Sind Univ. Res. Jour. (Sci. Ser.) Vol: 38(1) 1 - 32 (2006)

Lithofacies and Lateral Extension of latest Cretaceous Dinosaur beds from Sulaiman Foldbelt, Pakistan

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Received Jan. 2005, Revised Dec. 2005

Abstract

The Late Cretaceous Pab Formation consists of quartzose sandstone with subordinate muds, deposited on the western continental margin of Indo-Pakistan plate, is well exposed in the Sulaiman and Kirthar foldbelts, and coeval strata like upper part of Lumshiwal and lower part of Hangu Formation are also exposed in the upper Indus basin like Trans Indus, Salt Range, Kohat and Potwar regions. The Pab Formation of Dhaola Range of central Sulaiman foldbelt is divided into three members namely Dhaola, Kali and Vitakri members. Vitakri member is the host of Latest Cretaceous (Maestrichtian) dinosaurs and other archosaurs from Sulaiman fold belt. Vitakri member or dinosaur beds will be used synonymous. Eight lithologic sections have been measured through the upper part of Pab Formation. Out of these, five lithologic sections across strike extent of some 80 km, and four (one is overlaping) lithologic sections along a strikewise extent of some 250 Km, provide new data on the depositional environments, lateral extention and depositional pattern of Latest Cretaceous dinosaur beds and their coeval sequences in the Sulaiman foldbelt.

The four main facies of Latest Cretaceous strata of upper part of Pab Formation identified in the Sulaiman foldbelt are; Facies F1 (Trough cross and planner laminated/bedded sandstone), Facies F2 (Massive reddish brown to red muds), Facies F3 (Carbonaceous shale) and Facies F4 (Tabular/planner and trough cross bedded sandstone interlayered with the subordinate greenish grey and minor reddish brown muds). These facies formed by a range of sand transporting mechanisms that includes classical meandering and overbank flood flows, oxbow and crevasse splays lakes, storm and river flood generated flows, and high and low energy tractional flows. Three facies associations identified in the upper part of Pab Formation are, meandering river and overbank flood association well exposed in the southern part of central Sulaiman foldbelt, oxbow lake and Crevasse splays lacustrine association found in the Kingri area of northern part of central Sulaiman foldbelt, and alluvial deltafan beech association (mostly submarine and rarely subaerial) located in the Kaha-Harrand section of southern Sulaiman foldbelt and in the Musa Khel and Mughal Kot sections of the northern Sulaiman foldbelt. Facies association patterns demonstrate the existence of three depositional systems in the Sulaiman foldbelt during the Latest Cretaceous. Sandbodies with subordinate muds formed in westward prograding mostly submarine and partly subaerial dominate north and south systems, while the central system like meandering river and associated flood bank, oxbow and crevase splays lacustrine environments deposited the sandstone, reddish brown muds, coal,carbonaceous shale and green muds in the central part of Sulaiman foldbelt. Quartzose nature of sandstone and paleoflow suggest supply from the uplifting Indo-Pakistan Shield to the eastward. Sediment gravity flow generally evolved from east-west.

The Dinosaur beds/Vitakri beds thickness varying from 15 meter(m) to 35 m, is increasaing toward WSW and decreasing ENE directions. The lateral extension of Latest Cretaceous (Maestrichtian) dinosaur beds of the Pab Formation have been observed in major four anticlinorium named as Vitakri-Mari Bohri anticlinorium (Barkhan and Kohlu districts), Dhaola anticlinorium (Barkhan and Kohlu districts), Phulali anticlinorium (Barkhan, Dera Bugti and Kohlu districts) and Fort Munro anticlinorium (Dera Ghazi Khan and Rajan Pur districts). A model of meandering river named as D.G.Khan-Vitakri river forming lobate belt shape, flowing EW from Indian shield to Fort Munro, and flowing ENE to WSW from Fort Munro to Mari Bohri via Vitakri. The exposed strata of dinosaur beds (Vitakri member) of southern part of central Sulaiman foldbelt is surrounded by coeval strata like the lacustrine charged by overbank flood in the near north(Badhi and Kingri), mostly submarine and partly subaerial alluvial deltafan in the farther north (Musa Khel and Mughal Kot area), deltafan and shelf marine in west, deltafan in the south(Kaha-Harrand area) , and terrestrial paleoland (and Indo-Pakistan Shield) in the east.

Keywords: Cretaceous dinosaur beds, Sulaiman fold belt, Pakistan.

Introduction

The Late Cretaceous Pab Formation consists of quartzose sandstone with subordinate muds, deposited on the western continental margin of Indo-Pakistan plate, is well exposed in the Sulaiman and Kirthar foldbelts, and its coeval strata like upper part of Lumshiwal and lower part of Hangu Formation are also exposed in the upper Indus basin like Trans Indus, Salt Range, Kohat and Potwar regions. The present study is restricted to the Sulaiman foldbelt of Pakistan (Figure-1). The Pab Formation of Dhaola Range of central Sulaiman foldbelt is divided into three members namely lower Dhaola, middle Kali and upper Vitakri members (Figure-5). Vitakri member (Figure-16) is the host of Latest Cretaceous dinosaurs and other archosaurs from Sulaiman fold belt, Pakistan. Eight lithological sections have been measured through the upper part of Pab Formation. Out of these, five lithological sections across strike extent (Figure-14)of some 80 km, and four (one is overlaping with across strike) lithological sections (Figure-15) along a strikewise extent of some 250 Km, provide new data on the depositional environments, lateral extention and depositiopnal pattern of latest Cretaceous dinosaur beds and their coeval strata in the Sulaiman foldbelt. Facies association and paleoflow patterns demonstrate the existence of three depositional systems (Figure-18) in the Sulaiman foldbelt during the Latest Cretaceous. Sandbodies with subordinate muds formed in westward prograding mostly submarine and partly subaerial dominate north and south system, while the central system like meandering river and associated flood bank, oxbow and crevase splays lacustrine environments deposited the sandstone, reddish brown muds, coal,carbonaceous shale and green muds in the central part of Sulaiman foldbelt. Quartzose nature of sandstone and paleoflow suggest supply from the uplifting Indo-Pakistan Shield to the eastward. Sediment gravity flow generally evolved from east to west.

The fluvial lithofacies of central system of sulaiman foldbelt is the host of following Latest Cretaceous fauna. From first discovery to uptill now round about three thousand fragmentary bones/pieces of bones/fossils have been collected by author from the terrestrial strata of Latest Cretaceous (Maestrichtian) dinosaur bed/Vitakri member of uppoer part of Pab Formation from Central Sulaioman foldbelt. Pakistani Titanosaurs tails tell five tales. Three genus and species (*Pakisaurus balochistani, Sulaimanisaurus gingerichi and Khetranisaurus barkhani)* of herbivorous Pakisaurid=Titanosaurid, and two genus and species (*Marisaurus jeffi and Balochisaurus malkani)* of herbivorous Saltasaurids are erected (Malkani,2004a,d). One genus and species (*Vitakridrinda sulaimani)* of carnivorous Abelisaur Theropod established (Malkani,2004a,d). One genus and species (*Pabwehshi pakistanensis)* of Mesoeucrocodylia are established (Wilson, et al. 2001, Malkani, 2004b). In addition to this, a partial skull(Malkani, 2003a) along with nearby findings of some cervicals, dorsals, caudals and appendicular elements (Malkani, in process) of *Marisaurus*, four armor bones(Malkani, 2003b), one braincase (Wilson, Malkani and Gingerich,2005), and an atlas-axis complex, (Malkani, in review) have been described. The author also uncovered a Rostrum of *balochisaurus* (Titanosaurian sauropod), a snout of *Vitakridrinda* (Abelisaurian Theropod), an overlapping dentary teeth(partial), and many cervical, dorsal, sacral and caudal vertebrae, and appendicular elements of Pakistani

Titanosaurian sauropod saurishian dinosaurs (Malkani, in process).

One genus and species (*Brohisaurus kirthari*) of Late Jurassic Titanosauria have been discovered from Kirthar foldbelt, Pakistan (Malkani, 2003c).

In this paper reports on the lithofacies, depositional environments and lateral extension of Latest Cretaceous dinosaur beds in Sulaiman foldbelt..

Geological and stratigraphical setting

The study area of Sulaiman fold belt is located in the Central part of Pakistan (Figure-1). Latest Cretaceous (Maestrichtian) dinosaurs are hosted by the Pab Formation of Sulaiman fold belt. The Latest Cretaceous Sediments in the study area underwent considerable tectonic deformation during the collision of Asian and Indo-Pakistan continental plates that commenced in the Late Cenozoic. As a result dinosaur beds along with other formations have been folded. The lateral extension (Figure2)of dinosaur beds of the Pab formation have been observed in the major four anticlinoriums (Figure-4) generally trending NNE to SSW, however the western part of Dhaola and Mari Bohri anticlines trend E-W forming lobate belts. The First, Vitakri-Mari Bohri anticlinorium is located in the Barkhan and Kohlu districts, extended more than 40 km started from Gumbrak in the northeast and running from Vitakri to Makhmar via Mari Bohri plunging in to the Mawand syncline on the west. Actualy this anticlinorium consists of two doubly plunging anticline named as Vitaki and Mari Bohri anticlines loacted on the direction of same fold axis. Further north of this anticlinorium, Ber-Fazil Chil and Jandran anticlines trending parralel are located. At the locality of Eastern plunge of Ber-Fazil Chil anticline which is faulted mand thrusted show the sediment gravity flow like igneous volcano. Previously it is marked as Kohlu Volcano by Bannert, D. *et al.*, (1995). The materials of gravity flow consist of mostly fragments of Pab and Rakhi Gaj formations. The dominant colour of matrix of flow is red to redish brown which may be due to intense faulting and red colour of Vitakri member of Pab Formation. This red colour gives a clue for the dinosaur red beds. The second, Dhaola anticlinorium is located in the Barkhan · and Kohlu districts, and extended more than 60km started from Badhi in the northeast and running from Badhi to Chapper via Mazara, Hanki, Ohi, Dhaola, Andhari, and plunging west in the Makhmar area. The third, Phulali anticlinorium is located in the Barkhan, Dera Bugti and Kohlu districts and extended upto 50 km started from Rakhni in the northeast and running from Phulali to Siah Koh via Pikal. This anticlinorium consists of three doubly plunging anticlines named as Phulali, Pikal and Siah Koh anticlines with same trend of fold axis. The fourth, Fort Munro anticlinorium is located in the Dera Ghazi Khan and Rajan Pur districts, and extended more than 70 km started from Sori Lund Rud in the NNE and running from Shadani to Kalchas via Mithwan, Anari-Fort Munro, Choti Nala, Kan, Chitri, Dragal /Ziarat Sheru, Kaha and Mari.

The Sulaiman foldbelt consists of sedimentary rocks ranging in age from Jurassic to Recent (Figure-3). The rocks comprising of shale, limestone, sandstone, siltstone, marl and conglomerate in different lithological units in ascending order as; Jurassic Sulaiman group representing Spingwar, Loralai and Chiltan formations, Cretaceous Parh group representing Sember, Goru and Parh formations, newly proposed Fort Munro group representing Mughal Kot, Fort Munro and Pab formations; Paleocene Ranikot

Group representing Khadro, Rakhi Gaj and Dungan formations; Eocene Ghazij Group represents Shaheed Ghat, Toi, Drug and Baska formations; (newly proposed) Kirthar group represents Habib Rahi, Domanda, Pir Koh and Drazinda formations, Oligocene-Pliocene Vahoa (newly proposed) group represents Chitarwata, Vahoa, Litra and Chaudhwan formations, Pleistocene Dada Formation, Subrecent and recent fluvial, eolian and colluvial deposits (Malkani, 2004c) (Figure-3, Table-1).

Table-1; STRATIGRAPHIC SEQUENCE OF SULAIMAN FOLDBELT

Age		Formation	Lithology
QUATERNARY	Recent	Modern channel deposits	Gravel, sand, silt and clay
		Sand, silt and clay deposits (cultivated lands)	Sand, silt and clay with minor gravel
	and	Sand, silt and clay deposits (non-cultivated lands)	Sand, silt and clay with minor gravel
		Colluvium deposits	Boulder, pebbles,cobbles,with sand silt and clay.
		Fan gravel deposits	Poorly consolidated gravel, sand, silt and clay.
	Sub-Recent	Terrace gravel deposits	Poorly consolidated gravel, sand, Silt and clay.
		Angular Unconformity	
	Pleistocene	Dada Formation	Conglomerate, sandstone and clays.
		Angular Unconformity	
TERTIARY	Pliocene	Chaudhwan Formation	Clays, conglomerate and sandstone
		Litra Formation	Sandstone, clays and conglomerate
	Miocene	Vihova Formation	Clays, sandstone and conglomerate
	Oligocene	Chittarwata Formation	Clays, conglomerate and sandstone
		Disconformity	
		Drazinda Formation	Shale with minor coquina.
		Pir Koh Formation	Limestone, marl and shale.
		Domanda Formation	Shale with minor coquina and gypsum.
		Habib Rahi Formation	Limestone, marl and shale.
	Eocene	Baska Formation	Gypsum, shale with minor silty dolomite.
		Drug Formation	Rubbly limestone and mudstone / shale.
		Toi Formation	Sandstone,shale, rubbly limestone and coal.
		Shaheed Ghat Formation	Mainly shale with minor marl / limestone and siltstone.
	Paleocene	Dungan Formation	Limestone, marl and shale
		Rakhi Gaj Formation	Shale, mudstone, siltstone, sandstone & limestone
		Khadro Formation	Limestone with minor shale and sandstone
		Disconformity	
CRETACOUS		Pab Formation	Sandstone with subordinate shale
	Late	Fort Munro Formation	Limestone, shale and coquina beds
		Mughal Kot Formation	Shale with minor marl/limestone and coquina beds
	Early	Parh Formation	Limestone with minor marl and shale
		Goru Formation	Shale and marl with minor limestone
		Sembar Formation	Mainly shale with minor marl and mudstone
	Late	Disconformity	
		Chiltan Formation	Mainly Limestone.
JURASSIC	Middle	Loralai Formation	Limestone with insignificant shal
	Early	Spingwar Formation	Shale, marl and limestone.

Previous investigations

Late Cretaceous Pab Formation is well exposed in the Sulaiman and Kirthar fold belts of Pakistan. Previous pioneer worker who described the Lithofacies and depositional environments of Pab Formation include Khan, *et al.*, (2002), Warwick, *et al.*, (1995), Sultan (1997), and Malkani, (2003b). Khan, et al. (2002), described the lithofacies and depositional environments of Mughal Kot and Pab formations of Pab Range and its northern extension up to Karkh area of Kirthar Range. Khan *et al.* (2002) argued that facies association and paleoflow patterns demonstrate the existence of two depositional systems in the central Kirthar area during the Late Cretaceous. Sandstone formed in a NW-prograding submarine fan dominate a southern system, while in the north the storm and river flood influenced shelfal sands were conveyed to the west and WNW. The shore face environment was assigned in the northern part (Karkh area) of central Kirthar foldbelt. Warwick, *et al.*, (1995) described the lithofacies of some Cretaceous and Paleocene rocks in Surghar and Salt Range coalfields.

Sultan, (1997) reported that the Pab Formation of Sulaiman foldbelt attain the thicknesses ranging up to 400 meter and are dominated by quartzose sandstone with minor muds, which were deposited on the western continental margin of the Indo-Pakistan plate. In the western part of the Sulaiman Province, the formation is marginal marine to fluvial. Fluvial deposits include cycles of fining upward grainsize, poor sediment sorting, decreasin upward bed thickness, trough cross bedding, reddish brown overbank deposits, and silty to muddy matrix in upper parts of Pab Sandstone. Sultan (1997) assigned Pab Formation dominantly upper shore face environments, with subordinate fluvial, lagoonal, estaurine, and lower shoreface facies.

Malkani, (2003b) assigned the fluvial origin of uppermost part of Latest Cretaceous Pab Formation in the central Sulaiman foldbelt. The Pab Formation of Vitakri region has been divided in to three members. The lower member is named as Dhaola member (Dhaola means white) which mainly consists of white, light brown, whitish grey, thin to thick bedded, fine to coarse grained and poor sorted quartzose sandstone. The type locality of this member is Dhoala Nala (Grid refernce; 29^0 42' 41'' N , 69^0 29' 48'' E). The middle member is named as Kali member(Kali means black) represents white, light brown, whitish grey, thin to thick bedded, fine to coarse grained, muddy matrix and poorly sorted quartzose sandstone with cyclic alternations of greenish grey to reddish brown mudstone. The matrix of Kali member is more muddy and ferruginous representing black desert varnish than Dhaola member. The type locality of Kali member is designated the southeast of Gumbrak village located in the northern flank of Dhaola anticlinorium (Grid refernce; 29^0 42' 41'' N , 69^0 29' 42'' E). The upper member named as Vitakri member/dinosaur beds, is the host of dinosaurs and other archosaurs, connsists of red , greenish grey mudstone with cyclic alternations of white, whitish grey to light brown, poorly sorted quartzose sandstone and conglomerate with a mudy matrix. The type locality (Grid refernce; 29^0 41' 19'' N , 69^0 23' 02'' E) of Vitakri member is the Vitakri village. It is well exposed in the east and southeast of Vitakri (Figure 6). The host rock of dinosaurs and other archosaur fossils is the reddish brown muds of the Vitakri member, represents fluviatile continental/terrestrial (meandering river and over bank system) environments Sandstone beds represents as channel fill

deposits and red brown mud/clay of over bank deposits. Fluvial environment (Figure 19) is interpreted on the basis of vertebrate fossil (dinosaurs and crocodiles) assemblages, absence of marine fauna, red and brown mud, iron concretions and calcrete found in the over bank mud/clay horizons; trough cross and planner bedding/lamination, poor sediment sorting and muddy matrix found in the channel fill sandstone. Generally three fining upward sequences (sandstone and mud/clay), starting from topmost sandstone of Kali member, passing through Vitakri member to lower Khadro shale are found in the central Sulaiman flodbelt.

Materials and methods

Most of the data presented here have been obtained from measured stratigraphic columnar logs at eight localities in the Sulaiman foldbelt (Figure 6-13, 19), supplemented by observations made in the field. Field work was done in the Sulaiman fold belt for about one month during early 2005. The measured sections of dinosaur beds include lithologic log of dinosaur beds in Mari Bohri area, eastern plunge of Mari-Bohri anticline (Figure-6), lithologic log of dinosaur beds in Kinwa Kali Kakor locality of Vitakri area (Figure-7,16), and lithologic log of dinosaur beds in Basti Nala(Zubra) area, north western limb of Dhaola anticlinorium (Figure-8), Barkhan district, Balochistan; lithologic log of dinosaur beds in Khar-Fort Munro area (Figure-9) and lithologic log of dinosaur beds in Rakhi Gaj area (Figure-10), Dera Ghazi Khan District, Punjab Province. Other measued sections of coeval strata of dinosaur beds include lithologic log of upper part of Late Cretaceous Pab Formation in Kaha-Harrand area (Figure-11), Rajan Pur district, Punjab, lithologic log of upper part of Late Cretaceous Pab Formation in Kingri area (Figure-12), and lithologic log of upper part of Late Cretaceous Pab Formation in Hazarghat/Musa Khel area (Figure-13) of Musa Khel district, Balochistan. Correlation chart of dinosaur beds across strike (Figure-14) and correlation chart of dinosaur beds and coeval strata along strike wise (Figure-15) in the Sulaiman foldbelt have been prepared. Stratigraphic correlations between the sections were made by using the best fit method. Paleoflow directions were tentatively known from the cross bedding and in situ occurrences of some dinosaur fossils.

Lithofacies of latest cretaceous strata of upper part of pab formation in sulaiman fold belt.

Eight representative lithologic sections through the Latest Cretaceous strata of upper part of Pab Formation in the Sulaiman foldbelt have been measured (Figure 6-13). The four main facies of Latest Cretaceous strata of upper part of Pab Formation are identified in the Sulaiman foldbelt on the basis of lithology, grain size, fossil occurrences and internal sedimentary structures. These Four facies are; Trough cross and planner laminated/bedded sandstone; Massive reddish brown to red muds; Carbonaceous shale; and Planner/tabular and trough cross bedded sandstone interlayered with the subordinate greenish grey and minor reddish brown muds. These facies formed by a range of sand transporting mechanisms that includes classical meandering and overbank flood flows, oxbow and crevasse splays lakes, storm and river flood generated flows, and high and low energy tractional flows.

Facies F1 (Trough cross and planner laminated/bedded sandstone)

The Facies F1 belongs to the Vitakri member/Dinosaur beds and uppermost

part of middle Kali member of Pab formation (Figure 14). This facies is confined to the southern portion of central Sulaiman foldbelt. This facies is characterised by white, whitish grey, thin to thick bedded, fine to coarse grained, quartzose, poorly sorted, laminated to planner bedded and trough cross bedded sandstone (Figure-17). The thickness of every sandstone units vary from 2m to 8m. The base of the small scale trough cross bedded cosets in lenticular fine sandstone are irregular, displaying shallow scouring in to underlying parallel laminated fine sandstone. The top of the small scale trough cross bedded cosets in lenticular fine sandstone are smooth and even with the parallel laminated fine sandstone (Figure-17). This facies have basal thin lag conglomerate.

Interpretation

This facies was deposited under high energy fluviatile condition by meandering river induced flows. This meandering river develop laterally restricted, effectively channelled paths from Indo-Pakistan shield to sea. Basal lag conglomerate help the criteria for channel deposition by meandering river. These conditions are well established in Late Tertiary to modern Indus river basin in Pakistan. Small scale trough cross bedding cosets and associated basal and upper parallel laminations(Figure-17) represents interesting depositional history. The parallel laminations developed at the bottom of the low scale trough cross beds represents a plane bed phase of upper flow regime transport at high flood velocity. When curerent velocity diminished into the lower flow regime at the time of waning flood stage, ripple cross lamination/ trough cross bedding formed on top of the plane lamina with some scouring. A later flood pulse deposited upper flow regime plane beds on top of the ripple cross lamination/ trough cross bedding (Figure-17). This coarse strata as sandstone is deposited as channel deposits by lateral accretion process.

Facies F2 (Massive reddish brown to red muds)

The Facies F2 belongs to only dinosaur beds/ Vitakri member of the upper part of the Pab Formation, is the host of Latest Cretraceous dinosaurs(Figure 14, 18). This facies is confined to the southern part of central Sulaiman foldbelt. This facies F2 varying in thickness from 2-15 meters(m.) consists of red to reddish brown, greenish grey, massive mudrocks having dinosaur fossils, ferruginous concretions and calcretes.

Interpretation

This facies was deposited on overbank flood flows under high energy fluviatile condition by meandering river. The red colour of muds, occurrence of dinosaur fossils, and ferruginous concretions represents overbank flood deposits. The alternation of relatively thick red muds with the sandstone represents overbank and channel deposition respectively. The fine strata as red mud is deposited as flood plain vertical accretion process. The sandstone unit is formed by lateral accretion of channel sand bars.

Facies F3 (Carbonaceous shale)

The Facies F3 belongs to the uppermost part of of Pab Formation and confined to Kingri and its vicinity in the northern portion of the central Sulaiman foldbelt. This facies is characterised by blackish grey/ dark grey to greenish grey shale (Figure 12,15). It also consists of poor grade coal in the Kingri area. Carbonaceous shale have two cyclic alternations with facies 1. The thickness of every cycle of carbonaceous and grey

shale vary from 2m to 8 m. It is thin in the Badhi area and thick in the Kingri section. Babhi area is located near the Rakhni.

Interpretation

This facies was deposited under lacustrine conditions representing oxbow lake and crevasse splays lake in the Badhi and Kingri areas. This facies is interlayerd with facies F1. Here Facies F1 represents lateral accretion of meandering channel.

Facies F4 (Tabular/planner and trough cross bedded sandstone interlayered with the subordinate greenish grey and minor reddish brown muds)

The Facies F4 belongs to the upper part of of Pab Formation and confined to the northern and southern part of Sulaiman foldbelt (Figure 11, 13). This facies is also well exposed just below the Facies association 1 in the southern portion of central Sulaiman foldbelt, just below the Facies association 2 in norther portion of central Sulaiman foldbelt. This facies is characterised by white, whitish grey, thin to thick bedded, fine to coarse grained, quartzose, poorly sorted and tabular/planner and trough cross bedded sandstone, and greenish grey to grey shale with minor reddish brown muds.

Interpretation

The facies F4 was deposited under high energy fluviatile condition by storm and river flood generated flows, high and low energy tractional flows. Sandstone with opposing planner cross bedded show the reversal tidal beach environments. The opposing planner cross bedding represents the bimodal paleocurrent direction possibly produced by ascending and descending tides. The occurrence of the minor reddih brown muds represents subaerial part of deltafan. The sandstone with grey muds represents submarine part of deltafan.

Depositional environments of latest cretaceous strata of upper part of pab formation in sulaiman fold belt

First of all I would like to describe the some general terms of sedimentary structures. Tabular cross bedding consists of cross bedded units that are broad in lateral dimensions with respect to set thickness and that have essentially planar bounding surfaces. Trough cross bedding consists of cross bedded units whose bounding surfaces are curved. Tabular cross bedding is formed mainly by the migration of large scale ripples (and dunes). Individual beds range in thickness from a few tens of centimeters to a meter or more, but bed thickness up to 10 meter can be formed (Harms et. al., 1975). Trough cross bedding can originate both by migration of small-scale ripples which produce small scale cross-bed sets and large-scale ripples which produce large scale cross-bed sets. Ripple cross lamination(climbing ripples) forms when deposition takes place very rapidly during migration of current or wave ripples. A series of cross laminae are produced by superimposing migrating ripples. The formation of ripple cross lamination appears to require an abundance of sediment, especially sediment in suspension which quickly burries and preserves original rippled layers. Abundant suspended sediment supply must be combined with just enough of laminae from the stoss side of ripples. Some ripple laminae may be in phase(one ripple crest lies directly above the other), indicating that the ripples did not migrate. In phase ripple laminae form under condition where a balance is achieved between traction transport and sediment supply so that ripples do not migrate despite a growing sediment

surface. Ripple cross lamination occurs in sediments deposited in environments characterised by rapid sedimentation from suspension (Fluvial flood plains, point bars,river deltas subject to periodic flooding, and environments of turbidite sedimentation. The parallel laminations developed at the bottom of the low scale trough cross beds represents a plane bed phase of upper flow regime transport at high flood velocity. When curerent velocity diminished into the lower flow regime at the time of waning flood stage, ripple cross lamination/ trough cross bedding formed on top of the plane lamina. A later flood pulse deposited upper flow regime plane beds on top of the ripple cross lamination/ trough cross bedding. Ripple provide information about sedimentary processes and paleocurrent direction but they are not unique indicators of depositional environments. Cross bedding formed primarily by migration of ripples and dunes (Boggs, S. J.,1995).

Flaser bedding is a type of ripple bedding in which the streaks of mud occur between sets of cross laminated sandy or silty sediment. Mud is concentrated mainly in the ripple trough but may also partly cover the crests. Flaser bedding suggests deposition under fluctuating hydraulic conditions. Period of current activity, when traction transport and deposition of rippled sand take place, alternate with periods of quiescence, when mud is deposited (Reineck and Singh, 1980). Lenticular bedding is a structure formed by interbedded mud and ripple cross laminated sands when condition is suitable for sand deposition. Hummocky cross-stratification is characterised by undulating sets of cross-laminae that are both concave up(swales) and convex up (hummocks) represents marine conditions. Alluvium is mostly deposited by meandering and braided streams. Meandering river having a single major channel showing high sinuosity and Braided river have network of channels showing low sinuosity (Boggs, S. J.,1995). Groove marks represents marine and fresh water environments.

Facies Associations

Three facies associations are identified from the above mentioned four main facies F1-F4 of the Latest Cretaceous strata of upper part of Pab Formation in the Sulaiman foldbelt. First facies association (FA1) is meandering river and overbank flood association, is well exposed in the southern part of central Sulaiman foldbelt. Second facies association (FA2) is oxbow lake and Crevasse splays lacustrine association is found in the Badhi and Kingri areas, of northern part of central Sulaiman foldbelt. Third facies association (FA3) is alluvial deltafan beech association (mostly submarine and rarely subaerial), is diagnosed in the Kaha-Harrand section of southern Sulaiman fold belt, and Musa Khel and Mughal kot areas which are located in the northern Sulaiman foldbelt.

Facies Associations FA1 (Meandering river and overbank flood association)

Facies Associations FA1 (Meandering river and overbank flood association) consists of facies F1 (trough cross and planner laminated/bedded sandstone) and facies F2 (relatively thick red muds). Facies Associations FA1 is located in the southern part of central Sulaiman foldbelt. This Facies Associations FA1 represents meandering river and overbank flood deposition. The three finnig upward sequences are observed in the latest Cretaceous strata (Figure 6-13). This is the classic fining upward sequence in a meandering river deposit. The lower coarse bed represents channel

deposits formed by point bar lateral accretion process and upper fine mud (red) represents overbank vertical accretion deposits. The cyclic alternations of facies F1 which consists of trough cross bedded sandstone represents deposition by meandering river and facies F2 which consists of relatively thick muds represents overbank flood envionments. This facies association represents the most proximal environmental setting identified in the study area This facies association occurs only in the southern part of central Sulaiman fldbelt, surrounded by lake in the near north (Badhi and Kingri), mostly submarine and partly subaerial alluvial deltafan in the farther north (Musa Khel and Mughal Kot area), deltafan and shelf marine in west, deltafan in the south, and terrestrial paleoland and Indo-Pakistan Shield in the east.(Figure-18).

Facies Associations FA2 (Oxbow lake and Crevasse splays lacustrine association)

Facies Associations FA2 (Oxbow lake and Crevasse splays lacustrine association) consists of facies F3 (Carbonaceous shale) and confined in the Badhi and Kingri areas, northern part of central Sulaiman foldbelt. This Facies Associations FA2 represents over bank flooding of meandering river and shifting the load in to lake. The three finnig upward sequences are observed in the latest Cretaceous strata. These are the classic fining upward sequences observed in the Kingri and Badhi areas. Kingri and Badhi areas show cyclic alternations of carbonaceous shale and sandy beds. Sandy beds represent channel deposition while carbonaceous shale, coal and greenish grey muds represent overbank flooding in the lakes which have carbonaceous source like plants. The lower sandy beds represents channel deposits formed by point bar lateral accretion process and upper carbonaceous dark shale and grey muds represent vertical accretion overbank flooding and vertical accretion deposits.

Facies Associations FA3 (Alluvial deltafan beech association mostly submarine and rarely subaerial)

Facies Associations FA3 (Alluvial deltafan beech association mostly submarine and rarely subaerial) consists of facies F4 (Tabular/planner and trough cross bedded sandstone interlayered with the subordinate greenish grey and minor reddish brown muds). Facies Associations FA3 is located in the Kaha-Harrand section which is located in the southern Sulaiman foldbelt; and Musa Khel and Mughal kot areas which are located in the northern Sulaiman foldbelt. This facies association FA3 represents alluvial deltafan shore face beech association (mostly submarine and rarely subaerial) and tidal effect. This facies association represents the distal environmental setting identified in the study area.

Lateral and vertical extension of dinosaur beds in sulaiman fold belt

Facies associations demonstrate the existence of three laterally variable depositional systems in the Sulaiman foldbelt during the Latest Cretaceous. Sandbodies with subordinate muds formed in westward prograding mostly submarine and partly subaerial dominate north and south systems, while in the central part of Sulaiman foldbelt , the meandering river and associated flood bank, oxbow and crevase splays lacustrine system deposited the sandstone, reddish brown muds, coal, carbonaceous shale and greenish grey muds. The Dinosaurs and associated other archosaurs found from the southern part of central Sulaiman foldbelt (Figure

2), belong to central meandering river and overbank system. Meandering river and overbank flooding system is also responsible for the oxbow lake or Crevasse splays lacustrine environments exposed in the Kingri and Badhi areas located in the northern part of central Sulaiman foldbelt. The coeval southern system represented by alluvial deltafan beech association (mostly submarine and rarely subaerial), is interpreted in Kaha-Harrand section of Soutern Sulaiman foldbelt. The coeval northern system represented by alluvial deltafan beech association (mostly submarine and rarely subaerial), is exposed in the Musa Khel/ Hazar Ghat section and Mughal Kot area (Figure-18).

The Dinosaur beds/Vitakri member thickness varying from 15 meter(m) to 35 m, is increasaing toward WSW and decreasing ENE directions. Dinosaurs and other archosaurs are hosted by Vitakri member. The lateral extention of dinosaur beds of the Pab Formation have been observed in major four anticlinorium (Figure 4) named as Vitakri-Bohri anticlinorium (Barkhan and Kohlu districts), Dhaola anticlinorium (Barkhan and Kohlu districts), Phulali anticlinorium (Barkhan, Dera Bugti and Kohlu districts) and Fort Munro anticlinorium (Dera Ghazi Khan and Rajan Pur districts). A model of meandering river named as D.G.Khan-Vitakri river forming lobate belt shape, flowing EW from Indian shield to Fort Munro, and flowing ENE to WSW from Fort Munro to Mari Bohri via Vitakri. The exposed strata of dinosaur beds (Vitakri member) of southern part of central Sulaiman foldbelt is surrounded by coeval strata like the lacustrine charged by overbank flood in the near north(Badhi and Kingri), mostly submarine and partly subaerial alluvial deltafan in the farther north (Musa Khel and Mughal Kot area), deltafan and shelf marine in west, deltafan in the south(Kaha-Harrand area) , and terrestrial paleoland (and Indo-Pakistan Shield) in the east (Figure 18).

No simple and consistent vertical facies trend has been identified in the rocks of Sulaiman foldbelt. The Jurassic Sulaiman group and early Cretaceous Parh Group represents fine pelagic and shallow marine deltaic environments, and the Late Cretaceous Mughal kot Formation represents muddy to sandy shelf and distal deltaaic environments. The Late Cretaceous Pab Formation of Dhaola Range is divided generally in to three member as lower member named as Dhaola , middle member named as Kali and upper member named as Vitakri (Figure-5). Dhaola member consists of mainly white, thin to thick bedded, poorly sorted quartzose sandstone. The most common sedimentary structure of lower/Dhaola member is the opposing planer/tabuilar cross beds may showing the tidal reversals in alluvial deltaic environments. Middle member named as Kali (Kali is a local word mean black), is represented by black weathering on this member which is comparatively more common than lower Dhaola member. Kali member represents white, light brown, whitish grey, thin to thick bedded, fine to coarse grained, muddy matrix and poor sorted quartzose sandstone having relatively high black desert varnish than lower member. In the type locality of Kali member many cycles of shale alternation with relatively thick sequence of sandstone are observed. A wood log has been found in the middle of Pab Formation of the Goz Wanga Pass area. The common sedimentary structure of middle/Kali member is the opposing planer cross beds/tabular beds may showing the tidal reversals in alluvial deltaic environments. The truncated flat bedding and cleaned quartzose sands in the Dhaola member and partly in Kali

member represent the beech environments.

The upper member named as Vitakri member is the host of dinosaur and that is the reason it is used synonymous as Dinosaur beds. Vitakri member represents fluvial meandering river and over bank system. It consists of red , green mud with subordinate whitish grey to white, poorly sorted, trough cross bedded, planner cross bedded, mudy matrix to quartzose sandstone and minor lag conglomerate(graded bedded). This is the classic fining upward sequence in a meandering river deposit. The fine strata as red mud is deposited as flood plain vertical accretion process. The sandstone on the top of Dinosaur beds is thin to thick bedded, slightly calcareous to non calcareous and soft and poorly sorted and have ferruginous nodules and brown rusty weathering on bivalve fossils.

The northern part of central Sulaiman foldbelt like the Kingri section (Figure 12) shows the lake deposits consisting of fine silt and mud introduced in to lakes from the main stream during overbank flooding. They are commonly well laminated and contain carbonaceous matter of plant remains. The carbonaceous content of Kingri section is too much high than Badhi section. The lithologic logs in the southern part of central Sulaiman foldbelt represent the three fining upward sequences representing cyclic alternation of trough-cross bedded sandstone with three cyclic alternation of mudstone facies which are started from uppermost Kali member, to lower Khadro Formation, through Vitakri members, are observed in the Central Sulaiman foldbelt. The lower coarse bed represents channel deposits formed by point bar lateral accretion process and upper fine mud(red) represents overbank vertical accretion deposits. So far Vitakri member is confimed as dinosaur host, that is the reason the detailed work has been done on this upper part of Pab Formation. During early Paleocene the transgression of sea happened which deposited the carbonate shallow marine limestone and shale(fossil bearing like bivalves, nautiloids and gastropods) of Khadro Formation which is followed by the deltaic siliciclastic Rakhi Gaj Formation and shallow marine carbonate Dungan Formation.

Conclusions

Four main facies, three facies associations and three depositional systems have been identified in the upper part of Pab Formation in the Sulaiman foldbelt. The four main facies of Latest Cretaceous strata of upper part of Pab Formation identified in the Sulaiman foldbelt are; Facies F1 (Trough cross and planner laminated/bedded sandstone), Facies F2 (Massive reddish brown to red muds), Facies F3 (Carbonaceous shale) and Facies F4 (Tabular/planner and trough cross bedded sandstone interlayered with the subordinate greenish grey and minor reddish brown muds). These facies formed by a range of sand transporting mechanisms that includes classical meandering and overbank flood flows, oxbow and crevasse splays lakes charged by overbank flooding, storm and river flood generated flows, and high and low energy tractional flows. Three facies associations identified in the upper part of Pab Formation are, meandering river and overbank flood association well exposed in the southern part of central Sulaiman foldbelt, oxbow lake and Crevasse splays lacustrine association found in the Kingri area of northern part of central Sulaiman foldbelt, and alluvial deltafan beech association (mostly submarine and rarely subaerial) located in the Kaha-Harrand section of southern Sulaiman foldbelt and in the Musa Khel and Mughal Kot

sections of the northern Sulaiman foldbelt.

Facies associations demonstrate the existence of three depositional system in the Sulaiman foldbelt during the Latest Cretaceous. Sandbodies with subordinate muds formed in westward prograding mostly submarine and partly subaerial dominate north and south system. While in the central part of Sulaiman foldbelt , the meandering river and associated flood bank, oxbow and crevase splays lacustrine system deposited the sandstone, reddish brown muds, coal,carbonaceous shale and green muds. Quartzose nature of sandstone and paleoflow suggest supply from the uplifting Indo-Pakistan Shield to the eastward. Sediment gravity flow generally evolved from east-west.

The depositional system of Dinosaur Beds interpreted as meandering river and overbank flood deposits in southern part of central Sulaiman foldbelt, associated coeval strata like oxbow and crevasse splays lacustrine deposits of northern part of central Sulaiman foldbelt. Meandering channel deposits are diagnosed on the basis of relatively thin sand with cyclic alternations of thick muds, trough cross lamination/bedding, parallel lamination, muddy matrix and basal lag conglomerate. The overbank flood deposits are diagnosed on the basis of red muds, having ferruginous concretions, calcretes and archosaur bones. The top of dinosaur beds are assumed as K-T boundary. The lateral extension of dinosaur beds of the Pab formation have been observed in major four anticlinoriums named as Vitakri-Mari Bohri anticlinorium (Barkhan and Kohlu districts), Dhaola anticlinorium (Barkhan and Kohlu districts), Phulali anticlinorium (Barkhan, Dera Bugti and Kohlu districts) and Fort Munro anticlinorium (Dera Ghazi Khan and Rajan Pur districts).

A model of meandering river named as D.G.Khan-Vitakri river forming lobate belt shape, flowing EW from Indo-Pakistan Shield to Fort Munro, and flowing ENE to WSW from Fort Munro to Mari Bohri via Vitakri (Figure 18). The exposed strata of dinosaur beds of southern part of central Sulaiman foldbelt is surrounded by coeval strata like the lacustrine charged by overbank flood in the near north(Badhi and Kingri), mostly submarine and partly subaerial alluvial deltafan in the farther north (Musa Khel and Mughal Kot area), deltafan and shelf marine in west, deltafan in the south , and terrestrial paleoland (and Indo-Pakistan Shield) in the east.

Acknowledgements

I am grateful to Mirza Talib Hasan, Director General, Geological Survey of Pakistan for his continued keen interest in this study and inducement to the working scientists. I am thankful to M. Akram Bhatti, Director, Paleontology and Stratigraphy Branch (P&S) for encouragement and keen interest in this study. I am thankful to Professor Dr. Imdad Brohi of Jamshoro University for best suggestion. I acknowledge Mr Joozer Marzban of GSP for help in preparation of figures. I am thankful to Dr. M. Raza Shah for providing facility of digital camera. I also acknowledge the efforts of Mr M. Faheem Khan of Balochistan University of Information Technology and Management Sciences, Quetta and Mr M. Abdur Rahim and M Ibraheem Khan of F. G. School, Quetta, for taking photographs. I am thankful to Mr. Shireen Khan Malghani for his best suggestions. Last but not least I am thankful to Mr. Zahid Hussain of GSP, Quetta for providing the GPS facility for this work.

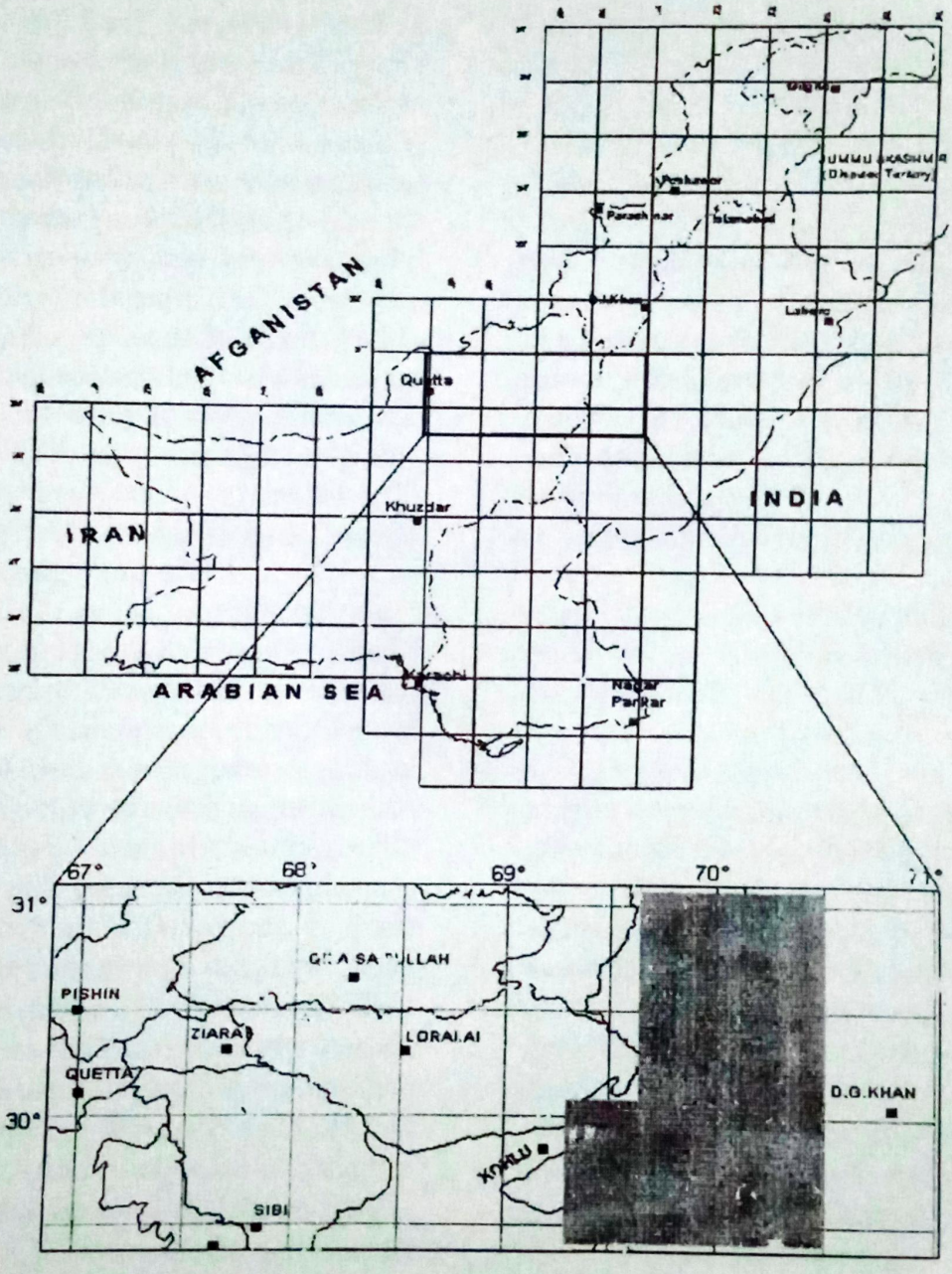


Figure 1. Grey rectangie represents the study area of Latest Cretaceous beds of upper part of Pab Formation in Sulaiman foldbelt, Pakistan.

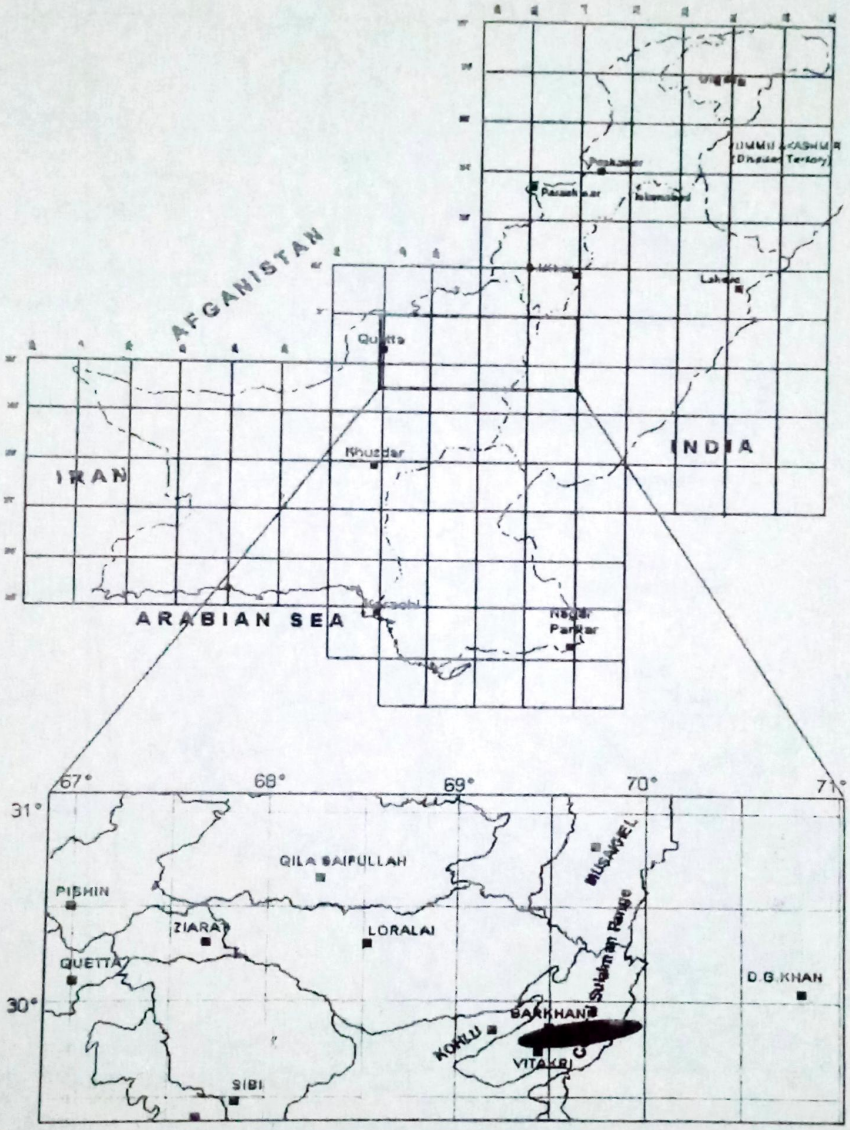
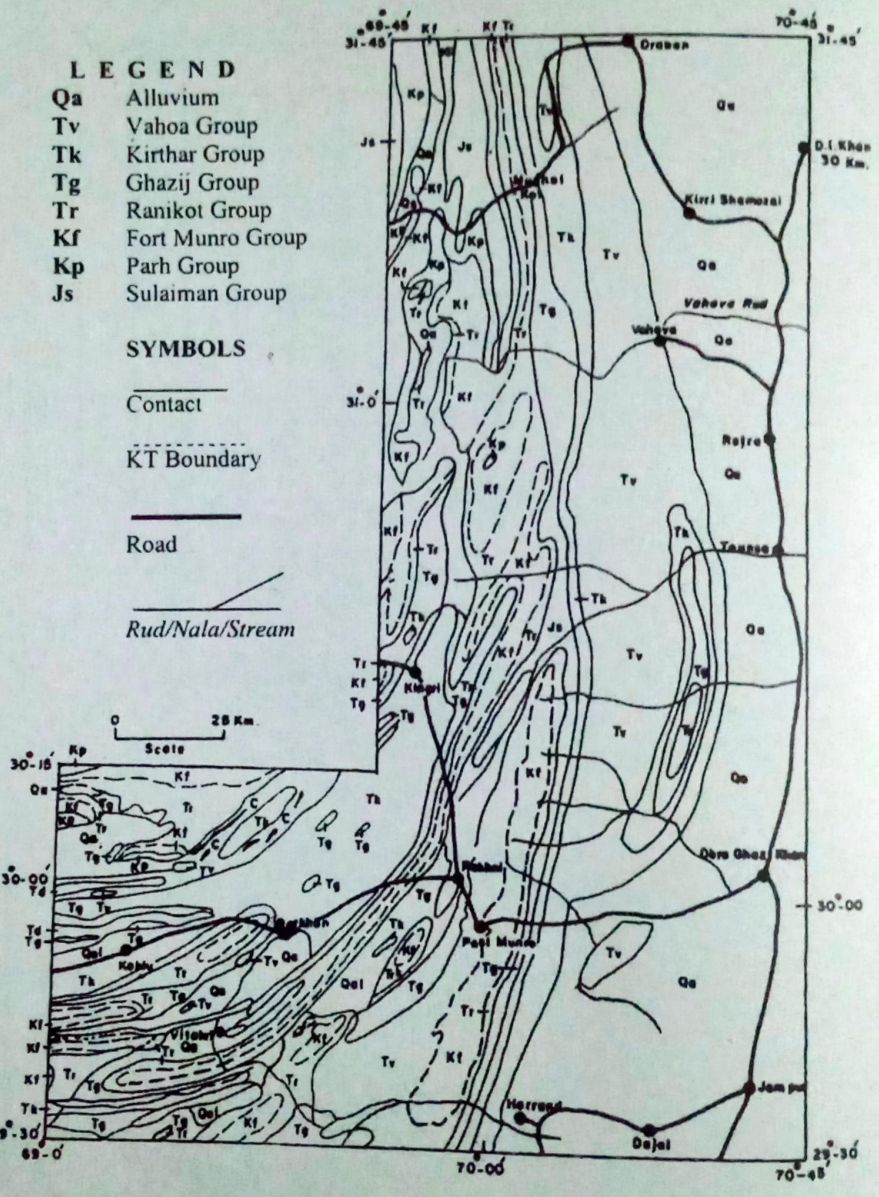


Figure-2. Balck Oval represents the lateral extension of Latest Cretaceous Dinosaur Beds of upper part of Pab Formation in Sulaiman foldbelt.



Geology by: M. Sadiq Malkani
Geological Survey of Pakistan, Quetta
2005

Figure 3. Geological Map of part of Sulaiman foldbelt, Pakistan.

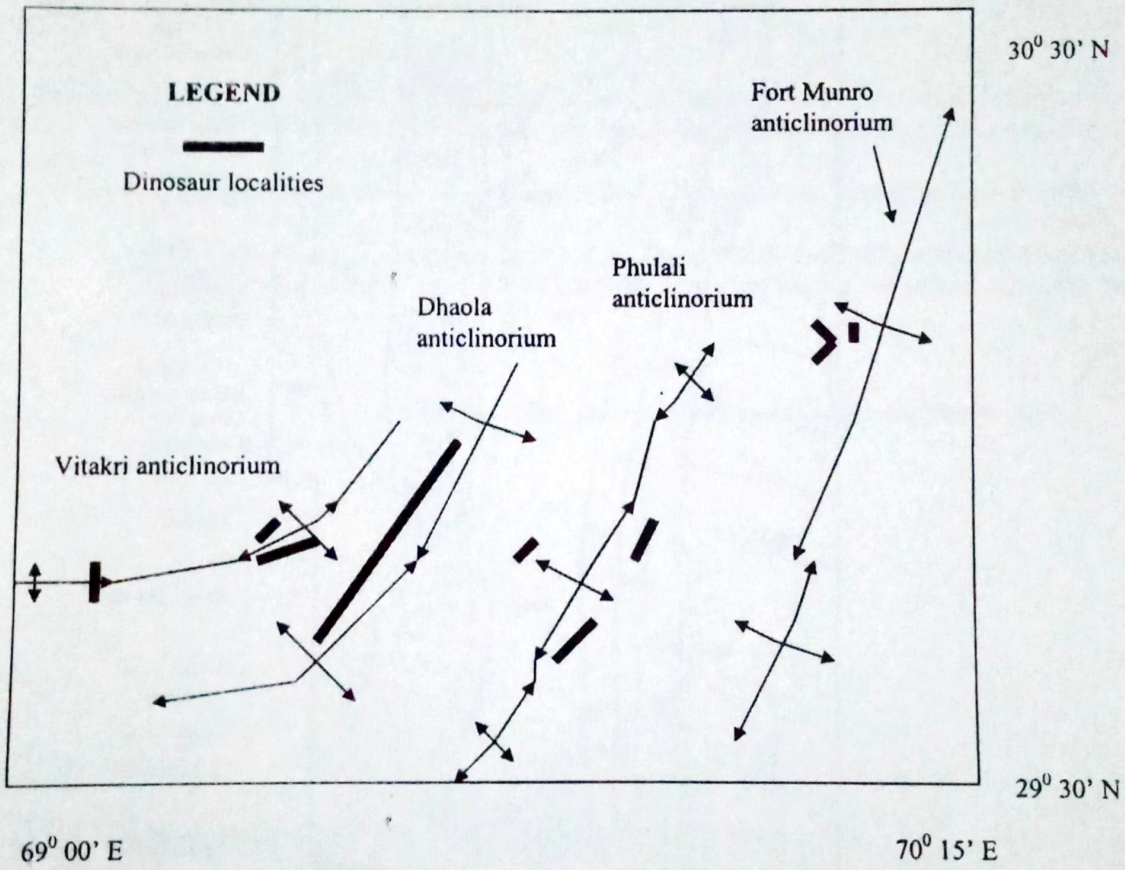


Figure 4. Map showing the Latest Cretaceous Dinosaur localities in central Sulaiman foldbelt, Pakistan.

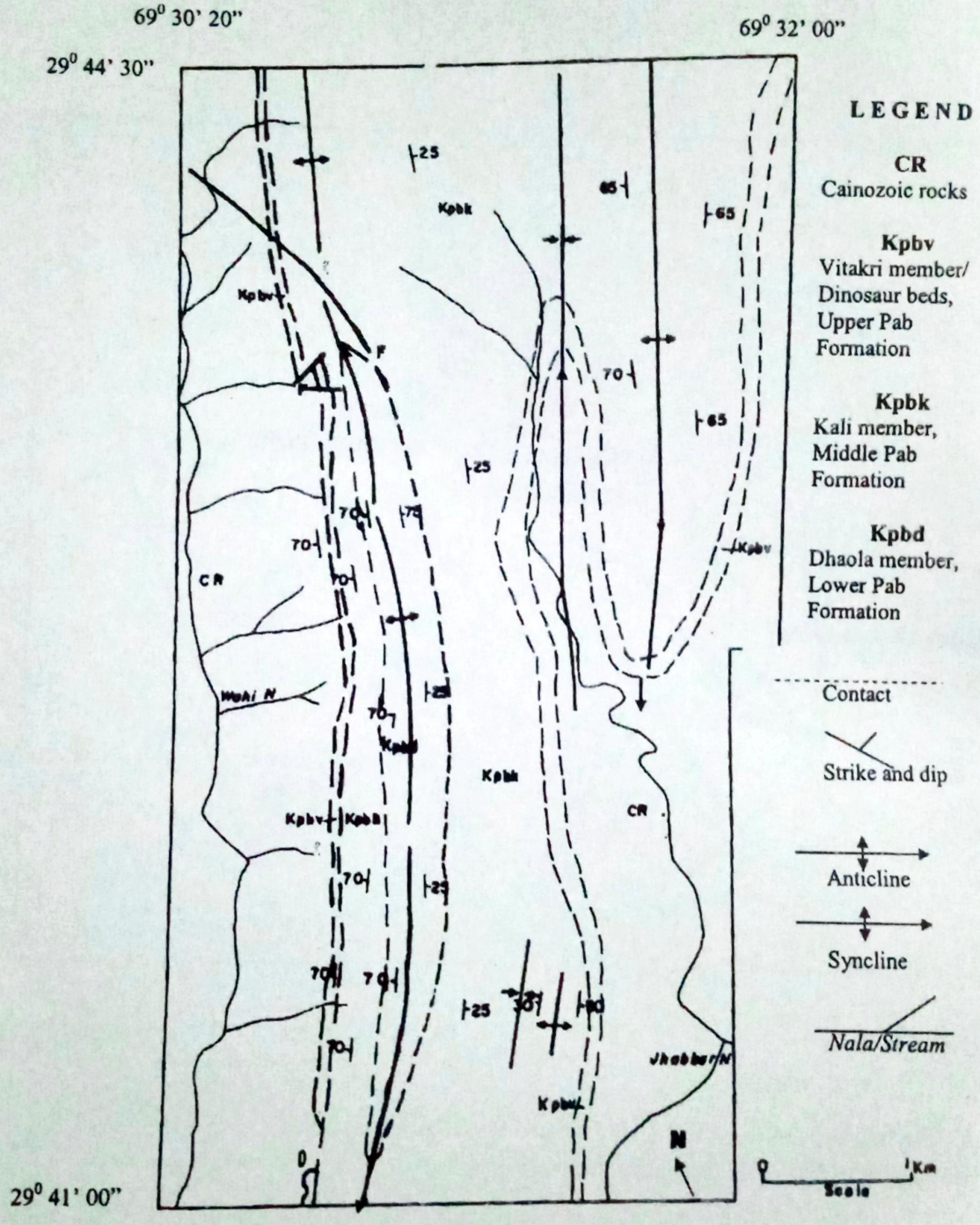


Figure 5. Geological Map representing the division of Pab Formation into Three members in Dhaola Range, Vitakri area, Barkhan District, Balochistan, Pakistan.

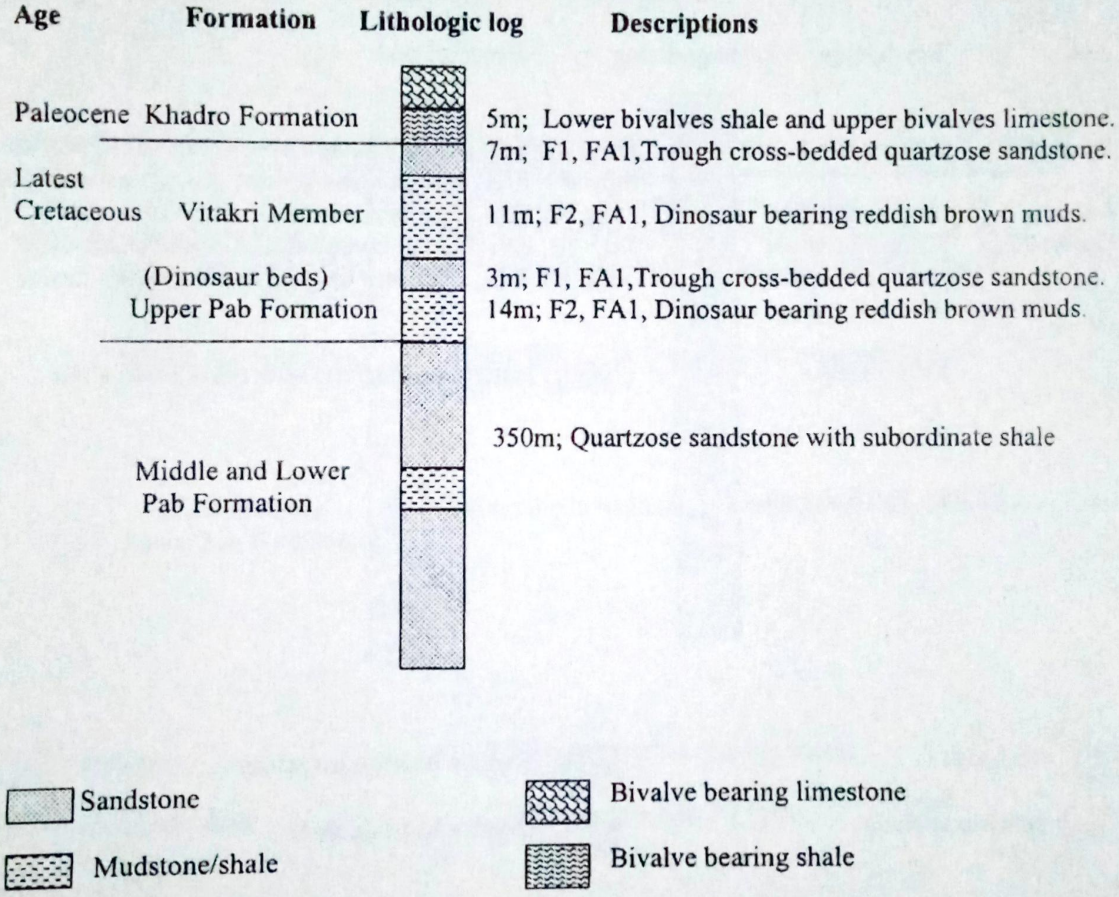


Figure-6: Lithologic log through the Latest Cretaceous Dinosaur beds/Vitakri member of Pab Formation of Mari Bohri area, Barkhan District, Balochistan, Pakistan. (For location please see section 1 in Figure-19). Figure not to the scale.

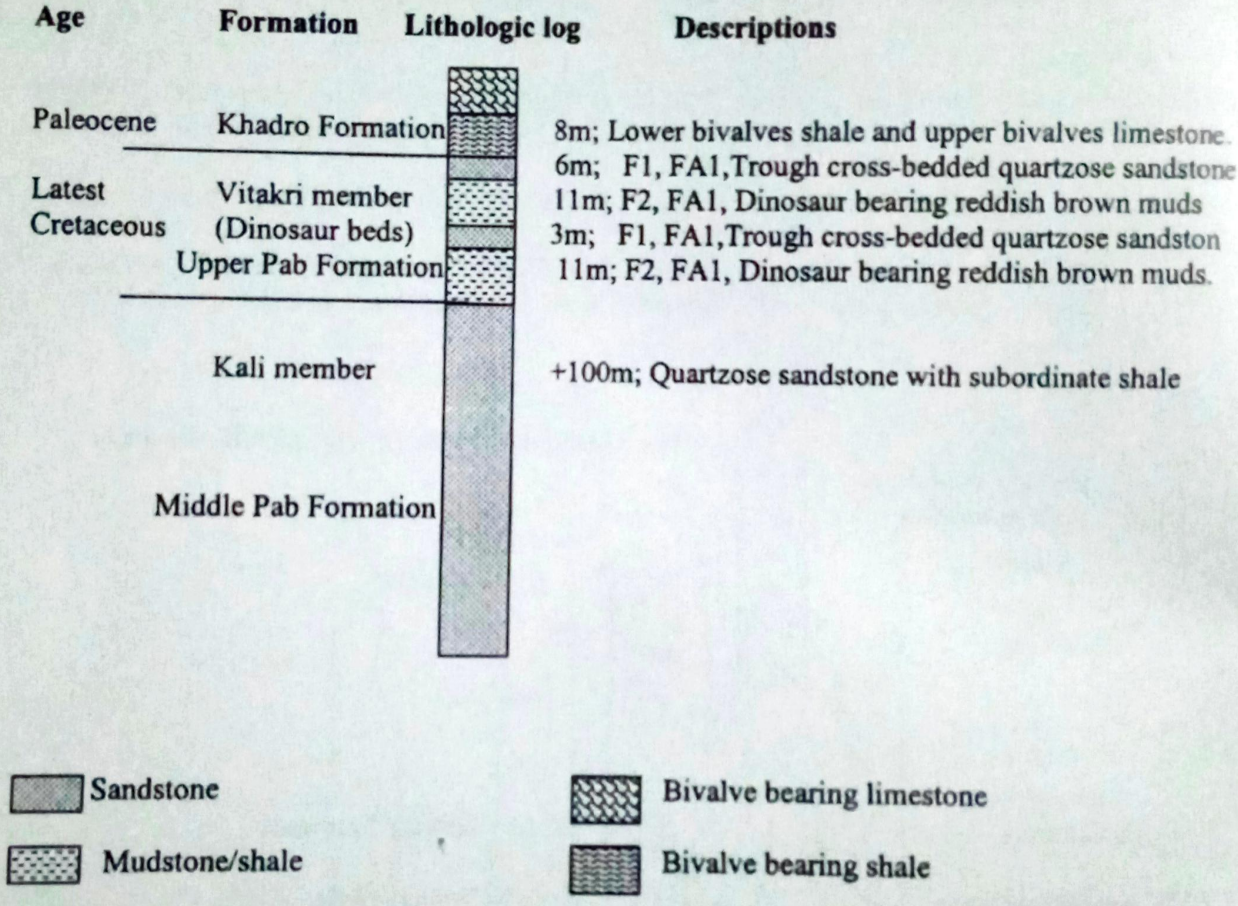


Figure 7. Lithologic log through the Latest Cretaceous Dinosaur beds/Vitakri member of Pab Formation of Kinwa Kali Kakor locality, Barkhan District, Balochistan, Pakistan. (For location please see section 2 in Figure 19). Figure not to the scale.

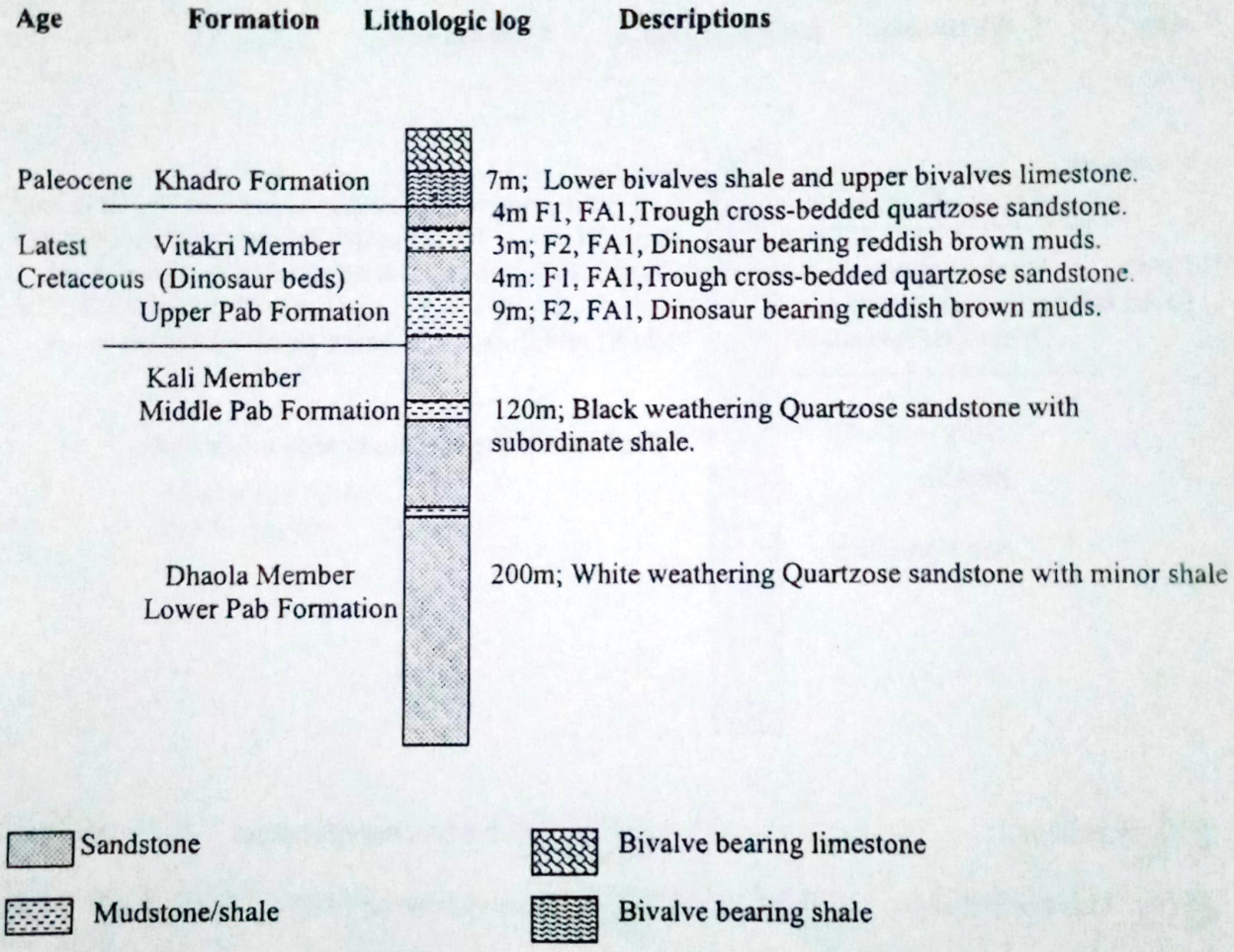


Figure 8. Lithologic log through the Late Cretaceous lower Dhaola, middle Kali and upper Vitakri/Dinosaur beds members of Pab Formation of Basti Nala Gambrak, northwestern limb of Dhaola anticlinorium, Barkhan District, Balochistan, Pakistan.
(For location please see section 3 in Figure 19). Figure not to the scale.

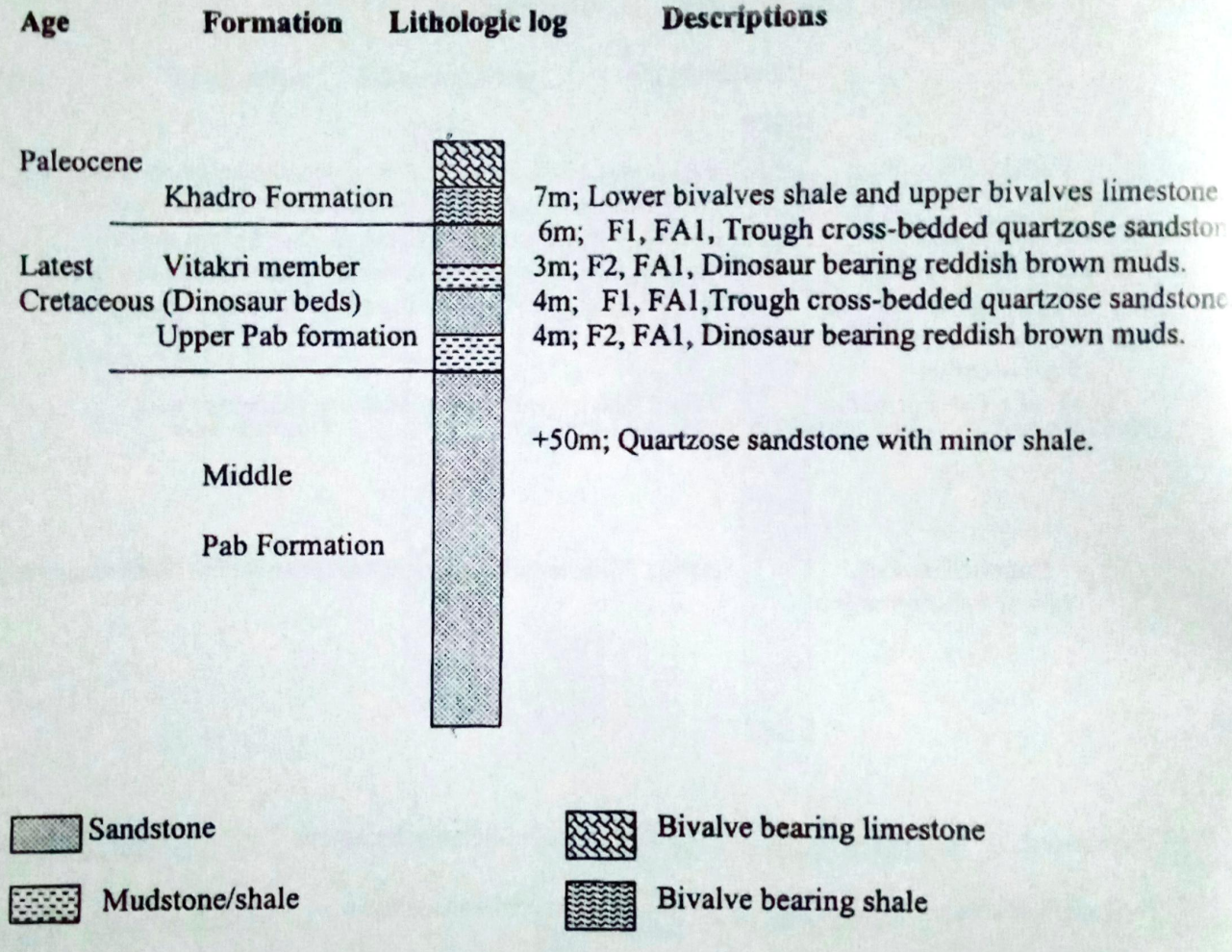


Figure 9. Lithologic log through the Latest Cretaceous Dinosaur beds/Vitakri member of Pab Formation of Khar-Fort Munro area, Dera Ghazi Khan District, Punjab, Pakistan. (For location please see section 4 in Figure 19). Figure not to the scale.

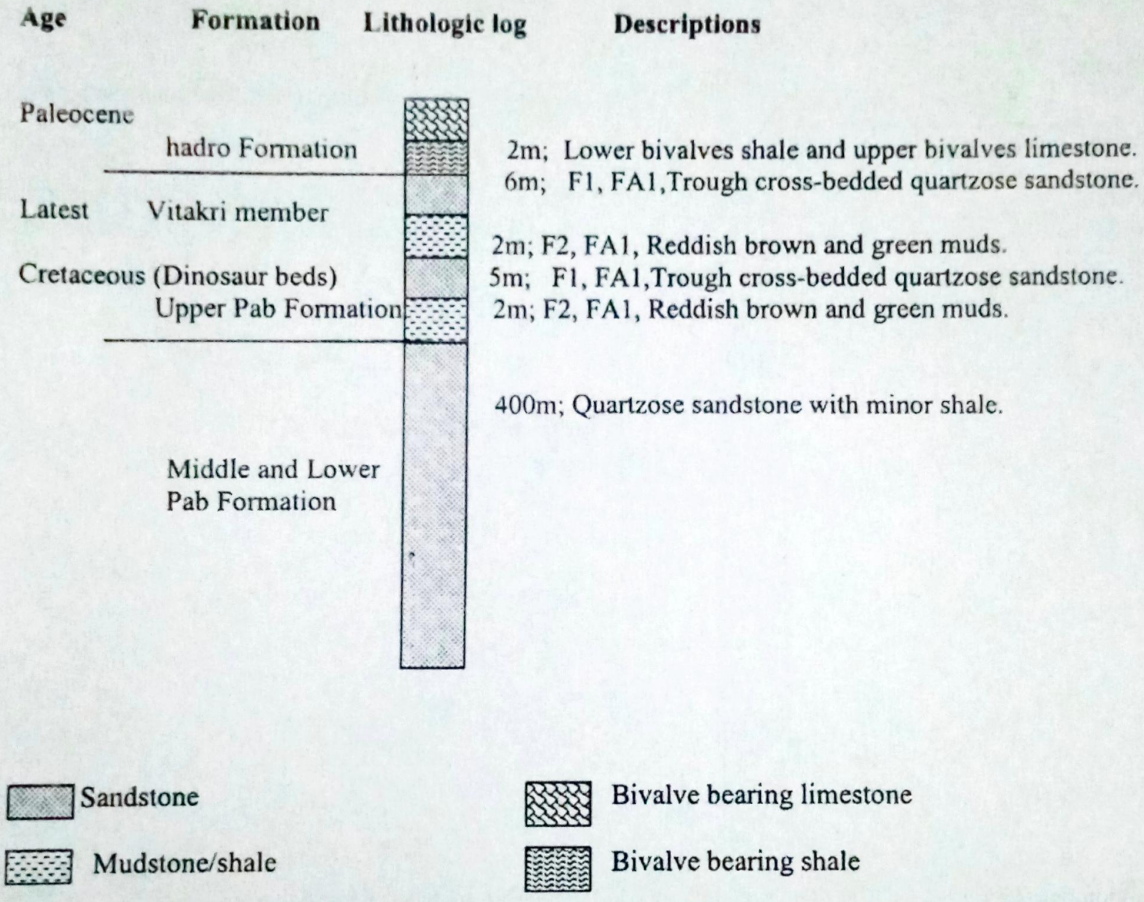


Figure 10. Lithologic log through the Latest Cretaceous Vitakri member/Dinosaur beds of Pab Formation of Rakhi Gaj area, Dera Ghazi Khan District, Punjab, Pakistan. (For location please see section 5 in Figure 19). Figure not to the scale.

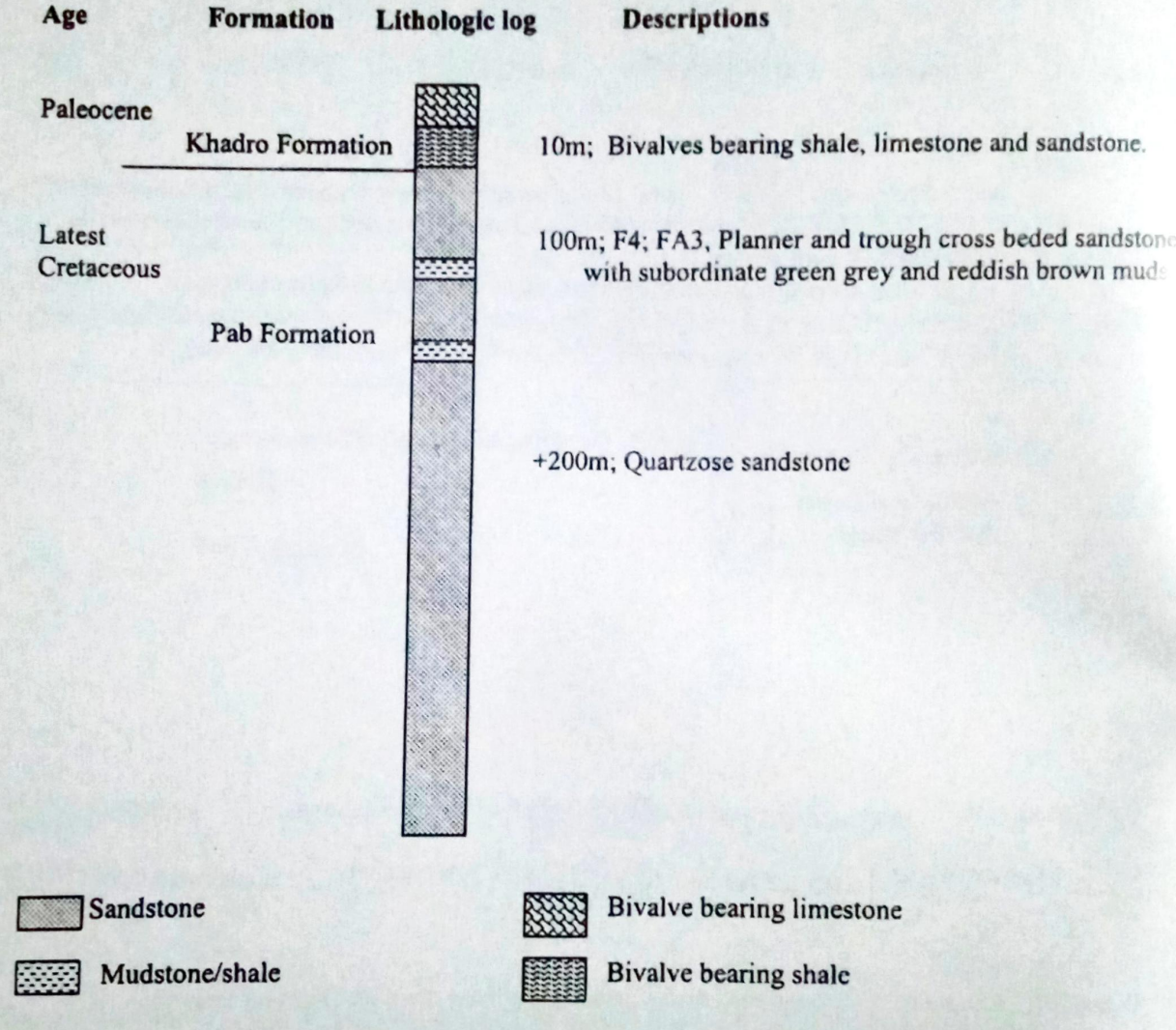


Figure 11. Lithologic log through the upper part of Latest Cretaceous Pab Formation of Kaha-Harrand section, Rajanpur District, Punjab, Pakistan.
(For location please see section 6 in Figure 19).Figure not to the scale.

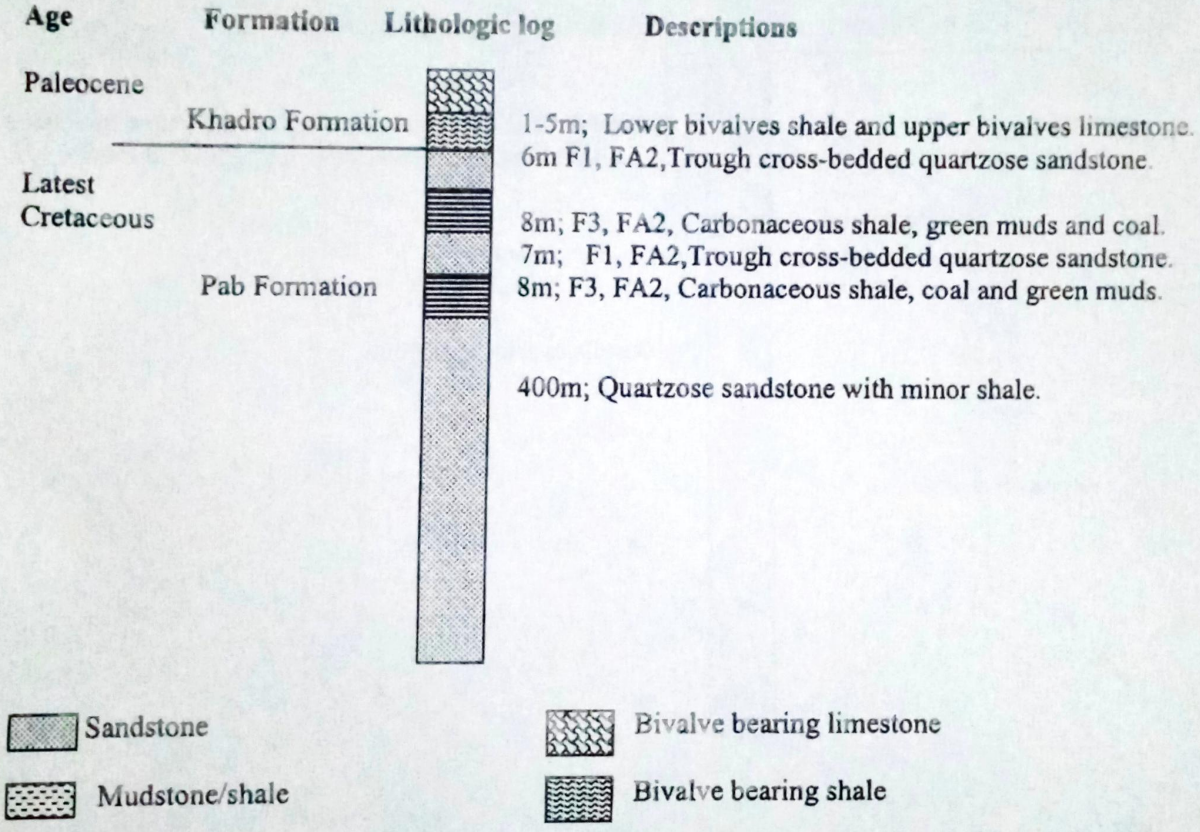


Figure-12. Lithologic log through the upper part of Latest Cretaceous Pab Formation of Kingri section, Musa Khel District, Balochistan, Pakistan.
(For location please see section 7 in Figure 19). Figure not to the scale.

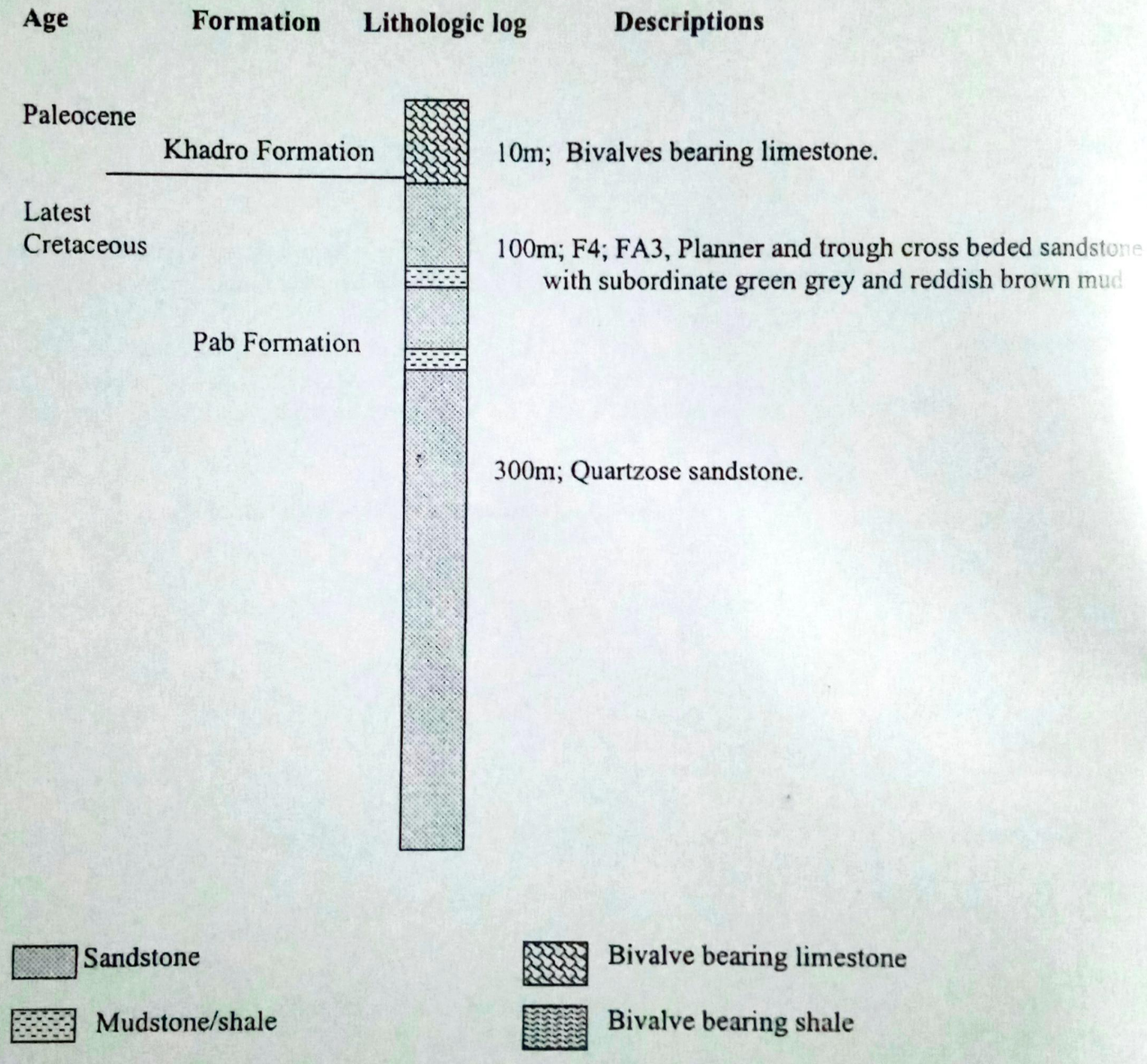


Figure 13. Lithologic log through the upper part of Latest Cretaceous Pab Formation of Musa Khel section, Musa Khel District, Balochistan, Pakistan.
(For location please see section 8 in Figure19). Figure not to the scale.

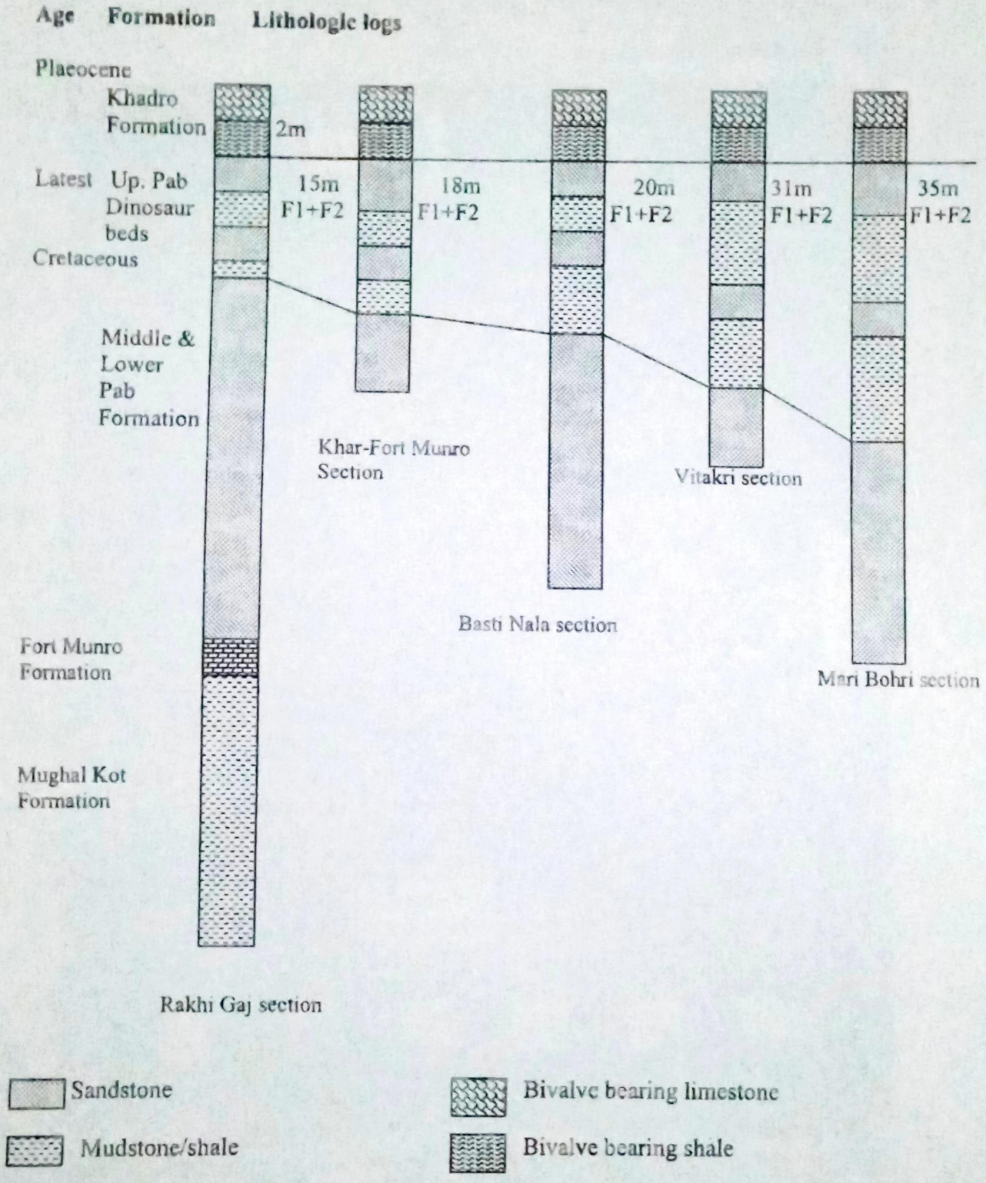


Figure 14. Correlation of Lithologic logs of Latest Cretaceous dinosaur beds in southern part of central Sulaiman Foldbelt. Correlation chart generally trends east to west (left to right). (For location for measured sections please see figure 19). Figure not to the scale. Pl. see the Fig.6-10 for thickness of different Lithologic units.

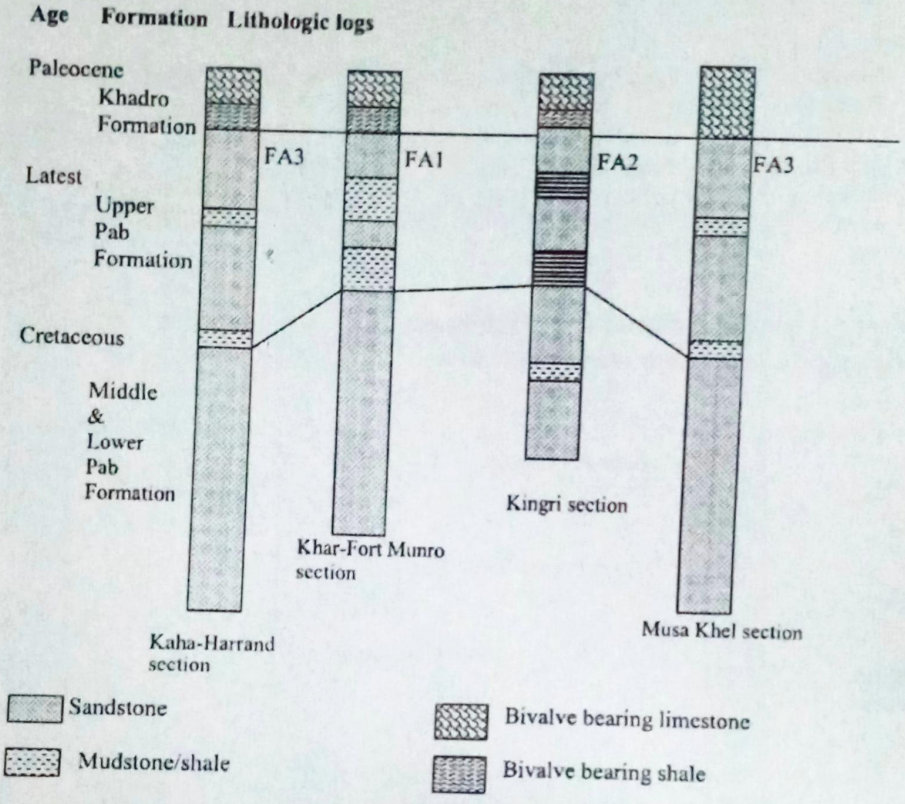


Figure 15. Correlation of Lithologic logs and facies associations' variation of Latest Cretaceous strata of upper part of Pab Formation in Sulaiman foldbelt. Correlation chart generally trends south to north (left to right).(For location of measured sections please see figure 19). Figure not to the scale. Pl. see the Fig.11-14 for thickness of different Lithologic units.

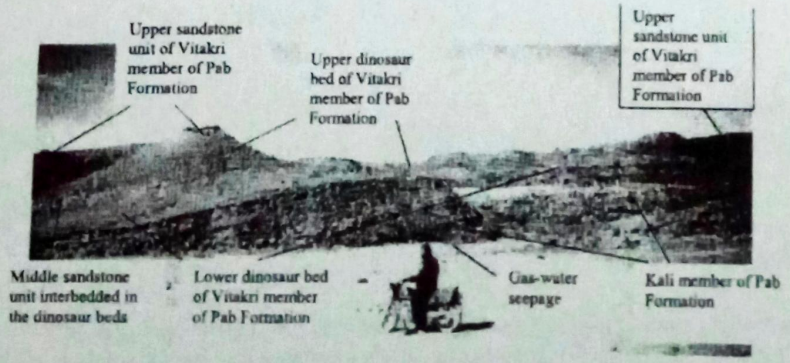


Figure 16. Photograph of middle Kali member and upper Vitakri member/dinosaur beds of Latest Cretaceous (Maestrichtian) Pab Formation from Kinwa Kali Kakor Locality of Vitakri area, Barkhan District, Balochistan, Pakistan. (For scale please see the man on motorcycle, for location see the section 2 in figure 19).

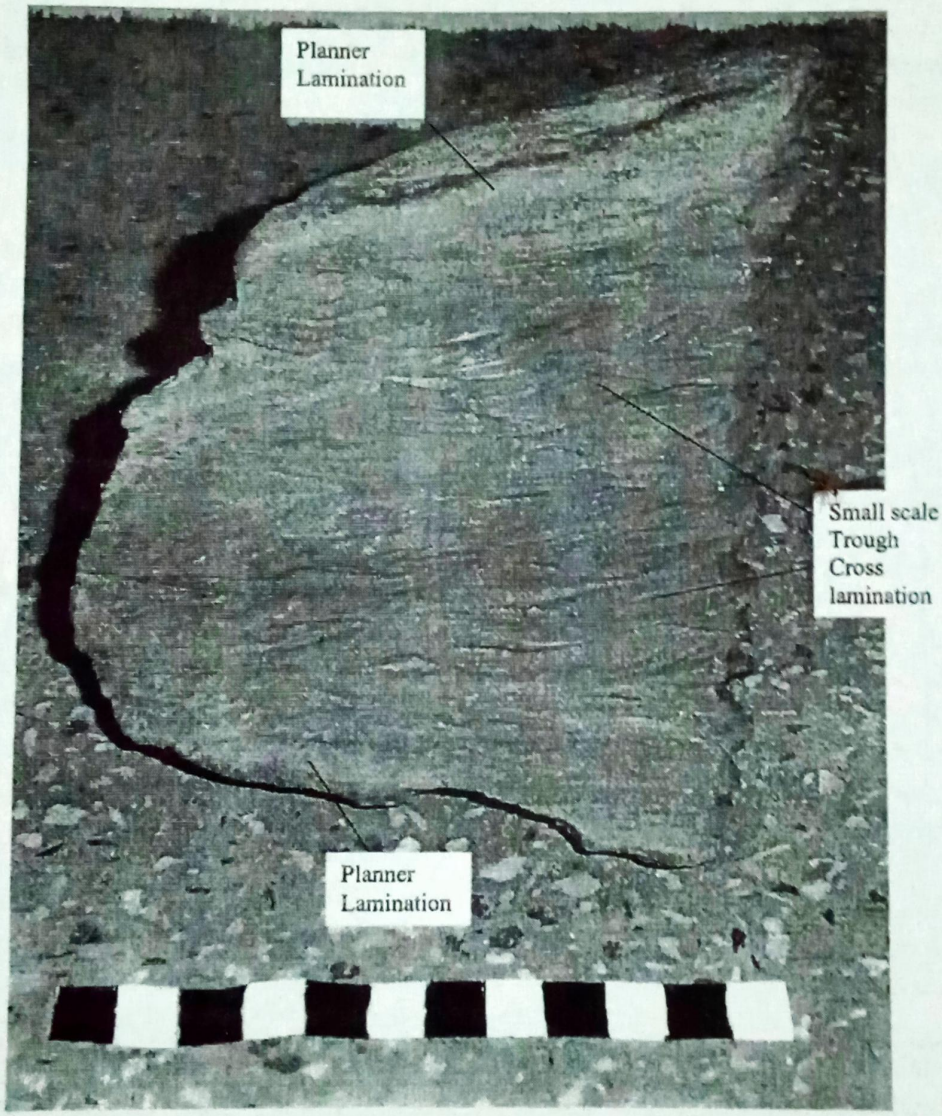


Figure 17. Photograph of sample collected from middle sandstone unit interbedded in the two dinosaur beds of Latest Cretaceous Viakri member of Pab Formation in the Kinwa Kali Kakor locality of Vitakri area, Barkhan District, Balochistan, Pakistan. Photograph showing small scale trough cross lamination bounded by planner Lamination. (Scale is in centimeter (cm.), every black digit represents 1 cm. For location please see the section 2 in Figure 19)

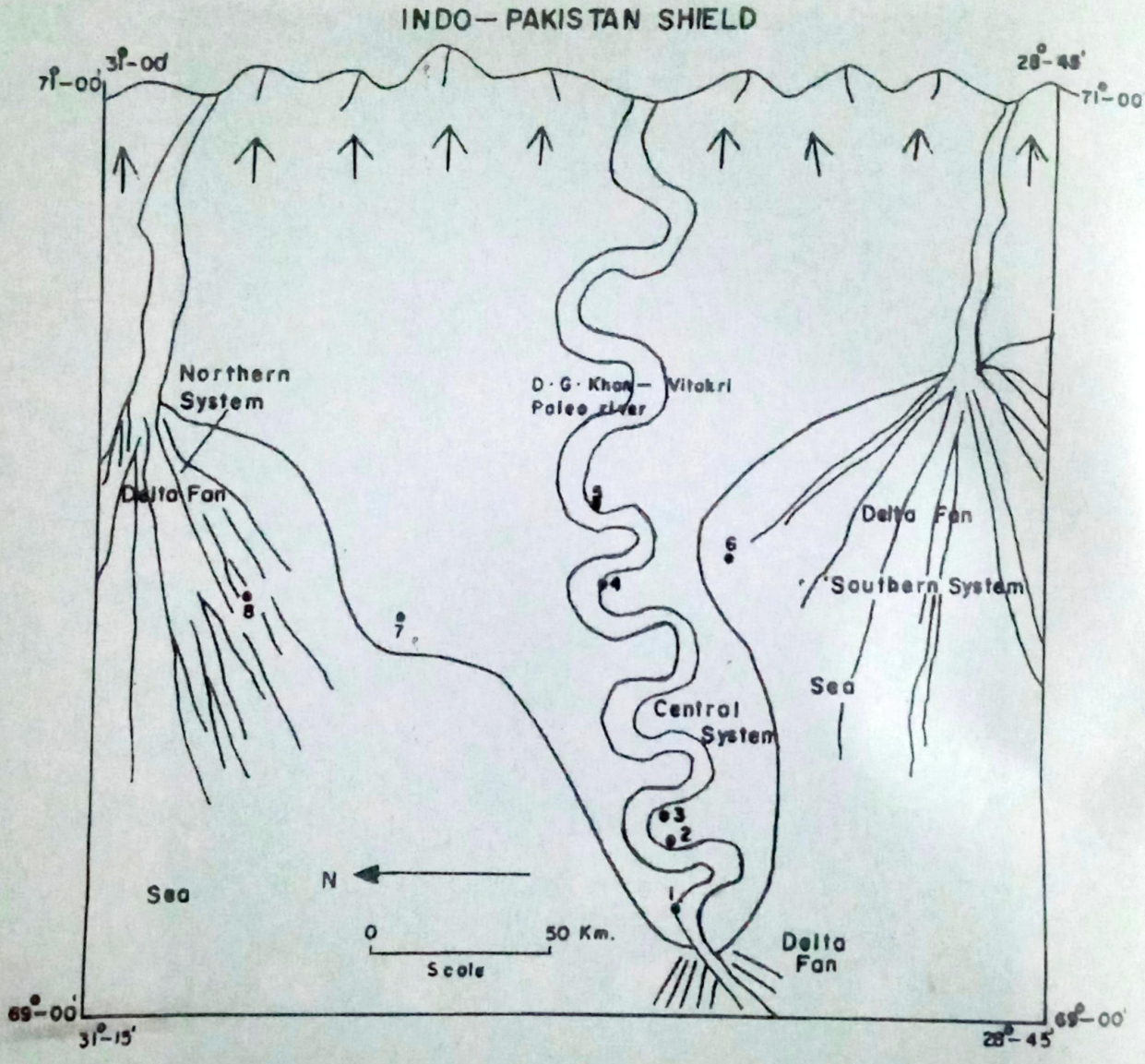


Figure 18. Conceptual paleoenvironmental model for the Latest Cretaceous Dinosaur beds in Vitakri and its vicinity areas of Sulaiman fold belt, Pakistan.