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NUCLEAR MINERALS IN PAKISTAN

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Strategic importance of Nuclear Minerals was recognized during early formative years of the Pakistan Atomic Energy Commission, and prospecting for uranium was started in Dera Ghazi Khan in collaboration with the Geological Survey of Pakistan (GSP) as early as 1961. Later, the responsibility for countrywide surveys and exploration was fully entrusted with PAEC and in this respect a Directorate of Nuclear Minerals(DNM) was established in 1966 at Lahore. Later, DNM was shifted to the Atomic Energy Centre (AEC), Lahore building and renamed as Atomic Energy Minerals Centre. It has state-of-the-art Chemistry, Mineralogy, Remote Sensing and Electronics Laboratories and an Ore Processing Pilot Plant. The Centre has Prospecting, Exploration, Geophysics, Geochemistry, Geo-tectonics, Mining and Drilling Sections. Regional Offices have been established to facilitate work at Karachi, Quetta and Peshawar.

Siwaliks were recognized as a favourable geological formation of prime importance. Sandstone-shale sequence of Siwaliks Formation is exposed in all provinces of Pakistan and in Azad Jammu and Kashmir (AJK), broadly categorized into Rajanpur-Dera Ghazi Khan, Bannu Basin-Kohat Plateau and Potwar-AJK zones. Baghalchur, Nangar Nai and Taunsa uranium deposits have been discovered in the Rajanpur- D.G.Khan Zone. Qabul Khel and Shanawah Uranium deposits have been discovered in the Shanawah- Kohat Plateau Zone. Prospection and exploration is in progress.

The first uranium mine was opened at Baghalchur, and uranium mill was established at D.G Khan in 1977-78 all by indigenous effort. The uranium mine was the most advanced and mechanized mine of that time in the country. Later, a second uranium mine was opened at Qabul Khel in 1992, which was based on a new and advanced in situ leach technology, developed to suit local geological and ore zone parameters. Mining of Nanganai and Taunsa Deposits was started respectively in 1996 and 2002, and is also based on in situ leach technology which is low cost and environment friendly

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1. Nuclear Mineral Establishments

Nuclear minerals provide a foundation for the atomic energy programmes of a country, and their indigenous production provides a measure of self-sufficiency. The strategic importance of nuclear minerals was realized early on, and the PAEC charter drafted in the late 1950s included a special mention of nuclear minerals. Emphasis was laid on the application of state-of-the-art modern techniques such as aero-radiometric surveying to locate favourable areas in a fast track mode. In line with this policy, a Nuclear Minerals Division was established at the Atomic Energy Centre at Lahore in 1961. In the first instance, geologists, mining engineers and chemists were recruited and work was started with the help of geologists from Geological Survey of Pakistan (GSP) and based on information available with them.

Work expanded and soon thereafter it became desirable to keep nuclear minerals either as a department of GSP or entrust it fully with PAEC. Federal Government made a decision in favour of the latter, and as a result the Directorate of Nuclear Minerals (DNM) was established in 1966 in a rented building at Lahore.

In 1971, the Directorate of Nuclear Minerals was shifted to the newly built building of PINSTECH. Barely a year had passed when the DNM again was shifted back to Lahore, and it was housed in the vacated building of the Atomic Energy Centre which had been shifted *en bloc* to PINSTECH. The DNM was renamed as the Atomic Energy Minerals Centre (AEMC). The AEC building had ample laboratory space and excellent laboratory fittings, which proved to be a boon to the nuclear minerals programme. The Minerals Centre made excellent use of the available space and set up modern chemistry, geochemistry, mineralogy, electronics, remote sensing and geophysics laboratories, partly with the help of the International Atomic Energy Agency (IAEA).

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Equipment such as XRF, XRD, AAS, DTA, spectrometers, flourimeters, C-S analyser, ore microscopes, polarizing microscopes, thin section preparation equipment, etc., were installed.

An Ore Processing Pilot Plant was set up in 1974 in a custom-designed and newly constructed building. It has a bulk sampling tower, crushing, grinding and hydrometallurgy section; magnetic, electromagnetic, electrostatic mineral separation section; gravitational and pneumatic table concentration section, column leaching section, etc., supported by hydrometallurgical laboratories. Now, it is planned to add pyrometallurgical facility.

Mineral Exploration Project (MINEPP) Jamrud, was established in the NWFP in 1975 to explore uraniferrous occurrences in the Shilman carbonatites and to develop a mining project. Exploration was carried out through drilling and aditing. A pilot scale ore processing facility was also established at the Jamrud premises. The exploration proved that the uranium mineralization has an erratic behavior and that there is no consistent ore body. The project was closed in 1981.

Mineral Sands Programme (MSP) was started in 1976 to explore for economic minerals, including zircon, in the marginal Islands of Indus River Delta and coastal placers. Offices and laboratories were housed in the PAEC Camp Office, which later shifted to Korangi Industrial Estate in Karachi where a mineral processing plant was set up 1n 1979 to produce final zircon and rutile products. The programme was closed in 1993 and the office was converted into Regional Exploration Office, Karachi, for exploration of uranium in the Province of Sindh.

After the closure of Project MINEPP, a Hard Rocks Division (HRD) was established at Jamrud, NWFP, in 1981 and hard rock prospecting already in progress was placed under its control. Later, in 1993, the HRD was renamed as Regional Exploration Office, Jamrud, whereas its functions remained the same.

The Regional Exploration Office, Quetta, was established in 2004 in a rented building to explore uranium anomalies discovered in 2002 in Taftan and to prospect Eruptive Zone and other favourable rock formations in Baluchistan.

Project BC-I, DG Khan was established in 1977 to exploit uranium ore deposits at Bhaghalchur. The project was required to continue exploration at the project site and to add to the known reserves and to also explore other anomalous sites for discovery of more ore deposits in D.G. Khan. Open pit and underground uranium mines were established at Baghalchur North and Baghalchur South. An ore processing plant of 300 tonnes per day capacity was set up at D G Khan to process ore from the mines. The project operations were finally closed in 2000 after completion of the heap leaching operations on the stock piled low grade ore.

In-situ Leach Mining and Processing Project (ISL&MP), Qabul Khel was set up in 1992 by the Atomic Energy Minerals Centre, Lahore. Earlier, pioneering experimental work was carried out by the Centre during 1989-92, in the lab and on the ground, on the application of a new and novel *in situ* leach mining technique. The In situ Leach Mining and leach liquor processing operations were successfully commissioned in 1995, which continue to-date. In 2005, uranium exploration of Kohat Plateau(DEU-II) and Project ISLM&P were combined under a new set up called Nuclear Minerals Complex-II (NMC-II)

Later, the Project BC-I, besides mining at BaghalChur, started experimental *in situ* leach mining at Nangar Nai in 1995. The mining and leach liquor operations were started in 2000 which continue to-date. Experimental in-situ leach mining was started on Taunsa ore body in 2002, which was discovered a year and half earlier, and production commenced in 2004. Both the mining operations and uranium exploration of Sulaiman Range (DEU-I)were grouped under Project NMC-I, DG Khan, established in 2001.

2. Structure of Nuclear Minerals

Atomic Energy Minerals Centre, Lahore, and its Regional Exploration Offices in Peshawar, Karachi and Quetta are responsible for prospecting and exploration of nuclear mineral deposits in the country leading to the estimation of ore reserves, ore process development and mine design, and finally project planning and preparation. Subsequently, independent projects are instituted which carry out work further and develop mines, plants and facilities at the site. The projects also carry the exploratory drilling to develop additional ore reserves within the designated project area.

3. Uranium Exploration: Strategies and Methodology

Uranium is a common trace element in the earth's crust, as common as tin, tungsten, and molybdenum. It occurs in most rocks in concentrations from 1-6 parts per million. Over time, geochemical processes release uranium from these source rocks, which gets mobilized and concentrated at suitable places called traps. Compared to the original rock content, a concentration factor of ~ 250 would make an economic deposit. Primarily, formation of a uranium deposit would require a source rock, release of uranium, mobilization of uranium solutions through geological passages, precipitation by geochemical and physical traps to form deposits and finally their preservation. The process takes millions of years to form deposits of economic value. Unfortunately, more often the process is interrupted by tectonic episodes and uranium either gets dissipated or lost to the environment, thereby leaving a large number of uranium or radioactive anomalies. Geological stability of a region is therefore of primary importance. The mega deposits of Australia, Canada, Africa and Central Asia were discovered in areas where geological stability persisted for more than 500 million (10^{-6}) years.

A typical uranium deposit, when projected on the ground, covers an area of about ¼ to ½ square kilometer, which is an infinitesimally small part of a large terrain considered favourable. It is like finding a needle in a huge haystack. So how does one pin point it? It requires a multi-phase concerted effort spanned over years, gradually limiting areas to only few target sites for exploration drilling and finally finding uranium ore.

In the first phase, areas and rock formations are initially defined as uranium favourable on the basis of literature survey and known criteria. This regional appraisal is based on sound metallogenic concepts, remote sensing studies and preliminary reconnaissance in the field. In the second phase, the selected regions are subjected to detailed reconnaissance involving geologic thematic mapping, airborne spectrometric surveys, carborne spectrometric surveys, regional geochemistry, radon studies and photo geology.

The third phase includes detailed appraisal of target anomalies through delineation of a precise metallogenic model, detailed geochemistry, trenching, pitting and preliminary drilling. Finally, in the fourth phase, systematic exploration drilling is carried out at the target sites to delineate an ore body. Preliminary ore reserve estimates are prepared alongside bulk sampling and ore processing studies. At the end of each phase, data is evaluated to either pass on the region/anomalous site to next phase or to keep it on hold for future studies if it is not found attractive at that time. The regions and anomalous sites are therefore studied over and over again, each time with a new approach.

After evaluating economic and technical aspects, the site is recommended for development drilling and for estimation of reasonably assured reserves (RAR) and estimated additional reserves (EAR). Project planning, preparation and development studies are carried out leading to establishment of a mine and processing plant.

Tremendous efforts were put in to open new areas in remote locations and to work under inhospitable environments for long periods, away from families. The geologists would toil the whole day long, for months at a time, looking for uranium mineralization, radioactive anomalies and favourable geological features, holding gamma counters and sneaking into nooks and corners of rocky landscape. Mining and drilling engineers would join them to drill bore holes and explore mineral deposits. Geophysicists and geochemists would chip in to carry out complementary surveys to support the programmes. Concerted efforts put in by chemists and physicists alongside their fellow workers in the field led to the discovery of uranium and zircon deposits in the country. Mining of these deposits and putting up process plants is another story worth recounting.

3.1. Exploration techniques

Exploration for uranium commenced in 1961 with foot radiometric surveys using hand held Gieger Muller gamma counters and scintillometers. After having established Siwaliks of Sulaiman Range (Dera Ghazi Khan) as uranium favourable, aero-radiometric surveys were carried out in 1964 for quick coverage of the area. Fixed wing airplane was used for the first survey; later, helicopters were also used depending upon the topography of the area. Car borne gamma spectrometric survey is another technique used to monitor rocks exposed along the roads. It provides a quick reconnaissance of an area and spectrometric data for initial assessment.

First geochemical survey was carried out in the Tharparkar Desert in 1974 and samples were collected from water wells. Later, stream sediment sampling and spring water sampling was also included and the technique was extensively used in other areas. Comparative study of the geochemical data provides complimentary information on favourability of rock formations, and may also provide a lead to delineation of areas/sites of particular interest.

Underground radioactive sources emanate radon gas which travels through pores, fractures and fissures and is released to the atmosphere. Radon probes were first used in 1968 to monitor accumulation of radon in the top soil in Kaghan. Later, use of Solid State Nuclear Track Detectors (SSNTD) was started in 1974 in Baghalchur. The detectors were buried in a grid pattern in the subsurface and recovered after three weeks. The radon gas left alpha tracks on the detector film which were etched at PINSTECH Labs and studied for their comparative intensity. Use of another radon detection technique called Radon on Activated Charcoal (ROAC) was started in 1983 in Potwar which proved more useful. Activated Charcoal cartridges were buried in the subsurface for eight days and their alpha activity was recorded immediately after recovery and their relative intensity could be studied while working in the field.

Geophysical techniques provide subsurface data at low cost which can be interpreted to find out geological features with possible relationship to the process of ore formation. Resistivity and Electromagnetic (EM and VLF) were used in 1987 at Qabul Khel. Later, Magnetic, shallow seismic and induced potential techniques were also used at other places.

Remote Sensing data can be interpreted for applications in mineral exploration. Imageries can be developed for certain specific geological purposes: for mapping of structural features and rock formations and understanding of mega structures etc at a very low cost. Satellite imageries were first used in 1977 to understand development of offshore bars and littoral drift of Indus River Delta sands. Later, a Remote Sensing Section was established at the Centre in 1991 and in house raw remote sensing processing and interpretation facility was developed. Since then, remote sensing has been used extensively in the office and the field. False colour imageries are interpreted and base maps are regularly prepared before proceeding for field work.

Geological maps are prepared at different stages of work and the data collected from the abovementioned techniques is plotted on the maps for correlation and interpretation, and for the express purpose of delineating exploration targets.

Finally, drilling is carried out to confirm physical presence of uranium; alternatively, inclines or adits are driven to the target zone if drilling is not possible. First borehole was drilled in October, 1968 at Baghalchur with a portable Winkie GW-15 drill. Later, skid mounted core drills, truck and track mounted combination drills, both for core and non core drilling, were used for exploration up to 350 M depth.

The boreholes are surveyed with borehole logging equipment and the gamma intensity is recorded to mark ore zones. Self-Potential(S-P) and resistivity values are also recorded to interpret lithological features. Ore grades are calculated from the gamma intensity data and cross checked with chemical analysis if the ore is in secular equilibrium. Under our particular geological environments, more often the ore is found in the state of disequilibrium which necessitates costly option of core drilling and chemical analysis of all the core samples. To meet on site exploration requirements, Beta-gamma technique is used for quick assaying of such samples in the field.

4. Discovery of uranium deposits in D G Khan

4.1. Baghalchur uranium deposit

In 1959, a foreign consulting geologist working with GSP, while going to Quetta via D G Khan, passed through Rakhi Munh, a place 25 km short of Fort Munroe. To our good luck, he had kept his gamma counter open and discovered a radioactive anomaly along the roadside. It provided a starting point for uranium prospecting in Pakistan in 1961.

The anomaly and its geological environments were studied in great detail. The host rock was found to be Middle Siwaliks sandstone/shale sequence, a fluvial sedimentary formation deposited during Miocene times about 12-17 million years ago. The PAEC and GSP geologists followed the lead and foot-surveyed the Middle Siwaliks sandstone exposures to the north and south of Rakhi Munh.

The work environments are now hard to imagine: stark and high-relief landscape, no country roads and the extreme climate. Potable water was hard to find, and it had to be transported along with other supplies from far off towns and for the most part on foot. Population was scarce. Camps were established after every 10 kilometres to survey surrounding areas on foot. Tents and other camping equipment were shifted on camel back. Sudden dusty winds, occasionally followed by rainstorm, would uproot the tents and leave the campers in the open, shuddering in the cold nights and drenched in water. The environment did not deter the explorers-who were young and filled with missionary zeal.

Moreover, the Baluch tribesmen were kind and simple. Harsh environments made them humble. The tribesmen built no homes and lived in thatched cottages and would move up the Sulaiman Range in summer along with their animals. They gave a free hand to the geologists.

Middle Siwaliks were surveyed along a 250 km stretch in the following four years and a large number of uranium and radioactive anomalies were discovered, including Baghalchur, Nangar Nai, Rahandan, Kaha Nala, Chezgi Nala, Khalgari Nala, Jaggar Chur, Pittok, Sori Nala etc. Baghalchur being the most prominent uranium anomaly, it was selected for detailed work and exploration. Surface extent of the uranium mineralization was plotted on a map, and an incline was driven to shallow depth to prove its subsurface extension. The Baghalchur area was subsequently recommended for exploration through drilling.

In September, 1968 a caravan of 80 camels left the city of D G Khan for Baghalchur. Cargo was a small drilling rig, a mud pump and drilling rods, a borehole logger, Gieger Muller counters and scintillometers, tents and other camping equipment. A group consisting of two geologists, a mining engineer, a drilling engineer, a surveyor and others followed the caravan of camels on foot. The distance was 56 kms. on a route through sandy and gravel bed nalas, mountain tracks and gravel packed terraces.

The team reached Baghalchur in 40 hours, and immediately engaged itself in setting up tents before sunset. Drilling was started in the next two days. On checking, the borehole logger somehow failed to respond, and had to be taken back to Lahore for repairs and return- which took 5 days. By that time the first borehole had been completed and the gamma logging was started the next day.

The first exploratory borehole at Baghalchur cut across uranium ore. This was also the first borehole drilled in the country for uranium. After the hard labour of past many years, the joy of finding uranium ore was immensely thrilling. Exploration continued in the following three years and oxidized ore body was proved in the Baghalchur North. Uranium mineral was identified as *tyuyamunite* and *meta-tyuyamunite*.

An IAEA Minerals Advisor visited Baghalchur site in 1969 and studied the results. IAEA expressed interest in the prospect and offered technical assistance for exploration of uranium. Subsequently, IAEA/UNDP Technical Assistance Project -PAK/003 was started in 1971 for exploration of uranium in Dera Ghazi Khan. The IAEA provided drilling rigs, borehole loggers, scintillometers, vehicles, communication equipment, assortment of spares, and, finally, the experts in exploration and drilling. Exploration continued for next 6 years with IAEA technical assistance. Another ore body was discovered in Baghalchur South in a basal paleochannal which contained black colour primary uranium ore identified as *uraninite*. Likewise, primary uranium ore was explored further downdip in Baghalchur North. Sizeable ore reserves were proved over the years, and the PAEC geologists and mining engineers learned modern exploration, borehole logging and drilling techniques.

4.2. Uranium mining and milling

Project BC-I was established in 1977 for mining of Baghalchur ore bodies. Ore body in Baghalchur North was mined through both open pit and underground mining techniques whereas that of Baghalchur South was mined through underground mining technique. The ore was transported to the Ore processing Mill located at D G Khan.

4.2.1. Open pit mining

Ore bodies at shallow depth were mined by open pit mining method. Benches, 10-15 feet high and 25-35 feet wide, were developed using box cut. Ore was mined using conventional drill and blast technique. The mucking and haulage was done by front end loaders and dumpers. Grade control was exercised by face monitoring with gamma probes and stock piling of ore in separate heaps. The country rock and the ore was mined separately to avoid excessive dilution.

4.2.2. Underground mining

Room and Pillar Mining method was used and room entries of 3m X 3m cross section were developed according to the ore body configuration at different levels. Both development and production excavations were carried out with drilling and blasting technique. Drilling was executed with drifter type pneumatic drills fitted on telescope air legs. Burn cut blast hole geometry was employed and 29-30 bore holes comprising of cut spreaders, relievers, lifters and perimeter holes were blasted to achieve an average advance of 1-1.25 meters per blast. Ground control was exercised by monitoring of the blast face with a gamma probe and marking out of barren rock which was blasted separately to avoid dilution.

The loading was carried out with skid steer type front end loaders of 0.5 m^3 bucket capacity. The muck was transported in a specially designed low height five wheel articulated dumpers with hauling capacity of 2 tons. The ore and waste was transported to the incline bottom from where it was hauled up in mine tubs.

Afterwards, the room entries were further widened to mine ore, which converted them into random stopes, and similarly the pillars were also extracted leaving barren rock or lean ore in the pillars. The excavated stopes were supported by wooden chokes. Water was constantly pumped out to keep the mine dry.

4.2.3 Uranium mill

The ore was blended at the plant to provide a uniform feed. It was crushed and ground to -30 mesh and leached with sulphuric acid in the leaching tanks with a residence time of 20 hours. Uranium was recovered from the resultant leach liquor through solvent extraction process.

4.2.4. Nangar Nai uranium deposit

After Baghalchur, the second deposit in D G Khan was discovered in Nangar Nai in 1980. The surface anomaly was explored through drilling, and mineralization was found to continue down dip to 200 m depth. Ore is associated with sand bars. Adjoining anomalies at Dabchur and Molibun were also explored and bore holes cut across uranium ore. The intervening area, which has a gravel terrace cover and is difficult to drill, may also have uranium ore. Uranium exploration has been continued in the area intermittently since then.

The deposit in being mined by *in situ* leach mining technique and a five spot pattern is being used for the purpose.

4.2.5. Taunsa uranium deposit

Normally, sedimentary beds dipping at high angles are not considered suitable for exploration. Discovery of uranium at Shanawah, however, prompted re-evaluation of Lal Ishab Anomaly near Taunsa in 1999, where beds dip at 70^o. Detailed radiometric prospecting and geological mapping indicated distinct radiometric zones along the strike in four sandstone beds. Drilling was started in 2001 and uranium ore was discovered at a shallow depth of 40m. The water table is at 20m depth at the southern most part of the ore body, which is a plus point for its exploitation by the in-situ leach mining technique. The area is under exploration for the last four years.

The deposit is being mined by *insitu* leach mining technique using line drive arrangement of injection and production wells.

5. Prospecting of Potwar Plateau and AJK

Prospecting in the Potwar Plateau was initiated in 1967, where Middle Siwaliks sandstone/shale sequence is exposed over a large part of it. The area was prospected on foot and a large number of anomalies were recorded. Aero-spectrometric surveys were carried out in 1974 and again in 1990-91, and the rocks exposed along the roads were surveyed by the car-borne spectrometric technique. A large number of anomalies were discovered all over the plateau in the Dhok Pathan and Nagri Nagri Formations. Likewise a good number of anomalies were discovered in Azad Jammu and Kashmir, which also hosts exposures of Middle Siwaliks sandstones. The anomalies were studied in geological detail and additional information was obtained through geochemical surveys and radon surveys using SSNTD (Solid State Nuclear Track Detectors) and ROAC(Radon on Activated Carbon Techniques) in 1967-70 and 1983-1991. Anomalies discovered in Jand, Uchhri, Chakrala, Chinji, Kallar Kahar, Dina, Sohawa, Kallar Sayyadan, Rohtas, Bhimber and Sanghr, etc., were drilled. Despite commendable work, no uranium deposits could be found. The deposits which could have possibly formed were probably destroyed due to later tectonic disturbances.

The Potwar Plateau is one of the major uranium-favourable environments in the country. Another effort was made with the technical assistance of IAEA during 1992-96 to understand uranium metallogeny of the area. Information available on Potwar was collected from all available sources; it was digitized, compiled, synthesized and finally evaluated to pinpoint target areas for detailed prospecting. The Daud Khel Block was subsequently selected on the basis of source material, uranium mobilization and relative tectonic stability. Prospecting in this area discovered major uranium anomalies in Lawa area, which were subjected to various types of studies and finally drilled in 1996 and 2000. More work is as yet required.

6. Discovery of Uranium Deposits in Bannu Basin, NWFP

In 1974, a driller working at Baghalchur brought a sample of grit which contained yellow mineralization. The sample was analysed in the Chemistry and Mineralogy Laboratories of AEMC and was found to contain secondary uranium mineralization called carnotite, and was rich in uranium. The sample had been collected by a fugitive and it was recovered by D I Khan police after he was apprehended. The origin of the sample was traced back to the Middle Siwalik rocks of Pizo Dome, Bannu Basin, where the fugitive had been in hiding. The Pizo Dome rocks were subsequently prospected in 1975, but the particular rock from where the sample was taken could not be traced. Next year, prospecting was started in the other parts of Bannu Basin

Bannu Basin is a large structural basin covering 6000 km^2, which is bound by mountain ranges on all sides, Khisore and Marwat Ranges in the South, Surghar Range in the East, Bhittani Range in the West. The basin is filled in with alluvium and is cut across by Kurram River. The Basin passed through many tectonic episodes, forced by the Kalabagh re-entrant in its short history of about 2.4 million years. It assumed its present shape about 0.4 million years ago. It has seen only short periods of geological stability when uranium got the chance to mobilize and get concentrated in structural and geochemical traps.

The Bannu Basin has extensive sandstone/ shale exposures along its margins pertaining to Middle Siwaliks time and has already been recognized as a top priority favourable area. However, due to limited resources util then, it was prospected. Systematic prospecting of the Bannu basin was started in 1975 and aero-spectrometric surveys using fixed-wing plane and helicopter were carried out in 1975 and 1976. Simultaneously, foot radiometric surveys were started in the Khisore and Marwat Ranges. Anomalies spotted by aerial surveys were tracked on ground and studied on detail. Geological maps were prepared and results were plotted on maps for correlation. By 1978, highly significant uranium and radioactive anomalies were found in Khisore Marwat Ranges, Surghar Range, Bhittani range and Karak anticline. Most significant anomalies were discovered in Qabul Khel and Shanawah-Takhat-i-Nusrati areas.

Shanawah- Takhat-i-Nusrati Area has significant target sites at Shava, Shanwah, Granag Nala, Spillmai Tangi, Zarkai, Garai, etc., which exhibit secondary uranium mineralization. In 1978-79 a drilling rig was hired from OGDC, and preliminary non-core drilling was carried out at all of the above sites to find possible sub-surface extension of the surface occurrences. Results were not found to be encouraging. Nevertheless, the area was thoroughly mapped and studied in geological detail in order to select a target sites and prepare a systematic plan for exploration.

6.1. Qabul Khel ore deposit

Qabul Khel Area has significant anomalous sites at Qabul Khel, Eagle Hill, LM-I & II, Mochimar and Darra Tang. The Qubal Khel site shows high radioactivity over a distance of 1 kilometre, and at places a tertiary florescent mineral named uranophane is also visible. The site was selected for preliminary exploratory drilling with portable Winkie Drills, and work was started in early 1979. The radioactivity was found to continue with depth. Subsequently, a systematic programme was prepared and exploration drilling was started in late 1979 with a hired drilling rig from OGDC. Simultaneously, core drilling was also started with a departmental Longyear-24 drilling rig to secure core samples for chemical analysis. The exploration grid was orientated along the strike direction and drilling was carried out at 35 m and 17.5 m spacing respectively along the strike and dip direction.

The exploration in Qabul Khel faced formidable problems right at the outset. The radioactive sandstone bed dipped at 27- 35^o, and radioactivity was found in its basal section. The sandstone was semi-consolidated and open holes would not stand long enough to allow borehole logging. For the same reason there was total loss of core particularly in the radioactive portion of the sandstone. The stability of hole was ensured by improving the quality of mud and by addition of chemicals. The non-core boreholes cut across highly radioactive zones one after another,indicating a thick continuous radioactive/ore zone over a distance of about 1.5 km.

The recovery of core samples, however, required extensive experimentation. Finally, face-discharge diamond core drilling bits solved the problem, and it became possible to secure core from the radioactive zone. However, a big surprise awaited the exploration team. The core, obtained from the highly radioactive zone, was analysed and was found to contain no chemical uranium. The core pulled from other parts of the high radioactivity zone proved the same results. A bigger core drill was borrowed from Project BC-I and larger diameter cores were obtained from target zones. Despite radioactivity, there was no uranium in the core samples. It was an unusual case of total leaching of uranium from an earlier uranium deposit, leaving behind daughters which explained the high radioactivity. It was considered that leached uranium had dissipated in the rocks and finally lost. It was decided to abandon the exploration programme in 1981.

On the contrary, the uranium could also have mobilized down to the water table, which could provide a physio-chemical trap to form a deposit. Earlier, the non-core drilling had intersected low radioactivity thick sections in the zones below water table which were hitherto considered insignificant. The afterthought prevailed and the exploration programme was held back. The core drilling was started in the zones below the water table which proved that low radioactivity zones contain high chemical uranium values. The first borehole drilled at Qabul Khel based on the new approach cut across 8 m of 0.28 % U_3O_8 and a new uranium deposit found at Qabul Khel.

Other anomalous sites at Qabul Khel were explored in the zones below the water table and uranium ore bodies were found at Eagle Hill, LM-I&II and Mochimar. Uranium ore in the ore bodies was found to be in disequilibrium and borehole gamma logs did not help in computation of ore grades. Therefore, costly core drilling and chemical analysis became necessary. In the next four years, the ore bodies were explored through core drilling and ore reserve estimates were calculated on the basis of chemical analysis.

Chemical leaching of primary or old deposits, mobilization of uranium solutions down the dip and its precipitation at water table in economic concentrations produced *infiltration type* uranium ore bodies. Based on the above, a working model was developed at Qabul Khel which was later used at Shanawah and Taunsa and more *infiltration type* ore bodies were discovered.

6.1.1 Development of in situ leach mining technology

Qabul Khel Sandstone, which hosts uranium ore, is largely unconsolidated, with a compressive strength of less than 1MPa. Ore zone is located below the water table. Conventional open pit and underground mining techniques, although possible, would involve costly dewatering and would still be hazardous. The high permeability and presence of water are negative factors for conventional mining; the same are, however, pre-requisites for insitu leach mining, a new technique developed in the 1970s.

Primarily, the technique involves a set of injection and production wells with filters located at particular ore levels. Oxidants and leaching chemicals (lixiviants) are injected into the aquifer through injection wells and then forced to pass through the ore zone. In the process, uranium mineralization gets oxidized and leached, and the leach liquor is collected at the production well. Incursion of lixiviants is controlled through maintaining production at slightly higher level than the injection. Over production generates a hydrologic cone of depression around the leaching area thus assuring containment of solutions. Additionally, monitoring wells are completed around the mining area and water samples are regularly analyzed for any possible excursion.

A set takes about two years to complete. A mine has a large number of patterns called a wellfield from where the leach liquor is collected for processing in a central leach liquor processing plant. Insitu Leach Mining is an environment friendly, modular and low cost technique.

6.1.2 In situ leach mining and processing

Five spot patterns comprising of four injection wells and one production well were used for injection of leaching chemicals (lixiviants) and pumping out of leach liquor containing uranium. Distance between the injection and the production wells was maintained at 15 m. Wells were completed with 6 in diameter PVC pipes and filters. A number pattern Monitoring wells was completed at the periphery of the deposit to check excursion of lixiviants out of the mining area. Earlier, pumping tests were carried out to determine hydrologic parameters for design of in situ leach operations.

Ammonium bicarbonate (4 grams/litre) was used as lixiviant and hydrogen peroxide (0.7grams/litre) as oxidant. The leach liquor was collected from the wellfield and pumped to settling tanks and then to sand bed filters. The clarified leach liquor in pumped to bottom fed ion exchange columns loaded with strong based anion exchange resin.

The ion exchange columns operate in two stages: loading and elution cycle. In the loading cycle, the uranium, present in the leach liquor in the form of uranyle-tricarbonate anion, is adsorbed on the surface of the resin and less than I ppm is left in the discharge called raffinate. The raffinate, which contains 2 grams/litre ammonium bicarbonate, is refortified for injection. In the elution cycle, the loaded resin is eluted by using 2.0 molar NaCl + 4 g/l $NaHCO_3$ and three bed volumes of eluate is collected to regenerate the resin for the fresh loading cycle. The eluate is precipitated with hydrogen peroxide and the precipitate is filtered in the rotary drum vacuum filter for production of yellow cake.

6.2. Shanawah ore deposit

Shawa and Shanawah anomalous sites, Bannu Basin, NWFP, were explored in 1978-79 and many times in the subsequent years. The exploration results of past work were analysed by the Project ISLM&P, Qabul Khel, in collaboration with AEMC, Lahore. Low grade uranium and its erratic distribution indicated a typical flushing zone. Again, it was surmised that uranium could have mobilized down to the water table and could have found a physio-chemical trap like Qabul Khel. Experience gained at Qabul Khel was used and water table depth was inferred from the reduced level(RL) of nearest discharge point in Kurram River considering the hydraulic gradient as zero. It came to be 235 metres. None of the boreholes drilled until then had punctured the particular zone of interest in relation to the water table. It was decided to resume exploration once again. In this respect, the project obtained special approval and funds for exploration with the new approach. The very first borehole core drilled in 1999 cut across 8 m of uranium ore assaying 0.08% U_3O_8. After Qabul Khel, a second uranium ore deposit was discovered in the Bannu Basin.

Subsequent exploration proved that two lower sandstone beds do also have thick sections of low-grade uranium ore. This has raised ore reserve potential of the Shanawah Area. Ore is at a relatively greater depth, and with the water table at 235 metres, it would be difficult to mine by the surface in situ leach mining technique. It can, however, be in situ leached from underground galleries driven above the water table. Given the expected ore reserve potential of the deposit, it can be mined within the acceptable economic limits.

7. Exploration for Uranium in Hard Rocks

Exploration in hard rocks was started in late sixties which are exposed over a very large area in the country. Regional appraisal indicated favourability of granite complexes and black shale formations. In this respect Ilum, Mansehra, Malakand, Ambela and Lahore Granitic Complexes were extensively prospected and mapped. A large number of uranium and radioactive anomalies were discovered in almost all the granite bodies. Over the years, activities were carried out during successive phases of exploration and target sites in Ilum, Malakand and Lahore Granite Complexes were drilled on various working models. Zones of interest were accessed through inclines and adits for detailed studies.

Black Shale Formations of Azad Jammu and Kashmir and Tarbela were prospected and found to host highly radioactive anomalies, some of which were explored through drilling.

Other favourable environments such as intra-mountain basin of Mansehra, volcanics of Kalam-Dir and Chitral, Sedimentary rocks of Peshawar

Basin, meta-sediments of Hunza (Chalt Nala)and were investigated at different times.

A carbonatite body at Shilman, Landi Kotal was prospected in 1973 which was found to host highly radioactive and uraniferrous anomalies. It was explored as a multi-mineral prospect for uranium, rare earths and apatite (fertilizer). However, distribution of mineral values was erratic and a composite ore-body did not exist. Later, another carbonatite body was prospected at Sallai Patti, Malakand which contained uranium, rare earths and apatite and had better consistency. The carbonatite body was explored in mid eighties and a low grade ore body was delineated through preliminary drilling. Its economic prospects were not found to be encouraging.

8. Exploration for Siwalik Equivalents in Kirthar Range

Exploration of main Manchar Formation was started in 2000 and highly significant uranium anomalies were discovered in Wahi Pandhi and Manchar Lake Area at a number places. Preliminary exploration has been carried out at a number of places which indicate good prospects.

Lately, Manchar Formation has yielded significant anomalies in Sehwan Sharif area which are being explored through drilling. Furthermore, prospecting in the Thano Bulla Khan area has indicated a number of anomalies in the Manchar Formation as well as in the Bara Formation thereby extending the scope of favourable areas in Kirthar Range and enhancing its overall potential.

9. Exploration for uranium in Kohat Plateau

The Middle Siwaliks has two subdivisions: Dhok pathan Formation and Nagri Formation. The former was considered more prospective due to discovery of uranium ore in it at DG Khan and Bannu Basin and its high share of discovered anomalies. Nevertheless, in 2001, prospecting of Nagri Formation of Kohat Plateau was started and highly significant radioactive anomalies were discovered in Nari Panoos, Banda Asar and Shahbaz Garhi Synclines, Gurgury and Karak Anticlines. Preliminary drilling has been carried out as yet at the Nari Panoos Syncline only.

10. Exploration for Zircon

Zircon is one of the important nuclear raw materials. Its prospecting was started simultaneously with that of uranium. Earlier on, researchers had reported the presence of uraninite crystals in the upper reaches of the Indus River System, which attracted the attention of PAEC geologists. The placers also contained zircon, rutile, monazite, ilmenite and gold. Placers of Indus River near Skardu were subsequently sampled on reconnaissance level. Main attention was, however, given to placers of Gilgit and Hunza Rivers and in this respect a regional office was opened in Gilgit in 1966. Thereafter, prospecting and exploration was continued for 4 years and finally closed in 1971. A similar programme was conducted on Indus River placers near Hazro in 1968-70. Preliminary heavy minerals concentration and recovery of gold was carried out using sluices, palongs and mercury amalgamators. Reserve estimates and mineral grades at both the places were found to be much below economic limits.

In view of the above-mentioned studies, and drawing an analogy with the Nile River Delta which contained monazite, the Indus River Delta was evaluated as favourable for prospecting of economic minerals including monazite and zircon. A programme for prospecting of zircon was started in 1975, and Indus River Delta marginal islands were sampled on reconnaissance level. Heavy mineral suit included zircon, rutile, ilmenite and magnetite. In view of urgent requirement of zircon for the fuel fabrication programme, a Mineral Sands Programme (MSP) was initiated in 1076. An office and laboratories were established at the PAEC Camp Office, Karachi, and a crash exploration programme was started to explore the offshore bar placers all along the 120 km stretch of the Indus River Delta. A pilot-scale mineral processing plant was set up to separate mono mineral fractions and to study design parameters for a commercial plant. In 1978, the MSP offices, laboratories and the pilot plant were shifted to a Korangi Industrial Estate in Karachi.

Exploration was completed by augur sampling on a 20×100 feet grid on the advice of an IAEA consultant in one year. Pilot-scale studies were conducted and mono mineral fractions of zircon, rutile, monazite and ilmenite were successfully separated.

Remote sensing studies were carried out on the development of offshore bars. The studies indicated littoral drift of Indus River sediments along the Mekran Coast with the prospect of formation of placer deposits. It prompted sampling of Mekran Coast Placers at Sonmiani. The samples indicated significant values of zircon and rutile. Thereafter, a systematic exploration programme was instituted and augur sampling was carried out on a 20×100 feet grid. Apart from Sonmiani, four more placers were explored at Phore, Birar-I&II, Sirinda, and Pir Jamalshah.

Mineral processing was started at Sonmiani to meet limited requirements of PAEC. In this regard a 5 TPH wet mineral processing plant was installed at the site. It contained physical concentration equipment such as Wright trays, Richert Cones, spiral classifiers and shaking tables. Heavy mineral concentrates were processed on wet magnetic separators and wet high-intensity magnetic separators. Magnetite and ilmenite were stockpiled at the site, and non-magnetic concentrate was sent to the dry plant installed at Korangi Industrial Estate premises of MSP (Mineral Sands Programme). Dry plant comprised dryers, magnet and high intensity magnetic separators, high tension and electrostatic separators, air tables etc to prepare mono-mineral fractions of zircon, rutile and monazite. The operations were closed in 1993.

11. Nuclear Waste Repositories.

Ambitious nuclear power generation programme of the country necessitate establishment of nuclear waste repositories in the country. Investigations were started in 2003 to select a suitable site and in this regard preliminary evaluation was carried out for salt deposits of Manzalai Synclanorium in Kohat Plateau, granite bodies of Nagar Parkar and shale formations of Khuzdar. Possibility of thick clay sequences in the Kohat Plateau is also being considered to host future repository sites.

12. Prospecting for Lithium

Prospecting for lithium was started in 1991-92. A reconnaissance survey of granites and associated gem bearing pegmatites were sampled and analyzed for lithium and its pathfinder elements. Granites and pegmatites of Garam Chashma in Chitral and in Dassu and Astore areas near Skardu were identified to be suitable exploration targets for lithium.

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