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A PRIMER ON THE OCCURRENCE OF COALBED METHANE IN LOW-RANK COALS, WITH SPECIAL REFERENCE TO ITS POTENTIAL OCCURRENCE IN PAKISTAN

by

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Introduction

This report compiles and updates a series of correspondence that took place between 1998 and early 2000 among the author and representatives of various consulting groups operating in the coal sector of Pakistan. The purpose of the original correspondence was to introduce basic concepts of coalbed methane (CBM) in low-rank coals to planners and other parties interested in the development of Pakistan's coal, particularly the large deposits of the Thar desert area of Sindh Province that were recently discovered (SanFilipo and Khan, 1994) by the Geological Survey of Pakistan (GSP) and the U.S. Geological Survey (USGS). The author tested two shallow boreholes in Sindh Province for CBM in 1992, including one in Thar, with very marginal results. Additional targets with better CBM prospects were recommended shortly thereafter (SanFilipo and others, 1994), but these were not followed up during subsequent drilling, nor were any other sites tested. Recent events, notably the rapid pace of CBM development in low-rank coals of the Powder River Basin of the U.S., and a show of CBM in commercial quantities in the Cambay Basin of India **-** both of which are similar in age and rank to most of Pakistan's coal **-** have indicated a need for reevaluating the initial CBM investigations made in Pakistan in 1992 and for a reassessment of the CBM prospects for the country at large.

Purpose and Scope

The purpose of this report is to provide a basic understanding of some of the parameters involved in assessing an area on a regional scale for commercial CBM potential in low-rank coals. The report begins with a brief overview of the modes of CBM occurrence, an understanding of which is essential in order to devise an assessment strategy for any particular locality. The prevailing models for CBM occurrence in low-rank coals have changed dramatically in recent years due to the growth of commercial CBM activity in the Powder River Basin (PRB), and are still evolving. The report takes into consideration these evolving models to outline a very general program for further assessing the CBM potential of Pakistan, drawing on the preliminary results of USGS investigations of CBM in very similar coals of the Gulf Coast Province of the U.S. Also outlined are some programmatic requirements that would need to be met in order to effect USGS participation in a more specific CBM exploration program in Pakistan. In addition to this report, a poster presentation of the preliminary results of USGS CBM investigations in the U.S. Gulf Coast (modified from SanFilipo and others, 2000) is available in limited quantities from the author upon request. The updated poster includes a previously unreleased addition on "The Pakistan Analogy" to Gulf Coast CBM, and was originally intended for informal presentation at the Institute of Engineers (Pakistan) 1st International Mining Engineering Conference in Quetta (indefinitely postponed from May 2000).

The Basics of CBM Occurrence

Coal is an unusual lithology in that it is both an excellent source and reservoir rock (Levine, 1993). CBM is usually generated in place and stored within the coal. It also differs from conventional reservoirs in that usually all but a negligible amount of the gas is sorbed on to the coal matrix rather than occurring as free gas or dissolved in formation water (McLennan, Schafer and Pratt, 1995), at least in theory. Most of the sorbed gas is adsorbed, that is densely packed as a single layer on the pore walls; as such, it behaves like a liquid rather than following the ideal gas law like conventional free gas (Yee, Seidle, and Hanson, 1993). Some is absorbed; that is, dissolved in the coal matrix (McLennan, Schafer and Pratt, 1995). While the sorption phenomena are caused by weak molecular attractions, the gas is ultimately held in the coal hydrostatically. The bottom line is that CBM is generally not free-flowing to the well bore; the reservoir pressure must be reduced by dewatering the coal to produce it. That is why it was overlooked for so long, or in the cases where it did flow naturally, considered a blowout nuisance, mining hazard, or greenhouse threat. However, the gas storage capacity of coal is very high; many times that of conventional reservoirs at low pressures (i.e. shallow depths) (Mavor and Nelson, 1997) - one analogy is that of sponge or silica gel (Yee, Seidle, and Hanson, 1993). The preferred method to test for CBM is to place freshly cored coal in airtight containers and measure the gas with a series of manometers as it desorbs. Commercial well completion usually involves hydrofracting or letting the hole cave under its own hydrostatic pressure (cavitation) and co-producing water and gas with the aid of pumps. As the coal is dewatered, most of the sorbed gas diffuses to fractures where it is released and migrates to the well-bore (McLennan, Schafer and Pratt, 1995, Mavor and Nelson, 1997).

CBM is thought to be generated during three distinct stages of the parent coal's maturation history (Rice, 1993): (1) an early biogenic stage (i.e. gas produced by bacterial activity during the conversion of peat to coal), (2) a thermogenic stage (i.e. gas produced by coal when its constituents volatilize as it increases in rank due to increasing temperatures encountered with greater depth of burial or proximity to igneous activity), and (3) a late biogenic stage (i.e. gas produced by bacterial activity after the coal has reached thermal maturity). Within the reservoir CBM can theoretically exist from any combination of these stages of generation. The mode of occurrence for CBM is usually inferred from hydrogen and carbon isotopic compositions (fig. 1) and 'wetness' expressed as the ratio of methane to higher alkanes (Whiticar, 1994). These parameters are then related back to maturation pathways that include various chemical and bacterial processes (e.g. fermentation and CO_2 [i.e. "carbonate"] reduction; Rice, 1993), which in turn can theoretically be related to the three stages of generation described above. There is probably considerable overlap in the chemical and biological pathways however, and these models are still evolving. They are important, however, because until very recently there has been only minor commercial interest in biogenic CBM. The vast majority of production has traditionally been ascribed to stage 2 gases, but these are now recognized to frequently contain a significant admixed component of stage 3 gas (Scott, Kaiser, and Ayers, 1994). The PRB has generally been regarded as a source of stage 1 gas (fig. 1),

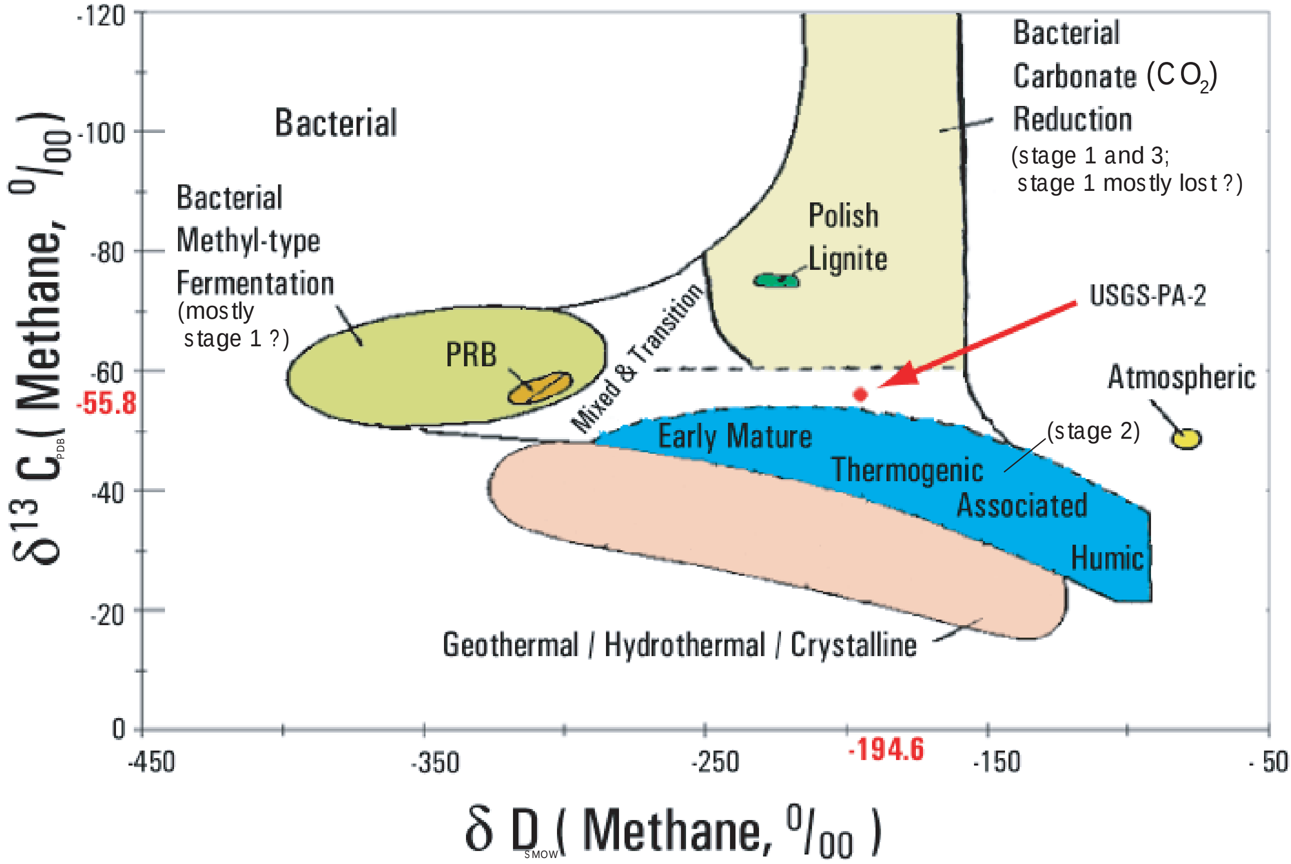

Figure 1. CD (Carbon-Deuterium) diagram for methane; the isotopic composition of carbon (y axis) is plotted against the isotopic composition of hydrogen (x axis), showing the fields for various methane sources. For conventional gases, the distinction between the CO_2 reduction and the bacterial fermentation metabolic pathways has been ascribed to the dominant process that occurs in marine versus nonmarine environments, respectively (Whiticar, 1994), or to temporal factors, with both pathways contributing to early formed gases, and late-stage gases more-or-less restricted to CO_2 reduction (Schoell, 1988; Law, Rice, and Flores, 1991). The controls on biogenic CBM generation are generally ascribed to temporal factors (i.e. stages), with the Powder River Basin (PRB in diagram) being perhaps the only documented accumulation of ancient early biogenic gas (stage 1 gas of this report). Early models (i.e. Law, Rice and Flores, 1991) considered accumulations of stage 1 CBM unlikely without conventional trapping mechanisms, but these are not present with the most recent production from the PRB. It should be noted that Rice (1993) has suggested that an observed deuterium enrichment of CBM-associated waters in the PRB can be attributed to fractionation from the gas, and that this implies a major stage 3 CO_2-reduction component to the PRB CBM. USGS-PA-2 in the diagram refers to a single gas sample obtained from a U.S. Gulf Coast coal that is very similar in age, rank, and depositional setting to most Pakistani coals. Based on the isotopic composition, this gas clearly could have been generated from a number of sources. Figure modified from Warwick and others, 2000; Whiticar, 1994; and Clayton, 1998.

but its commercial potential was only recently realized. The vast majority of Pakistan's CBM potential is probably from biogenic sources, although at this point distinguishing stage 1 from stage 3 is, at best, problematic.

The process of gas generation is integral to the formation and maturation of coal; all coals generate stage 1 gases in the transformation from peat to coal, and if sufficiently mature will generate stage 2 gases. Stage 3 gases could in theory be generated from any coal under the right hydrologic conditions regardless of maturity. To have commercial potential, however, CBM, like any other gas occurrence, must have a trapping mechanism and be economically recoverable. Because stage 1 gases form early in the coalification process, when the matrix is not yet 'tight', these gases have traditionally been thought to escape (e.g. swamp gas) or be incorporated in the solid coal matrix as it matures (see Law, Rice and Flores, 1991; Rice, 1993; and Scott, Kaiser, and Ayers 1994: note that in published discussions of the relative importance of these processes to ancient gas accumulations, the important distinction of coal from other [i.e. marine] source rocks is not always clearly maintained). With further maturation, stage 2 gas is generated, but at some point, the sorptive capacity of the coal apparently begins to decrease (Rice, 1993) - although this point is contentious (Levine, 1993, Yee, Seidle, and Hanson, 1993, Bustin and Clarkson, 1998). In any case, the most productive CBM wells have been from medium-rank coals such as in the San Juan Basin, where the best production is from high-volatile bituminous coals - despite higher rank coal occurring deeper in the basin. The enhanced producibility may be a function of the addition of stage 3 gases or the retention of initial permeability (Scott, Kaiser and Ayers, 1994), and exploration efforts have tended to look for medium-rank coals at intermediate depths of less than 3000 ft.

Because CBM is generally not in a free state, a conventional-type trapping mechanism is not required. For example, the San Juan Basin is a "basin-centered gas accumulation"; that is, it is synformal (shaped like a bowl rather than having the domal configuration of most traps), and the gas is below the hydrostatic head rather than above it. This is a gross oversimplification - suffice it to say that for CBM to accumulate, a conventional trapping mechanism is not necessary, but the right hydrostatic conditions are. Until recently, the conventional wisdom has been that stage 2 and 3 gases could be trapped in a variety of structural settings, but since stage 1 gas was formed during the peat-to-coal transition as dewatering was occurring, it would most likely be lost to leakage if a conventional trap was not present. Indeed the only CBM production with an isotopically 'confirmed' stage 1 component is from the PRB (fig. 1), where the earliest production was in fact from conventional traps associated with compaction structures (Law, Rice, and Flores, 1991).

To summarize, the prevailing wisdom until very recently was that most coalbed methane targets needed to be sufficiently mature to have a thermogenic component, but not buried so deeply as to have lost their permeability. For biogenic CBM to be commercial, a conventional trap of free gas was thought to be required, which rarely occurs with coal.

The current activity in the PRB, and to a lesser degree the recognition of stage 3 gases in other basins, is changing the CBM paradigm. A number of companies in the PRB - generally small independents - have been producing CBM from shallow wells using relatively simple completion techniques (Ayers, 2000). Rather than being confined to compaction structures, the new production is mostly down-dip from large surface mines, where producibility is enhanced by dewatering at the mines. The wells are highly profitable, and there are a number of as yet poorly understood factors that may be contributing to their success. Most importantly, the reservoirs are producing more than what was predicted from desorption tests. Recent work has suggested that the enhanced production comes from free gas trapped by capillary pressure (Bustin, 1999) or loosely adsorbed (i.e. not 'monolayer') gas. Basically, there is much yet to be learned about CBM, and in the opinion of the author, at the current state of knowledge, this is an empirical process. You test the coal to see if it has gas.

Pakistan CBM Prospectivity

As is the case with other fossil fuels (e.g. surface mineable coal, oil and gas compared to neighboring areas of Iran, etc.), Pakistan appears to be on the margins of possible CBM occurrence. Most of the larger coal fields, which are generally in Sindh Province, have apparently not reached the thermal gas generation threshold. Most of the known coal fields of Sindh are very sandy and have a hydrologic connection to the Indus Basin, both of which could have induced leakage of any gases that were ever present (see Mastalerz and Kvale, 2000). The known coal fields that appear to be of sufficiently high rank to have reached the thermal gas generating stage, located mostly in Balochistan, Punjab, and the Northwest Frontier Province, typically have relatively thin coal, and they generally occur in structurally complex areas where well completion could be difficult. To date, the only desorption measurements made for Pakistani coals appear to be those done by the author for several cores from two GSP/USGS boreholes drilled for the U.S. Agency for International Development (USAID) COALREAP program in 1992. One hole was in the central Thar field and the other was in the south Lakhra field (fig. 2). Very little gas was desorbed, but this was to be expected given the hydrologic setting of these two areas. The tests were made during the course of ongoing exploration for mineable coal, at holes that were drilled on structural highs that were never expected to be the best CBM targets (fig. 3). The results of these desorption tests are presented in SanFilipo and others (1994), but because of the low gas yield, they were never corrected for lost gas nor converted to yield per ton (a rough approximation indicates a maximum yield of about 4 to 5 scf/ton).

On the other hand, the recent PRB activity, the fact that there was some gas present in our tests, and most importantly, the results of a USAID-sponsored CBM program (Kelafant and Stern, 1998) for similar low-rank coals in the Cambay Basin of India (fig. 2) indicate that a more systematic appraisal of the CBM potential of Pakistan is warranted. Most encouraging is the fact that for the coals of Cambay, which from a depositional standpoint is more-or-less an extension of the Thar field, the desorption results from depths greater than 2000 ft are fairly high (200 scf/ton). Coincidently, a USGS test well drilled in the Gulf Coast of Texas had a small show of gas that was almost all methane (i.e. very little CO_2) from coals that are geologically very similar to those of Sindh (Warwick and others, 1999; SanFilipo and others, in press). Although our desorption measurements in Sindh looked insignificant at the time they were done, they are in fact

Figure 2. Coal fields of Pakistan, showing generalized locations of preliminary CBM tests (Lakhra and Thar) in Paksitan, and the Mehsana CBM project in India, which is currently shut-in until leasing issues can be resolved (Kelafant and Stern, 1998).

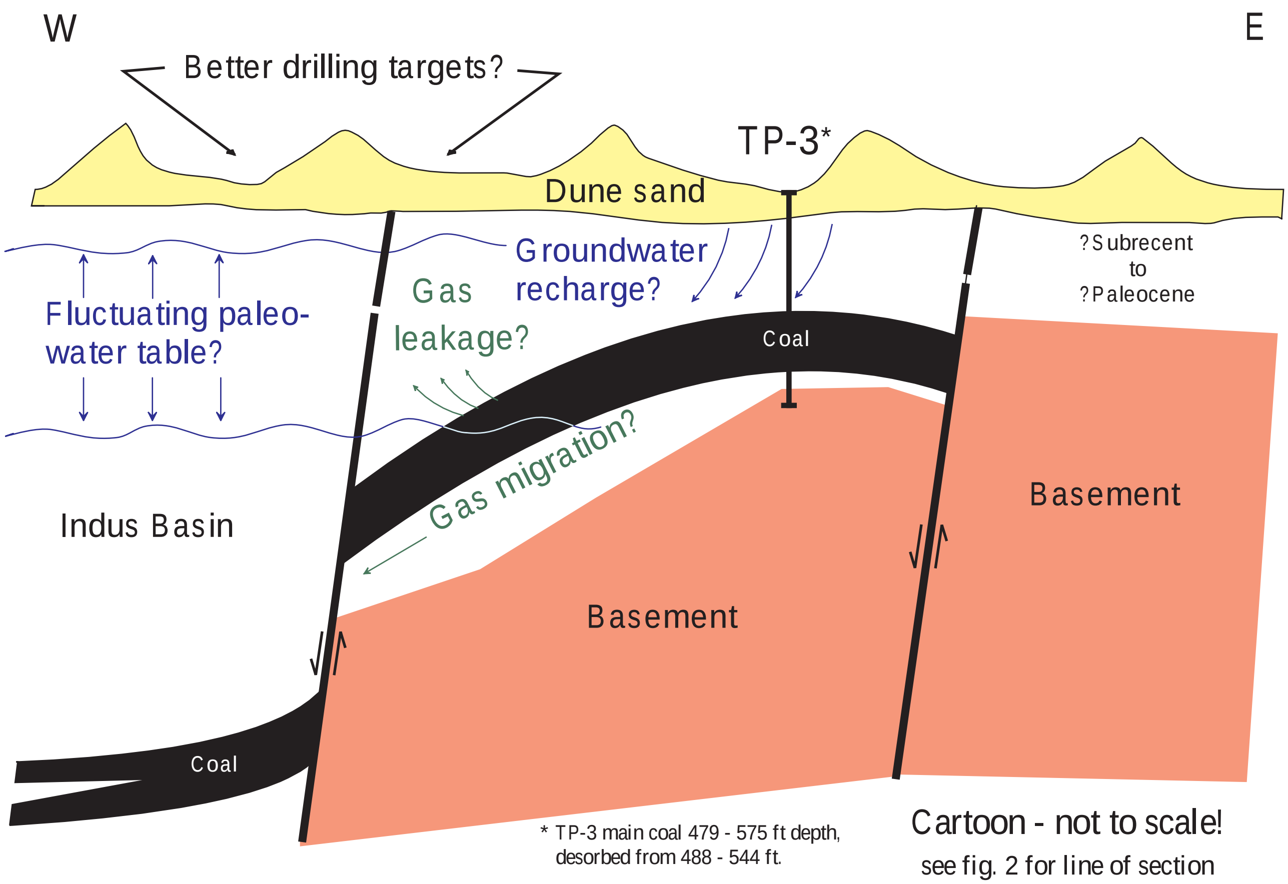

Figure 3. Conceptual model for Thar Desert CBM prospectivity. Borehole TP-3 was tested for CBM by the author and colleagues from the GSP during the initial phase of coal drilling in the Thar Desert in 1992. Only minor amounts of gas were recovered, but the techniques employed were primitive, and the site was probably not the best prospect for CBM. This site was selected for drilling early in the program because of the thick and relatively shallow coal that was recorded in nearby water wells. The primary objective at the time was delineating the Thar coal discovery, and CBM was a secondary objective. Although there was thought to be some potential at this location for a conventional-type trap, with a water drive from below (similar to the earliest producing areas of the Powder River Basin), these are rare for CBM. Unlike conventional reservoirs, CBM typically has a water cap. TP-3 lies on the top of the Thar basement platform, where it could have been subjected to groundwater recharge capable of flushing adsorption sites (a similar type of phenomenon seems to have occurred between barren and CBM-bearing holes in the U.S. Gulf Coast, see SanFilipo and others, in press). More importantly, the position of oxidized sediments in the TP-3 core indicates a fluctuating water table over geologic time (reported to have fluctuated several hundred feet in adjacent areas of India during the recent drought alone), which could have induced leakage of any accumulated gas. The site tested at Lakhra was on a similar geologic structure, and although deeper than most drilling in that coal field, was still relatively shallow for CBM (minor amounts of gas were desorbed from 568 to 629 ft depth), as were most holes drilled for COALREAP, which had mineable coal as the primary objective. Better CBM drilling targets probably occur as the coal deepens towards the large fault system that bounds the Thar coal field to the west (shown above) and on the flanks of the Lakhra and similar structures.

very similar to what was observed in Texas from similar depths. Furthermore, some Gulf Coast CBM yields for depths greater than 2500 ft were recently published (Griffiths and Pilcher, 2000), and they are very similar to the yields from Cambay. Although the Gulf Coast may have somewhat more connectivity to more mature coals down-dip, all things considered, the Sindh-Cambay area and the U.S. Gulf Coast seem very similar in terms of coal geology and CBM potential. The Texas coals and Cambay coals have very low sorption times, which implies that there may be free gas present, and perhaps our shallow tests in Sindh underestimated the gas-in-place. At the time, CBM was a new frontier, and we used primitive equipment and did not analyze the gases. More tests are needed to adequately assess this unconventional energy resource, which seems especially justified given the fact that Pakistan's conventional oil and gas resources are limited and much of its coal may be only marginally economic for mining. From a deliverability standpoint, there is a fairly extensive pipeline system in place for much of Pakistan, and many of the existing conventional fields produce from wells that could conceivably be reworked for CBM if coal is present. Moreover, though generally thin, subsurface coal appears to be fairly widespread in most areas of Pakistan other than western Balochistan and the extreme north. Thus, there are many remote areas where CBM could potentially provide gas for local use without necessarily connecting to the national distribution system.

Initiating A Pakistan CBM Exploration Effort

There are a few generic things that could be done to initiate CBM activity in Pakistan. First of all, a thorough inventory of the coal resources of Pakistan needs to be initiated, including occurrences that can be identified from oil and gas and water well drilling outside of the traditional coal mining areas. Ultimately a national coal database (similar to the USGS National Coal Resource Data System) should the established and maintained by a single agency, preferably the GSP. The desorption equipment that was left with GSP after the USAID program ended should be refurbished and utilized as soon as possible; mainly this means replacing the seals. Two GSP geologists have been trained in using this equipment, and as a matter of course, all GSP drilling projects in coal-bearing areas should test a few boreholes representative of the geology in the project area (CBM occurrence can vary considerably over short distances, and one hole per area is not enough). In addition, other agencies, such as the Hydrocarbon Development Institute of Pakistan (HDIP) and the Oil and Gas Development Corporation (OGDC), could work with GSP or acquire their own equipment to desorb cuttings from oil and gas holes that intercept coal, especially at the depths greater than 1500 ft, where the CBM potential is greater and GSP's drilling capabilities may be stretched. These groups may already be doing reflectance measurements as a matter of routine maturation investigations, in which case the additional effort required to desorb bedded coal would not be much. It would also be advisable to do isotopic work on some conventional gas samples to see if they are sourced in coal (this data may already be available, but it is doubtful that anyone has thought about it in terms of CBM). None of these activities are particularly difficult, but it would be advisable to engage an outside expert in CBM to help start things off. There are not that many good CBM targets in Pakistan, and with sufficient input from key agencies like OGDC, HDIP and GSP, it would not be too difficult to complete a fairly good initial assessment. From a technical standpoint, the USGS would be well positioned to contribute to such a project, considering its breadth of experience in Pakistan and its current CBM capabilities, which include a mobile lab designed for easy deployment to remote areas. However, there are currently no cooperative agreements or funding mechanisms in place for USGS coal or CBM activities in Pakistan.

In addition to the generic recommendations above, there are three target areas in Pakstan that should be specifically investigated for CBM; none could be considered exceptional prospects, but all warrant serious work:

1) **Stage 1 or 3 gas in Western Thar**: There is a major basement fault system separating the Thar basement platform on the eastern (upthrown) side and the Indus Basin to the west (fig. 3). Within and immediately west of the fault zone the hydrologic conditions for preserving biogenic gas may exist. This is somewhat of a geologic analogy to Cambay, although it is probably not as good a CBM prospect (available information indicates the coal thins to the west in Thar and is not quite as deep as Cambay), but it does warrant investigation. Following the initial 1992 drilling in Thar a recommendation to drill a "stratigraphic test" east of Mithi to get information on the deeper geology and to test for CBM was rejected in favor of more holes in the shallower blocks (see SanFilipo and others, 1994). In my opinion, the cost of drilling such a hole is small relative to what has already been invested in Thar, and would be well worth the effort by the Government of Pakistan. As is always the case, a thorough inventory of existing OGDC borehole and seismic records should be done prior to drilling. In addition to evaluating the best CBM prospects per se, a deeper hole in Thar would establish some limits on what might be produced from shallower depths in advance of mining, which has been suggested as a means of financing surface mine development in Thar (Bliss, in prep).

Always an important consideration with CBM production, but especially so given the desert nature of the Thar coal field, is associated water. In the U.S., disposal of water co-produced with CBM is a major cost factor. The water released with CBM is generally of reasonably good quality, however, and given the shortages in Thar, such water would likely be harvested. This could potentially amount to billions of liters, far more than other aquifers in the area currently produce, and probably of much higher quality. On the other hand, if surface mining were to expose this water to pyrite oxidation as it collected in the pits, it would quickly acidify and otherwise deteriorate, and much would probably be lost to evaporation. So while it may seem far-fetched, CBM production in advance of mining could help preserve a precious water resource, and the economies of coal mining, water disposal, and CBM should be considered integrally. In addition to this, there are several sandstone aquifers within the coal-bearing strata (Jaleel, Alam, and Shah, 1999). These are deeper than the alluvial aquifers that are relied on in many areas, and exploration or production wells from CBM activities could potentially be converted to water use after abandonment, perhaps on a cost-sharing basis as an incentive for mutual development.

2) **Stage 1, 2 or 3 gas in the thrust and fold belt of Balochistan, Punjab, the NWFP, and western Sindh** (fig. 2). Although coal of sufficient rank to have passed through the thermal gas window is reported to exist in several areas of Pakistan, these areas are structurally complex, the coal is relatively thin, and available data is scarce and

somewhat contradictory (see Ahmed, Gauhar, and Siddiqi, 1986; Shah, 1990; Warwick and Javed, 1990; and Kazmi, 1995). There are, however, some areas of the Appalachian Basin of North America that are successfully producing CBM from thin coal beds in somewhat similar structural settings. In addition, there may be areas of structural deformation in Pakistan that could have trapped stage 1 gases in structures similar to the early Powder River Basin producing areas, or stage 3 gases in hydrologic conditions similar to the San Juan Basin. Maturation trends, depth to coal, and coal thickness need to be mapped in more detail; to date there has been very little attention paid to the coal that occurs in areas outside of the traditional mining districts. Most importantly, gas desorption and vitrinite reflectance for coals encountered during conventional oil and gas drilling should be measured. Deep mines should be tested as well, although these may have lost their gas (in any case, adsorption tests could be run to measure the gas storage capacity). The recent mine explosion at the 4700 ft level at Degari (Pakistan Business Recorder, April 20, 2000, www.brecorder.com) attests to the gas-prone nature of the deeper coals. CBM production in the mining areas, even on a small scale, might significantly improve mine safety and provide gas for local household and industrial consumption. Note that Ghaznavi(1988) reported a rank of subbituminous A (bordering on high volatile C bituminous) for a single sample from Degari, i.e., only at the threshold of thermal CBM generation, and definitely not the most mature coal in Pakistan.

3) **Stage 1 or 3 gas in the Indus Basin and adjacent areas**. The coal in the Badin area apparently does not reach the thicknesses predicted by Kazmi and others, 1990 (see SanFilipo and others, 1994), and may be too shallow to be a viable CBM prospect, but this has not been clearly established. To the north, the depth to coal probably generally increases, as it may to the southwest towards the Indus Fan. Again, coal encountered during conventional oil and gas activities should be tested. GSP's current(?) drilling in Cholistan is deep enough to warrant CBM testing, but it is not clear if they have successfully drilled to the main coal as yet. Redirecting the targets to the east of the recent drilling near Bahawalpur might be warranted from the standpoint of CBM as well as for the current objective of delineating mineable coal. With access to existing oil and gas drilling and seismic records, it should be possible to establish one or two tentative sites that would go a long way toward addressing the question of coal in Cholistan.

Summary

Recent changes in the concepts of coalbed methane occurrence in low-rank coals, along with empirical evidence from coal deposits similar to those in Pakistan, indicate that the possibility of commercial CBM accumulations in Pakistan exists. Although the potential is modest by global standards, it does warrant further investigation, particularly in conjunction with the exploration for large deposits of mineable coal in the Thar and Cholistan regions, and in areas of known rank elevation in the fold belt. In addition to commercial potential as a fuel, CBM production could encourage the development of otherwise inaccessible water resources in the arid regions and increase the safety of underground mining. In order to properly conduct the necessary investigations, the latest techniques in CBM evaluation will need to be introduced to Pakistan. In general, no coal deposit should be prematurely discounted for CBM potential solely on the basis of rank.

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