

HIGH RESOLUTION SEISMIC EXPLORATION

FOR

GOLD

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ABSTRACT

In the summer of 1987, a high resolution seismic survey covering approximately 2000 km offshore Nome, Alaska, was conducted in support of a placer gold exploration program. The digital acquisition and processing systems developed provided the interpreter with coherent data in the 1000 hz range to depths of more than 200 m. All of the usual problems associated with marine data (reverberations, ghosting, signature processing, etc.) were successfully treated in this microcosmic exploration effort. Subsequent drilling and mining operations were guided primarily by the geophysical interpretation.

INTRODUCTION

The acquisition, in 1985, of 8100 hectares of offshore Alaskan State mining leases near Nome, Alaska by Western Gold Exploration and Mining Company, Limited Partnership (WestGold), led to a major effort by the company to evaluate the economic potential of the marine placer deposits in the area. (Fig.1)

High resolution reflection seismic acquisition and processing techniques were developed to evaluate the various geologic environments present offshore Nome, and ultimately other areas offshore the State of Alaska. The complex nature of the offshore glaciomarine sedimentary environment necessitated acquiring the data with the optimum combination of resolution and coherency. The data were acquired using modern digital acquisition systems so that they could be optimized using digital signal processing techniques. Interpretation was completed on an interactive graphics workstation.

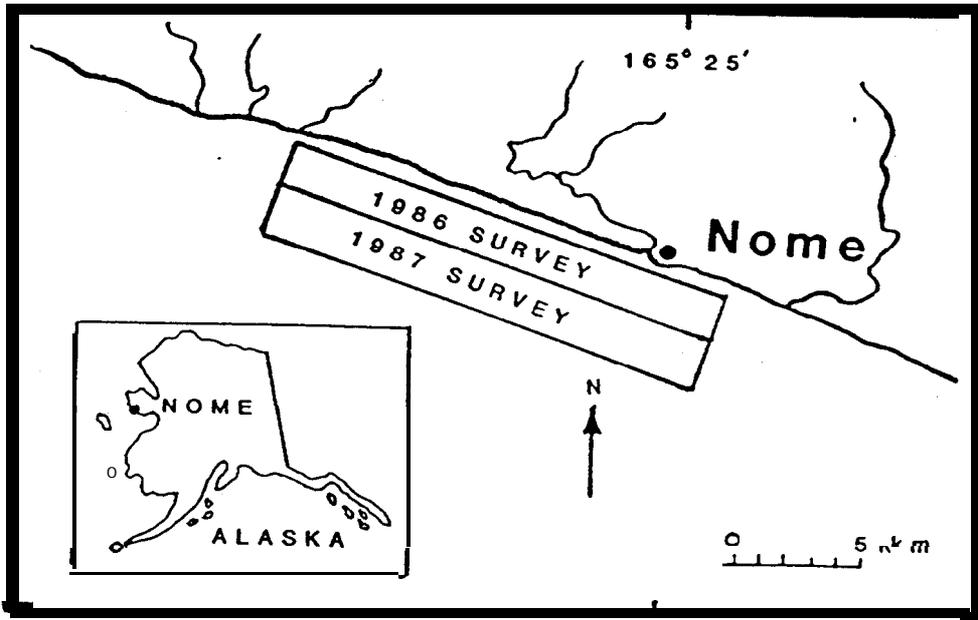
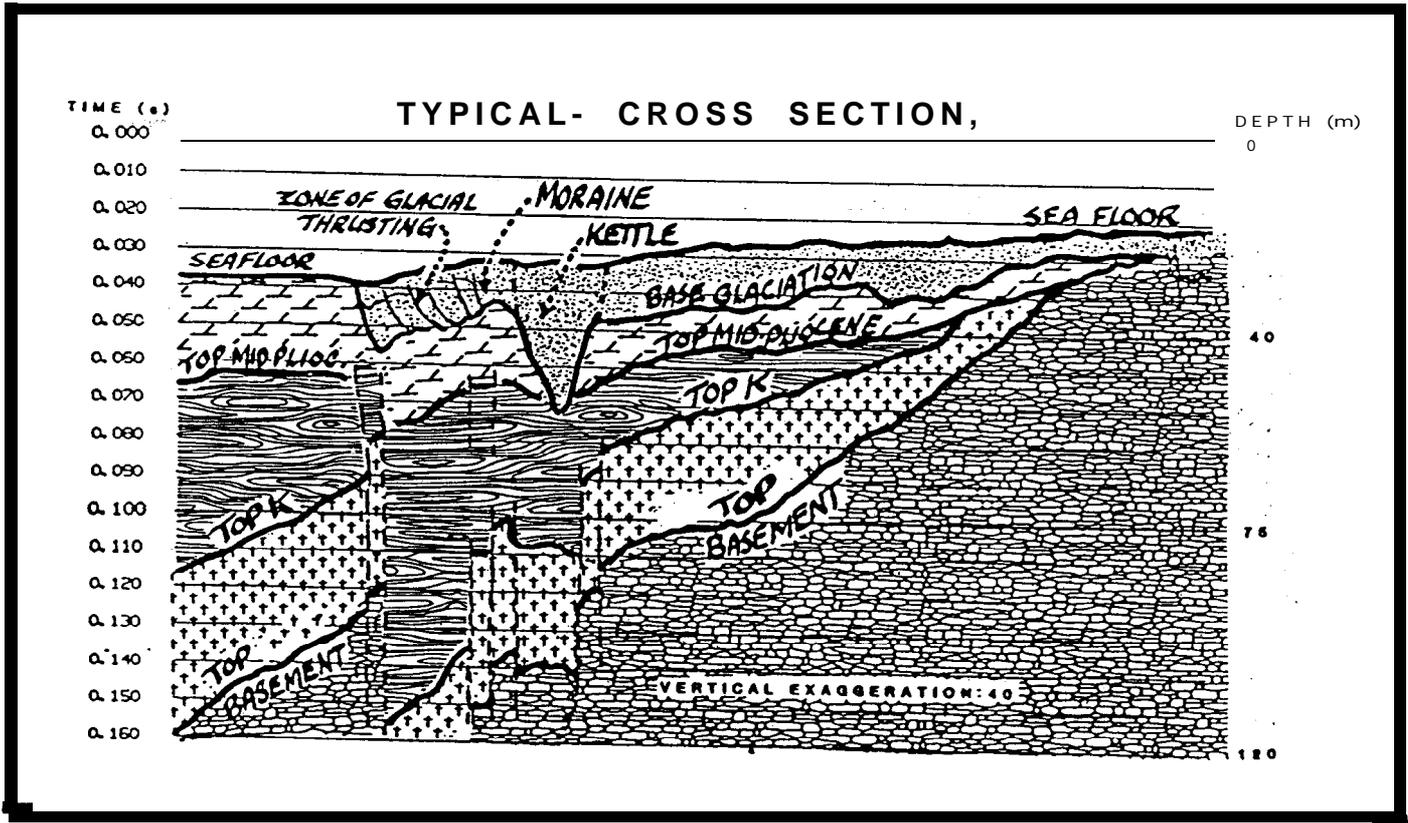


Fig. 1- Seismic survey map



Fig_2 - Typical cross section based on interpretation of line 3181

Geologic Setting

Nome, Alaska is located on the southern coast of the Seward Peninsula, in western Alaska (Fig. 1). The area within a 10 kilometer radius of Nome has produced approximately 5 million ounces of gold from fluvial, beach, and glaciomarine placer deposits. The gold bearing placers, both onshore and offshore, are derived from the weathering and subsequent glacial transport of the gold bearing Paleozoic crystalline rocks from the mountains which surround Nome.

The coastal plain at Nome and the adjacent offshore areas are underlain by Pleistocene and Pliocene age glacial and marine sediments. These deposits are overlain by Wisconsin and Holocene age alluvium, silt, and peat, Tagg and Greene (1973). Offshore; glacial drift of early Pleistocene age Iron Creek glaciation and Illinoian age Nome River glaciation has been reworked by fluvial and coastal intervals, with intervening periods of lowered sea level. These periods were characterized by the expansion seaward of glacial ice and the erosion of underlying glacial drift by fluvial processes, Kaufman (1986); Hopkins, et al. (1960).

A generalized cross section (Fig. 2), illustrates a typical structural and stratigraphic sequence encountered offshore Nome. Early Paleozoic age crystalline basement rocks, faulted during the development of the Norton Basin in late Cretaceous time, are overlain by Cretaceous and Tertiary marine sediments. The Norton Basin continued developing until the late Pleistocene, as evidenced on the seismic data, by the displacement of glacial sediments.

Glacial sediments deposited during the Nome River Glaciation, overlie basement in the nearshore area. Continuing seaward, crystalline basement is replaced by onlapping Cretaceous and Tertiary marine sediments. At the terminus of the glacial drift, shearing and thrusting of the Pliocene marine sediments, caused by the advancing glacial ice, is evident on the seismic data.

Sea level transgression, regression, and subsequent fluvial erosion, have created an extremely complex sedimentary environment offshore, Nome. Multiple facies changes within glacial sediments may occur within a few

meters, this complexity is exacerbated with the infill of local bathymetric low areas by fine sands and silts. This complicates the interpretation of the relevant paleogeomorphologic features when using a shallow investigative geophysical tool, such as side scan sonar.

To classify the stratigraphic relationships with an accuracy suitable to choose exploration drilling targets, requires a seismic technique which will deliver the resolution to define the complex glacial stratigraphy and the power to consistently transmit energy to basement.

Review of Previous Work

Before WestGold's acquisition of the leasehold, the area was evaluated during the 1960's by other industrial entities and government agencies. The previous work, although reconnaissance, provided the general geologic **framework for future work.**

Work completed by private industry concentrated on winter drilling evaluations in 1964 and 1969, using a skid mounted Becker AP- 1000 **hammer drill.** Both programs utilized the annual sea ice as a drill platform. A total of nearly 900 holes were completed during the two programs. The holes in each program were drilled along arbitrary grid lines in order to systematically sample the entire leasehold accessible from the coastline seaward 2500 meters, and along the entire width of the leasehold. Geophysical surveys were not completed in conjunction with these programs, Daily (1964).

The first high resolution geophysical acquisition in the Nome area, in which the results were published in the public domain, was completed by the U. s. Geological Survey in 1967. This survey used a 450 J analog **sparker** system with a wet paper recorder. 800 km of data were acquired with a line spacing of approximately 1.6 km, Tagg and Greene (1973). Due to the complex nature of the glacial sedimentary environment, the survey density was only adequate to produce a general interpretation of the regional geology.

During the summers of 1967 and 1968, the USGS, in cooperation with the U.S.B.M., undertook a seafloor sampling program in the same area. 51 holes were drilled using both a Becker drill and a sonic drill. 700 surficial grab samples were also collected, Nelson and Hopkins (1972).

These studies indicated the presence of placer gold concentrated in reworked glacial drift and drowned fluvial environments. The sampling density was insufficient to determine whether the gold placer concentrations were continuous enough, and of sufficient grade to mine the resource profitably.

Seismic Studies by WestGold Prior to 1987

In 1986 a total of some 1400 km of a high resolution seismic data were acquired using standard analog technology. This included a bubble pulser, dry paper analog recorder, crystal time delay unit, and a suite of analog filters. The bubble pulser was fired at a uniform 0.5s intervals, with distances referenced by time. The seismic lines were recorded generally parallel to the shore and regional strike of the geologic structure, making interpretation difficult in areas of high dip rates and complex stratigraphy. The problem was enhanced by the inability of the source to transmit energy through the indurated glacial drift. A further embarrassment was the limited range and unsophisticated nature of the available analog processing.

In an attempt to rescue the potentially valuable reflection data from the analog abyss, the tapes were digitized and subjected to modern signal processing techniques. The digital improvement proved surprisingly beneficial in subsequent drilling and mining operations.

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The experience with the 1986 analog-digital survey led to the decision to design a digital acquisition and signal processing system for the proposed 1987 survey. The recording program would incorporate high frequency, broad bandwidth sources with modern digital recording instruments. Navigation would be controlled using distance rather than time, and all data would be recorded with a real time break, generated by a fire control unit, initialized by the navigation system.

ACQUISITION SYSTEM DESIGN

Specification and Constraints

The success of an exploration program depends critically on the careful planning and execution of the recording system. This means that one must weigh the exploration requirements of resolution, coherency, and coverage, against the practicalities of cost, equipment availability, operating conditions, and technical limitations.

Vertical resolution may be viewed as the spatial separation of individually resolvable (distinguishable) events. In the 1987 Nome survey, the resolution requirements of 1 to 2 m, may be translated temporally as,

$$AT \leq 2.5 \text{ ms,}$$

where AT represents the time separation of resolvable reflections, and at the same time, the effective pulse width of the wavelet, as well. This latter interpretation allows us to define resolution in terms of spectral band width, ΔF .

$$\Delta F \geq \frac{1}{\text{delta T}} \approx 400 \text{ hz .}$$

It should be emphasized that this is bandwidth, not the highest required frequency (F_{max}). A bell-shaped spectrum, with half-amplitude points defining the effective width, could satisfy the resolution requirements with a band extending from 200 hz to 600 hz, 600 hz to 1000 hz, etc. In general, $F_{\text{max}} > \Delta F$. The F_{max} value is important in that it determines the required temporal and spatial sampling intervals (T_s and ΔG respectively).

$$T_s \leq \frac{1}{4 F_{\max}}$$

$$\Delta G \leq \frac{V}{2 F_{\max} \cdot G(\theta)}$$

where, V = average (or rms) velocity at the target depth,

θ = maximum anticipated structural dip,

G = a function of θ_{\max} , which is often set at $\sin \theta$ for quick approximation.

Alias filters and processing considerations have been contemplated in defining T_s and ΔG .

For the 1987 Nome survey, the following sampling intervals were determined.

$$T_s = .25 \text{ ms}$$

$$\Delta G = 5 \text{ m}$$

While .25 ms sampling protects the frequency spectrum well beyond the expected usable range (the alias filter cut-off is nominally set at 1440 Hz), the receiver station (hydrophone "group") interval, ΔG , is somewhat larger than desirable. In this regard a compromise was made in deference to equipment and recording time limitations, as well as technical factors such as required offsets (X_{\max} , below).

Recording Equipment

□ SOURCE. For the purposes of the survey, resolution and penetration to a basement with anticipated depths of some 200 m, it was decided that the relatively weak "bubble Pulser and "boomer". sources used in earlier (1986) surveys would be supplanted with a more powerful, yet broadband watergun. An SSI 15 cubic inch watergun was selected. Figure 3 shows the gun as 'configured during the survey : suspended from a modified, buoy, so as to maintain a constant depth below sea level of about 15 inches. The ghost-free signature and its spectrum are shown in Fig. 4. Note that in spite of a rather complicated signature waveform, the frequency spectrum is, quite broad, initially, at least,. satisfying the bandwidth requirements. This situation, however, will deteriorate quite rapidly 'as certain practical aspects of the real recording are included in the total wavelet picture. Among them : source and receiver ghosting multiples, array effects and instrumental filtering.

A further degradation results when the gun has been used in continuous operation for extended periods. Accordingly, a second watergun of identical design was on hand as an immediate replacement for the original when the inevitable mechanical deterioration occurred. This proved to be an effective scheme for maintaining a properly functioning source, with a consistent source signature, at all times.

□ CABLES/RECEIVERS. An a-channel Geco "arrayflex' cable was used, with 6 data channels ($\Delta G = 5$ m) and 2 auxillary channels for time break and signature monitoring.

Each hydrophone group (channel) comprised an 8-element linear array with phone spacing of .625 m. This array, with an effective length of 5 m, proved adequate in noise suppression, but at the cost of some signal sacrifice on the early reflection arrivals at far offsets. To retain full fold at all times, from the ocean bottom reflection to basement, shorter arrays (and a smaller ΔG) should be used. While the problem was anticipated, the existing cable configuration was left intact in view of firing rate limitations, channel capacity, and other technical considerations.

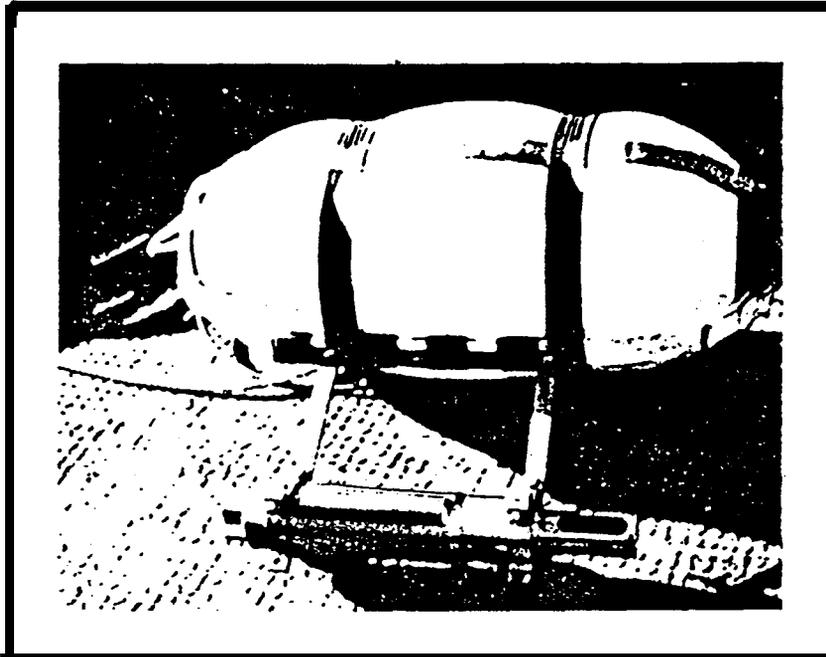


Fig. 3 - Watergun seismic source (15 in.³) Mounted below buoy at 15 in_

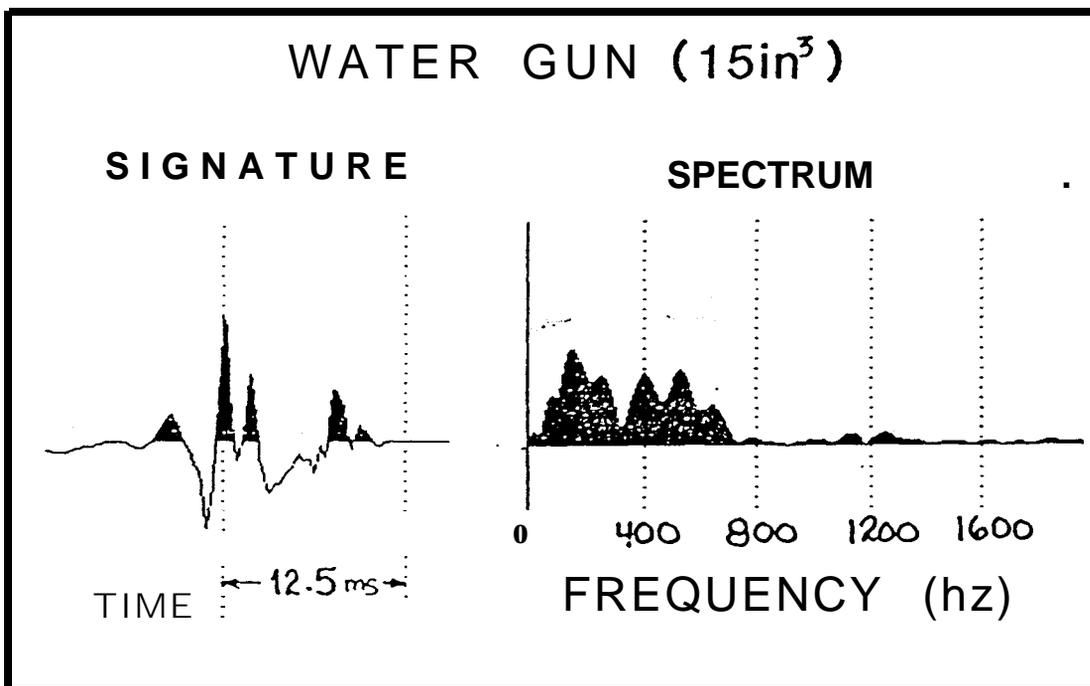


Fig 4 - Watergun signature and spectrum. Phase the culprit.

* **DIGITAL RECORDING EQUIPMENT.** To facilitate 8 channel, 300 ms digital recording at .25 ms sampling, an EG&G ES-2420 seismograph was selected. Coupled with the available tape drives, the system was able to accommodate the navigation- triggered 2.5 m (1.3 s) firing interval, and record the seismic data in a SEG-D, demultiplexed format.

* **NAVIGATION.** A Maxiran I radio navigation system was already in place for accurate positioning of the on going drilling and mining operations. It was augmented with additional beacons to insure accuracy as the seismic lines moved along the coastline. The data reduction and registration of the navigation data with bathymetric and tide data proved to be one of the weaker aspects of the acquisition package. When the navigation results (separately contracted) were finally received at the processing center, a puzzling discrepancy led to the discovery that the coordinates were shifted by some 100 m from their proper location. Fortunately, the error was generally consistent' and easily corrected and verified using the high resolution seismic data.

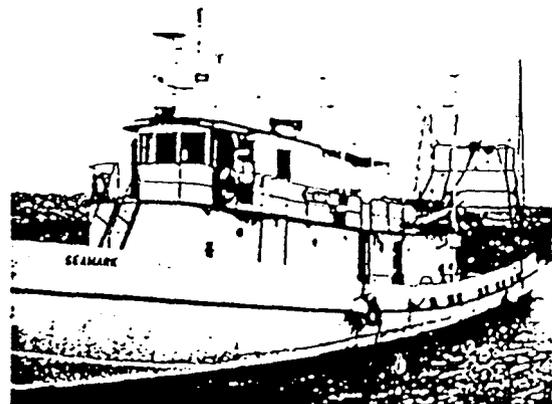
□ **ADDITIONAL GEOPHYSICAL EQUIPMENT.**

- Side scan sonar
- Marine magnetometer
- Digital High Resolution Bathymetry (linked to the navigation data)

□ **THE VESSEL.** The system was housed on the R/V SEAMARK Fig.5 a ship which had been used in the waters around Alaska for high resolution surveys in the past. A further advantage of this vessel was the presence of a compressor to be used in the water gun operation.

fig. 5 – Seismic vessel: R/V SEAMARK

used in the 1987 survey offshore Nome



Recording Geometry Parameters

The various parameters to be used (by specification) or determined, are defined below.

- ◇ N.....the number of data channels (6)
- ◇ F.....the common depth.point (COP) fold number (multiplicity factor) which gives the number of traces in each gather to be stacked after proper geometric correction
- ◇ xs..... distance (inline) from ship stem to the source
- ◇ Xn..... ..distance from source to the n-th receiver group (offset).
Xmin = X1; Xmax = X6
- ◇ ΔG. group (receiver) interval : $\Delta G = (X_n) - (X_{n-1}) = 5 \text{ m}$
- ◇ n, Ah..... array parameters; n is the number of hydrophones per group (8) with a separation of Ah (.625 m)
- ◇ ΔS..... source interval
- ◇ zs..... source depth (15 in.)
- ◇ Zc..... cable depth (at X1)
- ◇ ~Zc.....cable depth variation from group 1 to group 6. (“droop”)
- ◇ deltaL..... “dip” line spacing

Naturally, not all of these parameters can be independently chosen. We begin with the fixed or specified parameters, and adjust the others in order of significance. Compromises are always made.

The fold, F, has a direct bearing on signal-to-noise ratio, multiple suppression, velocity analysis, and amplitude variation with offset analysis (AVO),

$$F = \frac{N}{2} \frac{\Delta G}{\Delta S}$$

The quantity, F, may be maximized for a fixed N by setting ΔS to a minimum value relative to ΔG . For marine recording this minimum is

$\Delta S = 1/2 \Delta G$. Therefore, with $\Delta G = 5 \text{ m}$,

$$\Delta S = 2.5 \text{ m},$$

and,

$$F = \frac{6}{2} \bullet \frac{5}{2.5} = 6.$$

The subsurface spacing (stacked trace interval) is, as always, $1/2 \Delta G$, in this case' a very reasonable 2.5 m.

The cable configuration fixes the distance from near (1) to far (6) group at $25 \text{ m} = (N-1) \Delta G$. The choice of X_s and X_{\min} (X_i) depends on actual operating conditions. Accordingly, a brief period of experimentation was scheduled at the beginning of the program. The experimental period was also to be used to measure source signatures, to test recording and navigation systems, and to evaluate the proposed cable depth variation effects.

The test data led to the following determinations.

- $X_s = 35 \text{ m}$ This moved the recording system safely out of the range of boat noise, etc.
- $X_{\min} = 15 \text{ m}$ while we would prefer $X_{\min} = 0$ (the theoretical goal of processing), the direct arrivals from the source at distances of 5 m or 10 m proved overpowering on the near receivers.

With X_1 set at 15 m, this put X_6 (X_{\max}) at an offset of 40 m.

Consideration of such factors as the accuracy of velocity analyses, angle of incidence variation (AVO studies), interference from direct arrivals and sea floor refractions, plus anticipated processing problems (stretching of waveforms during normal moveout (NMO) corrections, amplitude adjustments varying with time and offset) led to the conclusion that this spatial configuration was a very good and practical compromise with the survey specifications.

The near group was suspended at a depth of about 2 m with group 6 held at a depth of approximately 3 m ($\Delta Z_c = 1 \text{ m}$). This arrangement gave the receivers reasonable protection from the ever present sea state (wave) noise, while accommodating a variation in depth to spread the potentially lethal frequency notches of the receiver ghosts over a range of frequencies (roughly 250 to 375 hz and their multiples: 500, 750, 1000, ...). In combination with stacking-deconvolution procedures, see Fig. 6, this technique proved to be a very effective way to suppress ghosting and the resultant signal degradation. The recording configuration is depicted in Fig. 7.

The line spacing, ΔL , was set at 25 m. Even for dip lines this is clearly suboptimum in the spatial sampling sense, but was necessitated by the extensive coverage requirements, limited recording time window, and anticipated weather shut-down time. Future surveys are planned so as to sample adequately for true 3-D coverage.

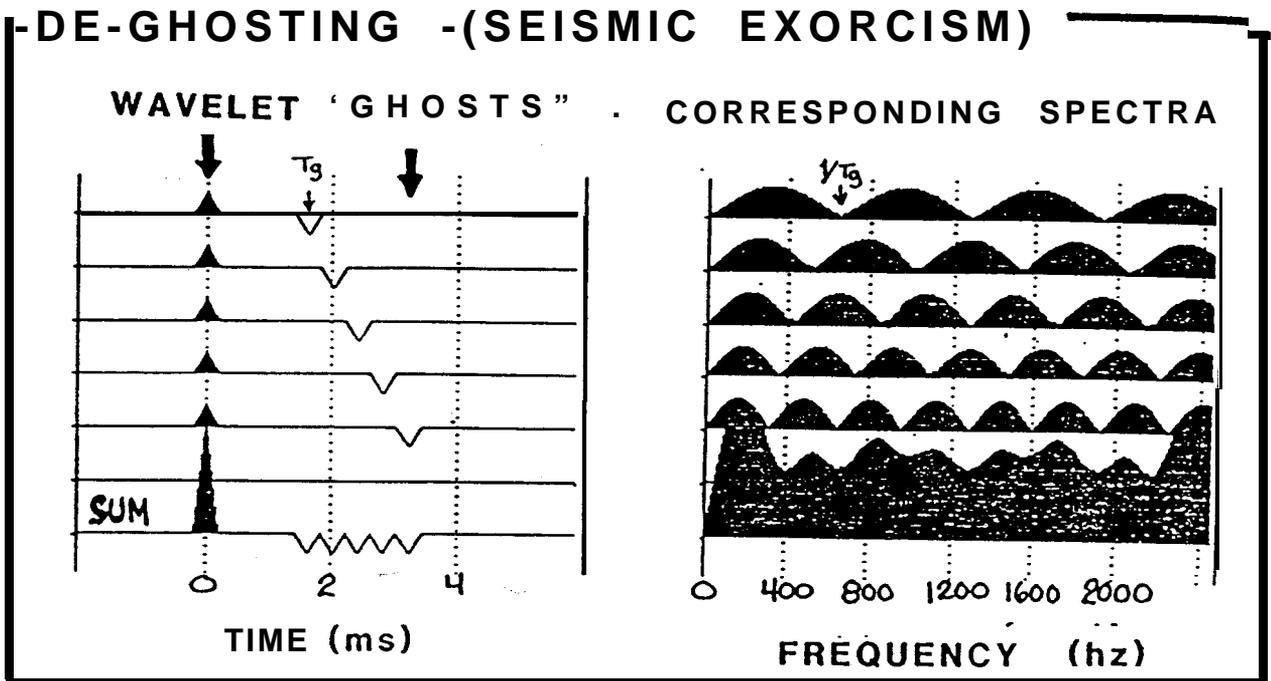


Fig. 6 - Summing the wevelets with varying ghost times, T_g , spreads the notches and facilitates deconvolution

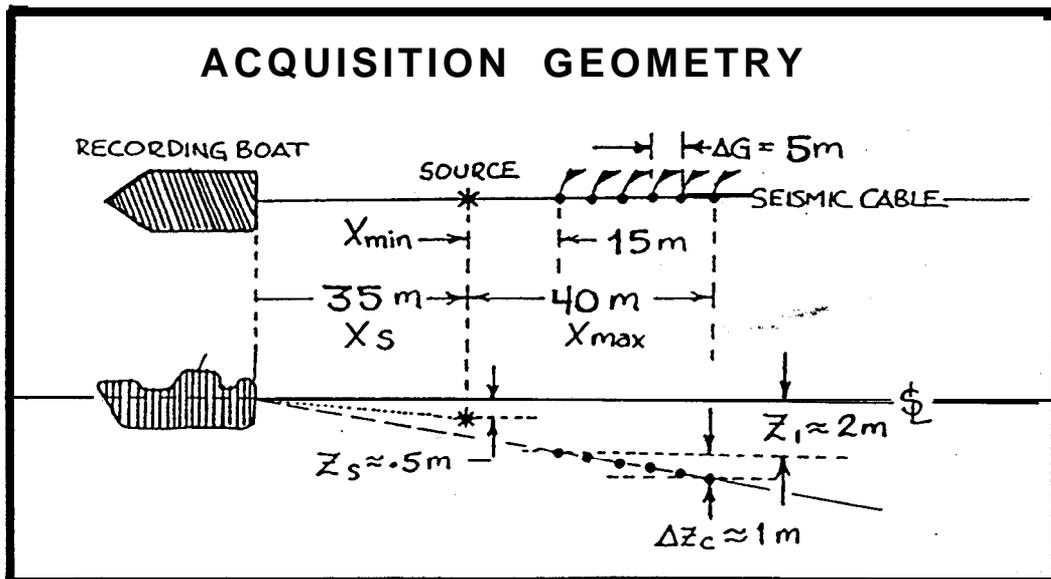


Fig. 7 - Typical recording configuration, 1987 survey

Operations

After a two day experimental and equipment shake down period, production recording was done for 30 days in weather varying from calm (1-2 ft. waves) to frightening (8 ft. waves). This effort resulted in some 520 lines covering about 2000 Km of the exploration area. More importantly, the processed data was ultimately of very high quality, and served well the exploration purpose of delineating mining operation sites.

HIGH RESOLUTION PROCESSING

General Considerations : Resolution and Coherency

High resolution is often regarded as largely a matter of achieving and maintaining a broad, flat spectrum of wavelet frequencies. While resolution does depend on bandwidth, there are other, perhaps more important considerations, namely, phase and coherency.

It is essential that the basic reflection waveform be processed to zero phase (symmetric in the time sense). The advantages of zero phase wavelet processing are these: (1) larger peak amplitude (compared to any other wavelet with the same spectrum), yielding maximum instantaneous signal-to-noise ratio (SNR); (2) lower amplitude side lobes - less ambiguity and better event separation; (3) timing accuracy - peak occurs at reflection time; and (4) better ties with intersecting lines and synthetics.

Coherency measures the lateral correlation or cohesiveness of the data. Without it, high resolution is a meaningless phrase - sharp events with nowhere to go. Coherency is primarily a matter of wavelet equalization. Each trace has in it a total wavelet which is a unique combination of that trace's source and receiver wavelet. The source includes not only the signature itself, but ghosting, source reverberations (multiples), and instrumentation, as well. The receiver wavelet comprises the hydrophone; ghosting, and reverberations.

HIGH RESOLUTION PROCESSING FLOW

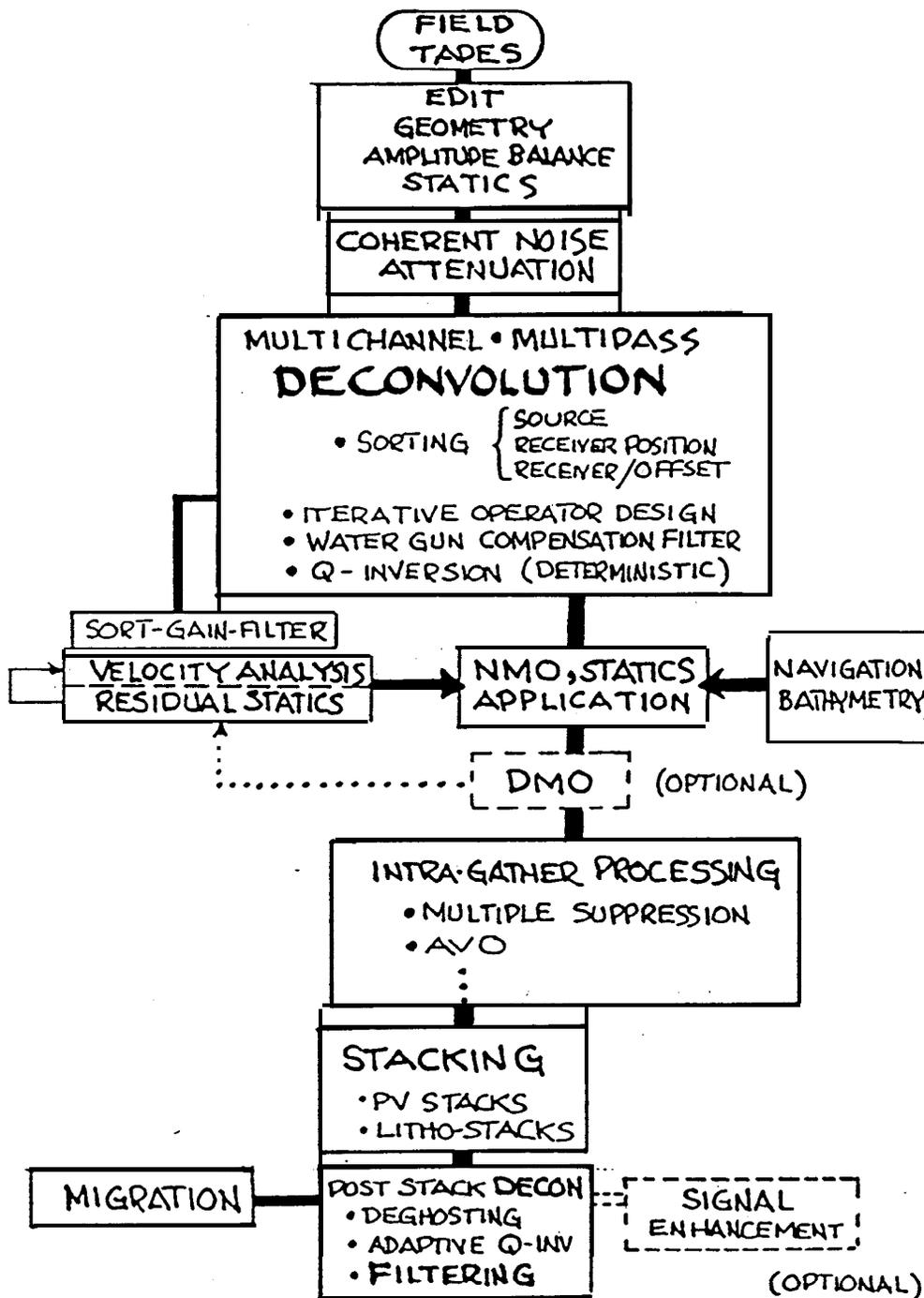


Fig. 8 - Typical processing flow during 1987 seismic survey

wavelet processing for coherency and resolution is achieved through the equalization of the potentially wide variety of wavelets populating the traces. This is best accomplished with a multipass, multichannel procedure as would be a natural mode of operation for surface consistent processing. In this procedure, the wavelet is iteratively deconvolved with a series of operators designed from gathers of selected commonalities (source, receiver/offset, receiver position).

Figure 8 shows the generalized flow of the seismic data with wavelet processing occupying a prominent position, early in the sequence. It should be noted that, in fact, wavelet processing continues throughout the flow, not only in the indicated position, but as part of the coherent noise reduction, stacking, dip moveout (DMO), migration, and post stack deconvolution, as well.

This principle is well illustrated by the case of deghosting. While preliminary deconvolution attacks the ghost-caused spectral notches, the subsequent stacking procedure produces a composite wavelet with multiple notches of greatly reduced depth. Post stack deconvolution then proves effective in "spiking" the resulting wavelet.

The idealized build up, and ultimate resolution; of the composite wavelet is shown in Figure 9. In the diagram we follow the growth of two wavelets; A and B. whose unique combination of source and receiver position causes them to differ in their final recorded form.

The wavelets processing protocol practiced in the gold survey has been simulated here by a series of multichannel (unshown data) and multipass operator designs and applications. The result is the same for both wavelets: spikes. One might wonder why the wavelet processing should not end here; a spike, after all, has infinite resolution. The problem, of course, is that the very procedure that spikes (and equalizes) the wavelet, also amplifies the noise frequencies that occupy the low signal amplitude portions of the spectrum (notches, etc). In order to suppress the noise, a zero phase filter of coherent (signal) frequencies is applied to the data. The key feature of the overall deconvolution, which ultimately leads to symmetric wavelet equalization, is tenacious adherence to spiking modes throughout the early processing.

DECONVOLUTION

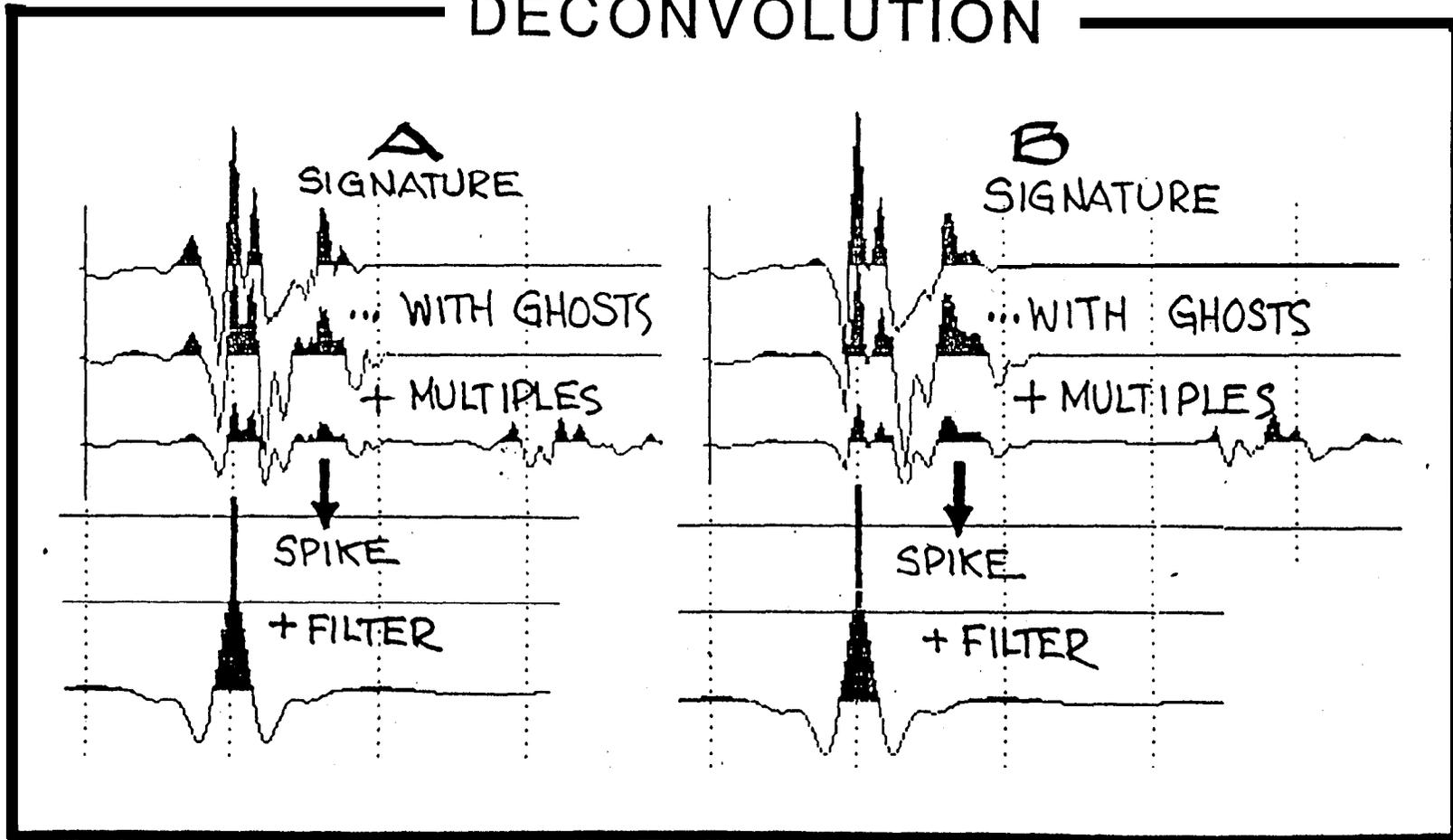


Fig. 9- Deconvolution equalizes wavelets (A,B) by first spiking and then applying a zero phase filter

In Fig. 10 one of the longer (8.4 km) dip lines, 3 181, is shown in both its raw (a) and processed (b) forms. 'Raw', here, refers to a plot of single channels (normally the near trace) data with no significant processing except datum shifts, nmo correction, and gain.

A truncated version of the same data is seen in Fig. 11, which is a photograph of a Landmark workstation screen display (original in color). Individual copies of the processed and raw data are seen in Figures 12 and 13, respectively.

Figures 14 and 15 depict a blow-up of the cross sectional region from source points 220 to 580. The figures differ only in display mode on the graphics terminal. At the right near SP 560 the edge of a kettle structure is apparent. Seaward of the kettle feature is a zone of glacial thrusting extending from, roughly SP 300 to 480. This zone is detailed in the insets.

Source points 1 120 - 1480, Line 3 181, are shown in the screen capture depicted in Fig. 16. The elimination of multiples in the processing reveals the details of the onlapping sediments over the basement and various unconformities.

The interpretation of Line 3181, Figures 10- 16, is the basis for the model given in Fig. 2. Note particularly the definition of the kettle features, faults, terminal moraines, unconformities, and subbottom detail. The interference caused by signature phase, ghosting, and multiples has largely vanished, giving definition to those significant subsurface characteristics related to placer deposition of gold.

interpretive Processing

The processed data were loaded on a Landmark workstation for section picking and mapping of important features. The interactive graphics workstation environment is ideally suited for the rapid, integrated interpretation of such a large volume of detailed data.

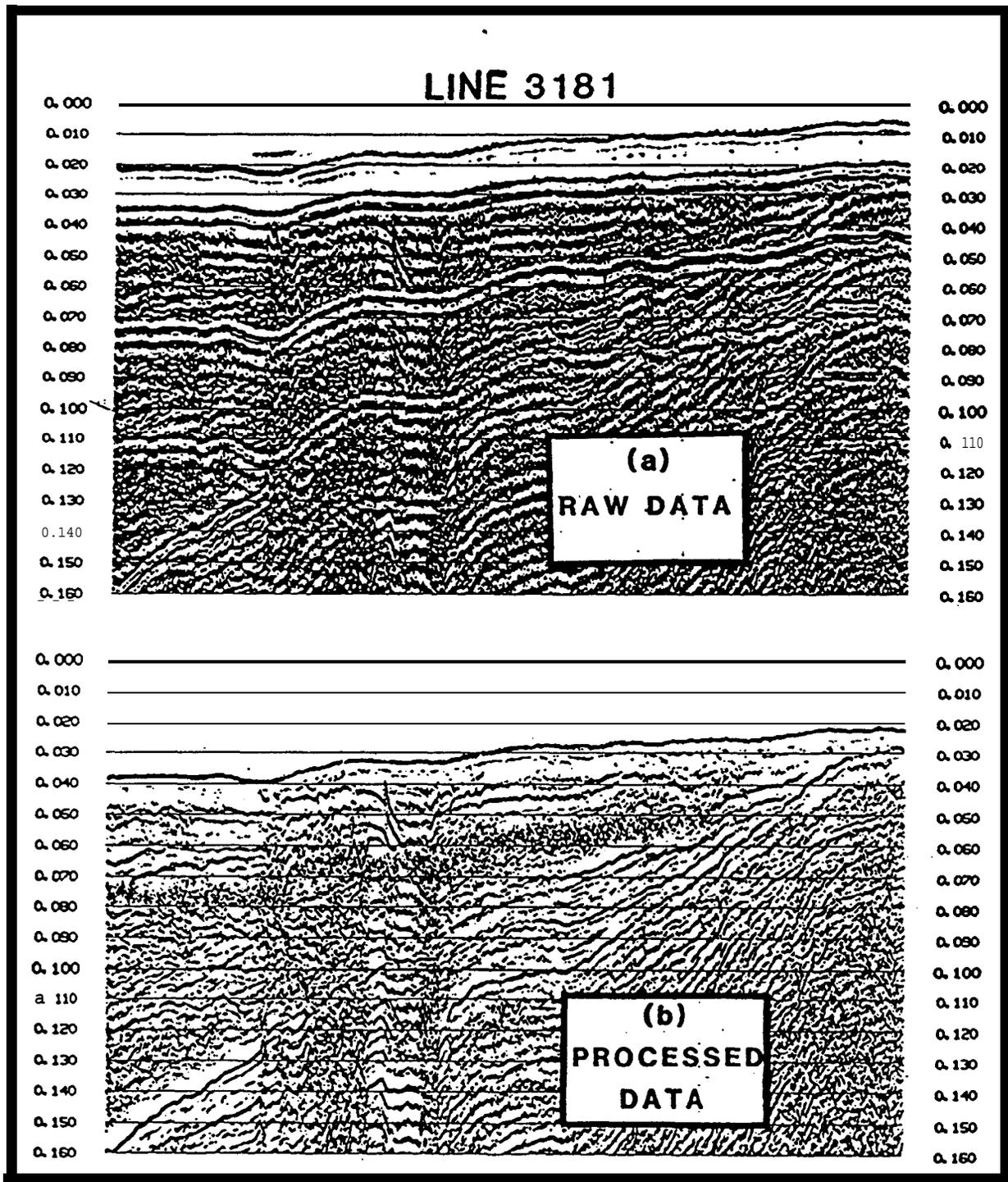
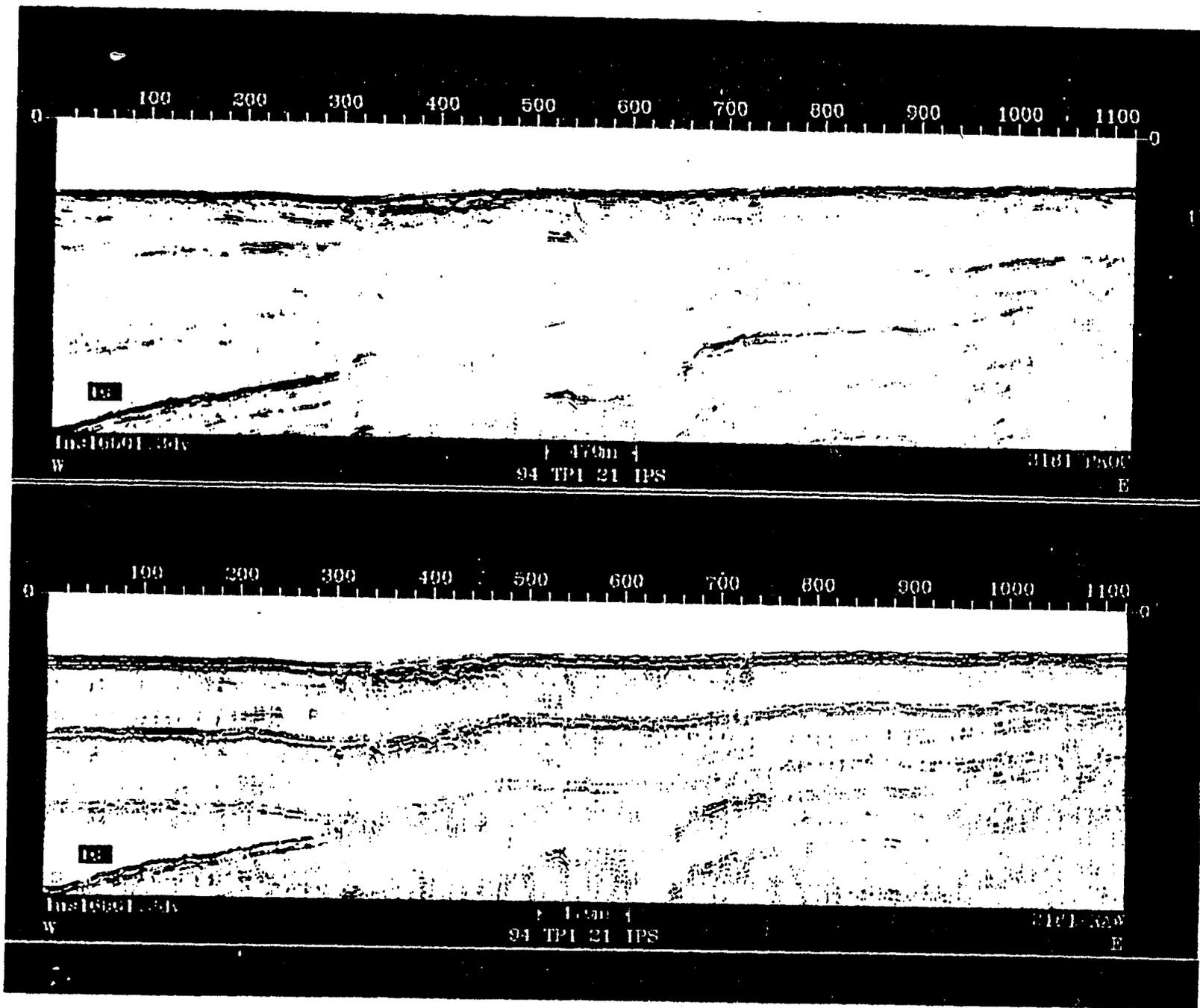


Fig- 10-Comparison of raw (a) and processed (b) data line 3181



(a)
PROCESSED
DATA

(b)
RAW DATA

Fig. 11 - Line 3181. Photograph of Landmerk Color Graphics screen.

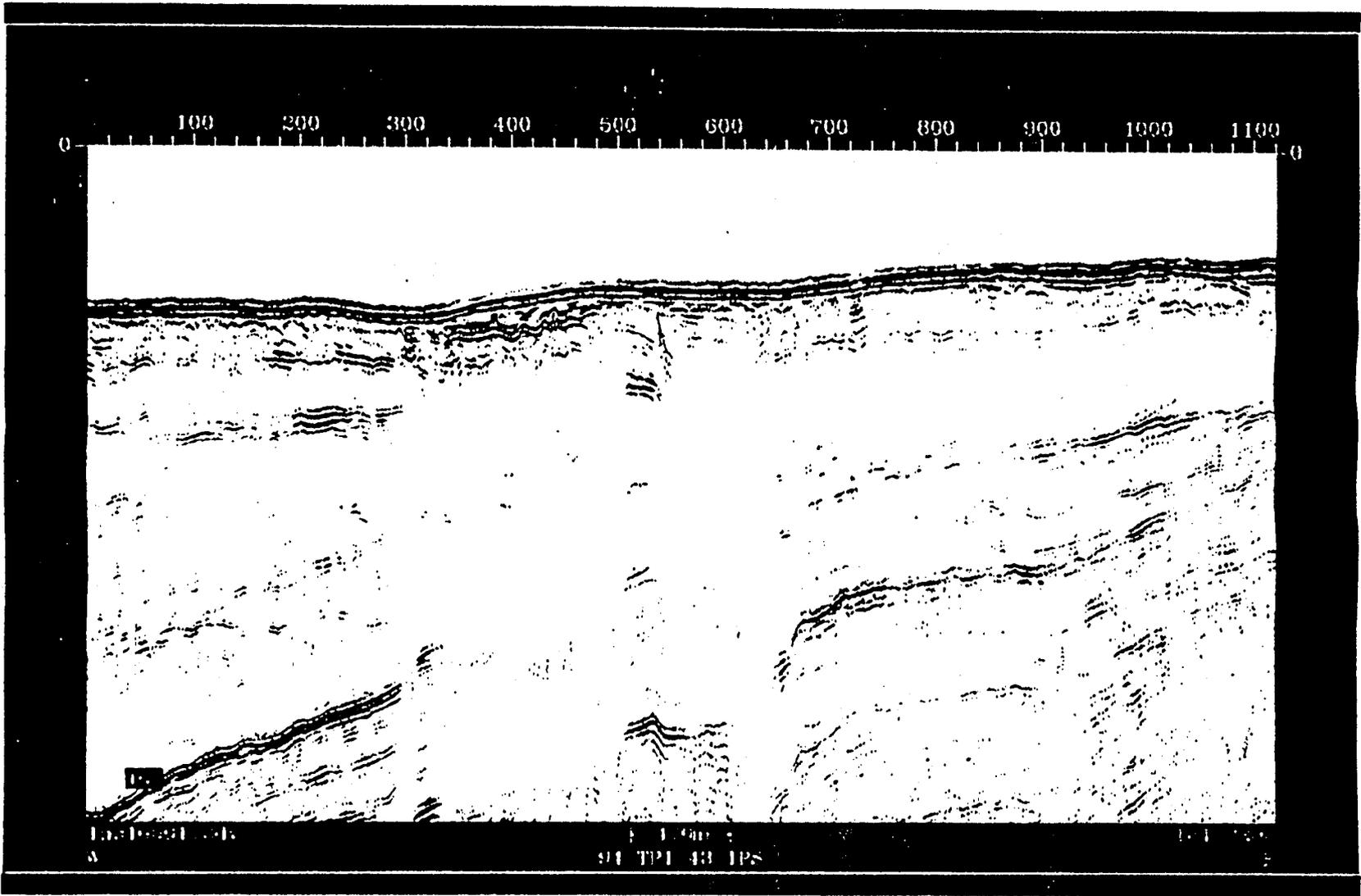


Fig. 12 - Line 3181. Processed data.

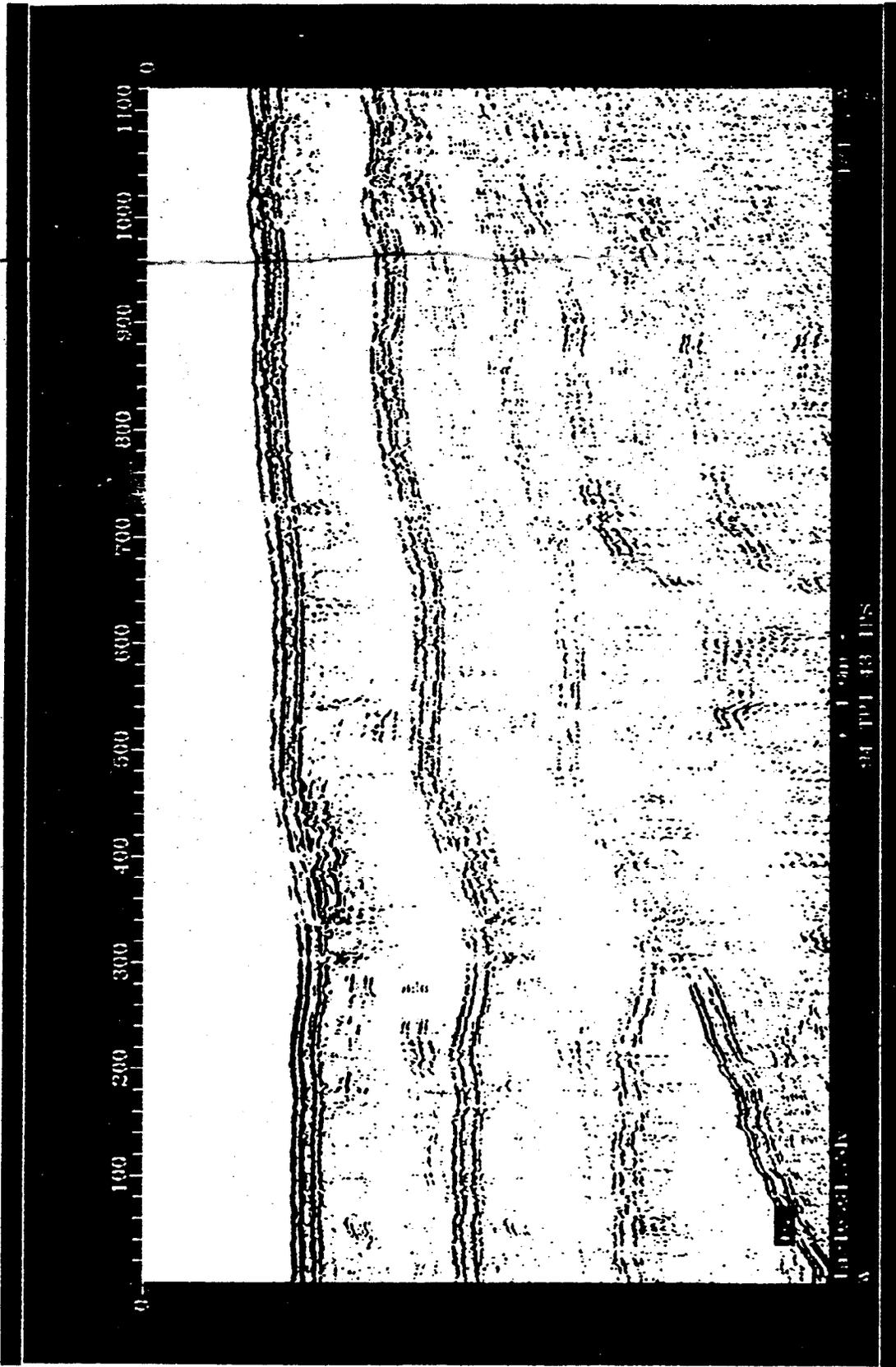


Fig. 13 - Line 3181. Raw data.

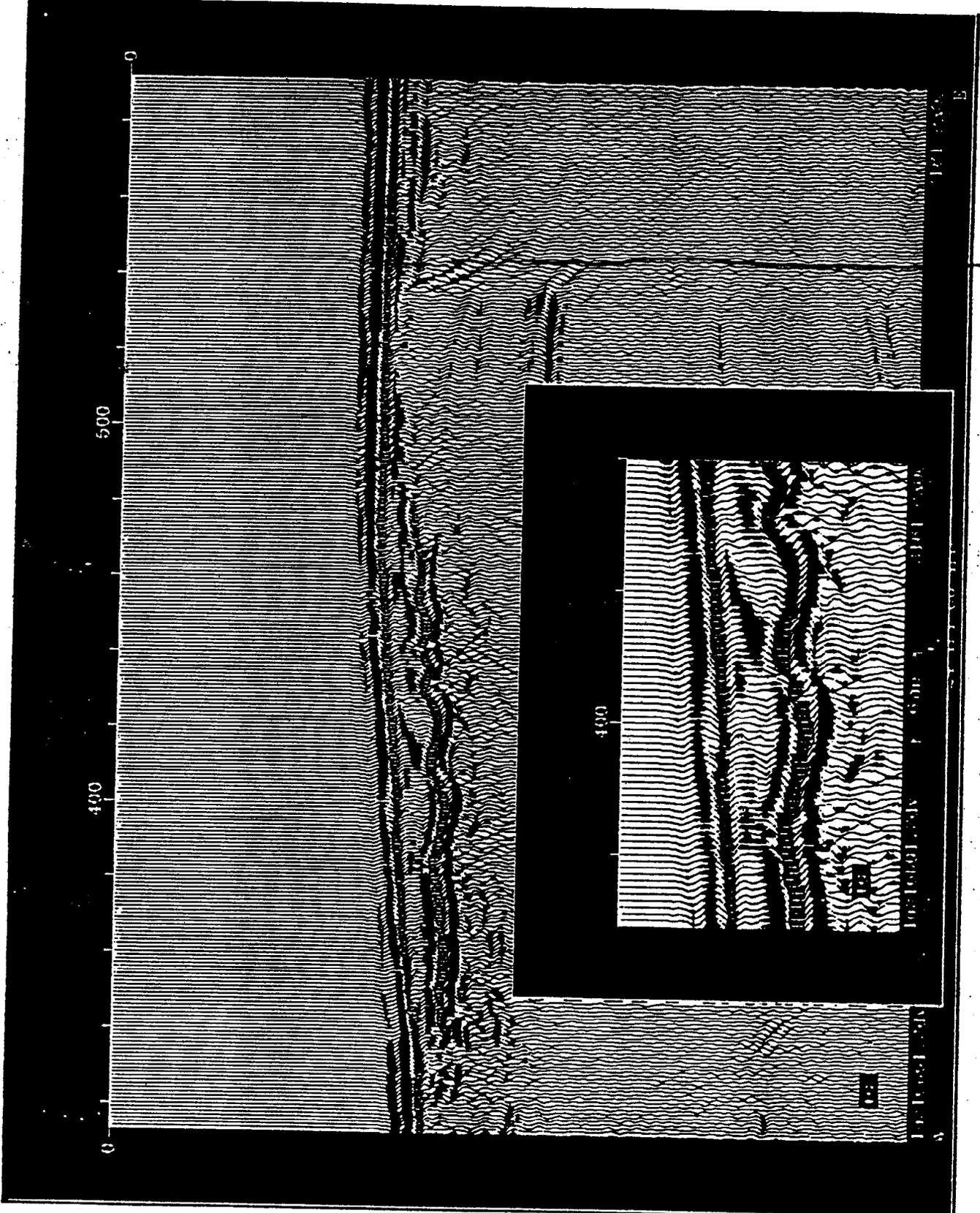


Fig. 14 - Line 3181, SP 220-580, with inset centered at SP 400.
Screen display is variable color overlay on wiggle trace (wt).

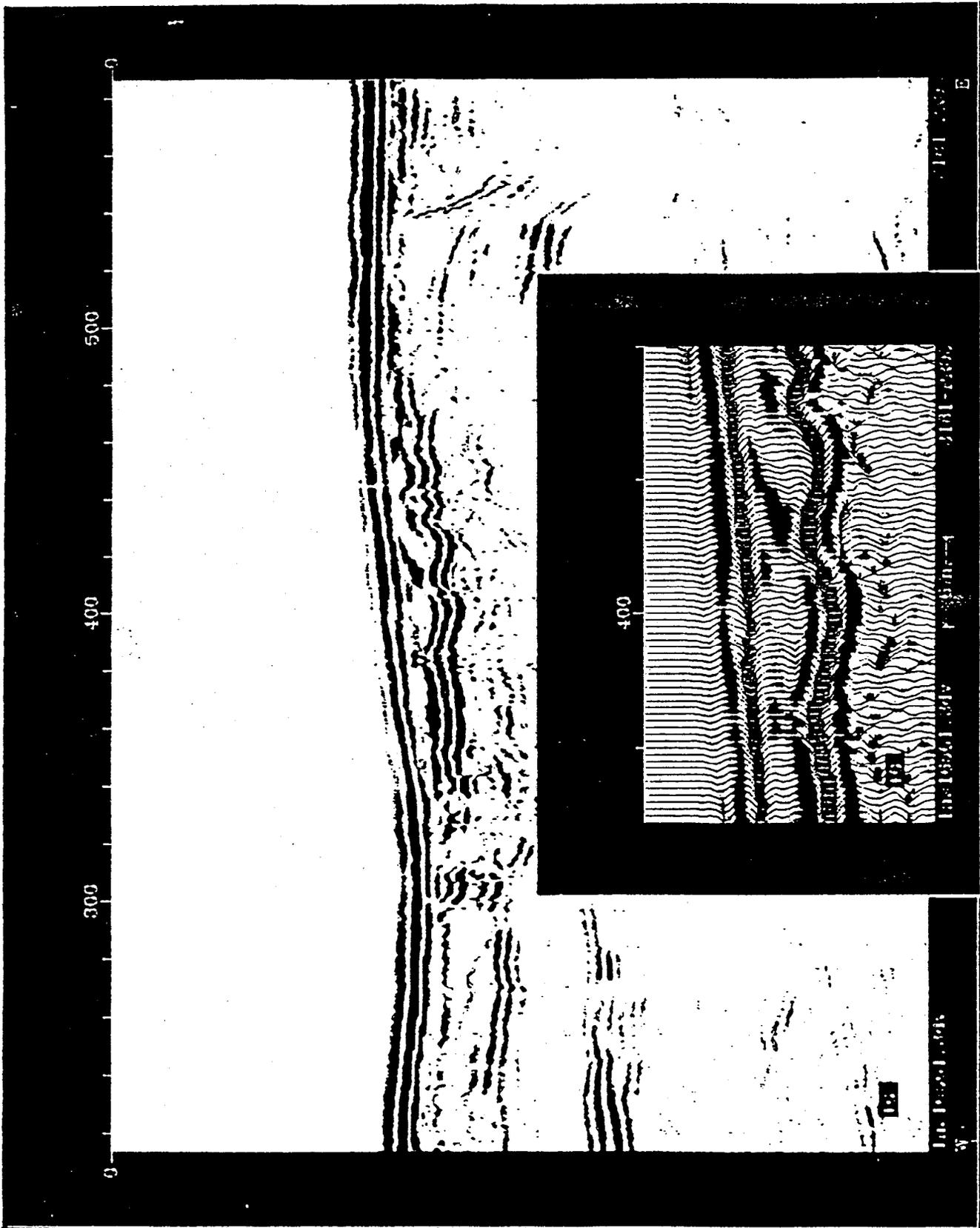


Fig. 15 - Line 3181, SP 220-580 with inset centered at SP 400.
 Screen display is variable density color with YDC/wt inset.

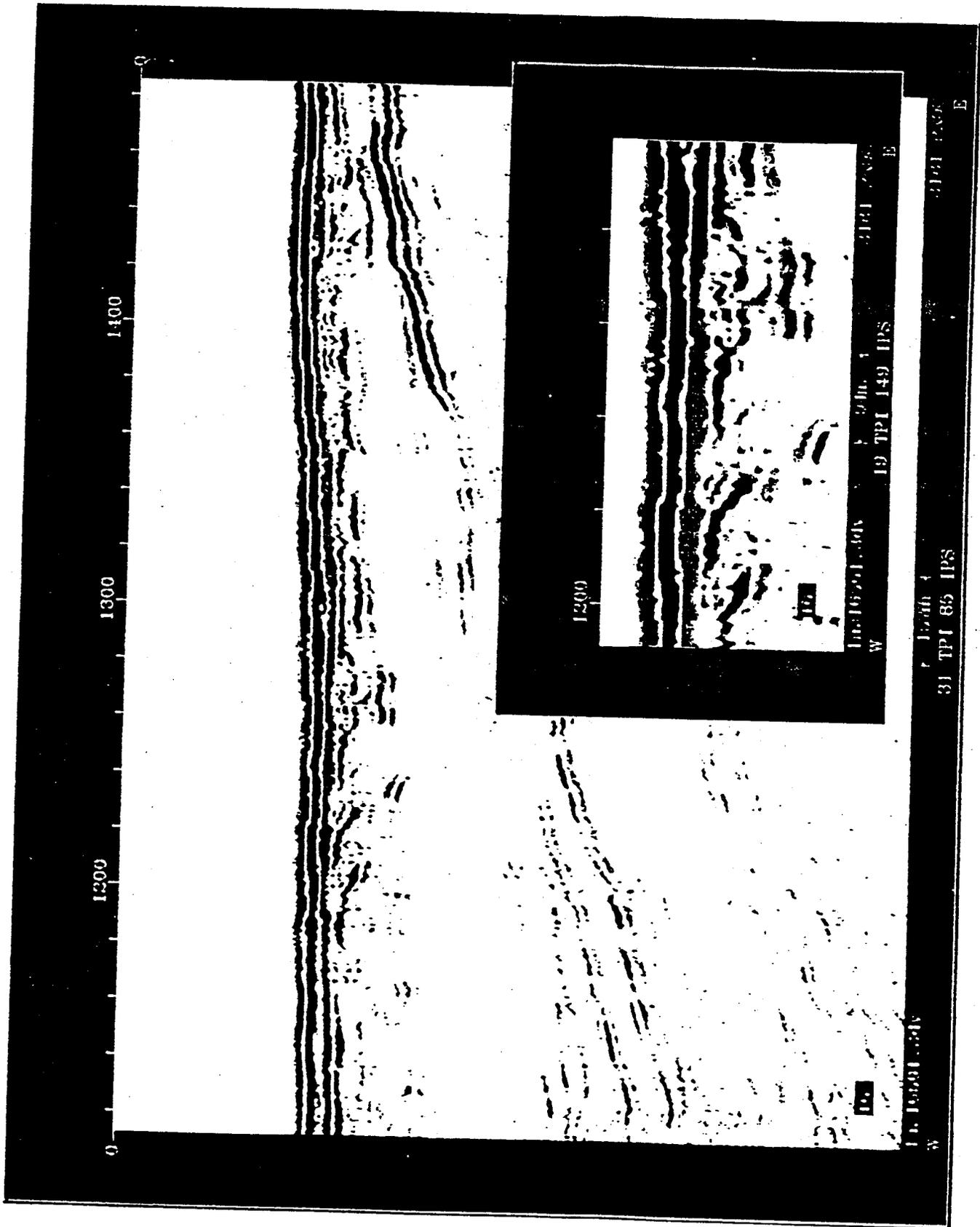


Fig. 16 - Line 3181, SP 1120-1480, screen capture of variable density color.

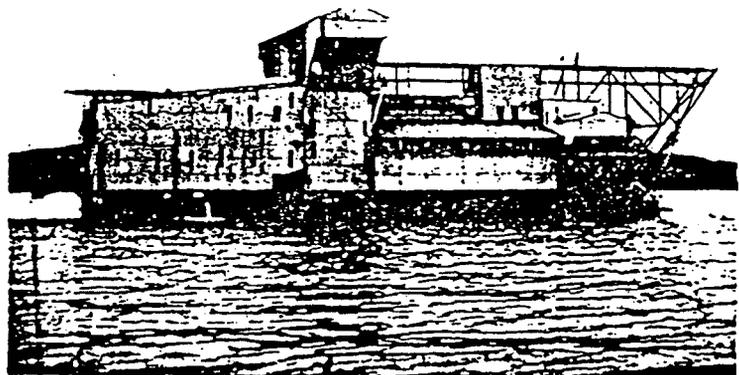
RESULTS

Integration of geological information with the 2000 km of high resolution, seismic data of the 1987 program, resulted in three successful drilling programs (1950 drill holes), providing confirmation of large ore reserves in the surveyed offshore area, Bronston (1989).

During two operating seasons in Nome, from late May to early November, in 1987 and 1988, the mining vessel, BIMA, Fig. 17, has extracted over 70000 oz of gold from placer deposits in Norton Sound. Future high resolution seismic programs are now planned with greater emphasis on three dimensional detail.

It is now clear that seismic methods, developed largely in the search for oil, can successfully be scaled to resolution demands of minerals exploration with profitable results.

**Fig. 17 - The BIMA
world's largest
mining vessel.**



ACKNOWLEDGEMENTS

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