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STRATIGRAPHY, PETROLOGY AND FACIES ASSOCIATIONS OF THE QUATERNARY SPIN KAREZ GROUP, HANNA-SPIN KAREZ AREA, QUETTA DISTRICT, PAKISTAN

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ABSTRACT
The Hanna-Spin Karez area which comprises the Quaternary succession of the Spin Karez Group is located adjacent to the junction of Sulaiman and Kirthar Fold-Thrust Belts (Quetta Syntaxes), southwest of the Zarghun Trough in the northwestern Balochistan, Pakistan. The area comprises over 800 m thick conformable succession of the Quaternary age, covering surface area of ~30 km^2. The succession has been named as the Spin Karez Group, which are further subdivide from base to top into three distinct lithostratigraphic units as: Hanna Lake Conglomerate, Hanna Red Clays and Spin Karez Conglomerate. The Hanna Lake Conglomerate comprises 200 m thick succession of boulder-pebble conglomerate. The Hanna Red Clays comprise over 500 m thick succession of dominantly red claystone rarely interbedded with siltstone and very fine-grained sandstone. The Spin Karez Conglomerate is composed of over 100 m thick succession of well-stratified and moderately- to well-sorted cobble/pebble conglomerate with occasional sandstone/siltstone lenses. The Triassic to Pliocene age older successions from the region's north and west provided the polymictic conglomerate, boulder to pebble size limestone, sandstone, chert, and conglomerate fragments. The Spin Karez Group comprises 15 types of gravel, sandstone and mudstone facies, which were grouped into 5 facies associations. The facies associations include braided channel deposits (FA-1), sheet-flood deposits (FA-2), floodplain deposits (FA-3), marginal lacustrine deposits (FA-4) and open-water lacustrine deposits (FA-5). The Spin Karez group evolved in three phases: i) Deposition of the Hanna Lake conglomerate started with the proximal and distal braided channel systems in the northern and southern parts of the study area respectively; ii) Deposition of the Hanna Red clays deposited in shallow lake with episodic sub-aerial exposure, providing reddish colour to the mud-dominant facies; iii) The depositional basin, once again, transformed to braided channel system, of the Spin Karez conglomerate, which evolved over the shallow water lake deposits of the Hanna Red clays. The Spin Karez group was mainly controlled by continued subsidence and regional tectonics during the Quaternary period that accommodated the space for the small shallow basin (~30 km^2) that stacked depositional systems.

KEYWORDS*:* Spin Karez Group, facies, facies association, braided channel system

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1. INTRODUCTION

The Hanna-Spin Karez area which comprises the Quaternary succession of the Spin Karez Group [1] is located adjacent to the junction of Sulaiman and Kirthar Fold-Thrust Belts (Quetta Syntaxes), southwest of the Zarghun Trough [Fig. 1] in the northwestern Balochistan, Pakistan [2, 3, and 4]. The

Hunting Survey Corporation [5] mapped the area on 1:253,000 scale, however, they indiscriminately mapped the Quaternary succession as recent deposits and named it Spin Karez Gravel. After the [5], enlarged unpublished map of the area was prepared by geologists of the Geological Survey of Pakistan (GSP), however, they did not recognize the Quaternary succession as distinct lithostratigraphic unit and mapped it as upper part of the Miocen Pleistocene Urak Group [6, 7].The surrounding area, which is part of the western Sulaiman Fold-Thrust Belt, comprises mainly marine sedimentary succession ranging from Jurassic to Holocene [Table. 1] [8]. The Spin Karez Group is up to 800

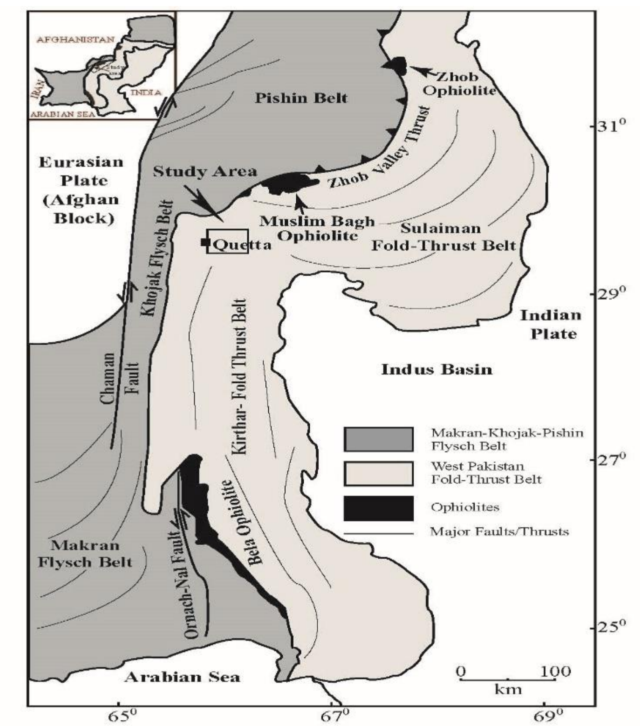
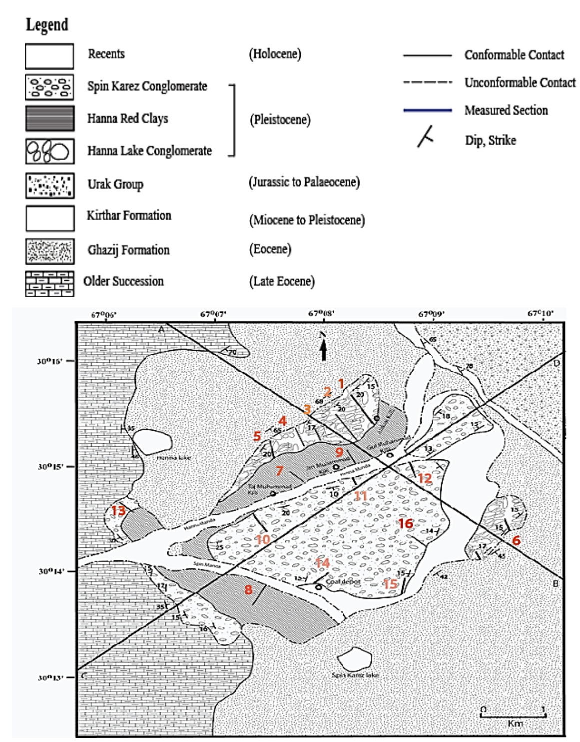


Figure 1. Geological map of the western Pakistan Fold- Thrust Belt, showing location of the study area modified after [3].

thick and covers surface area of ~30 km^2 [1]. It comprises conglomerate, mudstone and sandstone lithologies deposited exclusively on top of the Eocene Ghazij Formation. Detailed stratigraphy and mapping of the Quaternary succession of the Hanna-Spin Karez area was carried out by [1]. They re-named the succession as "Spin Karez Group" and further divided it into three distinct lithostratigraphic units of formation rank, which are Hanna Lake Conglomerate, Hanna Red Clays and Spin Karez Conglomerate.

2. METHODOLOGY

The project is field oriented and needed extensive field work. The Quaternary succession of the Spin Karez area was mapped on a scale of 1:25,000 (enlarged 1:50,000) in order to understand its relationship with the and facies associations. Sedimentary logs of the measured sections were prepared using Coral Draw and Adobe Illustrator. This helped us to understand and interpret the facies, facies associations and depositional environments of constituent formations of the Group. older rock successions and mutual stratigraphic relationship of the various rock units. Depending on the availability of appropriate sections, overall 16 sections of Spin Karez Group were logged, among which 06 sections were logged in the Hanna Lake Conglomerate, 03 in the Hanna Red Clays and 07 in the Spin Karez Conglomerate, in order to recognize characters of the sedimentary successions and identify facies.



Geological map of the Quaternary Spin Karez Group, showing older successions and measured sections (1) is Killi Attakzai Hanna Lake section (3) Killi Samad Khan Hanna Lake section, (7) Hanna Red Clay, Dam section (modified after [1].

The purpose of the study was to describe the lithostratigraphy of the Hanna-Spin Karez Group and further elaborate the composition, provenance, facies, facies associations in order to understand the depositional environments and basin evolution of the Group.

3. SRTATIGRAPHY

3.1. Stratigraphy of the surrounding area

The nearby area comprises successions of sedimentary rocks ranging in age from Jurassic through Pleistocene [Table. 1]; namely the Jurassic Shirinab Formation and Chiltan Limestone, Lower to Middle Cretaceous Parh Group, Upper Cretaceous-Palaeocene succession the Hanna Lake Limestone, Fort Munro Formation, Pab Formation and Dungan Formation, all with mutually conformable contacts except the upper contact of the Jurassic Chiltan Limestone with the Lower Cretaceous Sember Formation and that of the Pab formation with the Dungan formation, which are disconformable. The succession is exposed in the nearby Muree Brewery, Hanna Lake and Takatoo areas.

The **Shirinab Formation** [5, 9] consists of interbedded limestone and shale. The limestone is thin to medium-bedded, grey to dark grey and black. It is finely crystalline to very coarse, with shelly, oolitic, pellitic and pisolitic texture. The shale is grey to dark grey, calcareous and ranges from soft flaky to hard fissile. The formation ranges in thickness from about 1500 m to 3000 m [5, 9]. Fossils reported from the Murree Brewery section, near Quetta, include: *Montlivaltia sp., Coroniceras sp., Terebratula sp., T. andleri, C. prisa, L. deslongehampsi, Nucula sp., and Gryphaea sp.,* [5], which indicate an Early Jurassic age [5, 9]. Its upper contact with the Chiltan Limestone is transitional.

The name **Chiltan Limestone** and **Takatu Limestone** was introduced by HSC [5,10,11] from the Chiltan and Takatu ranges southwest and northeast of the Quetta city, respectively. It is composed of thick succession of very thick bedded and partly reefoid limestone forming high peaks and prominent ranges. The limestone is dark brownish to dark grey, finely crystalline and partly oolitic and pisolitic. On the basis of ammonites [9] **Table 1.** Stratigraphic succession of the western Sulaiman Fold-Thrust Belt and adjoining Zarghun-Trough modified after [1, 8]. considered it to be of Middle Jurassic age. Its upper contact with the Sember Formation is disconformable.

The **Parh Group** of [5] has been sub-divided into the Late Jurassic-Early Cretaceous (Neocomian) Sembar Formation [12, 9], Lower Albian-Cenomanian Goru Formation [12, 13 and 14] and Berremian-Santonian Parh Limestone [5, 14,and 15] [Table 1].

Table 1. Stratigraphic succession of the western Sulaiman Fold-Thrust Belt and adjoining Zarghun-Trough modified after [1, 8].

Group / Formation		Lithology	Age
Holocene deposits		Conglomerate, sandstone and mudstone	Holocene
Angular unconformity			
Spin Karez Group	Spin Karez Conglomerate	Conglomerate	Late Pleistocene
	Hanna Red Clays	Reddish brown claystone	Middle Pleistocene
	Hanna Lake Conglomerate	Conglomerate, sandstone and mudstone	Early Pleistocene
Angular unconformity with the Ghazij Formtion			
Urak Group	Urak Formation	Conglomerate	Miocene-Pleistocene
	Shin Matai Formation	Green sandstone	
	Uzda Pusha Formation	Reddish brown claystone	
Disconformity (Angular unconformity in some areas)			
Spin Tangai Formation		Limestone, shale and sandstone	Middle-Late Eocene
Ghazij Formation		Thin to medium bedded shale, mud and clay	Early Eocene
Dungan Formation		White, creamy and brownish grey limestone	Palaeocene
Pab Formation		Brownish grey and creamy quartzose sandstone	Late Cretaceous
Disconformity			
Fort Munro Formation		Dark grey, thin bedded limestone	Late Cretaceous
Disconformity			
Hanna Lake Limestone		Dull, dark brownish grey thick-bedded barely fossiliferous limestone	Late Cretaceous
Disconformity			
Parh Limestone		White, creamy biomicritic thin-bedded limestone	Late Cretaceous
Goru Formation		Reddish brown and pale green biomicritic limestone, marl and rare shale	Middle Cretaceous
Sembar Formation		Dark brownish, greenish and pale green shale, sandstone and limestone	Early Cretaceous
Disconformity			
Chiltan Limestone		Dark brownish grey, thick-bedded limestone	Middle Jurassic

The **Sembar Formation** is lowermost unit of the Parh Group [12], which is composed of pale green to brownish grey shale interbedded with minor proportions of siltstone, arenaceous limestone and sandstone. The shale commonly contains *Belemnites* fossils, however, foraminifera and ammonites have also been reported, which suggest Late Jurassic-Early Cretaceous (Neocomian) age [9, 12, 16 and 17]. The Sembar Formation transitionally underlies the **Goru Formation**, which was named by [12], for upper part of the "Belemnite Beds". It comprises shale and siltstone interbedded with limestone. The limestone is light to medium grey, thin bedded and biomicritic, whereas, shale and siltstone are grey, greenish grey and maroon. Limestone contains micro-foraminifers of the Globotruncana family. Based on the Foraminifera from the Bangu Nala, near Quetta, an Early Cretaceous (Albian to Cenomanian) age was proposed [12, 13 and14]. Upper contact of the formation is conformable with the Parh Limestone.

The **Parh Limestone** [12, 18] is light grey, white, creamy, thin to medium bedded and biomicritic. Around the Zarghun Trough, upper part of the Parh Limestone contains partial to complete dolomitized horizons in upper part of the formation. The limestone is rich in micro-foraminifers [14, 15], an Early to Late Cretaceous (Berremian to Santonian) age has been assigned. In the surrounding areas its upper contact is disconformable with the Hanna Lake Limestone.

The **Hanna Lake Limestone** was introduced by [8, 19 and 20] for the dull brownish grey, thick bedded, finely crystalline micritic, biomicritic and argillaceous limestone. It is clearly distinguishable in Bolan Pass, Gwani Nala, Murree-Brewery and Hanna Lake areas. It is partly the lateral equivalent of the Bibai Formation [21, 22, 23, 24 25] and Mughal Kot Formation [9, 12]. Based on stratigraphic position [Table 1], its age is proposed as Late Campanian to Early Maastrichtian [19]. Upper contact of the formation with the Fort Munro Formation is disconformable.

The **Fort Munro Formation** represents the Fort Munro Limestone member of [12] and Orbitoides Limestone of [14 and 26]. It comprises dark bluish grey to dark grey, hard, nodular, micritic and bio-micritic limestone. In the Quetta area, the formation is composed of dark grey nodular, orbitoidal limestone, containing various species of Orbitoides, such as *Siderolites, Daviesina, Sulcoperenlina and Omphalocycles* [14], which suggest a Late Maastrichtian age. Its upper contact with the Pab Formation is disconformable.

The **Pab Formation** was introduced and described by [27] from the Pab Range in the Kirther Belt. It is dominantly composed of highly quartzose sandstone of brownish grey and cream colour. The formation in Quetta area, although very thin (1-3 m), is exposed in Zharai and Hanna Lake sections, where sandstone is light brownish grey to cream coloured, fine to very fine grained, well sorted and highly quartzose. It pinches out in the Muree Brewery and Gawani Nala, however, reappears in Bolan Pass near Dozan Railway Station. Upper contact of the formation is disconformable with the Dungan Formation. On the basis of orbitoides, and other types of foraminifera, reported from its type locality, [5, 12 and 27] assigned an Upper Maastrichtian age.

The **Dungan Formation** of Oldham [28] was redefined by Williams and Shah [12, 10]. It generally comprises nodular to massive limestone with subordinate marl, sandstone and intra-formational conglomerates. In the surrounding area it comprises compact limestone of dark brownish grey, pinkish grey, brownish grey to buff grey colours, which is interbedded with brownish grey shale. In the Hanna Lake section, it is composed of thin bedded nodular limestone in the lower part and thick bedded compact limestone in the upper part. No shale is present in the Hanna Lake section. In the Muree Brewery section it comprises only 8 m thick succession of light grey, compact, hard, thick bedded and highly fossiliferous limestone, which possess *Miscellanea, Alveolina, Glamalveolina, Lockhartia, Ranikotalia, Disticboplex Somalina, Discocyclina, Katbina* [14], which represents an Upper Palaeocene-Early Eocene age. The formation conformably and transitionally underlies the Early Eocene Ghazij Formation.

The **Ghazij Formation** has highly variable lithological characters. Its lower part is composed of greenish grey to olive green calcareous shale with occasional thin beds of medium to fine grained calcareous, buff coloured sandstone. The middle part comprises greenish grey sandstone, shale, coal seams and a thick conglomerate horizon. The sandstone is fissile, thick bedded, calcareous, in places conglomeratic, highly fossiliferous, usually associated with greenish grey, carbonaceous shale, calcareous siltstone and rarely brownish grey shelly limestone. Coal seams are mostly restricted to this part. The upper part is composed of reddish grey to brown claystone interbedded with sandstone. Occasional layers of shelly arenaceous limestone are also present. Upper contact of the formation is conformably the Spin Tangai Formation.

The **Kirthar Formation** of Noetling [28], is equivalent of the Spin Tangai Limestone of Oldham [28] and Fatmi [9]. The Spin Tangai Gorge, in the western Sulaiman Fold-Thrust Belt, has been proposed as the principal reference section for the formation. In the Zarghun Trough [Table 1] it is clearly distinguishable into the lower limestone part and upper shale part. The lower part of the formation is composed of yellow, light grey, pinkish white, buff and brown, thin to thick bedded argillaceous limestone. Most of the limestone beds are nodular; the basal part of which is rich in *Assilina*. The upper part is composed of olive, yellowish and brownish grey, soft and flaky shale. It is highly fossiliferous with abundant mollusks, brachiopods, echinoids and foraminifera. Jones [5] reported various species of foraminifera, gastropods, echinoids, bivalves. Vertebrate remains have also been reported by [5, 18, 26, 28, 30, 31and 32], on the basis of which the formation has been assigned Middle to Late Eocene age. The formation disconformably underlies Uzhda Pusha Formation of the Urak Group [6].

The nearby Zarghun-Sibbi Trough comprises the **"Urak Group",** which was named by [6] after the village of Urak, northeast of the Quetta city. The group is composed of over 4000 m thick clastic sediments, comprising the Uzhda Pusha Formation, Shin Matai Formation and Urak Conglomerate [5, 6, 33, and 34]. The **Uzda Pusha Formation** [6] mainly comprises sandstone with subordinate clay and pebbly conglomerate. Sandstone is light grey to greenish grey, coarse to very coarse grained and poorly sorted. The formation contains rich assemblage of vertebrate fossils [35, 36, 37, 38, and 39]. The Oil and Gas Development Corporation (1965, unpublished reports) assigned Middle to Late Miocene age to the formation in the Quetta-Sibi area. The formation transitionally underlies the **Shin Matai Formation** [6], which comprises monotonous cyclic alterations of sandstone and claystone beds. The sandstone is grey to brownish grey and reddish brown, medium to course grained, and thick bedded. The claystone is brownish grey, reddish brown, rusty orange, silty and sandy. Lenses and layers of conglomerate are present. Pascoe [39], on the basis of vertebrate fossils, assigned an Early to Middle Pliocene age to the formation. In the Zarghun Trough the formation transitionally and conformably underlies the Urak Formation.

The **Urak Formation** represents the Urak Conglomerate of Kazmi and Raza [6] and the upper division of the "Sibi Group" of Jones [5]. Section near the Urak Village in Quetta District, has been proposed as the type section. The formation comprises compact, massive conglomerate with subordinate sandstone and siltstone. The conglomerate consists of a variety of pebbles and boulders of various sizes. It is poorly sorted, rounded to well-rounded and clast-supported. The formation is poorly fossiliferous; however, on the basis of its stratigraphic position assigned an Early Pleistocene age.

3.2 Stratigraphy of the Spin Karez Group

The newly proposed Quaternary "**Spin Karez Group"** and its lithostratigraphic divisions exposed in the Hanna-Spin Karez area [Fig. 3a; 1] are hereby named as the Hanna Lake Conglomerate, Hanna Red Clays and Spin Karez Conglomerate [Table 1].

3.2.1 Hanna Lake Conglomerate

The **Hanna Lake Conglomerate** [1] is the lowermost formation of the Spin Karez Group [Fig. 2a]. The formation is named after the Hanna Lake, located 8 km north of the Quetta City. It is mostly exposed along the northwestern margin of northeast- southwest oriented Hanna valley. Section exposed west of the Attakzai Killi in the Hanna valley is designated as its reference section. It comprises boulder- to cobble-conglomerate in its lower part and cobble- to pebble-conglomerate, interbedded with sandstone or siltstone, in the upper part. Some conglomerate beds in the lower part has maximum clast size up to 1.5 m. It is very poorly sorted, sub-angular to sub-rounded, crudely-stratified and several tens of meters thick. Upper part of the Hanna Lake Conglomerate comprises moderately- to well-sorted cobble to pebble conglomerate interbedded with very coarse grained to pebbly sandstone and siltstone. Clasts are composed of various types of limestone, sandstone, conglomerate and chert fragments. Overall thickness of the formation is over 200 m. The formation overlies the Early Eocene Ghazij Formation with an angular unconformity and underlies the Hanna Red Clays with confirmable and transitional contact [Fig. 2b]. Based on the presence of boulders and cobbles of the Pliocene-Pleistocene Urak Conglomerate, which is the uppermost unit of the Urak Group, Early Pleistocene age is envisaged for the Hanna Lake Conglomerate.

3.2.2. *Hanna Red Clays*

The **Hanna Red Clays** is named [1] after the Hanna valley. It is well exposed east and south of the Hanna valley and nort-northeast of the Spin Karez (Spin Lake). In the Hanna valley it is mostly covered by the Holocene stream deposits and partly exposed in patches. Section exposed east of the Attakzai Killi in the Hanna valley is designated as its reference section. Lower part the formation comprises very thick succession of light to dark reddish grey claystone with minor proportion of sandstone and siltstones. The upper part is dominantly claystone, showing alternating bands of dark and light reddish grey and, partly, bluish grey colours. Thickness of the formation is about over 500 m. Its upper contact, exposed to the east of the Hanna valley is confirmable and transitional with the Spin Karez Conglomerate. Based on its stratigraphic position a Middle Pleistocene age is proposed for the Hanna Red Clays.

2.2.3 Spin Karez Conglomerate

The Spin Karez Conglomerate is named [1] after the Spin Karez (Spin Lake), 10 km east-northeast of the Quetta city, located on the Quetta-Sor Range road. It is exposed along the southeastern side of the Hanna valley making nearly vertical cliffs [Figs. 4b]. Section exposed near the Killi Babu Muhammad Jan, in the Hanna valley, is designated as its reference section. Lower part of the formation is mostly composed of cobble/pebble conglomerate with very minor proportions of siltstone, sandstone and claystone. Upper part comprises very thick and compact pebble conglomerates, which are composed of rounded- to well-rounded and moderately- to well-sorted clasts. Maximum clast size reaches up to 25 cm. Conglomerate clasts comprise various types of limestones, sandstones, conglomerates and cherts. The formation is over 100 m thick in the Hanna valley. The formation conformably and transitionally overlies the Hanna Red Clays and represents the Late Pleistocene age. Upper contact of the formation was not observed in the area.

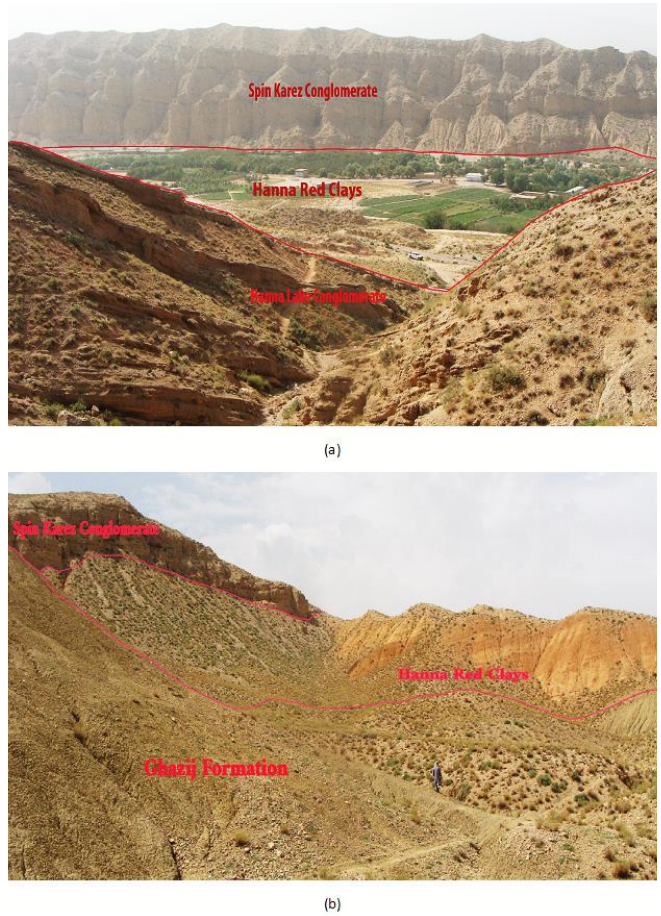


Figure 2. Photographs showing all three members from bottom to top: (a) Hanna Lake Conglomerate (lower part), Hanna Red Clays (middle part) and Spin-Karez Conglomerate (upper part); (b) The Quarternary Spin Karez deposits overlying the Early Eocene Ghazij Formation with an angular unconformity.

4. PETROLOGY AND PROVENANCE OF THE CONGLOMERATES

4.1. Petrology

Petrology of the conglomerates of the Hanna Lake and Spin Karez conglomerates of the Spin Karez Group described below:

4.1.1. *Hanna Lake Conglomerate*

The Hanna Lake Conglomerate is the boulder/cobble conglomerate in its lower part, which is followed upward by a succession of cobble/pebble conglomerate interbedded with sandstone and siltstone. Conglomerate of the lower part is composed of very large size boulders may reach up to 1.5 m. It is very poorly sorted, sub-angular to sub-rounded and poorly stratified. Upper part of the formation comprises moderately to well-sorted cobble/pebble conglomerate, interbedded with very coarse grained to pebbly sandstone and siltstone.

The conglomerate is composed of various rock types, which include a variety of limestone, sandstones, conglomerates and chert fragments [Table. 2].

Table 2. Various types of rock fragments recorded in conglomerates of the Spin Karez Group.

S. No.	Type of fragment	Lithological characters	Provenance
1	Limestone	Darkish grey color Intraclastic, pisoidal, Ooidal Sub-lithic, Angular to Rounded	Chiltan limestone
2	Arenaceous limestone	Brownish in color, Quartz grains, coarse sand grains, intraclasts(angular grains) Highly fossiliferous Different color grains, red, brownish, white, yellowish.	Sirki member of Kirthar formation
3	Quartzose sandstone	Yellowish grey in color Medium sand grains Maximum quartz grains(quartzose) Multi color grains, red,bluesh, creamy, in color Medium to fine grains Quartzose White to creamy color	Pab sandstone Pab sandstone
4	Arenaceous limestone	Creamy, light grey in color Highly fossiliferous, Intra clastic, Oncoids.	Dungan formation
5	Conglomerate oligomict	Rounded to well rounded Moderate sorted Clast types are chert, Oolitic limestone clast (maximum clasts from chiltan limestone) chiltan intraformational conglomerate Dark grey, creamy color Limy matrix	Chiltan limestone
6	Limestone	Rounded Creamy, white, grey in color Fossiliferous, assilina, nummulities, fossil shells, larger forams	Habib Rahi limestone member of the Kirthar Formation
7	conglomerate Polymict	Rounded to well-rounded clast, average clasts are pebbly Oral, spherical in shape	Sandstone of the Ghazij Formation

4.1.2. *Spin Karez Conglomerate*

The Spin Karez conglomerate is rounded to well-rounded and moderately to well-sorted cobbles and pebble conglomerate. Maximum clast size of conglomerate reaches up to 25 cm.

The conglomerate is composed of various types of rock fragments, which also include a variety of limestone, sandstones, conglomerates and chert fragments.

4.2. Provenance

Various types of the rock fragments recorded in conglomerates of the Spin Karez Group are listed in [Table 2], which also indicate their lithological characteristics and proposed the provenance. From the verities of the rock fragments it may be seen that they have been derived from the nearby mountains, most appropriately the Takatu Range, currently exposed to the west and northwest of the Spin Karez Group. The rock succession currently exposed in the Takatu Range and surrounding areas comprise Jurassic Shirinab and Chiltan / Takatu formations, Cretaceous Parh Group, the Late Cretaceous Hanna Lake Limestone and Fort Munroe Limestone, Paleocene Dungan Limestone, Eocene Ghazij Formation, Miocene-Pleistocene Uzda Pusha, Shin Matai and Urak formations [Table 1]. All these formations are exposed in the Takatu Range and adjoining areas and providing detritus, comprising a variety of limestone, sandstone, conglomerate and chert fragments, as mentioned in [Table 2].

This notion of the mentioned proposed provenance also gets support from the east-southeast-ward palaeo-current directions deduced from various sedimentary structures in the sandstone and conglomerate horizons of the Spin Karez Group, which indicate source area towards west and northwest. The same conclusion may be drawn from the variation of thicknesses of the Hanna Lake and Spin Karez conglomerates, which are very thick in the northwest (proximal area) and become significantly thin towards the southeast (distal area).

5. FACIES

Facies codes of [40, 41, and 42] have been used to describe and interpret facies of the fluvial successions. For the purpose of definitions and interpretations of the facies and associations, the classification schemes of [42, 43, and 44] have been used. In addition, classification schemes of [45], [46] and [47], were also considered for the interpretation. Succession of the Spin Karez Group is mostly clastics and may broadly be subdivided into three groups of facies, like conglomerate, sandstone and fine-grained (mudstone and siltstone) sediments. Overall 15 distinct facies were identified and defined [Table 3] in the Spin Karez Group, out of which 13 were found in the Hanna Lake Conglomerate, 11 in the Hanna Red Clays and 8 in the Spin Karez Conglomerate, which are listed in [Table 4].

6. FACIES ASSOCIATIONS

Facies of the Spin Karez Group [Table 3] have been grouped into facies associations and coded after [41, 42]. Overall the Spin Karez Group is composed of five types of facies associations (Table 5), coded as FA-1, FA-2, FA-3, FA-4 and FA-5. The Hanna Lake Conglomerates is composed of three (FA-1, FA-2, FA-3), and Spin Karez Conglomerate comprises two facies associations (FA-1 and FA-3), respectively. The Hanna Red Clays, however, is composed of two facies associations (FA-4 and FA-5). Facies associations of the Group are described as under:

6.1. Hanna Lake and Spin-Karez conglomerates

6.1.1. *Facies association (FA-1) (Clast-supported conglomerate-braided channel deposits)*

This facies association (FA-1) is characterized by massive to crudely bedded, clast-supported conglomerate, comprising facies of clast-supported, disorganized gravel (Gcm), horizontally stratified gravel (Gh), trough cross-stratified gravel (Gt), planar cross-stratified gravel (Gp), with minor facies of horizontally stratified sandstone (Sh), massive sandstone (Sm) [42].The gravel facies Gcm, Gh, Gt and Gp, however, are the dominant facies [Fig. 4a with FA-1 are lens-shaped and laterally pinches-out within five to a few tens of meters, typically against the matrix-supported conglomerate. The overlying conglomerate truncates the sandstone and mudstone facies. They are commonly < 1 m thick and marked typically by erosive base of the conglomerate facies [Fig. 5a]. & 4b] whereas, non-persistent wedges of the sandstone facies Sh, Sp, St, Sm, and mudstone facies Fm also occur in minor proportions. The sandstone and mudstone facies associated The dominating Gcm, Gh, and Gt facies of the conglomerate with concave-upward sharp and erosional bases and poorly-saved lenses of sand and mud facies indicate deposition within a gravelly braided channel system, where unstable low-sinuosity shallow channels were freely migrating laterally within a defined channel-belt. Most of the Gh units reflect deposition by longitudinal bars [43, 48, 49, 5051, 52 and 53] and down-stream migration of transverse bars formed the subordinate Gp facies [43, 50, 54 and 55]. Isolated beds of the trough cross-stratified conglomerates (Gt facies) have been commonly interpreted to represent scour-fill features [56, 57]. Tabular sand bodies with predominantly parallel-lamination typically indicate braided channels [58, 59, 61, 60 and 62]. The FA-1 is present in the Hanna Lake and Spin Karez conglomerates; however, most commonly found throughout the Hanna Lake Conglomerate.

6.1.2. *Facies association FA-2 (sheet-flood deposits)*

The facies association FA-2 (sheet-flood deposits) comprises various facies of horizontally stratified gravel (Gh), massive sandstone (Sm), plainly-laminated sandstone (Sh), planar cross-stratified sandstone (Sp) and trough cross-stratified sandstone (St) [Fig. 4c & 4d]. The sandstone mostly displays lenticular to sheet-like morphology, however, laterally they may be non-persistent to persistent. Locally the vertical succession of facies changes from Sm to Fm or Sh to Fm. The basal bounding surfaces are gradational to erosional. The horizontally laminated sandstone facies (Sh) and massive sandstone facies (Sm) are most dominant within the association FA-2. However, sandstone having low-angle cross-stratification (facies Sl), planar cross- stratification (facies Sp), ripple cross-stratification (facies Sr) and gravel-sand couplets are subordinate. Characteristics of the facies association FA-2 indicate deposition in distal parts of the braided channel system. Sandstone with sheet-like morphology indicates intermittent high-energy currents in the form of sheet-floods [62 63, 64 and 65]. The laterally continuous, laminated, sheet-like sandstone bodies are interpreted as sand-sheets that form vertically stacked products of the -lived and high-energy depositional episodes in the commonly low energy environment that is gentle depositional surfaces. Facies association FA-2 (sheet-flood deposits) is present only in southeastern part of the Hanna Lake Conglomerate of the Spin Karez Group.

6.1.3. *Facies association FA-3 (flood plain deposits)*

This association comprises of light to dark brown to rusty brown massive mudstone (facies short Fm) and finely laminated mudstone/siltstone sandstone (facies sm). Siltstone and finely laminated sandstone (facies Sh) intercalation are sporadically present [Fig. 5b]. Thickness of the mudstone facies varies from less than a meter to over 25 m. Mudstone morphology is tabular to lenticular. Sandstone and siltstone is generally tabular in shape and thickness ranges from 10 to 16 cm and show lateral continuity with sharp to erosive basal contact.

Table 3. Description and interpretation of the sedimentary facies found in the Spin Karez Group; facies codes after [41, 42] and [84].

Facies code	Lithofacies	Description	Outcrop image	Interpretation
Gmg	Matrix-supported, disorganized gravel	Massive, matrix-supported conglomerate with angular to sub-angular clasts of 5-25cm, muddy matrix, poorly sorted. Scale: Coin: 02cm		Mass-flows deposits from hyper-concentrated or turbulent flows
Gcm	Clast-supported, disorganized gravel	Massive, clast-supported conglomerate with rounded to sub-rounded clasts of 15-55cm, very coarse sandy to small pebbly matrix, poorly sorted. Scale: Marker: 14cm		Pseudoplastic debris flow deposit
Gh	Horizontally stratified gravel	Curdely-stratified, clast-supported conglomerate with rounded to sub-rounded clasts of 8-40cm, normal to reverse grading with imbrication, coarse sandy matrix, moderately sorted. Scale: Man: 200cm		Non-cohesive debris flow; bedload deposition as diffused gravel sheets or lag deposits by high-energy floods
Gt	Trough cross-stratified gravel	Clast-supported trough cross-stratified conglomerate, pebble to cobble with imbrication, rounded to sub-rounded clasts.		Transverse bars, minor channel fills
Gp	Planar cross-stratified gravel	Clast-supported planar cross-stratified conglomerate, pebble to cobble, rounded to sub-rounded clasts.		Transverse bars
St	Trough cross-stratified sandstone	Medium to very coarse sandstone with trough cross-stratification with a few conglomeratic levels. Scale: measuring tape: 08cm		Sinuous-crested and linguoid (3-D) dunes
Sp	Planar cross-stratified sandstone	Medium to very coarse sandstone with planar-cross stratification, moderate to good sorting. Scale: Coin: 02cm		Transverse and linguoid bedforms (2-D) dunes
Sr	Ripple cross-stratified sandstone	Fine- to coarse-grained sandstone with rippe cross-stratification, asymmetrical ripples, poor to moderate sorting with scattered pebbles. Scale: Coin: 02cm		Ripples (lower flow regime)
Sh	Horizontally stratified sandstone	Horizontally stratifieded sandstone with parting lineations. Scale: Coin: 02cm		Plane bed flow (critical flow)
Sl	Slightly inclined sandstone	Low-angle cross-stratified sandstone, coarse-grained. Scale: Coin: 02cm		Scour fills, crevasse splays, antidunes
Sm	Massive sandstone	Medium- to very-coarse grained, massive sandstone, occasionally granular with conglomeratic levels, moderate to good sorting. Scale: Coin: 02cm		Rapid deposition by suspension or sediment gravity flow deposits
Ss	Scour-fill sandstone	Laminated to massive scour--fill sandstone. Scale: marker: 14cm		Scour fill
Fl	Laminated mudstone / siltstone	Parallel-laminated light to dark brown, grey mud. Scale: Coin: 02cm		Waning flood deposits or overbank, abandoned channel
Fm	Massive mudstone / siltstone	Massive mudstone / siltstone with fine sandstone. Scale: Coin: 02cm		Suspension deposits of waning flows in overbank area or abandoned channel
Fsm	Laminated to massive mudstone	Laminated to massive mudstone / claystone with gypsum beds. Scale: Coin: 02cm		Back swamp deposits

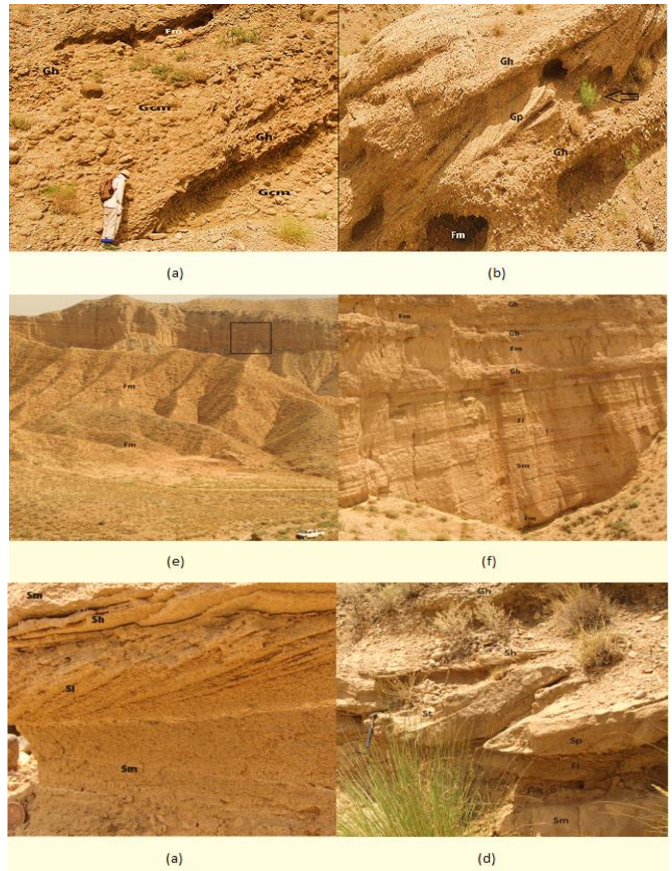


Figure 4. Photographs showing: (a) lithofacies Gcm, Gh and Gt showing facies association FA-1, scale: man ~200 cm; (b) lithofacies Gh, Gp and Fm forming facies association FA-1, scale: bush: ~30 cm; (c) lithofacies Sm, Sl and Sh forming facies association FA-2, scale: coin: 02 cm; (d) lithofacies Gh, Sh, St, Sp, Sm, Fm and Fl forming facies association FA-2, scale: hammer: 30 cm; (e) fine grained facies overlain by Spin Karez Conglomerate, scale: car; (f) close-up view of the inset area of the above picture showing lithofacies Gh, Sm, Fm and Fl, forming facies association FA-3.

Locally the mudstone / siltstone facies mark truncation boundaries with the overlying conglomerate and sandstone. The FA-3 is characterized by suspension deposits of the floodplain [40, 65]. Mader [66] interpreted it to deposit in low-energy floodplain environment, which serve as settling basin for fine-grained overbank sediments that pass over levees during high stream stage. Occurrences of reddish and brownish colours of mudstones indicate well-drained floodplains, which underwent periods of non-deposition and exposure followed by oxidation [67, 68, 69 and 70]. The occasional presence of sandstone facies within the mudstone facies are interpreted as overbank deposits. The laminated mudstone facies represent floodplain deposits formed in water-logged bodies with reducing conditions [42, 71]. The occurrence of facies Fl and Fm, is a common product of waning flow velocity associated with flow termination and channel abandonment [42, 73]. The facies association FA-3 is present both in the Hanna Lake and Spin Karez conglomerates.

Table 4. Occurrence of the lithofacies in varioussections of the Spin-Karez Group after [41] and [83].
Occurrence: / = rare; // = common; /// = abundant

Facies Code	Section 01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16
	Hanna Lake Conglomerate						Hanna Red Clays			Spin Karez Conglomerate						
Gmg							/									
Gcm	///	///	//	//		///					/					
Gh	//	///	///	///	///	//	/			///	///	///	///	///	///	///
Gt	//	//	/	/	//	//				/	/	/	//	/	/	//
Gp	/	/	/	/	//	/				/	/	/	/	/	//	//
St			//	//	//											
Sp			/	//	/		//									
Sr			//	/			/									
Sh		//	//	//	//		//		/			/	/			
Sl			/	/			/									
Sm			//	//	//		///		//	/		/	/			
Ss		/		/			/					/				
Fl		//	//	//	//		///	/	//							
Fm	/	/	//	///	///	/	//				/	//	//	/	/	/
Fsc							/	///	///							

6.2. Hanna Red Clays

The Hanna Red Clays are ~500 m thick clay-dominant succession, that mainly comprise fine-grained mudstone facies and thin- to thick bedded sandstone facies that comprises two types of facies associations; FA-4 (the marginal lacustrine deposits) and FA-5 (open-water lacustrine deposits) [Table 4], which are described below:

Table 5. Facies associations of the Spin Karez Group; modified after [41, 42].

Facies association	Major lithofacies	Grain size
Hanna Lake Conglomerate		
Braided channel deposits (FA-1)	Gh, Sm, Sh, Ss, Fm,	Pebble to cobble conglomerate, fine to coarse-grained sandstone and mud
	Gcm, Gh	Clast-supported, pebble to boulder conglomerate
	Gh, Gt, Gp	Clast-supported, pebble to boulder conglomerate
Sheet-flood deposits (FA-2)	St, Sp, Sm, with minor Sh, Fm, Gh	Pebble conglomerate, fine to coarse-grained sandstone
	Sp, St, Sm, Sh, Sl, Gh	Pebble conglomerate, fine to coarse-grained sandstone
	St, Sp	Fine to coarse-grained sandstone
	Sh, Sl, Sr, Fl	Medium to coarse sandstone and mudstone
Floodplain deposits (FA-3)	Fm, Fl	Mudstone and siltstone
Hanna Red Clays		
Marginal lacustrine deposits (FA-4)	Gmg, Sm, Sh, Fl, Fm	Fine to medium sandstone, mudstone and siltstone
An open-water lacustrine deposits (FA-5)	Fsc, Fm	Mudstone and claystone with gypsum beds
Spin Karez Conglomerate		
Braided channel deposits (FA-1)	Gcm, Gh, Sm, Fm	Clast-supported, pebble to cobble conglomerate and sandstone

6.2.1. *Facies association FA-4 (marginal lacustrine deposits)*

This FA-4 comprises light to dark brown and rusty brown terrigenous mudstone, siltstone interbedded with reddish brown sandstone forming cyclic succession, with small bands of matrix-supported breccia [Fig. 4f]. The association dominantly comprises massive mudstone (facies Fm), finely plane- and wavy-laminated mudstone facies (Fl), laminated to massive mudstone / siltstone facies (Fsm) intercalated with sandstone facies [Fig. 5c]. The associated groups of sandstone and conglomerate facies include massive sandstone facies (Sm), cross-bedded sandstone facies (Sp), horizontally-stratified sandstone facies (Sh) and <12 cm thick horizons of matrix-supported, lenticular and angular to sub-angular conglomerate facies (Gmg). The reddish-brown, massive mudstone is interpreted as siliciclastic mud that accumulated from suspension by distal sheet floods. After deposition the mud remained sub-aerially exposed thus evolved under the oxidizing conditions. The finely laminated ripples indicate lake shore currents. Facies association FA-4 records deposition in a marginal lake environment, where water level fluctuated periodically [74, 75 and 76]. The marginal lacustrine association is marked by a heterogeneous mixture of facies, often closely and repetitively interbedded [77]. The sandstone beds probably represent frequent incursion of concentrated flows into the lake environment (sand bars) that was, otherwise, characterized by suspension settling of the mud. The FA-4 is present near the transitional lower and upper contacts of the Hanna Red Clays with the Hanna Lake and Spin Karez conglomerates, respectively.

6.2.2. Facies association FA-5 (open-water lacustrine deposits)

This facies association (FA-5) comprises light to reddish dark brown terrigenous mudstone and claystone found in the Hanna Red Clays [Fig. 4f]. It is dominantly composed of massive and finely-laminated mudstone / siltstone facies (Fsm) and (Fm) with minor proportions of horizontal / ripple cross-laminated facies (Fl) [Fig. 5c]. The mudstone facies are very thick, reaching up to several tens of meters. Rarely, up to 8 cm thick gypsum beds are found. The dark brownish grey and red colour, which is characteristic of the mudstone facies, is interpreted as offshore lake deposits formed by settling of suspended sediments of the water bodies characterized by oxidation of the strata due to sub-aerial exposure that signifies shallow depth and / or intermittent drying of the lake [78, 79]. The preserved evaporite (gypsum) suggests supply of salt water to the lake. The dominantly massive mudstone, with localized laminated and rippled facies and

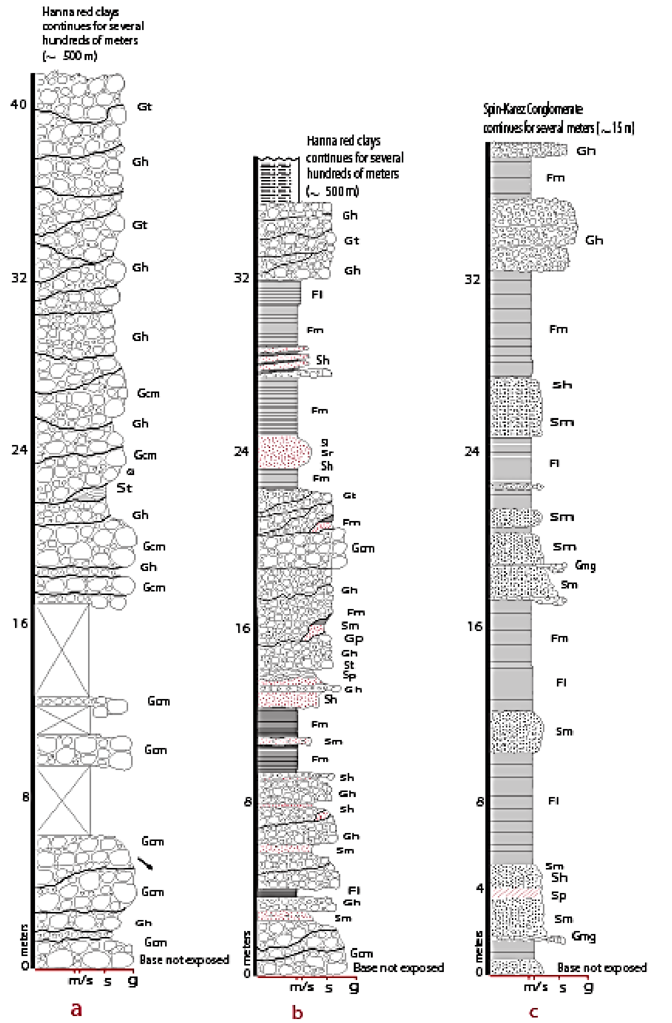
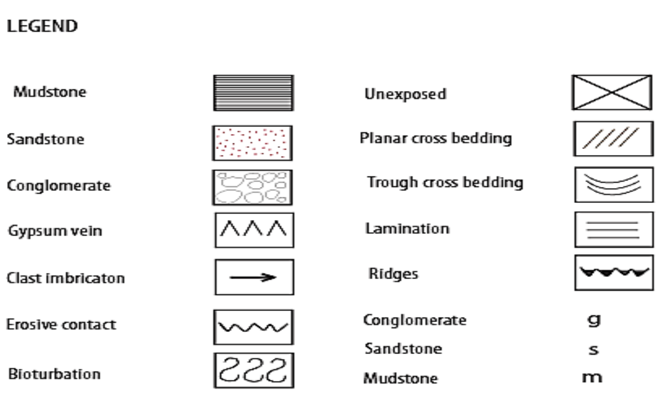


Figure 5. (a) sedimentary log of Hanna Lake Conglomerate, Killi Attakzai Section (1), (N 30° 26.33; E 67° 13.93); (b) sedimentary log of Hanna Lake Conglomerate, Killi Samad Khan section (3), (N 30° 25.56; E 67° 12.64); (c) sedimentary log of Hanna Red Clay, Dam section (7), (N 30° 25.62; E 67° 15.36).

thinly-stratified gypsum, represents a closed salt lake environment.



7. DISCUSSION

The Quaternary succession of the Spin Karez Group [1, 5], which covers an area of about 30 km^2, is exposed near the Quetta Syntaxes and Zarghun Knot (a famous orographic feature) at the junction of Kirthar and Sulaiman Fold-Thrust belts, Pakistan [2, 3, 4]. The Group is exposed within and both sides of "Hanna Valley" and extends from the Eastern

Margin of "Hanna Lake" to the "Spin Karez" area. The HSC [5] mapped the area as the "Spin Karez Gravel". Naseer [1] remapped the Quaternary succession of the area and re-named the succession as the Spin Karez Group. If the Stratigraphic Codes are applied on the Quaternary succession of the study area, it will clearly be entitled to the status of a "Group" [80]. Naseer [1] also subdivided the succession into three lithostratigraphic units, namely, the Hanna Lake Conglomerate, Hanna Red Clays and Spin Karez Conglomerate. The lithostratigraphic units of the Spin Karez Group are thick, have distinct lithological characters and mappable, therefore, deserve the status of formations as per the stratigraphic procedures [80]. Previous workers, however, did not realize that the successions actually is a mappable lithostratigraphic unit, further divisible into 3 distinct mapable lithostratigraphic units and deserves the status of a "Group".

The Spin Karez Group comprises ~800 m thick fluvial and lacustrine succession with surface area of ~30 km^2, which was deposited on top of the thick mudstone-dominant succession of the Eocene Ghazij Formation. The incompetent, mudstone-dominant, lithology of the Ghazij Formation provided accommodation for development of the Group, which was primarily controlled by subsidence and regional tectonics. We suggest that the succession was deposited in a trough that developed within the incompetent claystone-dominant succession of the Early Eocene Ghazij Formation between the present Hanna Lake and Spin Karez areas. To the north and west of the trough the older rock succession of Jurassic through Pleistocene age is exposed, whereas, to the northeast younger rock succession of Late Eocene through Pleistocene age is exposed.

Very high thickness, coupled with very limited surface area (accommodating space), of the Group suggest that vertical accretion prevailed over the lateral and downstream accretion, which shows high rate of subsidence of the basin. Moreover, the Hanna Lake Conglomerate, which is the oldest (lower-most) unit of the Group, dips 24° to the SE. The upper-most unit of the Group, the Spin Karez Conglomerate, overlying the Hanna Red Clays, however, is comparatively very low dipping (< 10^o). Overall the Group comprises a SE-plunging, open-type, syncline, the trend of which is highly contrasting to the trend of the surrounding older succession (of Jurassic through Pleistocene), showing little and/or no relevance with the regional tectonics. This further supports domination of the process of subsidence of the depositional basin.

The basin experienced two different kinds of sedimentary fills; a) fluvial deposits of the Hanna Lake and Spin Karez conglomerates and, b) lacustrine deposits of the Hanna Red Clays. Variations in the regional tectonic conditions of the surrounding area gave rise to the change of depositional environments from gravelly braided channel systems (Hanna Lake Conglomerate) to the shallow lacustrine deposits (Hanna Red Clays) and back to the gravelly braided channel system (Spin Karez Conglomerate) [81, 82]. Our study indicates that deposition of the Spin Karez Group evolved in three phases; i) Deposition of the Hanna Lake Conglomerate started, in the Quaternary period, in the proximal and medial to distal braided channel system in the northern and southern parts of the area, respectively, over the mud-dominant strata of the Lower Eocene Ghazij Formation. Deposition continued along with the subsidence of the depositional basin. Composition of the detritus resembles with the neighboring mountains of the western Sulaiman Fold-Thrust Belt, to the north and west, which were the source terrain of the detritus. ii) Deposition of the Hanna Red Clays continued that gradually evolved to the development of a shallow lake that comprised lake-shore and open shallow-water lake deposits, which also indicate episodic exposure to sub-aerial conditions and oxidation providing reddish colour to the facies. iii) The depositional system, once again, resumed to the braided channel system of the Spin Karez Conglomerate that gradually developed over the shallow lake deposits of the Hanna Red Clays. The accommodation space of the small shallow basin (~30 km^2) stacked the three depositional systems, of the Spin Karez Group, over each other during the Quaternary period and dynamics of the basin were mainly controlled by continued subsidence and regional tectonics. Being composed of thick permeable succession of mostly conglomerate, its further study will be useful for understanding the groundwater situation of the area.

8. SUMMARY AND CONCLUSIONS

i) The group has been recognized and mapped recently by Naseer, [1]. However, sedimentology of various constituent formations of the group has not been studied in detail. This study was timely and significant to further elaborate the geotectonic history of the area and play an active role for understanding the exploitation of the water resource.

ii) The Quaternary succession exposed in the Hanna-Spin Karez area is over 800 m thick. We propose the name "Spin Karez Group" for the overall succession, which is clearly divisible into three discrete lithostratigraphic units of formation rank. The Early Eocene Ghazij Formation underlies the succession with an angular unconformity. We propose the names "Hanna Lake Conglomerate", "Hanna Red Clays" and "Spin Karez Conglomerate for the constituent units of the Group.

iii) Conglomerate of the Spin Karez Group is the boulder-pebble size, which is poorly sorted, sub-angular to sub-rounded and poorly stratified, interbedded with very coarse grained to pebbly sandstone and siltstone. It is composed of various types of rock fragments, which include a several varieties of limestone, sandstone, conglomerates and chert. Lithological characteristics of the varieties of the rock fragments indicate derivation from the nearby mountains, most appropriately the Takatu Range, currently exposed to west and northwest of the Spin Karez Group.

iv) The older rock succession, exposed in the Takatu Range and surrounding areas, comprise Jurassic Shirinab and Chiltan / Takatu formations, Cretaceous Parh Group, the Late Cretaceous Hanna Lake Limestone and Fort Munro Limestone, Paleocene Dungan Limestone, Eocene Ghazij Formation, Miocene-Pleistocene Uzda Pusha, Shin Matai and Urak formations, which were exposed in the source area and providing detritus to the Spin Karez Group.

v) Overall 15 distinct facies were identified in the Spin Karez Group, which may broadly be subdivided into gravel, sand and fine-grained groups. The Hanna Lake Conglomerate comprises 13 facies, the Hanna Red Clays 11 and the Spin Karez Conglomerate 08 facies.

vi) The Group comprises five types of facies associations, which include: braided channel deposits (FA-1), sheet-flood deposits (FA-2), floodplain deposits (FA-3), marginal lacustrine deposits (FA-4) and open-water lacustrine deposits (FA-5). The Hanna Lake Conglomerate comprises three facies associations (FA-1, FA-2, FA-3), the Spin Karez Conglomerate two facies associations (FA-1 and FA-3) and the Hanna Red Clays also comprises two facies associations (FA-4 and FA-5).

vii) Overall the Hanna Lake and Spin Karez conglomerate comprise facies associations that are characteristic of the braided channel system and the Hanna Red Clays comprise facies associations that are characteristic of the marginal and open-water lacustrine deposits.

viii) It is proposed that accommodation space for the small shallow basin (~30 km^2) that stacked depositional systems of the Spin Karez group during the Quaternary period was mainly controlled by continued subsidence and regional tectonics.

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All the authors have equally contributed to this study from conceptualization to the write up of the final draft.

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