

REPUBLIC OF TURKEY
FIRAT UNIVERSITY
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES



**RESERVOIR CHARACTERIZATIONS OF THE UPPER
CRETACEOUS DEEP MARINE TURBIDITES TO THE
CLOSE NORTHERN PART OF SULAIMANIYAH,
(NORTHERN IRAQ)**

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Master Thesis

Department: Geological Engineering

Program: General Geology (Sedimentology)

Supervisor: Assoc. Prof. Dr. Hasan ÇELİK

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HEMIN MUHAMMAD HAMA SALIH

SUMMARY

RESERVOIR CHARACTERIZATIONS OF THE UPPER CRETACEOUS DEEP MARINE TURBIDITES TO THE CLOSE NORTHERN PART OF SULAIMANIYAH, (NORTHERN IRAQ)

In this study reservoir characterization of the Upper Cretaceous low density turbidite sandstones of Tanjero Formation, northwestern part of Sulaimaniyah city, Northern Iraq, were analyzed. The sandstone portion of the unit have been examined through field and laboratory based studies. Seven logs were measured and described in detail. Average thickness of the measured sections is 158 m. The field logs start from the contact between underlying Shiranish Formation to more than 150 meters in thickness in the turbidite unit. 44 rock samples were taken for petrographic analysis, porosity and permeability tests from the logs for laboratory analyses.

Seven distinctive main lithofacies groups consisting of forty-eight subfacies were identified from seven measured sections for facies analysis. The groups classified as grain size are coarse grain sandstone beds (CGSB: includes four subfacies), medium grain sandstone beds (MGSB: includes twelve subfacies), fine grain sandstone beds (FGSB: includes eighteen subfacies), very fine grain sandstone beds (VFGSB: includes two subfacies), shale and silt sized thin bedded turbidites (STBT: includes five subfacies), fine sand thin bedded turbidites (FSTBT: includes four subfacies) and medium sand thin bedded turbidites (MSTBT: includes three subfacies). The subdivisions of the groups are separated according to their internal sedimentary structures. All facies groups represent low density turbidites composed of different divisions of the Bouma sequence. These facies represent about middle part of outer fan and lobe fringe to lobe distal fringe sand rich depositional system.

Petrographic analysis points out that, the sandstones are calcilithite (litharenite), very fine to medium grained in size consisting of chert, siltstone, mudstone, radiolarian chert and radiolarian mudstone fragments, angular to subangular in shape, very poorly to moderately sorted, transported over short distances and represent submature stage. Mainly long grain, concavo convex and sutured grain contact types and high contact index (4.7) represent moderate to tightly packing, moderate compaction which are negatively

effecting the reservoir quality. Lithic recycle category obtained from petrography is the only tectonic provenance composed of sedimentary rocks of the Lower Cretaceous Qulqula Formation for the sandstones.

Porosity of the studied sandstones range from 5.51% to 11.59 % which is poor to beginning of fair with an average value of 7.11%. The obtained permeability varies between 10.71-2315.65 md and their mean value is 866.35 md representing high permeability. As the modal components of the sandstones are made up of 99.621 % reworked sedimentary rock fragments with high carbonate rock clasts, and existence of calcite minerals, the reservoir quality of the turbidite sandstones was strongly negatively influenced by the alteration of these elements creating mainly calcite cementations. The effect of calcite occurrences and solid bitumen fillings ranging between 1-15 percentage plugging of pores cause a final reduced porosity. As a result, the turbidite sandstones of the Tanjero Formation cropping out to the northwest of Sulaimaniyah have general poor porosity and a very good permeability.

Keywords: Tanjero Formation, turbidite sandstone, reservoir characterization, northwestern Sulaimaniyah, Northern Iraq

ÖZET

SÜLEYMANİYE YAKIN KUZEYİNDEKİ ÜST KRETASE YAŞLI DERİN DENİZ TÜRBİDİTLERİNİN HAZNE KAYA ÖZELLİKLERİ (KUZEY IRAK)

Bu çalışmada Süleymaniye ilinin (Kuzey Irak) kuzeybatısında yüzeyleme veren Geç Kretase yaşlı Tanjero Formasyonu'na ait düşük yoğunluklu türbidit kumtaşlarının rezervuar özellikleri, arazi ve laboratuvar çalışmalarıyla incelenmiştir. Bu kapsamda kalınlıkları 120-190 m arasında değişen yedi adet stratigrafik kesit ölçülmüş, bu kesitlerden rezervuar araştırması için 44 kayaç örneği alınmıştır. Bu örnekler ince kesit petrografi araştırması ile porozite ve permeabilite testlerinde kullanılmıştır.

Ölçülü stratigrafik kesitlerden yedi ayrı litofasiyes grubu ve bunlara bağlı 48 alt fasiyes ortaya çıkarılmıştır. Tane boyuna göre yapılan sınıflamada kaba taneli kumtaşı tabakası (KTKT: Dört adet alt fasiyes içerir), orta taneli kumtaşı tabakası (OTKT: Oniki alt fasiyes içerir), ince taneli kumtaşı tabakası (İTKT: Onsekiz alt fasiyes içerir), çok ince taneli kumtaşı tabakası (ÇİTKT: İki alt fasiye içerir), şeyl ve silt boyutundaki türbidit tabakası (ŞSTT: Beş alt fasiyes içerir), ince taneli ve ince tabakalı türbiditler (İTT: Dört alt fasiyes içerir), orta taneli ince tabakalı türbiditler (OTİTT: Üç alt fasiyes içerir). Ana fasiyes gruplarının alt fasiyesleri içerdikleri sedimanter yapılara göre ayırtlanmıştır. Bütün gruplar Bouma istifinin farklı bölümlerini içeren düşük yoğunluklu türbiditlerden oluşmaktadır. Bu fasiyesler depolanma ortamı olarak dış yelpazenin orta kısımları ile lob kenarı ve lob dış kenarını temsil etmektedirler.

Petrografik analizler sonucunda bu kumtaşlarının kalklitit (litarenit) olduğu ve çok ince ve orta taneli çört, silttaşı, çamurtaşı, radyolaryalı çört, radyolaryalı çamurtaşı gibi taşınmış sedimanter kayaç paçalarından oluştuğu ve yarı köşeli-köşeli, zayıf ve orta derecede boylanmış, kısa mesafeden taşınmış ve yarı olgunluk evresini temsil eden özelliklere sahip olduğu ortaya çıkmıştır. Uzun tane kontağı ile konkavo konveks ve süturlu tane kontak türleri ve yüksek kontak indeksi (4.7), orta-yüksek paketlenme, orta derecede kompaktlaşma gibi özellikler bu kumtaşlarının düşük rezervuar kalitesine sahip olduğunun göstergeleridir. Petrografik analizlerden elde edilen veriler ışığında ortaya çıkan "litik döngü kategorisi" bu türbiditler için tespit edilen ve Alt Kretase yaşlı Kulkula Formasyonu'nu içeren, tamamen sedimanter kayalardan meydana gelmiş bir kaynak alanı (provenans) temsil etmektedir.

İnceleme alanındaki kumtaşlarının porozitesi %5.51 ile %11.59 arasında değişmekte olup %7.11 ortalama sahiptir. Bu ortalama hazne kayaç açısından oldukça düşüktür. Permeabilite değerleri ise 10.71 ile 2315.65 milidarcy arasında ve 866.35 milidarcy gibi yüksek bir ortalama sahiptir.

Ortalama olarak %99.621 oranında tanelerinin taşınmış sedimanter kayaç parçalarından olması ve bunların içerisinde karbonat kayaç parçalarının yüksek oranlarda olması ayrıca kalsit minerallerinin bulunması nedeniyle oluşan alterasyon ve yeniden kristallenme ile kalsit oluşumu poroziteyi düşürerek bu kumtaşlarının rezervuar kalitesini oldukça olumsuz yönde etkilemiştir. Geriye kalan boşlukların katı bitum tarafından doldurulmuş olması (oranı ince kesit örneklerinde %1-%15 arasında değişmektedir), petrografik özelliklerine dayanılarak hesaplanan % 30 oranındaki ilksel poroziteyi % 7.11'e düşürmüştür.

Bu bulgulara göre Süleymaniye kuzeybatısında yüzeyleme veren Tanjero Formasyonu'na ait kumtaşlarının düşük porozite ve çok iyi permeabilite özelliklerine sahip olduğu ortaya konulmuştur.

Anahtar kelimeler: Tanjero Formasyonu, türbidit kumtaşları, rezervuar özellikleri, kuzeybatı Süleymaniye, Kuzey Irak

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1. INTRODUCTION

This study was done as an MSc thesis at the Geological Engineering Department of Engineering Faculty in Firat University on the turbidite outcrop of Upper Cretaceous Tanjero Formation cropping out northwestern part of Sulaimaniyah city in Northern Iraq.

Iraq is an oil country, there are many researches, about reservoir in Iraq but all of them were worked on carbonate rocks because of its abundance as comparison with clastic rocks. There is no study about clastic reservoir characterization in Iraq, and in this study Tanjero Formation selected for that purpose as a clastic turbidite formation.

Many studies were done for Tanjero Formation in general subjects previously except reservoir characterization assessment as mentioned below.

Kassab (1975) studied biostratigraphy, Al-Mehaidi (1975) discussed briefly the stratigraphy and tectonic, Al-Rawi (1981) studied sedimentology and petrology of Tanjero Formation, Abdel-Kireem (1986b) studied Planktonic Forams and stratigraphy of Tanjero Formation. Saadallah and Hassan (1987) studied sedimentological analysis of the formation, Jaza (1992) concerned with sedimentary facies analysis, Minas (1997) studied sequence stratigraphy, Lawa et al. (1998) studied carbonate layers in the upper part of the formation, Al-Rawi and Al-Rawi (2002) studied the formation as turbidite example of flysch type.

Karim studied basin analysis of Tanjero Formation in 2004 and tempestite in Tanjero Formation in 2007. Sharbazheri (2007) studied age of unconformity within Tanjero Formation. Sharbazheri (2010) studied planktonic foraminiferal biostratigraphy of the Upper Cretaceous

In this thesis characterizations of clastic reservoir are studied by dealing with porosity, permeability, facies analysis, petrography, palaeoflow direction and provenance, depositional environment for assessing reservoir properties of a superbly exhumed sandstone of the Tanjero Formation in Northern Iraq, around Sulaimaniyah area.

This study is sharing to be the first examine of the reservoir characterization on the clastic turbidite succession of Tanjero Formation which is one of the main unit cropped out in the area. The location of the study is situated northwest of Sulaimaniyah city center. The other contemporaneous study is being held by Tavan Mohammed Hama Salih, in the same department supervised by Assoc. Prof. Hasan Çelik, located to the southeast of the city close to Arbat town.

2. PREVIOUS WORKS

Tanjero Formation is first defined and described under the name of Tanjero Clastic Formation by Dunnington in 1952. The writer selected the type section at Sirwan Valley, 1km to the south of Kani Karweshkan village, near Halabja Town and at the right bank of Sirwan River (upstream of Dialla River) and described briefly the distribution, age, lithology, fossil content, and stratigraphy of the formation, in addition to surface distribution at different localities in northeastern Iraq Bellen et al. (1959).

Kassab (1975) studied biostratigraphy of the formation and gave the age of Late Campanian –Maastrichtian to the formation.

Al-Mehaidi (1975) discussed briefly the stratigraphy and tectonic of the formation within the Chuarta area and mentioned the occurrence of the Aqra Formation in the upper part of Tanjero Formation.

Al-Rawi (1981) studied sedimentology and petrology of Tanjero Formation detailed. He mentioned that lower part at Sulaimaniyah has shallow environment of deposition and concluded that the paleocurrent is toward northwest and parallel to the axis of the Tanjero trough. He studied clay mineralogy and sandstone, and he classified the sandstones according to Pettijohn (1975) and plotted them on triangles.

Abdel-Kireem (1986a) studied the formation within stratigraphy of Upper Cretaceous and Lower Tertiary of Sulaimaniyah- Dokan Region. He recommended removing the “clastic” word from the name of the formation and to put its lower part with Shiranish Formation.

Abdel-Kireem (1986b) studied planktonic forams and stratigraphy of Tanjero Formation. He assigned, for the formation, the age of Middle-Late Maastrichtian in Dokan area.

Saadallah and Hassan (1987) made sedimentological analysis of the formation in selected sections from Dokan and Sulaimaniyah areas. They concluded that the palaeocurrent is toward west and southwest.

Jaza (1992) concerned with sedimentary facies analysis of the formation in Sulaimaniyah and Dokan area. He recognized the turbidite and submarine fan (as depositional feature of the basin) in the formation.

Minas (1997) studied sequence stratigraphy of the formation and put Tanjero Formation in deeper environment than Shiranish Formation and considered the formation as a transgressive part of the cycle.

Lawa et al. (1998) studied carbonate layers in the upper part of the formation at Chuarta-Mawat area and defined them as Aqra Formation, which interfingered with Tanjero Formation.

Al-Rawi and Al-Rawi (2002) studied the formation as turbidite example of flysch type in northeast and north of Iraq. They defined the depositional environment of the formation as deep marine, except the limestone beds, which are deposited in shallow one.

Karim (2004) studied basin analysis of Tanjero Formation in Sulaimaniyah area, NE-Iraq. He found and recorded many sedimentary structures for the first time and discussed them in detail. He changed the previous two parts (lower and upper) of the formation into three parts (lower, middle and upper). He proved that the lithology of the formation is nearly a reflection of that of Qulqula Radiolarian Formation.

Karim (2004), Karim and Surdashy (2005a) indicated the palaeocurrent by sedimentary structures and direction of channels and incised valleys, as southern and southwestern direction.

Karim (2004), Karim and Surdashy (2005b) proved that the basin of Tanjero Formation is early foreland basin when previously it considered as trench or miogeosyncline. They found the basin of the formation combined tectonically with that of underlying Shiranish Formation in a single basin, which is called initial Zagros Foreland Basin.

Karim (2005c) studied origin of ball and pillow-like structures in Tanjero Formation in Sulaimaniyah area, NE-Iraq.

Karim and Surdashy (2006a) studied sequence stratigraphy of Upper Cretaceous Tanjero Formation in Sulaimaniyah Area, NE-Iraq. They divided the formation by two main depositional sequences and correlated in eight sections, which are named lower and upper sequences.

Karim (2006b) studied the environment of Tanjero Formation. He found many sedimentary structures for the first time, found rate of sedimentation of the formation (high and in some cases more than 30 cm in a day). He found that the depositional environment of lower and upper parts of the formation is shallow marine when the middle part represents deep marine basin.

Karim (2007) studied tempestite in Tanjero Formation. He found that many sedimentary structures are developed in shallow water environments in the upper and middle parts of the formation. The writer stated that the structures are revealed reworking

of the sediments by storms during accumulation of Tanjero Formation and the reworked sediments are either deposited as tempestite or transported to deep water by turbidity currents and deposited as turbidites.

Sharbazheri (2007) studied age of unconformity within Tanjero Formation in Chwarta area Northeast of Iraq. He estimated the duration of the thick succession of Kato conglomerate, red claystone layers in the formation as 1.23 my and found that the Kato conglomerate represents an unconformity at the lower part of Tanjero Formation.

Sharbazheri (2010) studied planktonic foraminiferal biostratigraphy of the Upper Cretaceous reddish to pale brown transitional succession in Smaqli area, Northeastern Iraq. He found that the duration of the reddish to pale brown succession (Shiranish-Tanjero transition unit) of the studied section in the area estimated to be more than 2.150 my.

Karim et al. (2012) studied relations between cretaceous stratigraphic units and found that the relations are organized in simple graphical model of temporal and spatial relations between Cretaceous Tanjero Formation (as deep facies) indicated as lateral equivalent facies of Aqra Formation.

Karim et al. (2014) studied origin of fossiliferous limestone beds (lens of Aqra Formation) inside the upper part of Tanjero Formation. They offered that the limestone was transported by submarine mass wasting from neritic environment in Chwarta-Mawat area to deep environment at present position.

The clastic turbidites of Upper Cretaceous Tanjero Formation in the northern Iraq around Sulaimaniyah area have not been worked in terms of petroleum reservoir so far. This study will open a new window for local investigators and show if the turbidites are suitable for oil and gas production, for the many other geologists and geophysicist working for oil companies in Iraq.

3. AIM OF THE STUDY

The aim of this thesis is to study on reservoir characterizations of Upper Cretaceous turbidite sandstones of Tanjero Formation on the close northern part of Sulaimaniyah by:

- Estimation of total porosity, permeability and determination of effective porosity.
- Establishing depositional environment of the unit by using facies and facies associations according to lobe hierarchy.
- Studying petrography of the formation and provenance analysis with palaeoflow analysis.



4. METHODS

4.1. Field work

The vertical sequence analysis of the Tanjero Formation was carried out by measuring detailed seven sections bed by bed thickness, rock type, bed contacts, sedimentary structures as well as direction of local palaeocurrent and the samples were collected along all the measured sections (logs) where the variety of lithology and grain sizes observed. Taking locations of the sections by using GPS.

4.2. Laboratory work

Laboratory works contains;

- a- Taking core plugs for 45 collected samples and testing porosity by (BLP-530 Gas Porosimeter) for all of them
- b- Taking 10 core plugs for testing permeability by (Reservoir Permeability Tester).
- c- Preparing 35 thin sections for studying petrography and provenance under polarized microscope.

4.3. Office work

This work includes collecting and organizing the previous works to prepare a base data for this work. Interpretation and analyzing logs, and using softwares for drawing measured sections, plotting palaeoflow direction rose diagrams, separating facies and editing photos, petrographic examines of the thin sections, writing thesis.

During the office work the entire sections were subdivided into a number of facies. These facies are grouped into facies models. Depositional sub-environments were assigned to each model through comparison of their sedimentary attributes, rock type, facies & vertical relationship with the inferred facies distribution from the deep-sea models finally, the preceding data are used to reconstruct the depositional environmental model of Tanjero Formation in the studied area

5. LOCATION

The studied area located in north western of Sulaimaniyah city (Figure 5.1) which located in north eastern part of Iraq and close to Iranian border, near Hanaran-i-Khwaroo village.

The area is located between latitudes 35 41 58.79 N and 35 41 32.90 N, and longitudes 45 22 45.50 E and 45 21 01.61 E.



Figure 5.1. Location map of the studied area (<http://geology.com/world/iraq-satellite-image.shtml>)

6. GEOLOGICAL SETTING

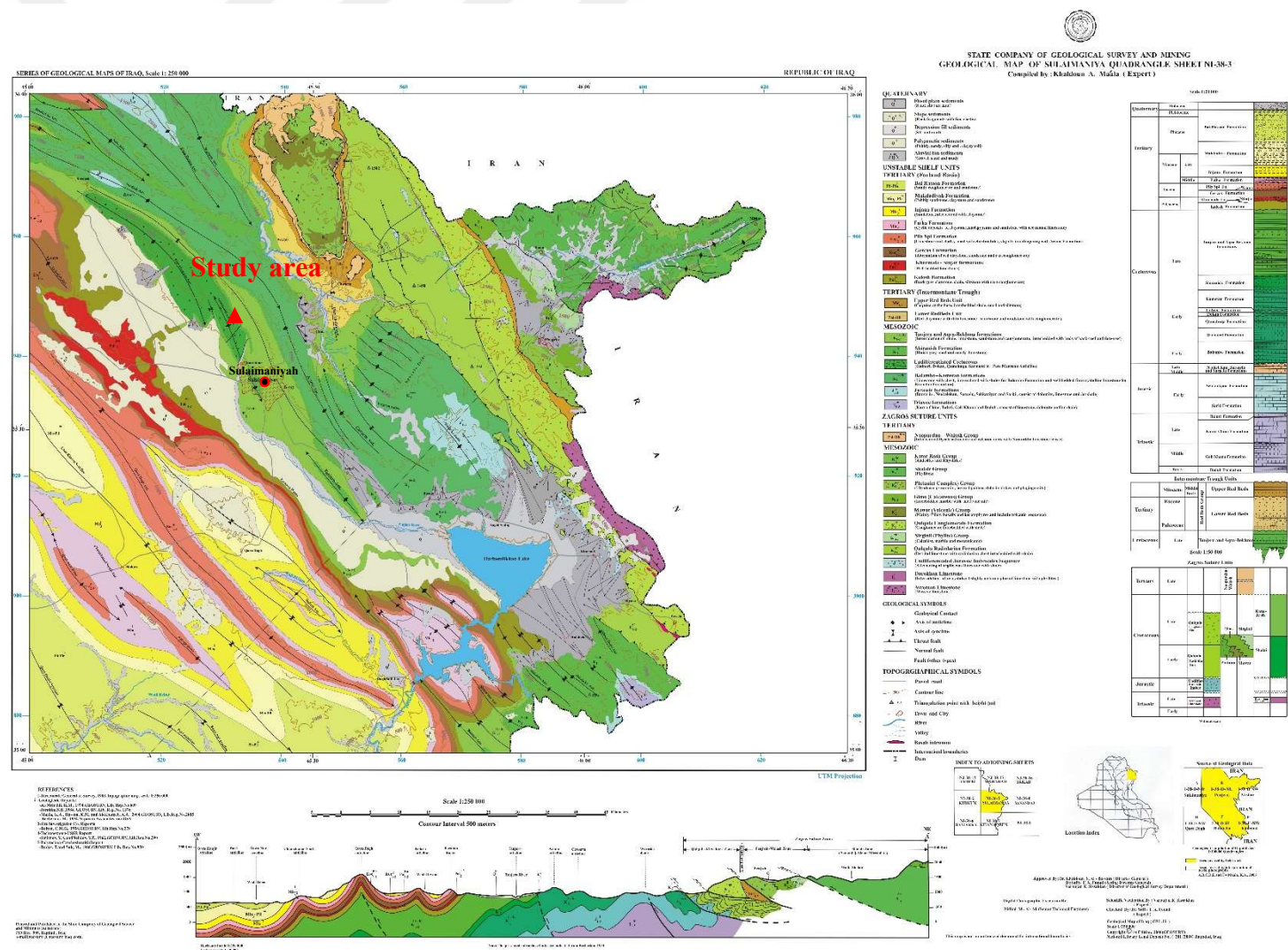
The studied area is located south of Zagros Thrust Belt, which is developed from the Neo-Tethys's Sea basin fill and collision of Iranian and Arabian plates. Structurally the area located in imbricated Zone (Buday and Jassim, 1987) which is characterized anticlines and synclines (Figure 6.1 and Figure 6.2) which are nearly coinciding with above mentioned mountains and valleys.

The formation (Figure 6.1) is located at the core of the synclines (inside valleys) only whereas their continuation along the axis and limb of the anticline is removed by erosion. The strata of the formation are highly deformed inside synclines showing minor folding and flowage of the incompetent beds such as marl and calcareous shale (Karim, 2004).

The weathering resistive limestone of Qamchuqa, Balambo and Kometan formations (Figure 7.2) are covering surface of anticline. In the core of some of these anticlines, Jurassic rocks are exposed such in Piramagroon, Sara, Kurra Kazaw and Karokh anticlines. The northern limit of Tanjero outcrop distribution nearly coincides with the boundary between Thrust and Imbricated Zones, while the southern boundary nearly corresponds with the boundary between High and Low Folded Zones (Karim, 2004).

In the studied area, Shiranish Formation underlies Tanjero Formation gradationally. The contact is marked at the first appearance of gray sandstone or siltstone beds at the top of Shiranish Formation (bluish white marl and marly limestone) and starting of olive green lithology of Tanjero Formation.

In the High Folded Zone, Kolosh Formation overlies Tanjero Formation unconformably (Figure 7.2) while in the Imbricated Zone, according to Bellen et al. (1959), Red Bed Series overlie the formation conformably. The type section of the formation is located at Sirwan valley near Halabja town about 50 km to the southeast of Sulaimaniyah City (Lawa et al., 1998, after Karim, 2004)



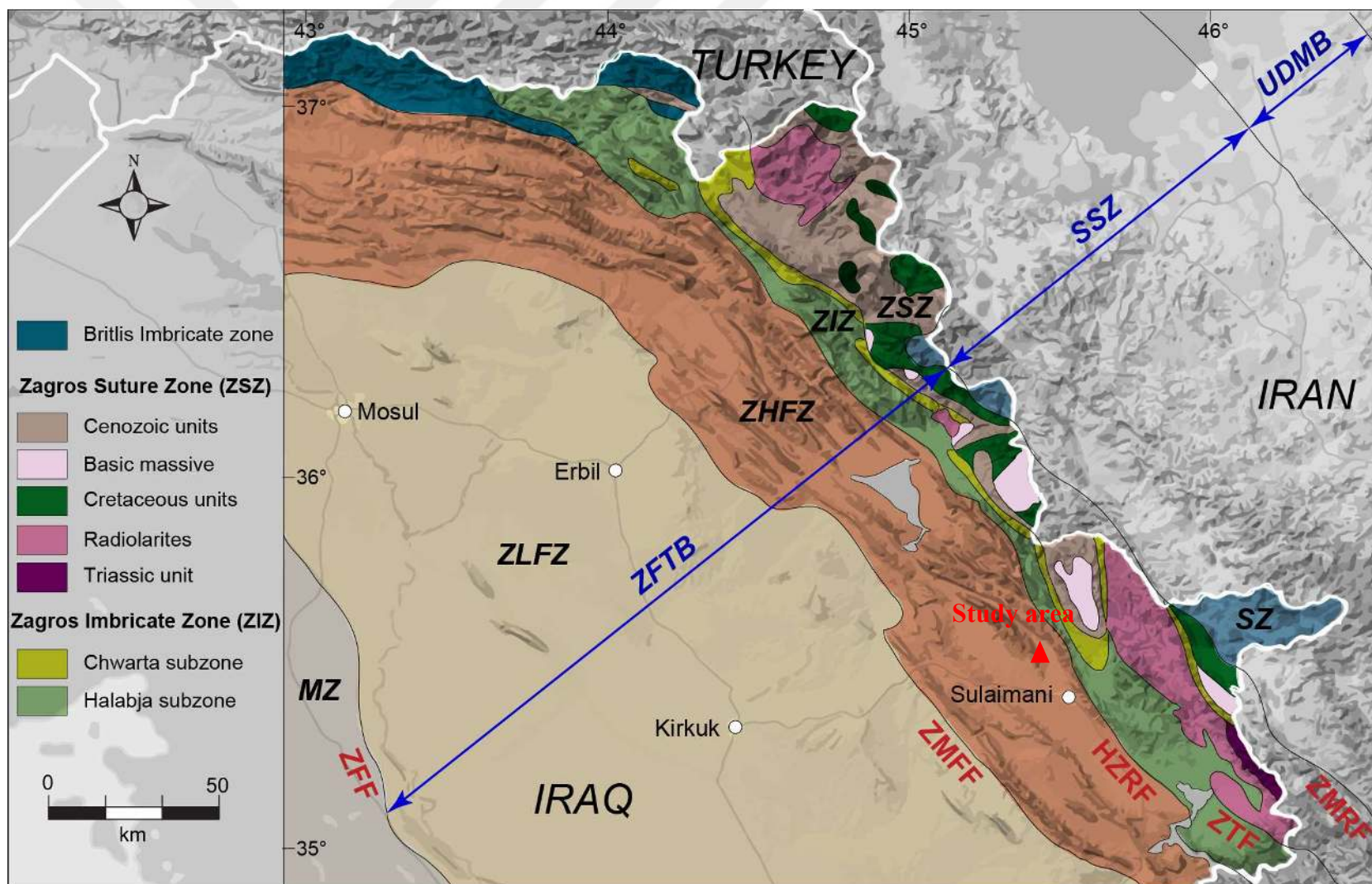


Figure 6.2. Tectonic map of northern Iraq (Baziany, 2014).

7. TANJERO FORMATION

7.1. Definition

The Tanjero Formation was first described by Dunnington in 1952 (Bellen et al., 1959). After the first definition all the investigators mentioned in the previous work part of the thesis used the name as it is.

7.2. Outcrop Distribution and Stratigraphic Contacts

The Tanjero Formation is distributed in the Imbricated zone in northeastern Iraq and High Folded zone southeast of the Greater Zab River (Buday, 1980).

The type section is located in Sirwan valley, near Halabja, southeast of Sulaimaniyah city, northeastern Iraq; between Kani Karweshkan and the scarp of Nador. Other localities throughout the eastern zone of Kurdistan, in most sections which expose Upper Cretaceous sediments, including measured and sampled sections at around Sulaimaniyah and Erbil cities (Bellen et al., 1959).

In the studied area located north west of Sulaimaniyah, close to Hanarani-Khwaroo village (Figure 5.1) the formation has a superb exposure of deep marine turbidites like in the (Figure 7.1) and the measured sections.



Figure 7.1. Sandstone beds of Tanjero Formation in the studied area. Close western part of the Hanarani-Khwaroo village.

In every place the lower boundary is contacted conformably and gradationally with the Shiranish Formation (Belen et al., 1959; Buday, 1980; Karim, 2004; Jassim and Goff, 2006), (Figure 7.2).

The Kolosh Formation and Red bed Series overlay the Tanjero Formation (Figure 7.2). The contact with the Red Bed Series is gradational like in the Chwarta area (Lawa et al., 1998), or gradational and unconformable in different localities in Chwarta and Qandil areas (Karim, 2004). The upper contact of the Tanjero Formation with the Paleogene Kolosh Formation is a disconformity (Bellen et al., 1959; Buday, 1980; Jassim and Goff, 2006). Nevertheless more recently Sharbazheri et al. (2009) from the study of the Foraminifera bio-zonation, found a conformable contact.



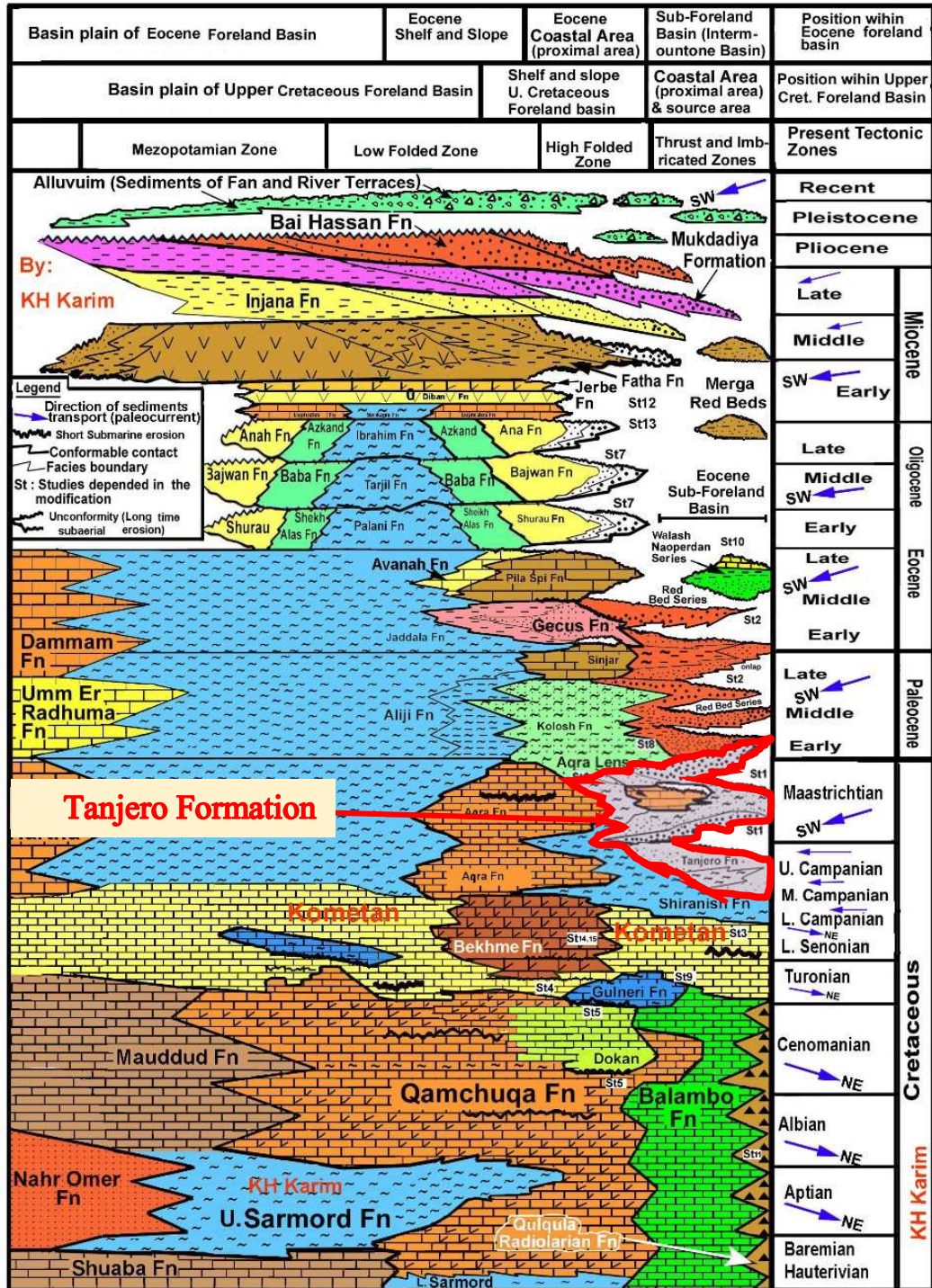


Figure 7.2. New chronostratigraphic column of Northeast Iraq in which the stratigraphy of the Imbricated and Thrust Zones are shown and most of the previous unconformities in the High and Low Folded Zone are rejected (modified from Bellen et al, 1959 and Omeri and Sadiq, 1977, after (Karim, 2010)).

7.3. Lithology

In the type locality the formation is divided into two parts. The lower part comprises 484 m of globigerinal marls and rare marly limestones with silts. The upper part is composed of 1532 m of silty marls, siltstones, sandstones, conglomerates, and sandy or silty organic detrital limestones, with intercalations of organic reef and shoal-type limestones. (Bellen et al., 1959).

Abdel-Kireem (1986) divided the Tanjero Formation in the Dokan area into three units. The upper unit is 124m thick, composed of sandy bio-clastic limestones, silty shales and graded sandstones. The middle unit is 209m thick and composed of chalky marls with abundant planktonic foraminifera. The lower unit is made of 460m of green marls and siltstones interbedded with fine-grained sandstones (Ahmed, 2013).

In 2004 Karim divided the Tanjero Formation into three parts. The writer stated that the lower part is composed of a thick succession of conglomerate in the areas close to the source areas in the north (such as the Qandil Mountain, and the Chwarta and Mawat areas), and of alternation of sand and calcareous shales in the area far from the source (such as Dokan area, Figure 1). The thickness of this part varies from 50 to 1000 m. The middle part includes thick beds of dark green calcareous marls with thin layers of sandstone and conglomerate. In Chwarta and Mawat areas the middle part is 300 m thick, while in Dokan area it is 130m thick. The upper part is composed of a succession of thick fossiliferous limestone alternating with black silty calcareous shale or marl (about 50-200 m thick).

In the studied area the formation is composed of alternation of sandstone and shale consist of some thick beds of sandstone connected with thin beds of shale, and some thin bedded turbidite (tbt) which consist of thin beds of sandstone connected with thick or thin shale beds. The color is mostly grey or greenish grey for both sandstone and shale, but in the lower part of the studied area which connected with the Shiranish-Tanjero Formations contact the color is light grey.

7.4. Measured Sections

Seven measured sections were taken around the Hanarani-Khwaroo village. The thickness of these measured sections vary from 120 m to 190 m (Figure 7.3 and the logs labelled as HL starting on the page number 16).

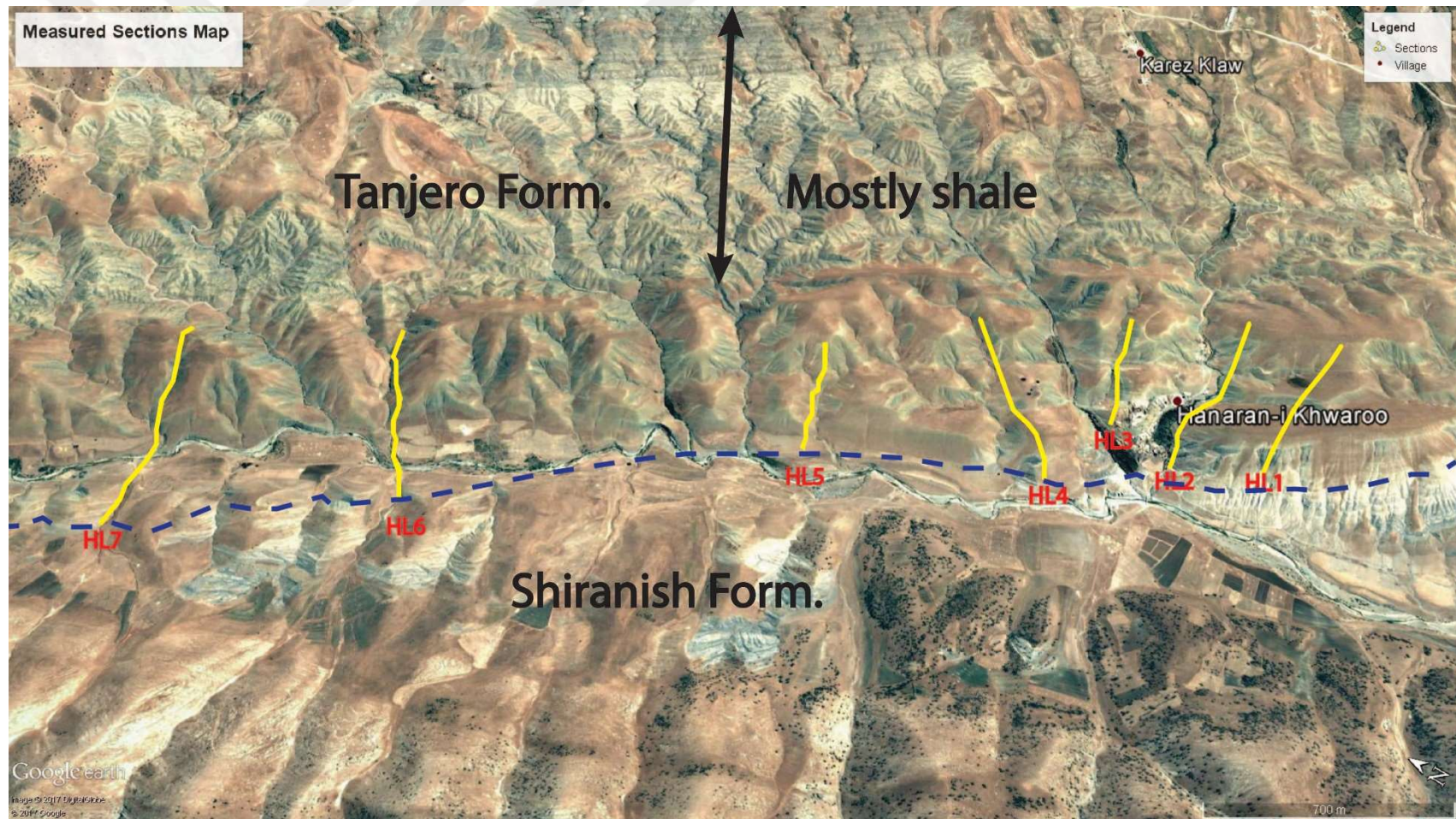
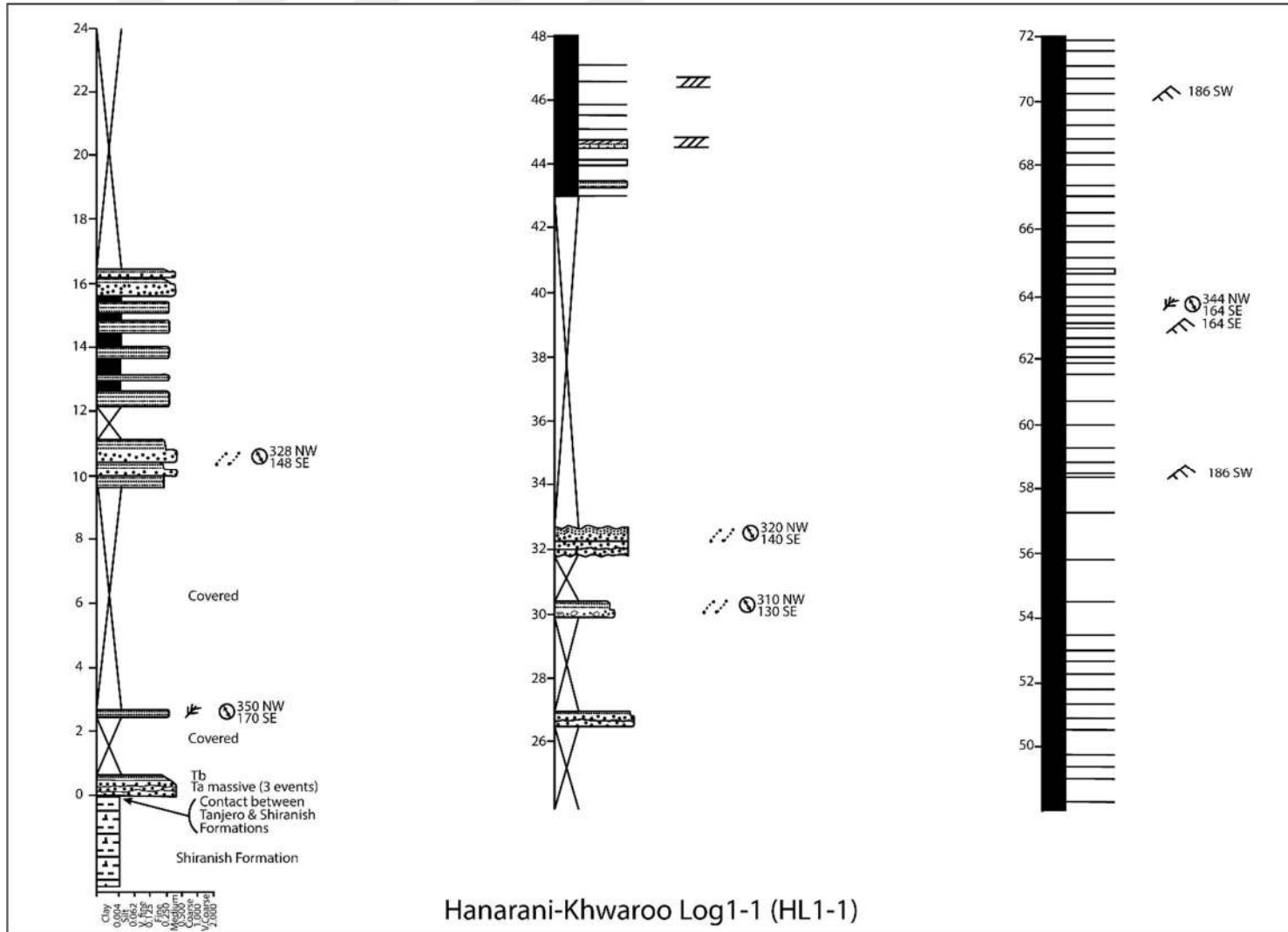
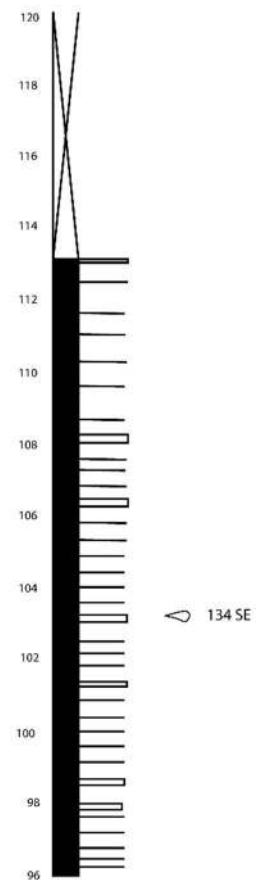
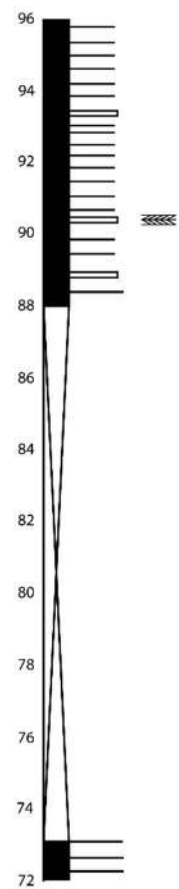


Figure 7.3. Google Earth image covering the study area around the Hanarani-Khwaroo village. Yellow lines are representing the logs taken. From right to left the log numbers are 1 to 7.

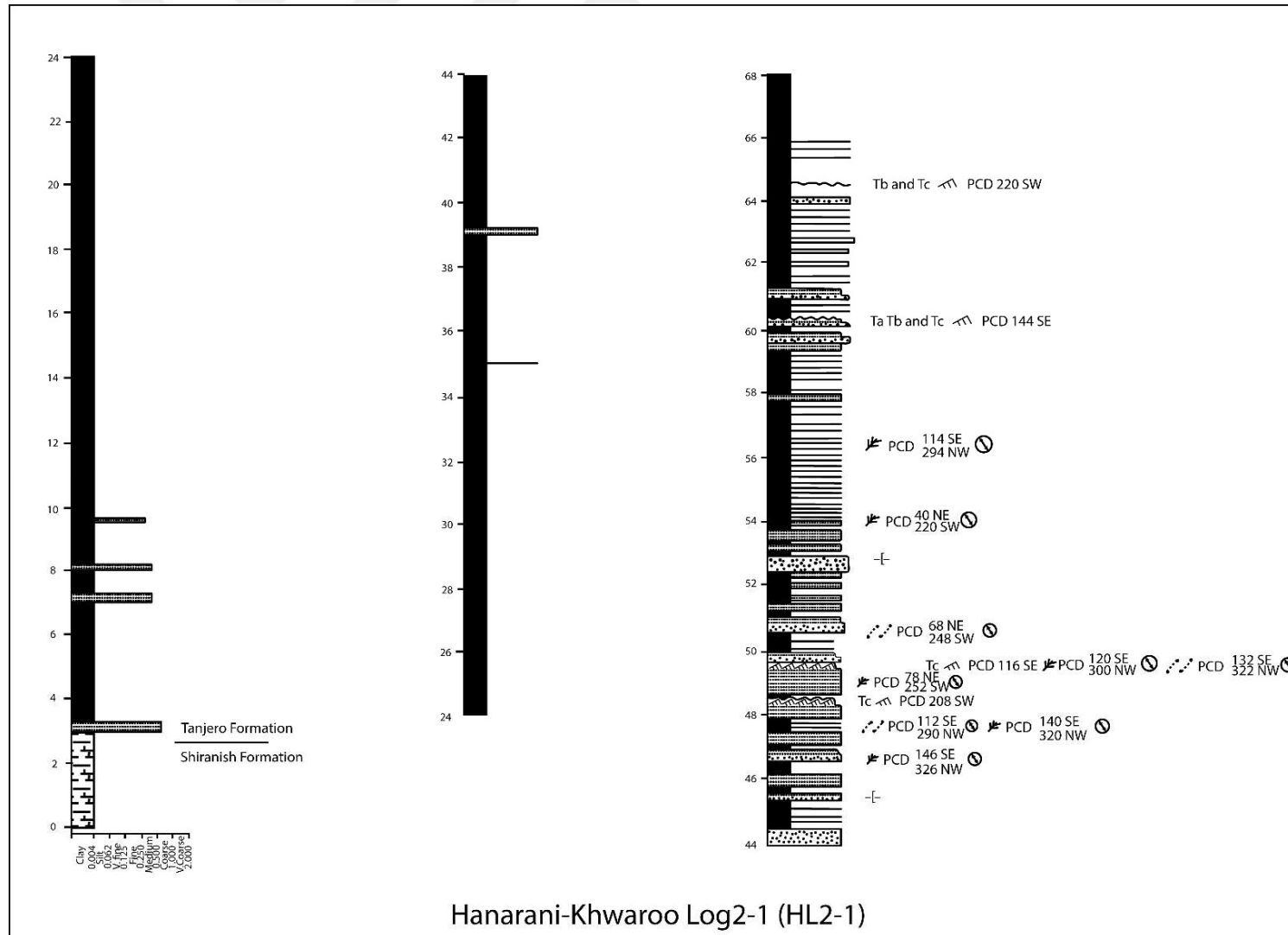
1. HL1 located in longitude $35^{\circ} 40' 14''$ N and latitude $45^{\circ} 22' 38''$ E

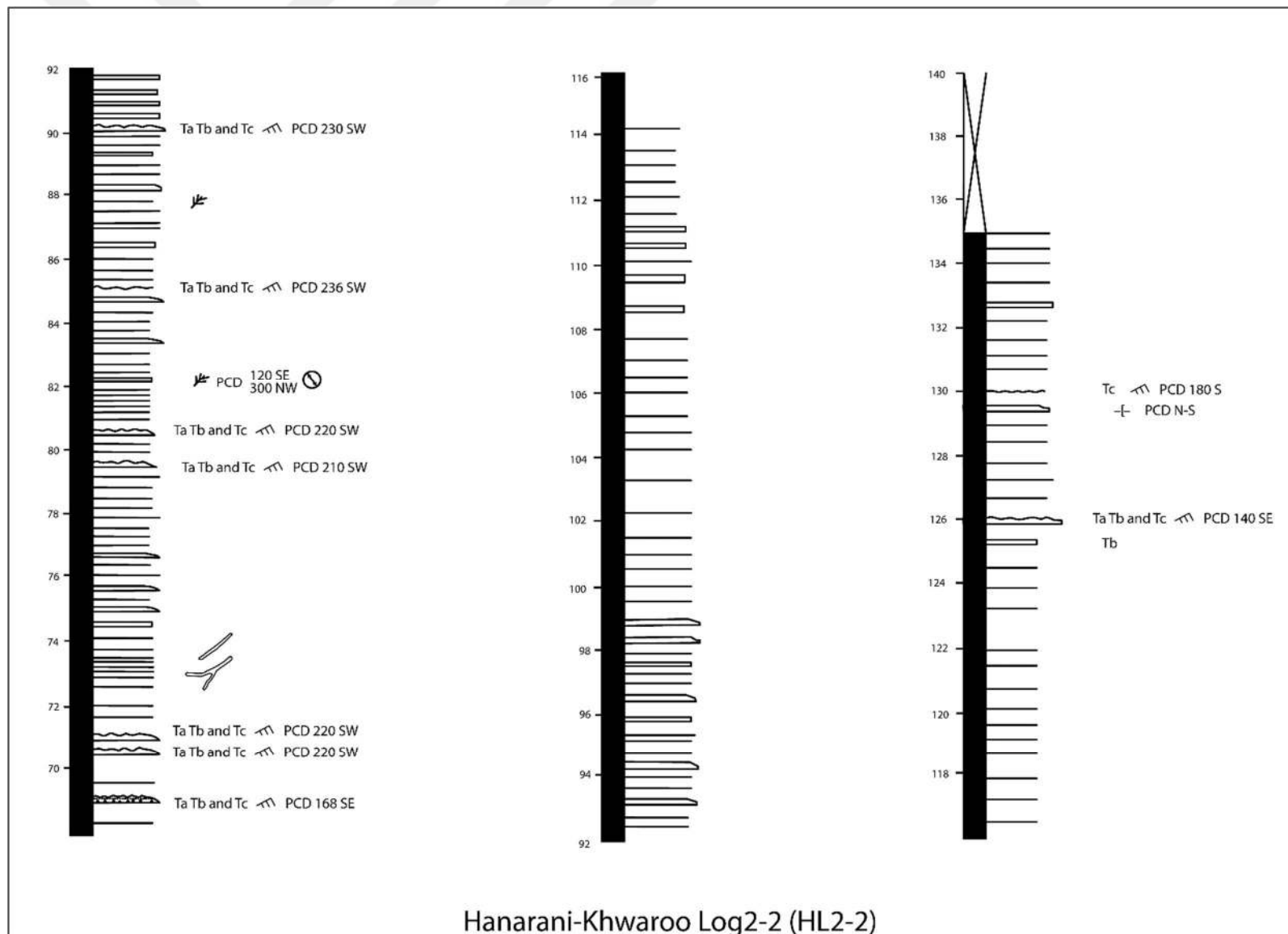




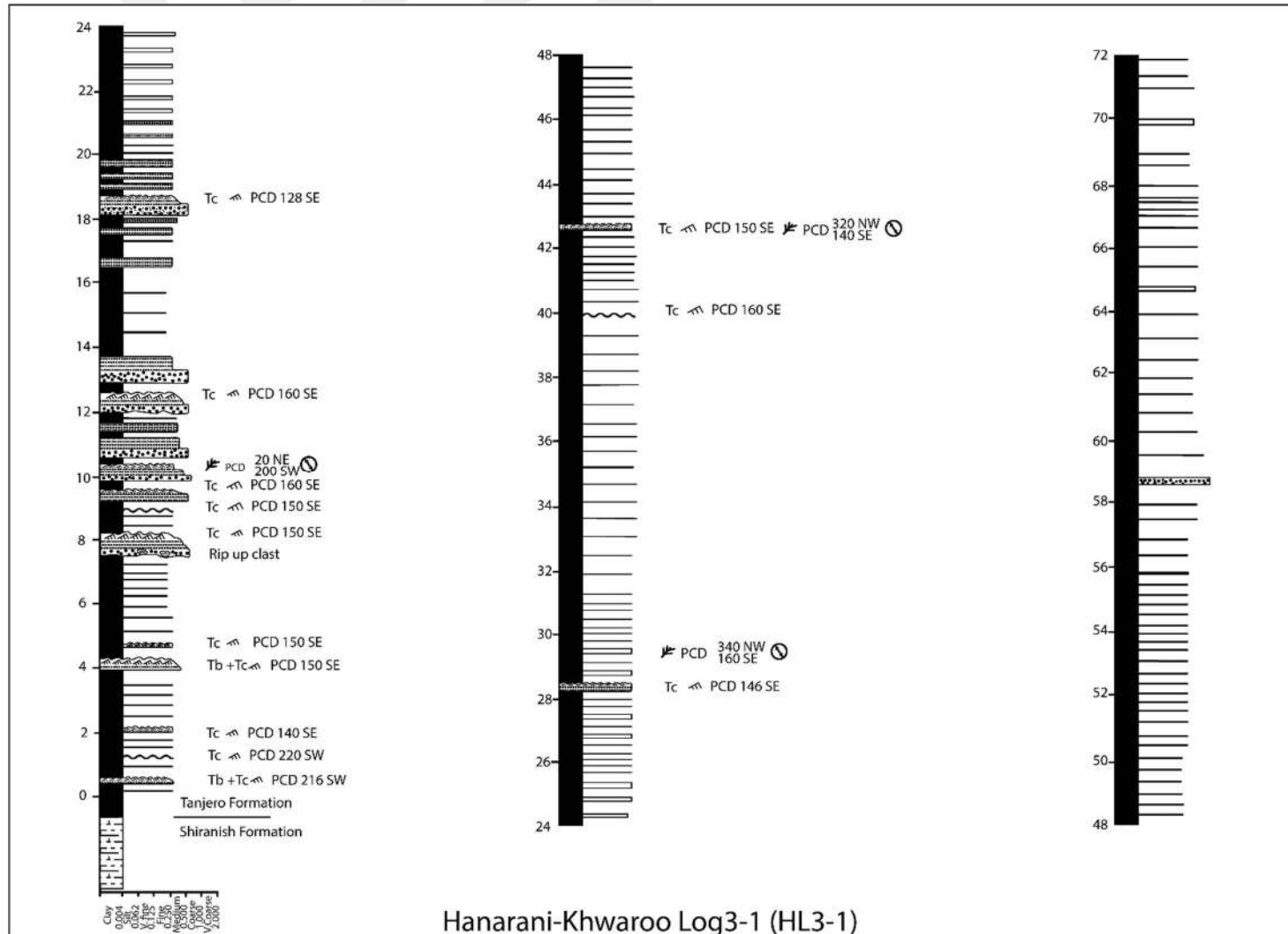
Hanarani-Khwaroo Log 1-2 (HL1-2)

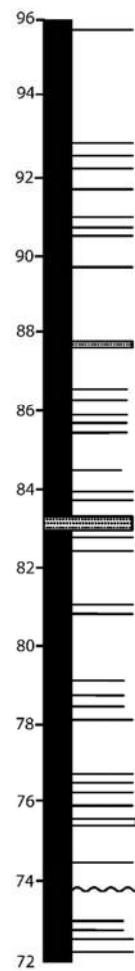
2. HL2 located in longitude 35 ° 40 ' 23 " N and latitude 45 ° 22 ' 35 " E



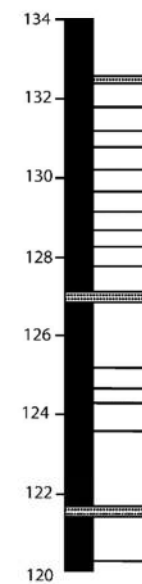
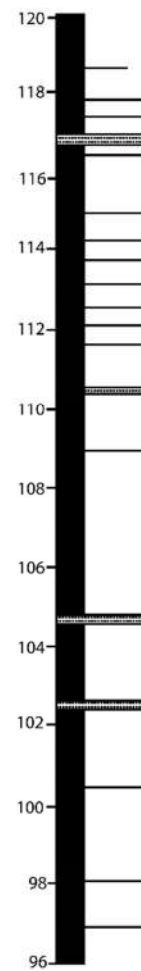


3. HL3 located in longitude 35 ° 40 ' 31 " N and latitude 45 ° 22 ' 37 " E



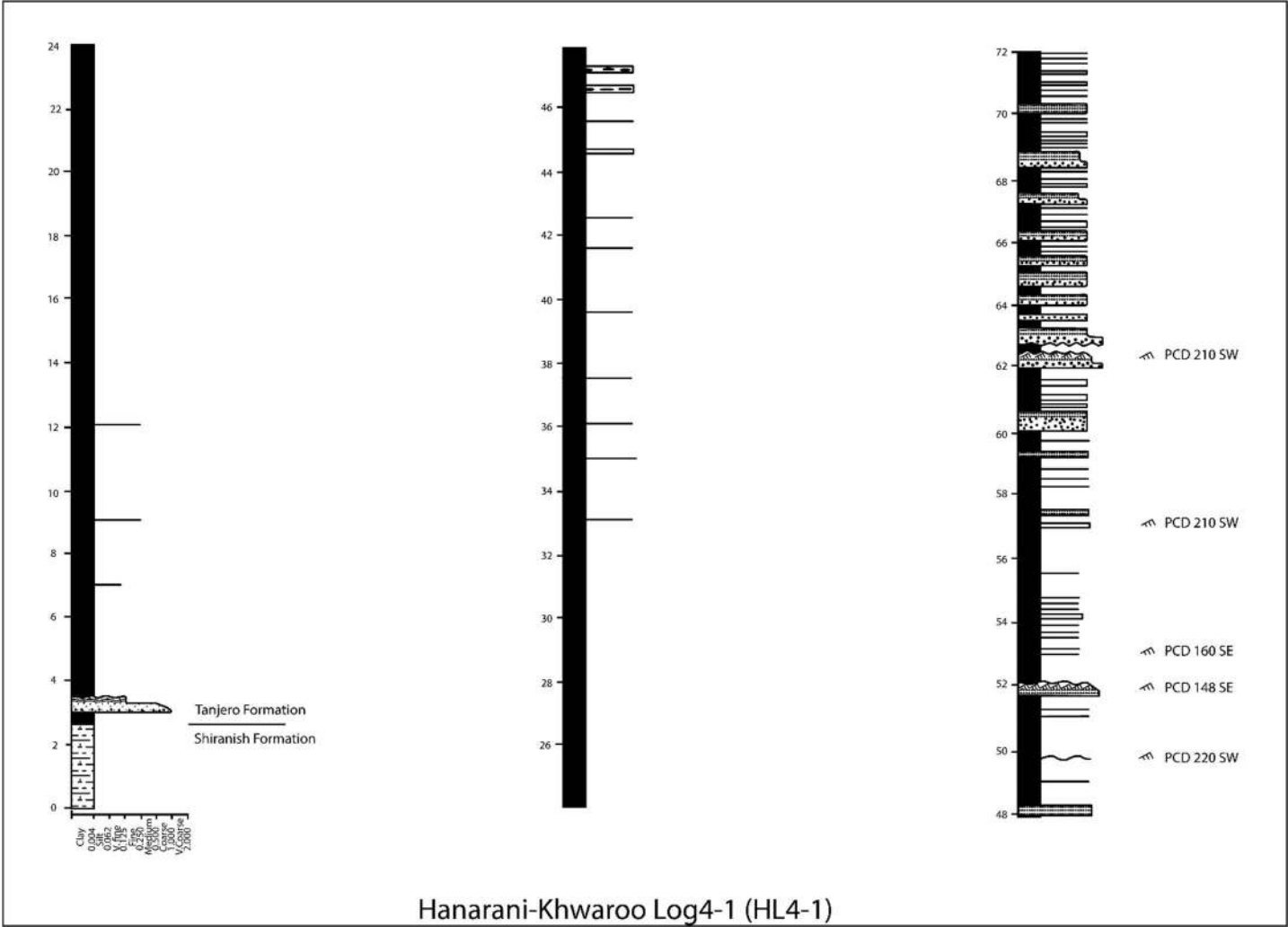


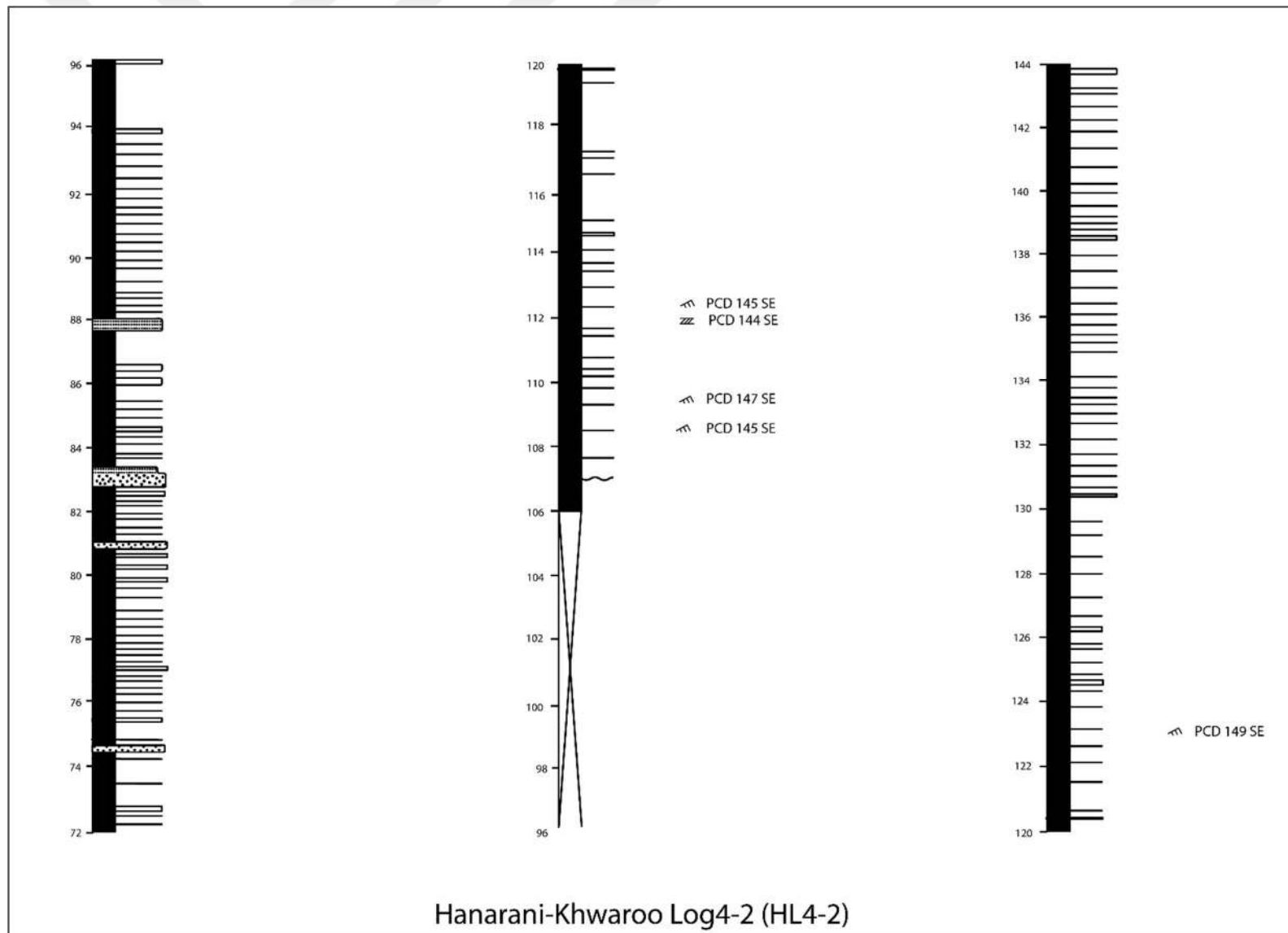
Tc  PCD 180 S

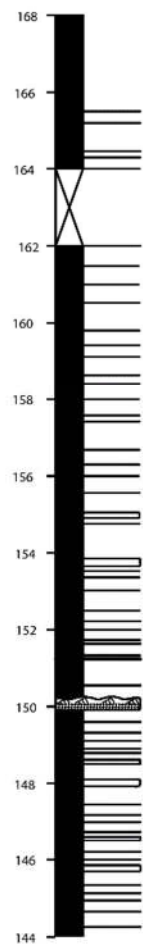


Hanarani-Khwaroo Log3-2 (HL3-2)

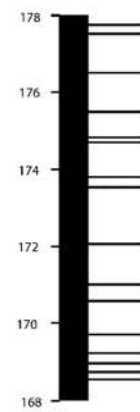
4. HL4 located in longitude 35 ° 40 ' 35 " N and latitude 45 ° 22 ' 24 " E





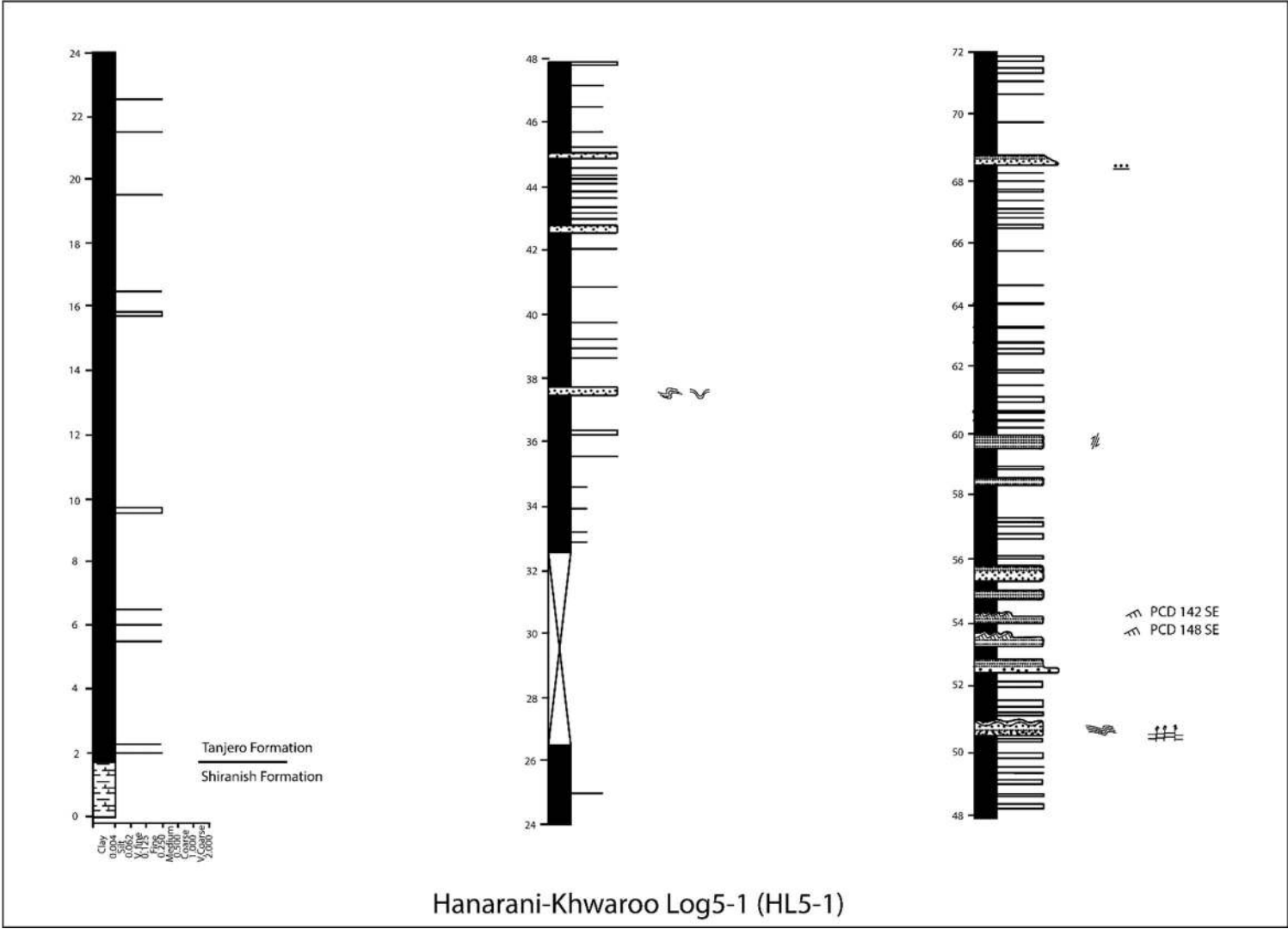


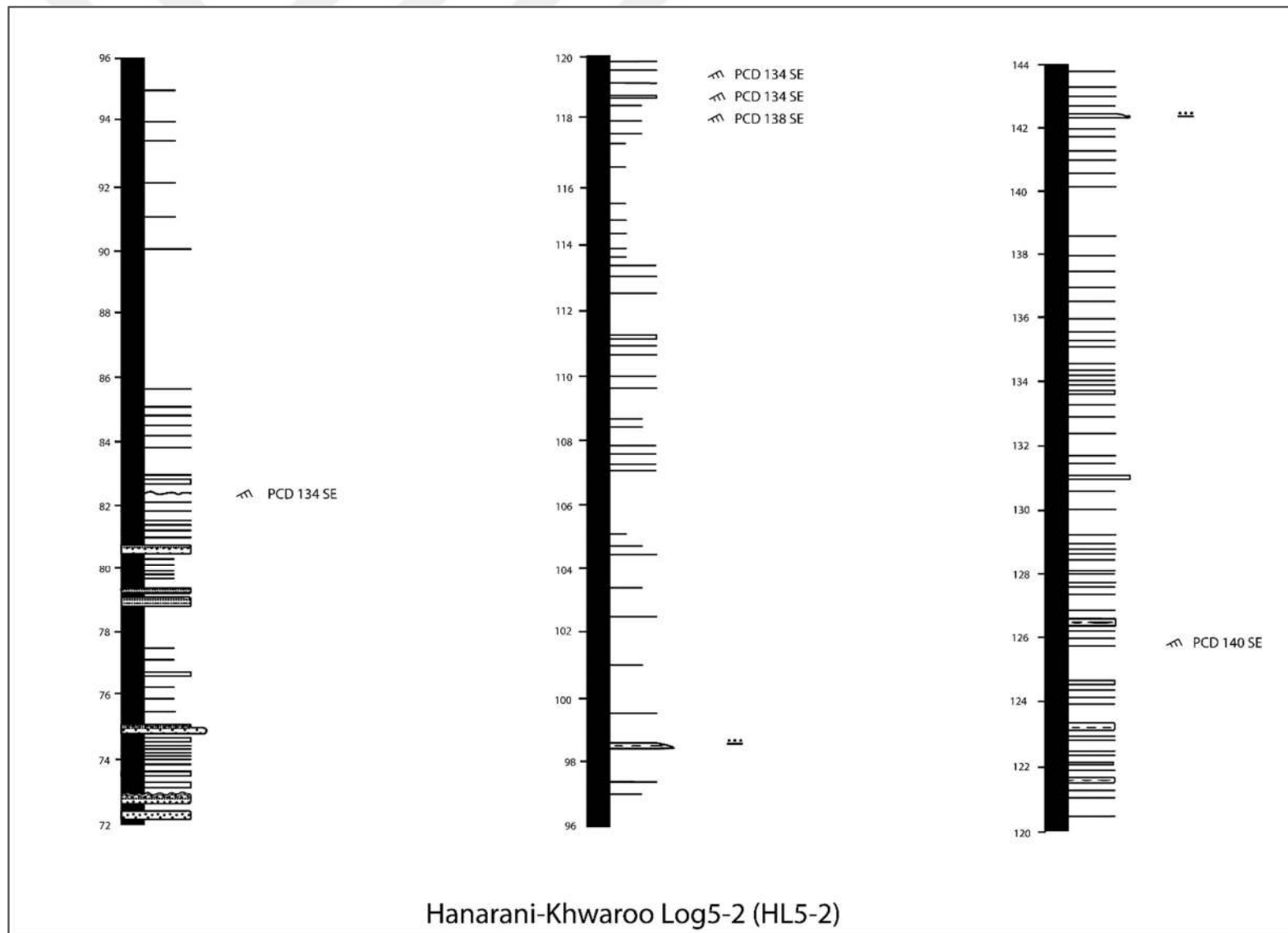
PCD 144 SE

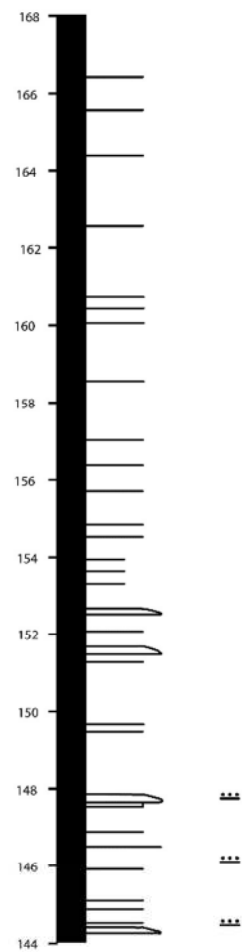


Hanarani-Khwaroo Log4-3 (HL4-3)

5. HL5 located in longitude 35 ° 40 ' 58 " N and latitude 45 ° 22 ' 13 " E

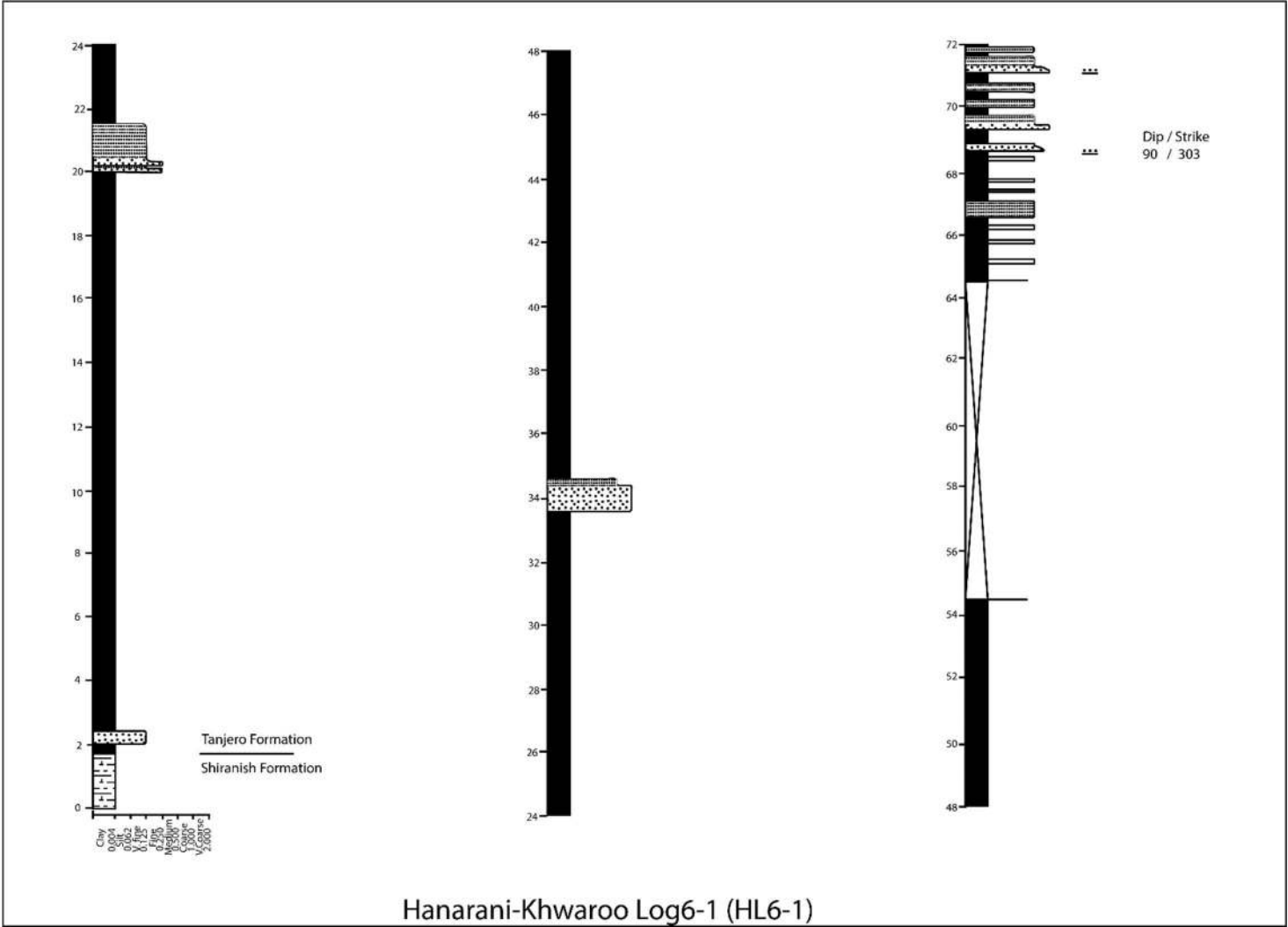




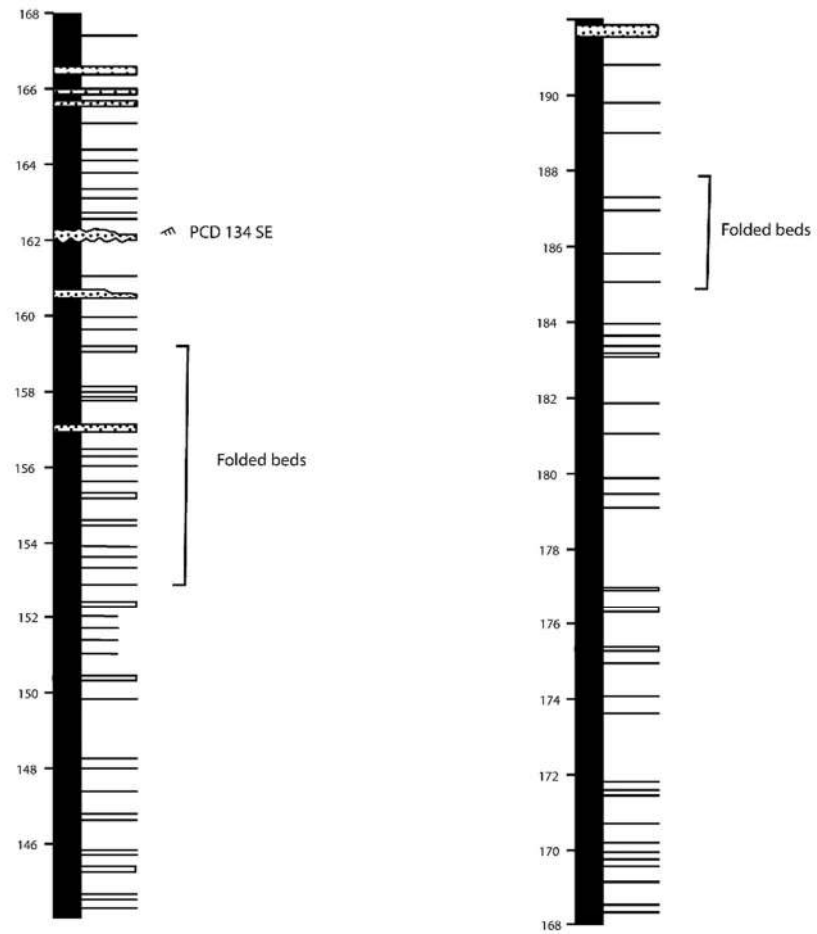


Hanarani-Khwaroo Log5-3 (HL5-3)

6. HL6 located in longitude 35 ° 41 ' 31 " N and latitude 45 ° 21 ' 38 " E

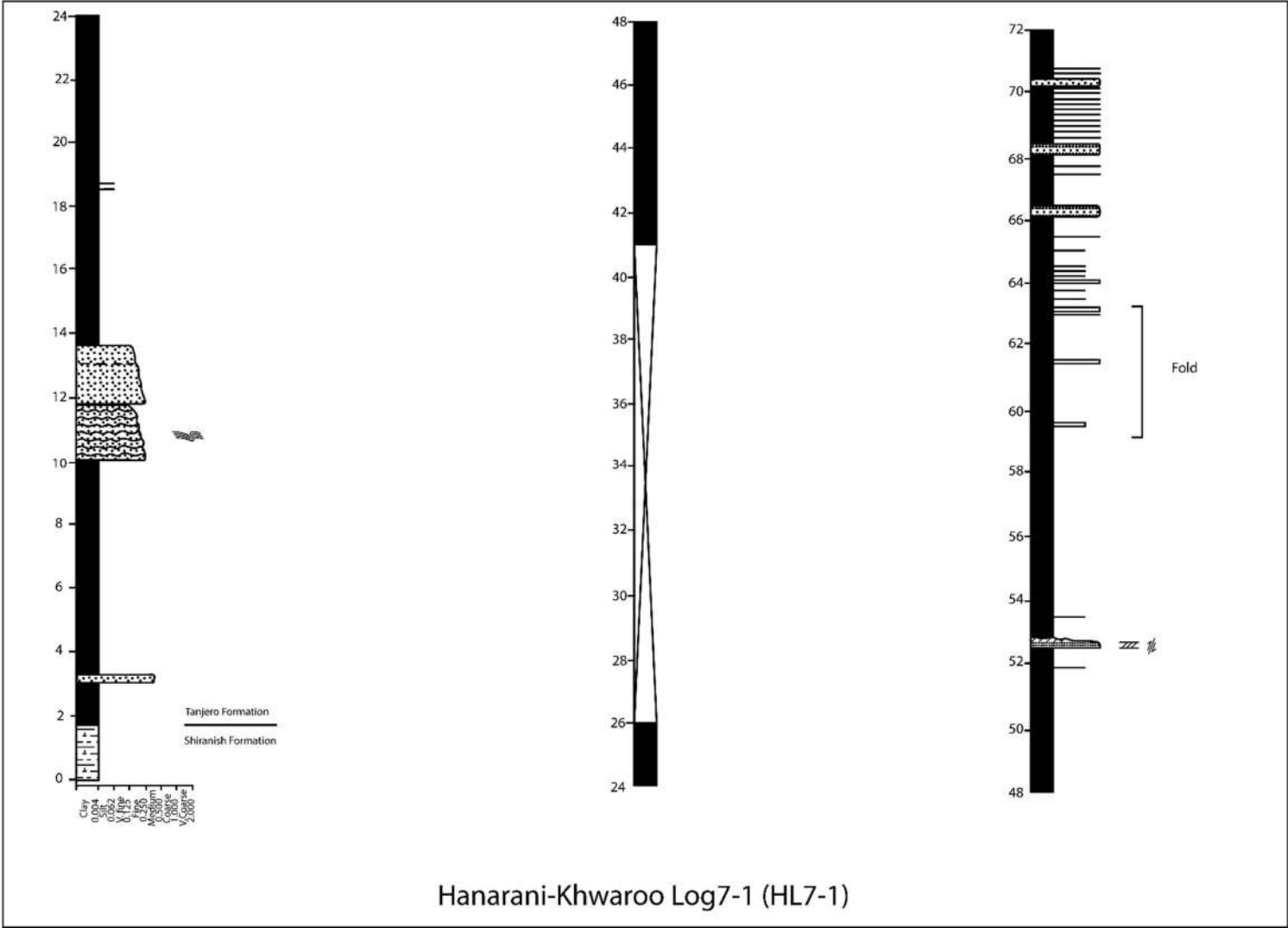


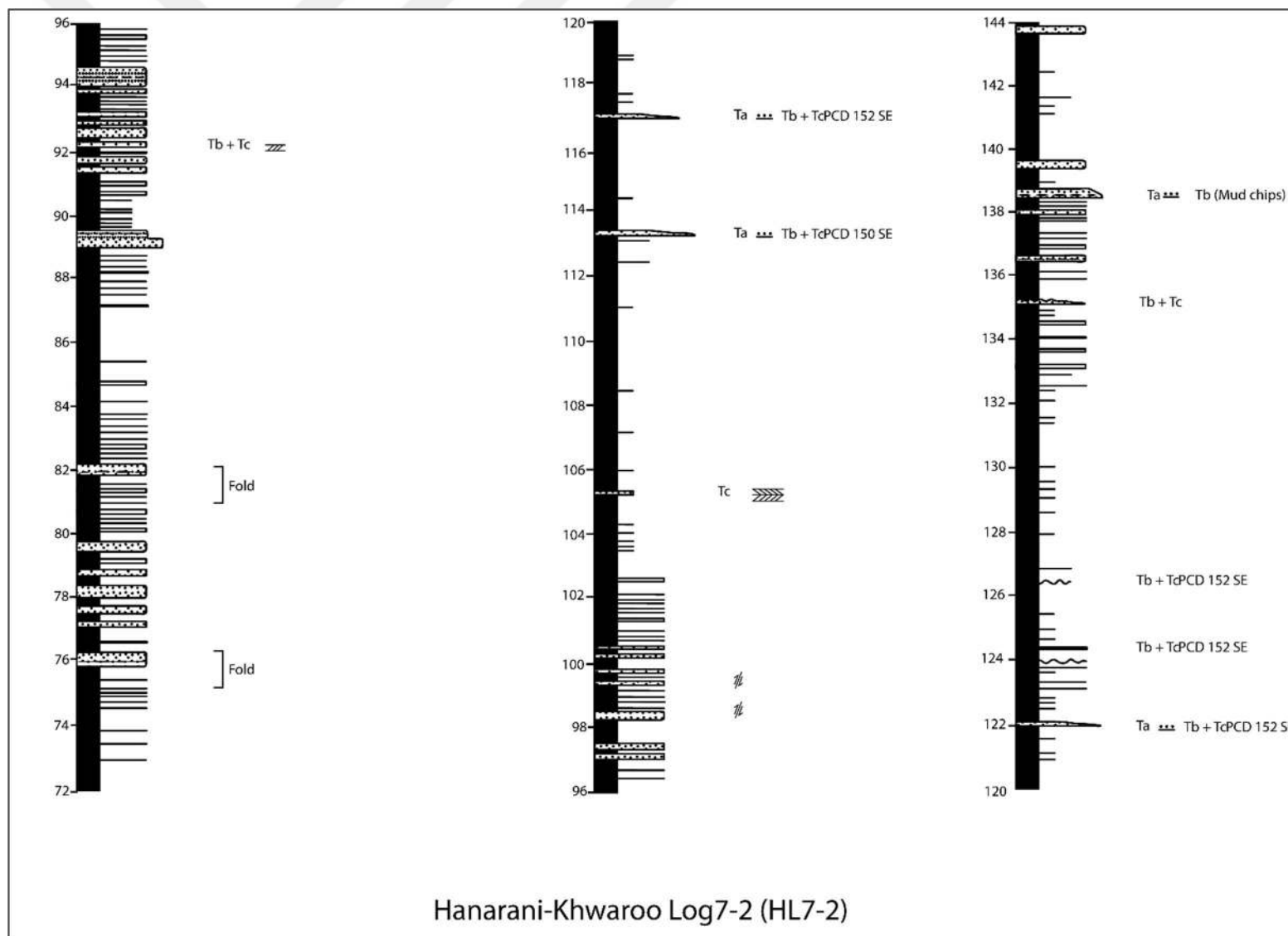


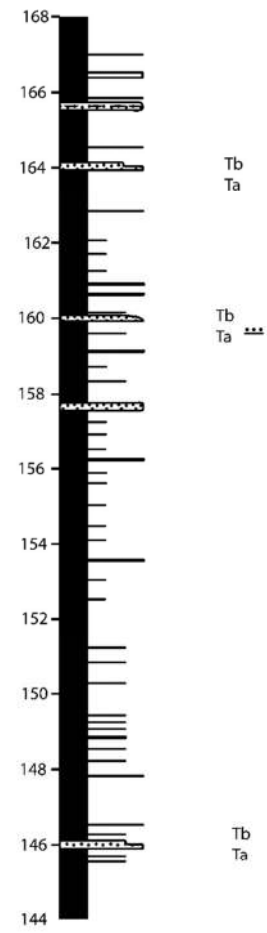


Hanarani-Khwaroo Log6-3 (HL6-3)

7. HL7 located in longitude 35 ° 41 ' 55 " N and latitude 45 ° 21 ' 15 " E







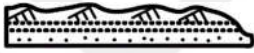
Hanarani-Khwaroo Log7-3 (HL7-3)

7.5. Facies types

Seven distinctive main lithofacies groups were identified, from seven measured sections detailed in the 7.4 part, consisting of forty-eight subfacies.

1. Coarse grained sandstone beds

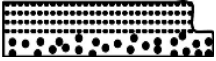
Four facies belong to this group represented by some parts of Bouma Sequence which listed in the table below.

No.	Facies types	Facies	Description
1	F.1a		Coarse grain sandstone; normal grading (Ta) flat base, (Tb) and ripple mark (Tc) with wavy top.
2	F.1b		Coarse grain sandstone; massive (Ta) flat base, (Tb) and ripple mark (Tc) with wavy top.
3	F.1c		Coarse grain sandstone; normal grading (Ta) flat base, reverse grading (Ta) with a thin bed of shale between them with flat top.
4	F.1d		Coarse grain sandstone; massive (Ta) with flat base and flat top.

2. Medium grained sandstone beds

12 facies belong to this group represented by some parts of Bouma Sequence which listed in the table below.

No.	Facies types	Facies	Description
5	F.2a		Medium grain sandstone; normal grading (Ta) with flat base, (Tb) and ripple mark (Tc) with wavy top.
6	F.2b		Medium grain sandstone; massive (Ta) with flat base, (Tb) and ripple mark (Tc) with wavy top.
7	F.2c		Medium grain sandstone; massive (Ta) with erosional base, (Tb) and ripple mark (Tc) with wavy top.

8	F.2d		Medium grain sandstone; massive (Ta) with rip up clast and erosional base, (Tb) and ripple mark (Tc) with wavy top.
9	F.2e		Massive (Ta) with flat base and (Tb) with flat top.
10	F.2f		Massive (Ta) with erosional base and (Tb) with flat top.
11	F.2g		Normal grading (Ta) with flat base and (Tb) with flat top.
12	F.2h		Normal grading (Ta) flat base, shale chips, with flat top.
13	F.2i		Massive (Ta) with flat base and flat top.
14	F.2j		Parallel lamination (Tb) with flat base and flat top.
15	F.2k		(Tb) and (Tc) ripple marks with flat base and wavy top.
16	F.2l		Two or three beds (Ta) with amalgamation surface and erosional base, and (Tb) with flat top.

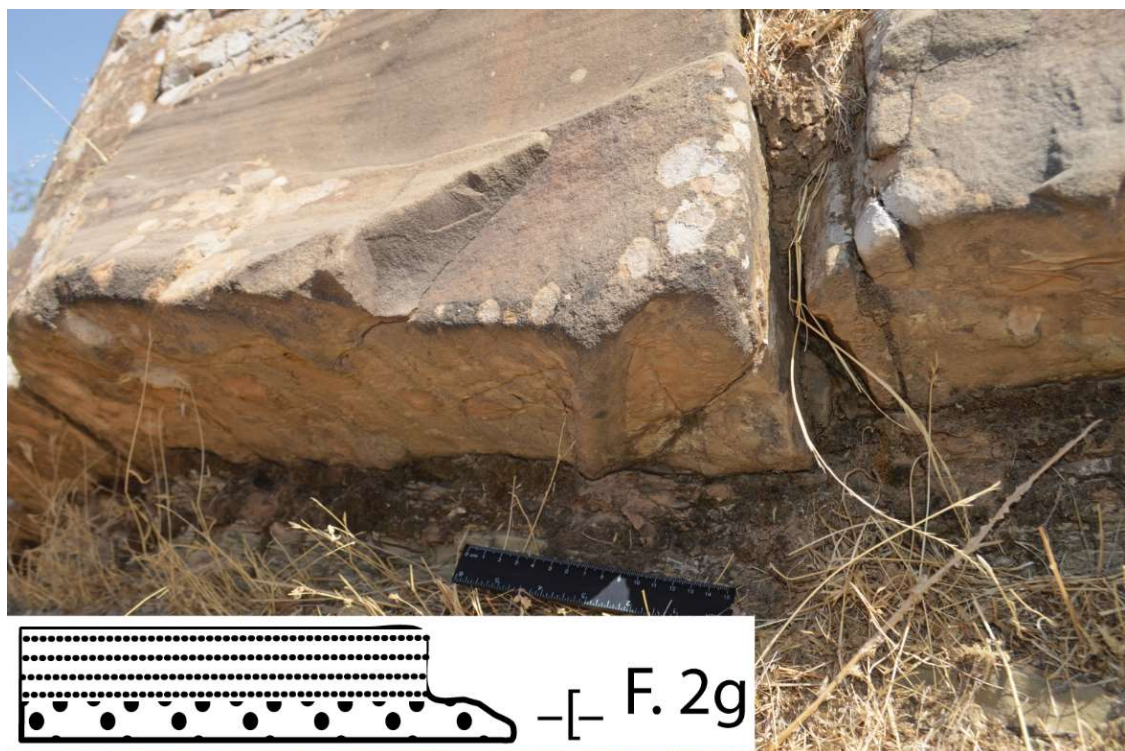


Figure 7.4. Image explains facies medium sandstone Ta normal grading and Tb parallel lamination with groove cast (F.2g).

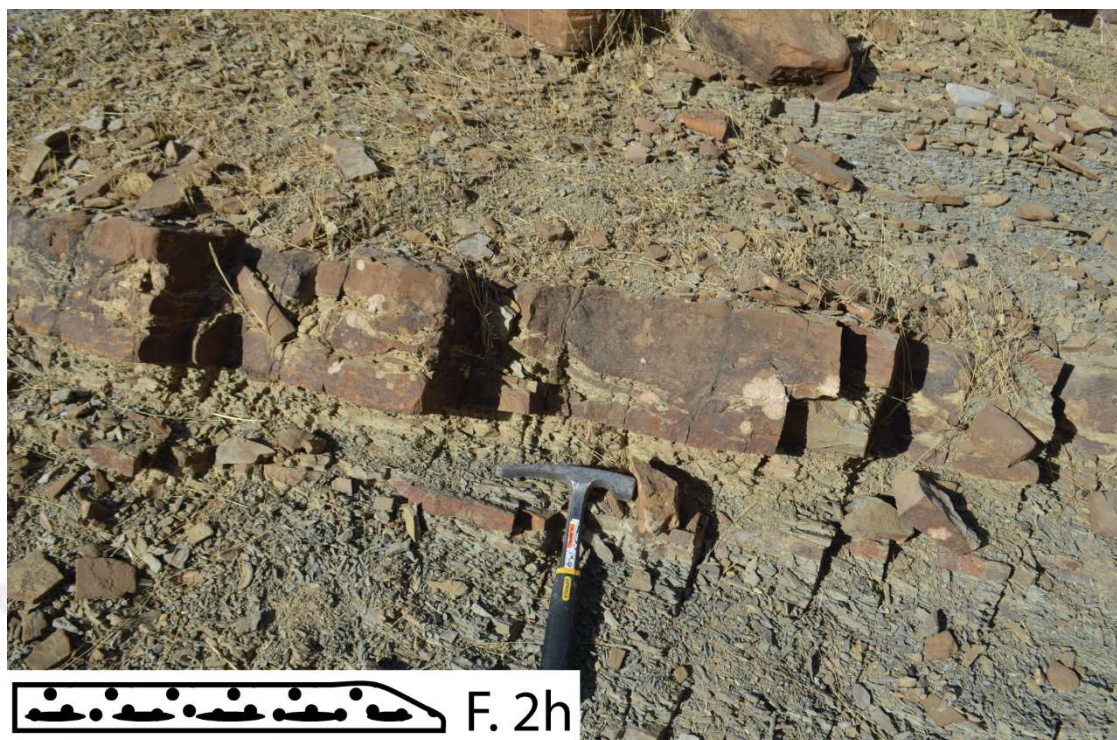
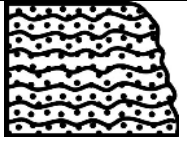


Figure 7.5. Image explains facies medium sandstone bed Ta normal grading with shale (rip up clasts) chips (or linked debrite/hybrid bed) (F.2h).

3. Fine grained sandstone beds

18 facies belong to this group represented by some parts of Bouma Sequence which listed in the table below.

No.	Facies types	Facies	Description
17	F.3a		Massive (Ta) with flat base and flat top.
18	F.3b		(Tb) with flat base and flat top, plant materials.
19	F.3c		Massive (Ta) and (Tb) with flat base and flat top.
20	F.3d		(Ta) normal grading with flat base, (Tb) and (Tc) ripple marks, wavy top.
21	F.3e		(Tb) and (Tc) ripple marks, with flat base and wavy top.
22	F.3f		Massive (Ta) with, (Tb) and (Tc) cross bedding, with flat base and flat top, flute cast.
23	F.3g		Ripple mark (Tc) with flat base and wavy top.

24	F.3h		Parallel lamination (Tb) with shale chips, with flat base and flat top.
25	F.3i		Massive (Ta) with flat base, (Tb) and (Tc) convolute lamination and wavy top.
26	F.3j		Massive (Ta) with erosional base and flat top.
27	F.3k		Massive (Ta) with erosional base, (Tb) and (Tc) with ripple marks and wavy top.
28	F.3l		A thick bed of convolute lamination (Tc) flat base and wavy top.
29	F.3m		Normal grading (Ta) with shale chips, flat base and flat top.
30	F.3n		Massive (Ta) and (Tb) with flat base and flat top, parting lineation.
31	F.3o		Massive (Ta) with shale chips with flat base and flat top.
32	F.3p		Massive (Ta) and (Tb) with shale chips with flat base and flat top.
33	F.3q		Normal grading (Ta) with flat base and flat top.
34	F.3r		Two or three beds of (Ta) with amalgamation surface and erosional base, (Tb) and (Tc) convolute lamination, wavy top, parting lineation.

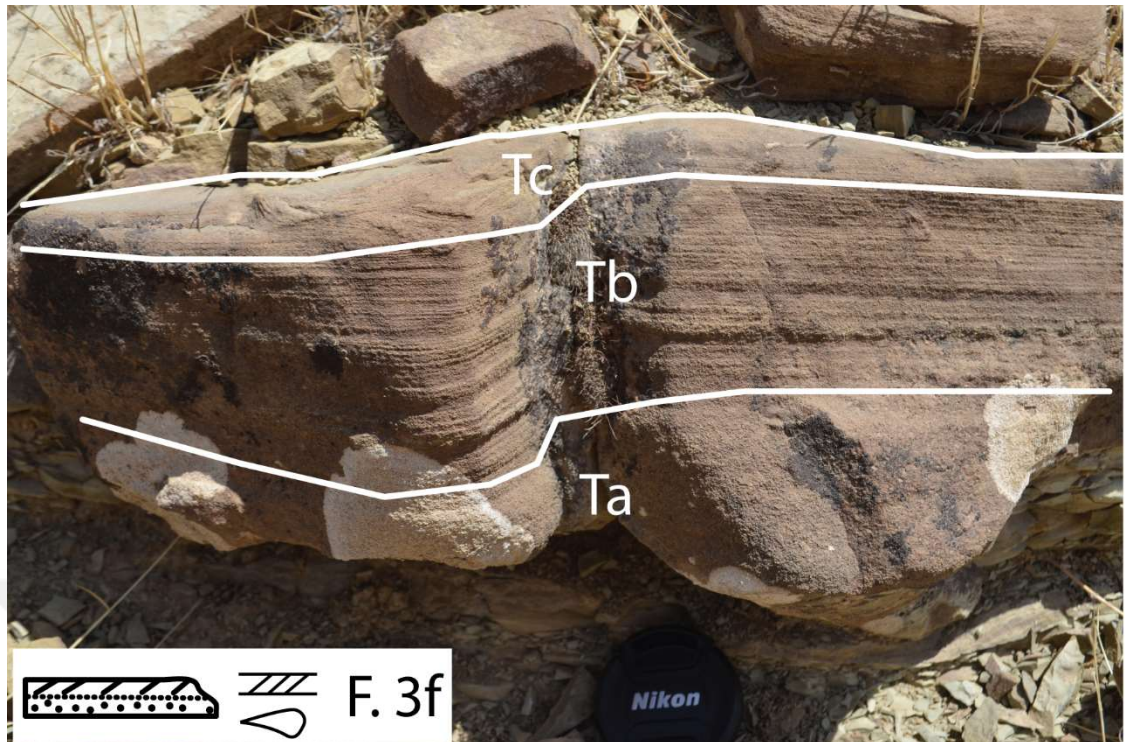


Figure 7.6. Image explains massive (Ta) with, (Tb) and (Tc) cross bedding, with flat base and flat top, flute cast.



Figure 7.7. Image explains facies 3e (Tb) and (Tc) ripple marks, with flat base and wavy top.



Figure 7.8. Image explains (facies 3r) two or three beds of (Ta) with amalgamation surface and erosional base, (Tb) and (Tc) convolute lamination, wavy top, parting lineation.

4. Very fine grained sandstone beds

2 facies belong to this group represented by some parts of Bouma Sequence which listed in the table below.

No.	Facies types	Facies	Description
35	F.4a		Massive (Ta) with flat base and flat top.
36	F.4b		Massive (Ta) with rip up clast; and (Tb) with flat base and flat top.

5. Shale, thin bedded siltstone and thin bedded of very fine sandstone

There are 5 facies of shale here, interbedded siltstone with mudstone and interbedded very fine sandstone and mudstone. The facies are distinguished by the ratio of shale according to the siltstone and sandstone.

No.	Facies types	Facies	Description
37	F.5		Shale
38	F.5a		Shale = 81% and siltstone thin beds =19%
39	F.5b		Shale = 85% and siltstone thin beds =15%
40	F.5c		Shale = 78% and very fine sandstone thin beds =22%
41	F.5d		Shale = 89% and very fine sandstone thin beds =11%

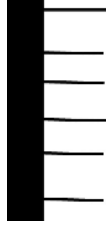
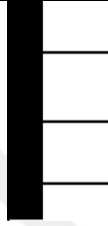


Figure 7.9. Image explaining (facies F.5) a thick bed of shale.

6. Thin bedded fine sandstone

This group includes 4 facies types of interbedded fine sandstone and mudstone, divided according to the ratio of sandstone to mudstone.

No.	Facies types	Facies	Description
42	F.6a		About 70% mudstone and thin bedded of fine sandstone 30%, with plant materials

43	F.6b		Shale = 88% and very fine sandstone thin beds =12%
44	F.6c		Shale = 92% and fine sandstone thin beds =08%
45	F.6d		Shale = 96% and fine sandstone thin beds =04%

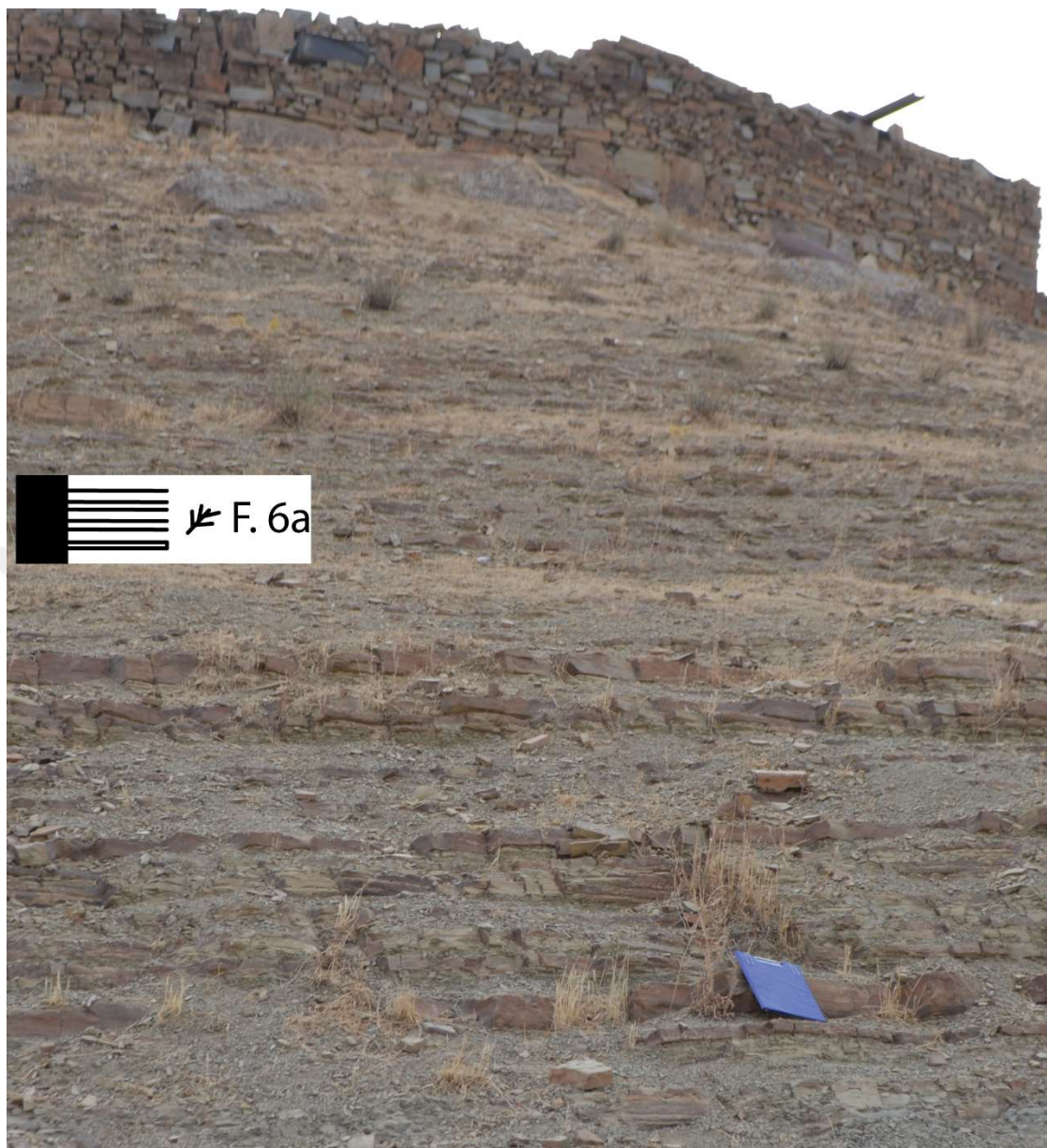


Figure 7.10. Image explains facies 6a about 70 % shale with thin bedded of fine sandstone 30%, with plant materials

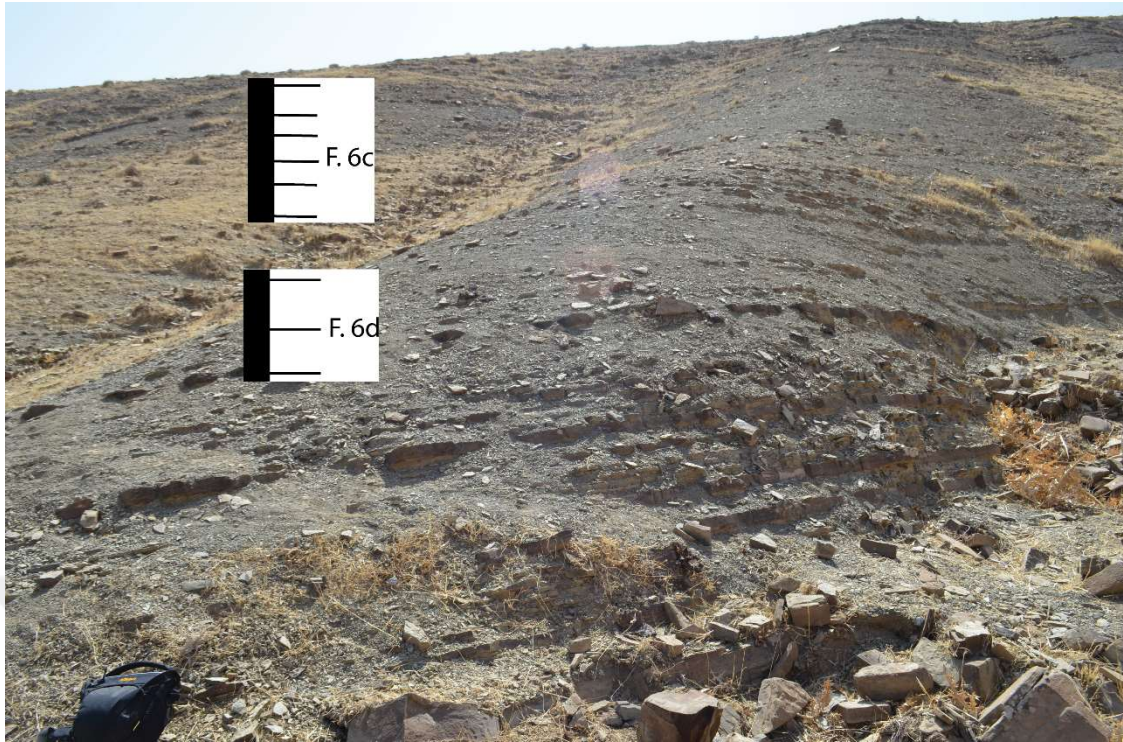
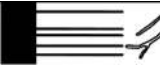


Figure 7.11. Image explains facies 6c shale = 92 % and fine sandstone thin beds =08 %; and facies 6d shale = 96 % and fine sandstone thin beds = 4 %.

7. Thin bedded medium sandstone

This group consists of 3 facies types of interbedded medium grained sandstone and mudstone, divided according to the ratio of sandstone to mudstone.

No.	Facies types	Facies	Description
46	F.7a		About 80% mudstone and thin bedded of medium sandstone 20%, with trace fossils
47	F.7b		Shale = 90% and medium sandstone thin beds =10%, with plant materials
48	F.7c		Shale = 94% and medium sandstone thin beds =06%

7.6. Paleoflow directions

Previously two other researchers studied paleoflow direction of Tanjero Formation, they used many sedimentary structures, channel and incised valleys for indicating the direction and their studies have been done in different places of northern Iraq as in the following paragraphs.

Al-Rawi (1981) studied palaeoflow direction of Tanjero Formation in different places, he used flute casts, groove casts, ripple marks and cross bedding. He found that N45W in Rawandoz area, N45W and N85W in Dokan area and N45W in Sulaimaniyah area. And he concluded that the source area is from the east and the main direction of transport is northwest –west.

Karim (2004) indicated palaeoflow direction by ripple marks, elongate fossils, cross bedding, oriented plant fragments, imbricate pebbles and the direction of channel and incised valleys and proved that the direction is toward south and southwest, and his studied area includes Sulaimaniyah area Azmar-bchkola valley, Darbandikhan and Chwarta area.

In the studied area many sedimentary structures in both types of unidirectional and bidirectional have been used to indicate the direction of palaeoflow of Tanjero Formation for this study:

Unidirectional sedimentary structures:

Unidirectional palaeoflow, measured by three types of sedimentary structures those are ripple marks, cross bedding and flute casts, indicated southeastern and southwestern and mostly toward S45E and all data are plotted on rose diagram as shown in (Figure 7.12).

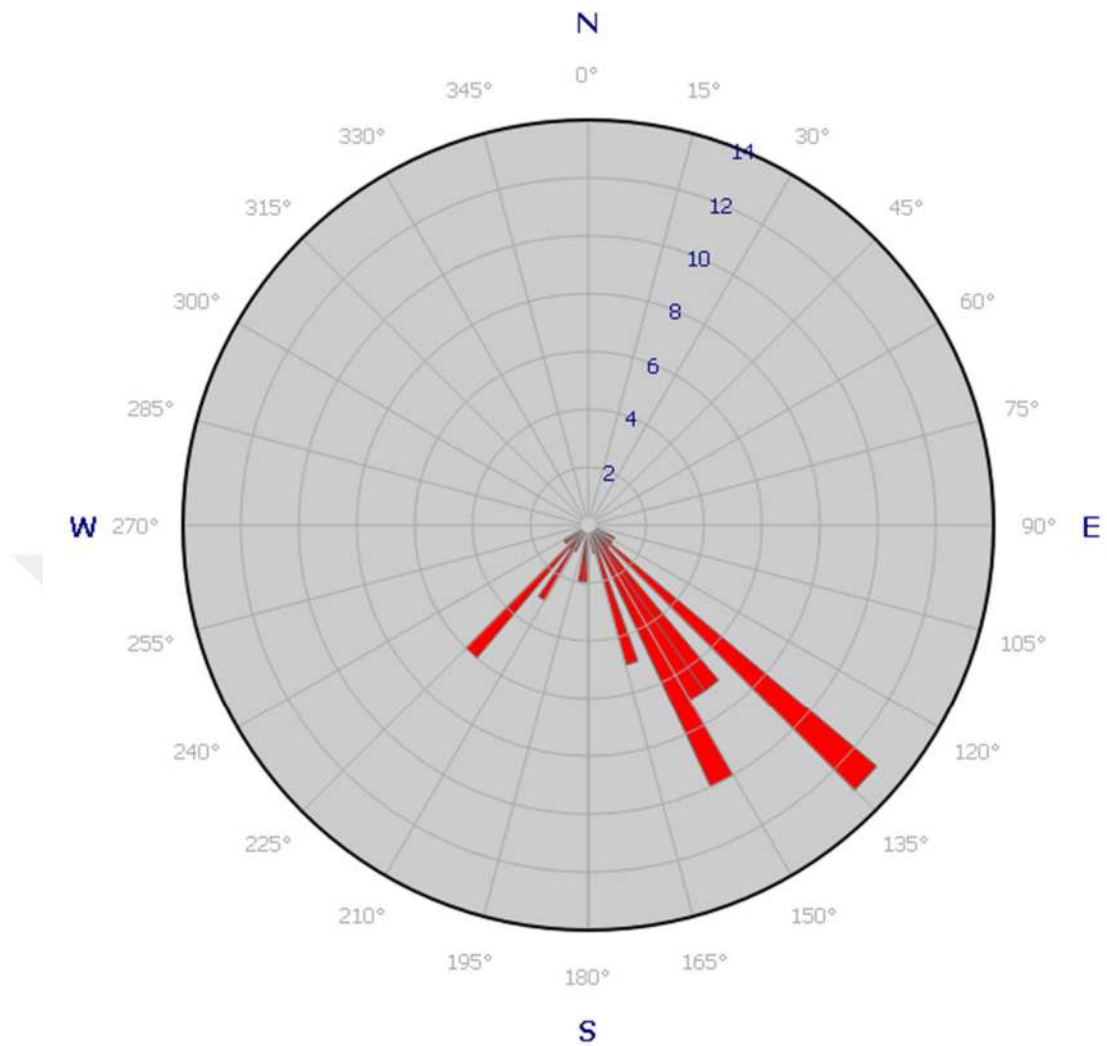


Figure 7.12. Rose diagram showing unidirectional paleoflow of Tanjero Formation in Hanarani-Khwaroo northeastern of Iraq, main direction is toward south east.

Bidirectional sedimentary structures:

Many sedimentary structures, observed in the studied area, could use for indicating bidirectional extent of the current like oriented plant materials, parting lineation and groove casts. After plotting them on rose diagram as appeared in (Figure 7.13) we found the main direction is in N40W-S40E.

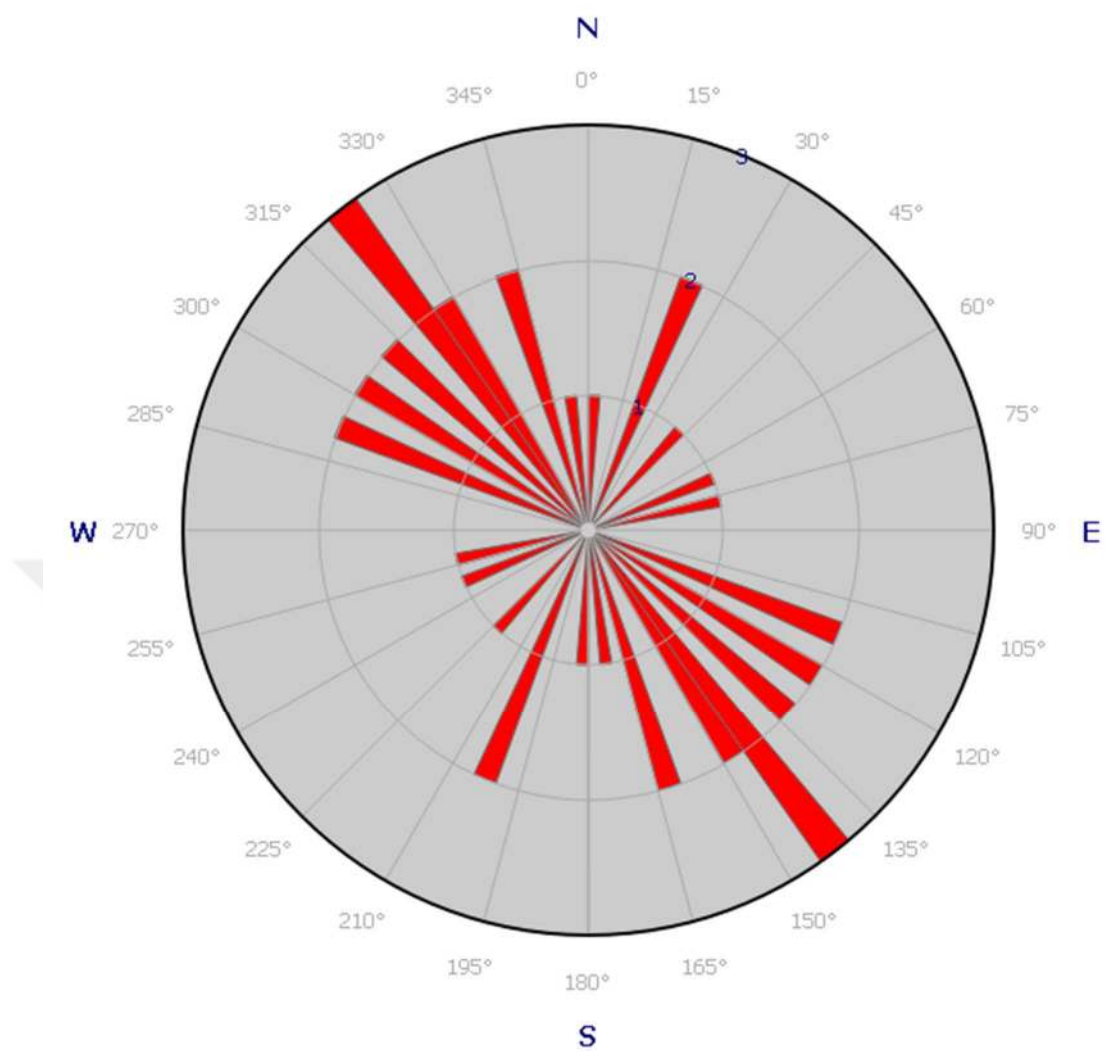


Figure 7.13. Rose Diagram showing Bidirectional palaeoflow of Tanjero Formation in Hanarani-Khwaroo northeastern of Iraq, main direction is northwest – northeast.

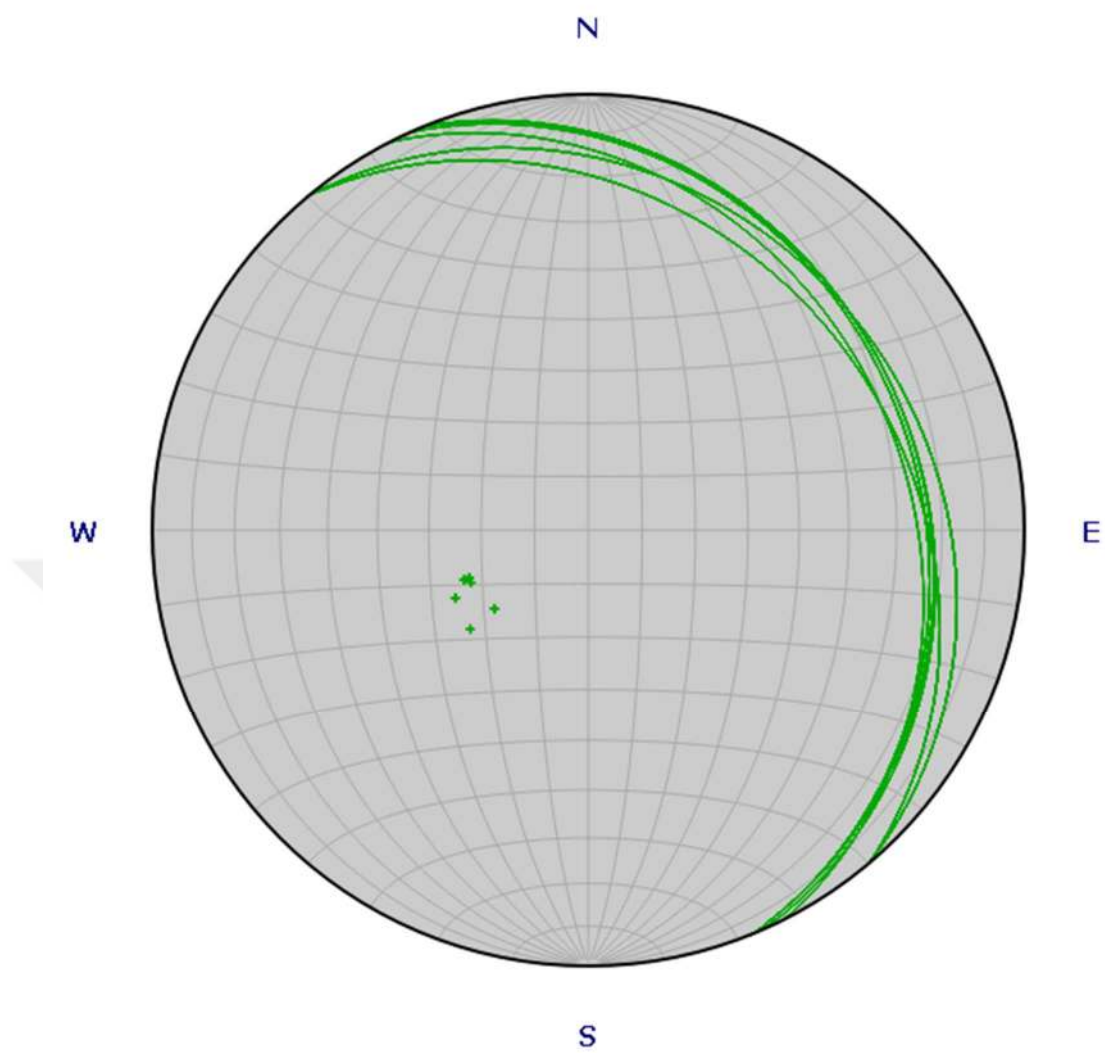


Figure 7.14. Bedding planes of sandstone beds in the studied area plotted on stereonet by using GeoRose software.

7.7. Depositional Environment

There are many studies about the depositional environment submarine fan of Tanjero Formation has done by previous workers, but there is no study about lobe hierarchy, now at first it was described briefly about earlier works and then made a point about lobe hierarchy and submarine fan according to analyzing the facies associations in the studied area.

Sedimentologic and petrographic features of Tanjero Formation is corresponding with flysch deposits (Dzulinski and Walton, 1965) this has also been mentioned by Van Bellen (1959); Al-Rawi (1981) and Saadaallah and Hassan (1987). The Tanjero basin is commonly can consider as elongated sub-marine fan not sub marine trench, (Nilsen, 1985) after (Jaza, 1992).

Jaza (1992) concluded that the Tanjero trough is more similar to an elongated submarine fan with NW-SE axis. The proximal part of the turbidite (inner fan-mid fan) of this elongate sub-marine fan is placed in Sulaimaniyah area and the distal part (outer fan and basin plain) elongated through northwest toward Dokan.

Based on the position of Tanjero and Shiranish formations the environment of Tanjero Formation in the general basin of Upper Cretaceous, according to the sedimentary structures facies analysis, and sequence stratigraphy, depositional environment of Tanjero Formation is shallower than Shiranish Formation (Karim, 2004).

Karim (2006b) found that the upper and lower part of Tanjero Formation is deposited in shallow marine and the middle part is deposited in deep basinal environment.

As for the lobe hierarchy concept it can be given the following very valuable works in briefly:

According to Prelat et al. (2009), Pr  lat and Hodgson (2013), four facies associations recognized based on the combination of three factors: the predominant facies, sandstone bed thickness and proportion of mudstone facies The four facies associations are comparable to four subsets of lobe deposits in deep-water fan system: lobe axis, lobe off-axis, lobe fringe and lobe distal fringe (Figure 7.15a) after (So et al., 2013).

When lobe fringe supported by a high proportion of mudstone, thin-bedded sandstone, alternation of silty fine-grained sandstone and mudstone beds, sheet-like geometry, and good lateral continuity, and lobe distal fringe deposits identified by lateral extensive thin-bedded and fine-grained (siltstone to mudstone) packages within lobe successions (Pr  lat and Hodgson, 2013).

Stow and Piper, 1984; Chakraborty and Pal, 2001; Meyer and Ross, 2007 stated that sheet-like geometry of fine-grained turbidite is interpreted to characterize deposits from the distal margin of lobe or basin plain in low-energy settings (Saito and Ito, 2002). This interpretation is supported by flat base, sheet-like geometry, lateral continuity, high proportion of mudstones and fine-grained turbidite. The thick mudstones are similar to hemipelagic deposits formed by slow suspension settling after (So et al., 2013).

Depending on the facies described in facies section, in the studied area we have massive or normally graded sandstone facies, normally graded very fine-grained sandstone facies and shale. And the ratio of sandstone ranges from 13% to 24% as comparison to mudstone and the average net to gross is 18.14 to 81.86 for the all sections (Table 7.1).

The facies types examined in this study indicate lobe fringe and lobe distal fringe according to Prelat et al. (2009), Pr  lat and Hodgson (2013), So et al. (2013) in the (Figure 7.15).

Table 7.1. Sandstone shale ratio in the studied area.

Log No.	Sandstone Ratio %	Shale Ratio %
Log 1	24	76
Log 2	18	82
Log 3	21	79
Log 4	18	82
Log 5	14	86
Log 6	13	87
Log 7	19	81
Avarage	18,14	81,86

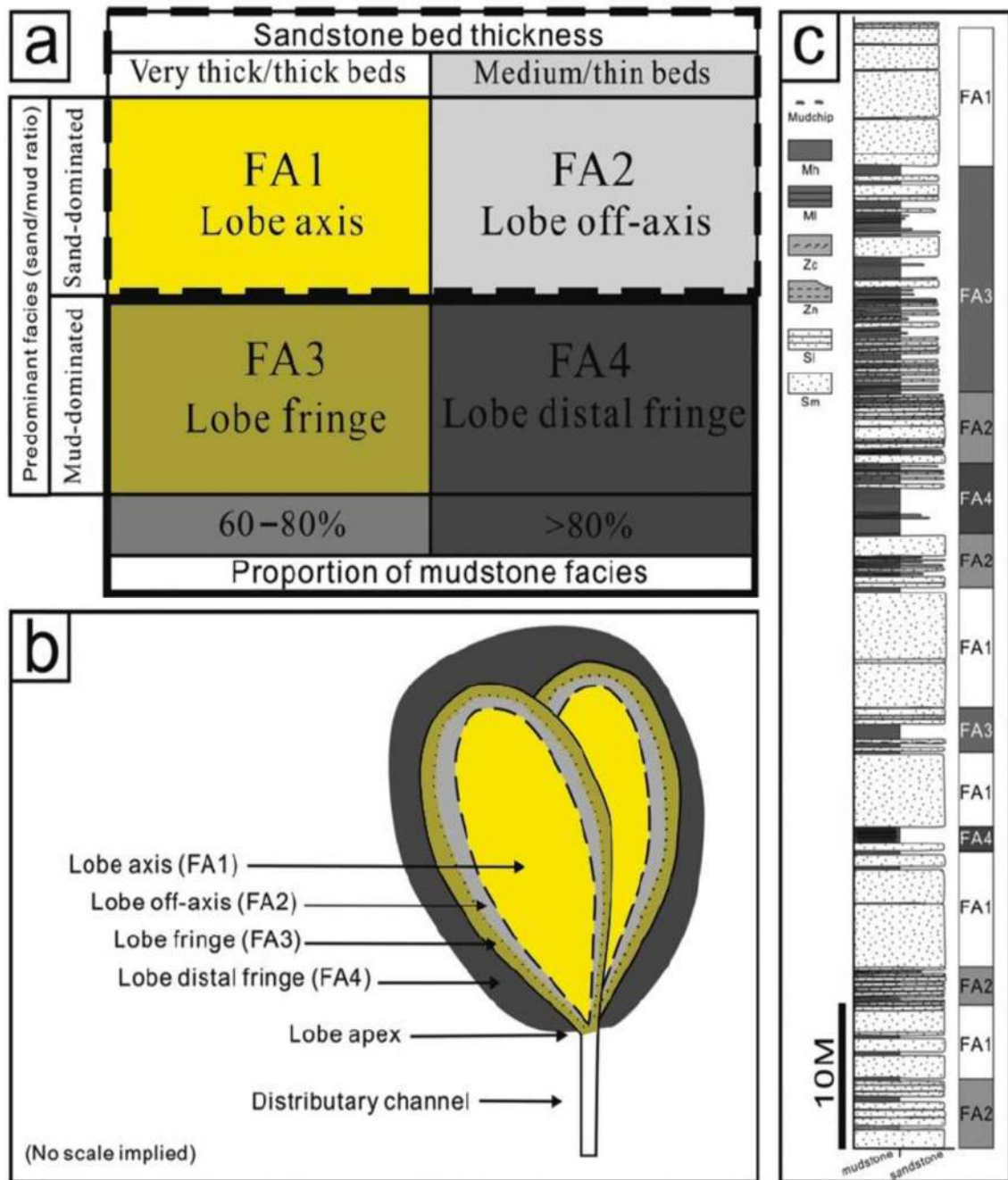


Figure 7.15. (a) Facies associations are classified on the basis of predominant lithology (sand or mud), sandstone bed thickness (very thick/thick beds or medium/thin beds: dashed line box) and proportion of mudstone facies (60–80% or >80%: bold line box). FA: facies association. (b) Schematic model for the facies associations of the Taean Formation. Individual facies associations represent different components of distributive lobe deposits (after Prelat et al., 2009). (c) The application of the facies associations using a sedimentary log in the Gomseom section. Sm: massive sandstone, Sl: laminated sandstone, Zn: normally graded, silty fine-grained sandstone, Zc: silty fine-grained sandstone and siltstone with climbing ripple, Ml: laminated mudstone, Mh: homogeneous mudstone (So et al., 2013).

Seven basic facies, namely A, B, C, D, E, F, and G, were proposed (Figure 7.16) (Mutti and Ricci Lucchi, 1978) these letters should not be confused with divisions of the Bouma sequence (Shanmugam and Moiola, 1988).

In general, a channelized sequence (inner and middle fan) with its thinning-upward cycles is composed of facies A and B, whereas a non-channelized sequence (outer fan) with its thickening-upward lobe cycles is represented by facies C and D. Although facies F and G occur in all environments, facies F is characteristic of any slope (including levee) and facies G is common in the basin plain, interchannel, and slope environments (Shanmugam and Moiola, 1988).

According to the above classification of facies and submarine fan in the studied area facieses are mostly include facies C and D and we can indicate the submarine fan model of Tanjero Formation in the studied area as outer fan.

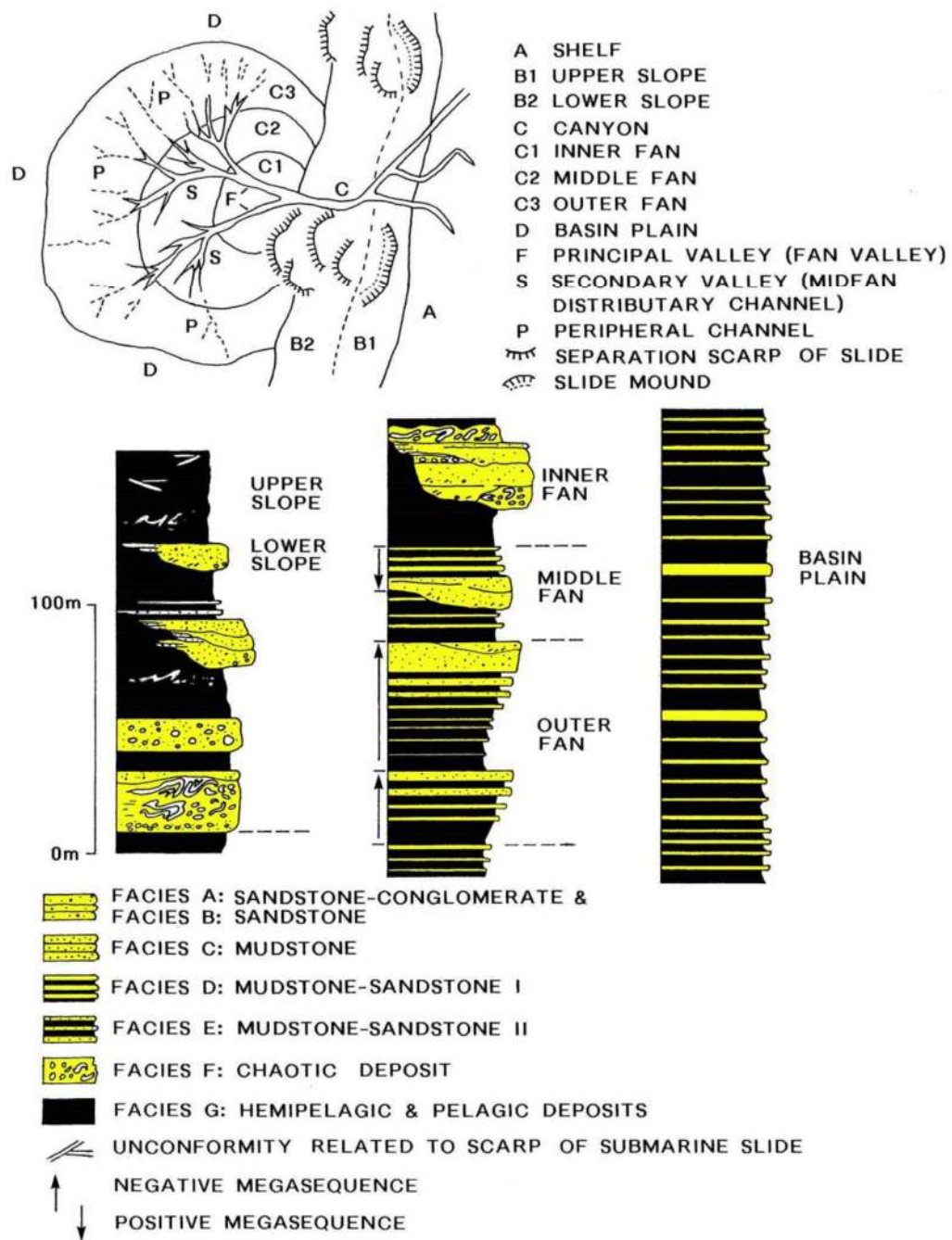


Figure 7.16. General fan model for ancient submarine fans; drawn after Mutti and Ricci Lucchi (1972), (Mattern, 2002)

8. RESERVOIR CHARACTERIZATION

8.1. Reservoir Parameters

To estimate reservoir characterization of the hydrocarbon we must explain porosity and permeability and other parameters and their relation with reservoir development.

1. Porosity
2. Permeability
3. Composition and texture of the studied sandstone based on petrographic investigations
4. Authigenic minerals
5. Diagenetic stages of the Tanjero sandstones (Al-Laboun et al., 2014)

In this study the first three items were analyzed for this section of the thesis.

8.2. Porosity

Porosity is the ratio of the pore volume to the bulk volume of material (Lucia, 1999).

Porosity of the studied sandstone (measured by BLP-530 Gas Porosimeter), as shown in the (Table 8.2), ranges from 5.51% to 9.98% (with an average value of 7.11%). Effective porosity was observed in the studied samples. According to North (1985) the porosity of the Tanjero Formation sandstone in the studied area is considered as poor (Table 8.1). Densely cemented and tightly packed samples are identified as low in porosity, but loosely packed and poorly cemented samples are identified as high in porosity (Al-Laboun et al., 2014).

Table 8.1. Range of porosity values (North, 1985)

Porosity %	Qualitative evaluation
0-5	Negligible
5-10	Poor
10-15	Fair
15-20	Good
20-25	Very good

Table 8.2. Porosity (%) and Permeability (millidarcy: md), Bulk volume (cm³) and Grain volume (cm³) for 45 samples of Tanjero Formation (sandstone) in Hanarani-Khwaroo.

No.	Sample Labels	Core Length (cm)	Core Diameter (cm)	P1 (PSI)	P2 (PSI)	Bulk Volume (cm ³)	V1	V2	Grain Volume (cm ³)	V3	Effective Porosity %	Permeability
1	HL1-1	4.44	3.79	179.90	92.40	50.09	58.64	161.18	47.01	114.170303	6.15	501.13
2	HL1-2	4.49	3.79	180.1	92.50	50.65	58.64	161.18	47.01	114.1736649	7.20	
3	HL1-4	4.53	3.79	180.2	93.4	51.11	58.64	161.18	48.04	113.1362741	5.99	950.53
4	HL1-6	4.35	3.79	179.8	91.5	49.07	58.64	161.18	45.95	115.2292022	6.37	
5	HL1-7	4.38	3.79	180.3	92.1	49.41	58.64	161.18	46.38	114.796873	6.13	550.95
6	HL1-8	4.67	3.79	179.9	94.7	52.68	58.64	161.18	49.78	111.3974234	5.51	2315.65
7	HL1-9	4.41	3.79	180	91.9	49.75	58.64	161.18	46.32	114.8552775	6.89	
8	HL1-16	4.34	3.79	180	91.6	48.96	58.64	161.18	45.97	115.231441	6.11	10.71
9	HL2-1	4.42	3.79	180.1	92.3	49.86	58.64	161.18	46.76	114.4210618	6.23	582.83
10	HL2-3	4.04	3.79	179.9	88.1	45.58	58.64	161.18	41.44	119.7427469	9.08	
11	HL2-4	4.52	3.79	180.1	92.5	50.99	58.64	161.18	47.01	114.1736649	7.82	
12	HL2-7	4.43	3.79	180.2	92.3	49.98	58.64	161.18	46.70	114.4845937	6.57	
13	HL2-10	3.99	3.79	180	88.1	45.01	58.64	161.18	41.37	119.8093076	8.09	
14	HL2-13	3.87	3.79	180.2	86.7	43.66	58.64	161.18	39.30	121.8792157	9.98	
15	HL3-2	4.46	3.79	179.8	92	50.32	58.64	161.18	46.58	114.6029565	7.43	
16	HL3-4	4.39	3.79	180	91.9	49.53	58.64	161.18	46.32	114.8552775	6.46	
17	HL3-5	4.53	3.79	180.2	93.4	51.11	58.64	161.18	48.04	113.1362741	5.99	1247.09
18	HL3-6	4.62	3.79	179.8	93.9	52.12	58.64	161.18	48.90	112.2840469	6.19	394.99
19	HL3-9	4.38	3.79	179.9	91.6	49.41	58.64	161.18	46.01	115.1674236	6.88	
20	HL3-11	4.58	3.79	180.1	93.8	51.67	58.64	161.18	48.59	112.5913006	5.96	
21	HL4-2	4.5	3.79	180.1	92.9	50.77	58.64	161.18	47.50	113.6820667	6.44	
22	HL4-3	4.75	3.79	165.4	87.7	53.59	58.64	161.18	50.59	110.593569	5.60	2057.04

Table 8.2. continued-

No.	Sample Labels	Core Length (cm)	Core Diameter (cm)	P1 (PSI)	P2 (PSI)	Bulk Volume (cm3)	V1	V2	Grain Volume (cm3)	V3	Effective Porosity %	Permeability
23	HL4-4	4.16	3.79	179.9	89.8	46.93	58.64	161.18	43.70	117.475902	6.88	
24	HL4-5	4	3.79	179.7	87.8	45.13	58.64	161.18	41.16	120.0183144	8.79	
25	HL4-6	4.63	3.79	181.8	92.7	52.23	58.64	161.18	46.18	115.0027184	11.59	
26	HL4-7	3.93	3.79	181.8	88.5	44.34	58.64	161.18	40.72	120.4604746	8.16	
27	HL4-8	4.5	3.79	181.5	93.8	50.77	58.64	161.18	47.71	113.4665245	6.01	883.17
28	HL5-1	4.37	3.79	181.6	92.3	49.30	58.64	161.18	45.81	115.3740412	7.09	
29	HL5-2	4.45	3.79	181.5	93.2	50.20	58.64	161.18	46.98	114.1969957	6.41	
30	HL5-3	3.63	3.79	181.5	85.7	40.95	58.64	161.18	36.99	124.1908985	9.68	
31	HL5-4	4.55	3.79	181.5	93.9	51.33	58.64	161.18	47.83	113.3456869	6.81	
32	HL5-5	3.88	3.79	181.1	87.7	43.77	58.64	161.18	40.09	121.0912657	8.42	
33	HL6-2	4.23	3.79	181.4	90.6	47.72	58.64	161.18	43.77	117.4094481	8.28	
34	HL6-3	4.62	3.79	181.2	94.7	52.12	58.64	161.18	48.98	112.2024076	6.03	838.4
35	HL6-4	4.39	3.79	181.2	92.2	49.53	58.64	161.18	45.94	115.2447722	7.25	
36	HL6-5	4.68	3.79	181.3	95.2	52.80	58.64	161.18	49.51	111.6747059	6.24	
37	HL6-6	4.33	3.79	180.8	91.6	48.85	58.64	161.18	45.44	115.7435808	6.99	
38	HL6-7	4.71	3.79	181	95.3	53.14	58.64	161.18	49.81	111.3729276	6.26	174.43
39	HL6-8	4.38	3.79	181.3	92.3	49.41	58.64	161.18	46.00	115.1834453	6.91	
40	HL7-1	3.93	3.79	181.3	87.9	44.34	58.64	161.18	40.23	120.9491695	9.26	
41	HL7-2	4.24	3.79	181.2	90.9	47.83	58.64	161.18	44.29	116.8929373	7.41	
42	HL7-3	4.42	3.79	180.9	92.5	49.86	58.64	161.18	46.50	114.6808216	6.75	
43	HL7-4	4.54	3.79	181.1	93.6	51.22	58.64	161.18	47.72	113.4583761	6.83	
44	HL7-5	4.42	3.79	181.2	92.7	49.86	58.64	161.18	46.56	114.6231715	6.63	
45	HL7-7	4.6	3.79	180.8	94.3	51.90	58.64	161.18	48.75	112.4296076	6.06	755.62
	Average										7.11	866.3492

According to permeability-porosity-grain size and sorting table in the (Figure 8.1) (Beard and Weyl, 1973) for very fine to medium grain size, very poorly to moderately sorting (Table 8.4) of the sandstones of Tanjero Formation presumably can be said that the sandstones had an initial porosity of about 30 % on average using the table (ranging from 25% to 35%, pale brownish transparent area in the Figure 8.1).

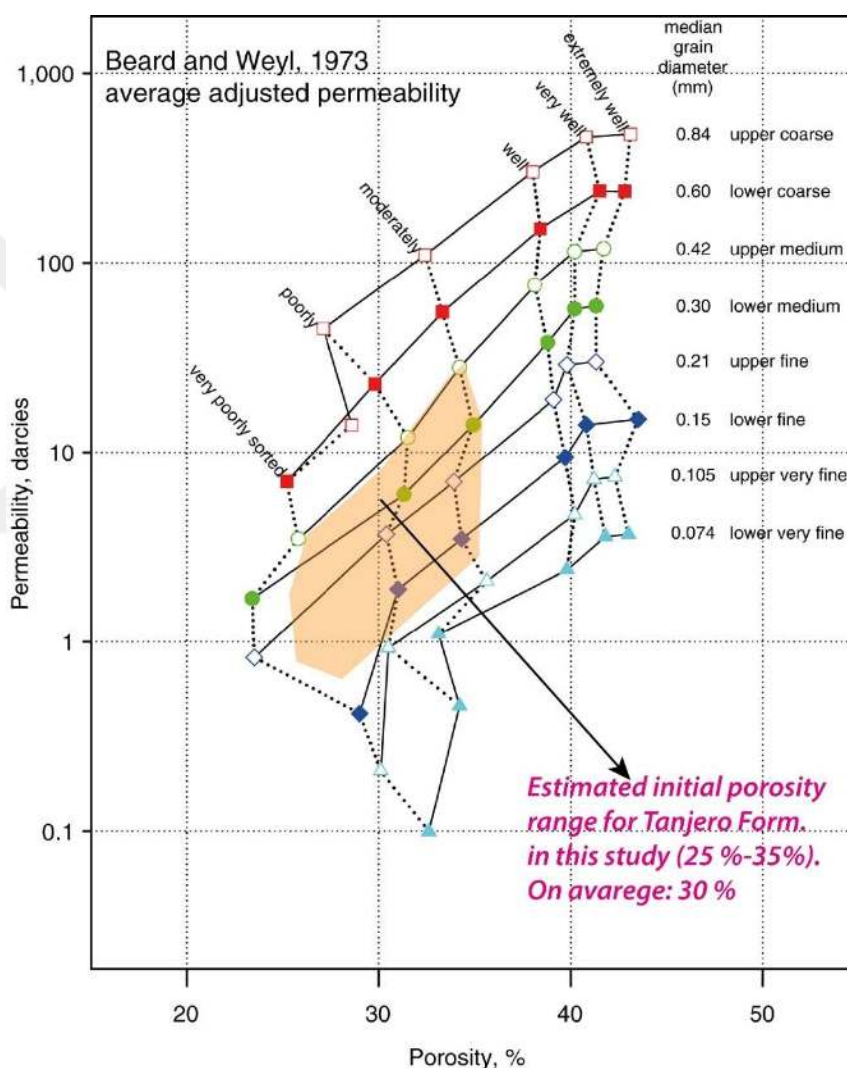


Figure 8.1. Permeability/porosity data from unconsolidated artificial sand packs by Beard and Weyl (1973). Symbols linked with solid lines denote size ranges; dotted lines distinguish sorting classes. Pale brownish area shown by the arrow represents the grain size-sorting and porosity ranges for the sandstone of Tanjero Formation for this study.

Since quartz rate is very low 0.37 on average (Table 8.4) there is no quartz overgrowth or quartz cementation to lose porosity of the sandstone in this study. High volume of dissolution of carbonate rock clasts is offset by precipitation of calcite in primary pores.

Sorting, packing and compaction are the other reasons reducing the initial porosity. Very poorly to moderate sorting, tightly packing and moderate compaction and the ratio of the bitumen fillings ranging from 1% to 15% calculated while point counting during petrographic examine on the thin sections, are blocking the pores. For these reasons experimental examines indicate poor, with an average value of 7.11%, porosity type (Table 8.1) for the sandstones.

As the range of the solid bitumen fillings glutting the pores is between 1 % and 15 % indicates that before the fillings the sandstones had a “good to very good” porosity (Table 8.1) value of $(7.11\% + 15\%) 22.11\%$ for many of the sandstone sample before the bitumen fillings (for example, look at Plate 8.10, Plate 8.11 and Plate 8.12 for amount of the bitumen fillings).

8.3. Permeability

Permeability is the ability of a medium to conduct fluids without changing its structure or parts displacement. Permeability of a rock depends on its effective porosity, which can be significantly affected by grain size, grain shape, sorting level, grain packing, and diagenetic processes.

The studied sandstones of Tanjero Formation reflect a wide range of permeability values, ranging from 10.71 to 2315.65 millidarcy, with an average value of 866.35 millidarcy (Table 8.3). These values can be qualitatively described as very good according to North (1985) after (Al-Laboun et al., 2014).

Table 8.3. Range of Permeability values (North, 1985)

Type of Permeability	Range of Permeability
Poor to fair	<1.0-15 md
Moderate	15-50 md
Good	50-250 md
Very good	250-1000 md
Excellent	>1000 md

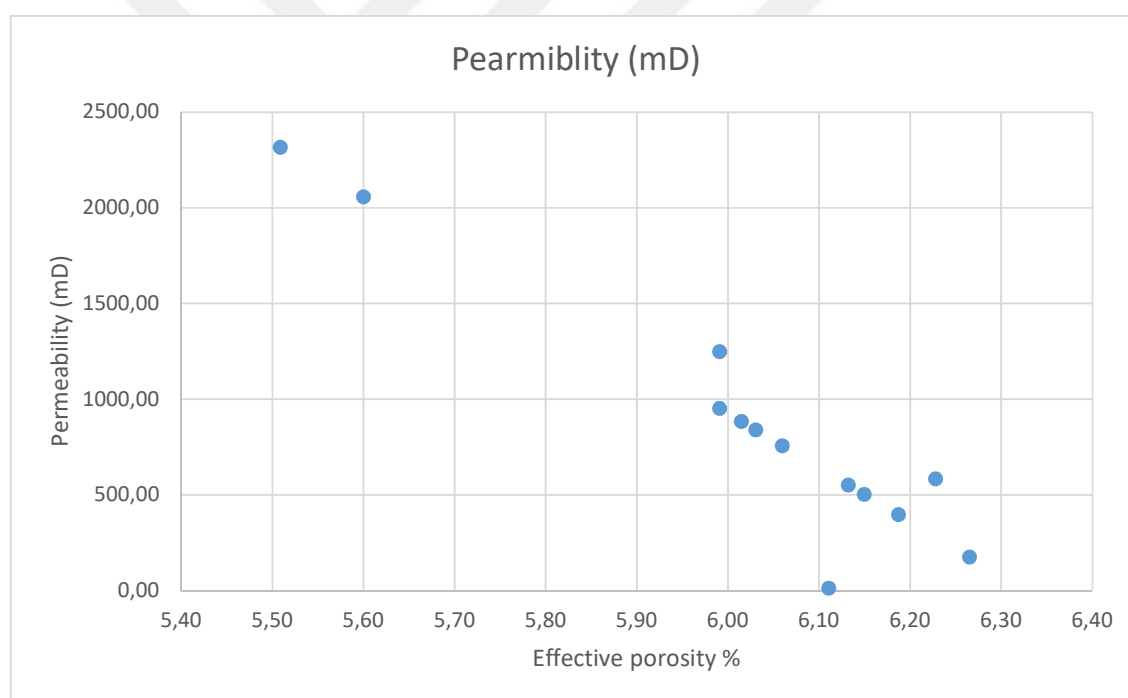


Figure 8.2. Figure showing relationship between permeability and effective porosity of Tanjero Formation sandstone in Hanarani-Khwaroo.

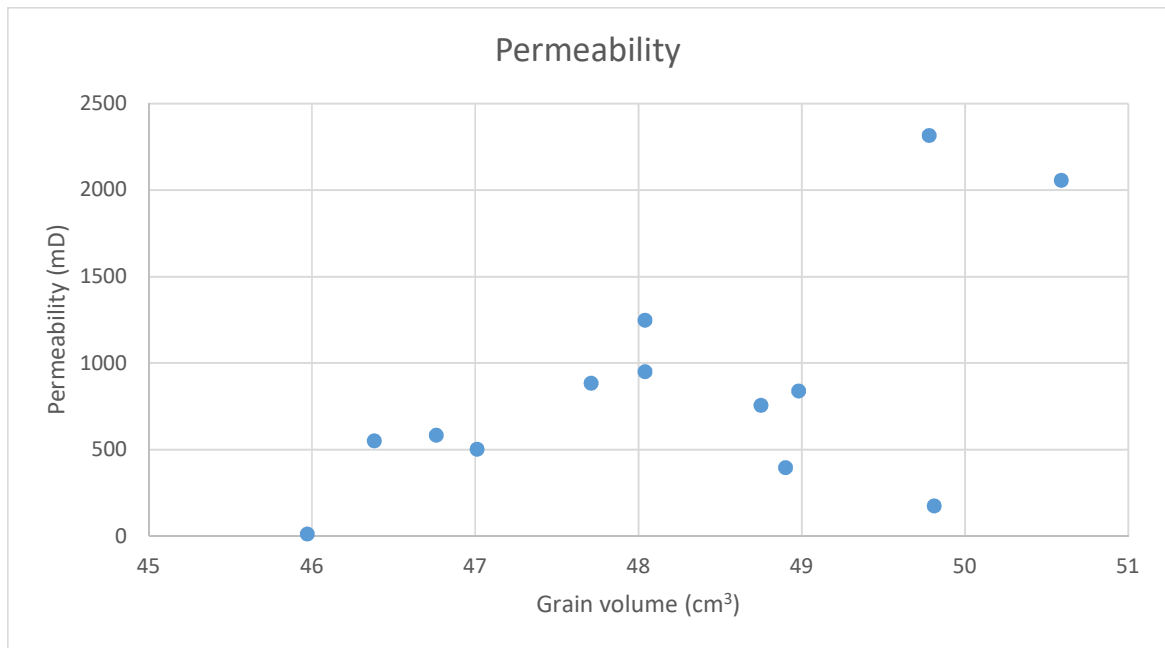


Figure 8.3. Figure showing relationship between permeability and grain volume of Tanjero Formation sandstone in Hanarani-Khwaroo.

8.4. Petrography

A detailed table was used for petrographic analysis which includes compositional ratios of Q, F and Rf (rock fragments), cement type, alteration/dissolution, fossils content, sedimentary structures, sorting, roundness, modal classification for Folk (1966) ternary diagrams, the number of photo taken in each thin section and rock name depended on grain size (Table 8.4).

Compositional analysis (Table 8.4) and classical point counting method were used to apply the quartz (Q), feldspars (F) and rock fragments (R) ternary diagram. For each thin section 500 points were counted. According to the analysis, the low density turbidites sandstones studied are classified as calcilithite according to Folk (1966) ternary diagrams (Figure 8.4).

The turbidite sandstone of Tanjero Formation in the studied area are very fine to medium grain sandstone (Table 8.4). Sandstone framework consist of subangular to subrounded rock fragments, very angular lithic cherts and quartz (Plate 8.1, Plate 8.2, Plate 8.4, Plate 8.6, Plate 8.10) with sutured, concavo convex, long grain and little tangential grain contact types (Plate 8.7, Plate 8.8, Plate 8.10).

These contact types reflecting the diagenetic events are implying that compaction degree is moderate. The effects of compaction are also manifested in the grain deformation. In the turbidite sandstone studied grains are not deformed, only exhibited evidences of fragile deformation in a few cases, mainly in the grains vertices or within internal grain cracks filled by mainly calcite and solid bitumen (Plate 8.11 and Plate 8.12).

Grain contact types and contact index (average number of contacts per grain) supply to us as scientists the packing character of the sandstone studied. The contact index of the sandstone is 4.7. The contact types of the sandstone in this study point out moderate to tightly packing.

Poorly sorting (Table 8.4) and high compaction ratio increases the grain contact index since the small grains fill the voids between the bigger lithic fragments.

The other grain contact type present in the sandstones of the unit is floating type which is seen greywacke calcilithites since the cement ratio is more than 15%, so the grains can stay in the calcite cement without having contact with the other fragments in some parts of the

thin sections (Table 8.4, greywackes, HL2-3, HL4-5, HL4-6 and HL7-3, however no microphotograph in the Plates).

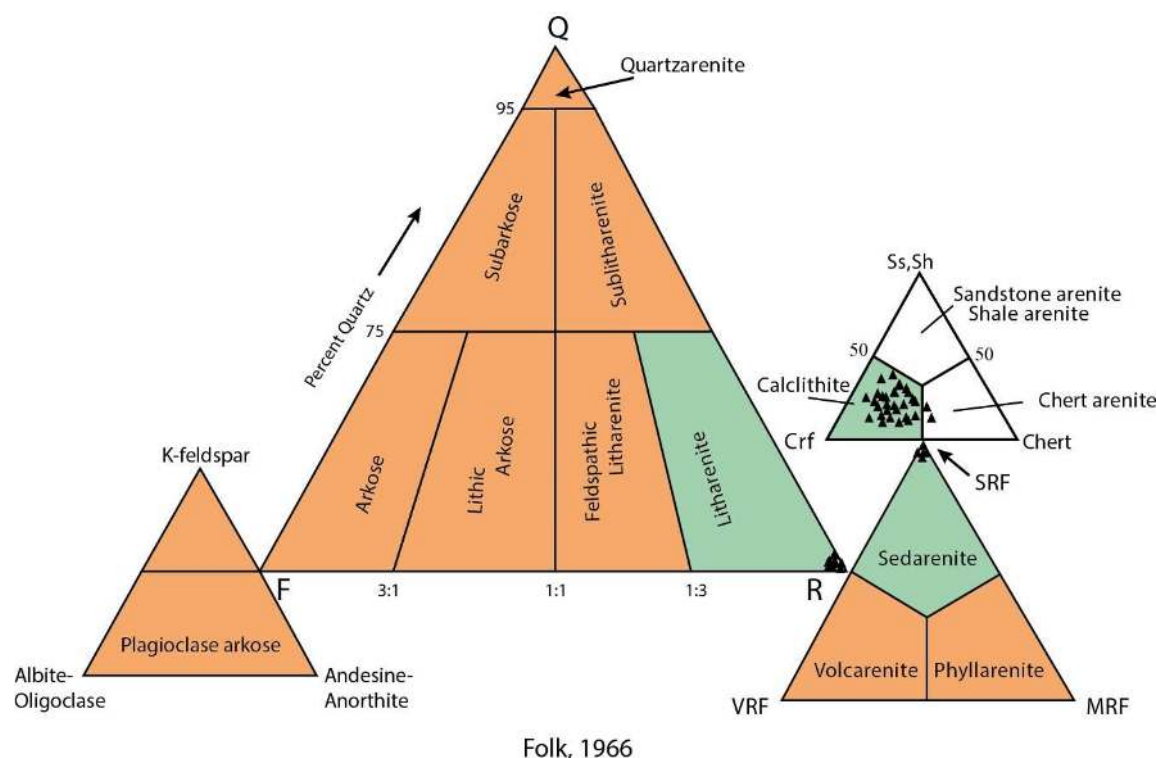


Figure 8.4. Q-F-R ternary diagrams showing the classification of the turbidite sandstone studied. All the samples fall in the calcilithite corner (also see the Table 8.4), (after Folk (1966), redrawn in computer).

Main cement is calcite filling the interstitial pores also replaces the grains, clay and matrix are secondary and in a very low ratio. Solid bitumen fillings are seen in many thin section (in the Table 8.4, Other components column) and it blocks pore spaces and stain the calcite cement to brownish – yellowish in colour (solid bitumen fillings are present in the all Plates except Plate 8.6).

The only quartz type from the source area in the turbidite sandstone studied is monocrystalline, very angular to angular with straight fully extinction common quartz (Plate 8.4, Plate 8.5 and Plate 8.6). The ratio of the quartz is 0.37% in average (Table 8.4) for the unit in this study.

Rare heavy mineral presence is notable with low concentration. Hematite and euhedral to subhedral black opaque minerals (were not differentiated in this study) are the most common. Feldspar ratio is 0.009% for the whole sandstone samples. It was seen with highly alteration in one sample (HL2-3 in Table 8.4) in this study with 0.3 percentages.

Carbonate rock fragments are the main lithoclasts constituent of the turbidite sandstone with 59.32 percentages. Chert without radiolaria has 16.65 percentages and the others are shale, silt, released-reworked radiolaria fossils, benthic fossil shell fragments, radiolarian chert and radiolarian mudstone fragments with a ratio of 24.03% (Table 8.4). No any metamorphic or magmatic rock clasts were seen in the sandstone thin sections in this study.

All the petrographic examines show that the turbidite sandstone of Upper Cretaceous Tanjero Formation, having less than 5 percentage clay, angular to subangular grains, poorly sorting, dominant tangential and point, a few sutured contact types, are submature (Figure 8.5).

Submature stage for the sandstones imply a short distance transportation of the lithic clasts into the deep marine environment of the Upper Cretaceous basin.

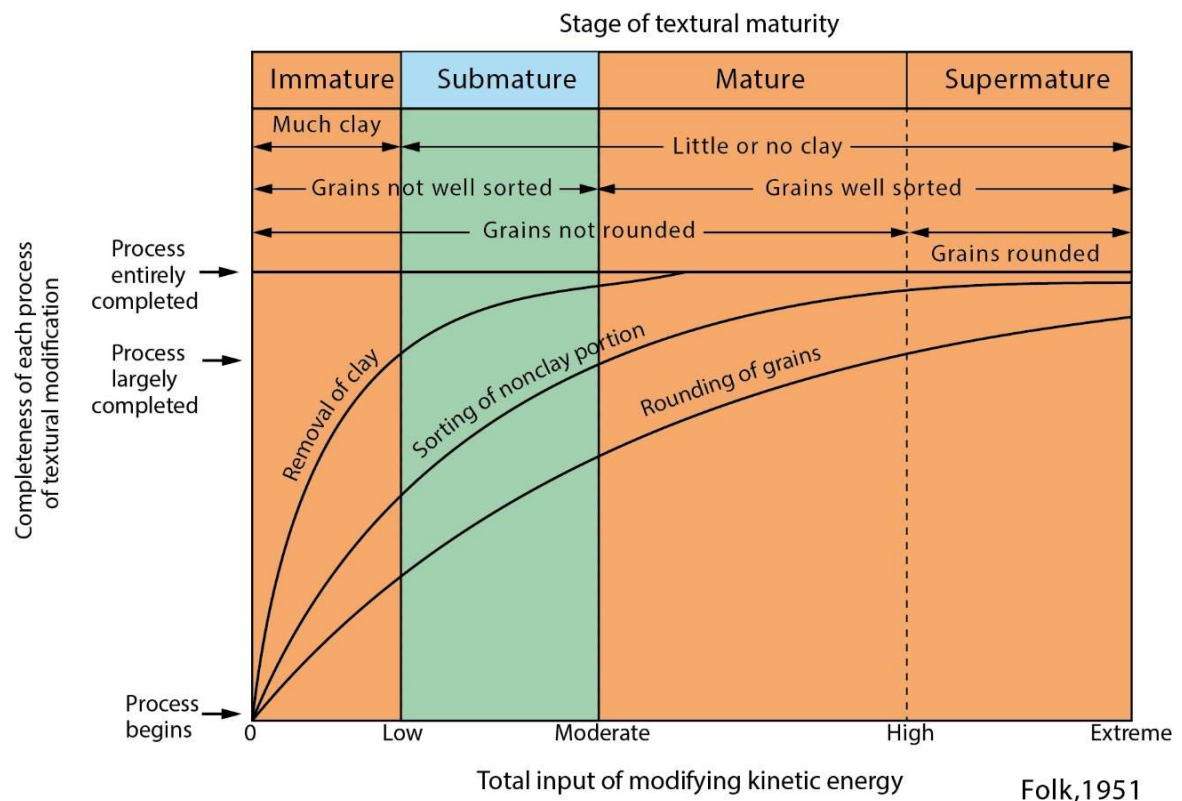


Figure 8.5. Turbidite sandstones of Tanjero Formation in the studied area indicate submature stage in the Folk (1951) textural maturity table. Clay content is less than 5 %; poorly sorted; grains are not rounded.

Table 8.4. Petrographic content of the thin sections (the numbers for Q, F and RF were rounded to the nearest whole numbers)

NO	Thin Section No:	Q%	F%	RF%	Cement	Matrix	Other components	Alteration/ dissolution	Fossils	Sedimentary structures	Sorting	Roundness	Modal Classification	No. of photos	Rock name
1	HL 1-1	1	-	99 (chrt:8,Crbnt:65, Mudstone +released radiolaria:27)	Calcite	-	Bitumen fillings + euhedral to subhedral opaque minerals	Carbonate rock clasts to calcite	Fossil shell fragments+ reworked radiolaria	Slightly pebble orientation	Moderately	Subangular rock clasts, very angular cherts and quartz	Calclithite	6	Very fine grained sandstone
2	HL 1-2	1.6	-	98.4 (chrt:27,Crbnt:55, Mudstone +released radiolaria:18)	Calcite	-	Bitumen fillings + Euhedral to subhedral opaque minerals	Carbonate rock clasts to calcite	Fossil shell fragments+ reworked radiolaria	Slightly pebble orientation	Moderately	Subangular rock fragments, very angular cherts and quartz	Calclithite	6	Very fine grained sandstone
3	HL 1-7	0.4	-	99.6 (chrt:25,Crbnt:60, mudstone with and/ released radiolaria:15)	Calcite	-	Bitumen fillings + euhedral to subhedral opaque minerals+ carbonized plant materials	Carbonate rock clasts to calcite	Fossil shell fragments+ reworked radiolaria	Slightly pebble orientation	Moderately	Subangular-subrounded rock fragments, very angular cherts and quartz	Calclithite	6	Very fine grained sandstone
4	HL1-8	0.5	-	99.5 (chrt:27,Crbnt:53, mudstone with and/ released radiolaria:20)	Calcite	-	Bitumen fillings + Euhedral to subhedral opaque minerals	Carbonate rock clasts to calcite	Fossil shell fragments+ reworked radiolaria	Slightly pebble orientation	Poorly	Subrounded rock fragments, very angular cherts and quartz	Calclithite	4	Very fine grained sandstone
5	HL1-9	0.3	-	99.7 (chrt:19, Crbnt:58, Siltstone, mudstone with and/ released radiolaria and others:23)	Calcite	-	Glauconite+ bitumen fillings + euhedral to subhedral opaque minerals	Carbonate rock fragments to calcite	Rare benthic shell fragments+ plenty of reworked radiolaria	-	Very poorly	Subangular rock fragments, very angular cherts and quartz	Calclithite	14	Pebbly fine grained sandstone

Table 8.4. Continues

NO	Thin Section No:	Q%	F%	RF%	Cement	Matrix	Other components	Alteration/ dissolution	Fossils	Sedimentary structures	Sorting	Roundness	Modal Classification	No. of photos	Rock name
6	HL1-14	1	-	99 (chrt:10, Crbnt:50, Siltstone, mudstone with and/ released radiolaria and others:40)	Calcite	-	Bitumen fillings + carbonized plant materials	Carbonate rock fragments to calcite	Reworked radiolaria	-	Poorly	Subangular-subrounded rock fragments, very angular cherts	Calclithite	10	Pebbly fine grained sandstone
7	HL 2-3	1	0.3	98.7 (chrt:10,Crbnt:55, Mudstone with and / released radiolaria and others:35)	Calcite	-	Bitumen fillings + euhedral to subhedral opaque minerals	Feldspar to clay+ Carbonate rock fragments to calcite	Rare benthic shell fragments+ reworked radiolaria	Wavy deformed secondary calcite in fractures	Moderately	Subrounded rock fragments, very angular cherts and quartz	Calclithite greywacke	8	Pebbly fine grain sandstone
8	HL 2-4	0.3	-	99.7 (chrt:33, Crbnt:46, Siltstone, mudstone with and/ released radiolaria and others:21)	Calcite	-	Glauconite+ Bitumen fillings + euhedral to subhedral opaque minerals	Carbonate rock fragments to calcite	Globigerina +benthic shell fragments+ reworked radiolaria	Grain orientation throughout the section	Very poorly	Subangular rock fragments, very angular cherts and quartz	Calclithite	20	Medium grained sandstone
9	HL 2-7	-	-	100 (chrt:10,Crbnt:60, Siltstone, mudstone with and/ released radiolaria and others:30)	Calcite	-	Opaque angular heavy minerals 2%+ glauconite (0.2 %) +Plant materials and pellets (0.3%)	Carbonate rock fragments to calcite	Reworked radiolaria	-	Poorly	Subangular-subrounded rock fragments, very angular cherts	Calclithite	2	Very fine grained sandstone
10	HL2-10	-	-	100 (chrt:10,Crbnt:65, Siltstone, mudstone with and/ released radiolaria and others:25)	Calcite	-	Bitumen fillings	?	Rare benthic shell fragments+ reworked radiolaria	-	Poorly	Subangular-subrounded rock fragments, very angular cherts	Calclithite	6	Very fine grained sandstone

Table 8.4. Continues

NO	Thin Section No:	Q%	F%	RF%	Cement	Matrix	Other components	Alteration/ dissolution	Fossils	Sedimentary structures	Sorting	Roundness	Modal Classification	No. of photos	Rock name
11	HL2-13	0.5	-	99.5 (chrt:17,Crbnt:37, Siltstone, mudstone with and/ released radiolaria and others:46)	Calcite	+	Opaque angular heavy minerals 1%+ bitumen fillings	Carbonate rock fragments to calcite	Reworked radiolaria	-	Poorly		Calclithite	6	Fine grained sandstone
12	HL 3-2	-	-	100 (chrt:30 ,Crbnt:50, Siltstone, mudstone with and/ released radiolaria and others:20)	Calcite	-	Very well rounded glauconite + carbonized plant materials+ bitumen fillings	Carbonate rock fragments to calcite	Reworked radiolaria and fossil shell fragments	Compaction and contact types	Poorly	Subangular-subrounded rock fragments, very angular cherts	Calclithite	24	Pebbly fine grained sandstone
13	HL 3-4	-	-	100 (chrt:26 ,Crbnt:54, Siltstone, mudstone with and/ released radiolaria and others:20)	Calcite	-	Very well rounded glauconite + carbonized plant materials+ bitumen fillings	Carbonate rock fragments to calcite	Reworked radiolaria and fossil shell fragments	Compaction and contact types	Poorly	Subangular-subrounded rock fragments, very angular cherts	Calclithite	-	Pebbly fine grained sandstone
14	HL 3-6	-	-	100 (chrt:5,Crbnt:80, Mudstone with radiolaria+ released radiolaria:15)	Calcite	-	Bitumen fillings	Carbonate rock fragments to calcite	Reworked radiolaria + globigerina	grain orientation makes lineation in the section	Moderately	Subangular-subrounded rock fragments, angular cherts	Calclithite	2	Very fine grained sandstone
15	HL3-11	0.5	-	99.5 (chrt:5 ,Crbnt:75, Siltstone, mudstone with and/ released radiolaria and coal fragments:20)	Calcite	-	Opaque euhedral heavy minerals 1%+ glauconite+ bitumen fillings+ carbonized plant materials	Carbonate rock fragments to calcite	Fossil shell fragments+ reworked radiolaria	-	Poorly	Subangular-subrounded rock fragments and quartz very angular cherts	Calclithite	37	Fine grained sandstone

Table 8.4. Continues

NO	Thin Section No:	Q%	F%	RF%	Cement	Matrix	Other components	Alteration/ dissolution	Fossils	Sedimentary structures	Sorting	Roundness	Modal Classification	No. of photos	Rock name
16	HL 4-1	1	-	99 (chrt:11 ,Crbnt:62, Siltstone, mudstone with and/ released radiolaria and others:27)	Calcite	-	Opaque euhedral heavy minerals 1.5%+ glauconite+ bitumen fillings+ carbonized plant materials	Carbonate rock fragments to calcite	Fossil shell fragments+ reworked radiolaria	grain orientation makes lineation in the section	Poorly	Subangular-subrounded rock fragments, very angular cherts and quartz	Calclithite	6	Very fine grained sandstone
17	HL 4-2	0.8	-	99.8 (chrt:32,Crbnt:40, Siltstone, mudstone with and/ released radiolaria and others:28)	Calcite	-	-	Carbonate rock fragments to calcite	Reworked radiolaria	-	Poorly	subrounded rock fragments, very angular cherts and quartz	Calclithite	8	Very fine grained sandstone
18	HL 4-3	-	-	100 (chrt:4,Crbnt:74, Siltstone, mudstone with and/ released radiolaria and others:22)	Calcite	-	-	Carbonate rock fragments to calcite	Reworked radiolaria	-	Moderately	subrounded rock fragments, very angular cherts	Calclithite	2	Very fine grained sandstone
19	HL 4-5	0.2	-	99.8 (chrt:9, crbnt:77, siltstone, mudstone with and/ released radiolaria and others:14)	Calcite about 25%	-	Opaque subhedral heavy minerals + glauconite + bright reddish hematite+ rare tiny bitumen fillings	Carbonate rock fragments to calcite	Rare benthic shell fragments+ reworked radiolaria + 2 globigerina	-	Moderately	Subangular-rock fragments, very angular cherts and quartz	Calclithite (greywacke)	7	Fine grained sandstone
20	HL 4-6	0.2	-	99.8 (chrt:14, crbnt:72, siltstone, mudstone with and/ released radiolaria and others:14)	Calcite about 25%	-	Opaque subhedral heavy minerals + glauconite + bright reddish hematite+ tiny bitumen fillings	Carbonate rock fragments to calcite	Rare benthic shell fragments+ reworked radiolaria	-	Poorly	Subangular-rock fragments, very angular and needle shaped cherts and angular quartz	Calclithite (greywacke)	10	Fine grained sandstone

Table 8.4. Continues

NO	Thin Section No:	Q%	F%	RF%	Cement	Matrix	Other components	Alteration/ dissolution	Fossils	Sedimentary structures	Sorting	Roundness	Modal Classification	No. of photos	Rock name
21	HL4-7	-	-	100 (chrt:27,Crbnt:55, Siltstone, mudstone with and/ released radiolaria and others:18)	Calcite	-	Opaque subhedral heavy minerals + Plant materials+ glauconite + bright reddish hematite+ rare bitumen fillings	Carbonate rock fragments to calcite	Rare benthic shell fragments+ reworked radiolaria	-	Very poorly	Subangular-subrounded rock fragments, very angular cherts	Calclithite	8	Fine grained sandstone
22	HL4-8	-	-	100 (chrt:27,Crbnt:55, Siltstone, mudstone with and/ released radiolaria and others:18)	Calcite	-	Opaque subhedral heavy minerals+ bitumen fillings	Carbonate rock fragments to calcite	Rare benthic shell fragments+ reworked radiolaria	-	Very poorly	Subangular-subrounded rock fragments, very angular cherts	Calclithite	10	Very fine grained sandstone
23	HL 5-2	0.5	-	99.5 (chrt:20,Crbnt:45, Siltstone, mudstone with and/ released radiolaria and others:35)	Calcite	-	Subangular glauconite + Black subhedral heavy minerals + bitumen fillings	Carbonate rock fragments to calcite	Rare benthic shell fragments+ reworked radiolaria	Slightly grain orientation	Very poorly	Subangular-subrounded rock fragments, very angular cherts	Calclithite	10	Very fine grained sandstone
24	HL 5-3	0.4	-	99.6 (chrt:6,Crbnt:72, Siltstone, mudstone with and/ released radiolaria and others:22)	Calcite	-	Subangular glauconite + bitumen fillings	Carbonate rock fragments to calcite	Rare benthic shell fragments+ reworked radiolaria	Slightly grain orientation	Poorly	Subangular-subrounded rock fragments, very angular cherts and quartz	Calclithite	4	Very fine grained sandstone
25	HL 5-4	0.2	-	99.8 (chrt:23,Crbnt:47, Siltstone, mudstone with and/ released radiolaria and others:30)	Calcite	-	Rare bitumen fillings + glauconite	Carbonate rock fragments to calcite	Rare benthic shell fragments+ plenty of reworked radiolaria	-	Poorly	Subangular rock fragments, very angular cherts and quartz	Calclithite	10	Very fine grained sandstone

Table 8.4. Continues

NO	Thin Section No:	Q%	F%	RF%	Cement	Matrix	Other components	Alteration/ dissolution	Fossils	Sedimentary structures	Sorting	Roundness	Modal Classification	No. of photos	Rock name
26	HL 6-3	0.5	-	99.5 (chrt:22,Crbnt:54, Siltstone, mudstone with and/ released radiolaria and others:34)	Calcite	-	Bitumen fillings	Carbonate rock fragments to calcite	Rare benthic shell fragments+ plenty of reworked radiolaria	Slightly grain orientation	Very poorly	Subangular-subrounded rock fragments, very angular cherts	Calclithite	4	Very fine grained sandstone
27	HL 6-5	-	-	100 (chrt:21,Crbnt:59, Siltstone, mudstone with and/ released radiolaria and others:20)	Calcite	-	Opaque subhedral heavy minerals +bitumen fillings	Carbonate rock fragments to calcite	Rare benthic shell fragments+ plenty of reworked radiolaria	Slightly grain orientation	Poorly	Subangular-subrounded rock fragments, very angular cherts	Calclithite	6	Fine grain siltstone
28	HL 6-7	0.2	-	99.8 (chrt:9, Crbnt:64, Siltstone, mudstone with and/ released radiolaria and others:27)	Calcite	-	Pretty much bitumen fillings+ glauconite	Carbonate rock fragments to calcite	Rare benthic shell fragments+ plenty of reworked radiolaria	Slightly grain orientation in some part of the section	Poorly	Subangular-subrounded rock fragments, very angular cherts and quartz	Calclithite	14	Fine grained sandstone
29	HL 7-3	0.4	-	99.6 (chrt:7, Crbnt:82, Siltstone, mudstone with and/ released radiolaria and others:11)	Calcite (25%)	-	Glauconite + hematite + rare bitumen fillings	Carbonate rock fragments to calcite	Rare benthic shell fragments+ plenty of reworked radiolaria	Slightly grain orientation and dark lithics form lamina like levels along the section	Moderately	Subangular-subrounded rock fragments, very angular cherts and quartz	Calclithite (greywacke)	7	Very fine grained sandstone
30	HL7-4	-	-	100 (chrt:17,Crbnt:56, Siltstone, mudstone with and/ released radiolaria and others:27)	Calcite	-	Subangular glauconite Black subhedral heavy minerals + bitumen fillings	Carbonate rock fragments to calcite	Rare benthic shell fragments+ plenty of reworked radiolaria	Slightly grain orientation	Poorly	Subangular-subrounded rock fragments, very angular cherts	Calclithite	6	Very fine grained sandstone

Table 8.4. Continues

NO	Thin Section No:	Q%	F%	RF%	Cement	Matrix	Other components	Alteration/ dissolution	Fossils	Sedimentary structures	Sorting	Roundness	Modal Classification	No. of photos	Rock name
31	HL7-7	-	-	100 (chrt:15,Crbnt:62, Siltstone, mudstone with and/ released radiolaria and others:23)	Calcite	+	?	Carbonate rock fragments to calcite	Rare benthic shell fragments (0.2%)+plenty of reworked radiolaria	-	Very poorly	Subangular-subrounded rock fragments, very angular cherts	Calclithite	20	Fine grained sandstone
Average		0.37	0.009	Lithic chert : 16.65 Carbonate rf: 59.32 Others :24.03	Calcite	-	Carbonized plant fragments, euhedral to subhedral opaque minerals, reddish brownish hematite, bright green subrounded glauconite, solid bitumen fillings (range between 1-15%) in pores	Carbonate rock fragments to calcite	Globigerina, reworked radiolaria, fossil shell fragments	Slightly grain orientation (not representative for the all sections)	Very poorly to moderately	Subangular-subrounded rock fragments, very angular cherts and quartz	Calclithite	9.4333	Very fine to medium grained sandstone
Note: All the quartzs in the thin sections are monocrystalline with straight and fully extinction															

8.5. Provenance

Petrographic data obtained from the thin sections were applied to the Qm-F-Lt ternary diagram of Dickinson et al. (1983) to interpret the tectonic provenance of the sandstones. The modal classification indicate that the sedimentary rocks are included within the “lithic recycled” category (Figure 8.6). Also palaeodirection rose diagrams (Figure 7.12 and Figure 7.13) from the unidirectional and bidirectional sedimentary structures in the turbidites, indicating SE palaeoflows which useful to accurately establish the location of source area.

Both the provenance ternary diagram and the composition of the turbidite sandstones of Tanjero Formation in the studied area indicate sedimentary rocks as source area. Taking together into account the petrographic and palaeocurrent data (Table 8.4, Figure 7.12 and Figure 8.6) it is possible to consider only one source area as the main responsible for the composition of sandstones.

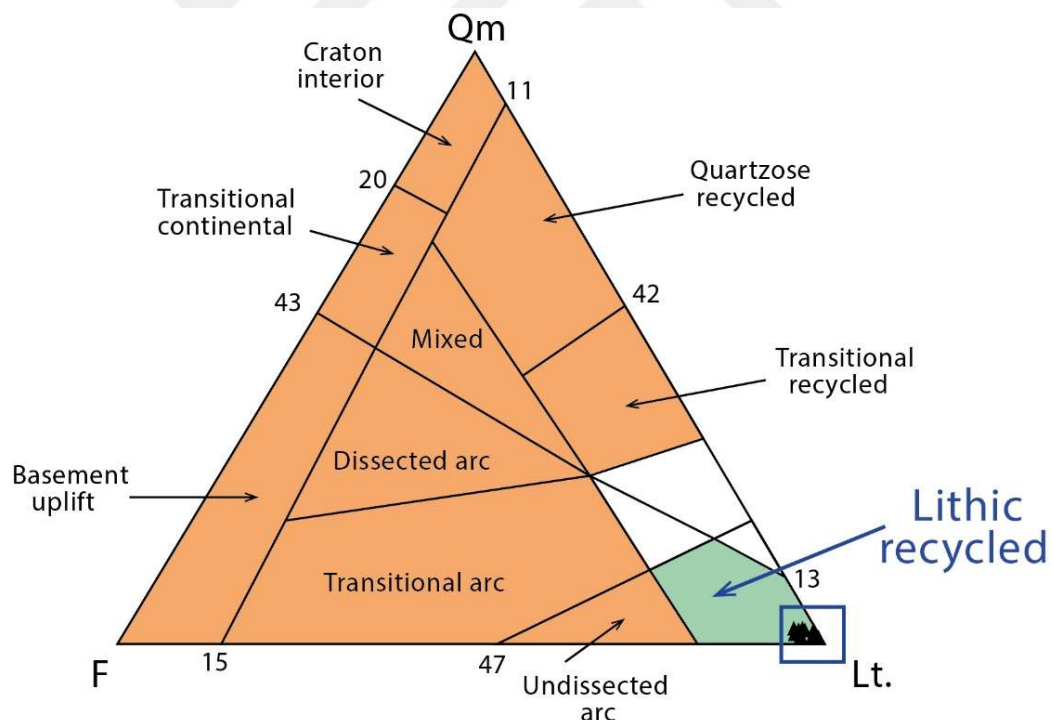


Figure 8.6. Qm-F-Lt ternary diagram showing tectonic provenance of the sandstone in the studied area indicates “lithic recycled” category. Position of the samples in the Lt corner is exaggerated to make it visible (after Dickinson et al. (1983), redrawn in computer).

Lithic clast types in the petrographic composition of the sandstones studied represent the sedimentary rock types of the Lower Cretaceous Qulqula Formation located in the lowermost right hand side of the stratigraphic column of the Northern Iraq region redrawn

by Karim (2010), (Figure 7.2). The formation represented a structural high to the north of the basin is composed of radiolarian chert, black limestone, radiolarian mudstone and limestone rocks of variable grade (Karim et al., 2006 and Karim, 2010).

The results for provenance analysis in this study support the interpretations in many works done by Karim especially in the studies in 2004, 2006, 2008 and 2010.

All the data from provenance analysis and petrography in this study show that provenance is not changing during deposition of the sandstones for the studied area because of the average sandstone composition doesn't vary along the measured sections.

The lithic fragments mentioned in the petrography part of the thesis were transported to the basin during the turbidite settling from the Qulqula Formation located to the North of the basin and remained the same during deposition. This is evidence of lowstand slope-fan deposits which consists of mainly rock fragments.

**PETROGRAPHIC EXPLANATIONS
OF SOME IMPORTANT THIN SECTION
MICROPHOTOGRAPHS**

-PLATES-

Plate 8.1

Thin section and *photo* numbers: HL1-1-0001-0002

BCrf: Black carbonate rock fragment

Bt: Solid bitumen fillings

Crf: Carbonate rock fragment

Ff: Fossil shell fragment

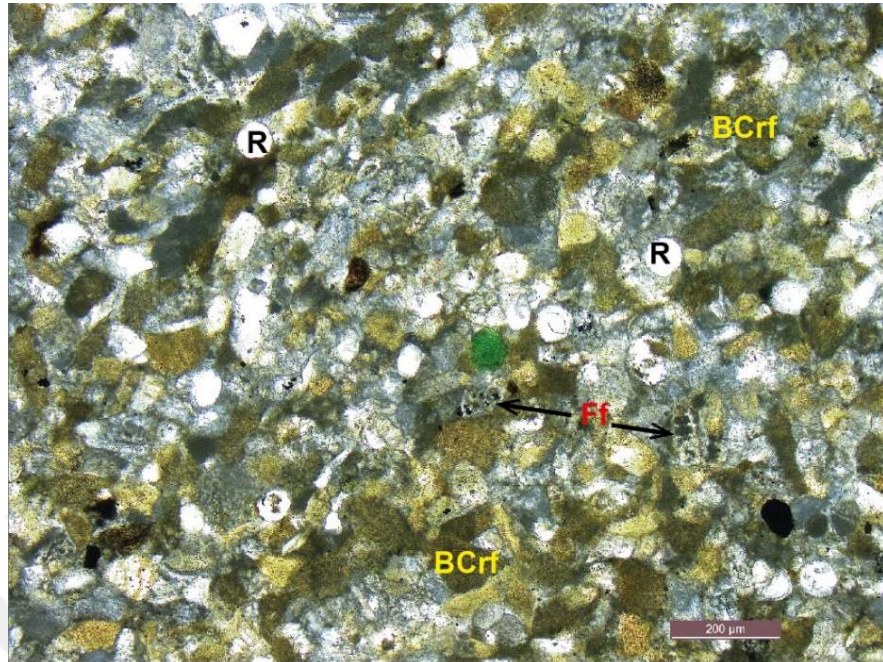
G: Glauconite

PPL: Plain Polarized Light

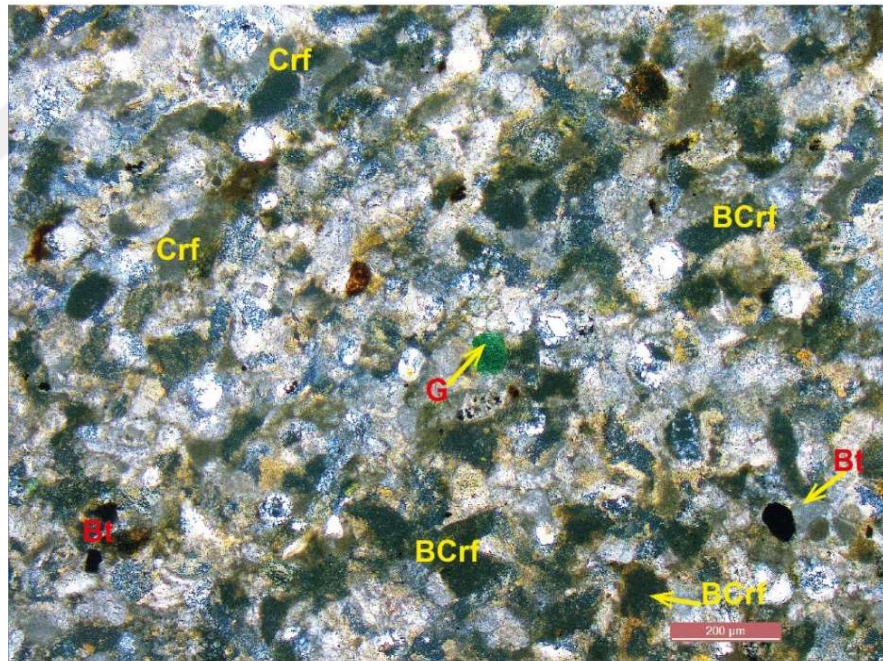
R: Radiolaria

XPL: Cross Polarized Light

Plate 8.1



PPL



XPL

These two photomicrographs (4X-Magnification) represent general composition of the turbidites studied of Tanjero Formation. As the scale is very small it is not possible labelling all the clasts in the images. Dark dirty yellowish to brownish (PPL) angular to subangular clasts are BCrf as labeled some of them. Bluish angular fragments (XPL), angular white fragments (PPL) are lithic chert clasts. Solid bitumen (Bt) fillings are staining the calcite cement to yellowish- brownish in color. White circles (PPL) are released-reworked radiolaria fossils. Two fossil shell clasts (reworked) are seen here which very rare in the all thin sections. More detail explanations will be in the following plates.

Plate 8.2

Thin section and *photo* numbers: HL1-7-0003-0004

BCrf: Black carbonate rock fragment

Bt: Solid bitumen fillings

Crf: Carbonate rock fragment

Ff: Fossil shell fragment

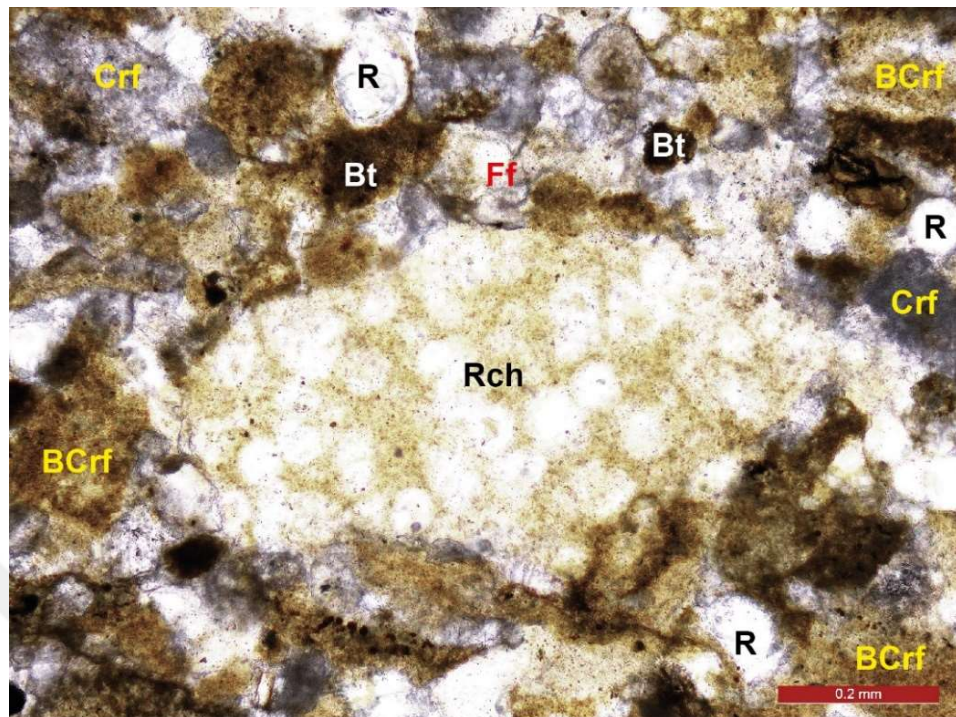
PPL: Plain Polarized Light

Rch: Radiolarian chert

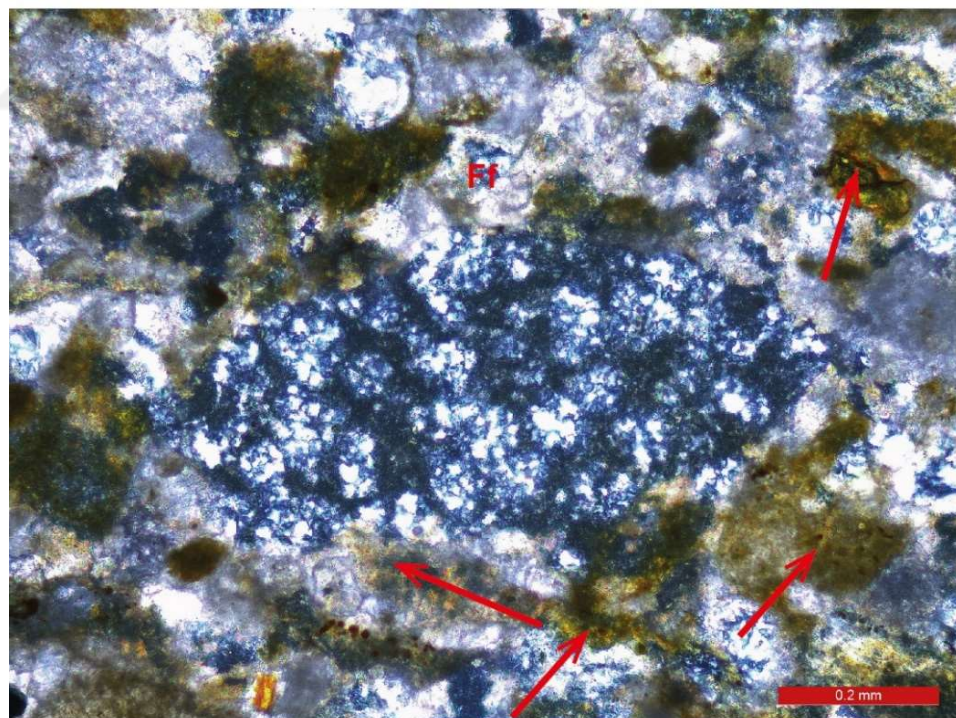
Red arrows: Bitumen stained calcite cement

XPL: Cross Polarized Light

Plate 8.2



PPL



XPL

A big radiolaria fossils (white circular specks in Rch in PPL image) bearing angular radiolarian lithic chert clast (Rch). This is the host rock for released and reworked radiolaria fossils in the source area. The released fossils possibly left the host rock either during weathering or transportation. Red arrows point out the bitumen stained calcite cement. Very poorly sorted example for the sandstone studied.

Plate 8.3

Thin section and *photo* numbers: HL1-7-0005-0006

BCrf: Black carbonate rock fragment

Bt: Solid bitumen fillings

MiCh: Microcrystalline chert

PPL: Plain Polarized Light

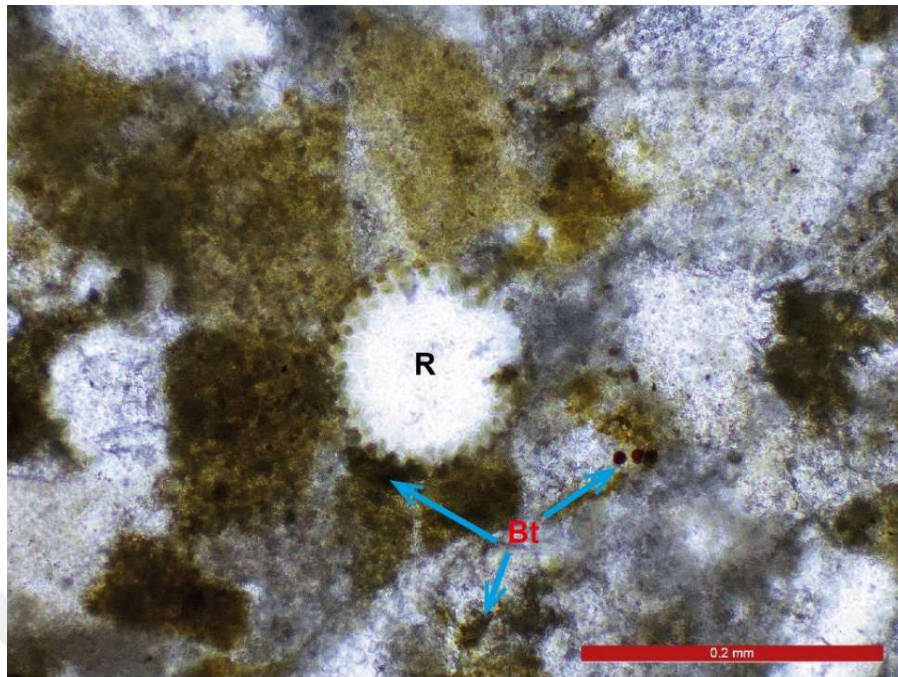
R: Radiolaria

Rch: Radiolarian chert

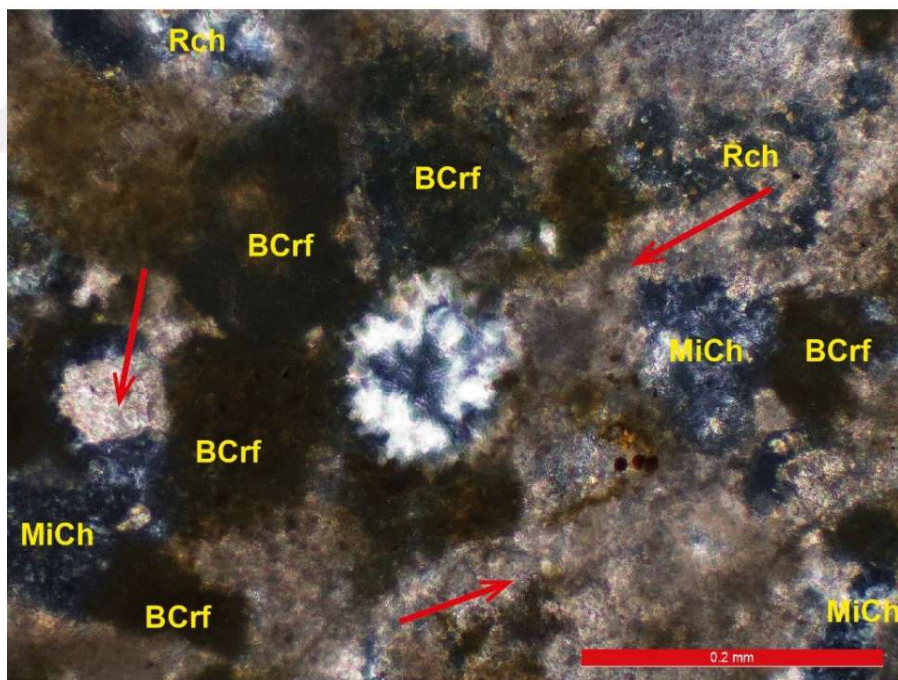
Red arrows: Bitumen stained calcite cement

XPL: Cross Polarized Light

Plate 8.3



PPL



XPL

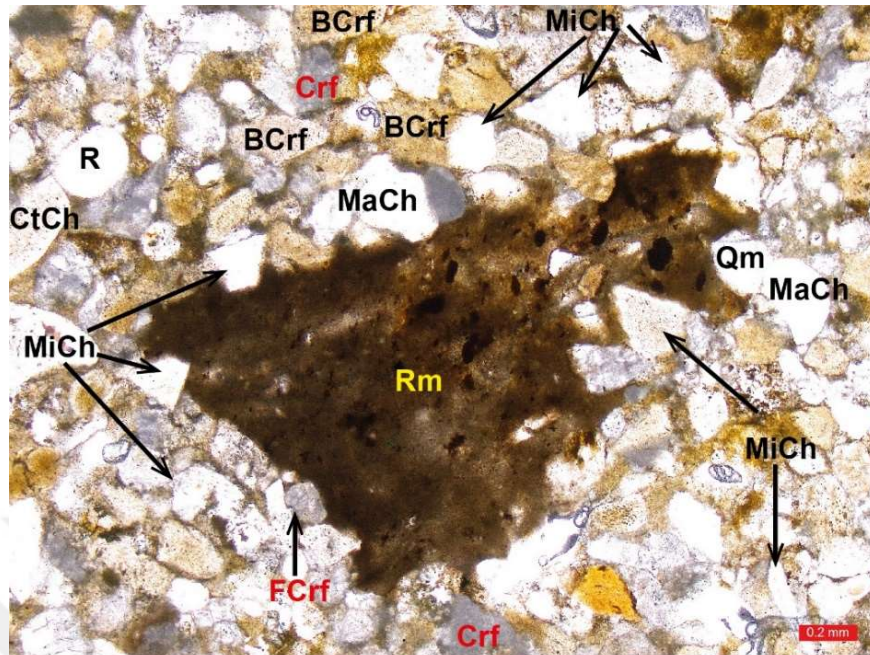
Released and reworked chalcedony filled (XPL view) radiolaria fossil in the center of the image. Although weathering and transportation the forms of the fossil were nearly well sheltered. Note the concavo convex contact type (the best view PPL image) between the R and the surrounding BCrf fragments. Disseminated (black small circles) solid bitumen fillings are shown by the blue arrow directed to the right up hand side. Bitumen stained calcite cement is represented by red arrows in the XPL image. Mostly all the clasts (especially Rch) were replaced by calcite so the contact of the clast are not very clear in (XPL).

Plate 8.4

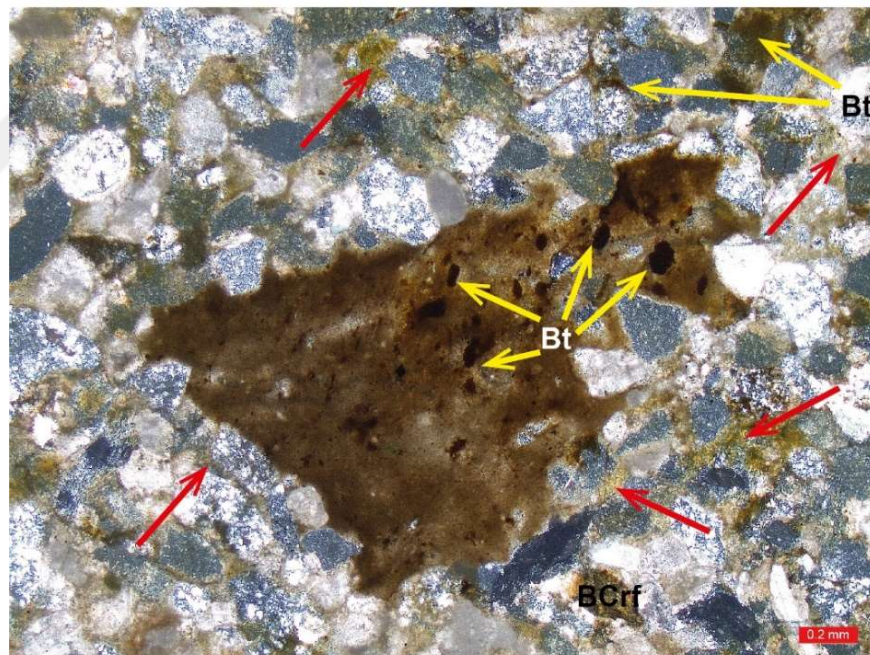
Thin section and *photo* numbers: HL1-9-0001-0002

BCrf: Black carbonate rock fragment
Bt: Solid bitumen fillings
Crf: Carbonate rock fragment
CtCh: Cryptocrystalline chert
FCrf: Fossiliferous carbonate rock fragment
MaCh: Macrocrystalline chert
MiCh: Microcrystalline chert
PPL: Plain Polarized Light
Qm: Monocrystalline quartz
R: Radiolaria
Rch: Radiolarian chert
Red arrows: Bitumen stained calcite cement
Rm: Radiolarian mudstone
XPL: Cross Polarized Light

Plate 8.4



PPL



XPL

About 2 mm in size radiolarian mudstone clast including chert clasts and solid bitumen fillings. Good example for concavo convex grain contact type since the partly embedding of the all other lithic clasts into the mudstone along the contact. The Rm is most likely was a relatively softer mud intraclast during compaction than the other constituents transported from the source area. Tangential, point and long grain contact types are also present in the images (more visible in the PPL) Solid bitumen fillings in some pores caused the changing of the color of calcite cement to greenish-yellowish. Very poorly sorted very angular cherts and subangular-subrounded carbonate rock fragments.

Plate 8.5

Thin section and *photo* numbers: HL1-9-0009-0010

BCrf: Black carbonate rock fragment

Bt: Solid bitumen fillings

C: Calcite crystals

Crf: Carbonate rock fragment

CtCh: Cryptocrystalline chert

G: Glauconite

MaCh: Macrocrystalline chert

MiCh: Microcrystalline chert

PPL: Plain Polarized Light

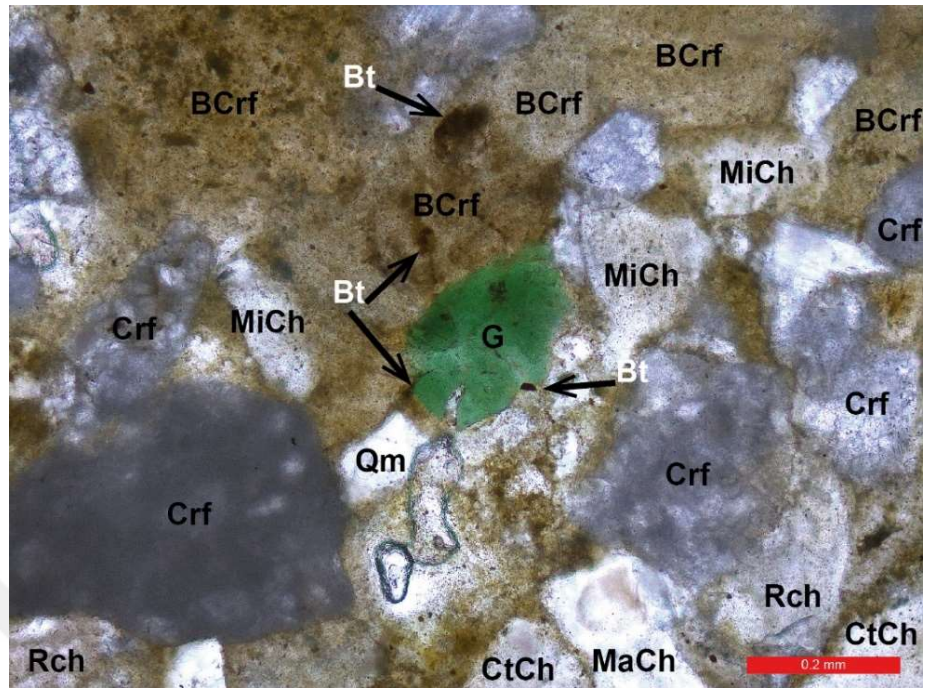
Qm: Monocrystalline quartz

Rch: Radiolarian chert

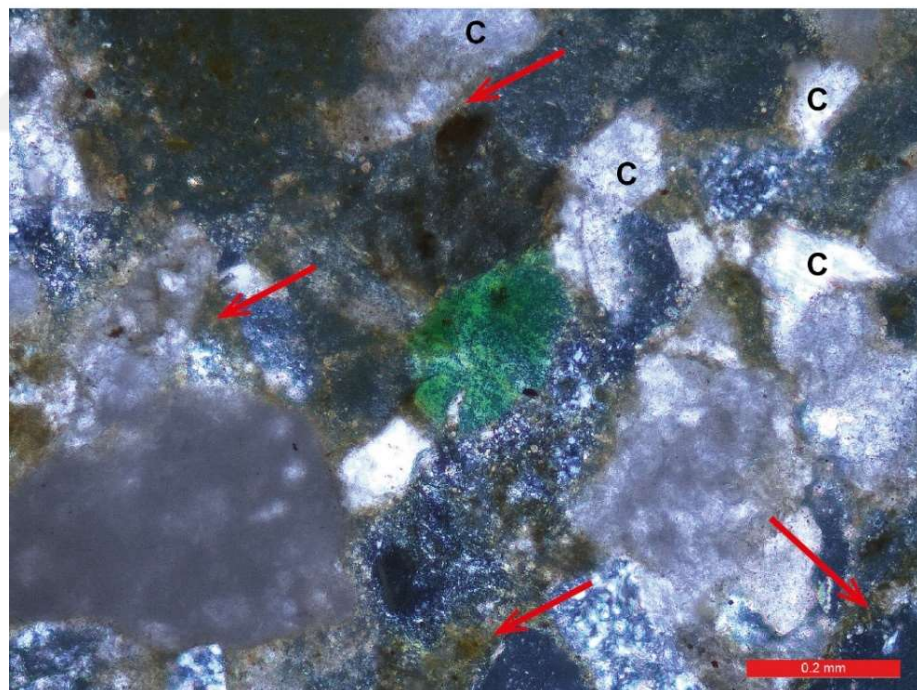
Red arrows: Bitumen stained calcite cement

XPL: Cross Polarized Light

Plate 8.5



PPL



XPL

Well rounded reworked bright green glauconite has calcite and bitumen intrusion into the lower part through a small fracture occurred before settling. Two air bubbles as section fault below G. Crf clasts have undefined microfossils as white speckles. Sutured contact type visible between Rch and Crf above the scale bar (PPL), concavo convex contact type between G and two BCrf above G, point contact type between big Crf and the two clasts above (PPL). Calcite cement around the clasts was stained as dark brownish-greenish-yellowish in color by bitumen fillings.

Plate 8.6

Thin section and *photo* numbers: HL1-9-0011-0012

BCrf: Black carbonate rock fragment

Bt: Solid bitumen fillings

Crf: Carbonate rock fragment

MiCh: Microcrystalline chert

PPL: Plain Polarized Light

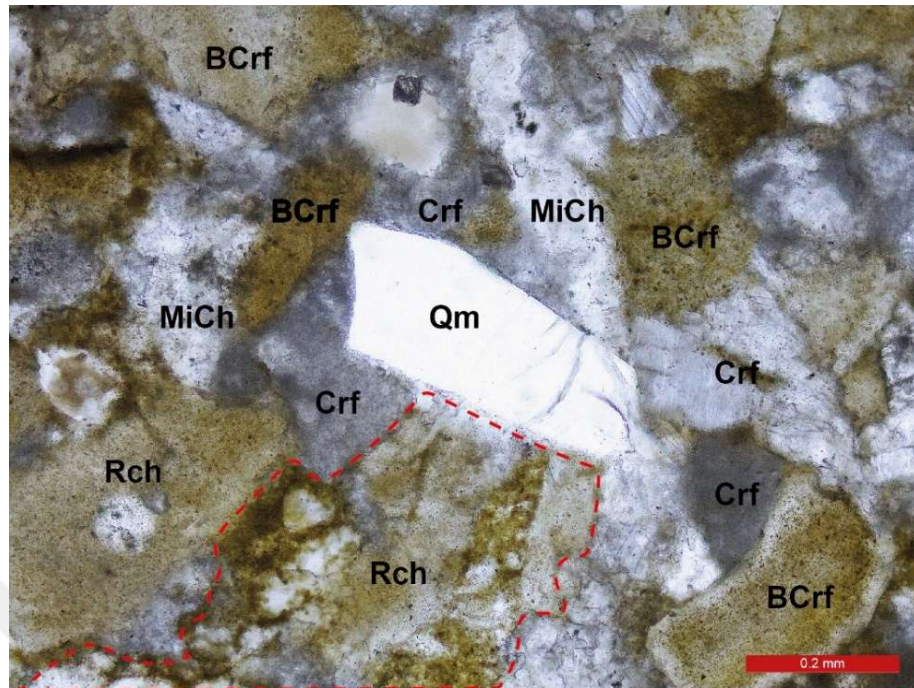
Qm: Monocrystalline quartz

Rch: Radiolarian chert

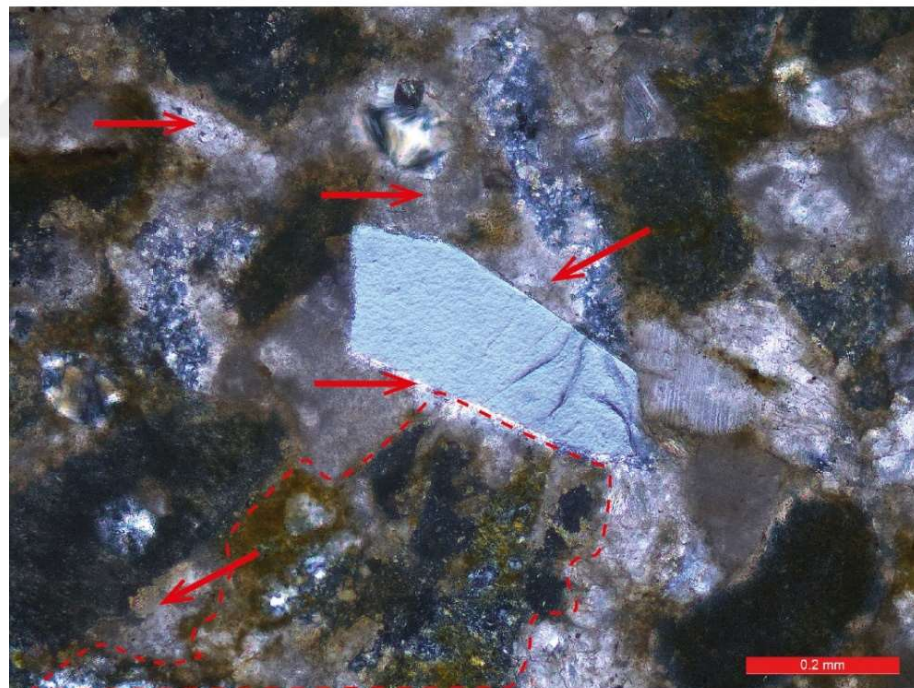
Red arrows: Calcite cement

XPL: Cross Polarized Light

Plate 8.6



PPL



XPL

A superb example for very angular monocrystalline quartz (Qm) having straight full extinction in the center of the images. It has a very less ratio in the all thin sections (Table 8.4). The Qm inserted into the Crf to the left hand side and split the Crf into two parts during compaction. Long grain contact between the majority of the lithic clasts indicate a tight packing and strong compaction. A big Rch grain located in the lower part of the photo mostly was replaced by calcite (bitumen stained, although Bt is not in this image but exist in the thin section HL1-9 as seen in Plate 8.6).

Plate 8.7

Thin section and *photo* numbers: HL2-4-0009-0010

BCrf: Black carbonate rock fragment

Blue zigzag arrows: Sutured grain contact type

Bt: Solid bitumen fillings

Crf: Carbonate rock fragment

CtCh: Cryptocrystalline chert

MaCh: Macrocrystalline chert

MiCh: Microcrystalline chert

PPL: Plain Polarized Light

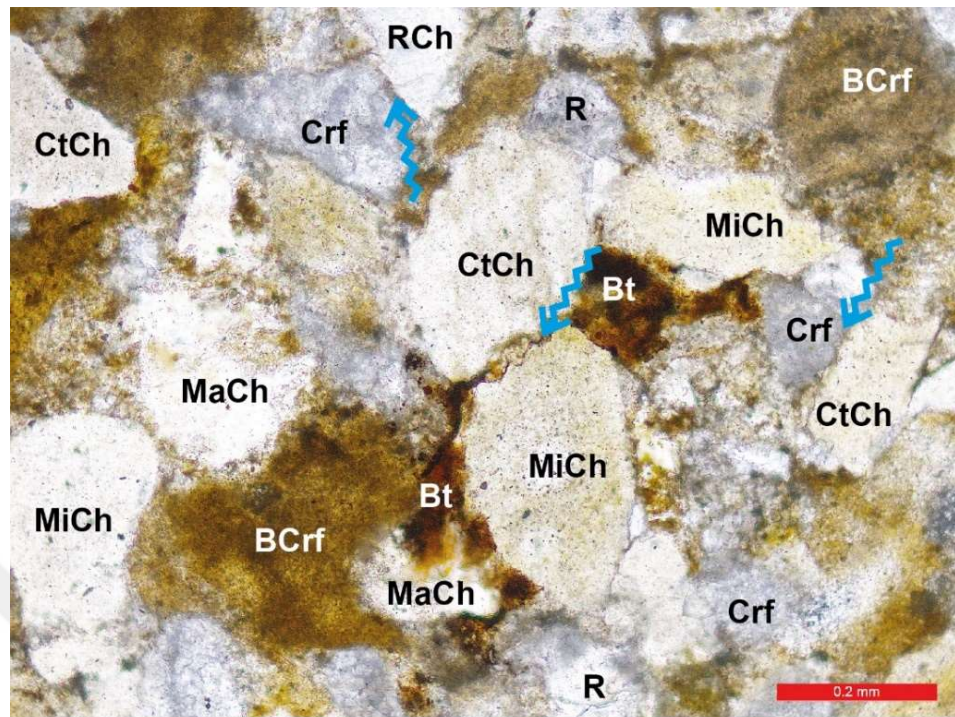
R: Radiolaria

Rch: Radiolarian chert

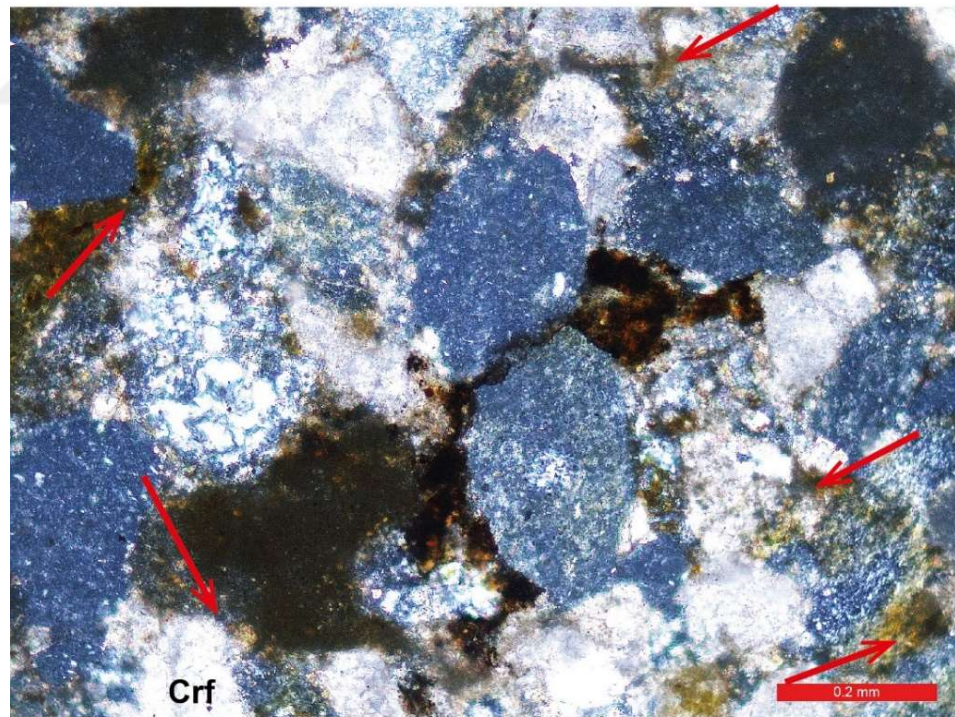
Red arrows: Bitumen stained calcite cement

XPL: Cross Polarized Light

Plate 8.7



PPL



XPL

Concavo convex and sutured grain contact types are important for this section. Two Mach grains have concavo convex contact with the dark BCrf clast in the lower left part of the center of the image. Blue arrows indicate the sutured grain contacts. Solid bitumen filling which one of the most effective agents reducing porosity of the sandstones is blocking the intergranular pores and stains the calcite cement.

Plate 8.8

Thin section and *photo* numbers: HL4-2-0007-0008

BCrf: Black carbonate rock fragment

Blue zigzag arrows: Sutured grain contact type

Bt: Solid bitumen fillings

Crf: Carbonate rock fragment

CtCh: Cryptocrystalline chert

H: Hematite

MaCh: Macrocrystalline chert

MiCh: Microcrystalline chert

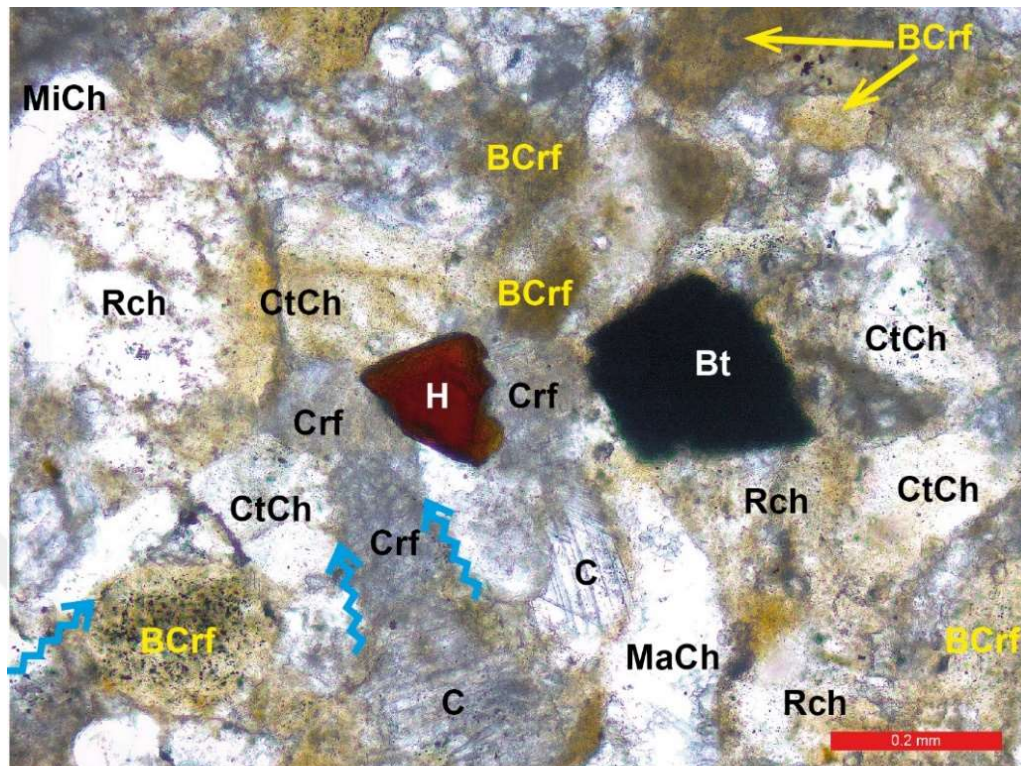
PPL: Plain Polarized Light

Rch: Radiolarian chert

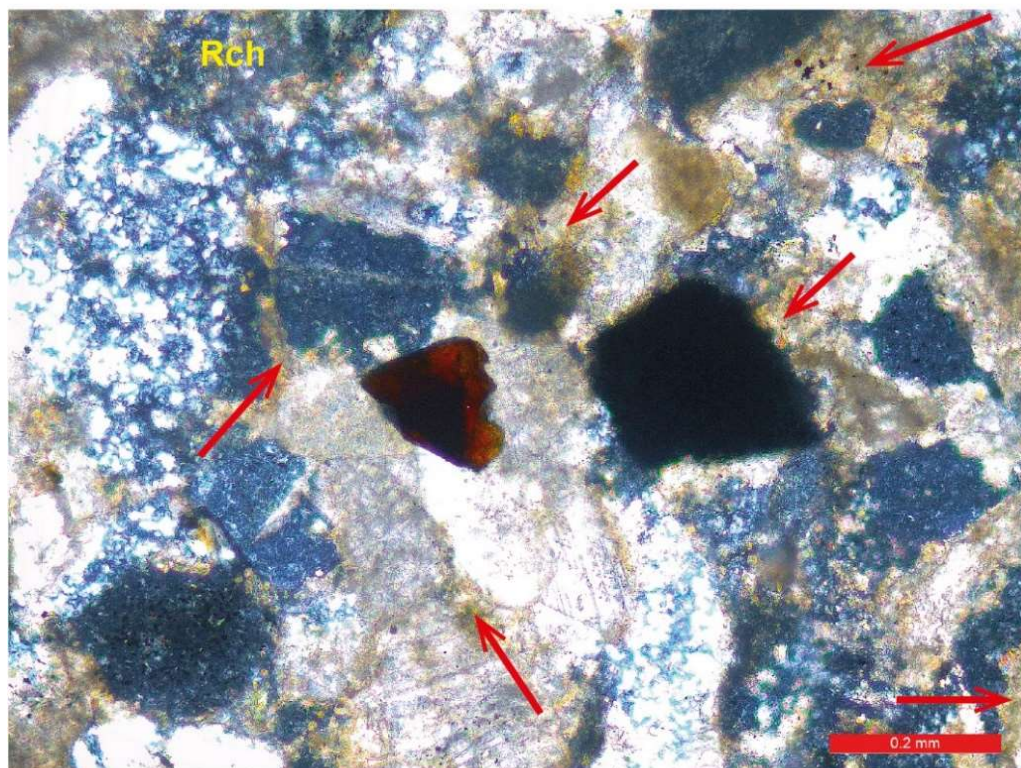
Red arrows: Bitumen stained calcite cement

XPL: Cross Polarized Light

Plate 8.8



PPL



XPL

Solid bitumen filling in an intergranular pore and brownish red hematite in the middle part of the photomicrograph. Tightly compaction and sutured grain contact show the high compaction ratio. Rch clasts were mostly replaced by calcite.

Plate 8.9

Thin section and *photo* numbers: HL4-7-0009-0010

BCrf: Black carbonate rock fragment

Bt: Solid bitumen fillings

CtCh: Cryptocrystalline chert

MaCh: Macrocrystalline chert

MiCh: Microcrystalline chert

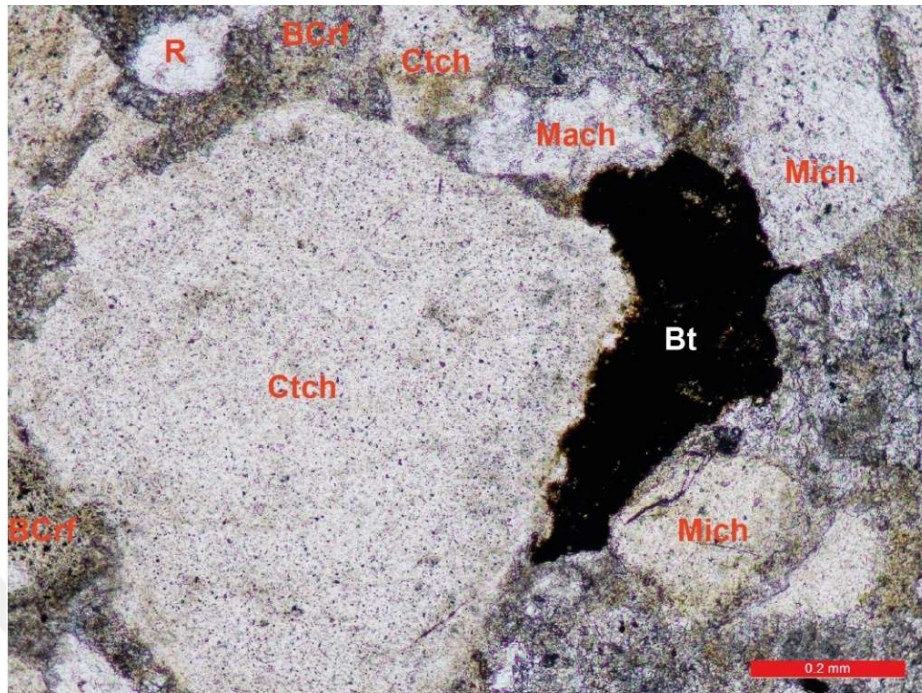
PPL: Plain Polarized Light

R: Radiolaria

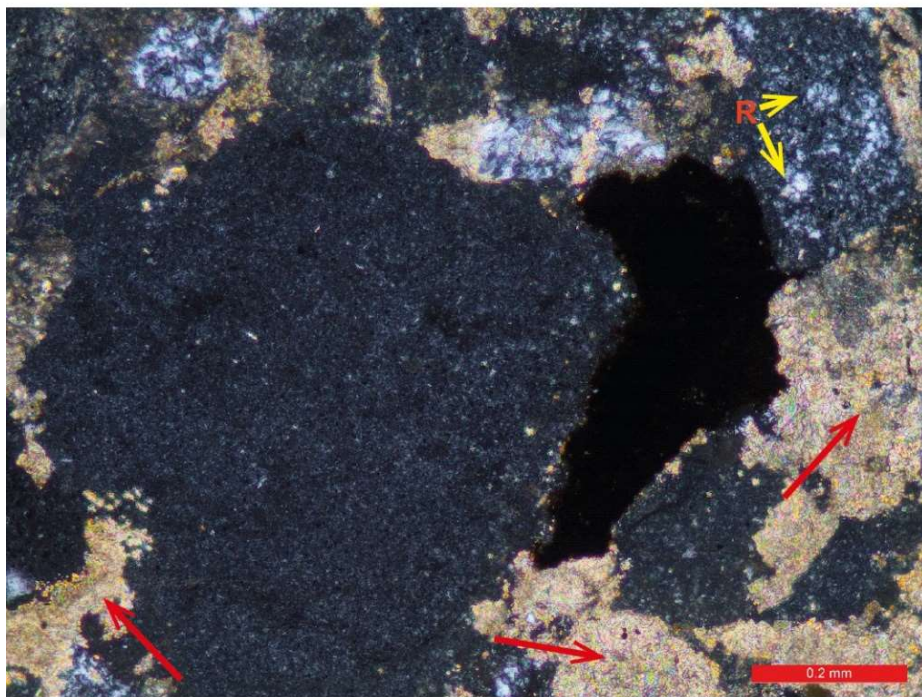
Red arrows: Calcite cement

XPL: Cross Polarized Light

Plate 8.9



PPL



XPL

Macrocrystalline microcrystalline and cryptocrystalline lithic chert clasts are seen together in one image. Red arrows represent slightly stained calcite cement. Solid bitumen visible in both images causes pale yellowish staining on the calcite cement. Note the point contact type between the big CtCh clast and two small lithic chert fragments above. Mich below bitumen filling has floating contact type as it is surrounded by fillings (Calcite cement and Bt).

Plate 8.10

Thin section and *photo* numbers: HL6-3-0005-0006

Ab: Air bubble (thin section fault)

BCrf: Black carbonate rock fragment

Blue zig-zag arrows: Sutured grain contact type

Bt: Solid bitumen fillings

Crf: Carbonate rock fragment

MaCh: Macrocrystalline chert

PPL: Plain Polarized Light

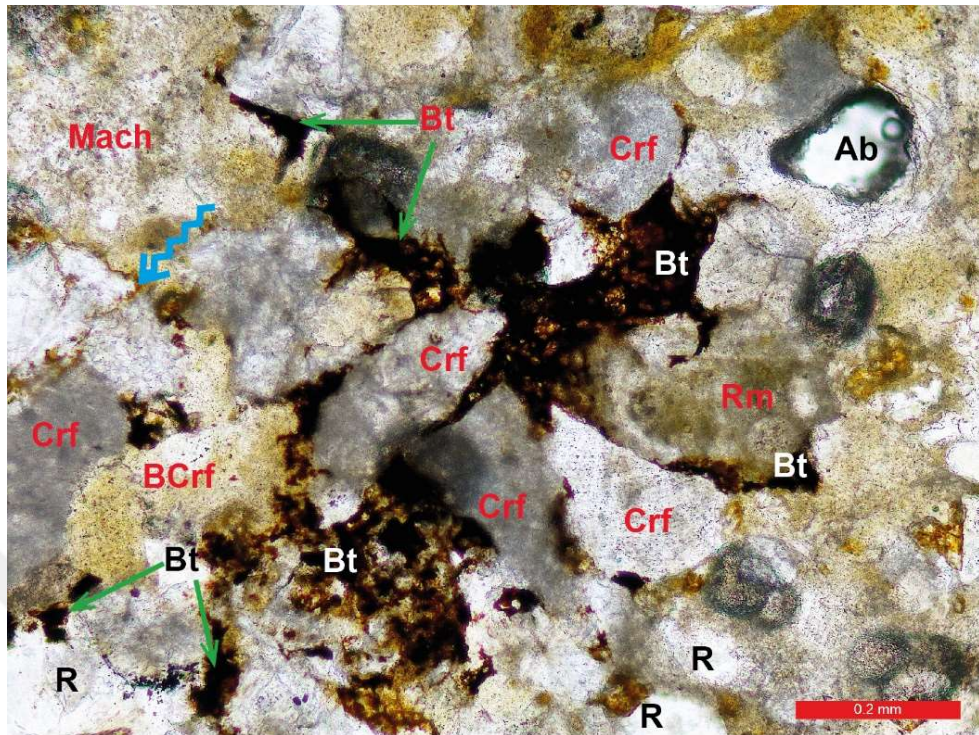
R: Radiolaria

Red arrows: Bitumen stained calcite cement

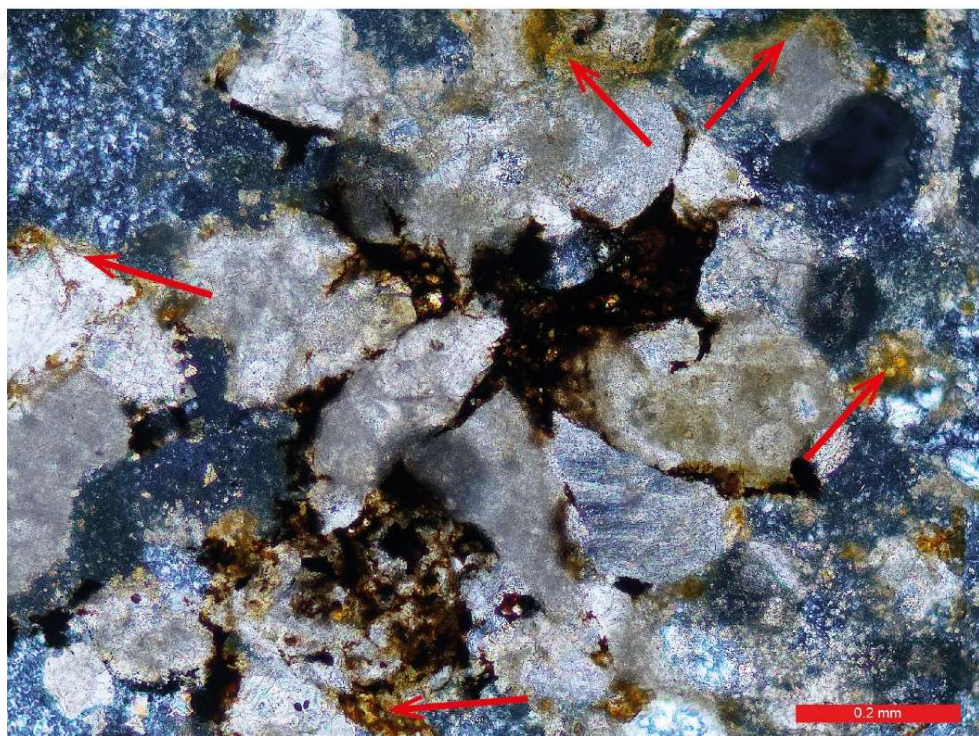
Rm: Radiolarian mudstone

XPL: Cross Polarized Light

Plate 8.10



PPL



XPL

Mostly intergranular and little intragranular (lower left part of the center in this image) pores were blocked by bitumen fillings (Bt). Tangential, concavo convex and sutured grain contact types indicate tightly packing and high compaction. Note the moderately sorted and very angular to subangular grains.

Plate 8.11

Thin section and *photo* numbers: HL6-7-0001-0002

BCrf: Black carbonate rock fragment

Bt: Solid bitumen fillings

Crf: Carbonate rock fragment

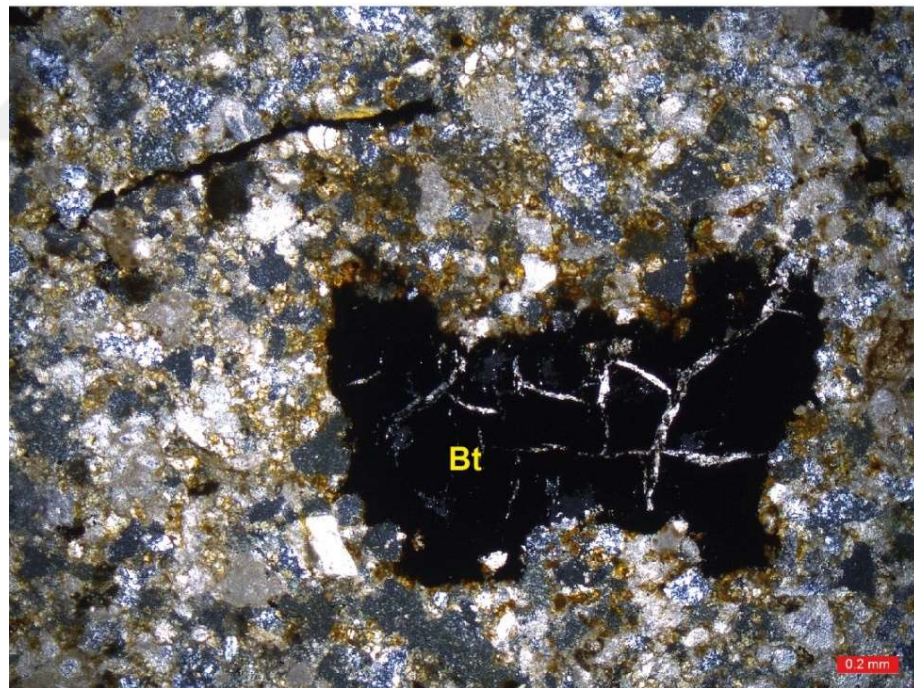
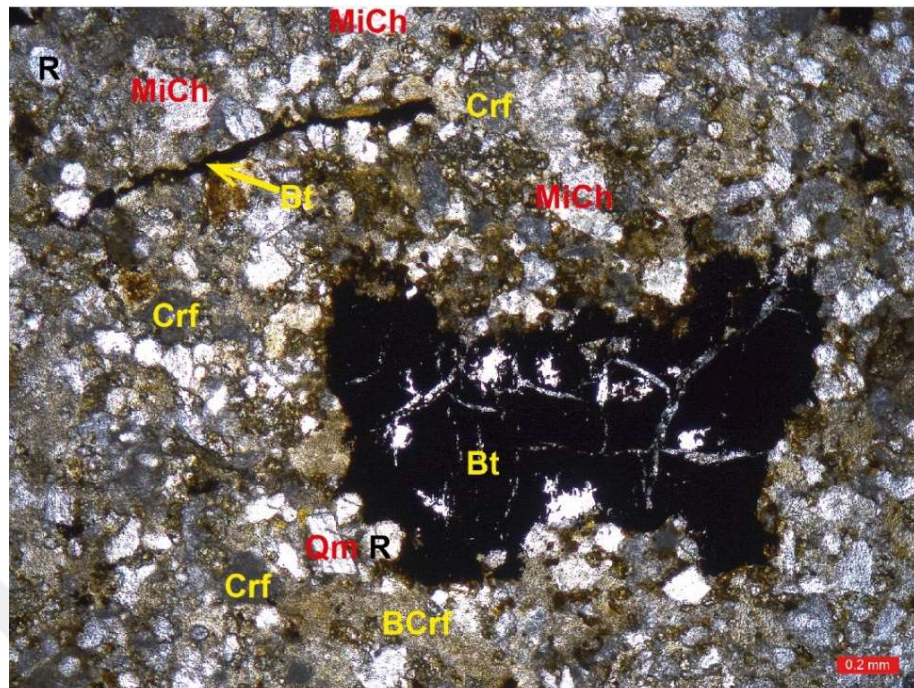
MiCh: Microcrystalline chert

PPL: Plain Polarized Light

R: Radiolaria

XPL: Cross Polarized Light

Plate 8.11



Microfractures in the solid bitumen were filled by calcite. Relative timing between the calcite fillings and bitumen shows that bitumen filled in pores before calcite, the fractures don't cut the section throughout, only limited in the bitumen filling. This relation indicates that the fractures occurred after bitumen became solid then the calcite filled into the fractures. Monocrystalline quartz with fully extinction to the left down of the bitumen. To the top left a microfracture is filled by bitumen. Subangular to subrounded Crf and very angular lithic chert fragments are the dominant constituents in this section.

Plate 8.12

Thin section and *photo* numbers: HL6-7-0007-0008

BCrf: Black carbonate rock fragment

Bt: Solid bitumen fillings

Crf: Carbonate rock fragment

CtCh: Cryptocrystalline chert

MaCh: Macrocrystalline chert

MiCh: Microcrystalline chert

PPL: Plain Polarized Light

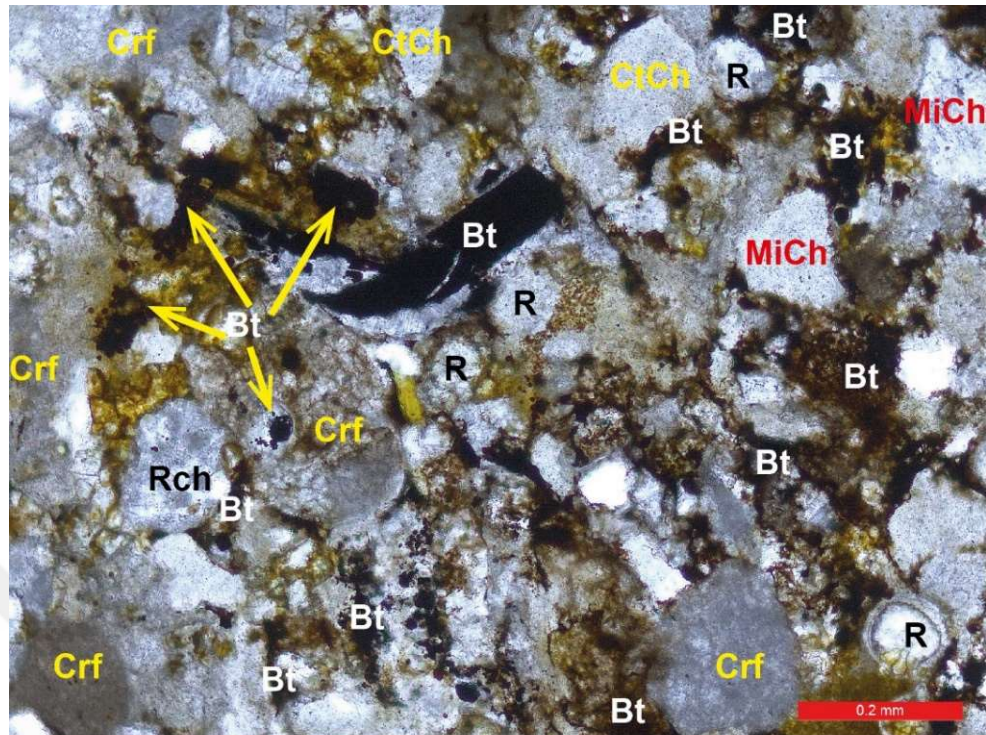
R: Radiolaria

Rch: Radiolarian chert

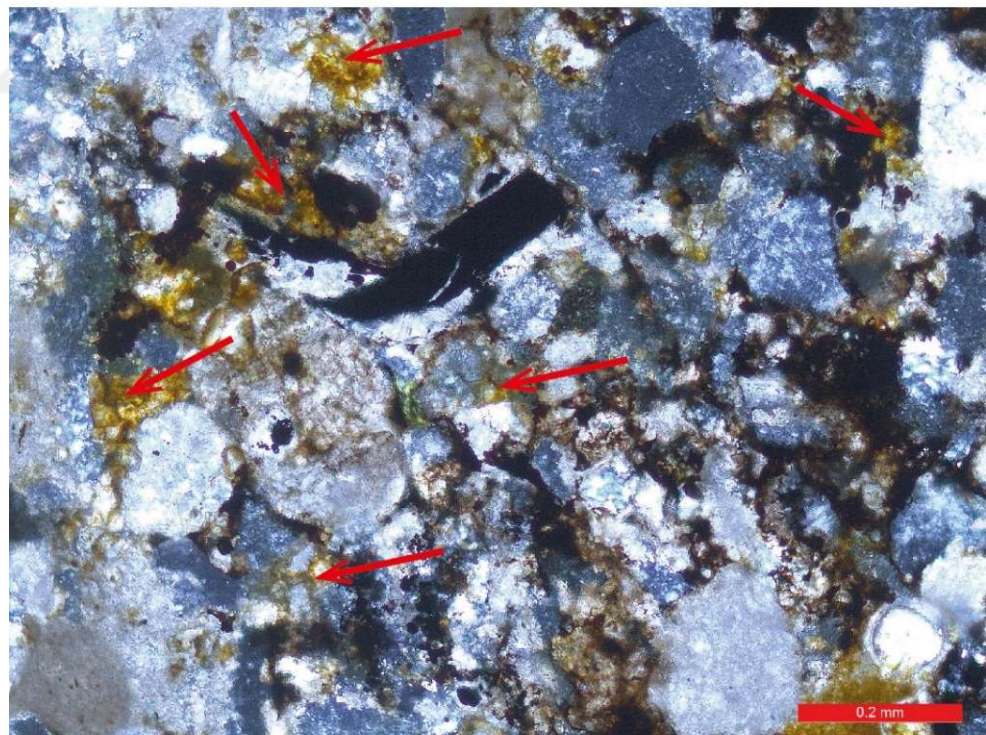
Red arrows: Bitumen stained calcite cement

XPL: Cross Polarized Light

Plate 8.12



PPL



XPL

Majority of the intergranular and intragranular pore spaces filled by solid bitumen before or syn-calcite precipitation while the sandstone had pretty much pore spaces during early diagenesis. At that time the turbidite sandstones of Tanjero Formation had a good porosity which filled by solid bitumen since oil migration.

9. CONCLUSIONS

This study was carried out northwestern part of Sulaimaniyah city, Northern Iraq, around the Hanaran villages on the Upper Cretaceous Tanjero Formation to examine the reservoir characterization of the deep marine turbidite sandstones.

The study includes porosity and permeability, facies analysis, petrographic analysis and related provenance category of the sandstones.

Calcite precipitation from the carbonate rock fragments and calcite replacement on the other lithic clasts, 1 to 15% solid bitumen fillings, tightly packing and moderate compaction are the main reasons for poor to beginning of fair porosity, which is ranging from 5.51 % to 11.59 % with an average value of 7.11% for the studied sandstones. Permeability varies between 10.71-2315.65 md and their mean value is 866.35 md representing high permeability.

The facies analysis, with detail seven measured stratigraphic sections (logs) framework including seven distinctive main lithofacies groups and forty-eight subfacies suggest middle part of outer fan and lobe fringe to lobe distal fringe sand rich depositional system in which the sandstone ratio is 18.14 % and shale ratio is 81.86 %. This sandstone/shale ratio (net to gross) is very low and represents distal turbidites.

Petrographic modal analysis of the thin sections of the sandstone fall into the calcilithite area of litharenite division.

The compositional characteristics show the presence of only sedimentary rocks in the source areas. According to the diagrams, the data obtained from the modal analysis illustrated to a lithic recycled orogen as the source area. Both the sandstone composition and the palaeocurrent data indicating the flow towards the SE, measured from flute mark and current ripples in Bouma Tc divisions, and petrographic constituent of the sandstone point out a lithic recycle orogen category for the turbidite.

This source area was the structural highs of the North of the Upper Cretaceous basin consisting of Lower Cretaceous Qulqula Formation.

Less than 5 percentage clay, very fine to medium grained in size consisting of chert, siltstone, mudstone, radiolarian chert and radiolarian mudstone fragments, angular to subangular in shape, very poorly to moderately sorted, transported over short distances and represent submature stage.

Very little amount of tangential, mainly long grain, concavo convex and sutured contact types and high contact index (4.7) represent moderate to tightly packing, moderate compaction which are negatively effecting the reservoir quality.

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- **Geological aspects of NE of Iraq**, summer training course, University of Sulaimani, College of Science, Department of Geology, (Jul. 1 – 31, 2004).
- Participating in **Roller Compacted Concrete Dam (RCC Dam)** course, Water Resources Researches Center of Kurdistan Region, from March 10, 2008 to March 13, 2008.
- Participating in **Environmental Impact Assessment (Water quality survey of Tanjero River)**, for Qara-Ali dam irrigation project, including field and laboratory work, by American Nature Iraq Organization, from March 28, 2008 to April 2, 2008.
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