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OVERVIEW: DELINEATION OF COALBED METHANE PROSPECTS USING HIGH-RESOLUTION SEISMIC REFLECTIONS AT FORT YUKON, ALASKA

by

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Disclaimer

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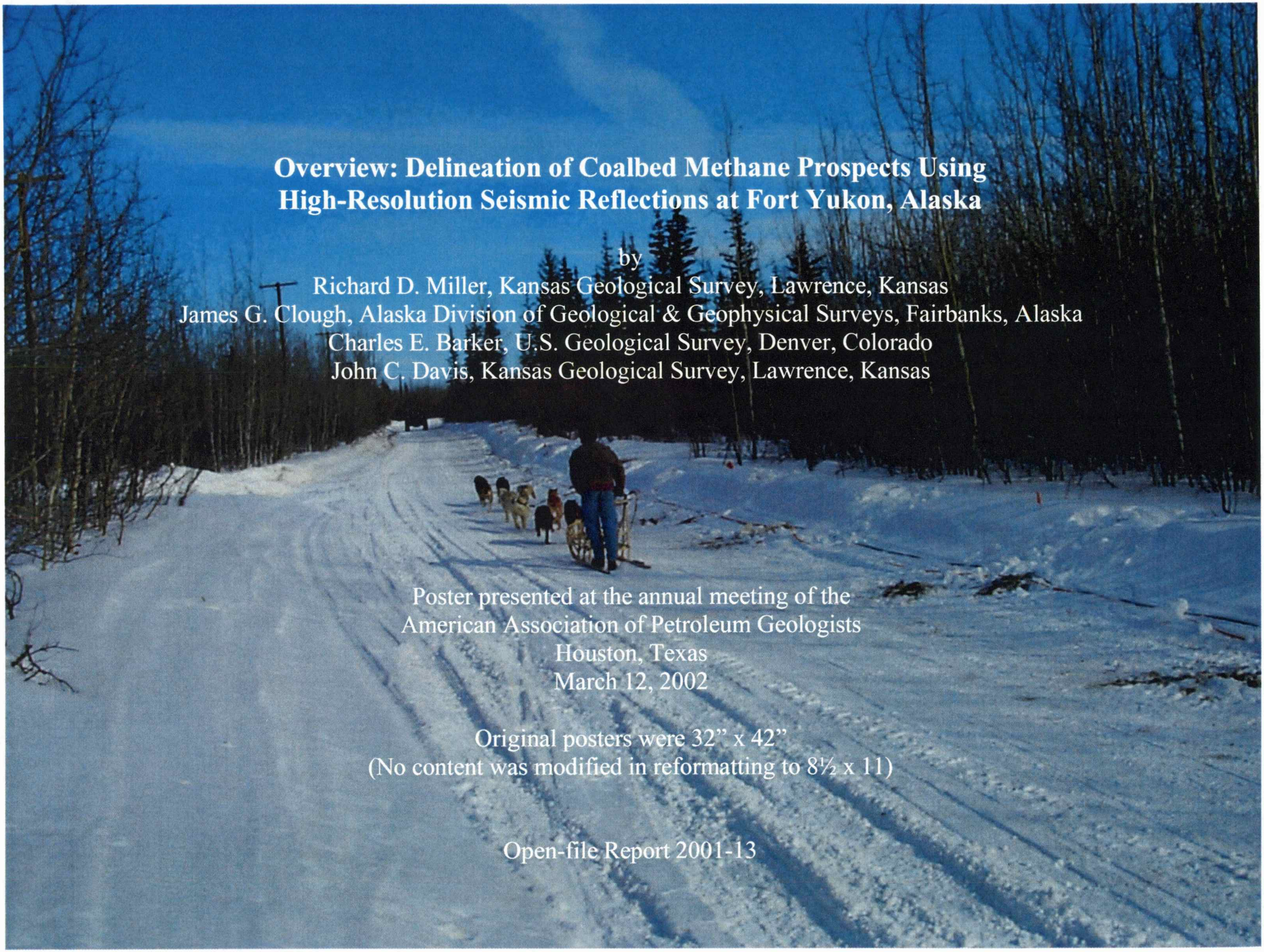

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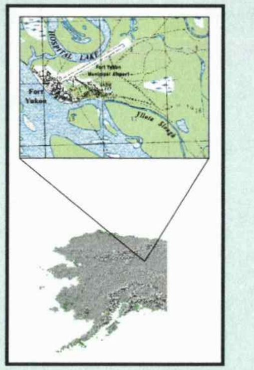
Introduction

Only in the last century has coalbed methane been recognized as a significant potential energy source rather than a mining hazard. While successful production of coalbed gas in the lower 48 states has continued to grow for nearly two decades, Alaska's coalbed methane resources still remain unexploited. However, within the next decade coalbed and shalebed methane will likely be significant sources of energy for urban and rural consumers throughout Alaska. State and federal agencies, municipal and tribal governments, regional Native corporations, and industry are combining their efforts to evaluate coalbed methane (CBM) and shalebed gas potential in rural Alaska. Gas produced using shallow well fields and short pipelines could have considerable impact in remote villages that are currently isolated from the power grid, dramatically lowering the cost of survival in these communities. Pollution caused by existing diesel generators would be reduced and industrial development (and thereby jobs) enhanced in areas where energy is currently subsidized and/or imported. A medium-sized community of 700 people uses ~250,000 gallons of diesel fuel per year, roughly half for electrical power generation and half for heating. This liquid fuel volume translates to ~34.5 million cubic feet of gas per year. At least 25 remote communities are situated on or near Alaska coal fields.

Fort Yukon, Alaska, has been classified a priority site based on village demographics, geologic setting, presence of potentially gassy coal, and the likelihood of bringing a CBM production unit on line. The component of the Fort Yukon study described here was designed to delineate potential coalbed methane resources directly under the Native Village of Fort Yukon. The people of Fort Yukon pay for fuel oil (diesel) at between 2 to 4 times the price in Anchorage or Fairbanks, so rural electric costs could rise to 4 times equivalent kWh rates paid in any of the three major cities of Alaska. This is the case not only for Fort Yukon, but for most of the more than 150 "roadless" rural communities in Alaska. Without passable roads into or out of Fort Yukon, unemployment exceeds 80 percent at times. Lacking a consistent commercial tax base for making capital improvements or sustaining social programs, the cost of living is considerably higher in Fort Yukon than the state and national averages.

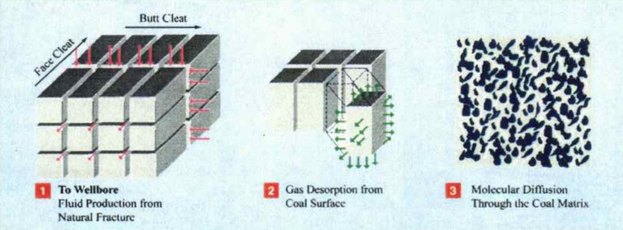


Several key factors are critical for a coal layer to be considered a viable methane source: net coal thickness, coal rank (low coal rank suggests biogenic gas whereas higher coal rank infers a thermogenic gas source), gas content, permeability (very low and very high are detrimental), hydrodynamics (water production is necessary for gas production), structure, and depth to target beds. Several of these key coalbed characteristics (net coal thickness, structure, depth content, and gas content) need to be determined and evaluated before methane reserves can be estimated and appraised as an economic energy source. Seismic reflection imaging can provide valuable information on thickness of potential coalbed gas zones and subsurface structures that may enhance or impede production. High-resolution seismic reflection has proven effective for imaging coal seams less than 3 m thick at depths in excess of 300 m for exploration and hazard evaluation.

Methane from Coal

Production of methane from coal beds is based on several characteristics of the specific coal and its geologic setting.

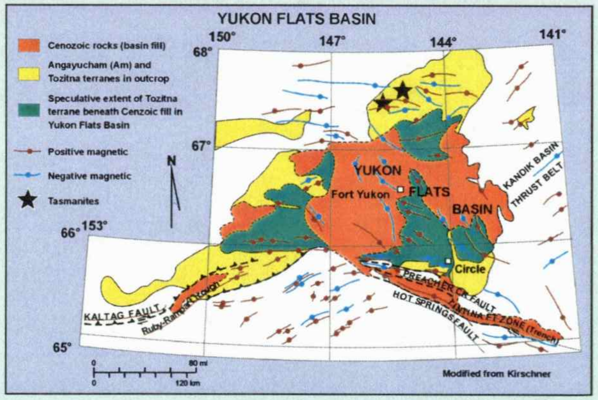
⇒ **coal is both the source and reservoir rock**
⇒ **coal is a microporous solid with an enormous internal surface area**
⇒ **coal permeability comes from fractures (cleats)**
⇒ **coal can sorb > 600 cubic feet of gas per ton**

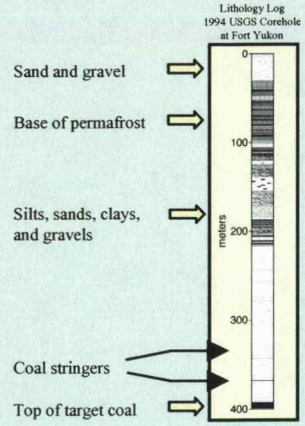


The process of sorption is critical to CBM reservoir behavior. Sorption is the physical process whereby gas is held by weak bonds on the surfaces of pores, cleats, and fractures. Burial depth is an important factor in determining coal reservoir characteristics, since increased pressure increases the amount of gas trapped in pores. Gas moves through the coal matrix by diffusion toward fractures. Permeability is completely dependent on fractures and cleats.

Geologic Setting

The Yukon Flats Basin of east-central Alaska is an alluvial and marshy, lake-dotted lowland of more than 8,500 square miles, located south of the Brooks Range and north of the Yukon-Tanana Uplands. Tectonically, the Yukon Flats Basin is interpreted as a pull-apart basin or rhombus graben; however, some evidence supports the notion that the basin formed as a result of crustal rotation. Regardless of the mechanism responsible for the basin's conception, it is commonly accepted that the process is still active today. The lowland that characterizes this basin extends upstream into other parts of the Yukon River and Porcupine River drainage basin. Based on gravity modeling, the Yukon Flats Basin may have as much as 3000 m of Cenozoic fill, while interpretation of seismic data acquired along the Yukon River pushes that estimate to over 4000 m of Cenozoic fill. On average, the sediment load (thickness) regionally across the basin is thought to be less than 1000 m. The upper 100 m of sediments in the basin is predominantly Tertiary lacustrine silts and clays. Covering most of Yukon Flats is an anomalously flat layer of Quaternary river deposits that more closely resembles a coastal plain setting rather than an inland basin. The surface elevation is around 200 m above sea level.

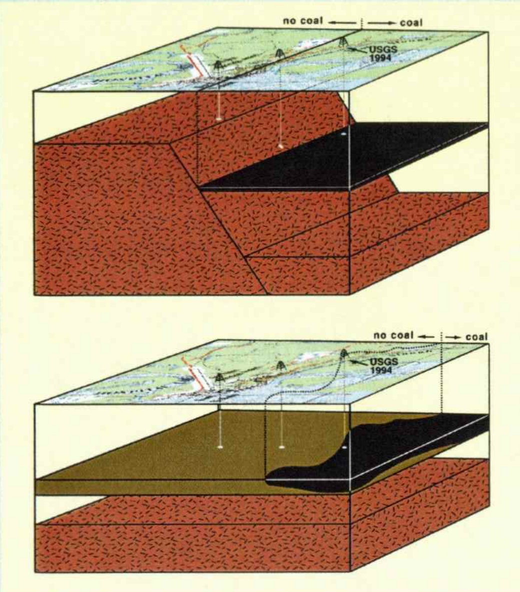




Based on a 1994 corehole commissioned by the USGS for climate studies, a coal zone is known to be gassy and to contain several individual coal beds that are lignite rank (0.3% mean random vitrinite reflectance). Petrographic studies show that the coal is composed mostly of detrital vitrinite and appears to be of lacustrine origin. Adsorption isotherm studies indicate a gas-saturated storage capacity of about 40 scf/ton (as received basis) at 400 m depth.

Seismic reflection profiling in permafrost environments, especially high-resolution profiling, is complicated by the near-surface high velocity layer defined by the base of the ice-bonded zone. Success using high-resolution seismic reflection to delineate relatively shallow (<1000 m) and thin (~3 to 10 m) methane hydrate lenses below a thick sequence (~600 m) of ice-bonded unconsolidated sediments in the Mackenzie Delta, Northwest Territory, provided key insights into the study of coal layers beneath Fort Yukon.

In the Fort Yukon area, the permafrost is around 75 m thick with unconsolidated, probably saturated, sediments present down to the primary target, a lignite coal bed at about 400 m. Permafrost environments present unique challenges to the acquisition, processing, and interpretation of seismic reflection data regardless of target or resolution requirements. In particular, laterally variable permafrost thicknesses and material properties and the presence of free gas within frozen sediments cause extreme lateral velocity changes and adversely affects the transmission of seismic energy. This frozen earth setting is especially troublesome when a significant part of the sediments between the target and the base of the permafrost are unconsolidated, resulting in a pronounced velocity inversion. Based on the type and configuration of surface heat sources (such as lakes and rivers), the permafrost thickness can vary significantly and therefore result in substantial static irregularities on CMP stacked seismic sections.



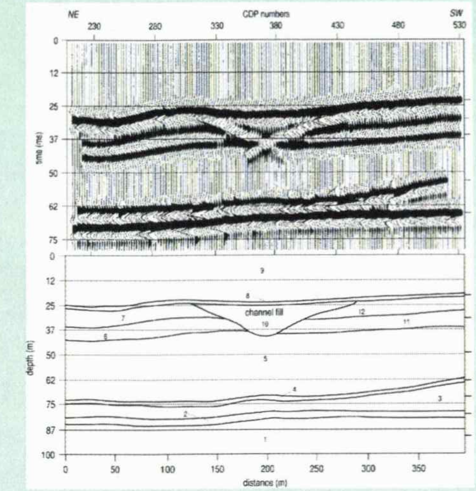
What if ????

Once coal has been determined to exist at sufficient rank and appropriate depth to produce methane gas for rural community use, **why is the resolution and delineation potential of high resolution seismic reflection necessary?** In this geologic setting the continuity of the coal, its structural characteristics (faults, fractures, and dip), and thickness cannot be adequately appraised from a single borehole. Also, the site selected for a detailed drilling and sampling program must reasonably represent the area to accurately appraise the methane production potential of this coal.

For example, it is not outside the realm of possibility that the 1994 USGS corehole encountered the coal seam on the down-thrown side of a large fault block. In such a setting there would be a significant risk in assuming that the coal is continuous and uniformly thick beneath and around the town. Changes in coal seam characteristics will affect the design of any well field intended to feed a municipal electrical power generating facility. It is also possible that the depositional environment was such that the core of the lacustrine coal could be a small channel no larger than the slough bounding the south side of the village. It is possible to imagine other fault and depositional scenarios that could dramatically reduce the producible volume and yield necessary to adequately supply the needs of Fort Yukon.

Resolution

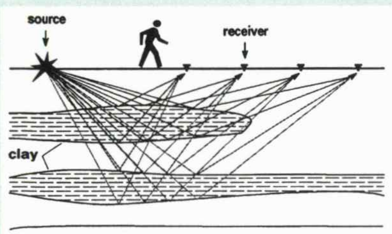
- Vertical limit
  - theoretical $\frac{1}{4}\lambda$
  - practical $\frac{1}{2}\lambda$
- Horizontal limit
  - Fresnel zone radius
  - $r \cong V/2 \sqrt{T_0/f}$



Detecting the top of a coal seam only requires an acoustic impedance contrast between the coal and the clay layer above the coal. Delineating the top and bottom of the coal layer, therefore providing an estimate of coal seam thickness, requires high frequencies and an acoustic impedance contrast between the top of the coal and the overlying material and the bottom of the coal and the underlying material.

Frequencies of around 180 Hz in this geologic setting will provide a practical vertical resolution of around 5 m with a theoretical limit of around 2.5 m. Using the core data, the acoustic impedance contrast between the coal and the overlying clay should be sufficient to provide a high amplitude reflection. Considering the drill penetrated 9 m of coal at the bottom of the 1994 USGS hole, it is also likely that the base of the coal will be detected.

High-Resolution Seismic Reflection



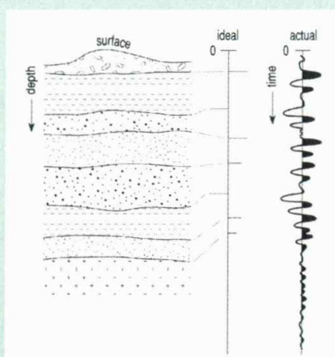
Seismic reflection is a geophysical technique that relies on sound waves to travel through the earth and interact with discrete changes in seismic velocity and/or mass density changes in a predictable way. These velocity and/or density changes are known as acoustic impedance contrasts. These contrasts commonly occur at natural boundaries, such as changes in lithology.

Imaging and resolving are two different objectives. The thickness of the coal layer (or any layer to be fully delineated) plays a role when resolution is the objective. To resolve the top and bottom of a layer, the reflection from the bottom must be separable from the reflection from the top. Improving resolution can be accomplished only if the velocity of the layer is decreased or the frequency of the seismic signal is increased. Of these two, only frequency of the seismic signal can be easily controlled.

Effective high-resolution seismic reflection surveys require redundancy in subsurface sampling, specifically by recording seismic energy within optimum source-to-receiver offsets and seismic signals that are high energy and high frequency. By definition, high-frequency seismic signals are greater than 80 Hz. For the Fort Yukon seismic study to be successful, frequencies of at least twice that were necessary.

Competing with the need for more traces (i.e., greater fold) is the need to minimize the number of wavelets summed together. Summing or stacking generally reduces higher frequency components of the signal. A balance must be maintained between these two critical characteristics of the data.

Interpreting geology from seismic data (especially high-resolution data where the resolution limits are always being pushed) requires an understanding of how the source wavelet (pulse generated by the seismic source) interacts with each uniquely different layer in the subsurface. Separating the unique reflection wavelet returning from the top of a layer from the unique reflection wavelet returning from the bottom of the same layer is a challenge when the layer is less than the seismic wavelength. Interpreting layer thickness and geometry when layer thickness is at or below the length of the dominant reflection wavelength requires incorporation of ground truth.



From a practical perspective, every "wiggle" does not have unique geologic significance. Techniques to remove the source wavelet, leaving just the earth response (ideal), are not particularly effective on high-resolution data. The inherently noisy nature of high-resolution data, the earth's strong attenuation of high frequencies with depth (inconsistent source wavelet with depth of penetration), and the absence of a large number of reflecting layers at random intervals all play against deconvolution (the process of removing the source wavelet). Trace-to-trace coherency and associated pattern discrimination represent the most effective means of interpreting high-resolution data. Realizing the theoretical vertical resolution limit and maximum potential of high-resolution seismic reflection data is not feasible.

Severe Limitations: "Small Footprint" and Airlift Portable (weight and size)

Transporting equipment to rural areas is expensive and constrained by airfield limitations, proximity to navigable waterways, and vehicle capacities. Without roads to transport seismic gear, most conventional equipment and field exploration methods cannot be considered for many rural villages. Considering the limited transport size and weight restrictions, even modifications for operating in this cold climate must be made efficiently.

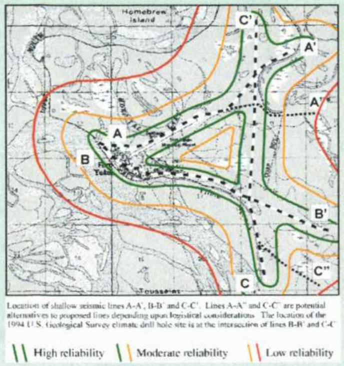
Adding to these problems is the need for "small footprint" exploration methods. Traversing wooded and high-relief areas in this delicate environment must conform to strict federal, state, municipal, and tribal government and Native corporation guidelines and constraints. Off-road travel cannot involve excessive destruction of vegetation or the scarring of the ground surface.

An L-382 Hercules transport with a 24,000 kg payload and 16 m long cargo hold transported the seismic equipment from Fairbanks to Fort Yukon and back (~400 miles total) at a cost of $32,000. This aircraft landed on the 1.5 km, ice/snow packed, gravel runway operated by the Alaska Department of Transportation.

Cargo included 6 pallets of cables and geophones, two 6 x 6 ATVs, one 4 x 6 seismograph ATV, one snowmobile, an IVI minivib, one pallet of computers, and one pallet of personal gear. Loading and unloading the aircraft took about 30 minutes.

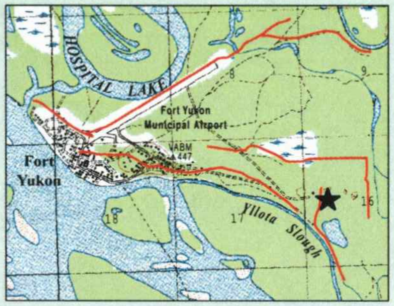
Survey Design

Survey design focused on optimally interpolating the coal reflection between all the 2-D lines, most importantly under the town and in the area immediately east of town. Environmental concerns and cultural features restricted line placements. Geostatistical analysis of interpolation error based on line spacing and orientation provided qualitative constraints on extrapolation confidence from the three lines originally proposed to surround the town. This idealized line deployment scheme was modified due to vegetation, cultural obstacles, and spring thaw.



Location of shallow seismic lines A-A', B-B' and C-C'. Lines A-A" and C-C" are potential alternatives to proposed lines depending upon logistical considerations. The location of the 1994 U.S. Geological Survey climate drill hole site is at the intersection of lines B-B' and C-C'

Based on access and obstacles, seven lines (red on figure to the right) were actually acquired in and around the town of Fort Yukon and the U.S. Air Force radar station immediately east of town. Snow removal was necessary for ATVs to move equipment and personnel along the lines. A short test survey line was acquired within a few meters of the 1994 USGS climate corehole (★), providing much needed ground truth. Proximity to the Yukon River and Hospital Lake complicated the subsurface variability of the permafrost.



Data Acquisition

Data were recorded to optimize reflection events between about 300 and 700 m below ground surface. Equipment and recording parameters were selected based on preliminary tests along line 1 (intersecting the corehole site). Due to transportation issues and the obvious need to minimize equipment moved to the site, most adjustments to the acquisition procedures, parameters, and equipment were fine tuning.

A 240-channel Geometrics Strataview seismic recording system shock mounted in a customized steel frame on a 4-wheel drive, 6-wheel John Deere Gator recorded the 12,000 sample per trace, uncorrelated data. Data were digitally sampled at 1 msec intervals for each of the three sweeps run per station. Each individual shot record was digitally saved separately on the seismograph's hard drives. The final data set, which included all seven lines, incorporated more than 2600 stations and required in excess of 60 gigabytes (100 CDs) of storage. To maintain as quiet a recording environment as possible, the entire recording system (including all support systems) was operated on 12 V battery power.

With temperatures dipping to -20° F, the seismograph, supporting equipment, and operator had to be protected from the cold. A double lined vinyl cover with operator boot was installed to enclose the ATV's seismograph area. A thermostatically controlled propane heater was also added to the vehicle to maintain an inside temperature of around 60° F. Cables connecting the seismograph to the geophones entered the seismograph compartment through velcro sealable slits. Several radio frequencies were used to maintain contact with crew and transmitted the vibrator operating data (source signal–ground force). A 110 V generator was used when backing up data from seismograph hard drives to external hard drives. External hard drives were the host for transporting data to the mobile processing center set up at the lodge.

Receivers

Based on testing at several other permafrost sites, conventional ice plates do not provide sufficient coupling for high frequency recording. All snow and ice was removed and pilot holes drilled (melted) into the frozen ground to optimize the high frequency recording potential of the three 10 Hz Mark Products digital grade geophones planted at each station. Hammer drills with 20 cm long carbide bits, powered by small electric generators, bored through the frozen gravelly surface material. Geophones were then inserted into the holes (still wet from frictional melting) and frozen into place at the bottom of trenches dug through snow and ice up to 1 m deep. This process dramatically increased the time and effort necessary to deploy geophone spreads, but the rewards were evident as upper corner frequencies of stacked reflections exceeded 180 Hz in some places.

Up to four drills were working simultaneously to plant geophones into the road bed, edge of the runway, dirt paths, through sloughs, and into organic-rich soil in wooded areas. A sufficient buffer was maintained between geophone planting and live recording stations to allow continuous data recording.

Source

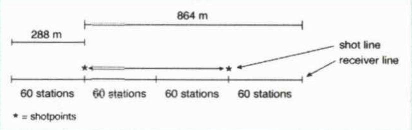
Considering the near-surface conditions, target depth, resolution requirements, environmental limitations, and transportation constraints, an IVI minivib outfitted with a prototype high output valve (3 to 4 × normal power above 150 Hz) was the optimum source configuration for this site and project. This center-articulating buggy-mount, high-frequency vibrator (15 to 500 Hz, 8000 lb peak force) provided the necessary mobility and coupling. With the "small footprint" and minimal ground compression the source did not leave an impression that would survive the summer, even along the trails and open areas where some thawing had occurred. The vibrator was winterized to allow operation in temperatures well below -40° F.

Snow was removed from roads and trails using a front end loader owned by the Native Village of Fort Yukon. The vibrator pad was seated onto thin (< 5 cm) frozen snow, ice, or frozen ground, but never onto loose, lightly compacted, or deep snow. Three 10 second upsweeps from 25 to 250 Hz were recorded at each shot station. Shot stations were on 10 m intervals. Ground force, mass accelerometer, and base plate accelerometer were recorded and saved for each shot. Software was used to control the vibrator's power output to maintain the maximum drive without overdriving the valve and/or decoupling the baseplate.

Surveying

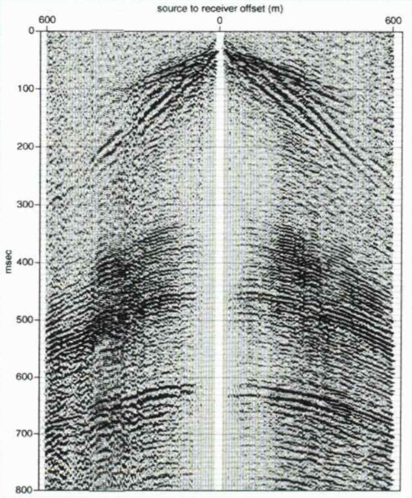
Accurate station surveying is essential for any high-resolution seismic reflection program. All stations necessary for elevation corrections and absolute location of the 2-D profiles were surveyed in with a Trimble 4800 and 4700 differential GPS at a ± 2 cm accuracy in x, y, and z. Initially, each station was located using a measuring chain or takeouts (5 m spacing) on the seismic cables.

Field Geometry—Source/Receiver



Relative orientation of source and receivers is critical for recording reflections from the optimum source offset distance. For targets that are relatively shallow and thin (by conventional standards) it is important to record reflections returning from reflectors at a specific set of incident angles or reflection angles. Complicating the problem in this setting is the base of the permafrost, which defines a velocity inversion in which the permafrost represents a high velocity layer. This high velocity layer dramatically alters reflection raypaths during their travel from source to reflector and then to receivers. To insure that the ever-changing optimum source offset was always recorded, 240 receivers were deployed in a fixed spread 1.2 km long. The optimum offset from the source was calculated to be between 50 and 300 m, both in front and behind the source. By recording geophones over this wide range of offsets, if the geology did change unexpectedly, the optimum reflection window still would be recorded.

Shot Gather

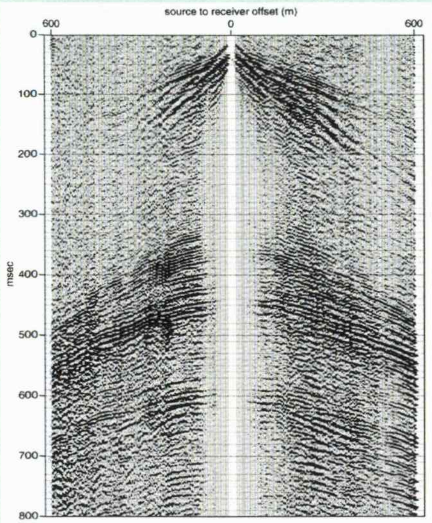


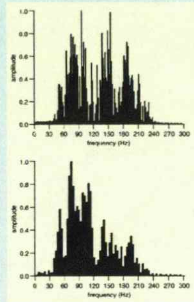
The single fixed 240-receiver spread allowed the source to occupy the middle 120 stations of the spread and still maintain a full complement of optimum minimum to maximum offsets (50 to 300 m) both in front and behind the source on all sweeps. An added advantage of this configuration is that it eliminates cable switches needed to select specific receivers relative to the source location to be recorded.

The receivers were spaced on 5 m intervals with shots occupying every other receiver station. The source was offline from 3 to 10 m. A total of around 60-fold data were recorded, but, since only the optimum offsets were used, the stacked sections are around 12 to 18 fold. By avoiding offset effects (wide angle, high velocity layer distortion, etc.), traces used in the stacked sections have the highest signal to noise, lowest wavelet distortion (from NMO stretching), and highest frequency.

More than a dozen high quality (high signal-to-noise ratio and dominant frequency) reflections are prominent from 300 m to the basement at around 620 m. Based on the USGS corehole, these reflections fully sample the depth of known coal and extend into the interval having a high possibility of coal units. Reflections fill the time-depth interval where the coal layer is known to exist. Considering the unique transition from very limited reflection returns (above 300 m where no coal was encountered) to the zone of abundant reflection arrivals (300 to 650 m where three reflections were encountered in the first 100 m), it is reasonable to suggest that the highly reflective zones may contain multiple coal seams. The basement reflection is easily identified by its characteristic lower frequency and more diffuse reflecting nature.

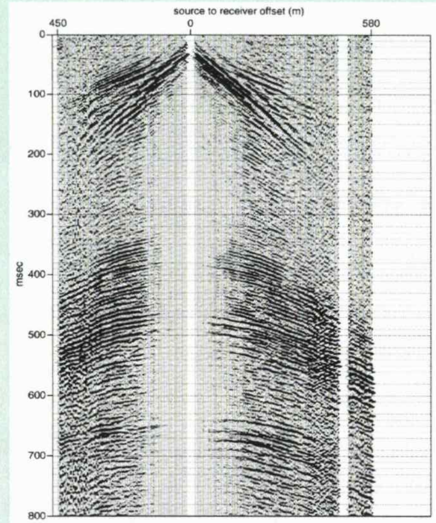
Data Resolution





Reflections above basement have a dominant frequency around 150 Hz with a usable upper corner frequency slightly greater than 200 Hz (upper spectra).

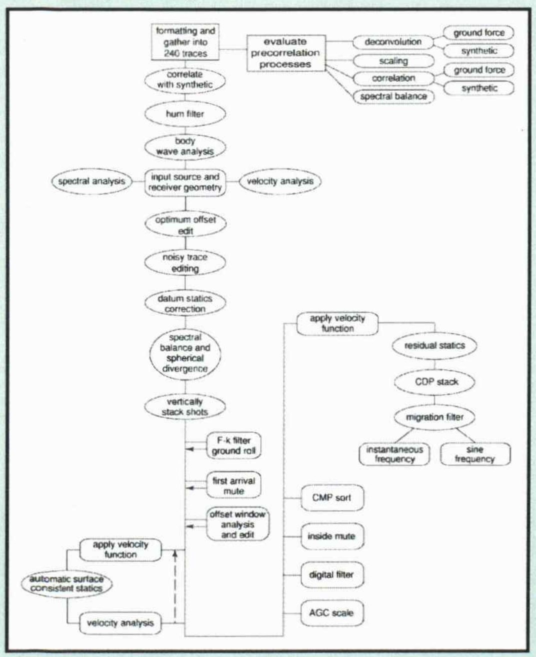
Reflections from the basement have a characteristically lower frequency at around 90 Hz (bottom spectra) and a much more diffuse, less trace-to-trace coherent appearance.



The shot gather on the left is from line 4 while the shot gather on the right is from line 5 (northernmost and southernmost lines, respectively). There are clearly three different groups of reflection arrivals. One set is about 50 msec in length and arrives between 350 and 400 msec. A second set comes in consistent with the high amplitude event at about 450 msec. The second reflecting "packet" is followed by about 100 msec of relative quiet, likely indicative of sand, gravel, clay, and silt units similar to those observed in the core between the base of the permafrost and the top of the 400 m coal unit. A final reflection packet is interpreted as the top of basement, with a weathered, diffuse appearance. The data possess a practical bed resolution potential of around 4.5 m, so the top and bottom of the 9+ m coal layer encountered 400 m below the ground surface in the drill hole should be resolvable with these data.

Data Processing

Flow Chart of Processing

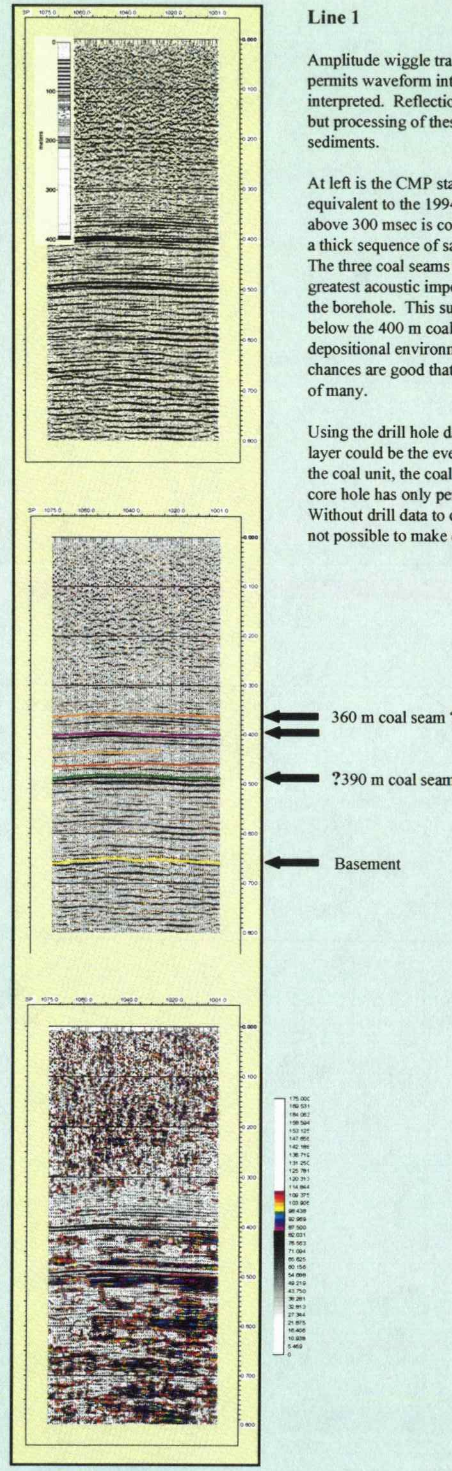


Precorrelation operations were instrumental in broadening and flattening the bandwidth and therefore increasing the resolution and improving source wavelet characteristics. Testing the effectiveness of deconvolution and correlation with the ground force and synthetic drive signals demonstrated that scaling followed by correlation with the synthetic drive signal produces the best bandwidth and upper corner frequency reflections.

Noise reduction was critical. Noise included: 60 Hz powerline and higher modes (removed by the hum filter), cultural noise (snow machines, automobiles, people walking, etc., removed by trace editing before the three sweeps/station were vertically stacked), and cable/geophone crew noise (walking, drilling geophone holes, moving cables, etc., removed after correlation, but before vertical stacking of three sweeps/station).

Concern for improperly stacked reflections as a result of the pronounced velocity inversion at the base of the permafrost required careful velocity and statics analysis. Obviously, velocity plays a role in NMO corrections, but as critical is velocity's role in many statics correction operations. Maintaining a focused and narrow window of source offsets is key to avoiding NMO artifacts in the presence of the extreme velocity inversion at the base of the permafrost. To insure the accuracy of the stacked sections and interpretations based on those data, special emphasis was placed on velocity irregularities due to the permafrost.

CMP lines were processed into a final stacked format using WinSeis, a commercial processing software package. The basic architecture and sequence of steps followed during the generation of the final stacked sections were similar to conventional petroleum exploration processing flows. Step-by-step QC was necessary to produce the high-resolution stacked sections at the limits of the data potential. The main distinctions between high-resolution and conventional data processing are related to the emphasis placed on velocity analysis, optimum offset window (especially for near-vertical raypaths), extending the upper corner frequency while broadening the bandwidth, minimizing extensive wavelet processing, care and precision of muting operations, constraining statics operations (maximum shifts no greater than ¼ wavelength of the dominant reflection energy with correlation windows at least 10 times the dominant wavelength), and coincident iterative velocity and statics analysis.



Line 1

Amplitude wiggle trace representations of the CMP stacked section permits waveform interference and sub-wavelength bedding to be interpreted. Reflections above 300 msec are present on shot gathers but processing of these data focused on the lower 400 m of basin sediments.

At left is the CMP stack of line 1, with station 165 approximately equivalent to the 1994 USGS corehole. A lack of reflection events above 300 msec is consistent with the shot gather and borehole, where a thick sequence of sands, clays, silts, and gravels were encountered. The three coal seams between 300 and 400 m will likely possess the greatest acoustic impedance contrast of any sediments encountered in the borehole. This supports the suggestion that high amplitude events below the 400 m coal may be coal seams as well. Considering the depositional environment and age of the sediments in this basin, the chances are good that the 400 m coal layer is only the first major coal of many.

Using the drill hole data as a starting point, the base of the 400 m coal layer could be the event at around 415 msec. If this event is the base of the coal unit, the coal seam is about 20 to 25 m thick. In that case, the core hole has only penetrated the upper half or so of the coal layer. Without drill data to correlate these reflection arrivals to reflectors it is not possible to make definitive, stratigraphic depth interpretations.

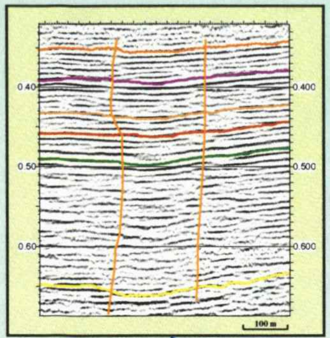
Interpretations of the tops of high amplitude reflections that appear across the entire site were made to assist correlating the coal (violet) and basement (yellow) reflections from line to line. Faults having less than 10 m relief and fracture zones were interpreted on lines 2, 4, 5, 6, and 7. Correlation of these features between lines was based on consistency in seismic character and displacement orientation.

The diffuse nature of the basement reflection evident on the stacked section is consistent with the character of the same basement reflection on shot gathers. The lack of a uniform wavelet and trace-to-trace coherency suggests that the bedrock surface may be characterized by a variable weathered zone that grades into competent hard rock.

Color frequency plots overlaid by the variable area wiggle trace display of the seismic data allows fault and fracture characteristics to be easily distinguished from static and folding. No faulting or fracturing is particularly evident on line 1, but this display format was an excellent tool on the longer profiles where line separations are over 2 km.

Diffraction patterns are considered diagnostic of faulting in this area. Several strong hyperbolic diffraction arrivals become prominent at specific frequencies in wiggle trace amplitude displays.

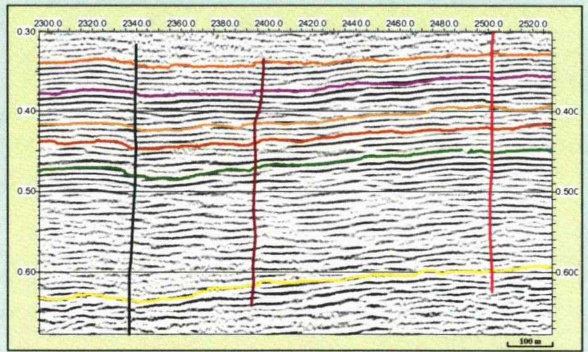
The Kingdom Suites seismic data interpretation software package was used to do frequency analysis and assist with interpretation of the coherent reflections.



A graben structure with movement along near vertical faults extends throughout the entire Cenozoic section and clearly penetrates the basement. This basement structure can be correlated to similar structures on other lines.

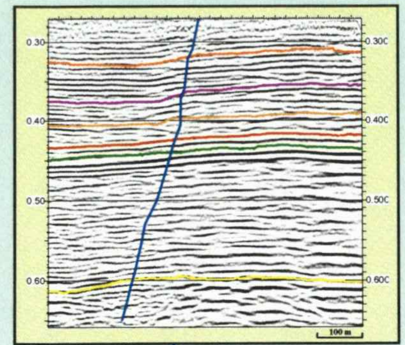
The coal reflection is present on all lines with waveform attributes suggesting the coal layer is over a half wavelength thick.

The "coal interval" has been classified based on similarity in reflection character. The interval extends from around 350 to around 500 m.



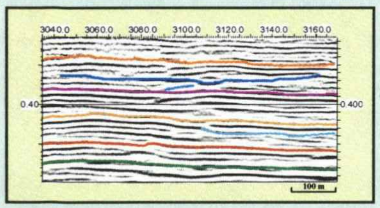
Faults are interpreted based on bed offset and diffraction patterns. Frequency analysis also provides support for placement of fault zones.

Diffraction patterns are evident on line 2 (to the left) at the basement reflection beneath station 2340.

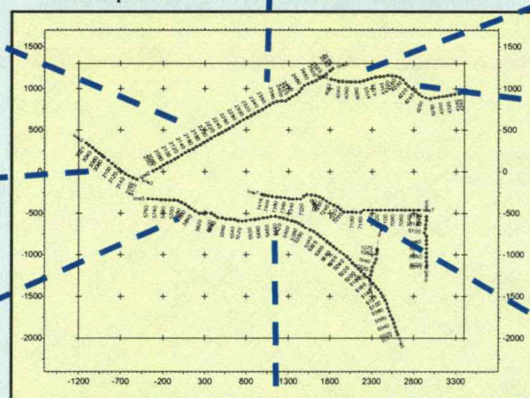


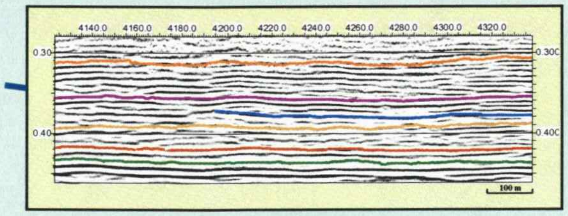
Diffraction patterns below the yellow event identified as basement on line 4 (above) are east of the actual fault trace. This is suggestive of a wider fault zone below the basement reflection.

Reflections from the western side of the survey area are consistent with no indication of faulting or fracturing. Several subtle depositional features can be interpreted within the "coal interval." These features resemble channels and could be areas of cut and fill.



Basemap with Seven Seismic Profiles and Station Numbers

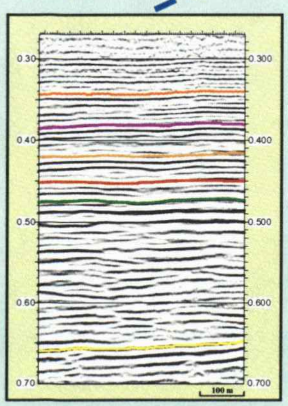




With the increased ground truth that will be provided by future drilling at this site, subtle channel features directly beneath the coal reflection interpreted in blue (above) should be correlatable to specific stratigraphic units.

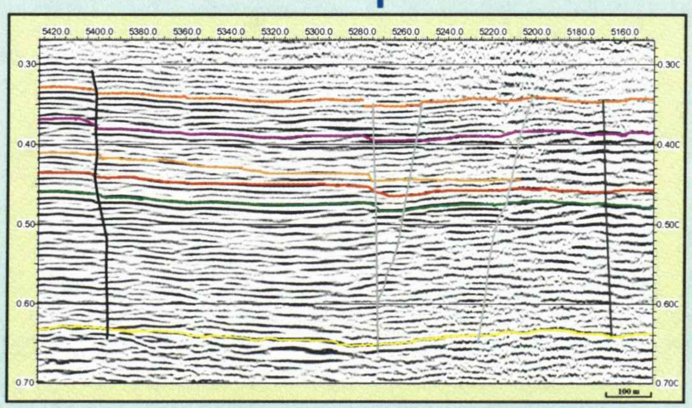
If this blue event represents the base of the coal along this line, the coal here could be over 25 m thick. In this depositional environment, thick sequences of coal could come and go based on ancient river meanders and changes in lake shorelines.

Uniform, relatively undisturbed reflections indicate an area with very consistent stratigraphy and limited or no structural features. The characteristics of individual events can easily be correlated with and between the seismic lines.

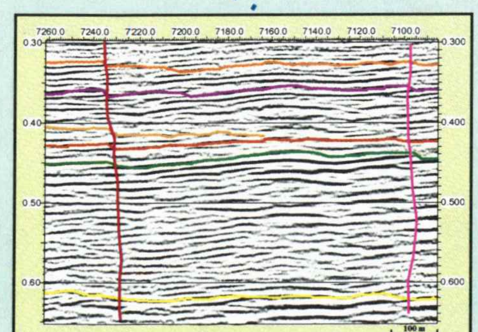


Several diffraction events, indicative of bed terminations or point sources, are evident all along the trace of the fault at station 5400 on line 5 (to the right). This fault has over 10 m of vertical displacement and requires consideration in future drilling programs.

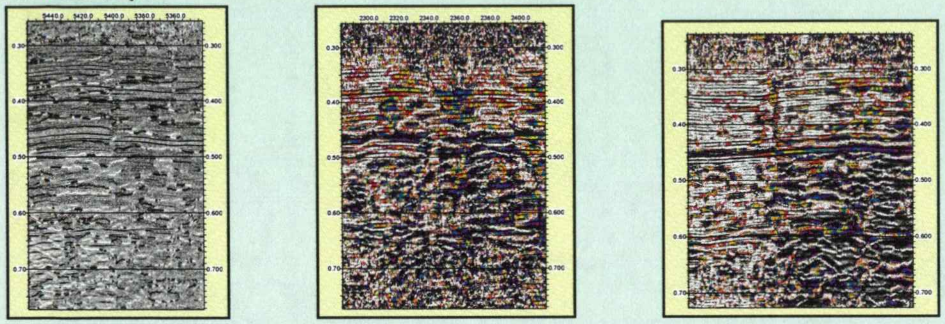
The coal reflection and "coal interval" is consistent with a high degree of similarity across all faults mapped on this survey.



The east end of both line 5 (to the left) and line 7 (to the right) are highly disturbed, likely indicative of signifi-cant fracturing of the rock layers. Line 1 (shown on the previous panel) is void of any faults or apparent fractures. This geometry suggests fault/fractures are oriented roughly northeast-southwest.



Attribute Analysis

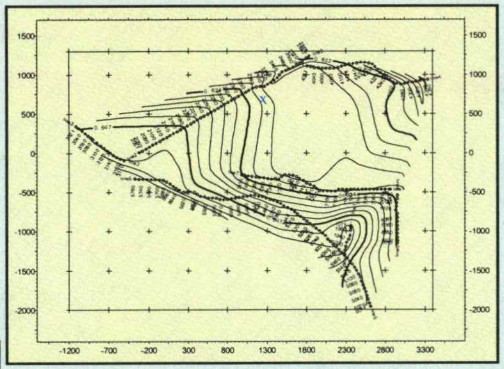


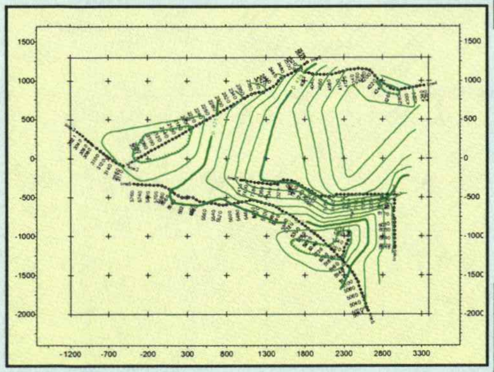
Coincident sign frequency and wiggle trace amplitude analysis was instrumental not only in detecting but more importantly in delineating faults and fracture zones. The maximum displacement observed on any fault is just under 10 m, so distinguishing faults that are mapable across the site from fractures zones having only localized bed distortions is an important consideration for future production tests. Diffraction patterns are diagnostic of the larger faults. The strongest diffractions are associated with major faults through the basement surface. Amplitude and frequency variations in the 400 m coal seam are related to changes in physical properties of the coal (thickness, velocity, attenuation, etc.). These data will contribute significantly to future characterization of the coal seam including: volume, gas concentrations, fracture density, and other properties related to production estimates.

Isotimes

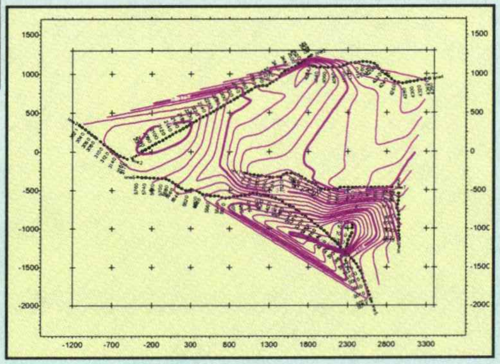
Horizons were mapped using a combination of automatic correlation routines that need some manual fine tuning. Reflections from the basement surface, the 500 msec (~500 m) high amplitude reflection, and the 390 msec (390 m deep) coal seam were mapped around the site. No control data were used and therefore these contours are based purely on seismic data. Considering that none of the lines crossed sufficiently to tie, the line-to-line correlations in time and waveform are quite good.

Basement configuration is consistent with the regional dip toward the center of the over 3000+ m basin to the southwest (figure to the right). The basement is 650 m or so deep near the barge landing on the Yukon River along line 3, and is less than 600 m near the eastern end of line 4.



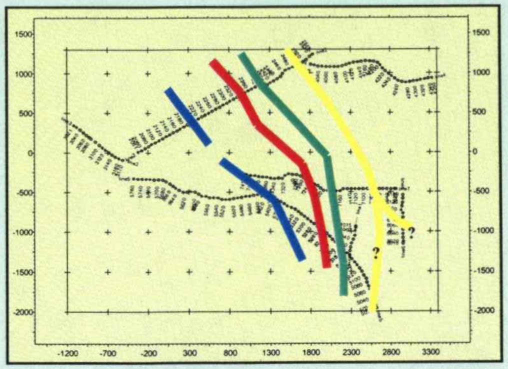


Near the bottom of the potential "coal interval" a high amplitude reflection occurs at around 500 msec. This event has a similar dip as the basement, but with a slightly different gradient at the northeastern end of line 2.



High gradient areas are in general consistent between all three contoured horizons. Using these contour data in association with attribute analysis and the relative throws on faults, fault and fault plane orientations can be designated with reasonable confidence. The coal seam is at a depth of around 390 to 400 m at the southern end of the survey area and rises to around 350 to 360 at the north-eastern corner of the area.

Faults and Fractures



Combining the attribute analysis, reflection offset estimates, and contouring of the three key horizon tops permits faults to be mapped across the site with a high degree of confidence. Faulting as interpreted (right figure) is consistent not only with these data but also with basement faults that control the deep basin to the south. Block faults dropped downward to the south and southwest control the structure of the basement and thickness of overlying sediments in this area.

Faults are mapped to be consistent with displacement amounts and the configuration of layers. Fractures are identified in areas where reflection coherence is reduced and spectral properties decrease.

Conclusions/Findings

This seismic reflection program successfully extended the geologic information obtained from the 1994 USGS corehole about the coal seam at 400 m depth across the Fort Yukon study area. Several objectives and goals were identified at the onset of this project. Each objective was successfully accomplished and in some cases expectations were significantly exceeded.

Goals & *Accomplishments*:

1) Generate high resolution (>120 Hz) signals with sufficient site wide coherency, resolution, and signal-to-noise ratio to allow the top and basal contact of the lignite coal encountered at around 400 m to be mapped;

Reflections with upper corner frequencies over 200 Hz and dominant frequencies over 150 Hz were generated and recorded site wide. Over a dozen uniquely distinguishable reflections are interpreted within the depth range of interest. Practical minimum resolution limits are around 5 m allowing both top and bottom of the 400 m coal seam to be imaged.

2) Optimize acquisition for 2 1/2-D imaging for line to line extrapolations;

Reflections wavelets possessed sufficient consistency and uniqueness that individual reflection events can be tied from line to line across distances as great as 2 km. Resolution was high enough that subtle stratigraphic features, varying over 100s of meters, were observed. Drilling will be required to confirm their geologic significance.

3) Evaluate and optimize equipment and parameters to maximize signal-to-noise and resolution potential, including offset sensitivity due to permafrost;

The permafrost setting presented unique challenges to achieving optimum offset. These were met by using an asymmetric, split-spread geometry recorded into a fixed oversized receiver spread. A high output value proved critical to pushing the dominant frequencies above 120 Hz.

4) Correlate reflections with units seen in borehole data;

The top of the coal at around 390 m matches perfectly with the borehole lithologic log.

5) Processing flows modified and optimized for extending the upper corner frequency;

Precorrelation and offset sensitive processing was customized for this project and its special data characteristics.

6) Evaluate and adapt source and receiver coupling to exceed any previous high frequency signal recorded in a land setting at depth greater than 400 m;

Drill emplaced geophone spikes and hard surface source pad coupling matched with a computer controlled optimized drive signal helped push the previous high of around 120 Hz dominant at 400 m to over 150 Hz at depths over 500 m.

7) Map the 400 m coal seam and any significant structural features above the basement;

A series of very small offset faults were imaged with trends consistent with basement faults to the south and with the general topography of the basement and multiple layers mapped above basement. Top and bottom of the coal seam will be mapable with additional ground truth.

8) Imaged below the 400 m coal seam for more potential coal horizons.

Speculation based on geology and reflection characteristics suggests that events between about 350 and 500 m producing strong reflection returns may be coal layers.

Acknowledgements

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