

**High Resolution Seismic Reflection Survey  
at Mud Mountain Dam  
near Enumclaw, Washington**

by

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Addendum to the final report submitted to  
U.S. Army Corps of Engineers  
Seattle Engineers District  
Seattle, Washington

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Open-file Report No. 97-65

January 15, 1997

**Addendum to Report  
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NOTE: Site and project details normally found in the Introduction and Geologic Setting sections of a report like this are contained in the first report (Miller et al., 1995, KGS Open-file Report #95-8) and are not repeated in this addendum.

**Summary**

The shallow seismic reflection program at Mud Mountain Dam focuses on defining and delineating stratigraphic and structural features within the Pleistocene sequence that overlies igneous bedrock. The portion of the project contained in the first report consisted of a series of acquisition/feasibility tests followed by two CDP profiles along gravel logging roads. The goal of the first CDP profiles was to extrapolate/extend sediments identified in sidehill outcrop into the embayment to establish some understanding of horizontal continuity. The second part of the seismic program (the portion reported here) included a series of source tests and a 300+ shotpoint CDP profile along the main access road to the Mud Mountain Dam overlook. This second survey line was designed to allow extrapolation and enhancement of interpretations from the first set of survey lines immediately north of the main dam road. Improvements in acquisition and processing techniques and equipment on the second trip allowed a much improved image of the subsurface and confidence in interpretation of the entire sedimentary sequence beneath the main access road.

Interpretations of the CDP profile collected during March of 1996 are consistent with drill holes 38, 23, 24, and 34. The bedrock reflection possesses almost 40 msec or about 100 ft of variation across this profile. An apparent bedrock high is interpreted beneath and slightly east of the logging road bridge. The configuration and topography of the bedrock surface suggests borehole 23 must have a TD very near the bedrock surface. The bedrock is deepest at the west end of the line beyond borehole 34. The Mud Mountain Complex (MMC) is stratigraphically the next higher unit. Several reflection events can be interpreted within this interval that are consistent with logs from on-line boreholes which show discrete changes in material. Reflections from the MMC and bedrock surface can be interpreted with a high degree of confidence and are both very consistent with logs.

The division between the MMC and Vashon Lake Bed (VLB) sequences and Hayden Creek Till (HCT) is acoustically distinct and can be confidently interpreted

everywhere except beneath the bridge where the fold drops and the lithology appears to change dramatically. It is difficult to determine with confidence whether the MMC possesses a relative elevation high near the center of the line due to missing data, hence two possible interpretations are provided. The interpretation suggesting a local thickening of the MMC near the center of the line is consistent with off-line borehole data. Above the MMC there appears to be a very complex set of erosional and depositional sequences that are made up of VLB, HCT, and Vashon Outwash (VO). The most likely interpretation of this sequence puts a complete relatively undisturbed section of bedrock, MMC, VLB, and VO at borehole 34 with dramatic cut-and-fill features possessing little or no distinct horizons above the deltaic layer. A very well-defined erosional channel cut-and-fill within the VLB is interpreted at boreholes 38 and 23. The high amplitude nature of the reflection with the VLB is likely related to saturation and possibly the pooling of water at that interface.

Between boreholes 38 and 23 a mound of HCT can be interpreted which is consistent with borehole 24, previous seismic lines, and hillside outcrop maps. The distinct character, reflection orientation, and shadowing effects of this area on deeper reflections is strong evidence to support a distinct horizontal change in material within this area. The borehole data was used to help identify the possible source of this acoustically unique area within the context of the entire seismic profile line. Preliminary processed sections possess distinct high angle apparent reflection arrivals with apparent dip to the west that are likely indicators of the western boundary of the HCT mound. The geologic interpretation of this HCT mound was only possible with the inclusion of borehole logs and interpretations.

Intermediate processed seismic sections enhanced the identification of secondary channels and approximate amounts of fill material redeposited into these apparent deep cuts into the VLB sequences. Without digital filtering and spectral balancing the channel feature between stations 1070 and 1110 is quite pronounced, possessing well-defined sides and top. The unique acoustic characteristics of this feature as displayed on the intermediate processed section is not consistent with the final processing flow that was designed to enhance reflections from deeper more consistent and competent layers. A much less well-defined channel is discernable between stations 1220 and 1280 on this same intermediate processed section. It is reasonable to suggest the strong reflection altered by these channels is the top of the VLB sequence. The high amplitude reflection truncated by the western edge of the western channel is consistent with the missing lower outwash layer as interpreted

in borehole 34. It is not unreasonable to suggest the section as sampled by well 34 might be unaltered while the section encountered in boreholes 38 and 23 have the upper portion of the VLB altered by erosional fill.

## **Introduction**

A second continuous profile was acquired on March 1 and 2, 1996, to continue 3-D extrapolation of structures delineated on previous seismic reflection surveys (Miller et al., 1995) and through sidehill outcrop studies (Hancock, personal communication and working maps, 1994) at Mud Mountain Dam. The previous hillside studies and seismic reflection surveys focused on the flanks of the Mud Mountain Dam north embayment (Figure 1). Timber roads along which seismic reflection data were acquired during the 1994 survey possessed a relative elevation difference of 50 and 80 ft to the seismic profile collected during the second trip during March of 1996. Time shifts of between 40 to 60 msec are necessary to offset the 50 to 80 ft of relative elevation difference to time tie profiles collected during these two trips. A 20 to 30% difference in near-surface average velocity between the two data sets is likely the result of increased saturation of the near-surface present during the second trip.

The second survey consisted of several source and geometry tests and a 300+ shotpoint CDP profile that extended from about 500 ft east of borehole 38 to about 200 ft west of borehole 34 (Figure 1). The survey was designed to image the same section and assist with continued 3-D extrapolation of features delineated during the first part of this study. The walkaway testing performed at the east end of the CDP profiles allowed identification of reflection events between about 100 and 500 feet. The survey was acquired along the paved road with receivers in the north road ditch (which in places contained standing water), while the source occupied locations on the paved road surface. The profile was centered on a 50+ ft high single-span bridge with fill material making up some portion of the upper 10 to 50 ft off both ends of the bridge.

## **Data Acquisition**

The acquisition parameters and equipment were selected and configured based on a series of complementary walkaway noise tests collected during both trips to this site. The testing completed during the first trip (Miller et al., 1995) provided a basis for the 8 ft station spacing, split-spread geometry, far-offset of at least 300 ft, and the need for a non-invasive, medium energy source. Walkaway tests during the

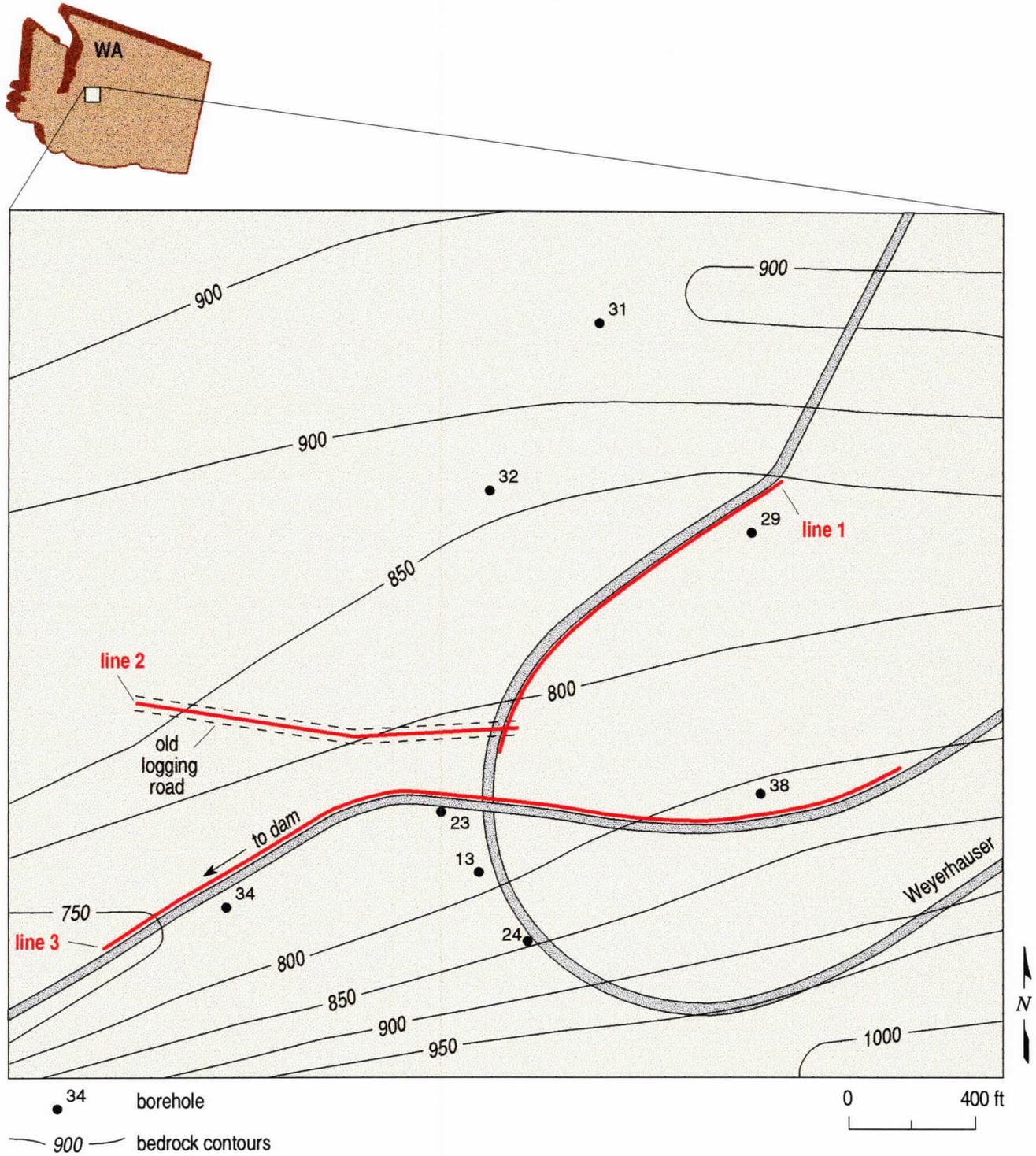


Figure 1. Site map indicating the relative location and orientation of the survey lines and bedrock elevations.

second trip were primarily intended to allow selection of the optimum source and geometry. The sources tested during the second trip included the 8-gauge auger gun, rubber band accelerated weight drop, and the IVI MiniVib. The MiniVib was tested with an extensive series of sweeps correlated with a variety of pilots. The increased number of recording channels available on the second trip (96 in comparison to 48) allowed for a split-spread geometry which greatly improved both dip control and close offset redundancy without compromising velocity control. The split-spread geometry allowed a close offset of 25 ft and a maximum offset of just over 400 ft. The 25 ft off-line offset allowed near channel recording of signal well within the threshold of the geophones and pre-amplifiers and avoided disturbing geophone coupling.

Data for this study were acquired on two 48-channel Geometrics StrataView seismographs networked to allow simultaneous 96-channel recording. The seismographs record and A/D convert the analog input data from the geophones into a 24-bit word. The 10 second pilot trace recorded on channel 1 of the master seismograph was correlated with the remaining 95 channels of 12 second data to produce a 1 second shot record. This in-field correlation allowed real-time preliminary analysis and QA/QC of the data. Data were recorded with a 1 msec sampling interval and stored in SEG2 format on internal hard drives within each seismograph.

The source was an IVI MiniVib calibrated to deliver a flat up-sweep from 30 to 200 Hz at a peak force of 6500 lbs. The 10 second ground force pilot calculated at the vibrator using the base plate and mass accelerometers was real-time telemetered to the seismograph and correlated with the 12 seconds of seismic data collected during that same time interval. The vibrator pad was placed on the asphalt road surface opposite the road ditch where the geophones were planted. Three sweeps were individually correlated and stored for each shotpoint, allowing future vertical stacking of each sweep for signal-to-noise enhancement and to negate the effects of random (wind) or pseudo random (cars, airplanes, etc.) noise sources.

Three Mark Products L28E 40 Hz geophones were wired in series and deployed in a 3 ft array at each station. The 8 ft receiver and shot spacing was selected based on walkaway tests performed during the first part of the seismic surveys conducted at Mud Mountain Dam. Geophones were planted at the base of a 3 to 4 ft deep road ditch where in places 1 to 8 inches of water was standing. The 14 cm spikes were critical in penetrating into solid planting material beneath the extremely saturated section of the ditch.

The production portion of the survey took one day to complete and included approximately 316 shotpoints, all collected along a single traverse split in half by a single-span bridge approximately 200 ft wide. The vibrator was ideally suited for the line conditions and constraints of invasive investigations. The three-sweep sequence allowed cancellation of most intermittent noise sources while boosting the signal levels to allow effective digital filtering. The normal moveout (NMO) velocity of the reflections imaged in the upper 300 msec on field files ranged from 3000 to 4000 ft/sec and the dominant frequency was about 60 to 70 Hz with an upper corner frequency of about 125 to 140 Hz, providing an excellent bandwidth for resolving the features of interest on this survey.

### **Processing**

The processing of seismic data from the second visit followed a flow and used parameters consistent with processing used to generate CDP stacked sections from the first visit to this site (Miller et al., 1995) (Table 1). The main distinctions between the two flows was the NMO velocity and use of spectral equalization. The different NMO velocity was due to the increased saturation of the near-surface and the likely increase in subsurface moisture levels. The spectral equalization was effective on this data set where it was not on the last due to the broader band reflection wavelet recorded with the vibrator and increased saturation, hence reduced attenuation of the upper few feet. The spectral properties observed with the auger gun (providing the best results with 2 ft subterrain burial) during the last visit suffered from dry near-surface conditions and poor ground penetration (due to near-surface rocks and boulders) and therefore reduced coupling. The same caution and step-by-step QA/QC was followed on this processing flow as with the previous data set.

### **Results**

Confident identification, mathematical verification, and geological consistency of reflections on field files is necessary to properly and accurately process shallow seismic reflection data, and as well it is of the utmost importance in differentiating reflections from refractions and other coherent noise in the shallow portions of CDP stacked sections. Raw and processed field files acquired during the production portion of the survey have identifiable reflection events between 50 and 250 msec (Figure 2). The reflection hyperbola are well defined, allowing correlation of most of the higher amplitude events on field files to stacked reflections on the CDP profile. From inspection of field files it is evident that the data possess a

## TABLE 1

### Processing flow

#### Primary Processing

format from SEG2 to KGSEGY

preliminary editing (automatic bad trace edit with 10 msec noise window)

trace balancing (150 msec window)

first arrival muting (direct wave and refraction)

surgical muting (removal of groundroll based on trace-by-trace arrival)

assign geometries (input source and receiver locations)

elevation correction to single, floating datums

sort into CDPs (re-order traces in common midpoints)

velocity analysis (whole data set analysis on 100 ft/sec increments)

spectral analysis (frequency vs amplitude plots)

NMO correction (station dependent ranging from 2750 to 4000 ft/sec)

correlation statics (2 msec max shift, 7 pilot traces, 200 msec window)

digital filtering (bandpass 25-50 110-250)

spectral balancing

secondary editing (manual review and removal of bad or noisy traces)

CDP stack

amplitude normalization (whole trace)

display

#### Secondary Processing

f-k filtering

f-k migration

deconvolution (spiking and second zero crossing)

Table 1. Processing flow for CDP stacked data. Parameters were determined by analysis for each prior step as well as through iterative analysis of particular operations.

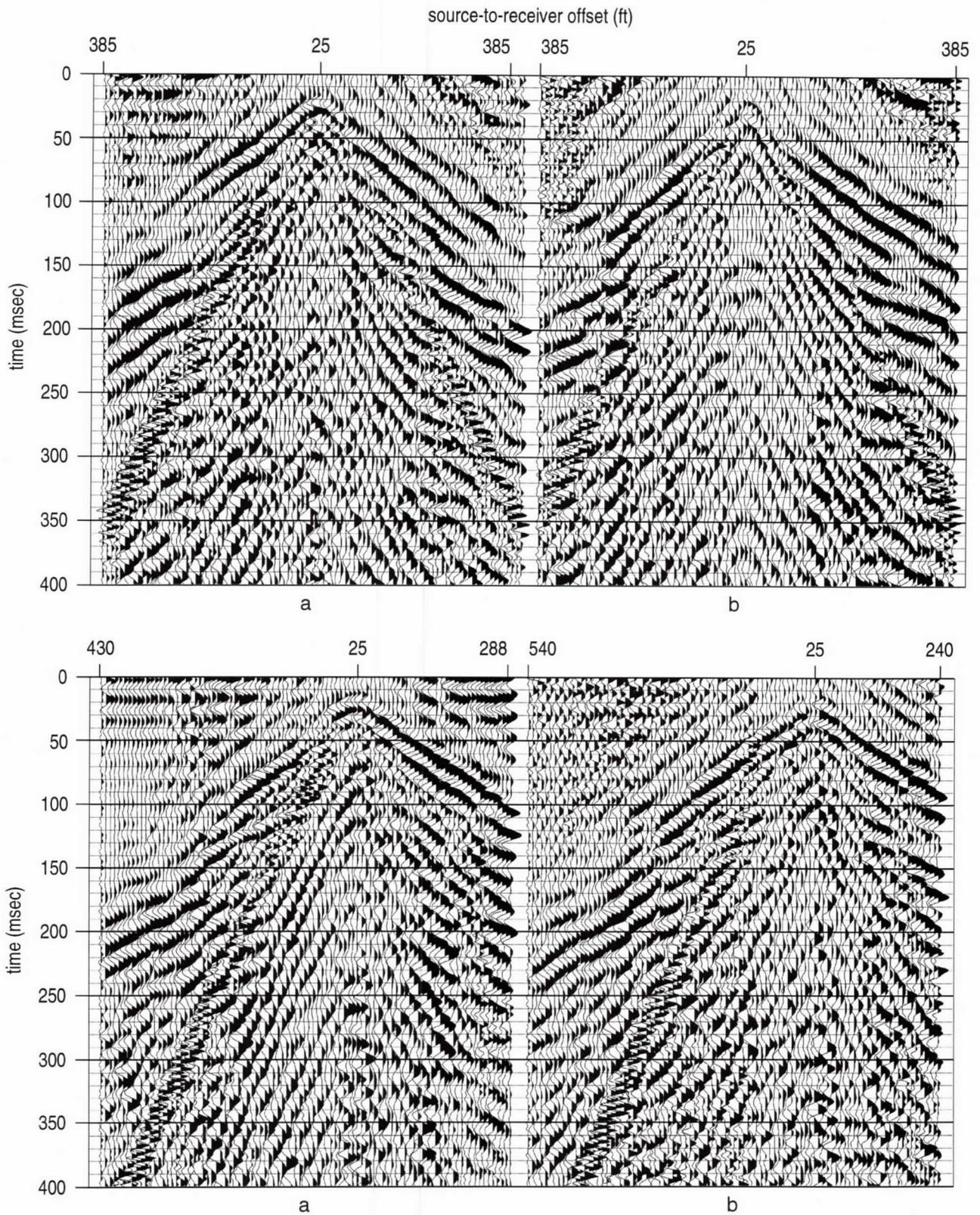


Figure 2. Two 48-channel field files showing the shot gather a) filtered and scaled, and b) filtered, scaled, and F-k filtered.

relatively narrow bandwidth, or, at a minimum, severely unbalanced spectra. Everything considered, the signal-to-noise ratio of these three-shot vertical stacks is very good with reflection identifiable on at least 70% of the field files.

Processed field files show the enhancement of the reflections interpreted on the raw field files (Figure 2). Digital filtering, first arrival muting, spectral balancing, ground roll/air wave surgical mute, refracted/direct wave f-k filter, and time varying amplitude scaling greatly improved the signal-to-noise ratio of the data set as a whole. The removal and/or attenuation of as much noise as possible, in conjunction with the redundancy of the stacked data, provided a very interpretable stacked section.

The dominant frequency of reflections from this site is around 60 to 70 Hz. The resolution potential is reasonably close to that of the previous trip. The increase in average velocity and slight decrease in apparent dominant frequency effectively reduced vertical and horizontal resolution slightly, but the increase in signal-to-noise ratio and the more uniform amplitude spectra within the reflection frequency band actually provides a better, more uniform image of the subsurface.

The CDP stacked section possesses several high amplitude reflections with as many subtle, less acoustically significant reflection interfaces interpretable between about 50 and 300 msec (Figure 3). The highest amplitude reflection both on the field files and the CDP stacked section is from a time depth of about 130 to 140 msec. Considering the average stacking velocity to that time depth, the reflector responsible for that event is likely about 220 to 240 ft deep. Based on previous experience interpreting reflection within unconsolidated sequences, reflectivity at an interface this high has usually been related to a perched water table or at least increased saturation of one of the two materials at a contact. Combining the calculated depth with the inference of perching or saturation it is most likely this interface is at the top of or within the VLB sequences. Considering this same criteria for identification of the VLB sequence, the reflection at about 90 msec on the west end of the line is also part of the VLB both in terms of time/depth conversion and the effects of increased moisture.

The borehole data from wells 38 and 23 suggest a gravel/cobble zone is present at a depth of about 170 ft that seems to be present locally in every borehole except 34 (Figure 4). This cobble zone is generally identified as the base of the outwash gravel and the marker that divides the VO from VLB. The apparent unique geologic setting at borehole 34 (unique due to the missing gravel marker) is quite clearly represented on the stacked section between CDP 1285 and the west end

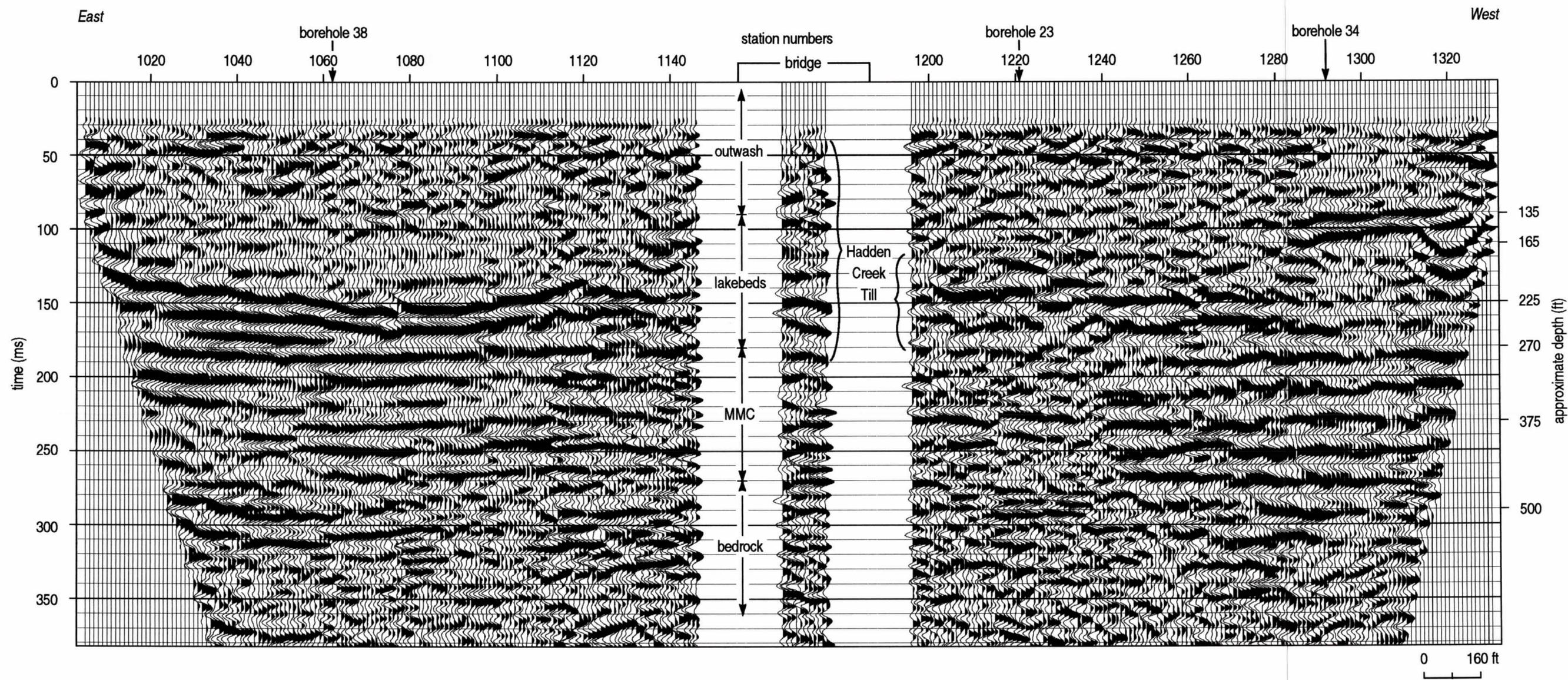


Figure 3. Nominal 48-fold CDP stacked section of line 3 at Mud Mountain Dam, Washington.

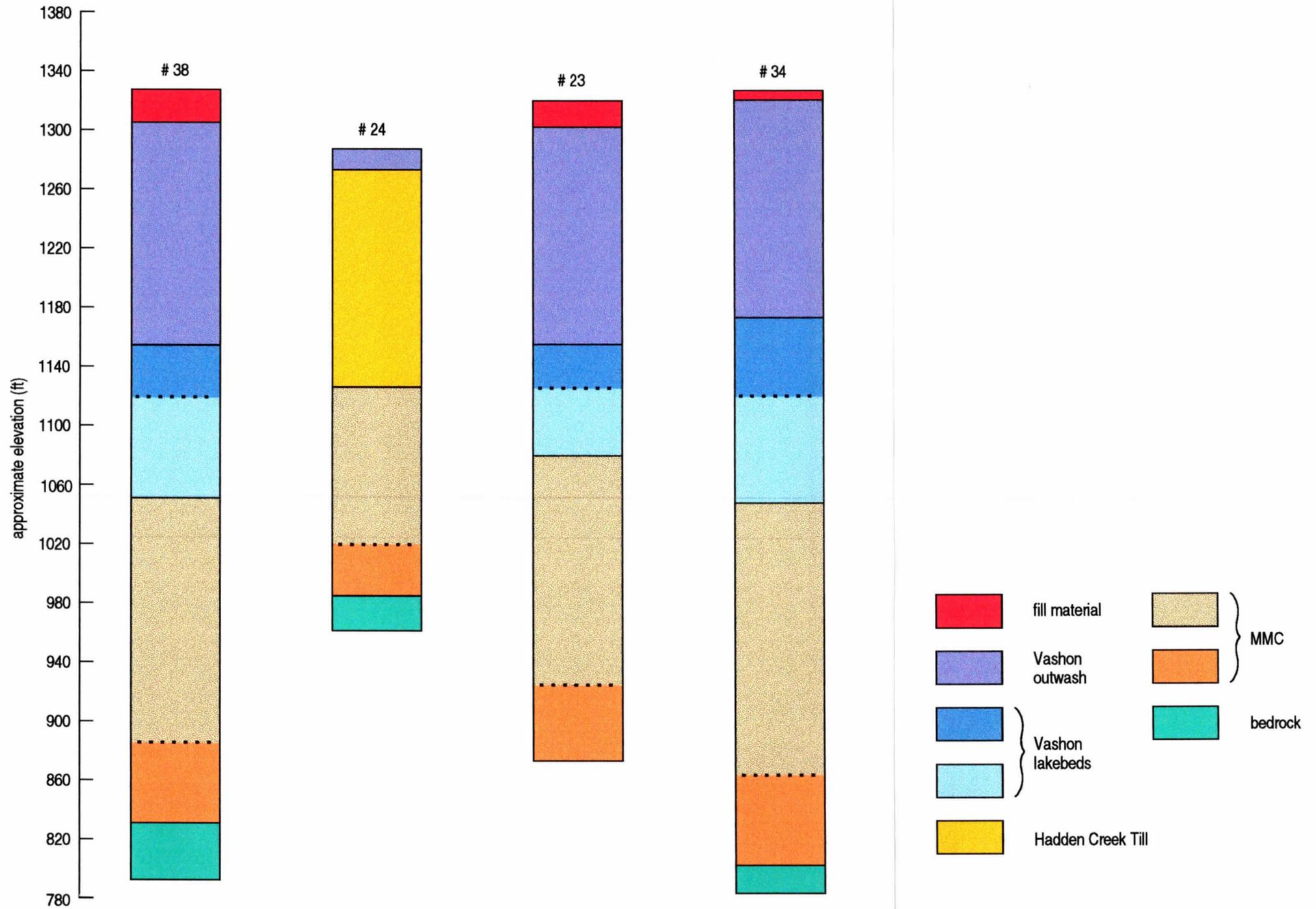


Figure 4. Geologic cross-section of line 3 based on wells #38, #24, #23, and #34, Mud Mountain Dam, Washington.

of the profile (Figure 5). Based on the geology of the interval, between about 150 ft and 200 ft in boreholes along this line, it seems likely the upper part of the interpreted VLB sequences between CDP 1285 and the end of the profile is likely a block of more resistant material that was either spared from erosion by or withstood the erosional action of the ancient White River. Another possibility is that this area is the only local remnant that avoided alpine glacial erosion/gouging and subsequent retreating and deposition that possibly produced this locally consistent boulder layer.

The synclinal shape of the high amplitude layer between CDPs 1040 and 1120 at a two-way travel time of around 140 msec is interpreted to be within the VLB sequence and is very likely the result of either river actions or possibly glacial movements. Thinning of the VLB as indicated by the apparent truncation of the reflection at 170 msec beneath station 1040 supports explanations for the topography of the 140 msec layer as being the result of erosion and not depositional or tectonic forces. The relative high amplitude of the 140 msec reflection on the east end of the line is likely indicative of either a saturated, relatively compacted, well sorted layer in contact with a diffuse, relative porous layer, and/or the higher amplitude could be associated with a relatively nonpermeable layer that is acting to perch water. The seismic section from the first trip provided an image of approximately the same geologic interval with similar well defined high amplitude reflections. It is most likely the less permeable materials that make up the VLB retain moisture, resulting in higher reflection coefficients and therefore more pronounced reflection events when in contact with other units.

Two locations on intermediate processed sections are likely candidates for relatively large deposits of fill material with little or no apparent layering (Figure 6). The dramatic lateral change in reflection characteristics evident at station 1090 and to a lesser degree at station 1250 have shapes and depths consistent with channel cut-and-fill features interpreted on stacked section from the previous survey. The reduction in clarity of these features on the final sections is a direct result of the processing flow which was designed to enhance reflection from interfaces deeper in the section. The apparent lower dominant frequency and narrower bandwidth (not evident on this display) of the reflection that marks the cap or top of the fill area is likely indicative of a much more diffuse reflecting surface. Based on the wavelet characteristic of the reflection from the top of the fill at 70 msec it was necessary to verify that no refracted energy was stacked into this coherent arrival. Significant to the interpretation of channel features are diffraction patterns evident on this inter-

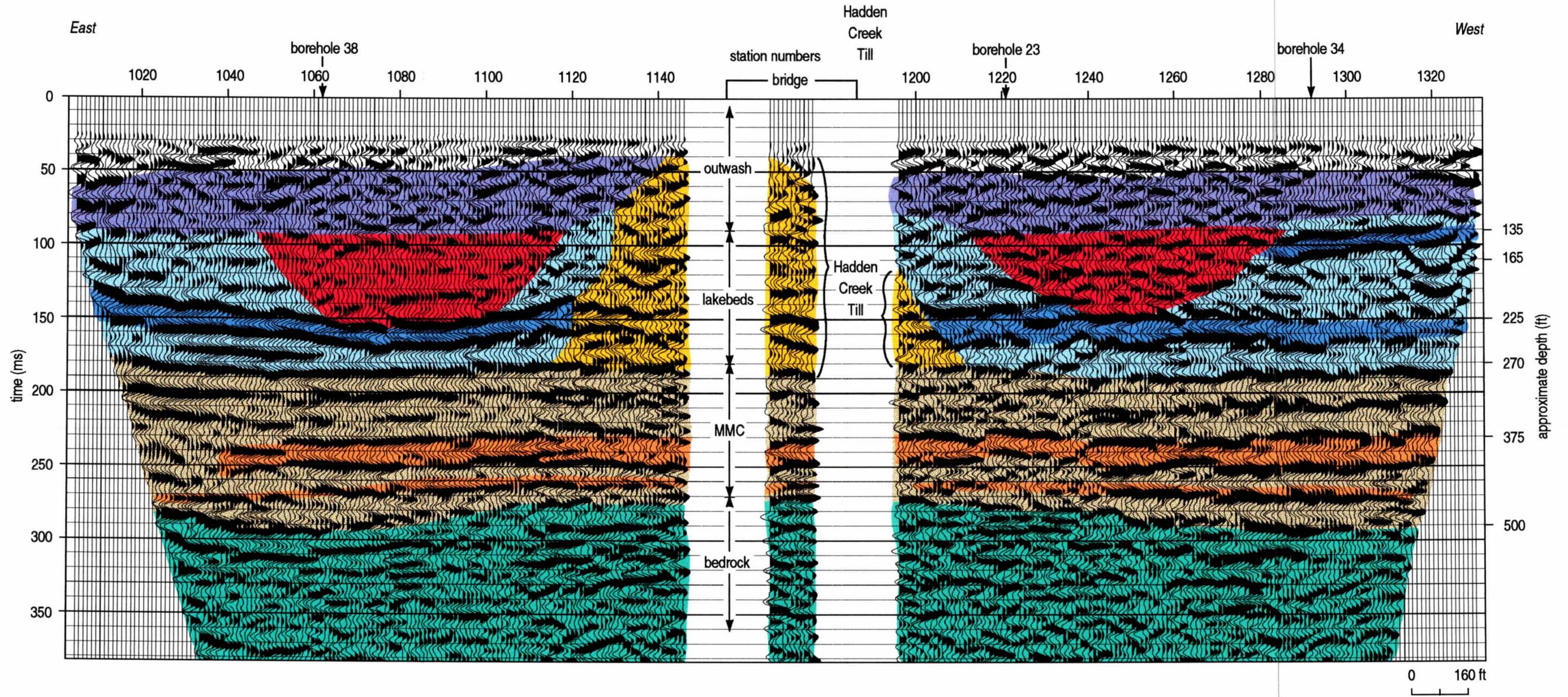


Figure 5. Interpreted CDP stacked section of line 3 at Mud Mountain Dam, Washington. The color codes are consistent with Figure 4. This interpretation suggests a large mound of till that completely removes labeled sediments near the bridge.

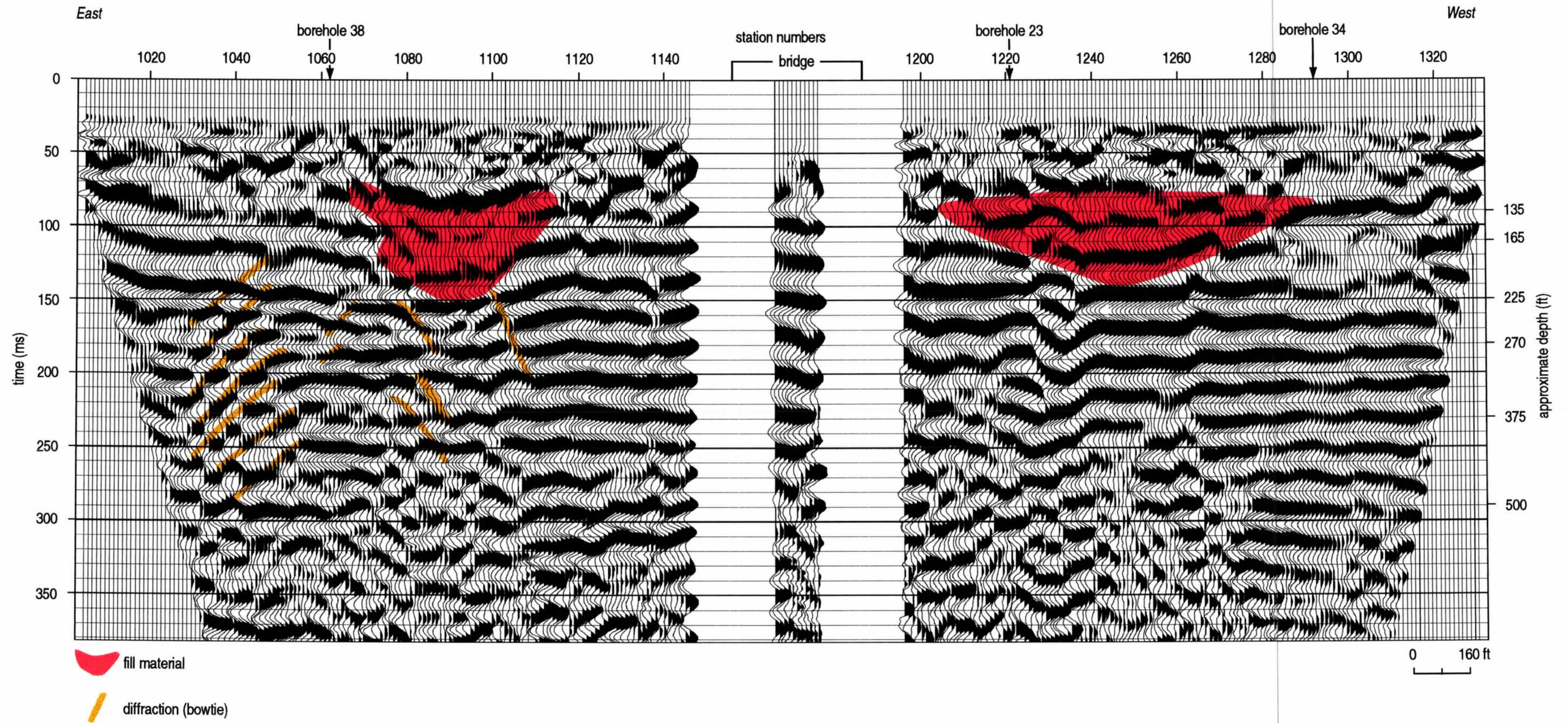


Figure 6. Intermediate CDP stacked section of line 3 at Mud Mountain Dam, Washington. This low frequency stack shows strong diffraction patterns and the appearance of a possible channel feature.

mediate processed section. The diffractions or in this case "bow ties" interfering beneath the channel features are indicators of a severely curved (small radius) surface that is sufficiently severe to produce a geometrically distorted image on the seismic section. Migration was used on the final section to correct the seismic image.

The upper contact of the MMC is very well defined both geologically in cuttings and acoustically by the strong reflection at about 180 msec. Based on stacking velocities this reflection is around 280 ft below ground surface. Considering the variability in velocity of the material above the MMC reflector, the 10 msec variation in arrival time across the line cannot be confidently interpreted as completely related to topography on the MMC surface. Due to the missing data in the area under and near the bridge it is difficult to determine if the MMC is slightly mounded or thickens beneath the bridge. It is likely, based on the general structure of underlying events, that either some uplift is present or a change in near-surface material has resulted in increased average velocities, and therefore reflections at depth are "pulled-up."

A couple of well-defined reflection events that are within the portion of the stacked seismic section interpreted to be MMC are likely from laterally consistent reflectors that should have similar character in local borehole data. In examining borehole logs, the shallower intermediate event is at a depth of around 400 ft and is probably the contact between fine grain clay particles and gravels/cobbles which has a very well-defined kick at around an elevation of 960 on electric logs. The deeper coherent event thins near the center of the line and is probably a clayey sand/gravel contact at about 465 ft in borehole 34. This same geologic layer is not present in borehole 23 due to its shallow TD, and in borehole 38 it is not nearly as evident on the electric logs. However, it is clearly a distinct acoustic contact. The MMC seems to possess several reflection events coherent and relatively flat across the profile with little in the way of structurally complex features.

The bedrock surface is easily interpreted based on its relative time/depth and the distinct character of the reflection wavelet. The bedrock structure is consistent with interpretations from boreholes suggesting a bedrock high near the center of the line. The bedrock elevation changes from 485 ft below ground surface at station 1030, 500 ft below ground surface at station 1070, 470 ft below ground surface at station 1170, to 525 ft below ground surface at station 1310. Topographically, the bedrock surface as defined by the seismic reflection section is very consistent with well data. There appears to be a basin or channel feature directly beneath borehole

38 that is about 500 ft across and 20 ft deep. The saddle feature created by the elevated bedrock surface at station 1170 should act to hydrologically divide the basin on the east from the low on the west.

The most speculative feature interpreted on this section is the mound of HCT. The apparent abrupt termination of the VLB sequence reflections and the interpreted presence of HCT on the previous seismic section and borehole 24 provides a very strong basis for suggesting this acoustically unique area is the image of a very steep-sided mound of HCT. If the interpretation of the HCT mound is accurate, the contact between the HCT and MMC is very uniform with the HCT and VLB both in contact with the relatively flat surface of the MMC. An alternate interpretation places the contact between the MMC and the HCT about 70 to 80 ft higher in the section (Figure 7). This interpretation is consistent with borehole 24 with the exception of the elevation of the bedrock surface beneath this remnant mound. It is reasonable to suggest that the HCT is present beneath the bridge based on the presence of HCT in borehole 24, the interpreted presence of the HCT on the previous seismic profile, and the evidence suggesting HCT exposed in hillside outcrop.

## **Conclusions**

The seismic reflection program at Mud Mountain Dam was effective in delineating the bedrock surface and apparent cut-and-fill channels within the Vashon Lake Bed sequences. The excellent match between the seismic profiles and the drill data allows confidence in extrapolating interpretations from well-to-well for determination of orientation and localized variability in sedimentation. The vibratory source allowed greater energy penetration with minimal to no environmental impact. The 96-channel recording format allow better control of velocity and provided improved coherency of deeper events by recording longer offsets than possible on the first profile when only 48 channels were used. The outwash material seems to have very little, if any, layered sedimentation or the velocity/density contrast at layer boundaries is extremely small. The shallow high resolution reflection technique clearly possesses the potential to resolve beds as thin as 15 ft at this site.

The cut-and-fill features in the VLB sequences appear to extend from stations 1040 to 1110 and from stations 1210 to 1280 with the potential for very unsorted piles of material (possibly similar to boulder outcrops on both flanks of the embayment) deposited in channels between stations 1075 and 1105. The depths of these channels

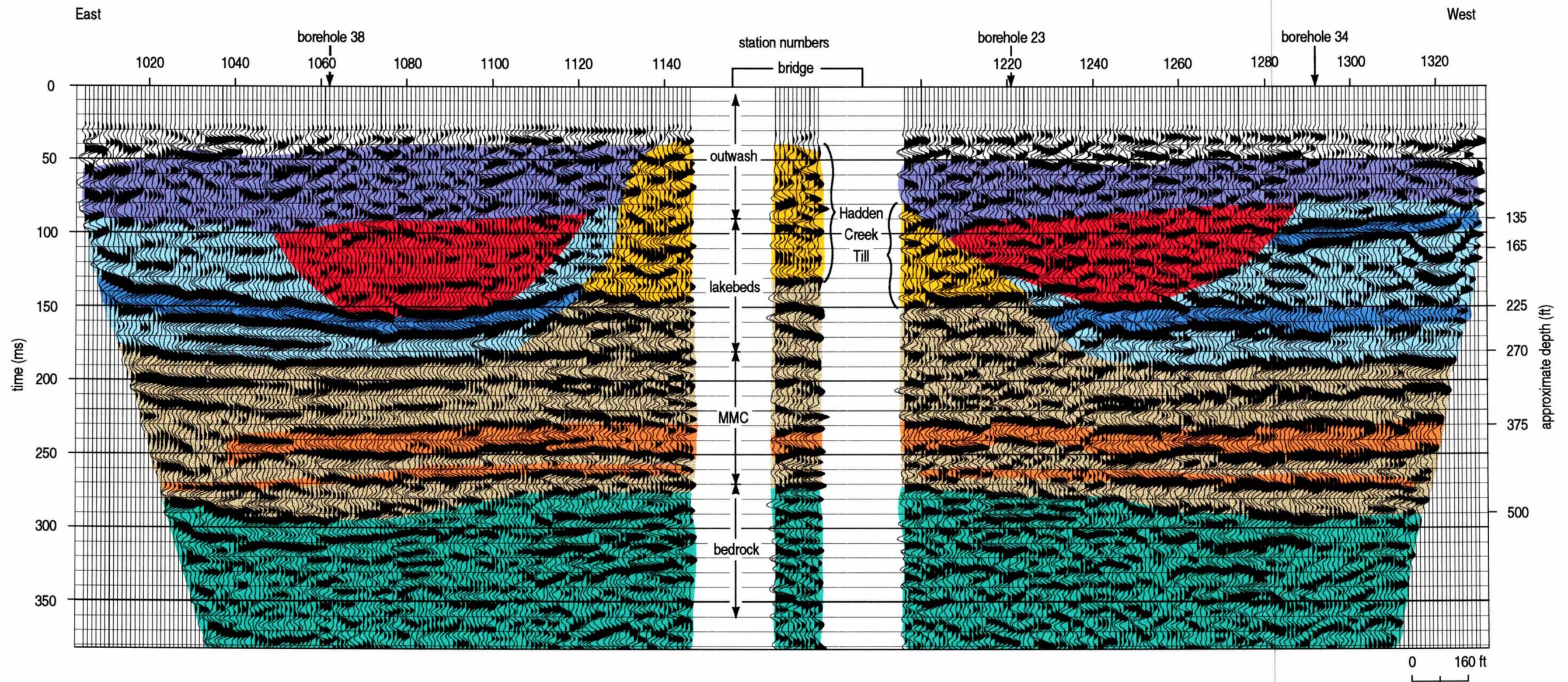


Figure 7. Alternate interpreted CDP stacked section of line 3 at Mud Mountain Dam, Washington, suggesting a mound near the bridge consisting of more MMC and less Hadden Creek Till.

are around 50 to 75 ft. Cuts into the VLB across the expanse of the embayment is likely more common than the presence of the complete VLB and deltaic sequences as present in borehole 34.

A basin or closed low in the bedrock surface is evident beneath well 38 with a low extending westward off the end of the seismic profile. The closed low or basin beneath well 38 could act as an isolated conduit for the movement of fluid.

Complete delineation of the cut-and-fill features as well as bedrock configuration would require a seismic profile that included the entire Mud Mountain access road. The data quality evident on this portion of the section would greatly enhance well-to-well ties, providing several potential drill locations for accurate monitoring of increased levels of saturation within the embayment.

### **Acknowledgments**

We would like to thank William Hancock for his assistance with field logistics and data acquisitions. Thanks also to Xujin Sun for his assistance with the field work.

### **References**

Miller, R.D., J.M. Anderson, D.R. Laflen, B.C. Bennett, and C.B. Park, 1995, High resolution seismic reflection survey at Mud Mountain Dam near Enumclaw, Washington: Kansas Geological Survey Open-file Report #95-8.