Bedded cherty limestone b) Brecciated intraformational limestone. The eastern continuation of the KG fault is demarcated in the present study by detailed geological cum structural mapping over an area of 5 sq km (1:2000 scale) and based the sub-surface data.

7.2 Structural analysis:

The eastern continuation of the splayed arms of the fault are demarcated by the zones of deformation associated with the fault. Two zones of deformation trending east-west are identified based on the variation in the dip of the beds and they correspond to the two splayed arms of the KG fault. The southern splayed arm of the fault is moderately deformed compared to the northern arm of fault which is intensely deformed. The intense deformation is manifested by the steep dip of the limestone beds.

Two major fracture trends – (i) 130-310 and (ii) 10-190 are observed in the study area. The 310-130 fracture set is more prominent in the study area and is also continuing in the basement granite. The 310-130 fracture set might have formed due to the tensional stresses produced due to the dextral strike slip movement in the area.

Transverse sections prepared by studying the sub-surface borehole cores drilled along the northern arm of the splay fault reveal intense deformation associated with the reverse fault, where granite wedge has pushed into the Bhima sediments causing brecciation. The reverse fault has produced a high angle curvilinear deformed zone dipping towards the south. The high angle dip of the beds on the surface is the result of the deformation caused by the sub-surface reverse fault. The southern arm of the fault is less deformed is a normal fault along the sediment-basement contact.

The 3-D model of a part of Kanchankayi area depicts the correlation of the surface and sub-surface data, defined by the deformed zone. Stacked transverse section of Kanchankayi-Hulkal sector reveals increase in the amount of deformation towards the eastern side.

7.3 Petromineralogical characteristics

The undeformed limestone is fine grained composed of micritic calcite (<4µm). Sparry calcite is present as patches as a result of diagenesis. Calcite grains are equant and anhedral. Stylolites are also noticed in some of the sections which are formed due to removal of mineral matter by pressure dissolution. Insoluble mineral like clay remain within the serrated surfaces of stylolites. Disseminated fine pyrite can also be observed in some of the undeformed samples which suggest slightly reducing conditions during the sedimentation. The deformed limestone is brecciated and has calcite veins traversing through the brecciated/fractured zones.

Brittle deformation in the limestone associated with the reverse faulting in the area has led to the development of numerous fractures which are later filled with secondary sparry calcite. In the petrographic studies, at least 2 sets of calcite veins are observed. The first set of veins is thin and are pre-brecciation/deformation event as they are later offset by the deformation. A second set of calcite vein is observed which is thicker and cuts across the brecciated zones. Near to the contact zone of basement granite in Kanchankayi area, brecciated limestone contains angular to sub-angular clasts of micritic calcite, granite, shale and arenite. Deformed biotite and kinked plagioclase in the basement granites also indicate brittle-ductile deformation.

The ore minerals in limestone are dominantly pyrite, minor arsenopyrite, bravoite and the uranium bearing minerals in limestone are coffinite and pitchblende. The radioactive minerals are mainly present along the veins of the fractured/brecciated limestone and are in association with sulphides, calcite and carboanceous matter. The presence of coarse pyrite along the fractures and in the calcite, veins suggest reducing conditions which has led to the precipitation of pyrite and pitchblende.

7.4 Fluid inclusion studies

Fluid inclusions are the best available tool to characterize the pressure, temperature, volumetric and compositional properties of fluids in a wide range of paleo-geologic settings (Roedder, 1984). In the present work, fluid inclusion studies on calcite veins associated with uranium mineralisation reveal that the primary inclusions in the calcite is mostly biphase (L+V) and are liquid dominated having degree of fill from 70 percent to 90 percent. The primary inclusions have temperatures of homogenisation from 117^0C to 144^0C and are found to be the first phase of fluid in the system. However, inclusions homogenizing around 80-90^0C could be of second episode of the hydrothermal activity (secondary inclusions). As the uranium minerals like pitchblende and coffinite are hosted within the calcite veins, the fluids responsible for the precipitation of calcite and uranium minerals is same. Thus, based on the data of primary inclusions it is inferred that the fluids responsible for the mineralisation of pitchblende and coffinite could be of the range of around 130^0C temperature. The study also indicates that hydrothermal activity is more than one episode. Primary inclusions indicate a higher temperature hydrothermal activity and the low temperature is indicated by the secondary inclusions having temperature of homogenization around 80^0C degrees.

7.5 Geochemical characterization:

Most of the radioactive brecciated limestone samples fall in the dolomitic limestone field while most of the non-radioactive limestone samples lie in the low Mg limestone field in Grapes (2011) SiO2-MgO-CaO ternary plot. The high MgO content in the deformed samples may be is due to the presence of fine chlorite and biotite present in the matrix of the brecciated zone and in some samples fine dolomite is also observed. SiO_2 content in the limestone has a wide variation ranging from 3.04-38.84% in the rock. High SiO_2 in the rock is due to presence of chert in limestone and siliclastic components in variable proportion as impurity in brecciated limestone. Petrographic studies also supports the observations as small quartz fragments are also seen in some brecciated zones of the limestone. The presence of siliceous impurity might be the result of post deformational influx from the granitic basement rocks. The high values of Pb observed in the radioactive samples is due to the radiogenic lead produced from the decay of uranium. The concentration of Th in the samples is very less and this suggests that the uranium in the limestone is remobilized uranium. Some of the radioactive samples also have high concentration of Mo and V.

CHAPTER 8

CONCLUSION

Detailed geological, structural, petromineralogical and geochemical studies on the Shahabad limestone in Kanchankayi-Hulkal-Halbhavi ($16^0$44' N-$16^0$45' N, $76^0$45' E -$76^0$50' E) sector of KG fault zone has led to the following conclusions:

- Detailed geological mapping (1:2000) carried out as part of the present study revealed that Shahabad limestone is the dominant lithounit in the area and can be classified mesoscopically as massive limestone, bedded limestone, bedded cherty limestone and brecciated intraformational limestone. The classification is based on the structure and chert content in the limestone. Other lithounits exposed in the study area, are Hulkal arenite and basement granite (mostly soil covered).
- Detailed structural mapping of Kanchankayi East-Hulkal-Halbhavi sector reveals 2 zones of deformation associated with the 2 splayed arms of the KG fault. The zones of deformation are demarcated by the steep to moderate dip of the limestone beds. The southern arm of the KG fault is along the sediment-basement contact and is less deformed where moderate dip of beds are observed. While, the northern splayed arm of the KG fault has transgressed into the Shahabad limestone where steep dip of limestone beds are observed indicating intense deformed zone. The major fracture set of 130-310^0 trend is identified in the Shahabad limestone. Such prominent fracture is associated with the tensional stresses formed due to dextral strike slip movement along the KG fault.
- Transverse sections prepared as part of the present study and borehole core studies, reveal intense deformation of limestone, shale, arenite and granite near the vicinity of the sub-surface fault (northern splayed arm of the fault). The transverse sections also

show that a displaced basement granite wedge has pushed into the overlaying Bhima sediments. Thus indicating the reverse fault setup in the northern splayed arm of the fault. A steep southerly dipping curvilinear deformed zone associated with the reverse fault can be demarcated on correlating the surface and sub-surface geological data. Stacked transverse sections was prepared in the present study by studying the cores of the boreholes and correlating the lithological data from both surface and sub-surface. The stacked sections of the area depicts that the uranium mineralisation in the area is along the zones of maximum deformation and is hosted in the brecciated limestone and granite.

- Petromineralogical study of the limestone (radioactive and non-radioactive) and granite (non-radioactive) samples from the area revealed that the major radioactive minerals in the area are pitchblende and coffinite which is present in the brecciated zones and along the fractures of the brecciated limestone. The radioactive minerals are mostly associated with pyrite, calcite veins and carbonaceous matter. Microstructural studies of limestone and granite near the vicinity of the reverse fault setup reveal brittle-ductile deformation. The offsets in calcite vein and the mixed brecciated rock comprising of arenite, shale, granite and limestone indicates brittle deformation while deformed biotite in granite indicates ductile deformation.
- In the present study, fluid inclusion microthermometry was carried out on calcite veins associated with uranium minerals like pitchblende and coffinite. The study involved heating of the fluid inclusions in calcite to find out their temperature of homogenisation . As the calcite and radioactive minerals are syngenetic, the homogenization temperature of the fluid inclusions in calcite will help in establishing the minimum entrapment temperature of fluids responsible for the mineralisation. From the heating studies, the temperature of homogenization of primary inclusions was found out to be

from 117^{0}C to 144^{0}C with majority of the primary inclusions being liquid dominated biphase(L+V) inclusions. Thus, the study reveals that the fluids responsible for the mineralisation of low temperature minerals like pitchblende and coffinite could be of the range of around 130^{0}C temperature.

- Limestone in the deformed zone are chloritized and contain more Mg as compared to the undeformed and unaltered limestone. The high variability of silica content in the rock is due to the chert content in limestone and the fine quartz present in the brecciated limestones. High Pb values in the radioactive samples is mostly due to the radiogenic lead produced from the decay of uranium. Less Th concentration with respect to the uranium concentration in the radioactive samples indicates that the uranium is remobilized.
- Based on all the above observations, a 3D geological model of Kanchankayi area has been prepared in the present study to trace the eastern the eastern continuity of the splayed arm of the KG fault and to show the surface and subsurface correlation of the deformed limestone beds.
- The exploration of uranium in structurally deformed areas require detailed understanding of the geological structure of the area and its association with uranium mineralization. In the studied area, uranium mineralisation is hosted within the brecciated limestone and granite associated with the northern splayed arm of the KG fault. The mineralisation in general, is following the zones of maximum deformation. In the future, the eastern continuity of the deformed zones should be traced by detailed geological mapping, geophysical techniques and reconnaitory sub-surface drilling.

The present work incorporated primarily the structural and petro-mineralogical studies to understand the structural setup and its implication on uranium mineralisation in the study area. Preliminary fluid inclusion studies involving finding out homogenization temperature of few inclusions in calcite veins from brecciated limestone samples were also carried out in the present work. Further scope of work demands detailed fluid inclusion studies involving both heating and freezing experiments, which may be carried out to decipher nature of the ore forming fluids. The data of composition, salinity and homogenizing temperature of the fluid inclusions obtained from such studies, will aid in better understanding of the nature of uranium mineralisation.

REFERENCES

Achar, K.K., Pandit, S.A., Natarajan, V., Kumar, M. and Dwivedy, K.K. (1997). Uranium mineralisation in the Neoproterozoic Bhima Basin, Karnataka, India. Recent Developments in Uranium Resources, Production and Demand, IAEA, Vienna, pp.1-22.

Armstrong, J.S., Verma, S.P., Madhavaraju, J., Lee Yi and Ramasamy, S. (2003). Geochemistry of upper Miocene Kudankulam limestones, Southern India. Int Geol Rev, 45, pp.16–26.

Atmaoui, N., Kukowski, N., Stöckhert, B. and König, D. (2005). Initiation and development of pull-apart basins with Riedel shear mechanism: Insights from scaled clay experiments. International Journal of Earth Sciences, 95, pp.225-238.

Bhat, G., Craig, J., Hafiz, M., Hakhoo, N., Thurow, J.W., Thusu, B. and Cozzi, A. (2012). Geology and hydrocarbon potential of Neoproterozoic–Cambrian Basins in Asia: An introduction. Geol. Soc. London, Special Publication pp.1-17.

Chaki. A., Paneerselvam, A. and Chavan, S.J. (2005). Uranium Exploration in Upper Proterozoic Bhima Basin. A new target Area. IAEA Vienna, Uranium Symposium, pp.40-46

Compton, R. (1985). Manual of Field Geology. Wiley & Sons, New York, 378p.

Crowell, J.C. (1974). Origin of late Cenozoic basins in southern California. Tectonics and sedimentation. Society of economic Palaeontologists and Mineralogists, Special Publication, 22, pp.190-204.

Davis, G. H. and Reynolds, S. J. (2012). Structural Geology of Rocks and Regions. 2nd edition, Wiley & Sons, New York, 864p.

Dey, S. (2015). Geological history of the Kaladgi-Badami and Bhima basins, South India: sedimentation in a Proterozoic intracratonic setup. Geol. Soc., London, Mem., 43, pp.283-296.

Dhanaraju, R., Mary K Kumar., Babu, E.V.S.S.K. and Pandit, S.A. (2002). Uranium mineralisation in the Neo-Proterozoic Bhima Basin at Gogi and near Ukinal – Ore petrology and mineral chemistry. Jour. Geol. Soc. India, 59, pp.299-321.

Drury, S.A., Harris, N.B.W., Holt, R.W., Reeves-Smith, G.J. and Wightman, R.T. (1984). Precambrian tectonics and crustal evolution in South India. Jour. Geophys., 92, pp.3-20.

Foote, R.B. (1876). Geology of the Southern Mahratta country. Mem. Geol. Survey. India, 12(1), 268 p.

Goldberg, E. D., Koide, M., Schmitt, R. A., and Smith, R. H. (1963). Rare-Earth distributions in the marine environment. J. Geophys. Res., 68, pp.4209– 4217.

Grapes, R. And Bucher, K. (2011). Petrogenesis of metamorphic rocks. Springer-Verlag Berlin-Heiderberg, 419p.

Jayaprakash A. V. (1999). Evolutionary history of Bhima basin. *In*: Field Workshop on integrated evaluation of Kaladgi and Bhima basin. Geol. Soc. India, pp.22-28.

Jayaprakash, A. V. (2007). Purana Basins of Karnataka. Geological Survey of India, Kolkata, 129, 137p.

Kale, V. S. and Peshwa, V. V. (1989). A Proterozoic pull-apart basin: interpretation based on remotely sensed data. *In*: Hanshaw, 28th International Geological Congress, Washington, DC, pp.149–150.

Kale, V. S. and Phansalkar, V. G. (1991). Purana basins of Peninsular India: a review. Basin Research, 3, pp.1–36.

Kale, V.S. and Peshwa, V.V (1995). Bhima Basin, Geol. Soc. India, Bangalore, pp.10-69.

Krishnan, M.S. (1968). Geology of India and Burma. Higginbothams, Madras, 536p.

Kumar, M., Rai, A.K. and Parihar, P.S. (2014). Ore genesis of Gogi Uranium Deposit in Bhima Basin, Yadgir District, Karnataka, India. Proceedings of the International symposium on Uranium raw material for the nuclear fuel cycle: Exploration, mining, Production, supply and demand, Economics and environmental Issues, 1, pp.523-539.

Maithy, P. K. and Babu, R. (1996). Carbonaceous macrofossils and organic walled microfossils from the Halkal Formation, Bhima Group, Karnataka with remarks on age. Paleobotanist, 45, pp.1–6.

Mathur, S.M. (1977). Some aspects of the stratigraphy and limestone resources of the Bhima Group. Indian Mineralogist, 18, pp.59-64.

Mishra, R.N., Jayaprakash, A.V., Hans, S.K. and Sundaram, V. (1987). Bhima Group of Upper Proterozoic – A Stratigraphic Puzzle, Purana Basins of Peninsular India. Mem. Geol. Soc. of India, 6, pp.227-237.

Murray, R.W, Buchholtz, M.R., Brink, M.R., Jones, D.L. and Gerlach, D.C. (1990). Rare earth elements as indicators of different marine depositional environments in chert and shale. Geology, 18, pp.268–271.

Nesse, W. D. (2000). Introduction to Mineralogy. Oxford University Press, 442p.

Pandey, B.K., Krishna, V., Pandey, U.K. and Sastry, D.V.L.N (2009). Radiometric dating of uranium mineralisation in the Proterozoic basins of eastern Dharwar craton, South India. *In*: Proceedings of the International Conference on Peaceful Uses of Atomic Energy, Bhabha atomic Research Centre, Mumbai, pp.77-83.

Pandit, S.A., Nataraja, V., Bhat, G., Dhana Raju, R., Swarnakar, B.M. and Banerjee, D.C. (1999). Neo- Proterozoic Bhima Basin as a potential target for uranium exploration-A case study from Gogi area Gulbarga district, Karnataka, India. *In* field workshop on integrated evaluation of the Kaladgi and Bhima Basin, Geol. Soc. India, Geol. Soc. India, pp.58-60.

Pandit, S.A., Natarajan, V., and Dhana Raju, R. (2002). Exploration of uranium in Bhima Basin in parts of Karnataka, Exploration and Research for Atomic Minerals, 14, pp.59-78.

Patnaik, S., Hegde, G., Paneerselvam, A., Jain, A. K., Verma, M. B. and Rai, A. K. (2011). Textural characterization of pyrite from Gogi uranium deposit, Karnataka: Implications for ore genesis. The Indian Mineralogist, 45, pp.121-129.

Pettijohn F. J. (1949). Sedimentary rocks. Harper and Brothers, New York, 526p.

Phillips, F.C. (1961). The use of stereographic projection in structural geology. 2nd Edition Edward Arnold (Publishers) Ltd., London, 86p.

Primmer, T.J., Kerr S.A. and Myers K.J. (1990). Feasibility of in situ elemental analysis in mudrocks evaluation. Geol. Soc. London Spl. Publ., 48, pp.203-210.

Roedder, E. (1984). Fluid inclusions. Reviews in Mineralogy. Mineral. Soc. America, Washington., 12, 644p.

Rose, A.W. And Wright, R.J. (1980). Geochemical exploration models for sedimentary uranium deposits. Journ. Of Geochem. Exploration, 13, pp. 153-179.

Roy, D., Bhattacharya, D., Mohanty, R., Patnaik, S., Pradhan, A.K., Chakrabarti, K. and Zakaulla, S. (2016). Study of deformation pattern in Gogi-Kurlagere fault zone at Gogi-Kanchankayi sector of Proterozoic Bhima Basin of northern Karnataka: its implication in control of uranium mineralization. Jour. Explorat. Res. Atomic Minerals, 26, pp.157-176.

Sarbajna, C., Durani, S., Rajagopalan, V. and Murthy, D.S.R. (2009). Wavelength dispersive X-ray fluorescence vis-à-vis inductively coupled plasma-optical emission spectrometry of major and trace elements in silicate rocks. Expl. Res. At. Miner., 19, pp.163-171.

Sarbajna, C., Durani, S., Pandey, S. and Singh, Y. (2017). Determination of uranium in Columbite-Tantalite by WDXRFS using an end window Rh excitation source and fluorimetry technique. Emerging trends in Analytical Chemistry, pp.139-140.

Senthil Kumar, P. and Srinivasan (2002). Fertility of Late Archean basement granite in the vicinity of U-mineralised Neo-Proterozoic Bhima Basin Peninsular India. Current Science, 82 (5), pp.571-576.

Sharma, M., Mishra, S., Dutta, S., Banerjee, S. and Shukla, Y. (2009). The affinity of Chuaria–Tawuia complex: A multidisciplinary study. Precambrian Research, 173, pp.123–136.

Tlig, S. and M'rabet, A. (1985). A comparative study of the rare earth elements (REE) distributions within the Lower Cretaceous dolomites and limestones of Central Tunisia. Sedimentology, 32, pp.897-907.

Unpublished AMD Bhima Investigations annual reports. 1989, 1996-95, 1997, 2008-2018.