Paleozoic Sequences as Potential Source Rocks for Petroleum in Northwestern Pakistan, with Particular Reference to the Silurian System, a Major Petroleum Source in the Middle East and North Africa*

Syed Tariq Hasany[1] and Fazl-i-Rabbi Khan[2]

Search and Discovery Article #30263 (2012)**
Posted December 31, 2012

*Adapted from oral presentation at PAPG Annual Technical Conference 2003, Islamabad, Pakistan, October 3-5, 2003

[1]Petronas Carigali Sdn-Bhd, Kuala Lumpur, Malaysia (hasany.syedtariq@petronas.com.my; tariqhasany@hotmail.com)
[2]National Centre of Excellence in Geology, Peshwar University, Peshwar, Pakistan (nceg@brian.net.pk)

Abstract

Silurian sequences in the Middle East and North Africa have been demonstrated to be major petroleum source rocks. The principal sources were black shales mostly of Early Silurian (Llandovery) age representing major events of anoxia. It is estimated that 9% of the world's petroleum reserves have been derived from Silurian source rocks. Devonian sequences have also contributed importantly as source rocks and also as host rocks for petroleum production in North Africa and Canada.

The Palaeozoic sequences of Pakistan and stratigraphic alignments between them are not well known, but a significant Silurian dark shale sequence with high organic content, the Lun Shale (Llandovery, identified by graptolites), is known from Chitral. It is, admittedly, much disturbed structurally, having been involved in the Himalayan Orogeny, but what happened (or may have happened) farther south during Silurian times is poorly known. Silurian sediments are nevertheless known from the Nowshera-Misri Banda area where the base of the Nowshera Limestone and underlying Kandar Formation (senior synonym of Panjpir Formation of Pogue et al., 1992) and, underlying that again, the Misri Banda Quartzite, are, despite poor exposures, potentially sources of much information about events during Silurian times in northern Pakistan. There is a modicum of information on the Devonian sequences around the Peshawar Basin and into the tribal areas.

Farther westwards in southern Afghanistan (such as the Dasht-i-Narwar) and Iran, Silurian sequences are associated with Devonian sequences. Colour Alteration Indices of conodonts from some of the latter sequences, such as in the vicinity of Tabas, fall within the oil and gas windows. Conceivably, the same situation may occur with mid-Palaeozoic (including Silurian) sequences concealed beneath the Mesozoic-Cainozoic sedimentary blanket of northwestern Pakistan.

During Silurian and Devonian times the Arabian and Indian plates (then conjoined) were located in the southern hemisphere between the Equator and 30^{o} south, with the Indian Plate lying closer to the Tropic of Capricorn and therefore in slightly less warm waters. What this may have meant for organic productivity at that time is uncertain, but highest productivity at the present time is in cool waters, notably in the Southern Ocean. However that may be, Palaeozoic reef occurrences, as in Canada, have proved to be prime loci for oil accumulation. Why not something similar in Pakistan for concealed occurrences in carbonate complexes (cf. the Nowshera Limestone)?

This article will discuss the potential for Palaeozoic oil and gas occurrences in northwestern Pakistan, having in mind the highly significant Silurian source rocks of the Middle East and North Africa.

Introduction

The ever-changing geographical position of the continents and ocean basins on Earth through geological time is fundamental to the environment of the planet. Evaluation of pre-Pangea geography and tectonics offer fresh opportunities to examine possible causative relations between tectonics and environmental and biologic diversity in present day continents which were scattered during the geologic past. Understanding of tectonics facilitates geoscientists to deduce the possible geological conditions and subsequently the distribution of the rocks and their gross properties of any given area of the world. Thereby, petroleum explorationists consistently use reconstructed tectonic models to establish the play type and Petroleum System in known areas as well in frontiers basins. A wide range of published literature is available describing the paleoclimatic setting of the various plates through geologic time.

Petroleum exploration in Pakistan primarily focused in the eastern half of the sedimentary basins, exclusively in the Indus Basin. No single Petroleum System has been assigned to be productive, but perhaps a combination of Paleocene and Cretaceous systems is generally thought to exist. Mature source rocks in the Indus Basin are the marine Patala Formation of Paleocene age in the Potwar Basin, north of Pakistan, and marine black shales of the Sembar Formation of Early Cretaceous age. However, black shales of the Jurassic aged Datta Formation also have potential to be productive.

In Pakistan negligible petroleum exploration endeavors have been carried out in the western basins, particularly in Peshawar Basin where Paleozoic rocks are exposed. The reason for inhibiting active pursuance of Paleozoic Petroleum Systems may be attributed to sparse outcrop data, history of tectonic disturbance and metamorphism which led to a belief that no Petroleum System could survive. However, it would be quite plausible to consider that substantial land mass filled with sediments would have been unaffected due to such destructive agents. A nearly complete Paleozoic sedimentary rock sequence is exposed in the ranges fringing the Peshawar Basin (Hussain et al., 1991). This basin is considered the western margin of the Indian craton which was the part of larger Gondwanaland.

Paleotectonic reconstruction map of Silurian time suggests that the present day western and northern part of the Indian Plate were the margins of this land mass and forming the continental margins. Much of the northern margin sedimentary strata either subjected to metamorphism, volcanic activity and Himalayan Orogeny which resulted in consumption of considerable volume of the strata during uplift and erosion or for any other reason. This article is aimed highlighting the importance of Paleozoic source rocks in the backdrop of plate tectonics and trying to establish a relationship between the well-recognized Silurian source in the Middle Eastern and North African basins.

We consider that, despite Paleozoic rock being subjected to various means of degradation, there is yet a significant volume present in the Peshawar Basin and perhaps extending further westward into Afghanistan. Likewise, Paleozoic extension, including the Silurian-Devonian System, may also be inferred in the Sulaiman and Kirthar basins blanketed by the thick cover of Mesozoic and Tertiary sequence along the Indian Plate margin. The Arabian-Iranian Plate has world class source rock in the Silurian. Other parts of major hydrocarbon contributions from Silurian source rocks are the North Africa basins, the Permian, Anadarko and Michigan basins in the USA, and the Erg Oriental and Erg Occidental basins in western South America.

Source Rock Prediction in Context of Plate Tectonics

Source rock distribution is not evenly spread in any given basin and difficult to predict in precise terms. However, the factors controlling the deposition and preservation of the source rock may be predicted. On a global scale such prediction can be carried out based on the particular plates geographic position and its comparison with the adjoining plates. Klemme and Ulmishek (1998) described the methodology to qualitatively assess the main factors. We are focusing on Paleozoic factors favored for the source accumulation.

Through Phanerozoic time, source rocks distribution are amplified substantially. Some 90% of the world's total petroleum reserves are estimated to be charged from only six stratigraphic units ranging in age from Silurian to Miocene. This uneven configuration of source rocks in time suggests no obvious cyclicity and the factors that controlled the formation of source rock vary from interval to interval.

Paleolatitudes

A warm, humid climate over marine waters, as exists at present day low to middle latitudes, is believed to be highly productive for the organisms to thrive, such as tropical rain forests on land and reef communities on the shelf. These types of climatic conditions are favorable for the deposition of the source rocks (Grunau, 1983). Klemme and Ulmishek (1991) have suggested that all principal stratigraphic intervals, except Silurian source rocks, were deposited between the paleoequator and 45 degree paleolatitudes. Higher reproduction with subsequent higher bioproductivity, especially in winter, and the absence of seasonal overturn of water in hydrologically stagnant basins favors deposition and preservation of organic matter in tropical and subtropical seas. On land, great bioproductivity is characteristic of tropical rain forests; however, peat bogs and other accumulations of organic material are uncommon there because of the high rate of matter decomposition (Nikonov, 1959; Bates, 1960) (Figure 1). Silurian source rocks with kerogen types I and II, perhaps deposited in the higher paleolatitudes, contained a significant increase of graptolites which helped to provide organic matter. The paleoecology of graptolites is poorly constrained; planktonic forms of these fauna probably survived in both cold and warm marine conditions (Erdtmann, 1982).

Between Ordovician and Silurian times Gondwanaland, including the cratons of Africa, South America, Madagascar, India, Antarctica and Australia, rotated through the angle of almost 180^{o}. Mobile belts comprised the margins of Gondwana in Australia, New Zealand, Tasmania, and Antarctica.

Structural Geometries

Source rock deposition has been significantly controlled by various structural geometries on the basin which are primarily initiated due to tectonic response. The majority of the source rocks are deposited in platforms, circular sags and linear sags. Paleozoic source rocks, including the Silurian mainly composed of type II kerogen black shales facies, were fundamentally deposited exclusively in anoxic and dysoxic conditions (Demaison and Moore, 1980). Such conditions preferentially occurred in platforms. Therefore, it may be considered that Silurian source rocks are commonly deposited in platforms in the geologic past throughout the world.

Biologic Evolution

The implication of biologic evolution for petroleum generation is poorly constrained. Only the maturity of higher land plants during the middle Paleozoic, resulting in the appearance of terrestrial organic matter as a new source for oil and gas, is commonly referred to. In oxic marine environments, the bulk of the organic matter is consumed by metazoans and the role of bacterial decomposition is limited (Degenes and Mopper, 1976; Pelet, 1987). In the anoxic environment, consumers are absent and all the organic matter is subject to bacterial decomposition. However, the anaerobic bacterial decomposition does not result in complete oxidation of organic matter. Its more stable components, such as lipids, tend to accumulate in sediments (Kelts, 1988). In terrestrial conditions, much of bioproduction (wood, for example) is not digestible for most animals and is decomposed by aerobic bacteria and saprophytic plants. The rate of bioproduction has little impact on source accumulation, but it has been significantly controlled by the balance between bioproduction and destruction (consumption and decomposition) of organic matter. Commonly, black shale facies were deposited in areas of low bioproductivity (Bralower and Thierstein, 1987; Stein 1986; Tyson, 1987).

Through Silurian to Early Carboniferous, the deposition of black shale facies on open marine shelves continued, but no longer occurred under oxic conditions. The dysoxic conditions, however, judging from the paleontologic record, remained quite common. Silurian graptolitic shales containing eurytropic benthic fauna in many regions in Russian craton (Mirchink et al., 1965). However, the anoxic environment dominated in deeper sag basins of the semi-enclosed inland “black shale sea” during deposition of most black shales.

Paleozoic Climatic Conditions

Thickpenny and Legget (1987) concluded that the Lower Paleozoic organic rich sediments deposited in greater thicknesses and over wider areas than at any other time during the Phanerozoic. They recognized “black shale” formed during three main episodes of deposition in a variety of depositional environments. The Paleozoic depositional conditions largely depended on high sea level stand, warm climatic conditions and low hydrosphere oxygen which were favorable factors for the source deposition (Figure 3). However, conditions must also rely on their own physiographic and geographic positions.

Climate and Tectonics of Silurian

During the Silurian, the Earth had faced many significant changes in the way in which landmasses were distributed around the globe (Figure 2). Although there were no major volcanic events, a deglaciation and subsequent rapid sea level rise occurring at that time produced varying periods of continent coverage and exposure (Figure 3). At that time, the continents were distributed very differently than they are today. The Silurian world consisted of a vast north polar ocean and a south polar super continent (Gondwana) with a ring of approximately six continents. By the Silurian Period, a large portion of the Rodinian landmass had become fragmented, and those fragments migrated toward the equatorial region. Most of these fragments were eventually assembled by a series of plate collisions into the super-continents of Laurussia and Laurasia. The southern parts of the South America and Africa were probably over the South Pole, whereas their northern parts were closer to the tropics.

No major volcanic activity during the Silurian occurred; however, the period is characterized by major orogenic events in eastern North America and in northwestern Europe, resulting in the formation of the mountain chains there; this was called the Caledonian Orogeny. In other areas, large igneous rock formations of the Middle Silurian arose, such as those in Central Europe, as well as light sedimentation throughout the Baltic region. While not characterized by dramatic tectonic activity, the Silurian world experienced gradual continental changes that would be the basis for greater global consequences in the future, such as those that created terrestrial ecosystems.

The Silurian oceans are also of particular interest for activity between the regions known as Laurentia, Baltica and Avalonia (Figure 2). The ocean basins between these areas substantially close together, continuing a geologic trend that had begun much earlier. The new marine habitats produced by these profound changes in the Silurian seas provided the framework for significant biological events in the evolution of life. Coral reefs for example, made their first appearances in the fossil record during this time.

The Silurian Period was a time when the Earth underwent considerable changes that had important consequences for the environment and the life within it. The Silurian witnessed a relative stabilization of the world's general climate, ending the previous pattern of erratic climatic fluctuations. One significant feature of these changes was the melting of large glacial formations (Figure 3).This contributed to a substantial and significant rise in the levels of the major seas, creating many new marine habitats.

The Silurian Period's condition of low continental elevations with a high global stand in sea level can be strongly distinguished from the present-day environment. The shallow seas ranged from tropical to subtropical in climate. Commonly present in the shallow seas were coral mound reefs with associated carbonate sediments.

Paleozoic Petroleum System in the Northern Margins of Gondwana

Distribution of Silurian source rocks from North Africa to Arabia, including Iran, is the most characteristic feature of the depositional history of the Silurian, and it is well documented that the Paleozoic Petroleum System is primarily related to Silurian source rocks (Figure 2, Figure 3, Figure 4, Figure 5 and Figure 6). Silurian rocks have been drilled in Saudi Arabia and also are present in outcrops in Iran, north of Bander Abbas (Bordenave, 2000).

The end of Ordovician was marked by a glaciation which extended widely over the Gondwana Continent. The rapid retreat of glaciers caused a rapid sea level rise during the Early Llandoverian, which resulted in the deposition of graptolitic black shales, covering nearly all the areas at the edge of the Gondwana Continent, including Arabia, North Africa, Lut block, and Northwestern Pakistan and Afghanistan (Figure 2). The basal transgressive layers, deposited in a very low energy environment, are organic-rich and highly radioactive.

Lowermost Silurian (Lower Llandovery) black shales represent the main Palaeozoic petroleum source rock throughout North Africa and Arabia.

A summary of the Paleozoic source rocks distribution in Iran, Saudi Arabia and Algeria is presented here. Much detail of these source rocks are deliberately avoided for the time and space constrain. Figure 5 illustrates the stratigraphic correlation column from North Africa to Indian subcontinenet.

Morocco

Silurian Source unit is present in parts of Moroccan sedimentary basins: Tadla, Doukkala, the anti-Atlas and the Tafilalet, with recorded Total Organic Carbon (TOC) values of up to 10.5% (S. Lüning et al., 2003; Alami and Achnin, 2003). However, comparing with many other North African and Arabian countries, the Silurian-Early Devonian shale-dominated sequence in Morocco also is found to be rich in organic carbon content. Graptolite biostratigraphy provided a high-resolution correlation framework.

Source rock analyses show that the contribution of a “hot shale” Silurian source rock, like the Tadla type, could be the precursor of hydrocarbon accumulations of Meskala and Zeltene fields. The fact that these rocks are currently deeply buried and only one thin Silurian formation has been sampled in two Meskala wells is not sufficient to conclude that the hot shales in the Essaouira Basin are absent.

In the Tadla Basin of central Morocco the Aeronian (Middle Llandovery) Shale samples were analysed and found to contain as much as 4.35% TOC based on gamma-ray data from the subsurface. However, this horizon appears to be laterally discontinuous within the basin. Secondly, late Telychian-Wenlock shales from the eastern Atlas Mountains were found to have TOC values of around 2.5%, and may be correlated with age-equivalent organic-rich strata in the Ghadames Basin (eastern Algeria, western Libya, southern Tunisia) and Iraq. Late Silurian shale-limestone alternations in Morocco apparently do not contain major amounts of organic matter, although comparable deposits in parts of western Algeria are believed to be organic rich. Early Devonian graptolitic black shales from the Tadla Basin and its margins contain high amounts of organic matter (around 5% TOC).

The organic rich deposition of Silurian-Early Devonian shales may be attributed to high primary productivity in Morocco. Sea level changes may have been a vital added feature. For instance, the Rhuddanian organic-rich shales were formed during the early stages of a transgression, when marine water circulation was yet restricted which was mainly controlled by pronounced pre-Silurian relief. At other times during the Silurian-Early Devonian in Morocco, deposits with elevated organic content appear to have been formed during periods of high sea level, which may be associated with high primary productivity supplemented with a sudden rise of the anoxic or dysoxic zones onto the continental shelf.

Algeria

Silurian source characteristics are proven to extend to the North African Berkine (Ghadames) Basin, in eastern Algeria. Two Petroleum Systems are responsible for the petroleum accumulation: Triassic reservoirs are charged from the Frasnian System that is confined to the central part of the basin, and there is a Llandoverian-Wenlockian System in the western part of the basin. Migration into Paleozoic reservoirs was followed by dis-migration into overlying Triassic traps after the Cretaceous compressive movements (Yahi et al., 2001).

Geochemical analyses indicate that in the radioactive shale members of the Llandoverian-Wenlockian TOC is measured from 1.60 to 10.70%, and in the Frasnian, TOC of 3.40 to 10.80%, which are the main source rocks in the Berkine Basin. These source rocks are interpreted to consist predominantly of amorphous and lipid-rich organic matter that was preserved under anoxic depositional conditions. Most of the maturity data indicate that the Frasnian source rock is at the oil generation stage and/or the late oil/gas generation stage depending upon position within the basin, Tmax is from 432^{o} to 461^{o} C and Vitrinite Reflectance 0.75 to 1.25%. The Llandoverian-Wenlockian source rock, on the other hand, is overmature, i.e. in the gas generation phase, with Tmaxo up to 542^{o} C. Because of more favorable maturity, the Frasnian source rock is likely responsible for the recent oil discoveries in the central depression (i.e. Bir Berkine, Berkine East, Wed Teh, Hassi Berkine, Sif Fatima, Rhourde El Khrouf, Sif Fatima, and Rhourde Messaoud). The Silurian source has no vitrinite, but solid bitumen is present in rock samples, indicating reflectance up to 1.3% which shows the rock is in the gas window.

Saudi Arabia

In Saudi Arabia at least six potential source rocks are identified, from marine shales of the Ordovician Qasim Formations to Permian age Khuff carbonates. However, Silurian shales of the Qalibah Formation are the principal petroleum source rock for the Paleozoic Unayzah and Khuff reservoirs.

The basal Silurian shales, known in Saudi Arabia as the Qusaiba “hot shales”, read high radioactivity on gamma ray logs (gamma ray count exceeds 150 API units) and contain a high amount of radioactive minerals. This shale has been proven to hold between 4-12% of organic carbon. The hot shale is much less bioturbated than the shales above it; however, the hot shale and the overlying less organically rich facies of the Qusaibah Member collectively contain a megafauna of the graptolites, mollusks, brachiopods, trilobites, eurypterid fragments, and hyolithids (Jones and Stump, 1999).

Organic matter in the Qusaibah Formation is oil prone, with amorphous material, mainly graptolitic or chitinous remains, forming 60% of total organic content. Several light oil, low sulfur discoveries in Early Permian sandstones (Unayzah Fm) were originated from Silurian source rocks (Mahmood et al., 1992; Monnier et al., 1990). Reservoirs in the Haushi clastics of Carboniferous age, at the western limit of Oman, are believed to be charged by a Silurian source.

The Qusaiba "hot-shales", widely distributed in Saudi Arabia, show a marked thinning on the western side of the old Qatar Arch (Mahmoud et al., 1992), which would have, as during the Proterozoic, separated a western from an eastern Silurian Basin. The United States Geological Survey (USGS, 2002) has estimated that 37 billion barrels of oil and 808 trillion cubic feet of gas of undiscovered conventional resources are sourced from Qusaiba shales.

The Eastern Silurian Basin extended from northwest Oman to the north of Bandar Abbas, while the Western Basin extended from North Africa to northeast Saudi Arabia, and probably to most of the Lurestan and Khuzestan provinces of Iran.

Iraq

The majority of the petroleum fields are located in the eastern unstable platform of Iraq. Reservoirs of Cretaceous and Jurassic are charged through Cretaceous and Jurassic source rocks. Paleozoic exploration is mainly confined to the western desert, bordering Jordan and Saudi Arabia in southern Iraq where isolated drilled wells have indicated the presence of Silurian source rock. In the Akkas-1 and Khalesi-1 wells in the western desert, Lower Silurian shales are found to be about 65 m thick. In Akkas-1 the TOC ranges between 0.96% to 16.62% and in Khalesia-1 TOC is from 1.0% to 9.94% with a hydrocarbon generation potential of about 49 Kg HC/ton (Aqrawi, 1998). Al Haba et al. (1994) estimated that Silurian shale has a generating potential of 16 billion barrels of hydrocarbons in a sedimentary area covering approximately 20,000 sq. km. The Devonian Ora Shale (TOC 1.48 to 3.45%) has also been found to have good potential for the yield of gas in the western desert (Hasany, 2001). Not much commercial production has been taken from Paleozoic reservoirs in Iraq.

Jordan and Israel

In Jordan, the Risha Gas Field in the northeast near the Iraq border, is a basin-centered gas field. The tight reservoir of Ordovician sandstone is sourced from the black shales of the Silurian Mudawwara Formation which has been found to contain TOC from 1% to 4% and the maturity level reaches to the end of oil and into early gas generation (Ahlbrandt et al., 1997). The Paleozoic Petroleum System in Israel is also related to Silurian source rock as in the other part of the Gulf States, Jordan and North Africa. The Silurian System is estimated to have reached maturity level during the Jurassic in Israel (Tovia et al., 1997).

Iran

Like Iraq, Palaeozoic sourced reservoirs are less focused for exploration in Iran. In the Zagros foothills of Iran, a variety of Proterozoic rocks were uplifted by Proterozoic salt diapirs (Hormuz Fm), but no source rocks were found in the few samples of the Hormuz Formation. No source rocks were found either in the Cambro-Ordovician layers outcropping at the base of the thrusted units in the high Zagros Mountains, or at Kuh-e Surmeh in Central Fars. The same observation was made in the few exploration wells drilled deep enough to penetrate the pre-Permian sediments. Reddish micaceous cross-bedded sandstones, dolomitic limestone and gray-to chocolate brown micaceous shales, deposited in fluviatile to shallow marine environments, during the Cambrian and the Ordovician, have TOC values lower than 0.4%.

In the Zagros Foothills, Silurian rocks outcrop only in two places, north of Bandar Abbas, at Kuh-e Gahkum and at Kuh-e Faraghan. At Kuh-e Faraghan, 600 m of barren shales are overlain by 70 m of black shales which contain a Middle Llandoverian fauna. At Kuh-e Gahkum, at least 40 m of black platty-bedded shales with a “coaly aspect” are radioactive and contain residual TOC values as high as 4.1%, although the organic matter is over-mature (Tmax of 457° C, and Hydrogen Index varying from 50 to 200 g HC/kg C). Cumulative isopachs show that Silurian rocks at Kuh-e Gahkum were buried to some 6000 m before the Zagros orogeny. The ä13C of Silurian shales (-30.8°/oo) is comparable to those of other Silurian shales of Oman and Saudi Arabia (Bordenave and Burwood, 1990).

Paleozoic in Northwestern Pakistan

The complete Paleozoic sequence of sedimentary rocks is exposed in the ranges fringing the Peshawar Basin (Figure 7). The oldest exposed unit is the Shagai Formation, believed to be Infra-Cambrian to Cambrian, mainly composed of shales and lenses of limestone and dolomite. The base of this formation is not exposed, whereas upper contact with the Khyber Limestone is exposed throughout the area (Khan et al., 1989).

Stratigraphy of Silurian Rocks in Pakistan

Silurian sequence in the mountains west of the Peshawar Basin consists of the Landikotal and Panjpir formations. However, Khan (1989) suggested the age of the Landi Kotal Formation to be Cambrian to Infra-Cambrian, which is predominantly composed of slates with rare argillaceous limestone and common dolerite intrusions (Stauffer, 1968a; Shah, 1977; Shah et al., 1980; ?=Lala China Slatey Shales of Tahir Kheli et al., 1975). The other is the Shagai Limestone, with an assemblage of slate and phyllite with subordinate quartzite, lenticular limestone, and dolostone (Stauffer, 1968a; Shah, 1977; Shah et al., 1980). Their age is problematic, and could be Proterozoic.

Peshawar Basin

The Peshawar intermontane basin is located at the southern margin of the Pakistan Himalaya. It is bounded on the south by the Attock-Cherat Range and on the east and west by the Gandhar and Khyber ranges respectively, both of which contain rocks transitional between metasediments of the lesser Himalaya and unmetamorphosed foreland basin sediments of Kohat-Potwar Plateau of the outer Himalaya. Granitic intrusions have been found in the metasediments which belong to the marginal mass of the Indian Plate. Tectonic setting of the basin is transitional between a sedimentary fold and thrust belt to the south and metamorphic terrane to the north. Plio-Pleistocene was the time when the basin emerged as a unique entity responding to the sediments transportation from the Attock-Cherat Range (Hussain et al., 1991; Burbank and Tahirkheli, 1985).

Paleozoic rocks exposed in the Peshawar Basin, as described by Hussain et al. (1991), belong to Cambrian to Early Devonian. The age determination is based on the conodonts. The oldest known rock is the Tanawal Formation of Precambrian age. Ambar Formation is the overlying unit on Tanawal and is comprised of dolomitic limestone, calcareous quartzite and subordinate argillite with chert veins. The lower contact with the Tanawal Formation of Precambrian age and upper contact with Misri Banda quartzite of Ordovician age are unconformable. The formation is correlated with the Abbotabad Formation in Hazara.

The Misri Banda Quartzite (?=Chamla and Swabi), consists of about 600 m of calcareous and dolomitic quartzite. This sequence was thought to be Devonian (Stauffer, 1968b) until discovery of the ichnofossil Cruziana rugosa from a locality east of Misri Banda Village that is close to the type section (Pogue and Hussain, 1986; Pogue et al., 1992). The trace fossil was thought to indicate the Lower-Middle Ordovician, but according to B.D. Webby (Personal communication, 1996), C rugosa does not supply any more compelling evidence for an Ordovician than for a Silurian age. If the Misri Banda Quartzite is older than the Kandar Formation, then it could be the source of the Llandovery-early Wenlock conodonts reported in the lower Kandar Formation. The unit could, moreover, correlate with the Caradocian-Llandovery-?Wenlock transgression-regression interval. This interval elsewhere in the northern Indian Subcontinent has an upper arenaceous interval that was earlier assigned to the Muth Quartzite of Spiti, Kashmir, and elsewhere in the Indian High Himalayas. This interval is now referred to the Takche Formation.

The Panjpir Formation is a dominantly argillaceous sequence underlying the Nowshera Formation (Devonian). This unit was also termed the Kandar Formation or Kandar Phyllite (Stauffer, 1968b; Ali and Anwar, 1969; =Swabi Shale of Martin et al., 1962, and of Hussain et al., 1990, and Pogue et al., 1992) crops out around the southeast and east margin of the Peshawar Basin (Figure 8). The Panjpir Formation consists of argillite, phyllite, crinoidal limestone and calcareous quartzite. The formation has a conformable contact with the Nowshera Formation. These rocks are generally dark grey to greenish grey, silty, fissile and chloritic. Age deterministic conodonts from crinoidal limestone suggest Late Silurian age.

Nowshera Formation is dominantly composed of limestone and dolimitic limestone (Marble), calcareous quartzite and sandstone and subordinate argillite. Stauffer (1968) subdivided the formation into reef core, carbonate containing reef breccia or fossil debris, and carbonate containing fewer or no fossils. At the type locality in Nowshera it is composed of fossiliferous carbonate followed by medium- to coarse-grained carbonate, cemented sandstone and quartzite. The lower part of the formation has corals, gastropods, cephalopods, stromatoporoids and Early Devonian (Lockhovian) age deterministic conodonts. The Nowshera Formation has an unconformable contact with the Jafar Kandao Formation which is distinctly marked by a discontinuous conglomerate bed composed of pebbles and cobbles of quartzite-argillite matrix. Nowshera Formation may be correlated with Ghundai Sar reef complex of the Khyber area (Stauffer, 1968; Shah et al., 1980).

Jaffar Kandao Formation is composed of argillite, conglomerate, argillaceous quartzite and lenses of limestone lying above the Nowshera Formation. On the basis of lithology, it is subdivided into lower, middle and upper parts. The lower part is mainly argillite with lenses of limestone, argillaceous quartzite and conglomerate. The middle part is comprised of interbedded argillite, calcareous quartzite and sandy limestone. And the upper part contains argillite, with lenses of argillaceous quartzite and conglomerate. The formation is overlain by greenschist which is the southern extension of an amphbolite which was interpreted as metamorphic tholeiitic basalt.

Source Rock Evaluation in Northwest of Pakistan

In order to identify the source potential within the Paleozoic rocks exposed near Peshawar and the Khyber agency, numerous samples have been taken. Sample analysis was carried out at Hydrocarbon Development Institute of Pakistan (HDIP) Islamabad and in the National Center of Excellence in Geology, (NCEG) Peshawar University, Peshawar. All the samples show higher TOC ranging from 4% to 15.98%. Most of the samples were collected in the areas near Landikotal, Ali Masjid and Lowara Meena. Oil and gas seeps are also reported from this area. Tests results and other information of the sample is given in Table 1. Figure 7 shows the location of the samples and oil and gas seeps in the area. No other tests to identify the maturity and genetic potential of these samples have been carried out. However, further evaluation is planned to be carried out in near future.

Oil and Gas Seeps in the Landi Kotal and Peshawar Areas

A seep is visible evidence at the Earth's surface of the present or past leakage of oil, gas or bitumen from the subsurface. Visible petroleum seeps are important in an exploration program because their presence implies that the first requirement has been satisfied and possibly others, if it is a major seep. Many large petroleum seeps are believed to be tertiary migration; that is, migration from an accumulation that has been disturbed by tilting of strata, changes in depth of burial, or development of new avenues of escape to the surface, such as a fault-fracture system.

In Peshawar Basin three (3) oil and gas seeps have been found:

1) Azakhel

Location: (X and Y data: N 1164000 E 3366000; Coordinates: 33° 48' 09"N and 71° 37' 08"E).

This oil and gas seep is located 24 km south of Peshawar where no apparent rocks crop out in the nearby area. About 1.5 km southeast of seep area, steeply dipping due south, red shale and sandstone of the Murree Formation is exposed in Deri Miagan, at the extreme southern margin of the Peshawar Basin near Hassankhel or Chandan Gari Azakhel. A water well was dug to 300 ft (91 m) and attempted to pump water out through a motor which failed to pump a full column of water. Free air bubbles were observed to be coming out of water. The odorless air bubbles proved to be combustible gas when it accidentally caught fire which remained ablaze for a few days. Locals used this gas for their domestic purposes. The pressure of the gas dropped after some days which was reported to be reactivated after some time. The drilled out soil was oil wet, soft and elastic. No further data of this gas seep is available.

2) Inzari Kandao

Location: (X and Y data: N 1205000 E 3317500; Coordinates: 34° 09" 13.03"N and 71° 08'30"E).

This oil and gas seep is located 40 km northwest of Peshawar and 8 km north of Landi Kotal near the Afghanistan border. Silurian-Devonian rocks are exposed in the area. The presence of petroleum was first noticed by the owner of the drinking water well. Oil was the dominant constituent of the seep. The water from the well was reported to become useless for drinking and was abandoned for drinking purposes. The flow of oil ceased, but the combustible gas is still active in the well and also in the nearby area.

3) Landi Kotal Bazaar

Location: (X and Y data: N 1199000 E: 3317500; Coordinates: 34° 06” 14”N and 71° 08’ 59.5”E).

This gas seep is located approximately 38 km north of Peshawar and about 8 km east of the Afghanistan border. In the area Silurian-Devonian rocks are exposed. This is a combustible gas seep. The flow of gas is not quite regular and at times it remains inactive.

Conclusions

The Silurian sequence has been documented as a world class source rock in North Africa and the Arabian Peninsula which has generated one of the world’s largest petroleum reserves. The Paleozoic sequence, principally the Silurian System, was not earlier considered in Pakistan as the potential Petroleum System. The plate tectonic framework provides a consistent methodology to identify the depositional conditions conducive for source rock. Reconstructing paleogeographic maps of the Silurian System illustrates similar depositional and biologic conditions in the northwestern margins of the Indian Plate as found in the North Africa and Arabian Peninsula. Post-depositional tectonic conditions are not significantly similar in these two distant parts of the world.

Our present work will hopefully initiate a debate to prove our concept or invalidate it. We invite other geoscientists to critically review and evaluate our concept.

With the following evidence, it can be inferred that the area lies in the progression of the well-known Paleozoic Petroleum source rocks having a convincingly good correlation with North Africa and Arabian-Iranian areas:

1) A thick sequence of Mid-Paleozoic rocks with the Silurian strata around the northwestern fringes of the Peshawar Plain, having yielded rich faunal contents.

2) A variable CAI response of the contained Conodonts fauna from the area reflecting a varied thermal maturity ranking which can help in confining the area of the particular thermal window for defining required thermal environment for the contained hydrocarbon development in the area.

3) The TOC of the contained black carbonaceous material from selected spots in the area indicating an encouraging sign as compared to the known TOC values in the similar stratigraphic sequences elsewhere from the Paleozoic Petroleum source rocks of the known references.

4) The recurring reported oil and gas seeps all around the outskirts of the area which supports the idea of concealed subsurface targets of an unknown nature and volume.

In view of its eccentric signatures being recorded in the Paleozoic sequence around the Peshawar Basin in northwestern Pakistan, there needs to be follow-up studies in line with the known facts, in order to assess its hydrocarbon potential.

Proper mapping of the Silurian horizon of the area should be conducted in order to establish its correlation with the known references elsewhere in the region, with particular emphasis being given to its basinal position and paleogeographic depositional environment. Also with a particular emphasis being given to the Tectono-Metamorphic aspect of the area, because the area lies in a peculiar tectonic setup along the transpressional boundary of the Indian Plate. A detailed structural reconstruction of the area would be required to interpret the hydrodynamics and fluid migration.

At the first stage we suggest a survey be undertaken to determine the pattern of thermal annealing that has been experienced by these sequences in northern and northwestern Pakistan, specifically for the regions from the northern edge of the Mesozoic-Cainozoic cover from the Pak-Afghan border through to the Indus to the Peshawar-Khyber road in the north, with sampling north of Khyber Road wherever the metamorphic grade is not excessive, especially in the Landi Kotal area. Radiometric data should be collected on the known carbon bearing horizons to construct the Gamma Ray logs for establishing any plausible correlation for its contained organic compounds.

The possibility of occurrence of the deeply buried Silurian System in the Sulaiman Basin is also not overruled. The structures where Cretaceous and older rocks are exposed should be considered for deeper Paleozoic exploration for petroleum, assuming that a Paleozoic Petroleum System exists in subsurface which was not considered for exploration in the past due to the absence of any known Petroleum System in the Early Mesozoic or Paleozoic System.

Acknowledgements

The authors would like to thank Pakistan Petroleum Limited and the University of Peshawar for permission to publish this paper. The authors further gratefully acknowledge the personal contributions of Nusrat Kamal Siddiqui, Miss Qurat-ul Ain, Saleem A. Hashmi, Irfan Lateef Khan, Sahaddat-ur-Rehman and Jawwad. We are grateful to the faculty members and students of the National Center of Excellence in Geology, Peshawar University.

Our profound thanks to PAPG and SPE and the organizers of the Annual Technical Conference 2003 who provided us this opportunity to present this article.

References

Ahlbrandt, T.S., O.A. Okasheh, and M.D. Lewan, 1997, A Middle East basin center hydrocarbon accumulation in Paleozoic rocks, eastern Jordan, Western desert, and surrounding regions: AAPG Bulletin, v. 81/8, p. 1359-1360.

Alsharhan, A.S., 1987, Geology and reservoir characteristics of carbonate build up in giant Bu Hasa oil field, Abu Dhabi, United Arab Emirates: AAPG Bulletin, v. 71/10, p. 1304-1318.

Alsharhan, A.S., and C.G. St. C. Kendall, 1986, Precambrian to Jurassic rocks of Arabian Gulf and adjacent areas: their facies, depositional setting, and hydrocarbon habitat: AAPG Bulletin, v. 70/8, p. 977-1002.

Aqrawi, A.A., 1998, Paleozoic stratigraphy and petroleum systems of the western and south western deserts of Iraq: Geo Arabia, v. 3/2, p. 229-248.

Bates, M., 1960, Ecology and evolution, *in* S. Tax (ed.), Evolution after Darwin, v. 1, The evolution of life: Chicago, University of Chicago Press, p. 547-568.

Bois, C., P. Bouche, and R. Pelet, 1982, Global geologic history and distribution of hydrocarbon reserves: AAPG Bulletin, v 66/9, p. 1248-1270.

Bordenave, M.L., 2002, Gas prospective areas in Zagros domain of Iran and in the Gulf Iranian waters: AAPG Search and Discovery Article #10040a, 10 p. Website accessed 28 December 2012. http://www.searchanddiscovery.com/documents/bordenave02/images/bordenave02.pdf

Bralower, T.J., and H.R. Thierstein, 1987, Organic carbon and metal accumulation in Holocene and mid-Cretaceous marine sediments: paleo-oceanographic significance, *in* J. Brooks, A.J. Brooks, and A.J. Fleet (eds.), Marine petroleum source rocks: Geological Society Special Publication No. 26, p. 345-370.

Brooks, J., C. Cornford, and R. Archer, 1987, The role of hydrocarbon source rocks in petroleum exploration in marine petroleum source rocks: Geological Society, London, Special Publication No. 26, Blackwell, p. 444.

Burbnak, D.W., and R.A.K. Tahirkheli, 1985, The magnetostratigraphy, fission-track dating, and stratigraphic evolution of the Peshawar intermontane basin, northern Pakistan: GSA Bulletin, v. 96, p. 539-552.

Degens, E.T., and K. Mopper, 1976, Factors controlling the distribution and early diagenesis of organic material in marine sediments, *in* R. Chester and J.P. Riley (eds.), Chemical Oceanography: London, Academic Press, v. 6, p. 59-113.

Demaison, G.J., and G.T. Moore, 1980, Anoxic environments and oil source bed genesis: AAPG Bulletin, v. 64/8, p. 1179-1209.

Erdtmann, B.D., 1982, Paleobiogeography and environments of planktonic dictyonemid graptolites during the earliest Ordovician, *in* M.G. Bassett and W.T. Dean (eds.), The Cambrian-Ordovician boundary: sections, fossil distribution, and correlations: National Museum of Wales, Geological Series No. 3, p. 9-27.

Gorin G.E., L.G. Racz, and M.R. Walter, 1982, Late Precambrian-Cambrian sediments of Huqf Group, Sultanate of Oman: AAPG Bulletin, v. 66/12, p. 2609-2627.

Grunau, H.R., 1983, Abundance of source rocks for oil and gas worldwide: Journal of Petroleum Geology, v. 6/1, p. 39-54.

Hasany, S.T., 2001, Hydrocarbon potential of the Block 9, western desert: Southwest Iraq: An evaluation report, 43 p. (internal company report).

Hunt, J.M., 1979, Petroleum geochemistry and geology: San Francisco, W.H. Freeman, 617 p.

Hussain, A., K.R. Pogue, S.R. Khan, and I. Ahmed, 1991, Paleozoic stratigraphy of the Peshawar Basin: Pakistan. Bull. Univ. Peshawar, v. 24, p. 85-97.

Husseini, M.I., 1991, Tectonic and depositional Model of the Arabian and adjoining plates during the Silurian-Devonian: AAPG Bulletin, v. 75/1, p. 108-120.

Jones, P.J., and T.E. Stump, 1999, Depositional and Tectonic setting of the Lower Silurian Hydrocarbon source rock facies, central Saudi Arabia: AAPG Bulletin, v. 83/2, p. 314-332.

Kadri, I.B., 1994, Petroleum Geology of Pakistan: Pakistan Petroleum Limited, 275 p.

Khan, A., M. Aslam, and R.N. Khan, 1989, Revised Stratigraphy of the Paleozoic rocks: Khyber Agency, NWFP, Pakistan, Info. Rel 431, p. 1-12.

Klemme, H.D., and G.F. Ulmishek, 1991, Effective petroleum source rocks of the world: stratigraphic distribution and controlling factors: AAPG Bulletin, v. 75/12, p. 1809-1857.

Koblentz-Mishkie, O.J., V.V. Volkovinsky, and Y. G. Kabanova, 1970, Planton primary production in the World ocean, *in* W. Wooster, (ed.), Scientific exploration of the South Pacific Ocean: National Academy of Sciences, Washington, D.C, p. 183-193.

Luning, S., D.K. Loyedell, O. Sutcliff, A. Atif Salem, E. Zanella, J. Craig, and D.A.T. Harper, 2000, Silurian Lower Devonian black shales in Morocco: Which are organically richest horizons?: Journal of Petroleum Geology, v. 23/3, p. 293-311.

Mahmoud, M.D., D. Vaslet, and M.I. Husseini, 1992, The Lower Silurian Qalibah Formation of Saudi Arabia: an important hydrocarbon source rock: AAPG Bulletin, v. 76/10, p. 1491-1506.

Martin, N.R., S.F.A. Siddiqui, and B.H. King, 1962, A geological reconnaissance of the region between the lower Swat and Indus Rivers of Pakistan: Geological Bulletin of the Punjab University, v. 2, p. 1-13.

McGillivray, J.G., and M.I. Husseini, 1992, The Paleozoic petroleum geology of Central Arabia: AAPG Bulletin, v. 76/10 p. 1473-1490.

North, F.K., 1980, Episodes of source-sediment deposition: Journal of Petroleum Geology, v. 2/3, p. 323-338.

North, F.K., 1985, Petroleum Geology: London, Allen and Unwin, 607 p.

North, F.K., 1979, Episodes of source-sediment deposition: Journal of Petroleum Geology, v. 2/2, p. 199-218.

Pareek, H.S., 1983, Stratigraphy of Northwestern India and its correlation with that of Indus Basin, Pakistan, Malagasy, and South America: Geophytology, p. 1-21.

Pelete, R., 1987, A model of organic sedimentation on present-day continental margins, *in* J. Brooks and A.J. Fleet (eds.), Marine petroleum source rocks: Geological Society Special Publication 26, p. 167-180.

Pogue, K.R., and A. Hussain, 1986, New light on the stratigraphy of the Nowshera area and the discovery of Early to Middle Ordovician trace fossils I NWFP: Geological Survey of Pakistan, Rec. 44, p. 1-31.

Pollastro, R.M., 2003, Total Petroleum Systems of the Paleozoic and Jurassic, Greater Ghawar Uplift and Adjoining Provinces of Central Saudi Arabia and Northern Arabian-Persian Gulf: USGS Bulletin 2202-H, p. 1-47.

Shah, S.M.I., 1977, Stratigraphy of Pakistan: GSP Memoir 12, p. 1-138.

Shah, S.M.I., R.A. Siddiqui, and J.A. Talent, 1980, Geology of the eastern Khyber Agency, NWFP, Pakistan: Geological Survey of Pakistan, Rec 44, p. 1-31.

Smith, A.G., J.C. Briden, and G.E. Drewry, 1973, Phanerozoic world maps, *in* N.F. Hughes, (ed.), Organisms and Continents Through Time: Special Papers in Palaeontology, v. 12, p. 1-42.

Stauffer, K.W., 1968, Silurian-Devonian reef complex near Nowshera, West Pakistan: Bulletin GSA, v. 79, p. 1331-1350.

Stauffer, K.W., 1968, Geology of the Khyber Pass, Khyber Agency, West Pakistan: USGS Project Report 22, p. 1-42.

Stein, R., 1986, Surface-water paleo-productivity as inferred from sediments deposited in oxic and anoxic deep-water environments of the Mesozoic Atlantic Ocean, *in* E.T. Degens, P.A. Meyers, and S.C. Brassel (eds.), Biogeochemistry of black shales: Mitteilunger aus dem Geologisch-Palaontologischen Institut der University Hamburg, v. 60, p. 55-70.

Talent, J., and O.N. Bhargava, 2003, Silurian of the Indian Subcontinent and adjacent regions, *in* E. Landing and M.E. Johnson (eds.), Silurian Lands and Seas, Paleogeography outside of Laurentia: New York State Museum Bulletin, The University of the State of New York, p. 221-239.

Thickpenny, A., and L.K. Legget, 1987, Stratigraphic distribution and paleo-oceanographic significance of European early Paleozoic organic-rich sediments, *in* J. Brooks and A.J. Fleet (eds.), Marine petroleum source rocks: Geological Society, London, Special Publication 26, p. 231-247.

Tovia, L., S. Valadimir, and I. Leifman, 1997, Paleozoic Petroleum System of the Middle East - A new potential in Israel: AAPG Bulletin, v. 81/8, p. 1396.

Tyson, R.V., 1987, The genesis and palynofacies characteristics of marine petroleum source rocks, *in* J. Brooks and A.J. Fleet (eds.), Marine petroleum source rocks: Geological Society Special Publication 26, p. 47-67.

Vail, P.R., M. Mitchum, Jr., and S. Thompson III, 1977, Global cycles of relative changes of the sea level, *in* C.E Payton (ed.), Seismic stratigraphy applications to hydrocarbon exploration: AAPG Memoir, v. 26, p. 38- 98.

Yahi, N., R.G. Schaefer, and R. Littke, 2001, Petroleum generation and accumulation in the Berkine Basin, Eastern Algeria: AAPG Bulletin, v. 85/8, p. 1439-1467.

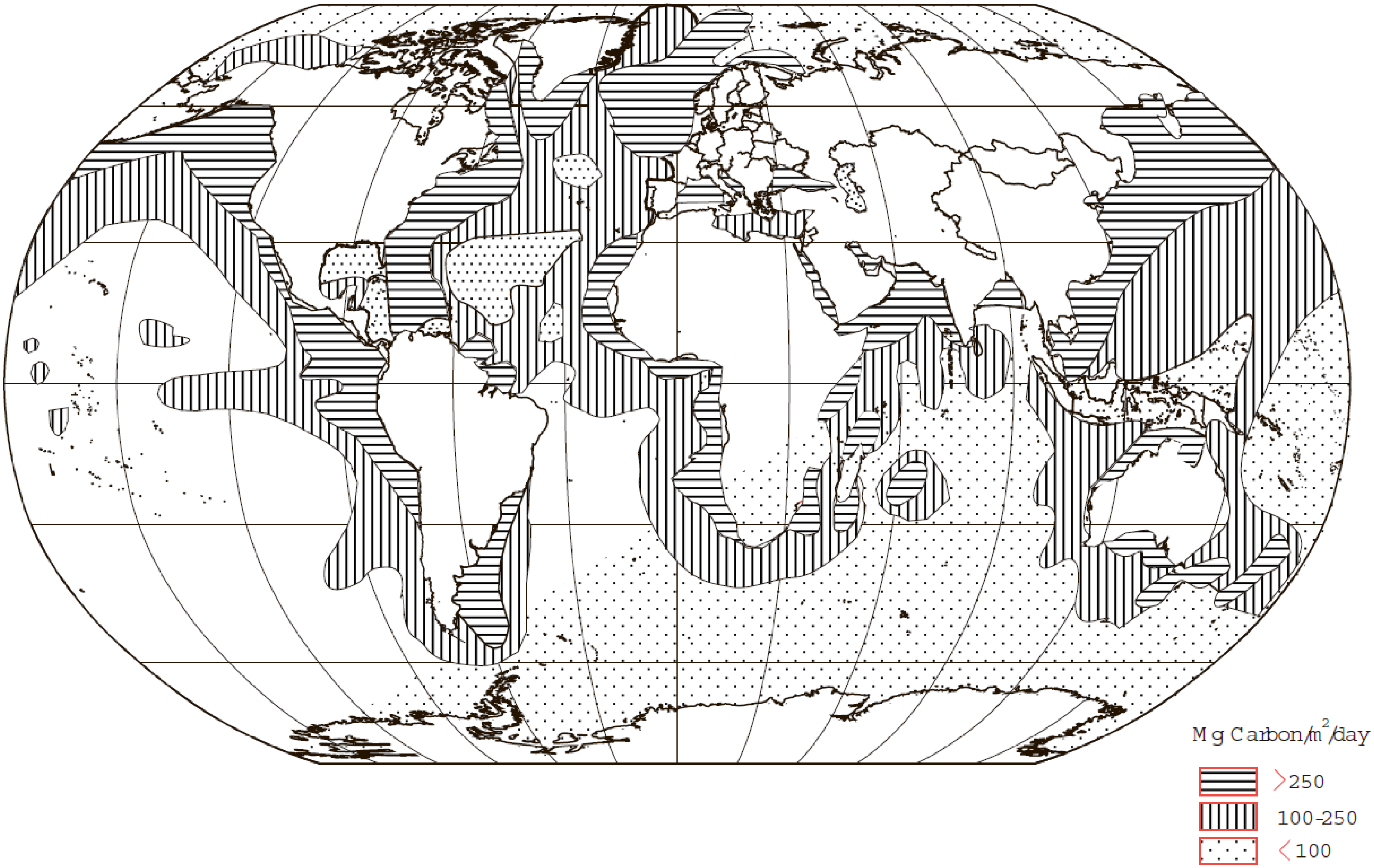

Figure 1. Distribution of biological production in world oceans (after various authors, including Koblents-Mishkie et al., 1970; Brooks et al., 1987)

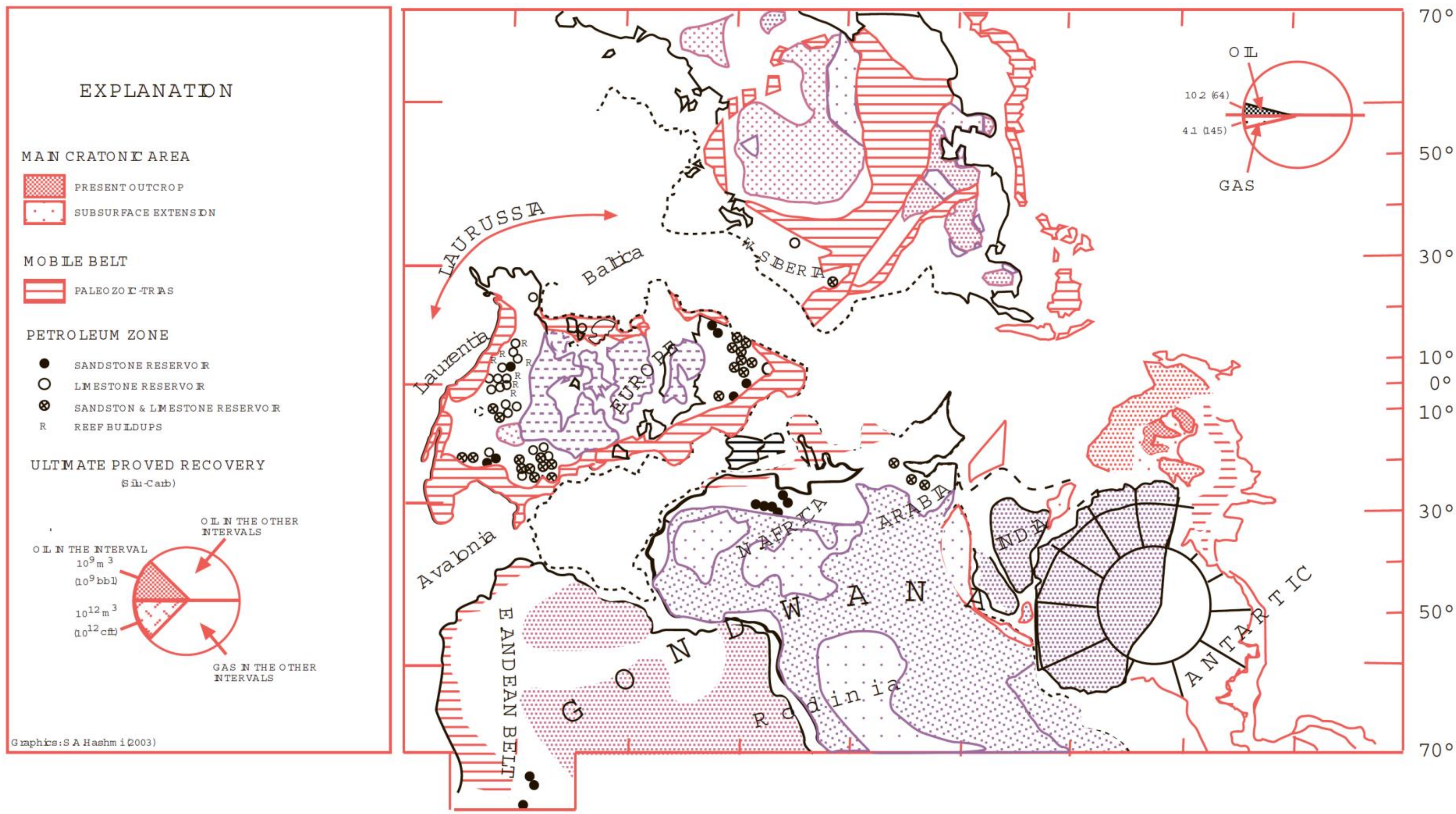

Figure 2. Paleo-reconstructed map of Silurian time showing present day Paleozoic reservoired petroleum fields across the globe (modified from Smith et al., 1973; Bois et al., 1982).

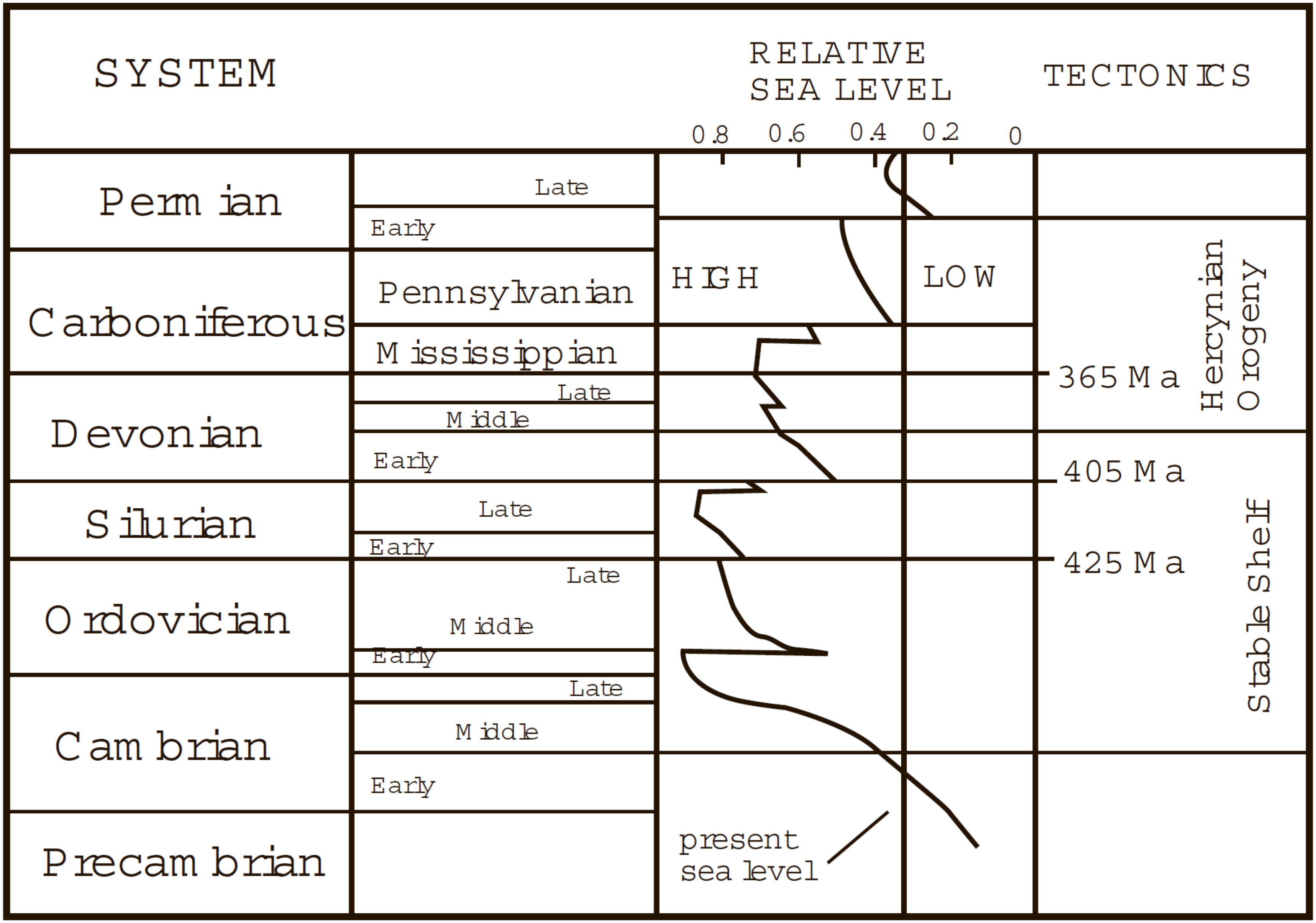

Figure 3. The global sea level curve (after Vail et al., 1977) shows an Early Silurian lowstand corresponding to the glaciation of Gondwana, followed by a post-glacial highstand. In the latest Silurian and again in Early Devonian, sea level dropped sharply giving rise to a Late Silurian Hiatus (after Husseini, 1991).

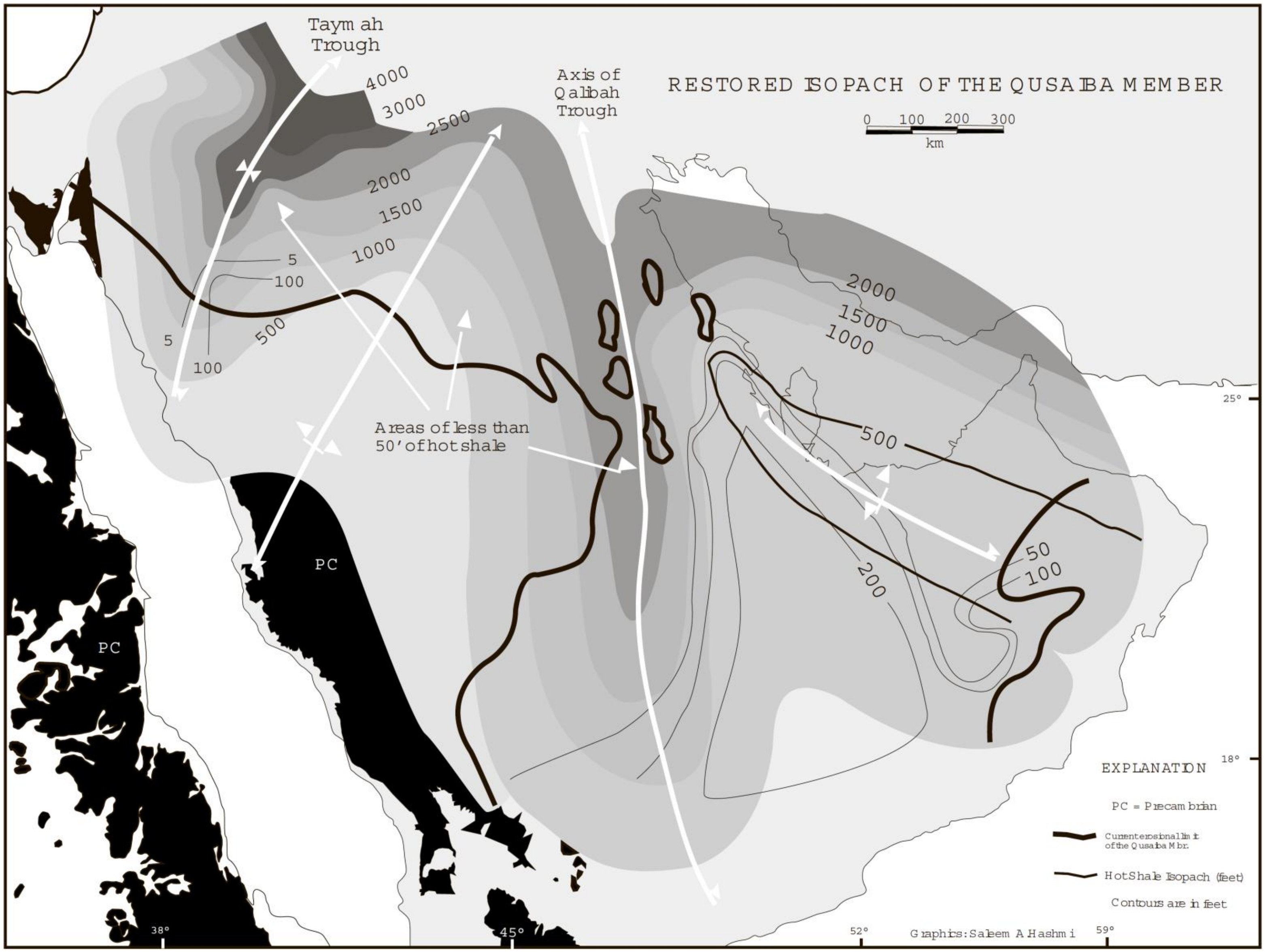

Figure 4. Restored isopach map of the Silurian Qusaiba Member of the Qalibah Formation (filled contours) with an isopach of the hot shale (overlay contours) covering the area from all of Saudi Arabia, United Arab Emirates, Qatar, Kuwait, Oman, Iraq and southwestern part of Iran. The Qusaiba Member is the major source rock for the Paleozoic reservoirs of Qatar, Saudi Arabia and Iraq (modified after Jones and Stumps, 1999).

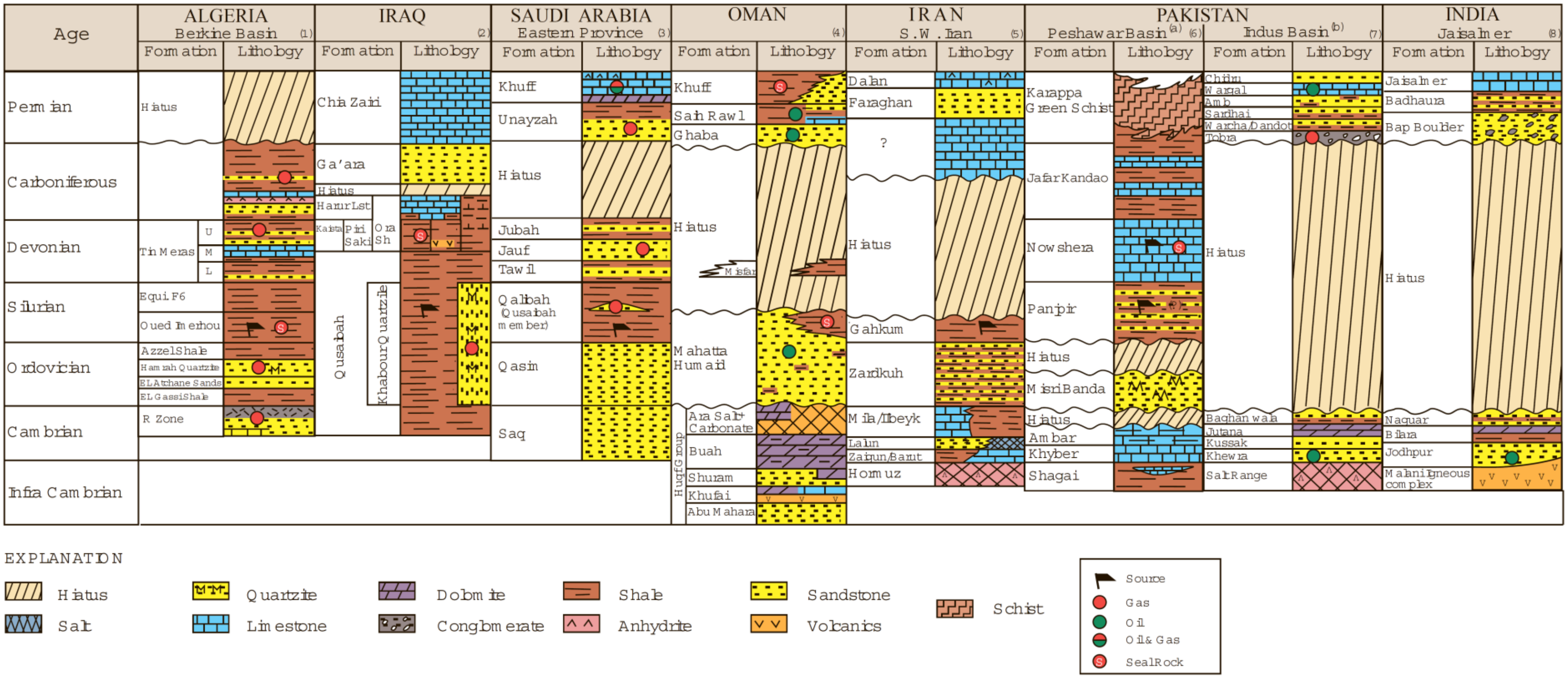

Figure 5. Generalized stratigraphic column of Paleozoic petroleum provinces from Algeria, Iraq, Saudi Arabia, Oman, Iran, Pakistan and India.

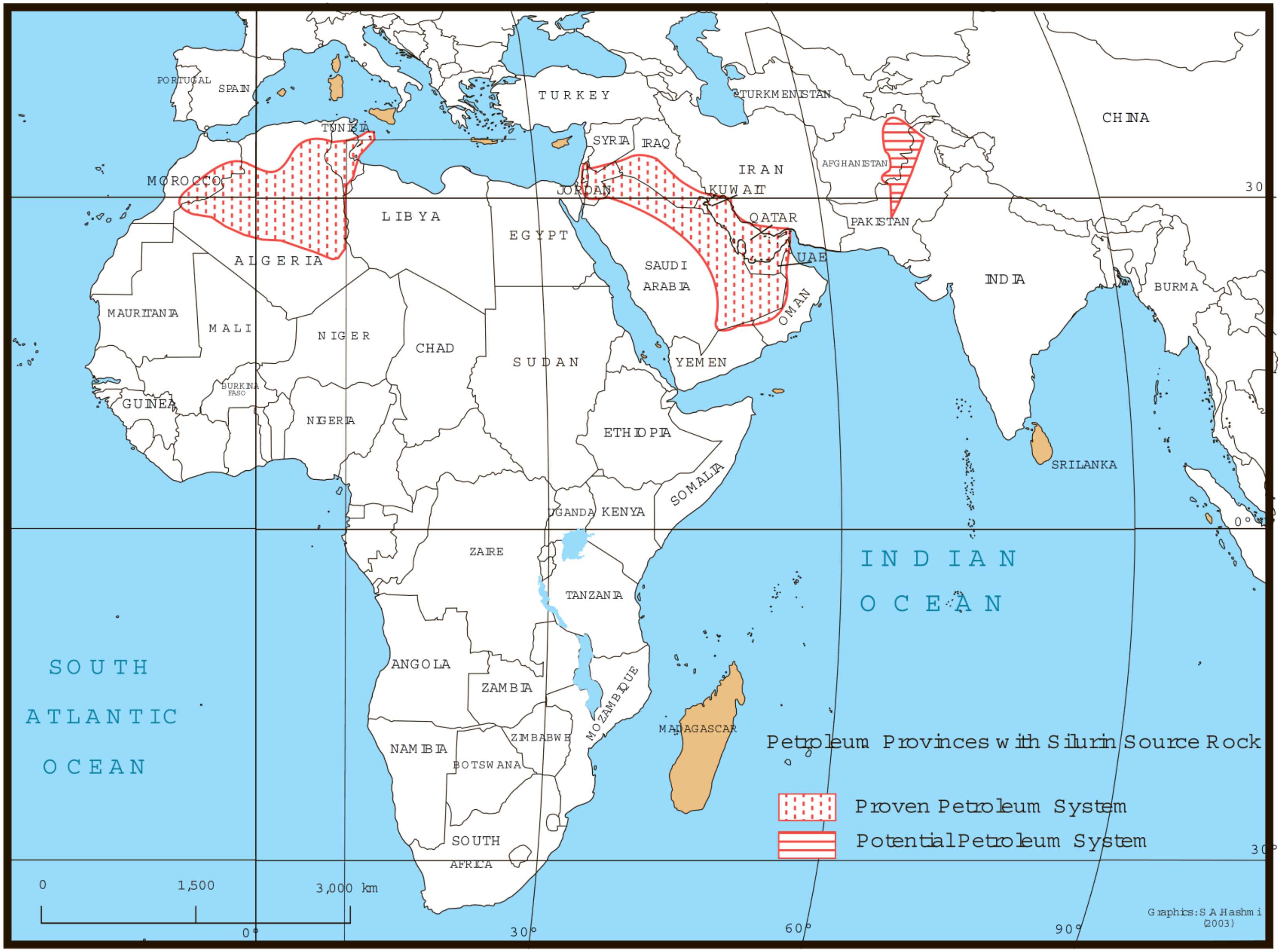

Figure 6. Map showing petroleum provinces of North Africa and Arabian-Iranian Basin. The unexplored Paleozoic (Silurian) Petroleum System is shown in northwest Pakistan and northeast Afghanistan.

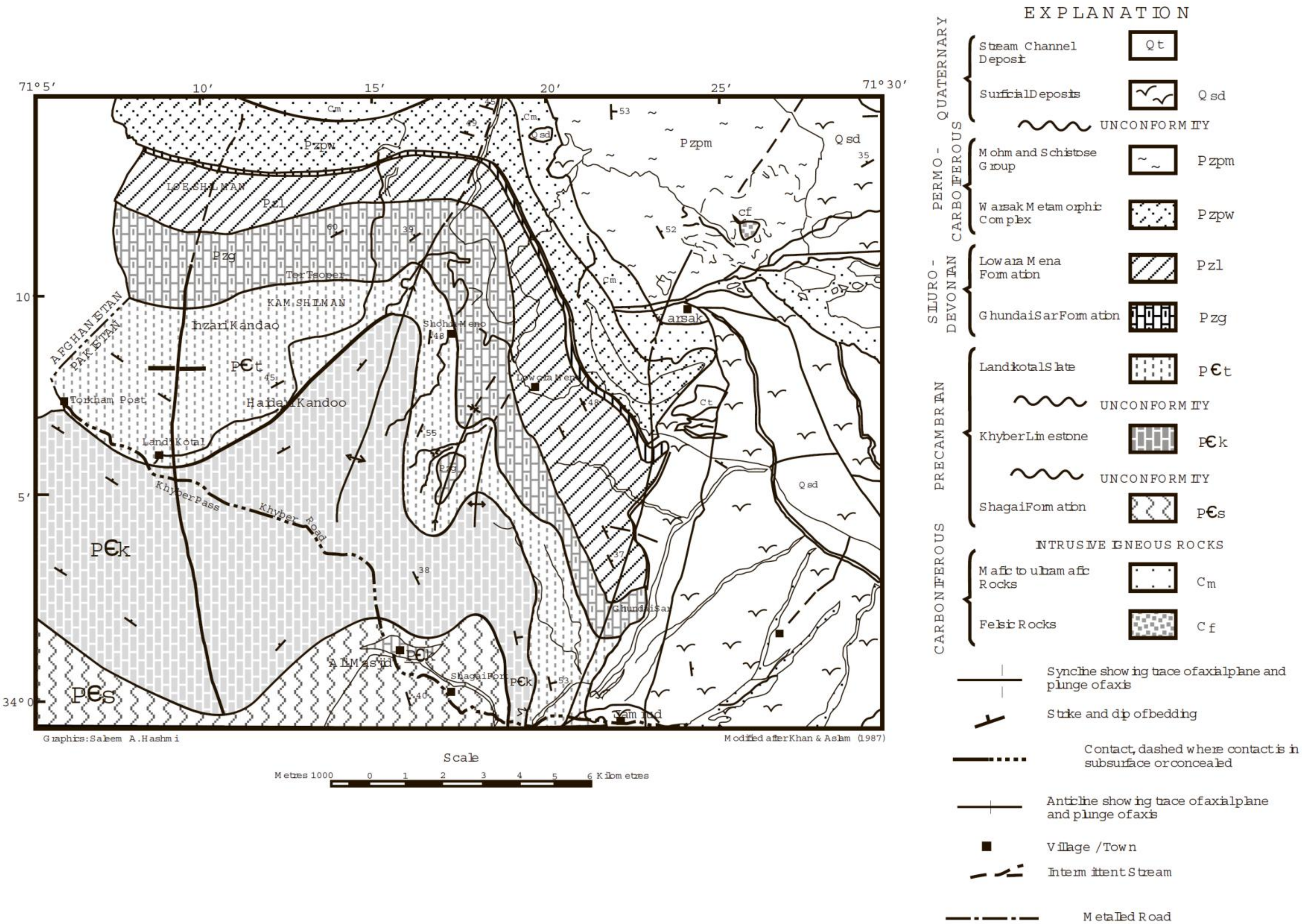

Figure 7. Regional geological map of the northern Khyber Agency, N.W.F.P., Pakistan. Boundaries of the formations are problematic and not very certain due to difficulty in age determination. The extreme inhospitable local conditions and rugged terrain prohibits working in the area. Information was limited to a few geological traverses and reports.

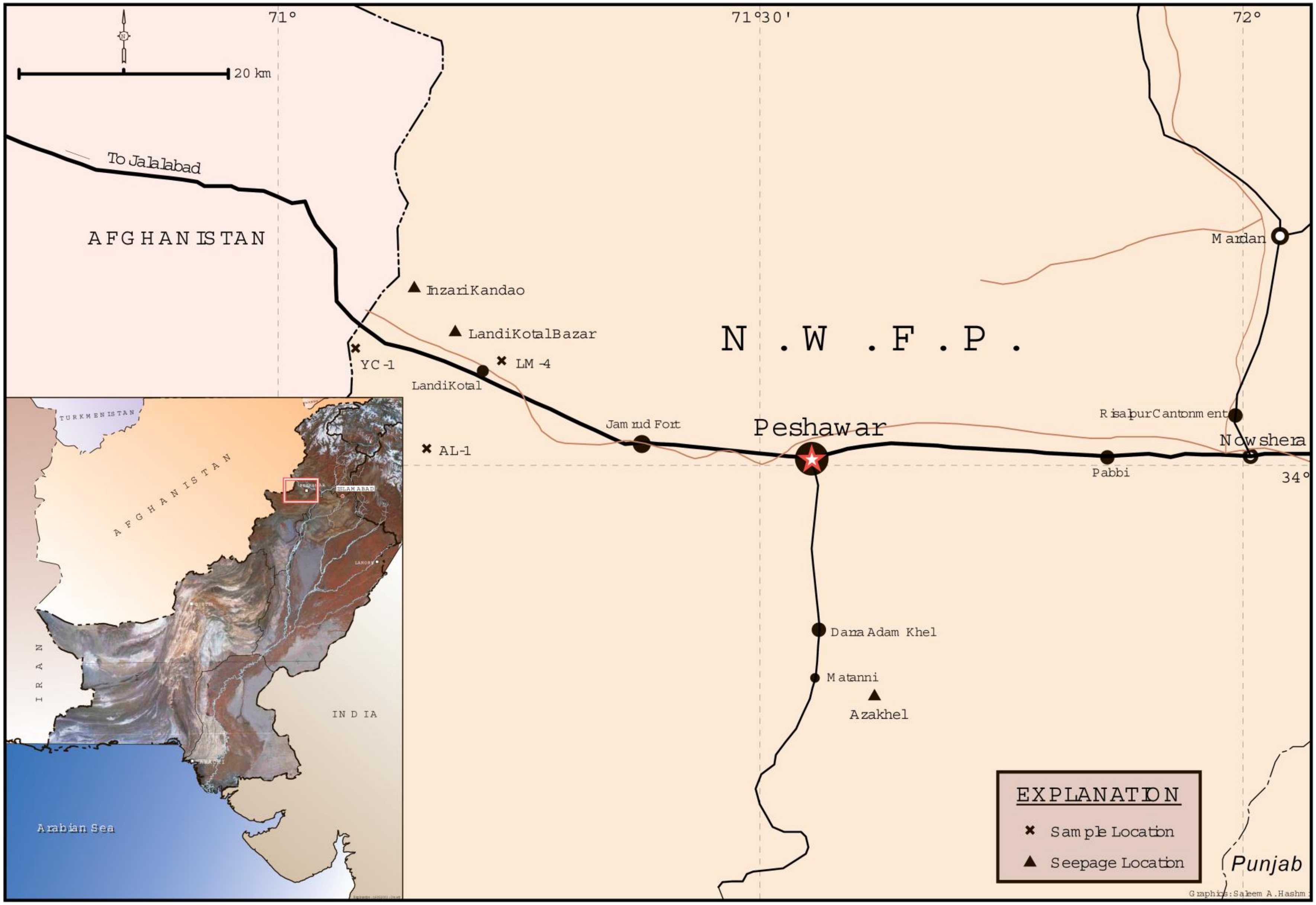

Figure 8. Location map of oil and gas seeps and source rock samples (see Table 1 for sample details).

S.No	Sample No	Location	Age	Lithology	TOC (%)	GPS data & Toposheet No
1	*YC-1*	*Yakha Cheena*	*Silurian - Devonian*	*Shale*	*8.57*	*1207000N. 3316000E 38 N/4*
2	*AL-1*	*Ali Masjid*	*Silurian - Devonian*	*Carbonaceous shale, silt and limestone*	*12.47*	*1190700N. 3329000E 38 N/8*
3	*LM-4*	*Lowara Mena*	*Silurian - Devonian*	*Shale, limestone*	*8.47*	*1203900N 3338500E 38/N8*

Table 1. TOC values from three Silurian/Devonian samples (for sample locations see Figure 8).