Shear-wave Database for Quaternary and Bedrock Geologic Units, Washington State

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WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

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This report has not been edited or reviewed for conformity with Division of Geology and Earth Resources standards and nomenclature

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Doug Sutherland - Commissioner of Public Lands

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ABSTRACT

The Department of Natural Resources, Division of Geology and Earth Resources has compiled a state-wide geologic unit correlated shear wave velocity database as part of a FEMA grant administered by the Washington Emergency Management Division. The goal of this grant was to prepare state-wide National Earthquake Hazard Reduction Program (NEHRP) site class maps. These maps require an average measurement of the shear wave velocity of the upper 30 meters of the soil-rock column. We measured 712 shallow seismic shear wave velocities in 48 different Quaternary and bedrock units. The resulting geologic unit correlated shear wave velocity database, including a compilation of other published and unpublished shallow seismic measurements conducted in the region, is presented in Microsoft Access 2000 format.

INTRODUCTION

The most damaging effect of an earthquake is strong shaking at the ground surface. For more than a century, engineers and seismologists have known that ground shaking during an earthquake is strongest in areas of soft soils, such as in river valleys or along the shorelines of bays and lakes. Measurements of earthquake ground motions made in the last few decades have allowed seismologists to more fully understand the physics of this long-observed phenomenon. Earthquake wave velocity is slower in soils than in the underlying rock of the Earth‘s crust. The difference in wave velocity between rock and soil causes the shaking at the ground surface to be amplified. Generally, the greater the wave velocity difference, the greater the amplification of ground surface shaking. Consequently, ground shaking in areas of soft soils underlain by stiffer soils or rock is generally stronger than in areas where there is little or no variation between the surface and substratum. This has been observed time and again in past earthquakes.

In the mid-1990s, a simplified method for characterizing the ground-motion amplifying effects of soft soils was developed by Roger Borcherdt of the U.S. Geological Survey, based on data collected from the Loma Prieta and Northridge earthquakes in California (Borcherdt, 1994). His empirical study related the average shear wave velocity (Vs) in the upper 100 feet (30 meters) of the soil-rock column to the amplification of shaking at ground surface. Shear waves are the earthquake waves that create the strongest horizontal shaking and are the most damaging to buildings and structures.

Borcherdt's method subdivides the near-surface geology into a number of site classes where each site class is defined by a unique range of average Vs in the upper 100 feet (30 meters). A modification of Borcherdt's empirical method was implemented by the Building Seismic Safety Council (BSSC) and the Federal Emergency Management Agency in the 1997 edition of the National Earthquake Hazard Reduction Program (NEHRP) Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (BSSC, 1997). Borcherdt's designation of site classes was simplified in BSSC (1997), and these simplified site class groupings are commonly referred to as NEHRP site classes. In 1997, this modified method of accounting for soil-column amplification effects was adopted by the International Conference of Building Officials in the Uniform Building Code (International Conference of Building Officials, 1997). This method of designating site classes for determination of seismic design ground motions is used in the 2003 version of the International Building Code (International Code Council, 2003), which was the current building code adopted for use in Washington State at the time this work was done.

There are no published correlations of age and type of geologic deposit with NEHRP site classes. Such correlations are necessary for constructing a statewide site class map using the available 1:100,000-scale geologic mapping. To establish such correlations, we collected Vs data in a variety of geologic units throughout the state. We used shear wave refraction surveys to obtain these Vs data. We also compiled published (Wong and others, 2003; Mabey and others, 1993) and unpublished (Matthew Mabey, Oregon Dept. of Transportation, written commun., 2003) Vs data for the Seattle, Olympia, and Portland areas. In addition, a small collection of unpublished V_S data from various locations in western Washington was compiled from a variety of sources and used in the development of this Vs database. The result of the data collection is a database of 712 Vs measurements in 48 different Quaternary and bedrock units from around Washington State. The database is presented in Microsoft Access 2000 format and as a series of three comma-delimited ASCII text files included in this report.

SHEAR-WAVE REFRACTION SURVEY METHODOLOGY

We chose shear wave refraction surveys as the least complex, direct method of measuring Vs in near surface (~ 100 ft) geologic material. Fieldwork for the shear wave velocity database was accomplished during the summer months of 2003 and 2004. Minimizing expenses was important to successfully collecting as many Vs measurements as possible over two field summers. After the initial cost of geophysical and field support supplies, travel costs for two field employees were the only expenditure directly related to the physical surveys. In addition, refraction methods are non-evasive, resulting in school districts allowing us access to their sports fields as well as private landowners offering their lands to perform surveys on.

Suitable Survey Locations

In order to relate Vs measurements to mapped surficial geology, sites were selected where the geology is relatively straightforward. Shear wave velocity surveys were conducted on a wide variety of Quaternary units by using the available 1:100,000 scale Washington statewide geology (Washington Division of Geology and Earth Resources staff, 2003) and, where available, more recent 1:24,000 scale geologic mapping to target our surveys to specific geologic units. Surficial

geology was generally verified by searching out road- or stream-cuts near the prospective survey site or by checking proximal water well borings. In locations were this type of verification was not available, we would dig shallow test pits or rely on the available geologic mapping.

The distance between shear wave source and receiver (the total length of the survey line) and the relative Vs contrast between layers at a refraction interface dictate the depth at which we could measure Vs. In practice, we found that in order measure Vs down to a depth of approximately 100 ft, we had to use a 300 ft survey line. We also found that areas with relatively little vegetation cover or well-mown areas helped to eliminate acoustic noise generated by vegetation swaying in the wind or wind blowing plants against the geophones. Allowing for these factors, the best survey sites were sparsely vegetated areas that had at least 300 ft of relatively flat ground. We tried to satisfy these survey location requirements by conducting surveys on play fields and post harvest agricultural fields as much as possible.

Equipment

The main equipment used in conducting the Vs surveys were a 24 channel Geometrics SmartSeis seismograph powered by a 12-volt marine battery (Fig. 1), 24 horizontal motion (shear wave) geophones (Figs. 2 and 3), a nine foot long 6x10" wood beam with 1.5" thick protective steel end caps, and an energy source. The horizontal motion geophones manufactured by Sercel of Houston, Texas, have a natural frequency of 14 Hz. The geophones were coupled to the ground with a 3-inch spike and included a carpenter level bubble on each to ensure proper horizontal orientation. The wood beam was coupled to the ground by parking the front two wheels of a field vehicle on top of the beam. We generated shear waves by striking one end of the beam. This caused a horizontal (shear) motion to be imparted to the ground. The 1.5" thick steel end caps fitted on the beam acted as both a buffer between the wood and the impacting source, preventing splintering, and as one side of a switch that triggered the seismograph to begin recording upon contact. The shear wave energy source for the 2003 field season was a 12 lb sledgehammer brandished by a field geologist. Between the 2003 and 2004 summer field seasons we designed and had fabricated a spring powered shear wave source (SPSW). During the 2004 field season we deployed the SPSW (Figs. 4 and 5) with the effect of reducing strain on field geologists and providing perfectly repeatable shear wave initiation shots. The SPSW operates by drawing an impactor head back on a stiff spring with a worm-drive winch (Fig. 4). The impactor is then held in the cocked position by electromagnets powered by a 12-volt marine battery, and fired by shutting off the electromagnets (Figs. 4 and 5). The SPSW delivers more mass at a lower velocity compared to the 12 lb sledge swing, striking the beam with similar or greater kinetic energy. The SPSW is superior to a human wielded 12 lb sledge, however, because the impactor strikes the beam with the same force and with the same pitch each time it is fired, creating a consistently repeatable shear wave source.

Figure 1. Geometrics SmartSeis in operation.

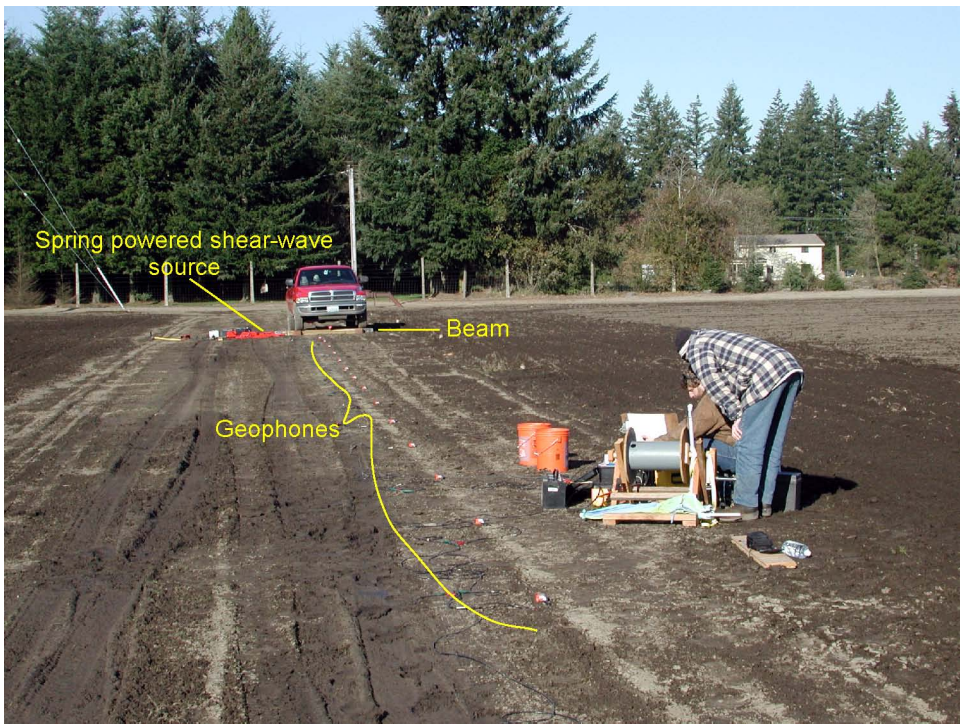

Figure 2. Survey setup including most of the geophones, the seismograph location, and the shear-wave source location.

Figure 3. Survey setup including some of the geophones, the spring-powered shear-wave source, and the beam.

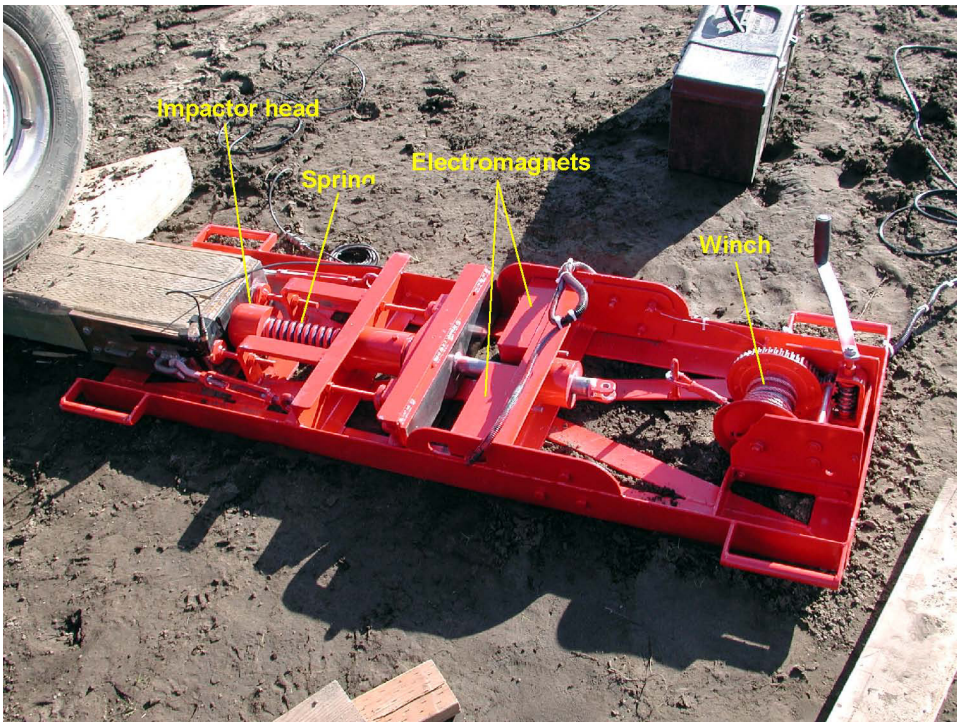

Figure 4. Diagram of the working parts of the spring-powered shear-wave source.

Figure 5. Diagram showing the power source and switch for the electromagnets and the contact trigger that starts the seismograph recording.

Survey Setup

After selecting a site, gaining access, and identifying the local surficial geology, the refraction survey was laid out based on a standard survey setup form (Appendix A). The standard survey setup form served two purposes: first, the form recorded many of the variables for each survey and second, the form helped make the survey process consistent. The most important survey variables included: the slope of the survey ground, possible sources of acoustic interference, and the geometry of the specific survey line. If the ground to be surveyed was sloping or uneven along the survey line, we used a stadia rod and a clinometer to complete a survey of the relative vertical displacement of each geophone. This data was later entered in as part of data processing.

The two most pervasive sources of acoustic interference that we encountered were wind and automobile traffic noise. In order to reduce wind interference we routinely buried the geophones six inches to a foot deep at survey environments that exhibited strong wind noise. Acoustic interference from proximal traffic was less easily dealt with; we were limited to timing our shear wave source shots to coincide with breaks in the flow of traffic. We always used a 24-geophone survey line. Typically we used a ~ 10 ft (3m) spread between geophones and a ~ 30 ft (10m) offset between the shear wave source shotpoint and the last geophone in the spread, for a total length between the last receiver in the line and the source of ~ 260 ft (79m).We only completed surveys that recorded shotpoints at each end of the survey line in order to correctly resolve the dip of any refracting unit and to enable calculation of the true Vs. In some instances we recorded a shotpoint in the middle of a survey line, which helped to image near surface layers and generally refine the data set. At each shotpoint we stacked the shear wave data 4 to 12 times to increase the signal-to-noise ratio. Stacking involved repeated source impacts recorded into the

same seismic data file. Theoretically, the seismic signal from each stack arrived at the same time from each refracting layer and thus was enhanced, while acoustic noise was random and tended to be reduced or canceled. The use of the Geometrics SmartSeis seismograph enabled the monitoring of background acoustic noise, stacking of signal, and the on screen manipulation and filtering of recorded signal.

DATA PROCESSING

All shear wave refraction data were processed using Rimrock Geophysics' software DOS-based application SIP version 4.1. SIP enabled filtering of the acquired data, picking first shear signal arrivals, assignment of velocity layers, and the calculation of Vs and depth to the layer. In order to ensure that the filtering and picking of first arrivals for the shear wave data from each shotpoint in a survey was treated equally, we used a standard signal picking form (Appendix B). After the data was successfully filtered for background noise and the first breaks were picked, individual velocity layers were assigned by plotting the first break picks on a time-distance plot. At this point, SIP allowed a correction to be applied if the survey was undertaken on uneven ground and the relative vertical displacement of each geophone had been recorded. With the potential different velocity layers assigned, SIP then used the Hobson-Overton least-squares method (Scott, 1977; Scott and others, 1972) to calculate layer velocities, and iterative ray tracing to obtain a first approximation depth model. An estimated minimum depth of the investigation was also calculated for all survey locations that did not encounter high Vs bedrock. This was accomplished by entering a velocity override into the SIP parameters for a higher velocity final layer. The probable geologic unit of this deepest minimum depth estimate layer was assigned based on knowledge of the local geology, and the velocity of this unit was arrived at through a compilation of average Vs data for each possible minimum depth unit surveyed during the 2003 field season (Table 1).

Table 1. Compilation of the average shear-wave velocities used for all minimum-depth units.

Minimum depth rock type	**Average shear-wave velocity (m/s)**
glacial and flood sand & silt	**400**
Ringold Formation	**410**
Latah Formation	**550**
weathered granite	**820**
Troutdale gravel	**830**
glacial (till & outwash) & flood gravel	**860**
sandstone	**860**
sedimentary deposits, undivided	**900**
generic slow bedrock	**1500**
granite	**1740**
basalt	**2470**

limestone	**3000**
gneiss	**3190**

Included in Appendix C of this report are screen captures of every step of the SIP process for each site surveyed. The appendix includes the following for each site surveyed: first break picks, layer assignment, depth model, and, in cases where no bedrock was encountered, a minimum depth model.

DATABASE STRUCTURE

The Vs database is presented in Microsoft Access 2000 format and as a series of three comma-delimited ASCII text files included with this report. The database is composed of three tables: Unitdescription, Location, and Velocity. The Unitdescription table lists our naming convention for geologic units and number of measurements for each geologic unit in the database. This table also includes brief descriptions of the geologic units. We adopted our own naming convention for the Quaternary sedimentary units in Washington State in order to group the vast number of Quaternary units by properties that shear wave velocity is sensitive to, such as grain size and depositional history, including compaction. Our naming convention was arrived at by reviewing the descriptions of all Quaternary sedimentary units described in the map reports for each of the published 1:100,000-scale geologic quadrangle maps. We classified each of these Quaternary sedimentary units with our naming convention using the report descriptions and our own professional observations and judgment. Tables 2, 3 and 4 illustrate our naming convention for the Quaternary sedimentary units.

Table 2. Geologic age naming convention.

Age	Definition	Designation
Holocene	Deposits younger than the end of either the Fraser or Wisconsin glaciations, depending on location	H
younger Pleistocene	Deposits that would yield a finite radiocarbon date (roughly younger than about 40,000 years before present)	yP
older Pleistocene	Deposits that would yield an infinite radiocarbon date (roughly greater than about 40,000 years before present)	oP
Pleistocene	Deposits where radiocarbon dating is absent and stratigraphic relations are inadequate to discriminate between a younger or older Pleistocene age	P
undivided Quaternary	Deposits that either span the Holocene and Pleistocene	Q

	epochs, or where the epochal age cannot be determined	

Table 3. Quaternary sedimentary deposit naming convention.

Depositional environment	Designation
artificial fill	afl
alluvium	al
colluvium	cv
alluvial fan deposits	af
beach deposits	b
aeolian	ae
lacustrine deposits	lc
mass-wasting and landslide deposits	ls
peat deposits	pt
terrace deposits	tr
sedimentary deposits	sd
talus deposits	tl
glacial advance outwash	gao
glacial recessional outwash	gro
glacial outwash	go
glaciolacustrine deposits	gl
glacial drift	gd
glacial till	gt
glacial outburst flood deposits	gf
glaciolacustrine and glacial outburst flood deposits	glf
glaciomarine drift	gmd
lahars	lh
tuff and tuff breccias	tf
volcaniclastic deposits	vc

Table 4. Grain texture naming convention.

Grain texture	Classification	Designation
predominately gravel and sand	coarse	c
predominately sand and silt	sandy	s
predominately silt and clay	fine	f
texture unknown or deposit well-graded and highly variable	texturally undifferentiated	no letter designation is used

The Location and Velocity tables are related by the unique identifier field Site_ID. The Location table gives an overview of each Vs survey including: the data source, the site name, the date the survey was completed, the depth surveyed, the number of geologic units measured at each site and the XY location where the survey was completed using the North American Datum (NAD) 1983 High Accuracy Reference Network (HARN) State Plane Washington South Federal Information Processing Standard 4062 coordinate system with US survey feet as the base unit. The Velocity table gives the result of the shear wave velocity surveys for each geologic unit. Appendix D provides an overview of the database structure summarizing the names, data types, and description of each field in the three tables.

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Appendix A

Standard survey setup form page 1.

Site Name:	Date:	Recorder's Name:

Location:
N _____
W _____
Waypoint name:
_____
Projection: _____

Geologic Observations:
(or geology to be tested, if known)

Photos:
(name or number & brief description)

Note any possible source of interference:
(For example: close buildings, trees & wind, other weather, power lines, traffic)

Describe survey ground:
(Is it flat? Is it dry or wet?)

Geometry:
Line Strike: _____
S-Wave phone polarity: _____
Phone Interval: _____

Phone # 1:
Compass: _____
LOC: _____
Phone # 24:
Compass: _____
LOC: _____

Acquisition Setup:
Directory: _____
Sample interval: S-wave:_____ P-wave:_____
Record Length: S-wave:_____ P-wave:_____

Trigger mechanism: _____
S-wave sensitivity: _____
P-wave sensitivity: _____
Acquisition Filter:
Filter #1: _____
Filter #2: _____

Background Noise:
S-Wave phones: _____ (mV)
Is it consistent?

P-Wave phones: _____ (mV)
Is it consistent?

Notes: (Site contact information or other notes)

Appendix A

Standard survey setup form page 2.

Recorder / Seismograph Operator:			**Energy Source Operator:**			**Assistants:**	
File Name	**Shot Distance** (m)	**Shot Location** (LOC)	**Line Side** (compass direction)	**Beam Side** (compass direction)	**Swing Polarity** (+ or -)	**Stack Polarity** (+ or -)	**# of Stacks**
Comments:							
Comments:							
Comments:							
Comments:							
Comments:							
Comments:							
Comments:							
Comments:							
Comments:							
Comments:							
Comments:							
Comments:							
Comments:							
Comments:							
Comments:							

Appendix B

Standard first shear-wave arrival picking form.

Site Name:	Date:	Recorder's Name:

Name of the file Read:	Sample Points Read:
_____	☐ Just the left half. ☐ Every 2nd point. ☐ Every 4th point.

Frequency Filters:

Filter Applied:		Number of Applications:
Filter 1:	_____ Hz	_____
Filter 2:	_____ Hz	_____
Filter 3:	_____ Hz	_____
Filter 4:	_____ Hz	_____
Filter 5:	_____ Hz	_____

Arrival Times:

First arrival time: _____ ms Last arrival time: _____ ms

Pick Offset
(Time increment for picking behind first break)

Phone/trace of time measurement: _____

Time increment: _____ ms

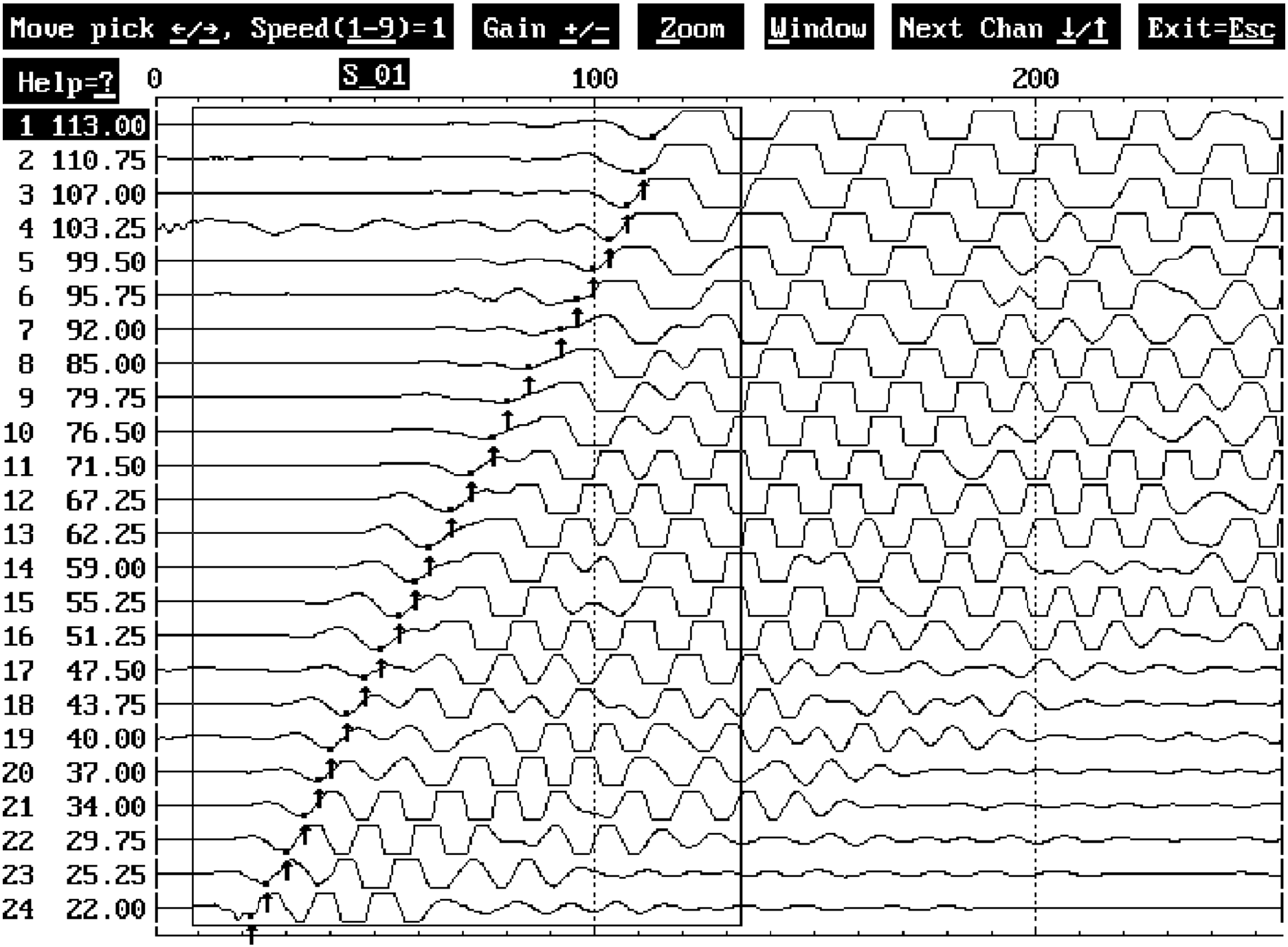
Phones/traces adjusted: _____

☐ Did you save the image of the final First Break Picks?

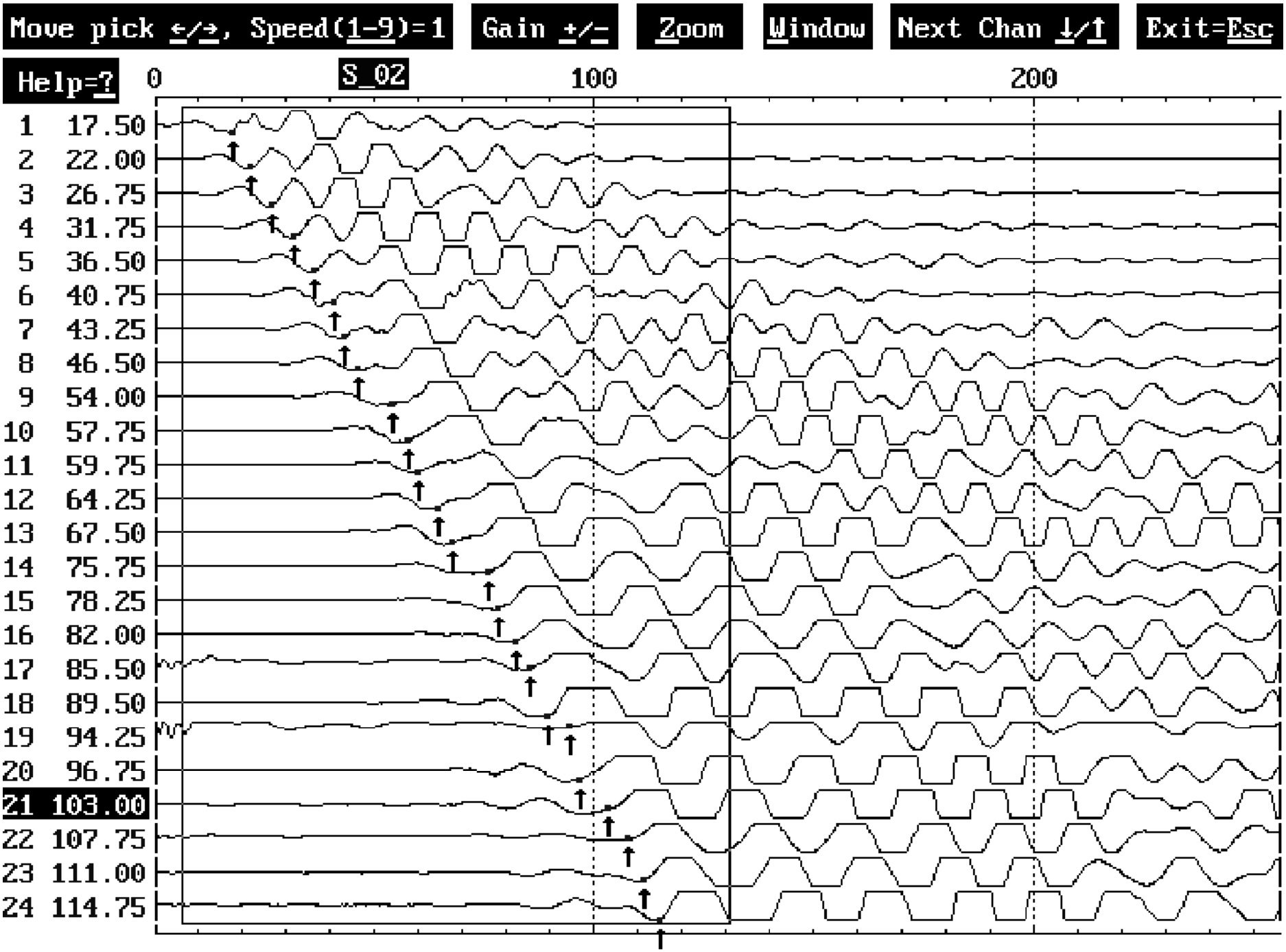
★ **When finished with all *.dat files in a survey remember to save/print images of the SIPIN final layer assignments and the SIPT2 depth models with the calculated layer velocities indicated.**

★ **After the depth models have been produced, do minimum depth calculations for all S-wave surveys that require a minimum depth to characterize the site.**

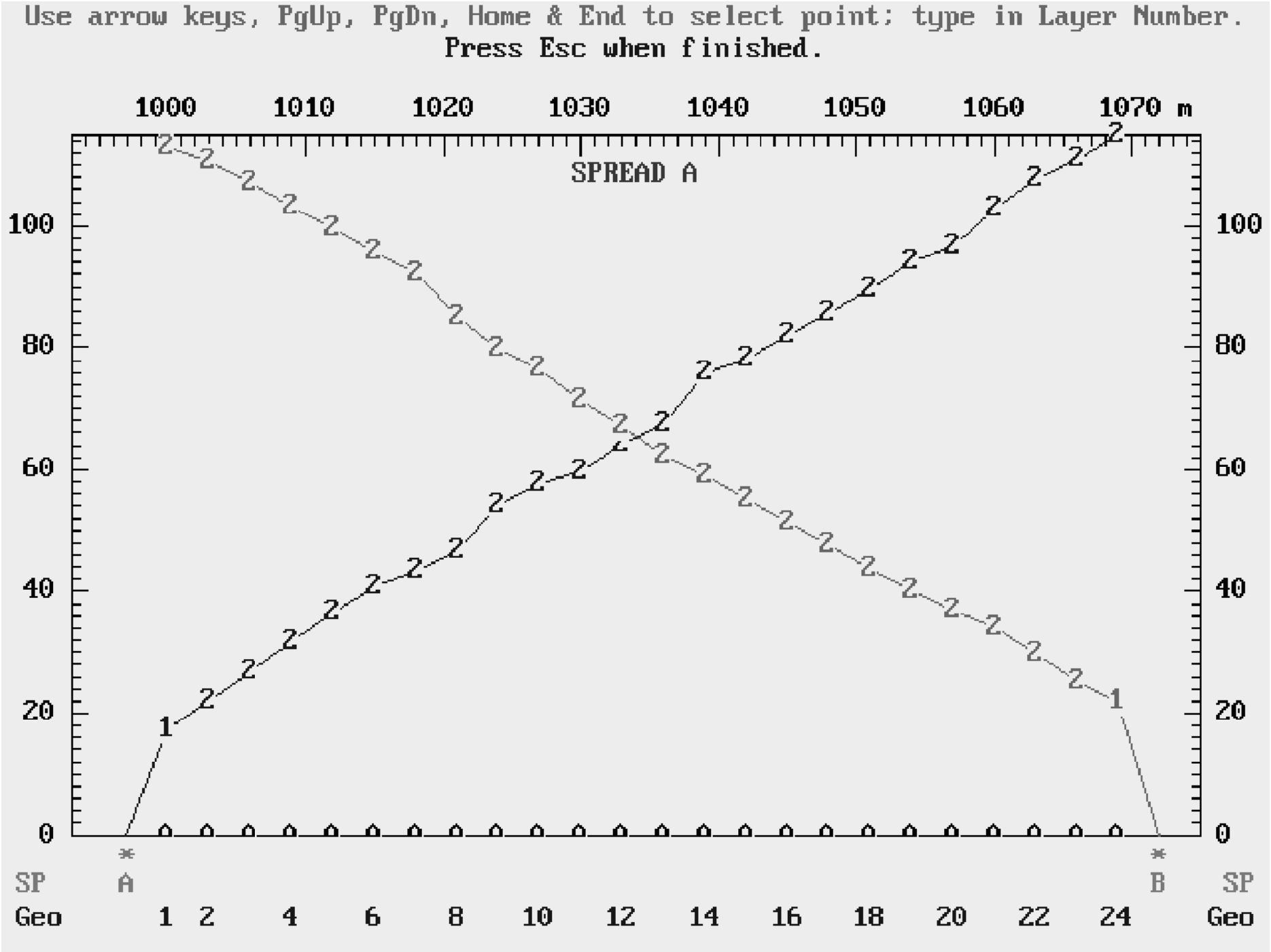
202nd Place S-wave



202nd Place S-wave



202nd Place S-wave



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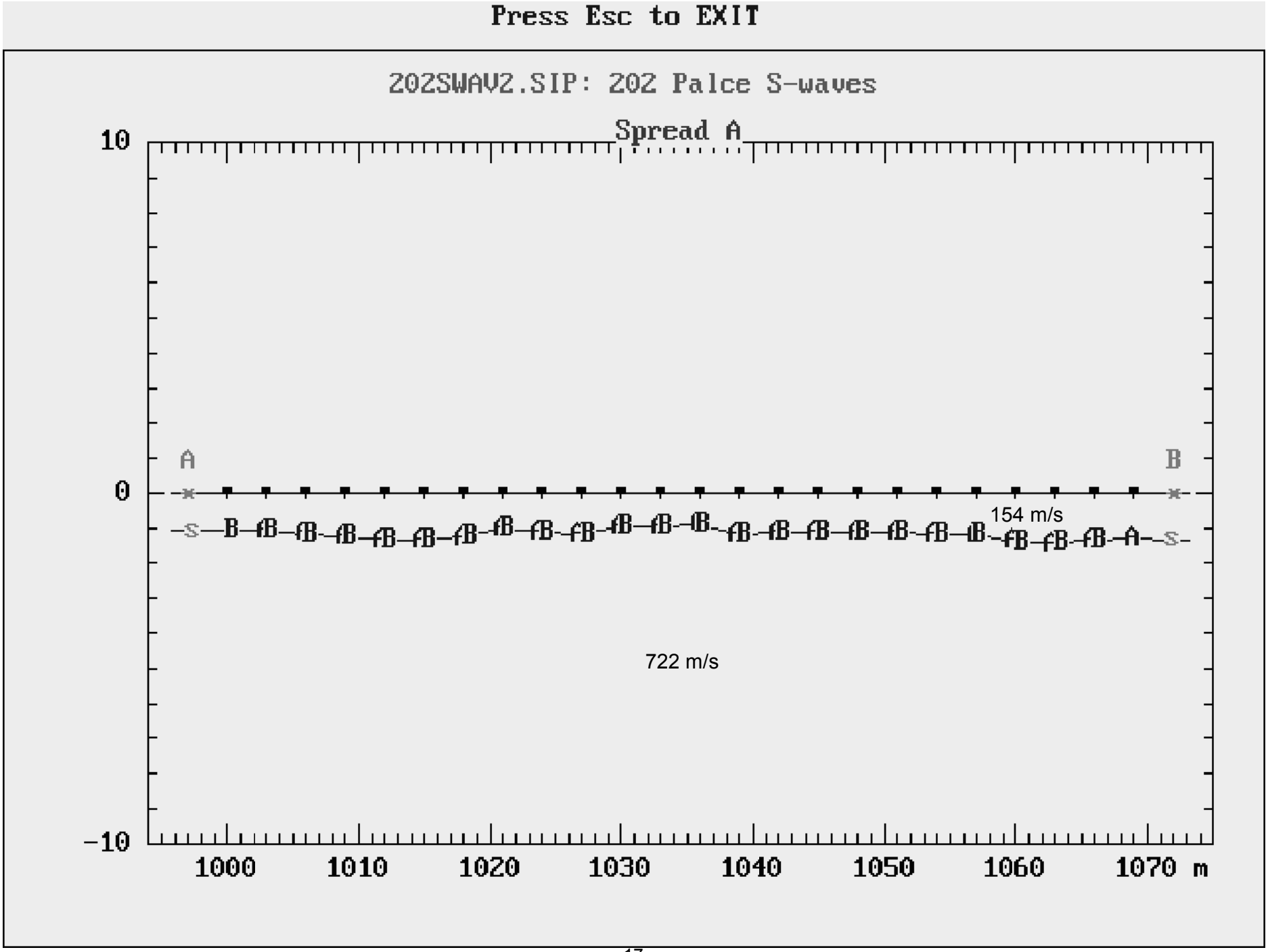

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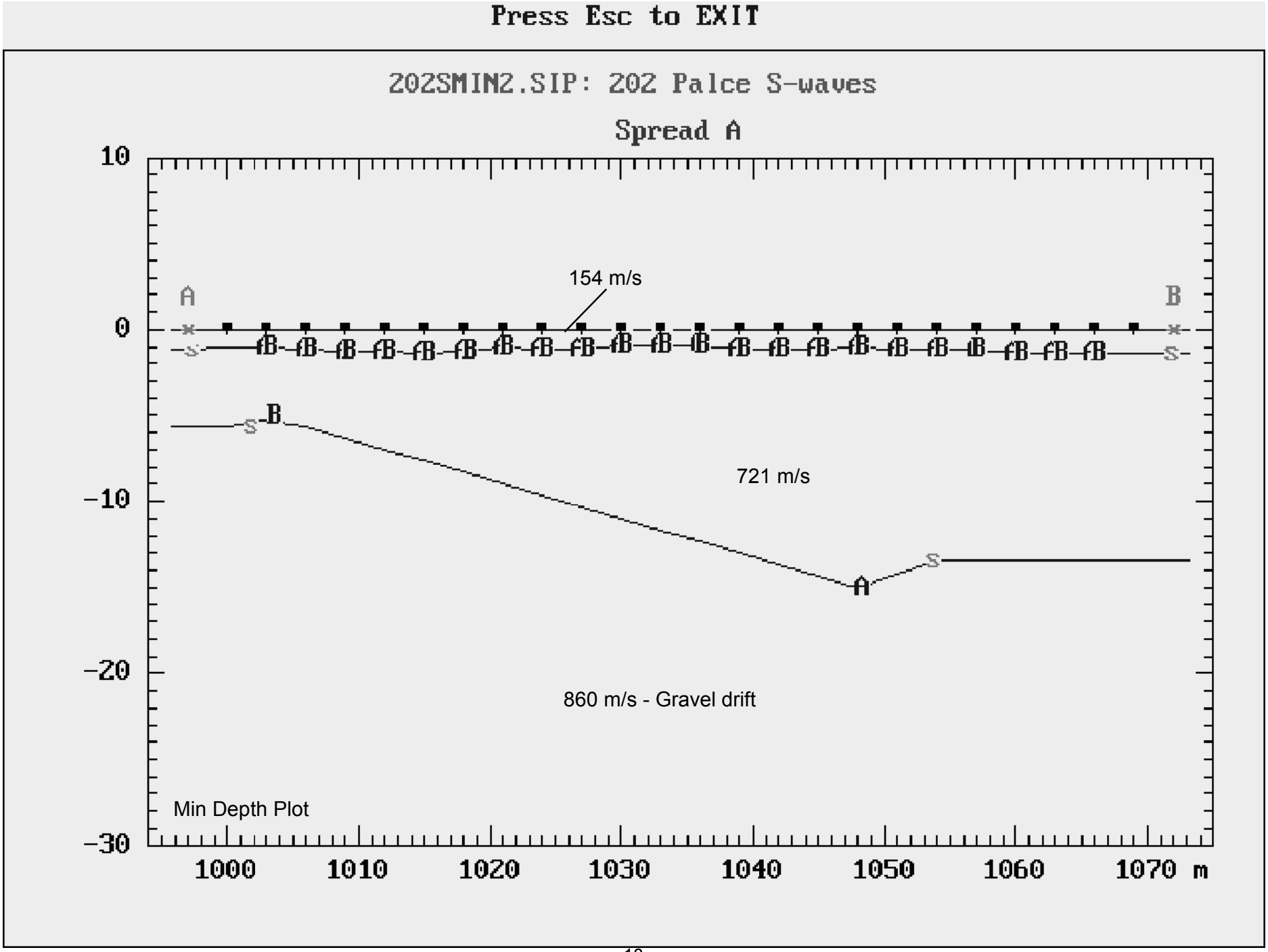
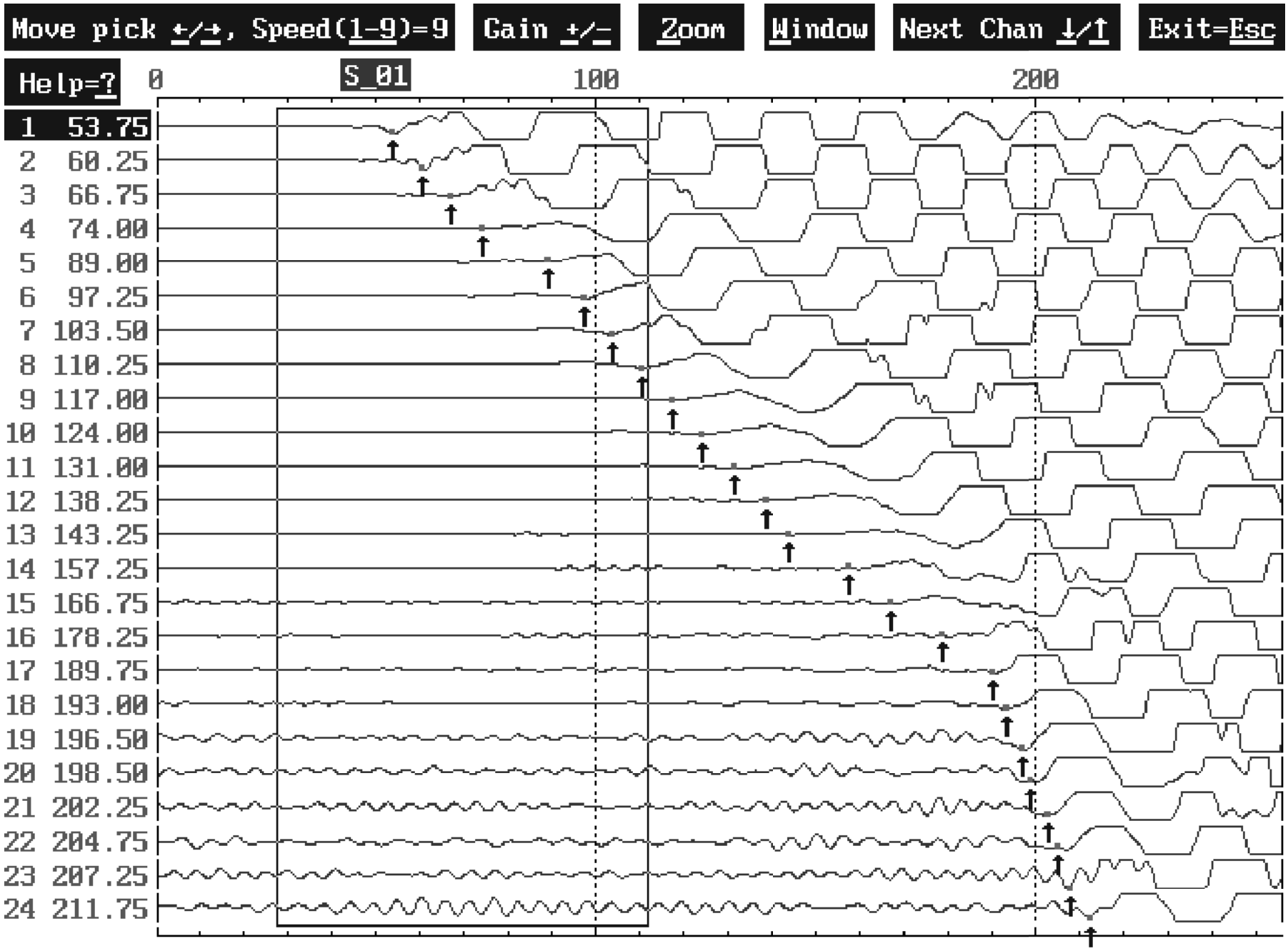


Clark County 389th ST S-wave



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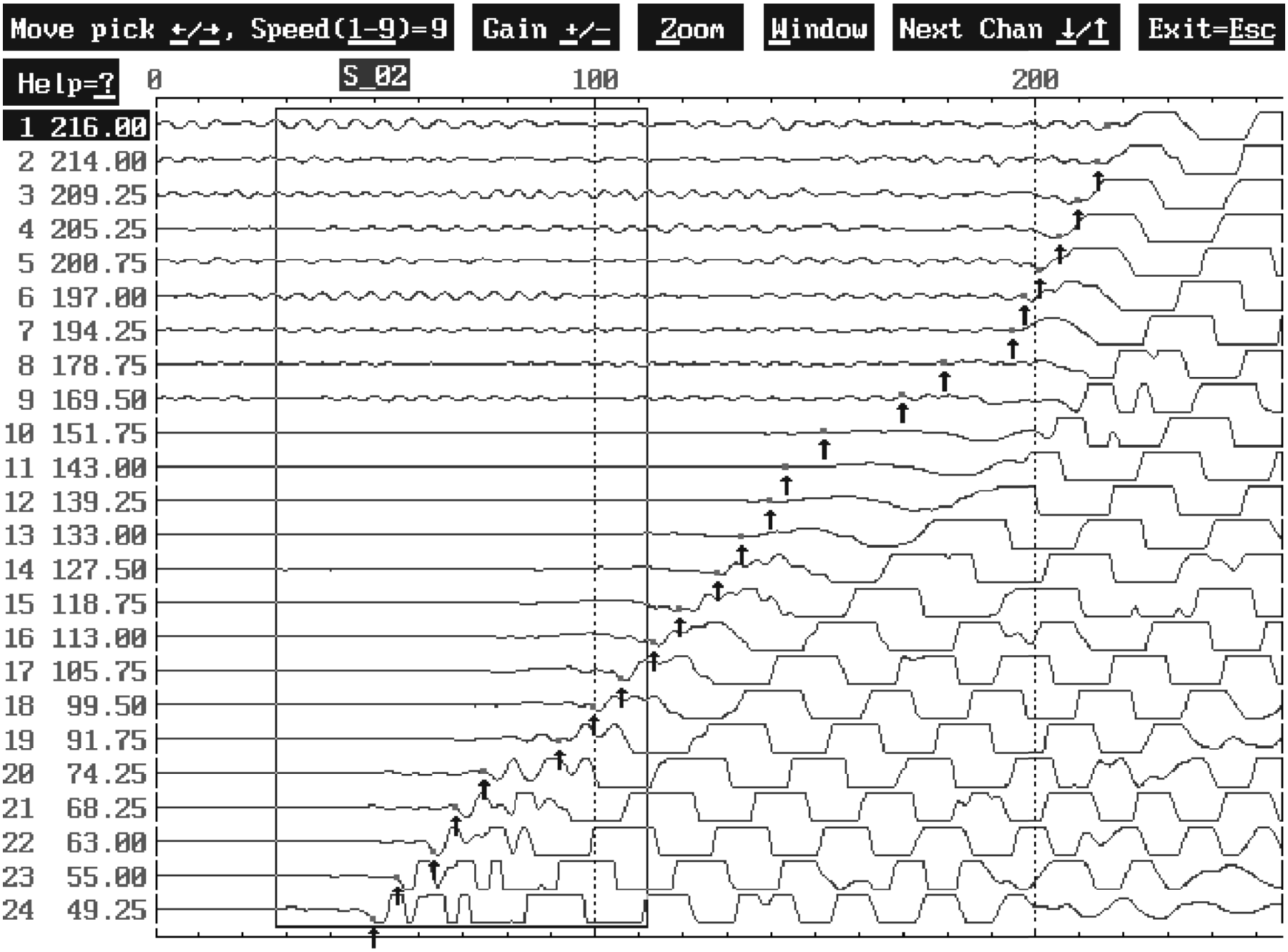

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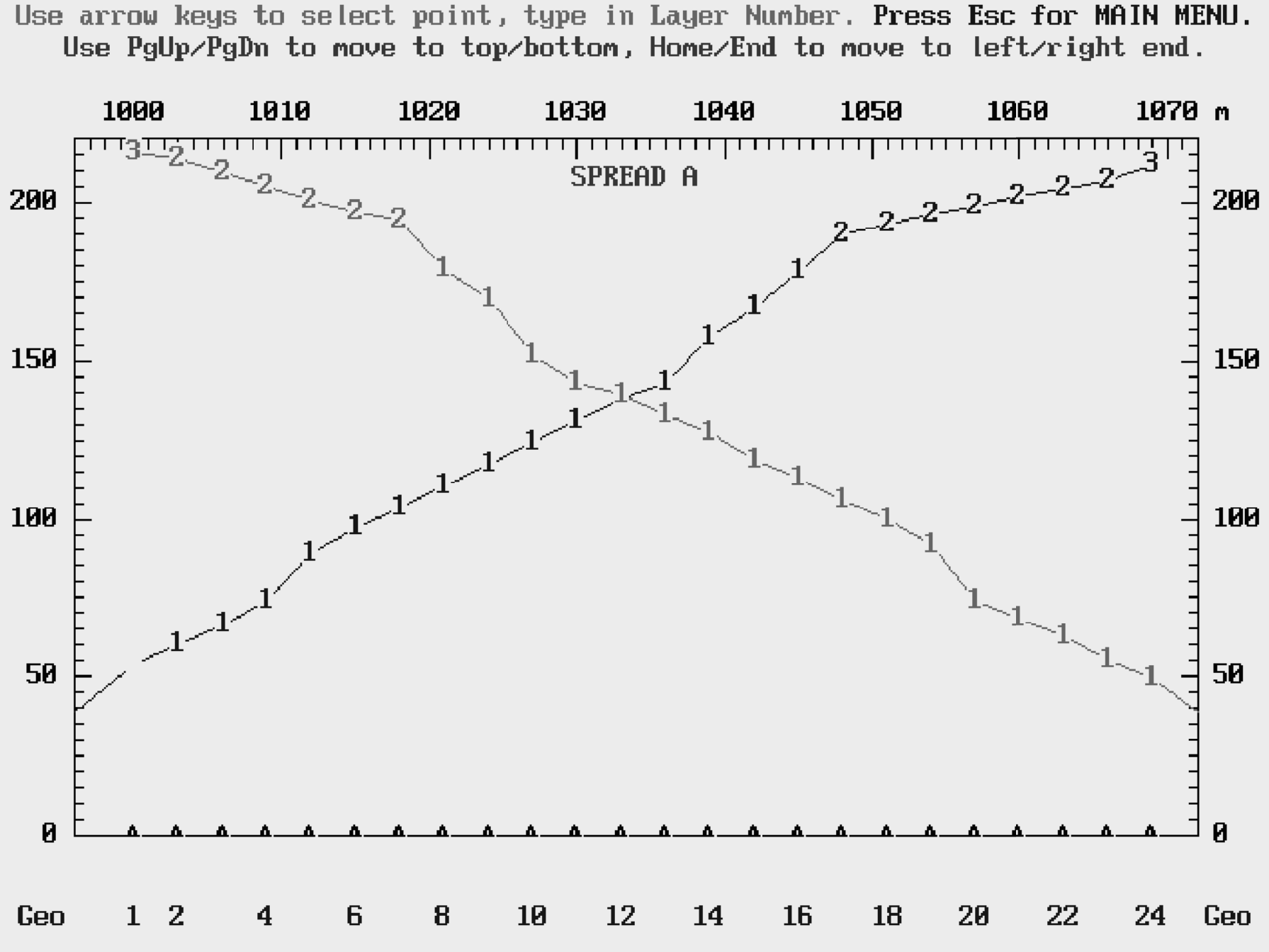

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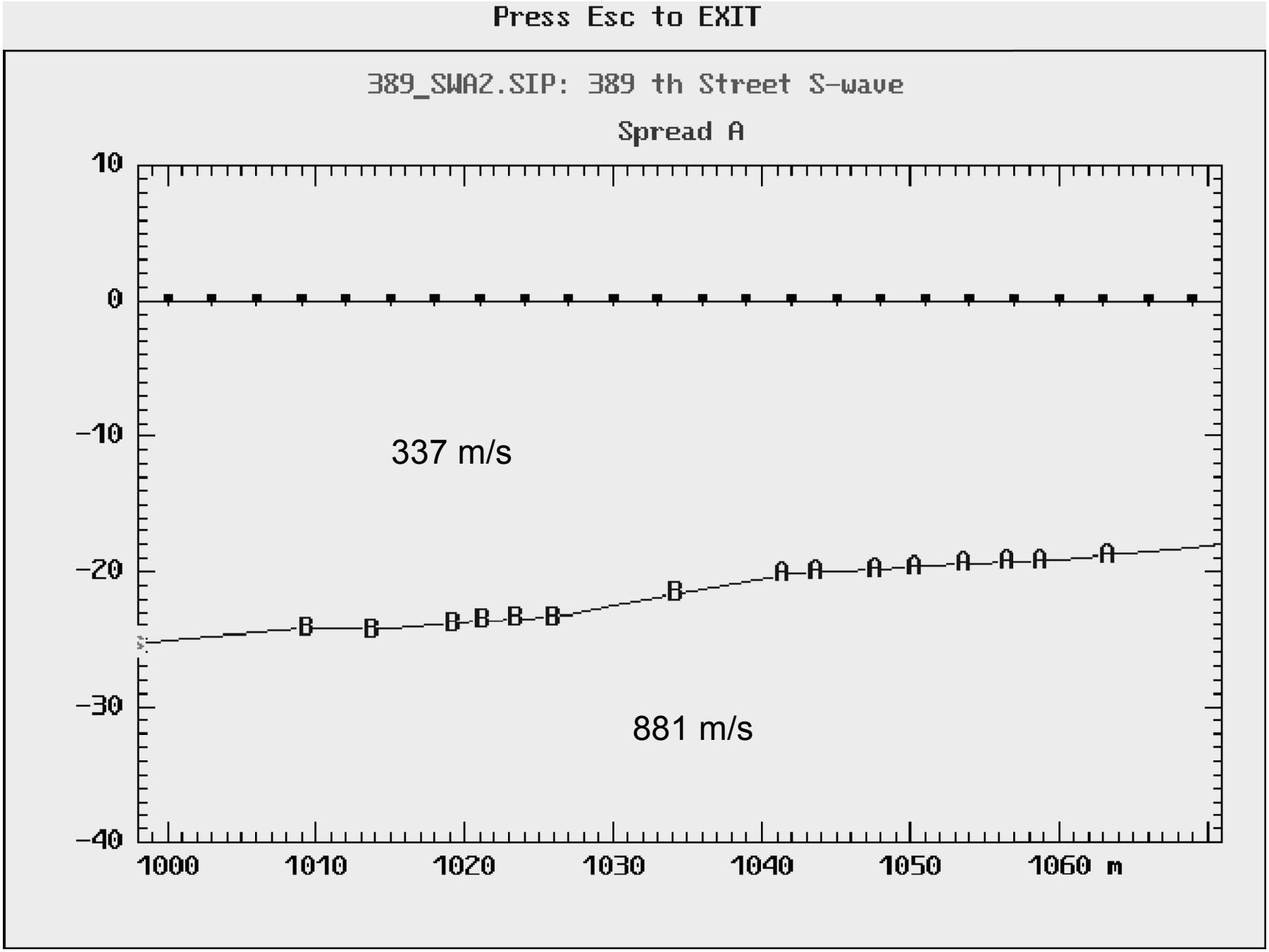
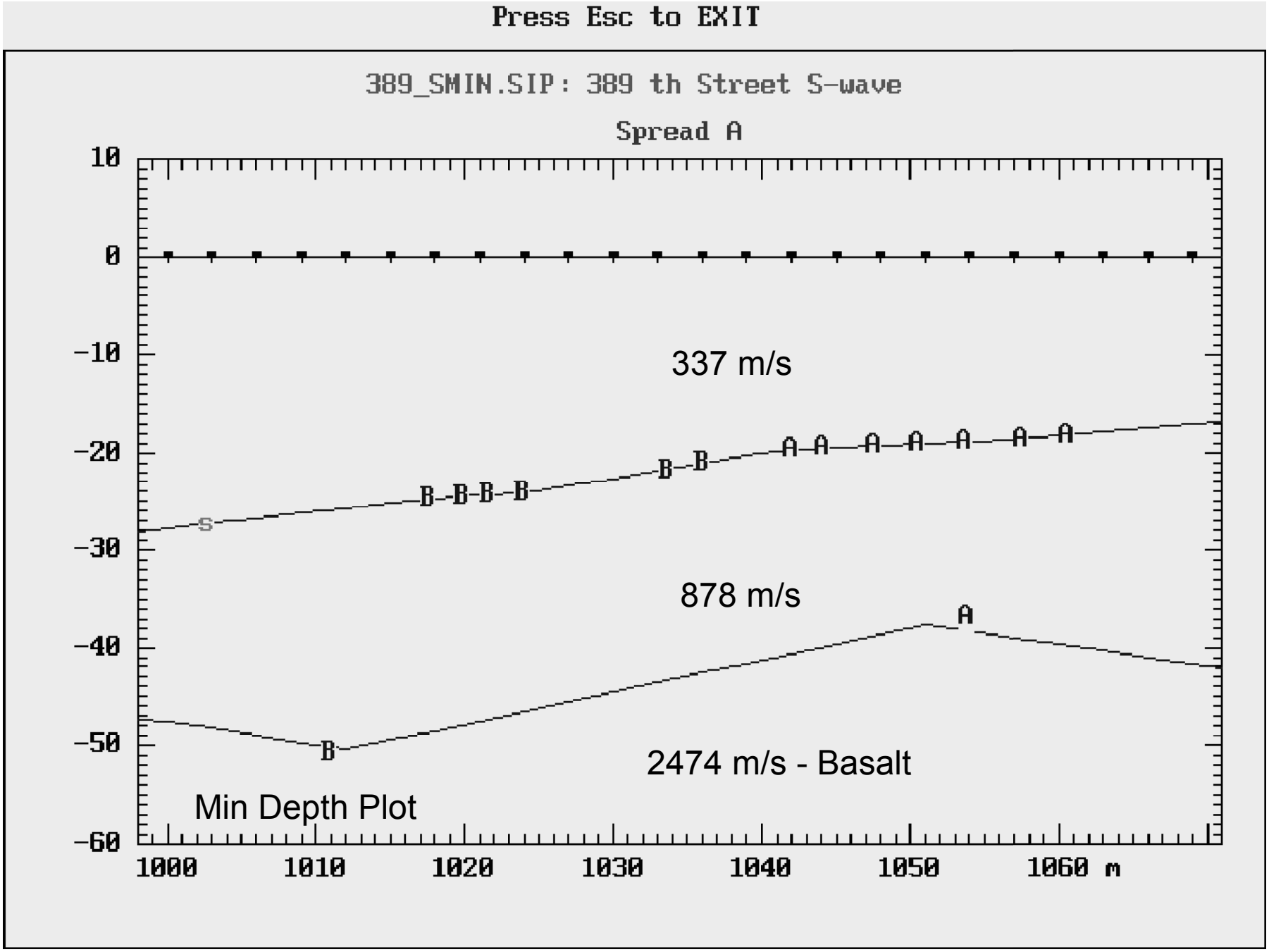
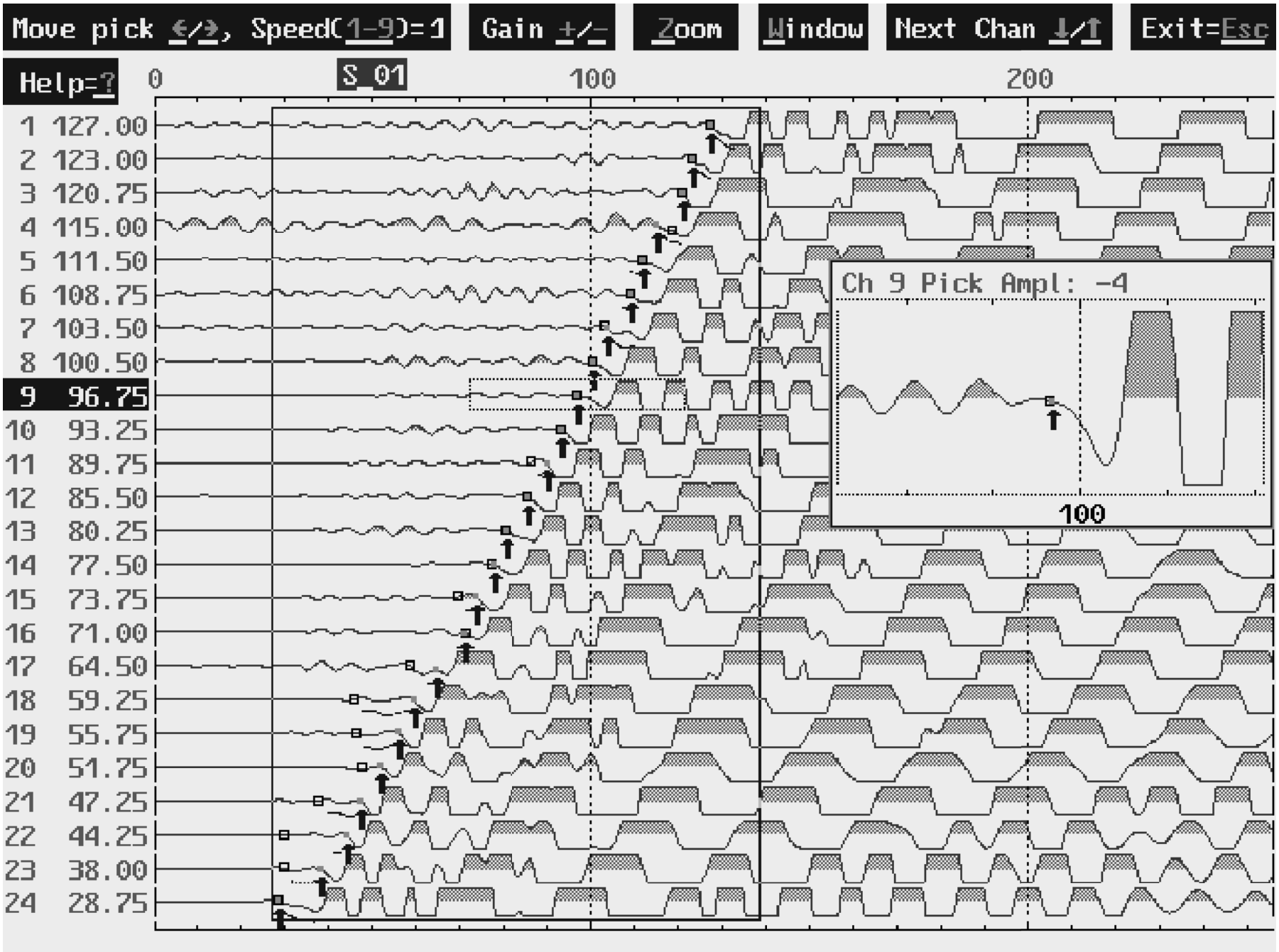


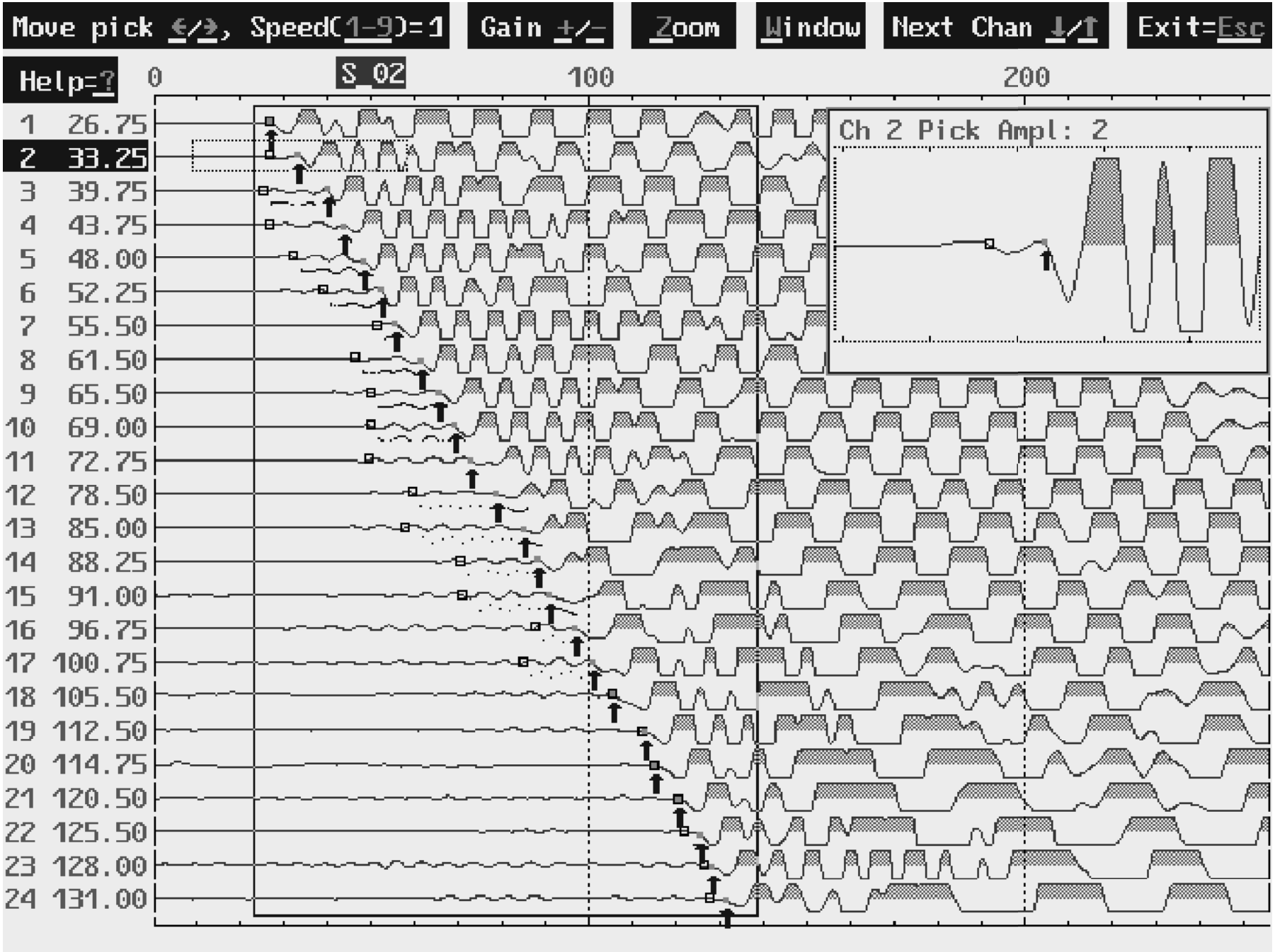
Clark County 389th ST S-wave



68th Ave Snohomish County S-wave



68th Ave Snohomish County S-wave



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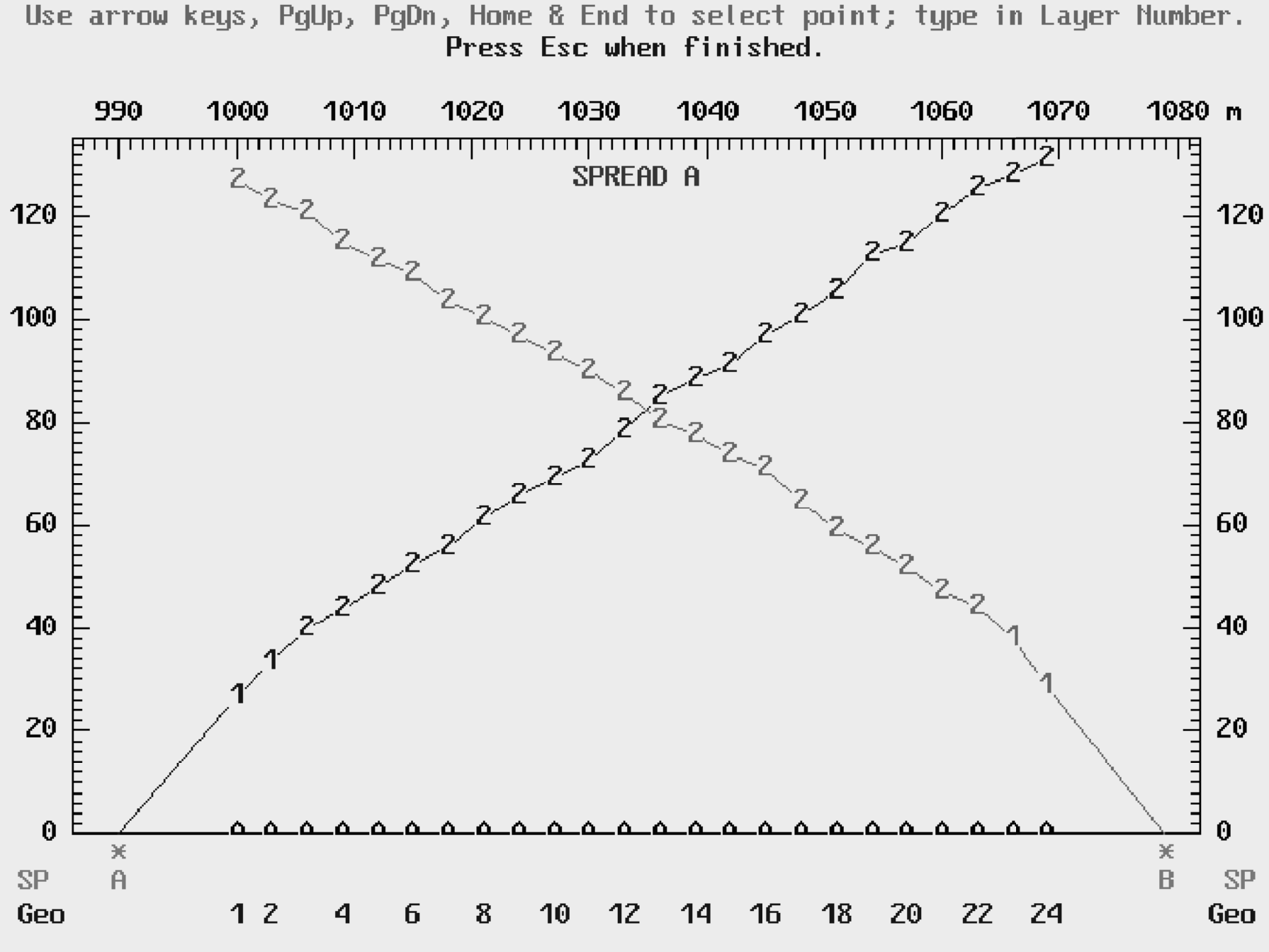

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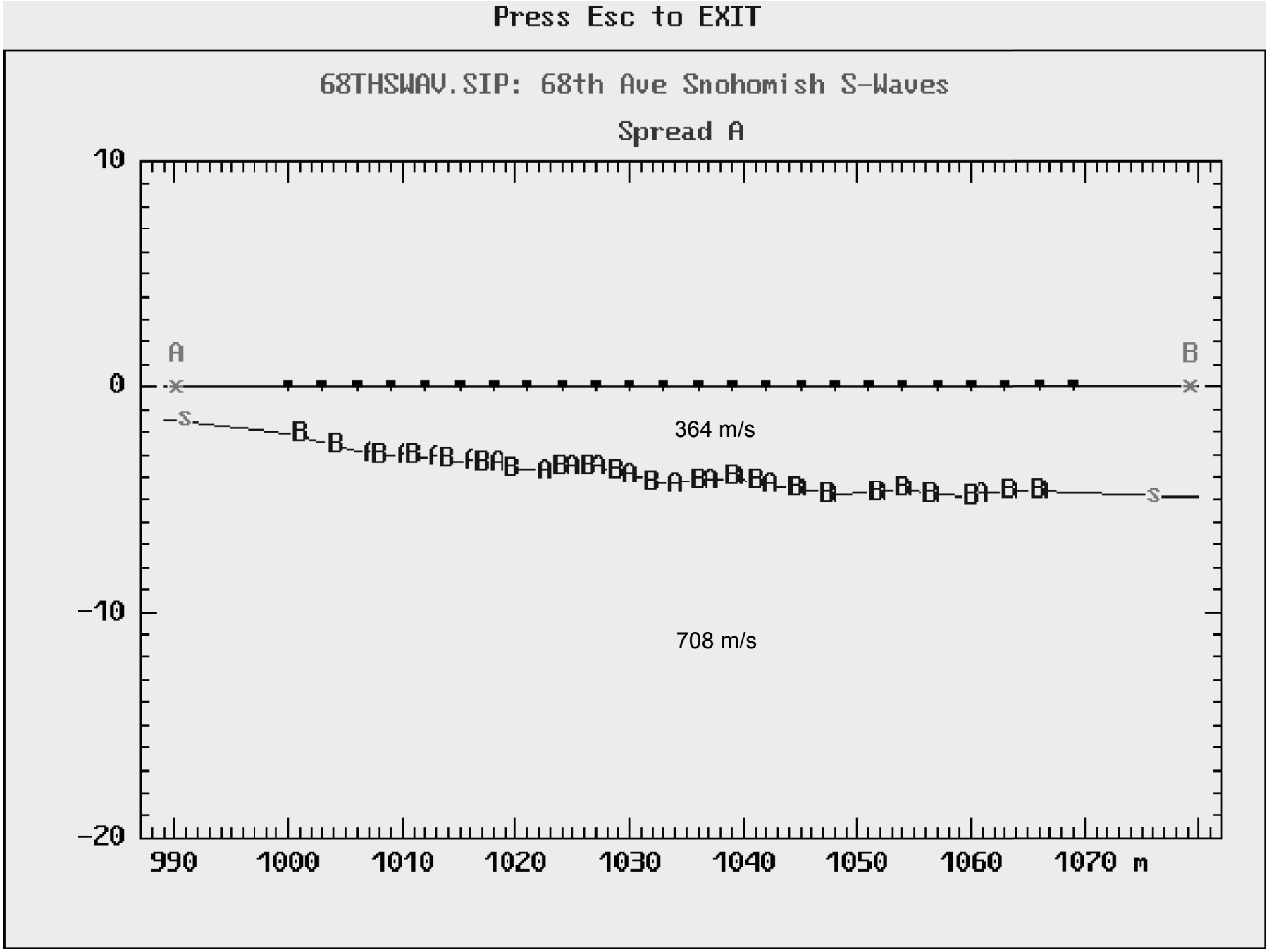

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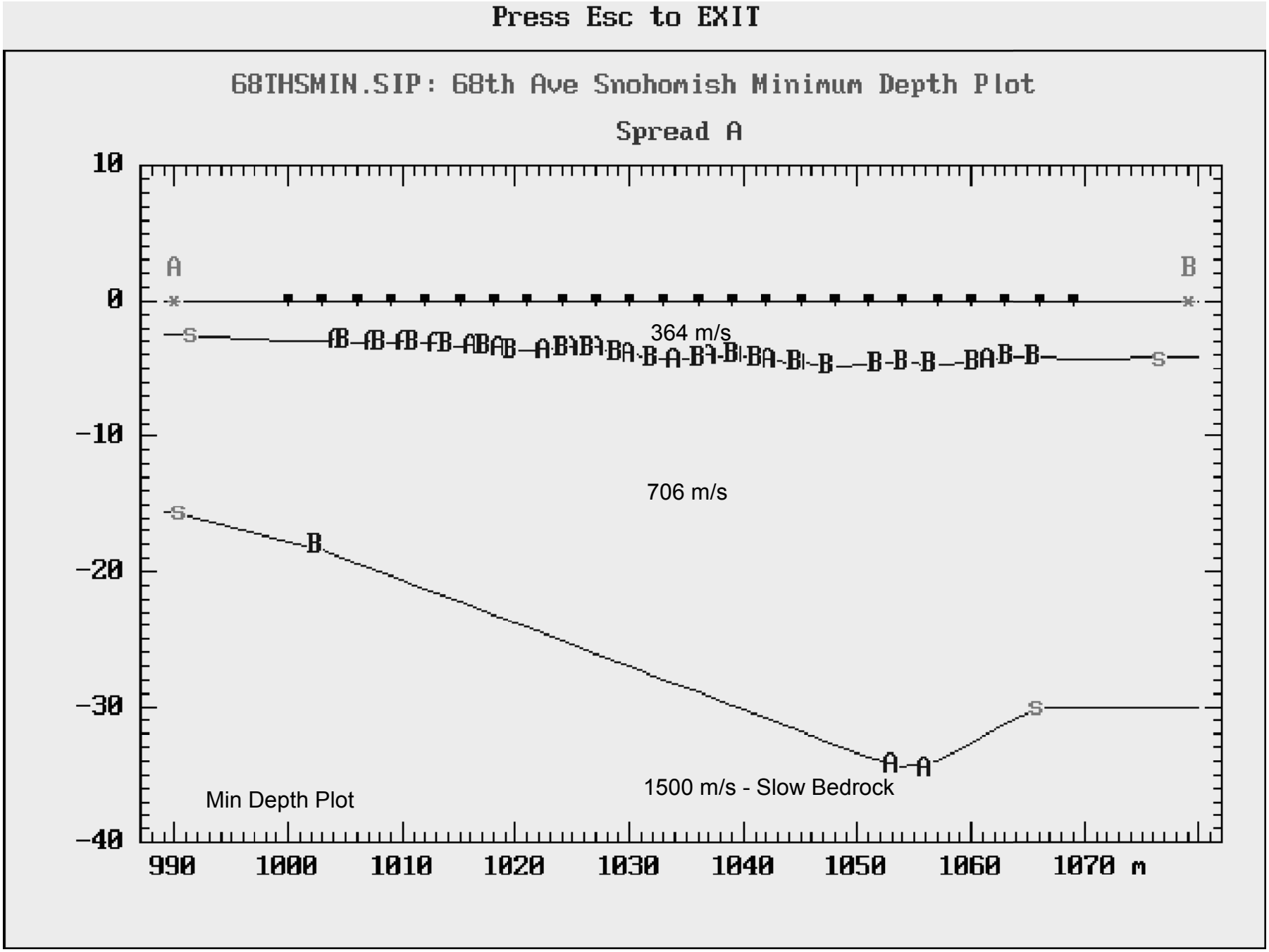
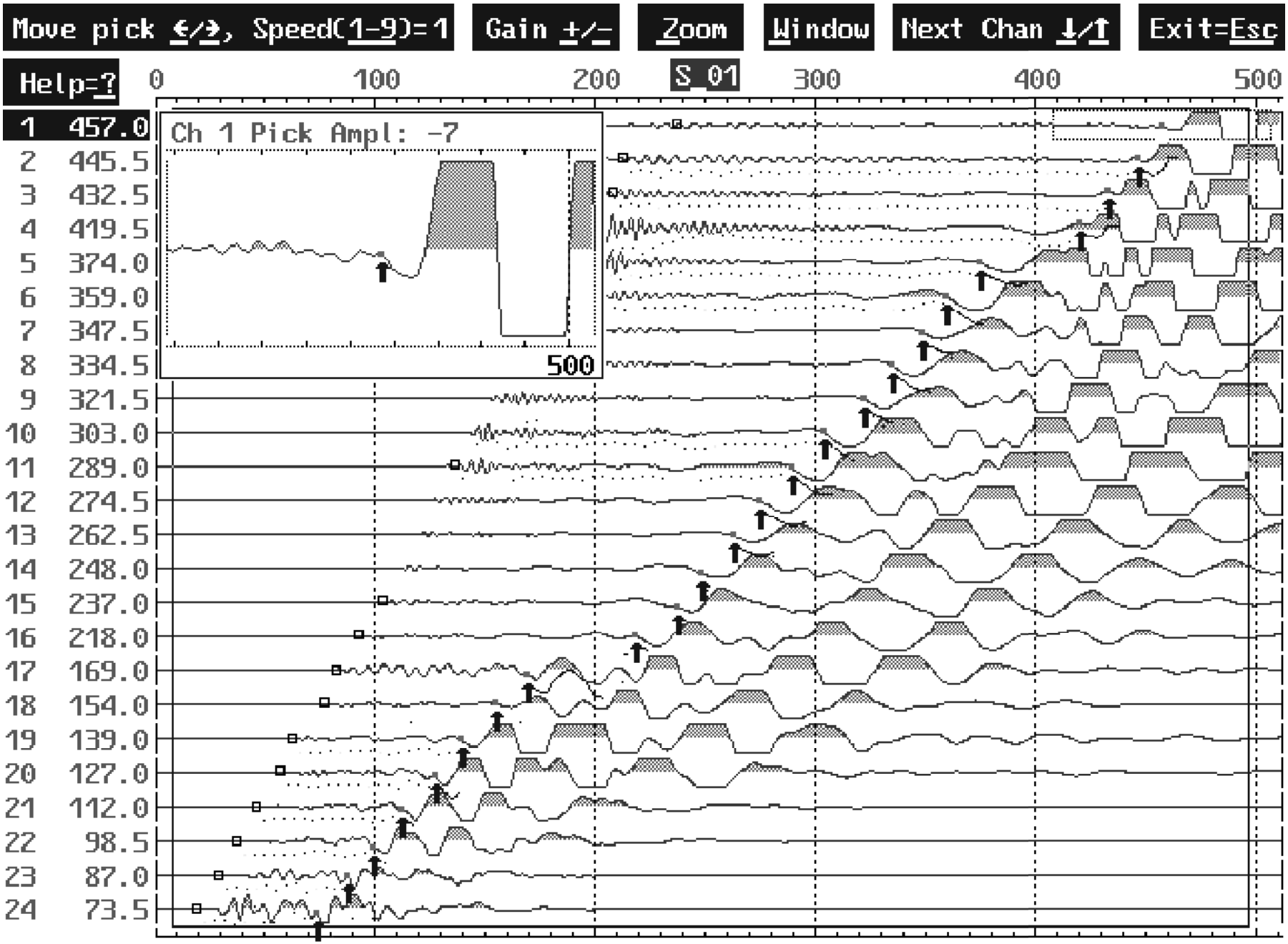


Abbot Road S-wave



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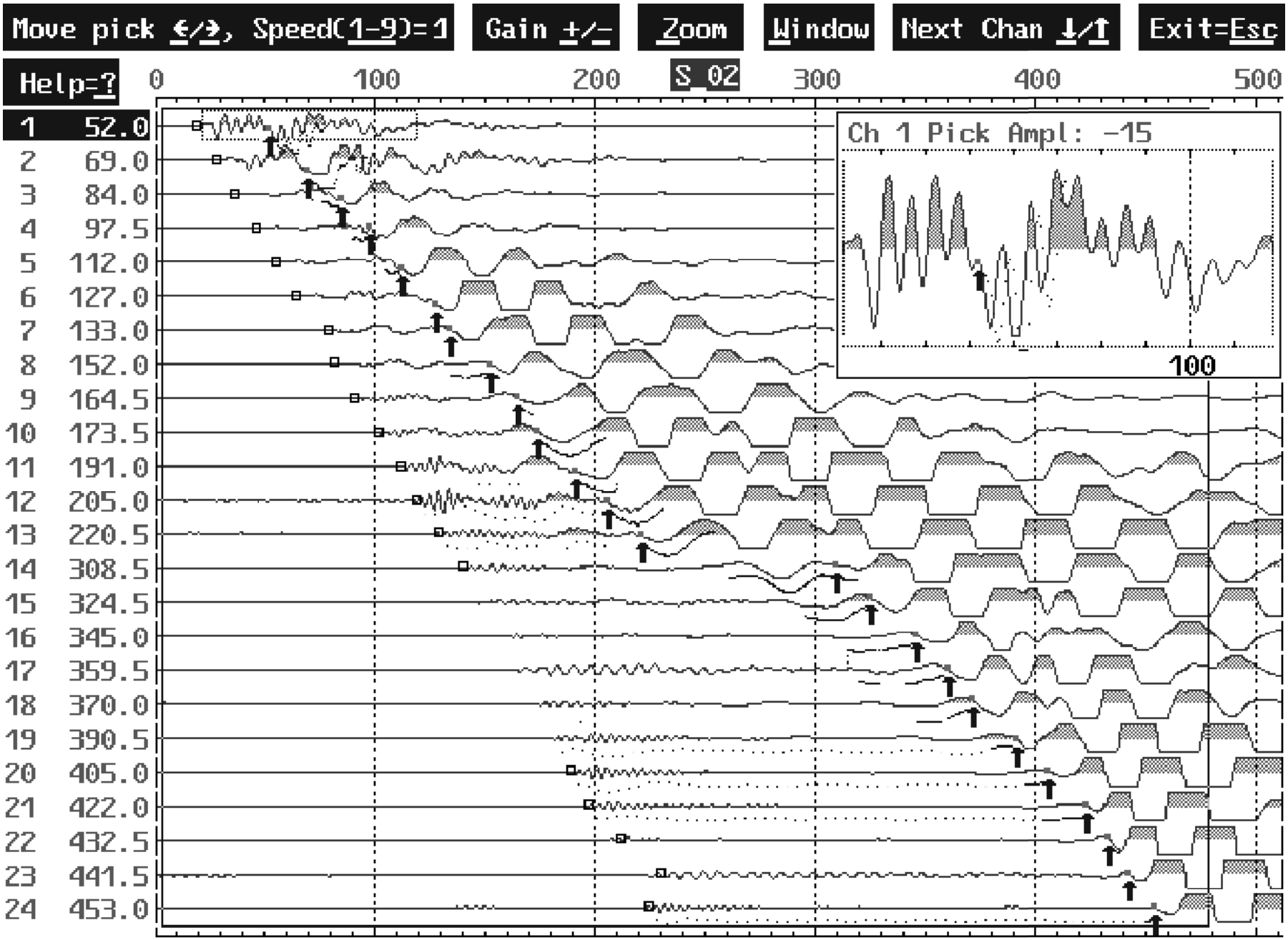

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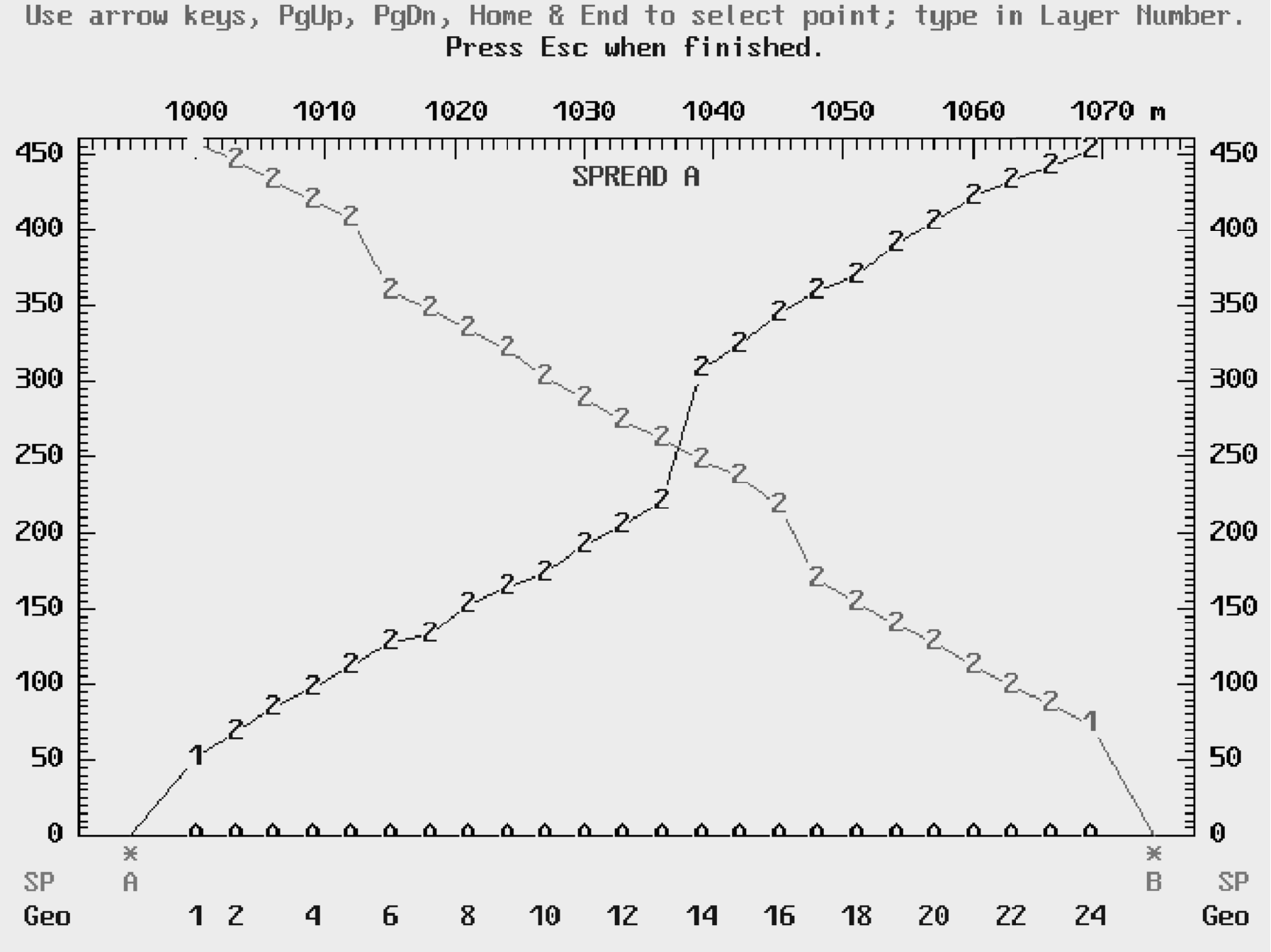

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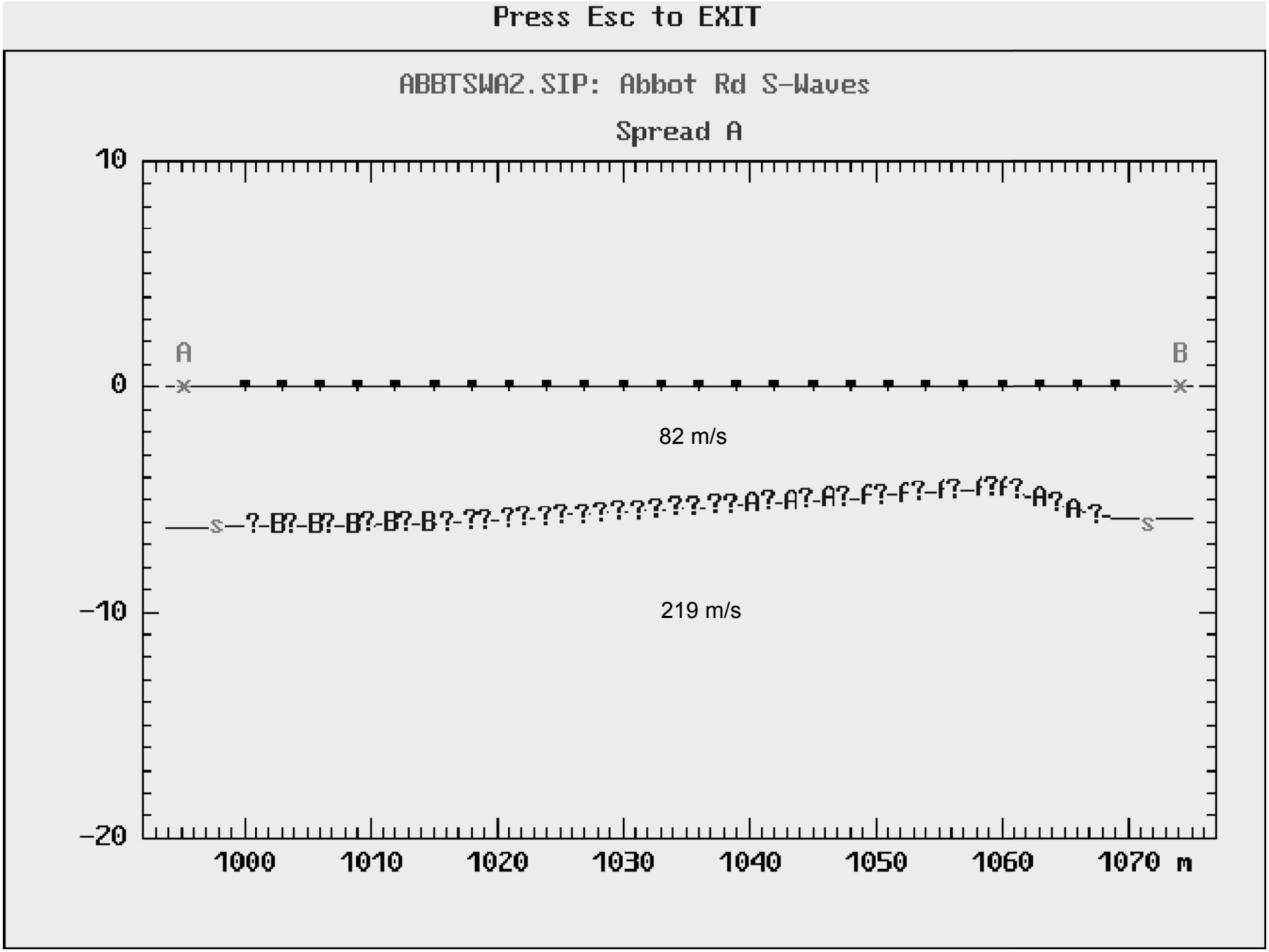

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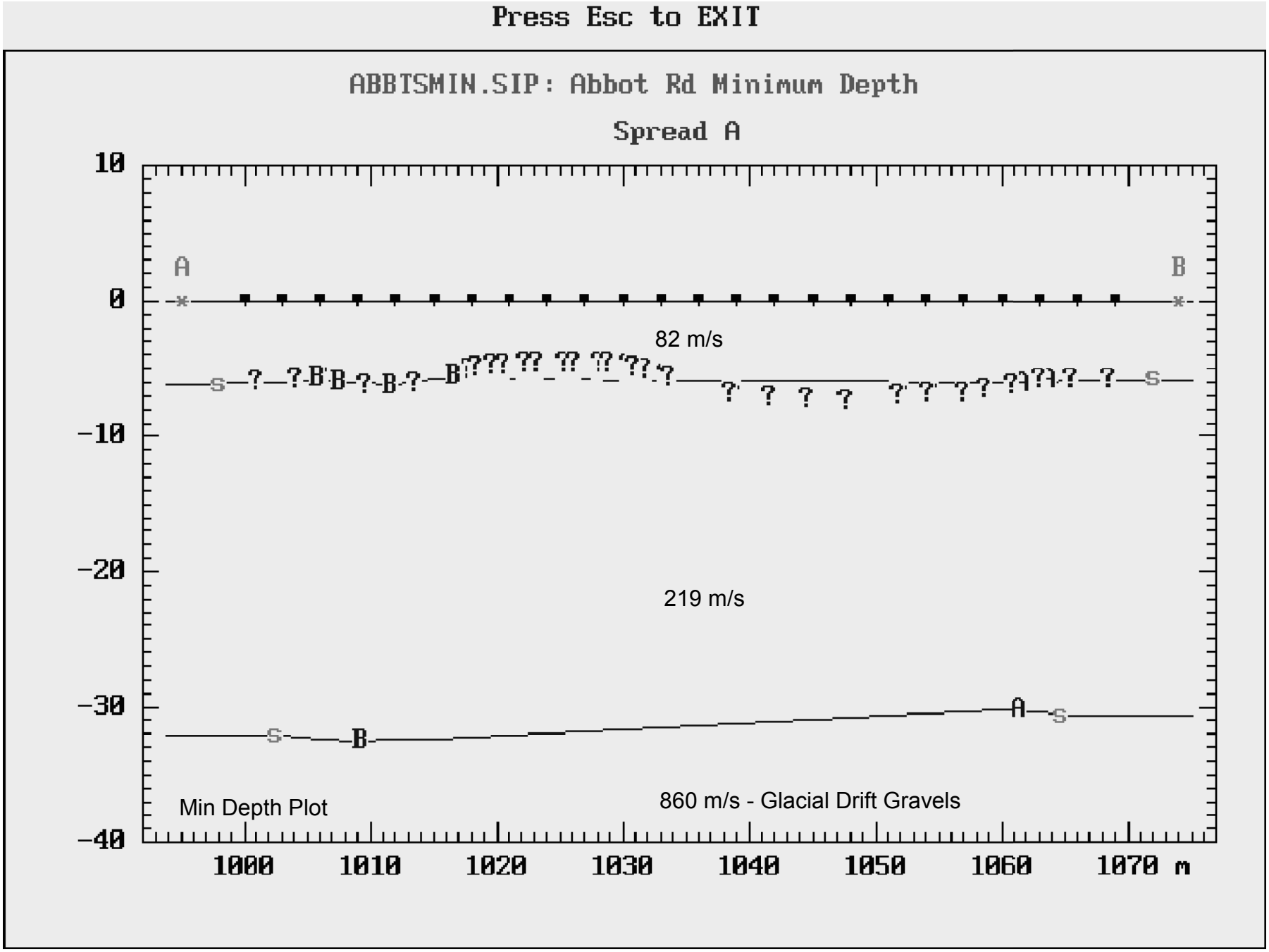
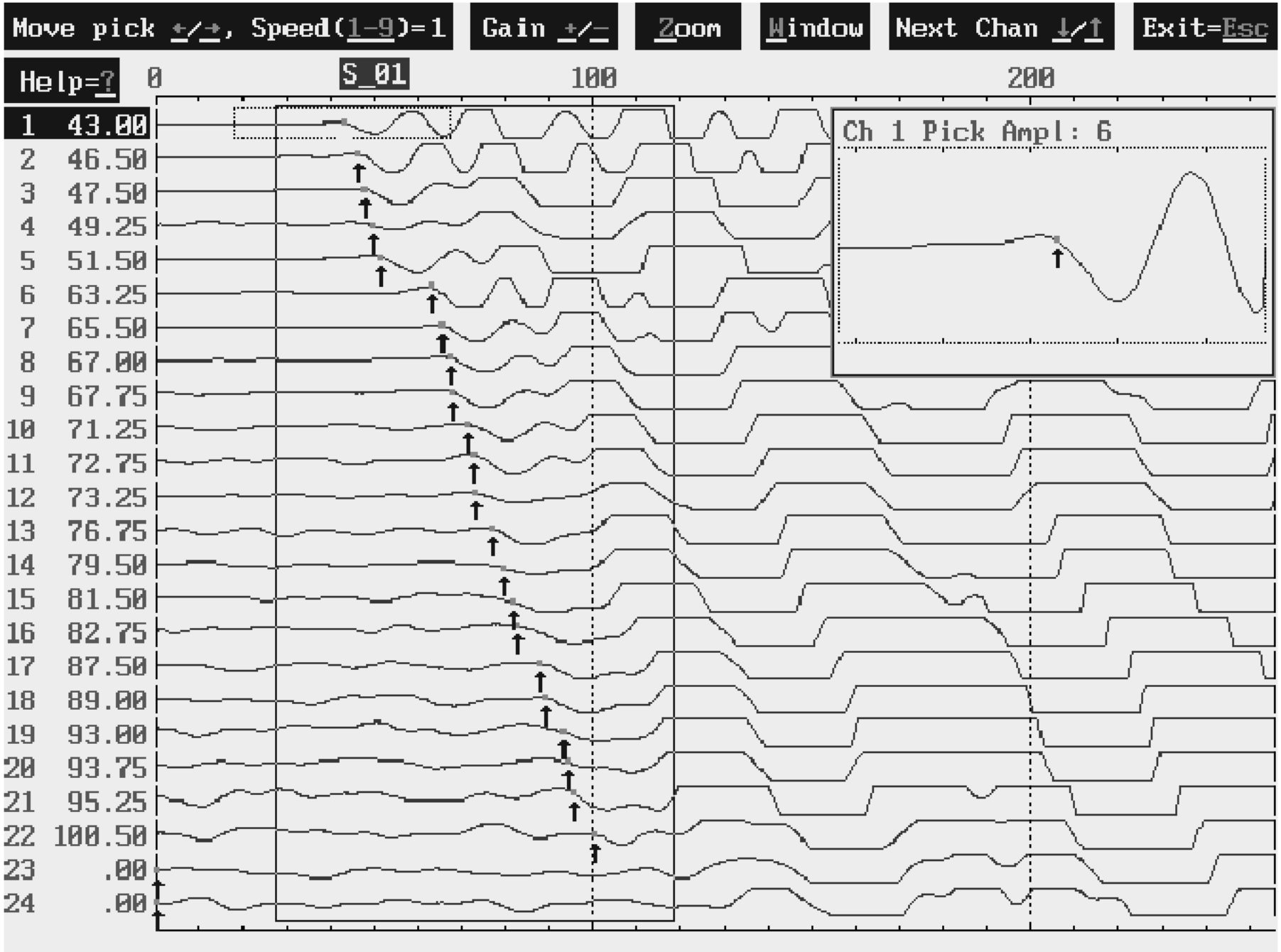


Ahtanum Valley Elementary S-wave



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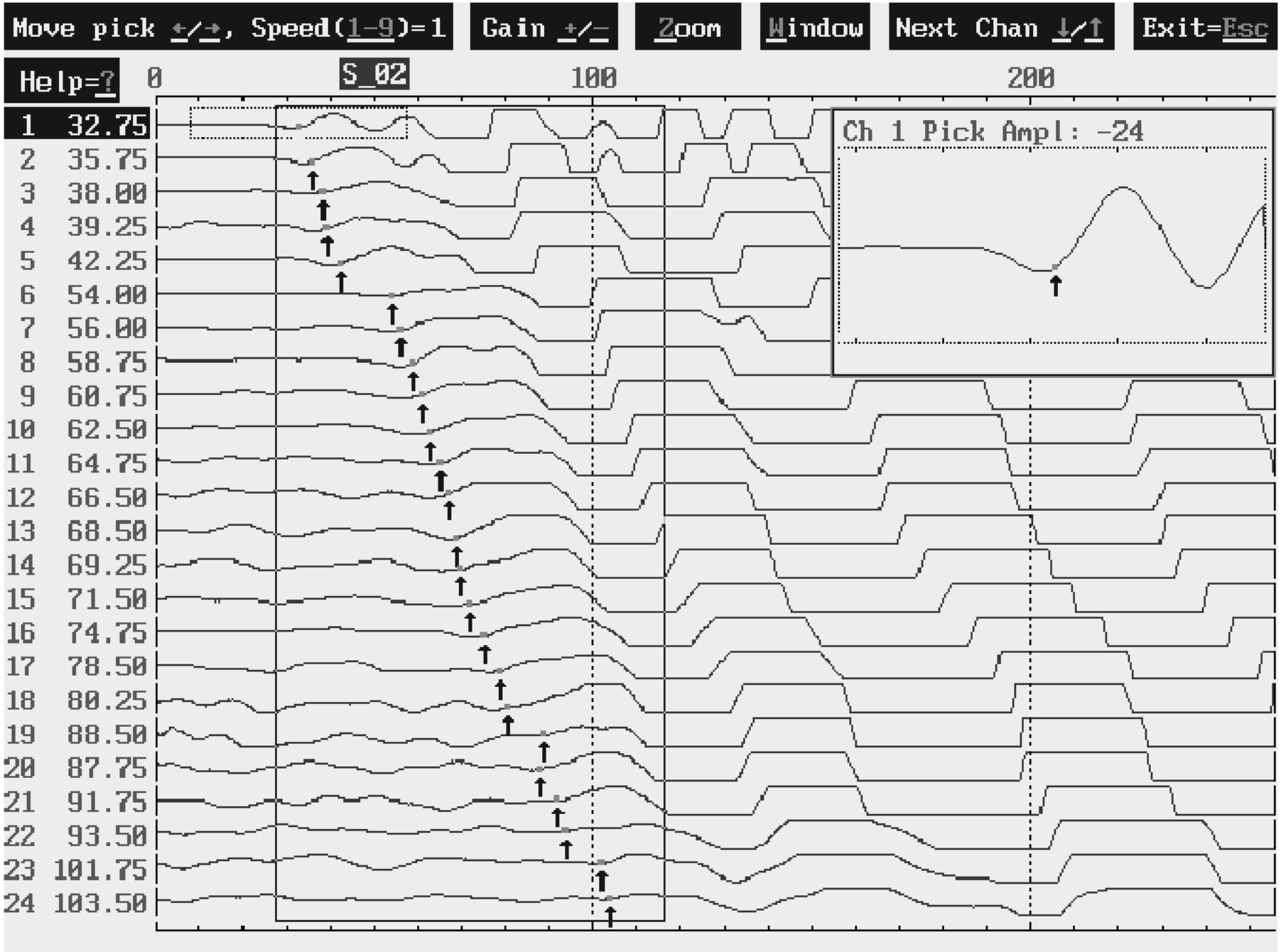

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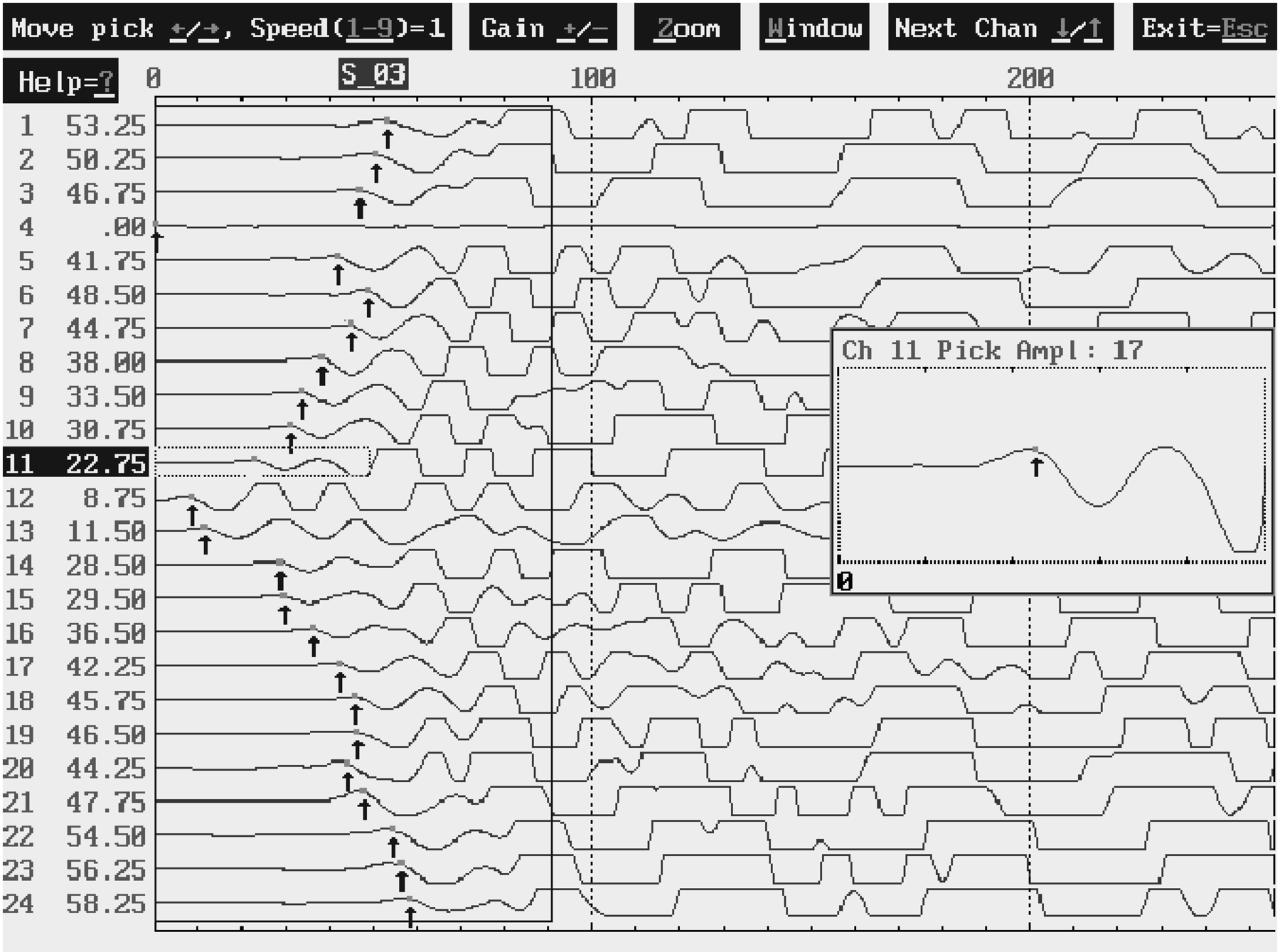

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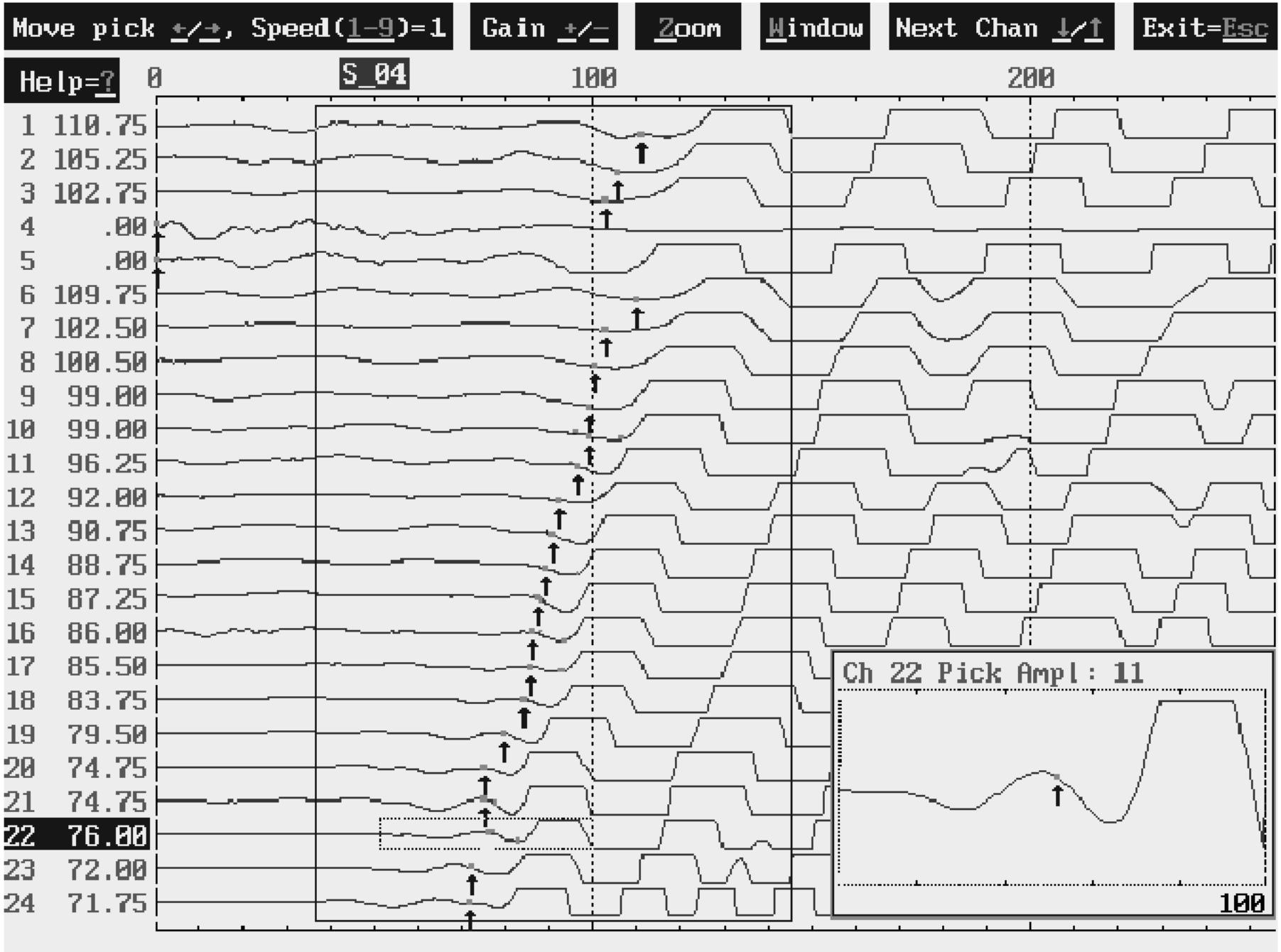

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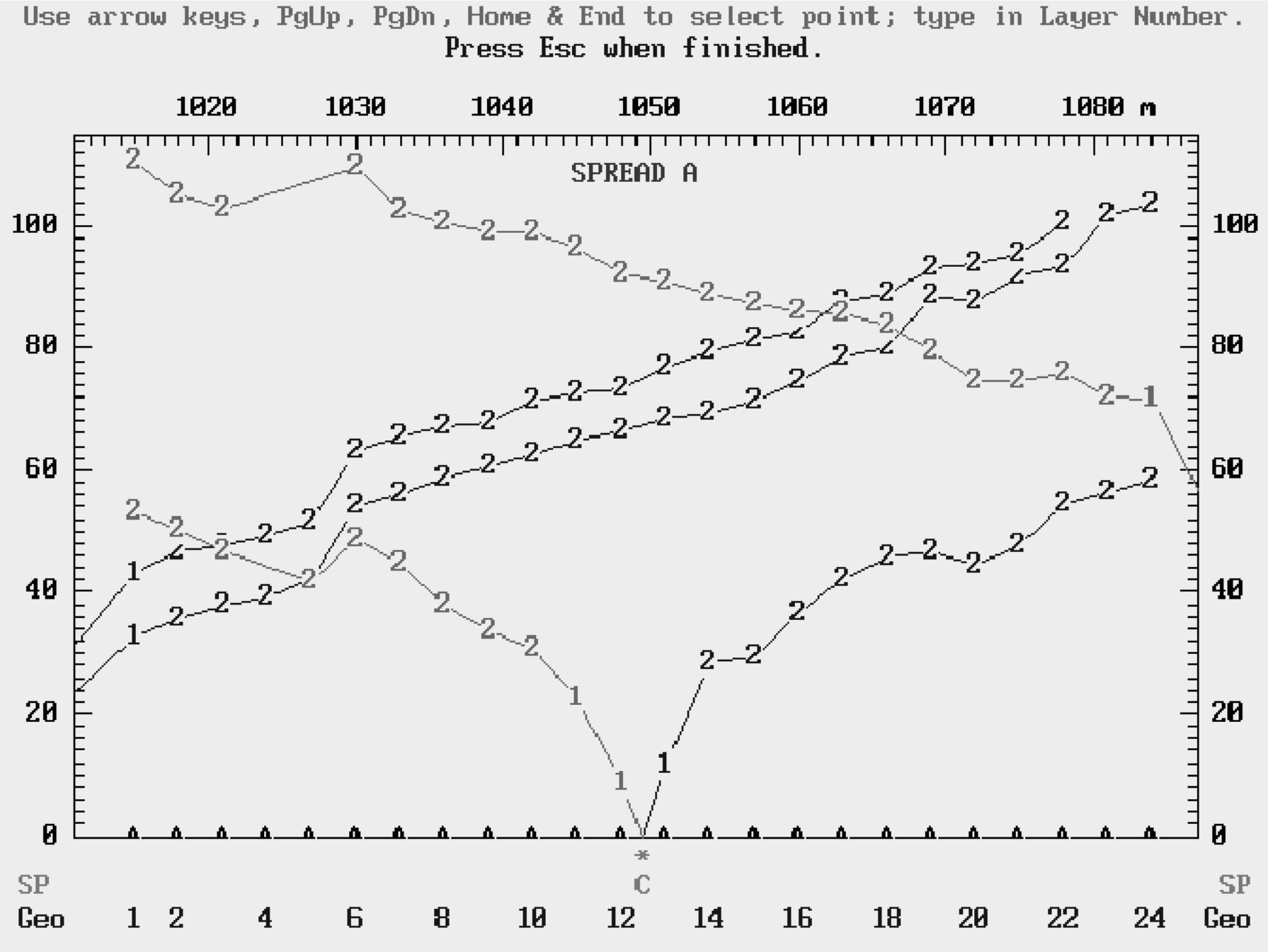

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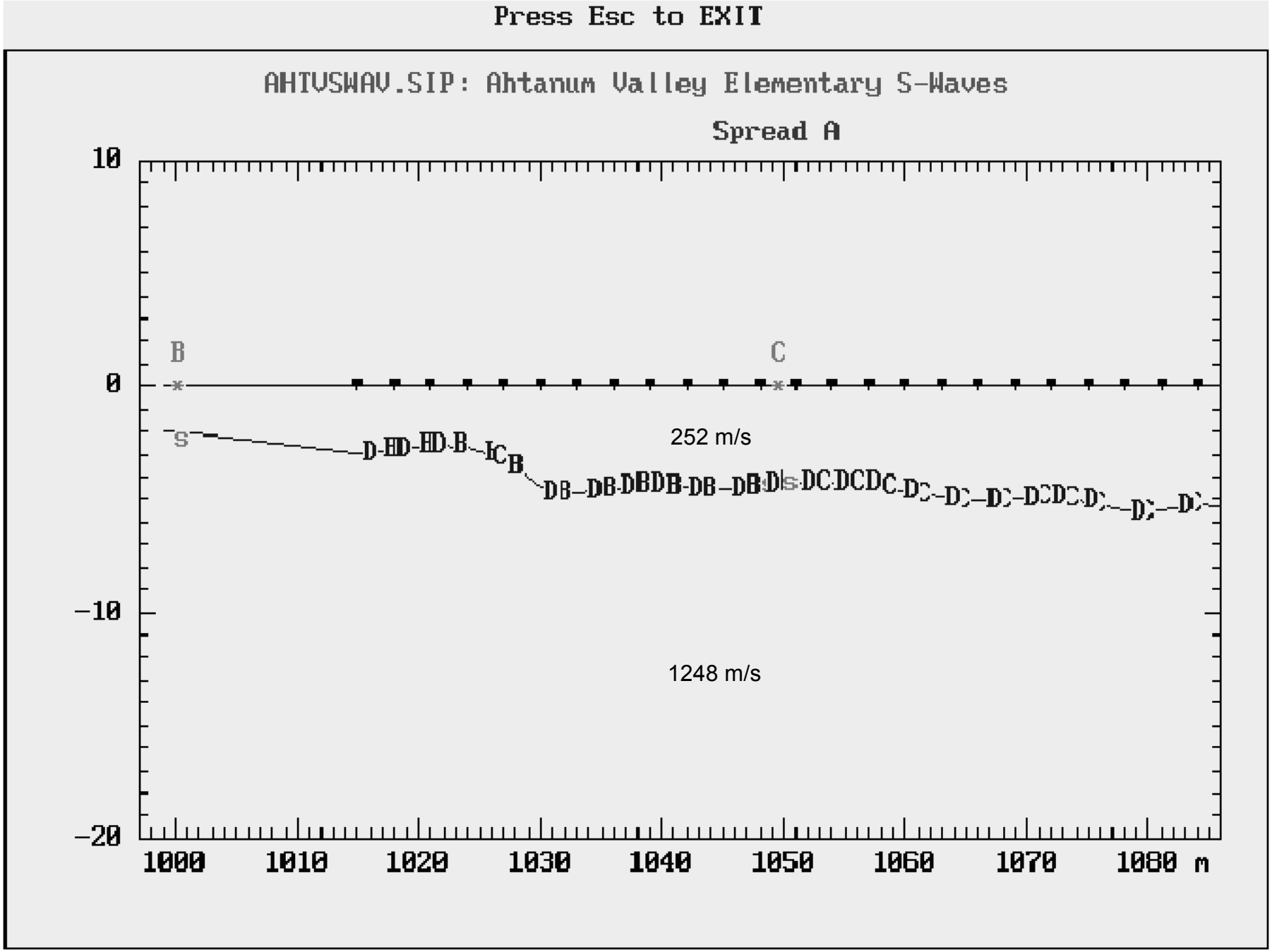

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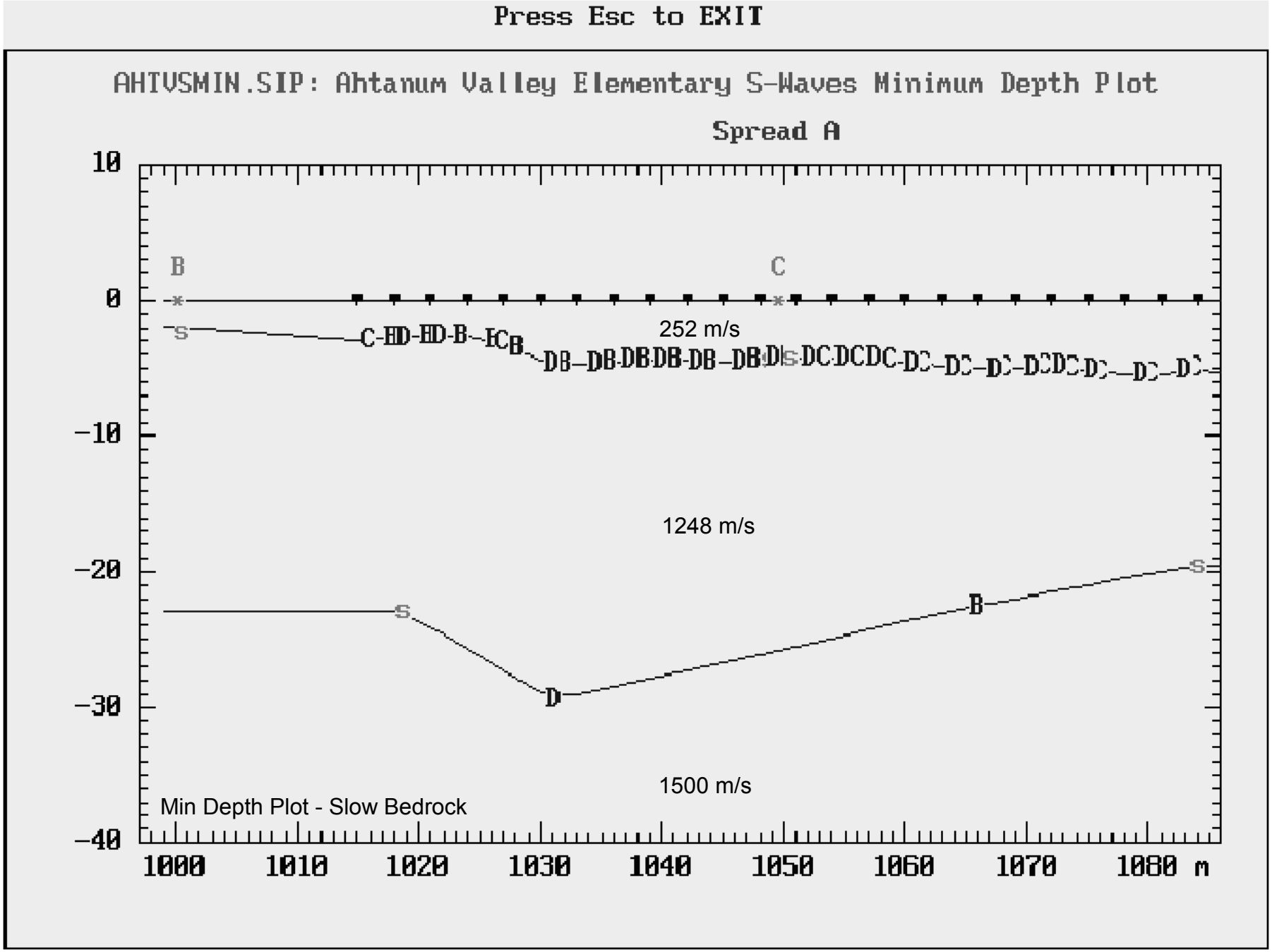
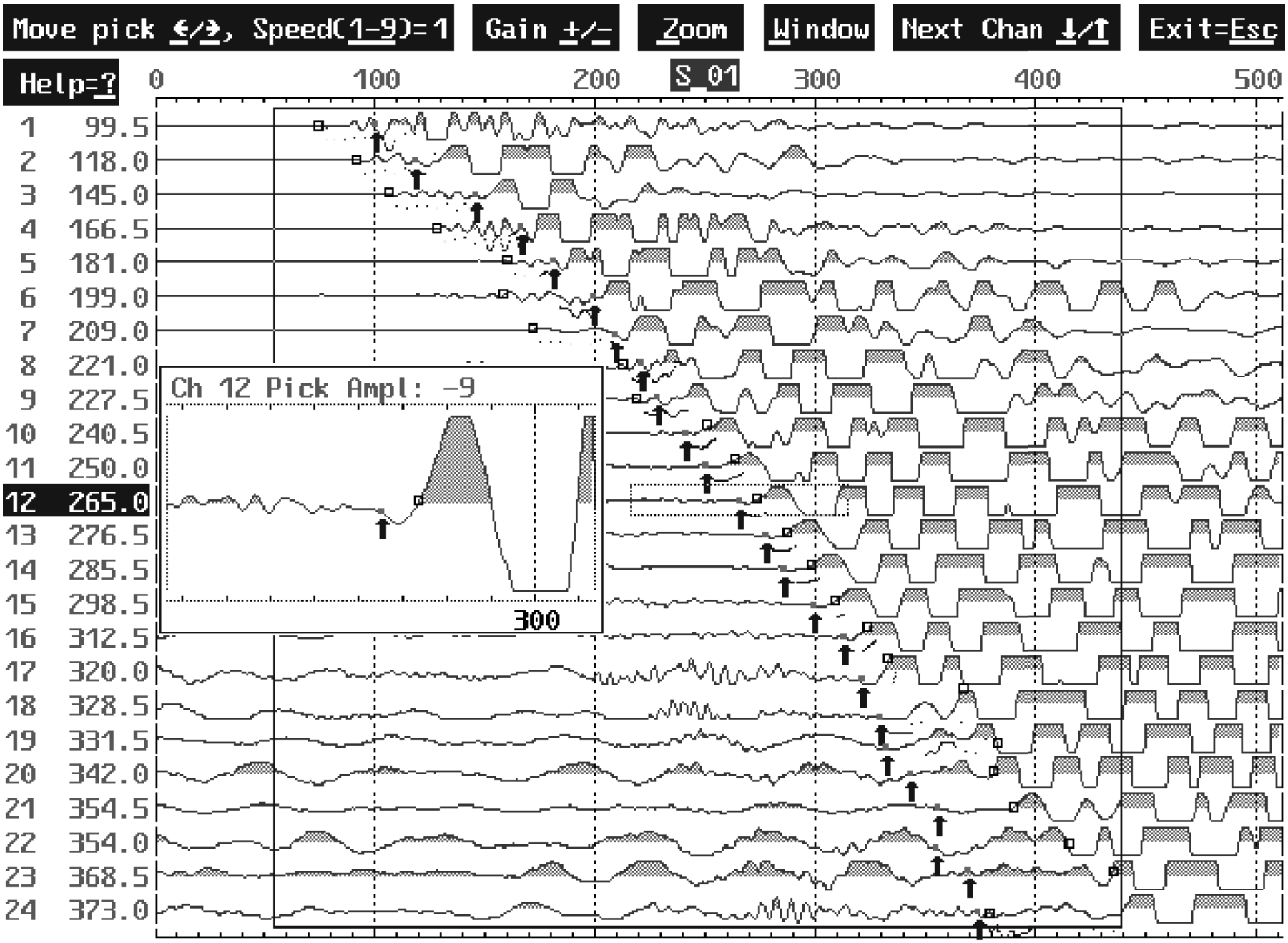


Allen Play Field S-wave



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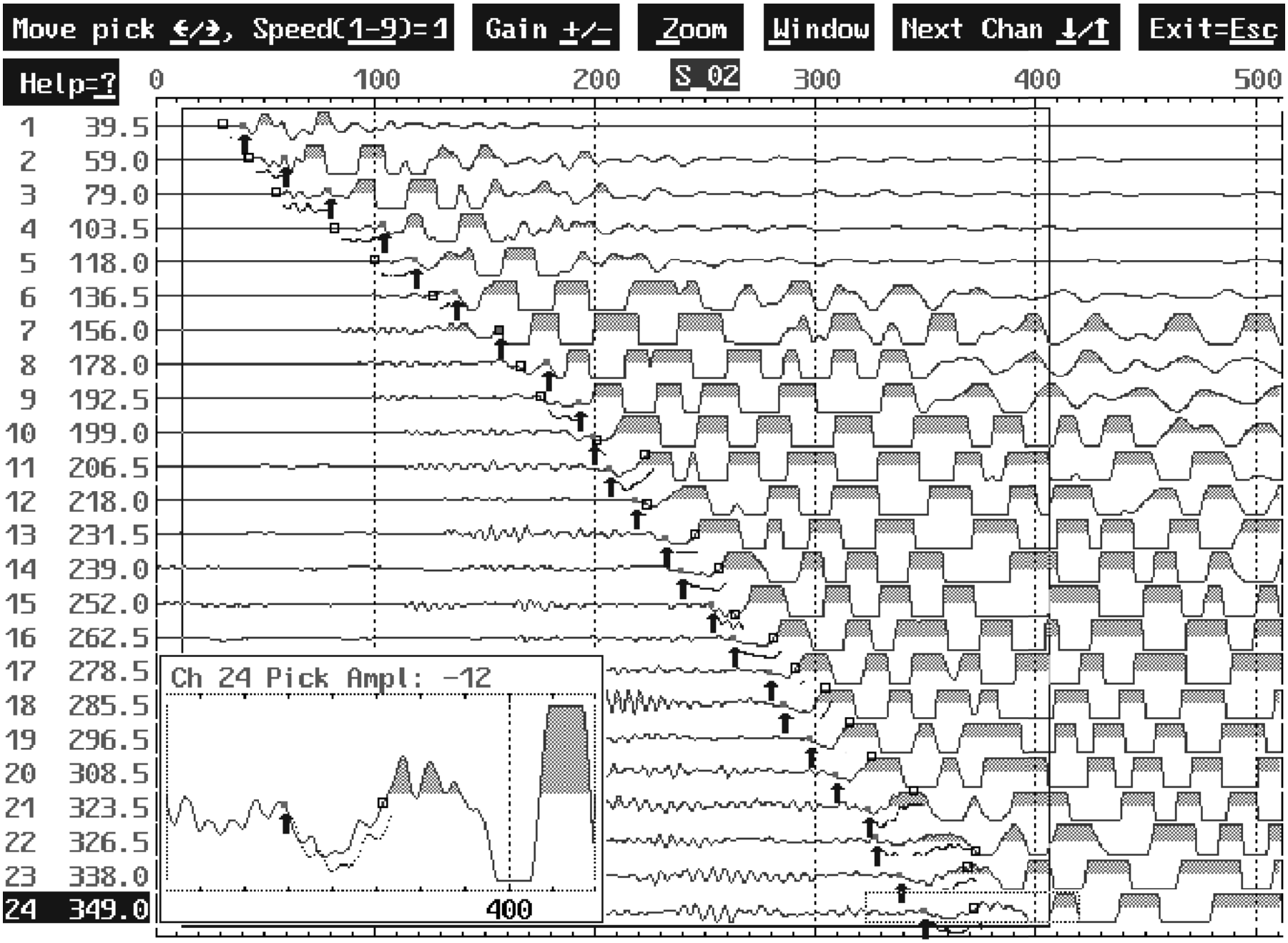

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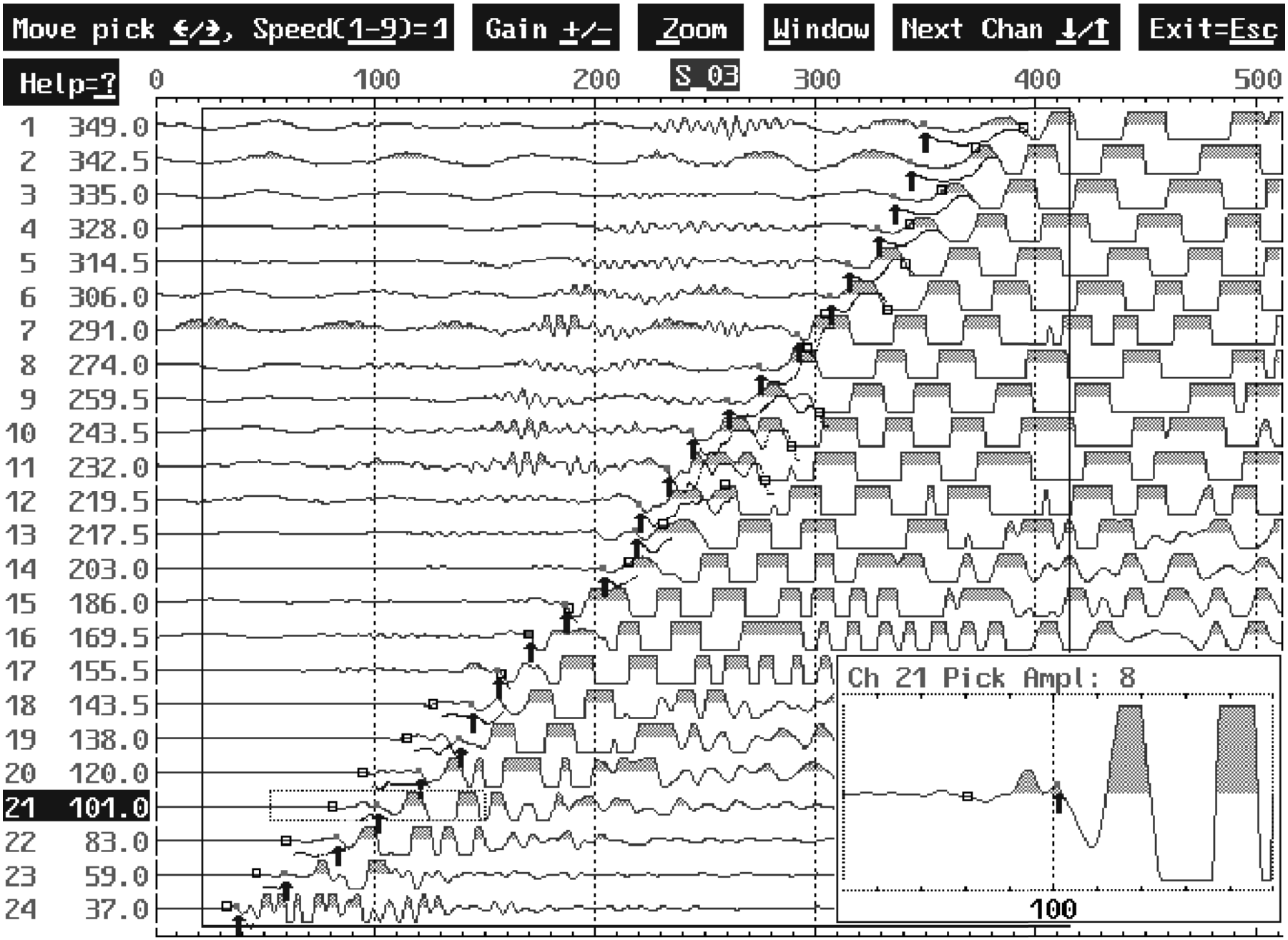

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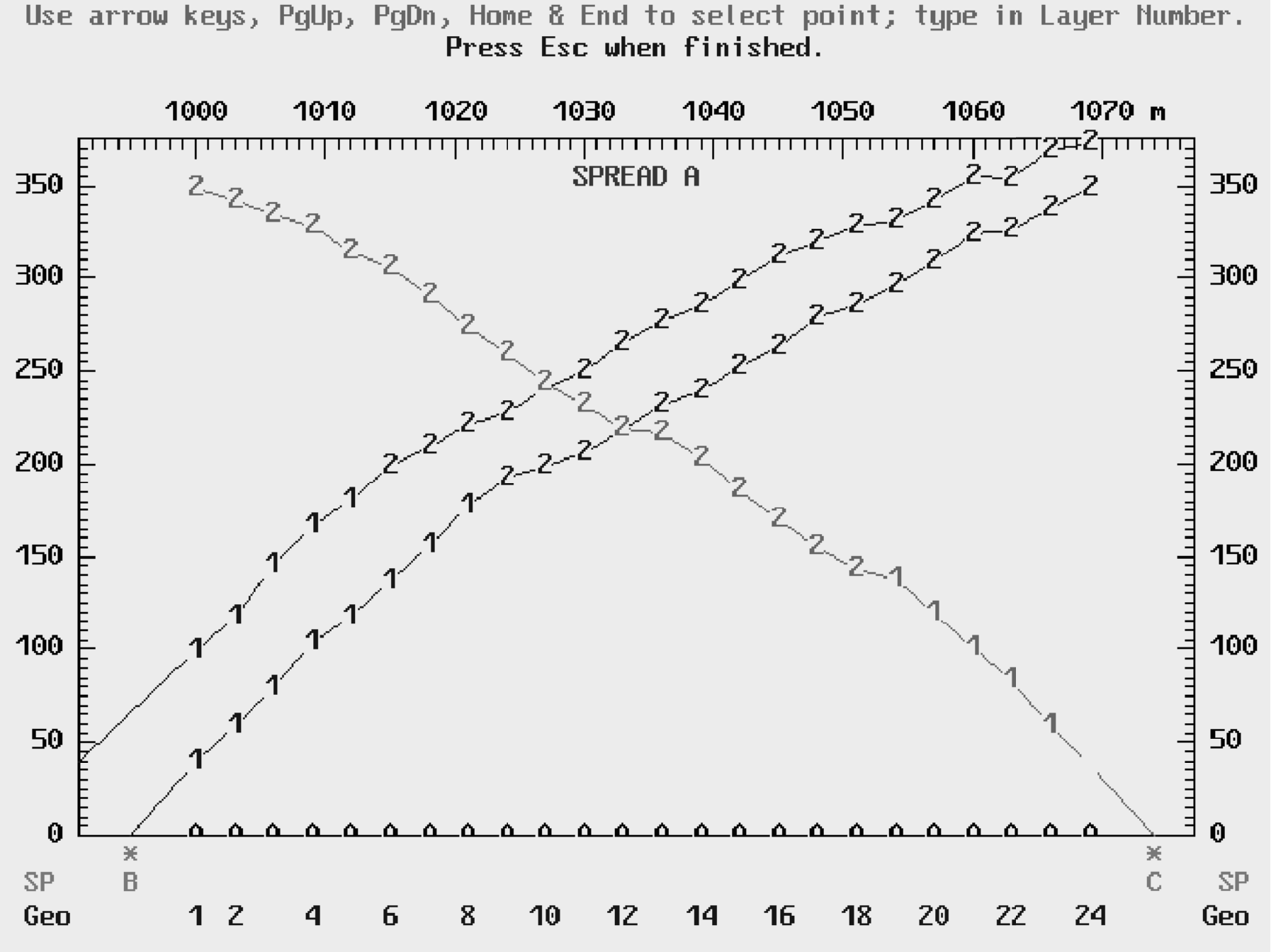

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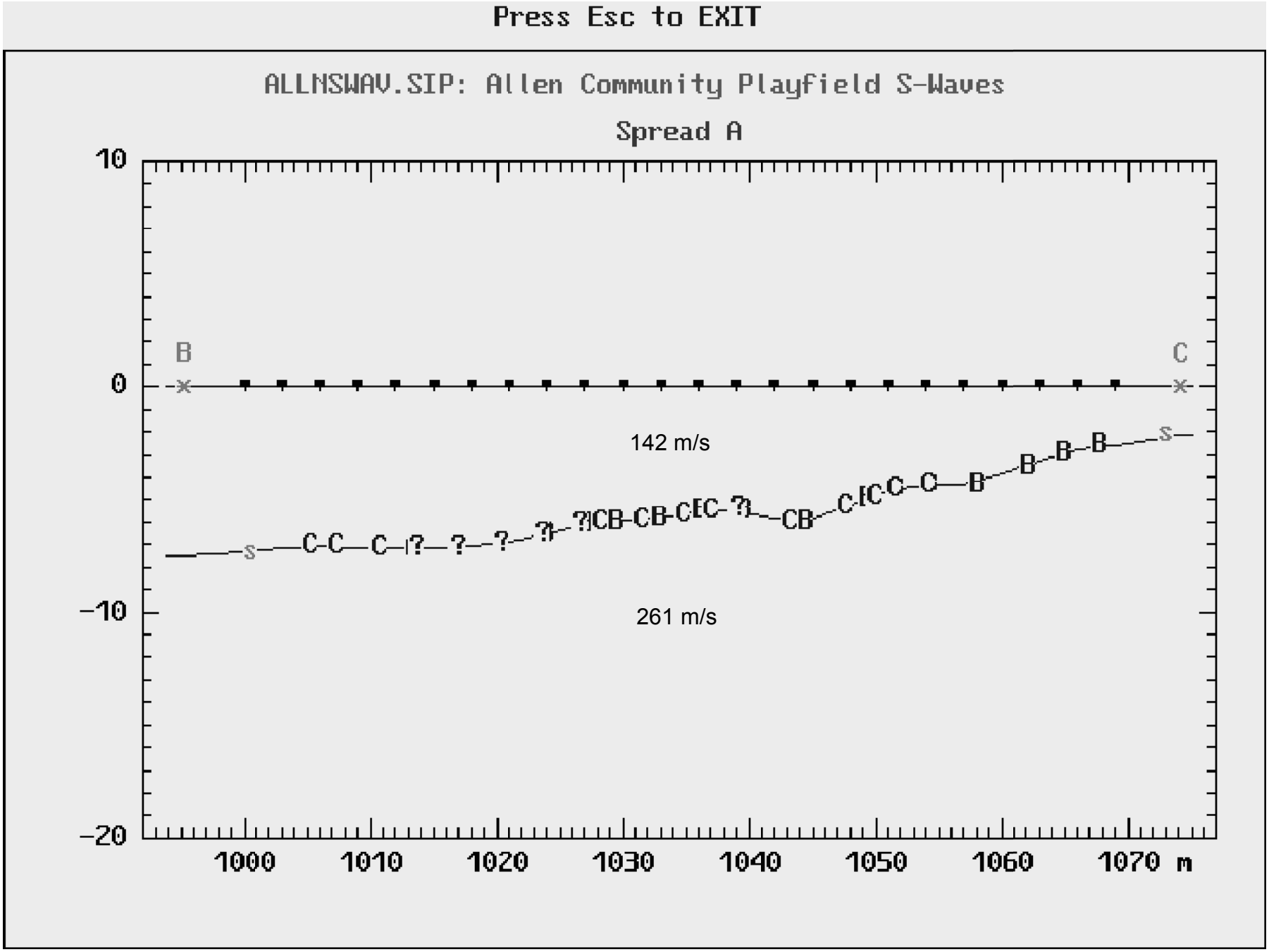

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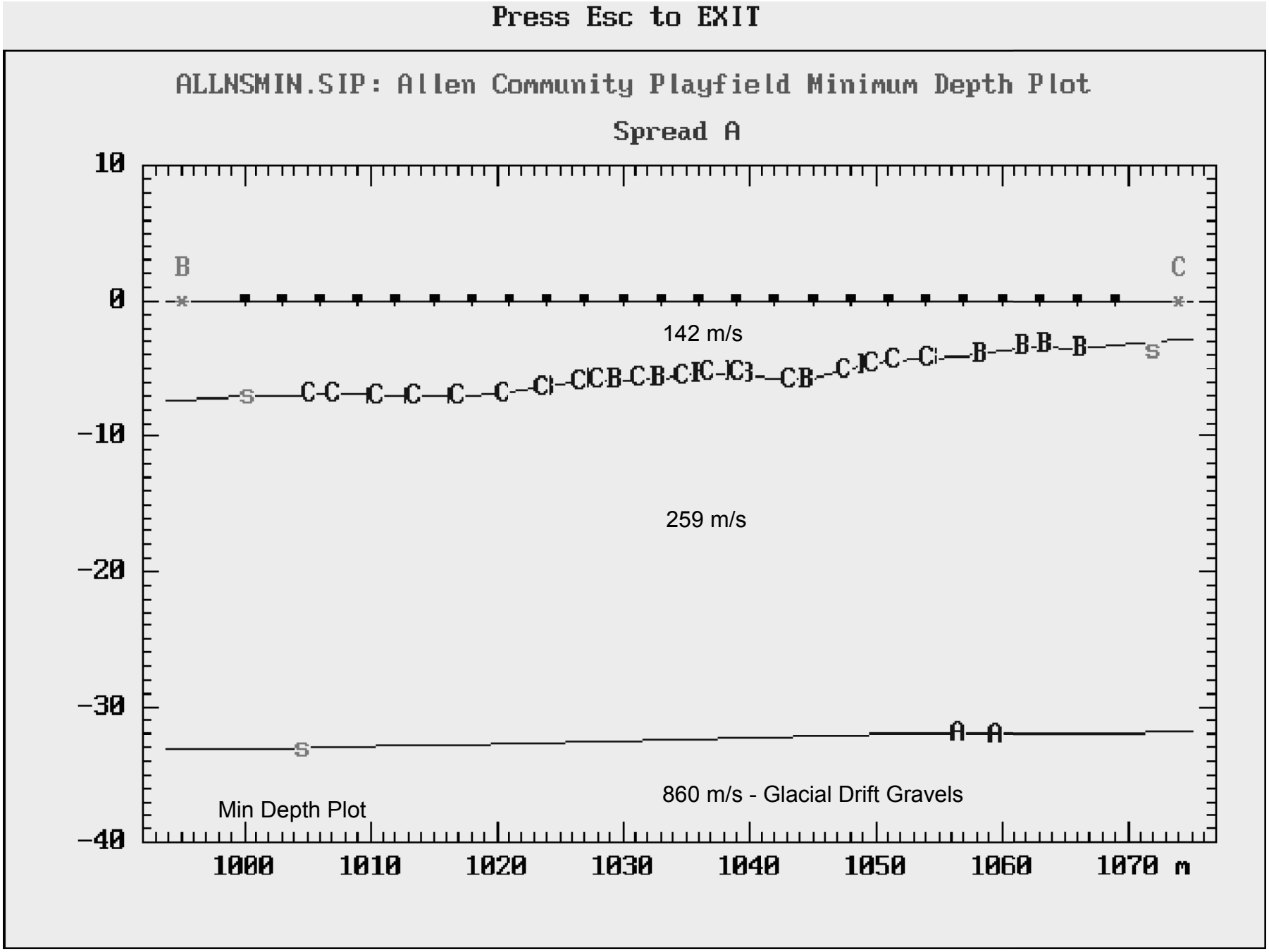
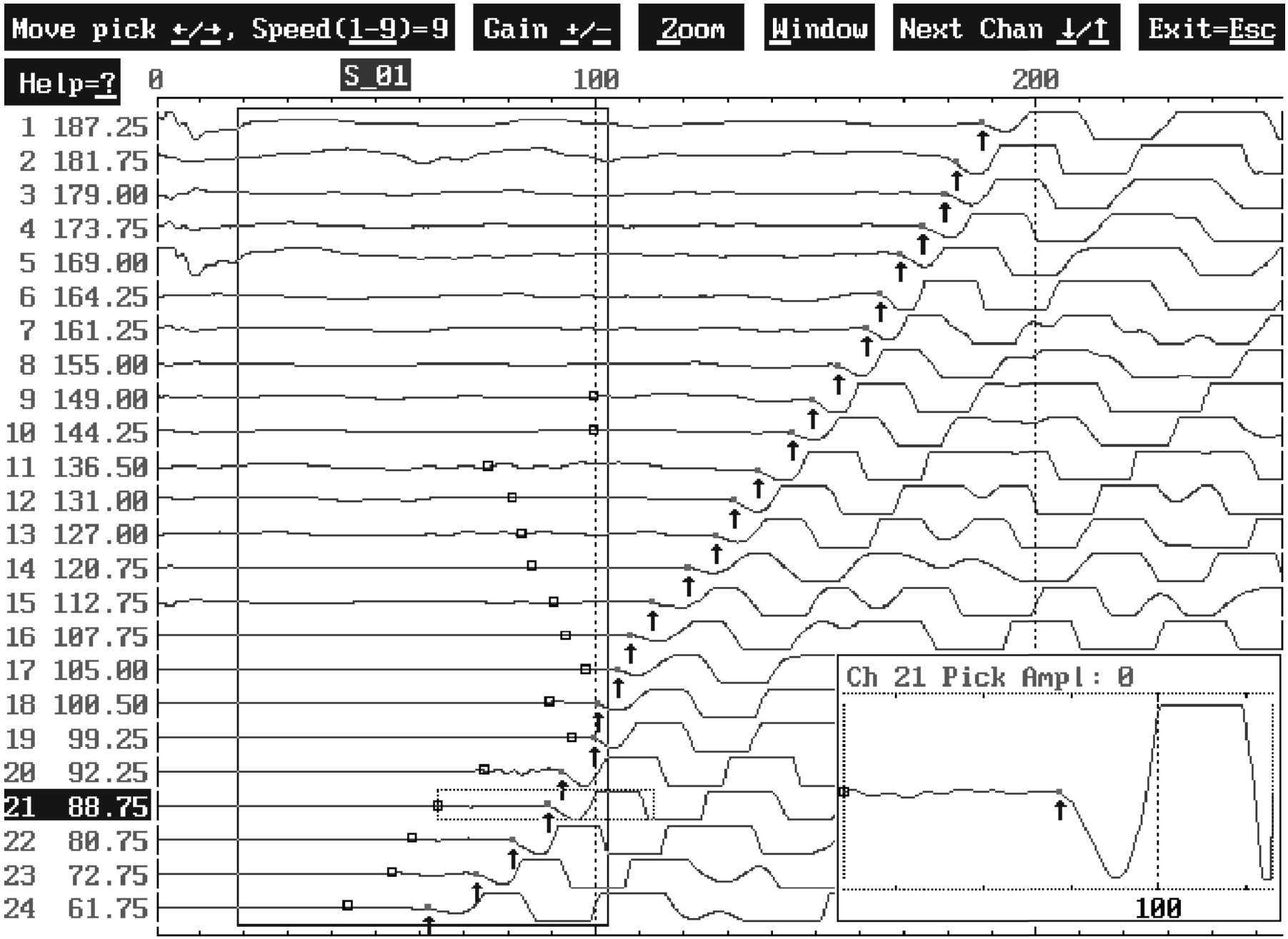


Allen Creek Elementary Field S-wave



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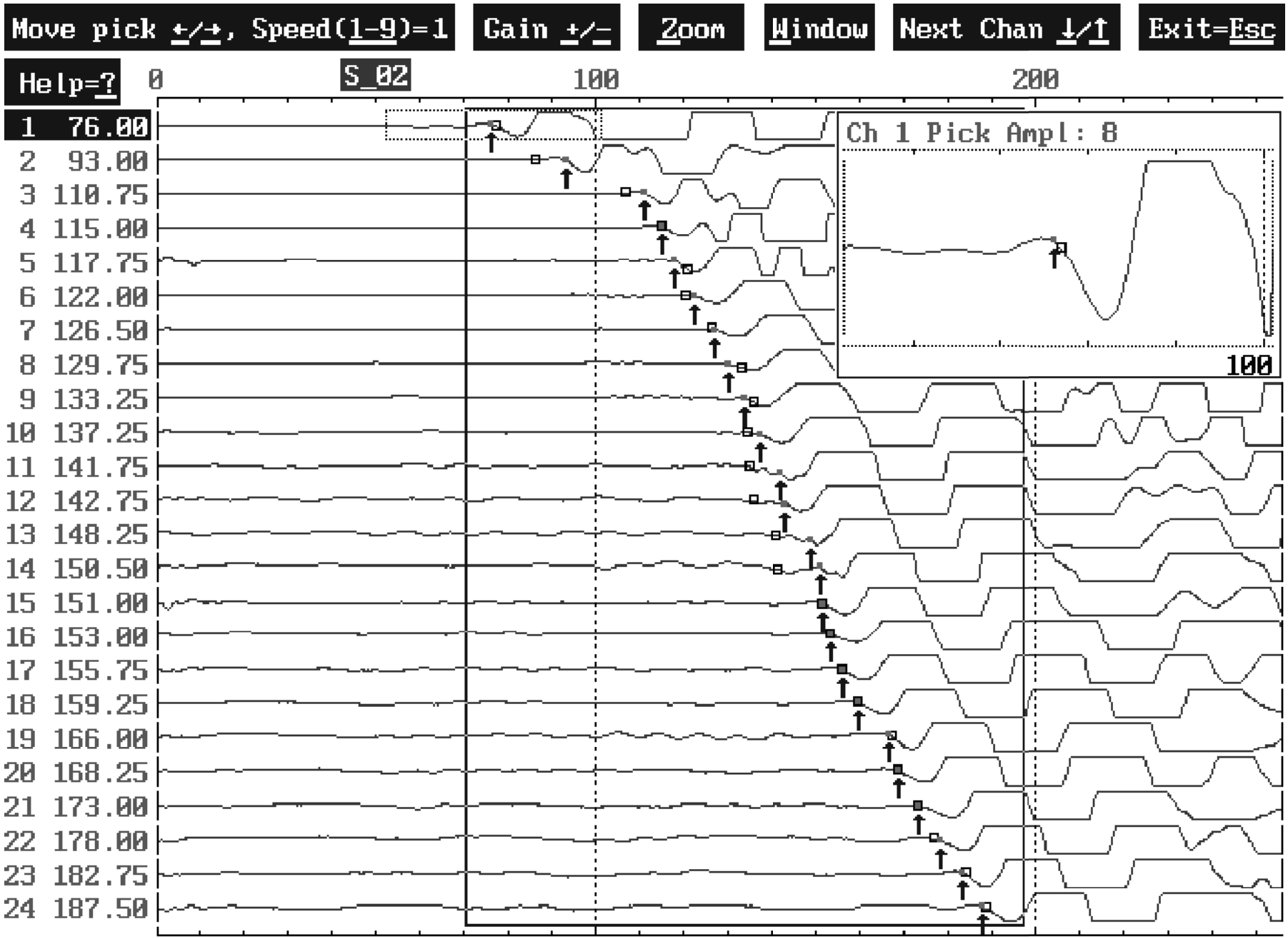

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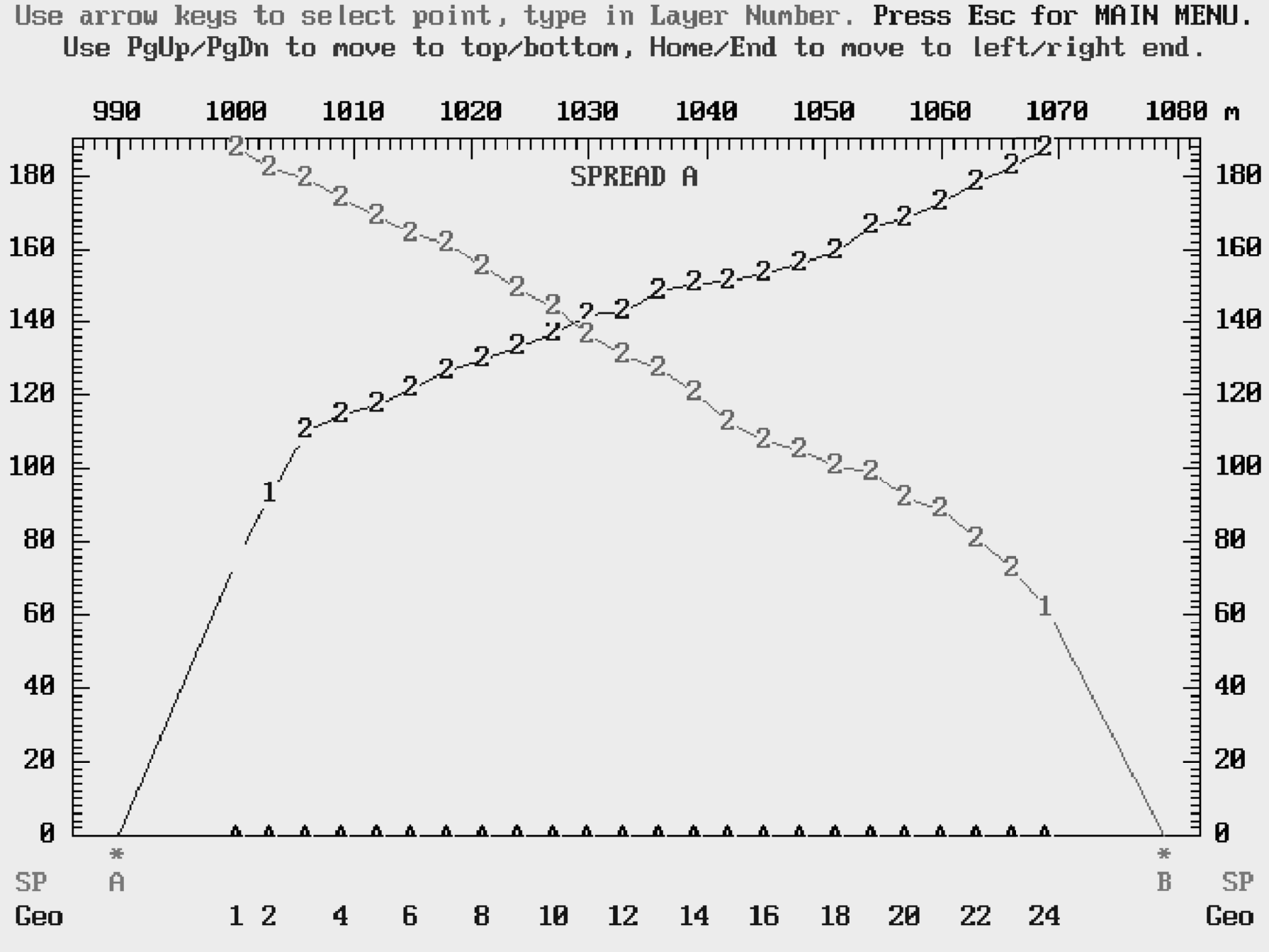

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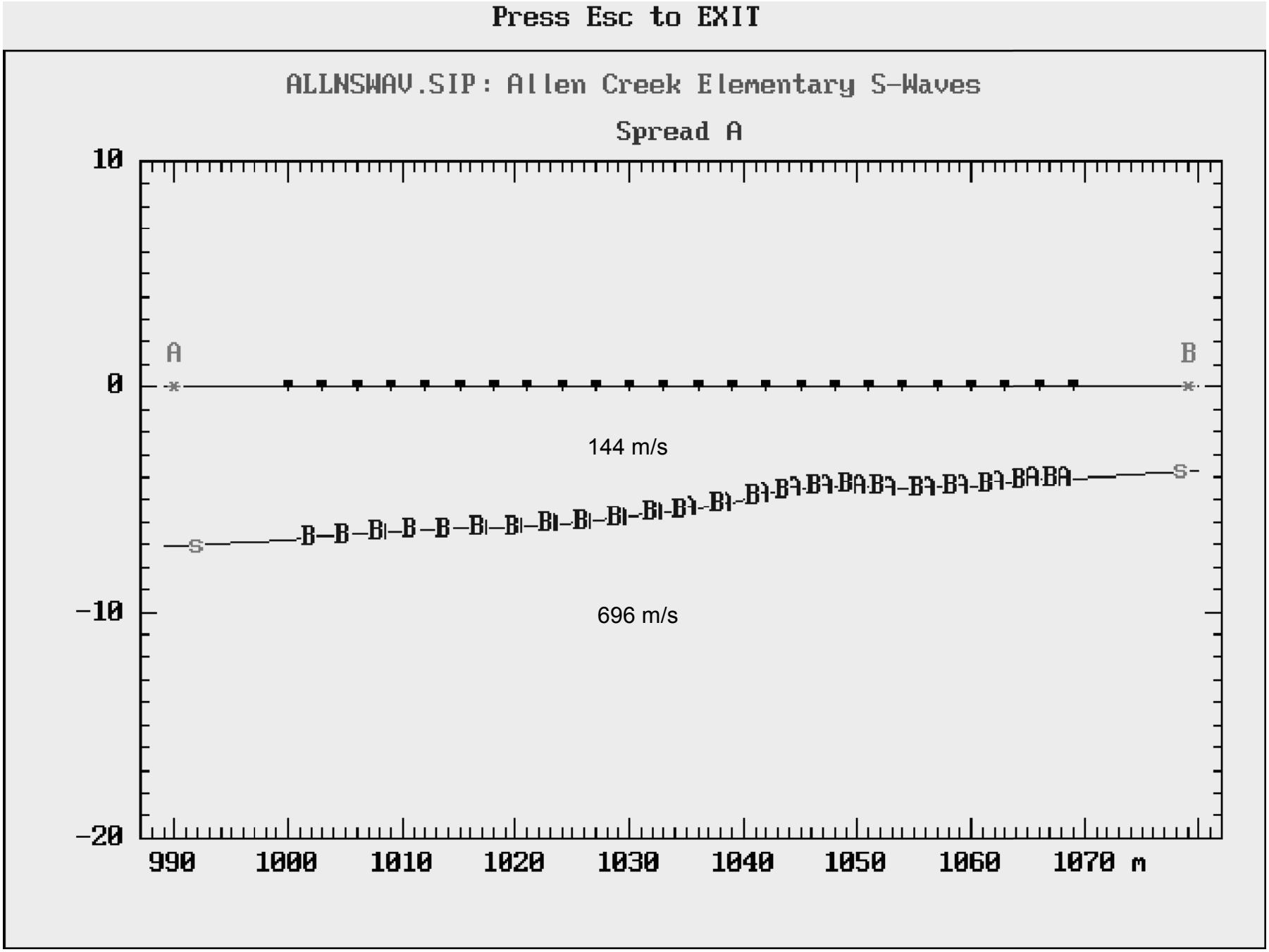

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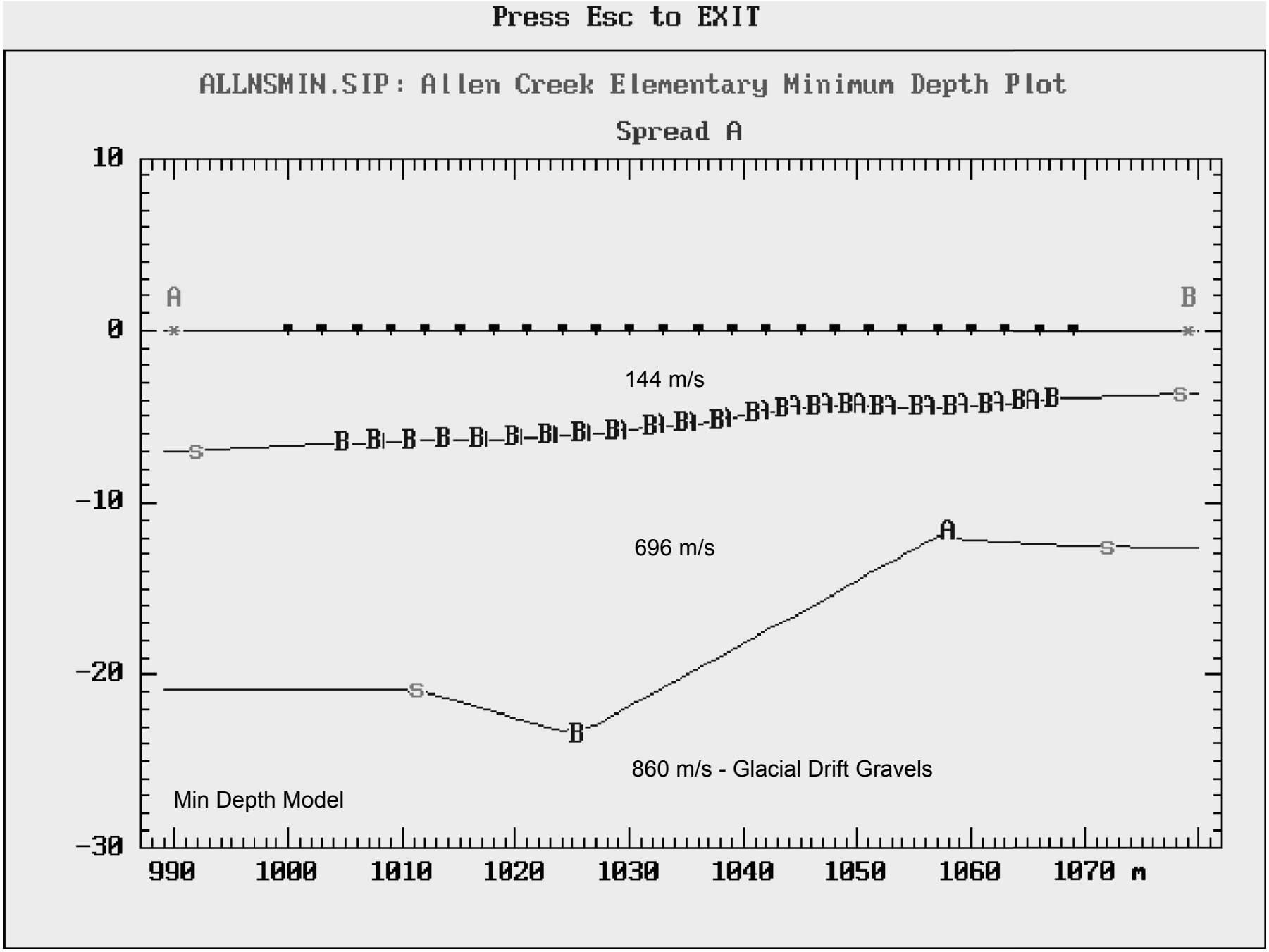
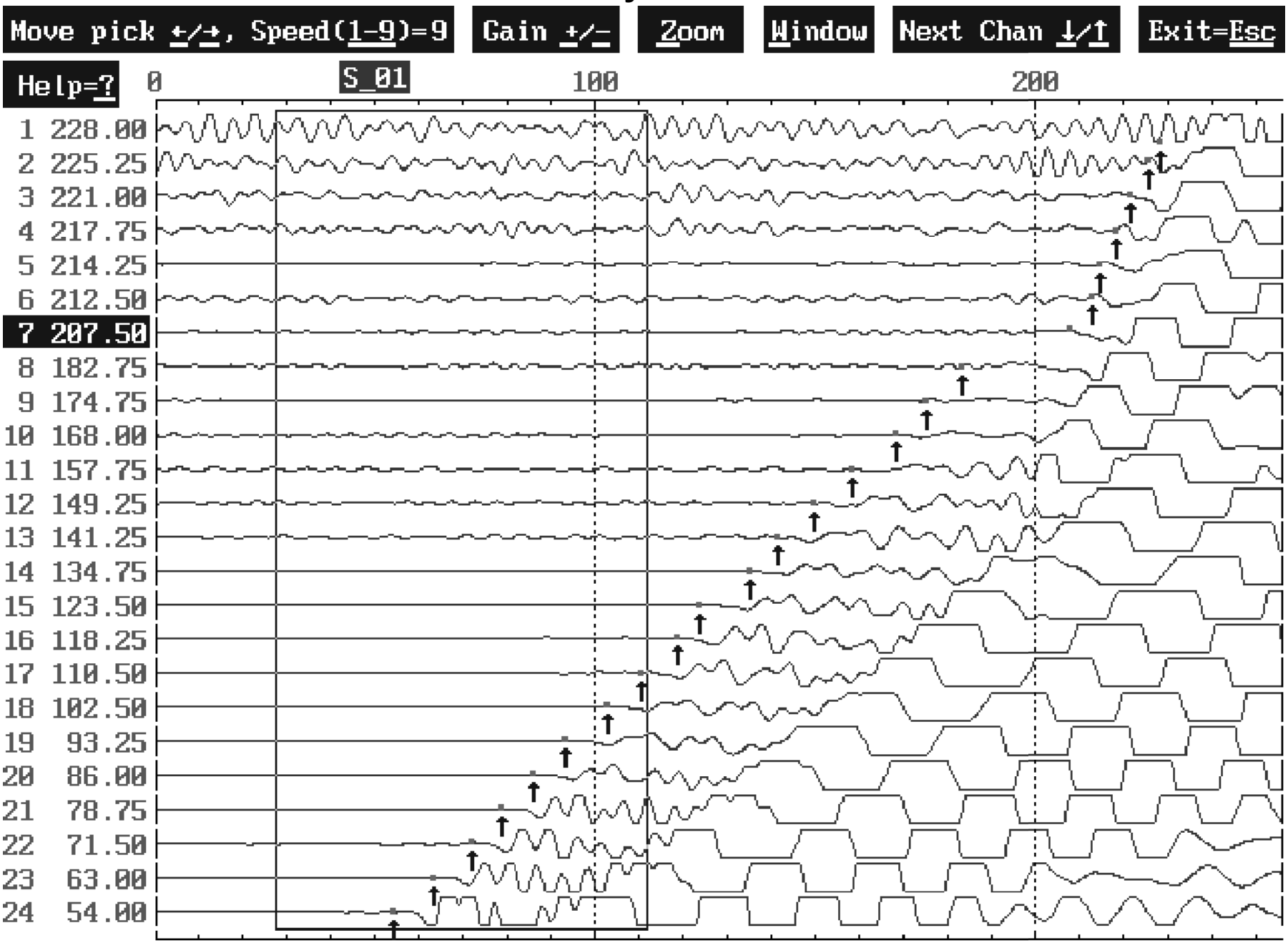


Annie's Berry Farm S-wave



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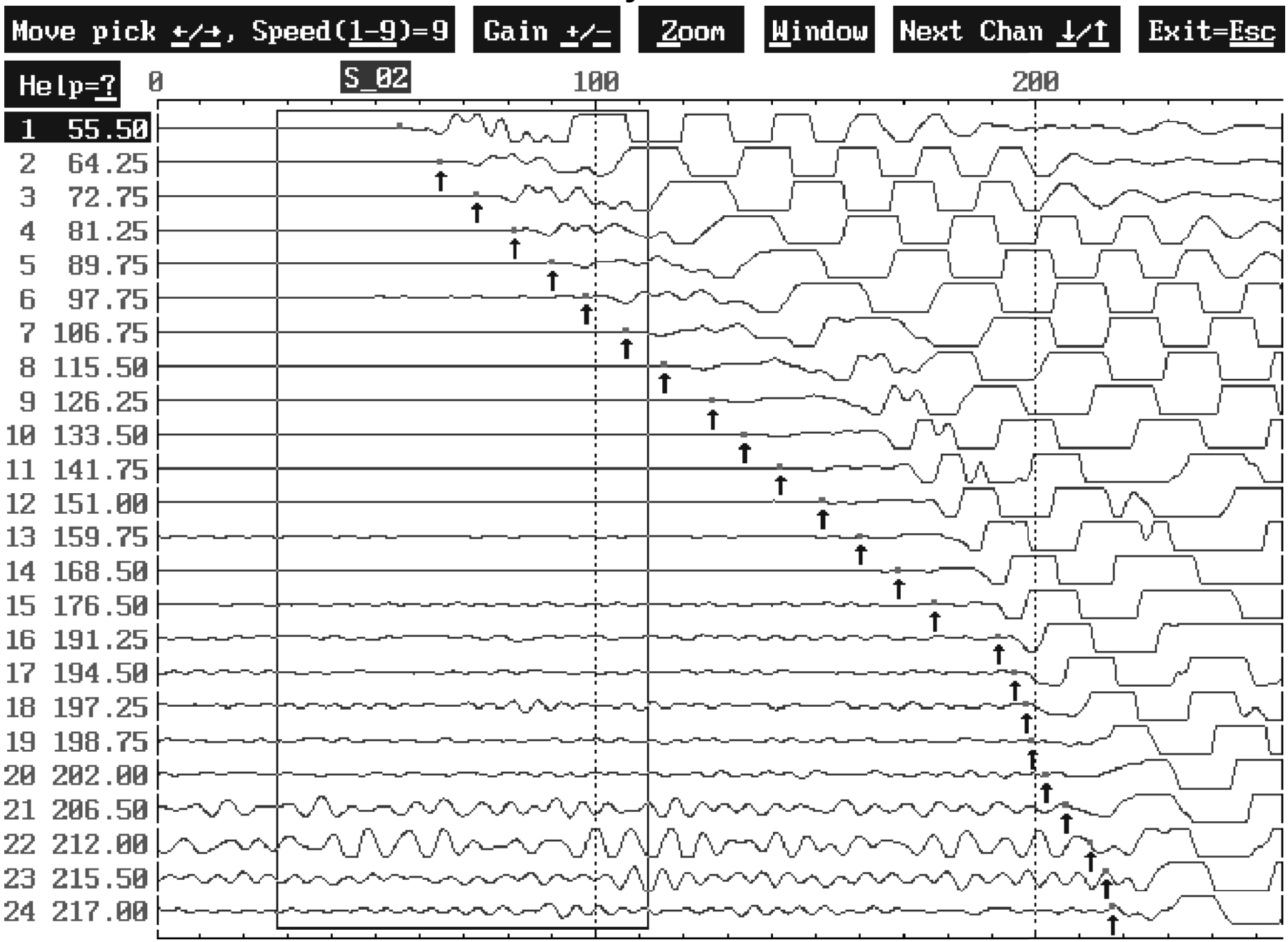

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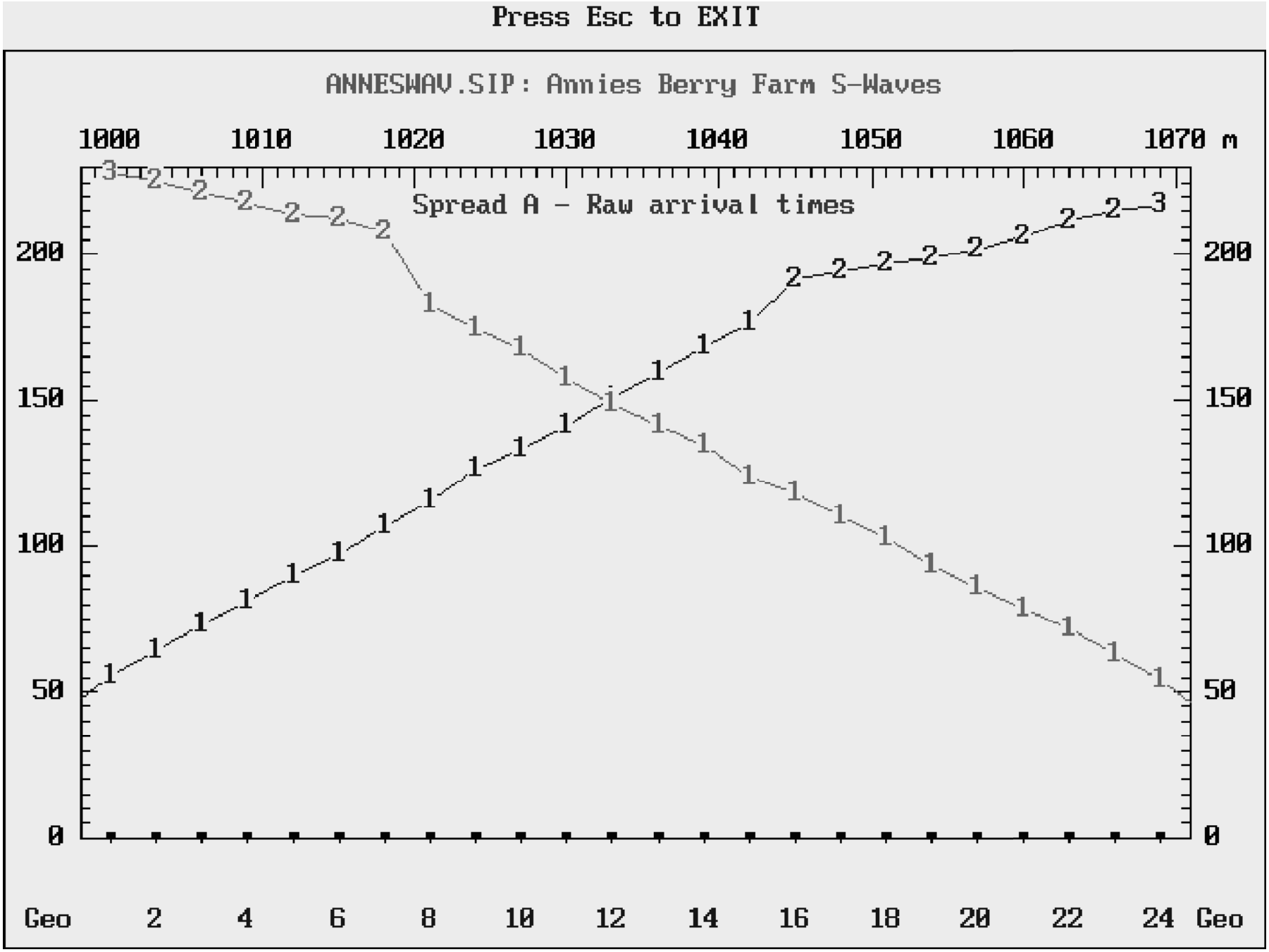

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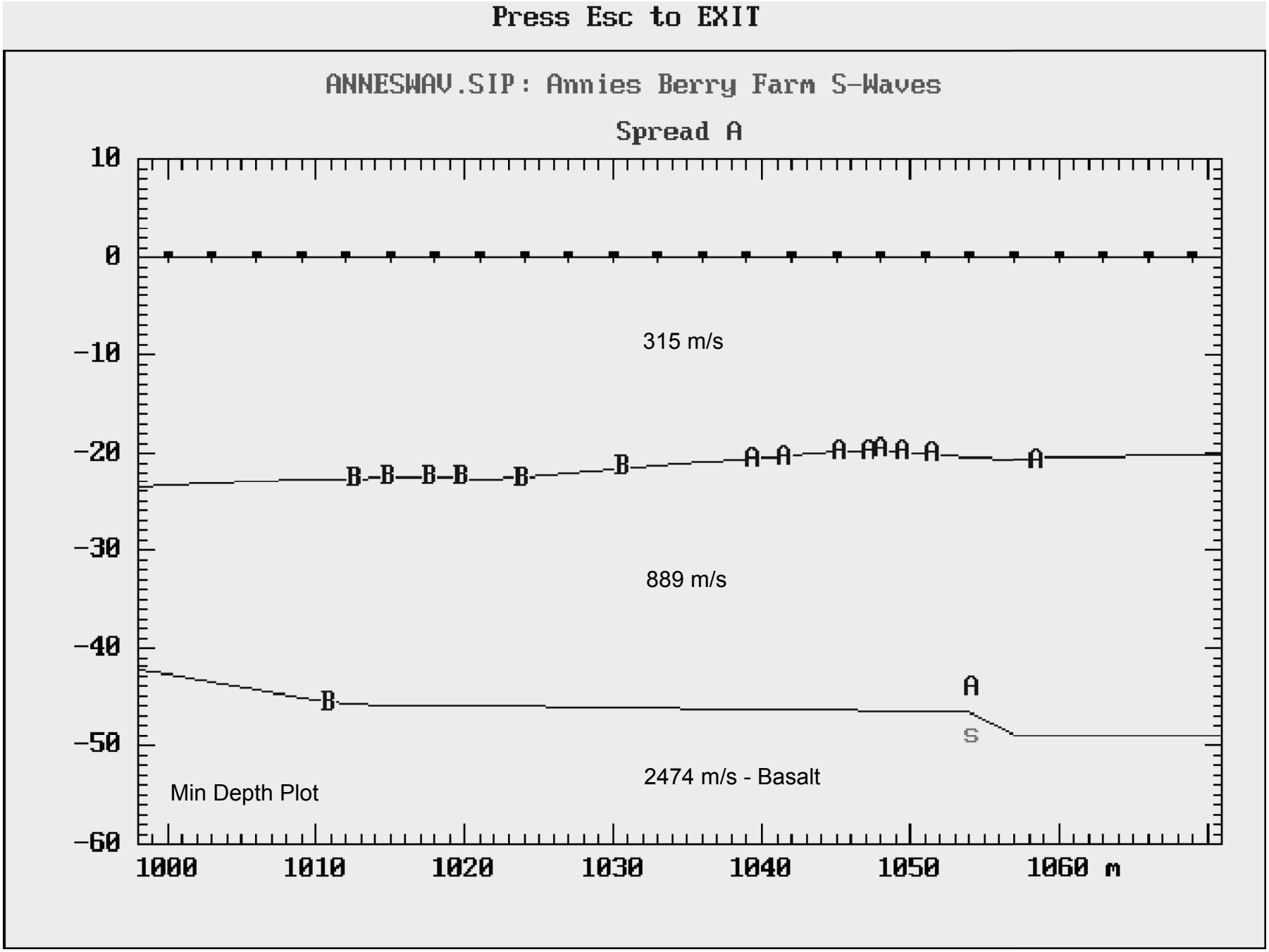
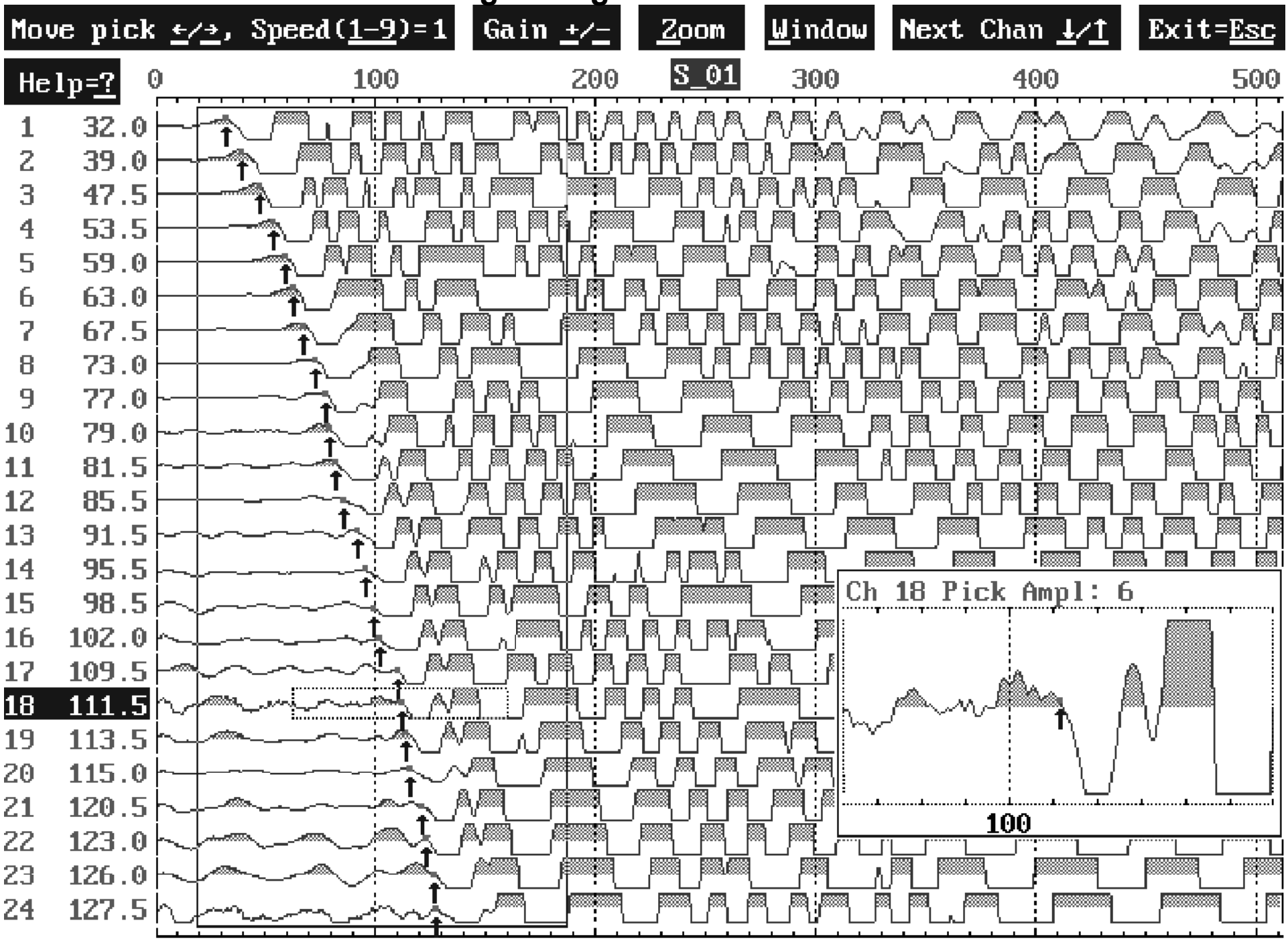


Arlington High School S-wave



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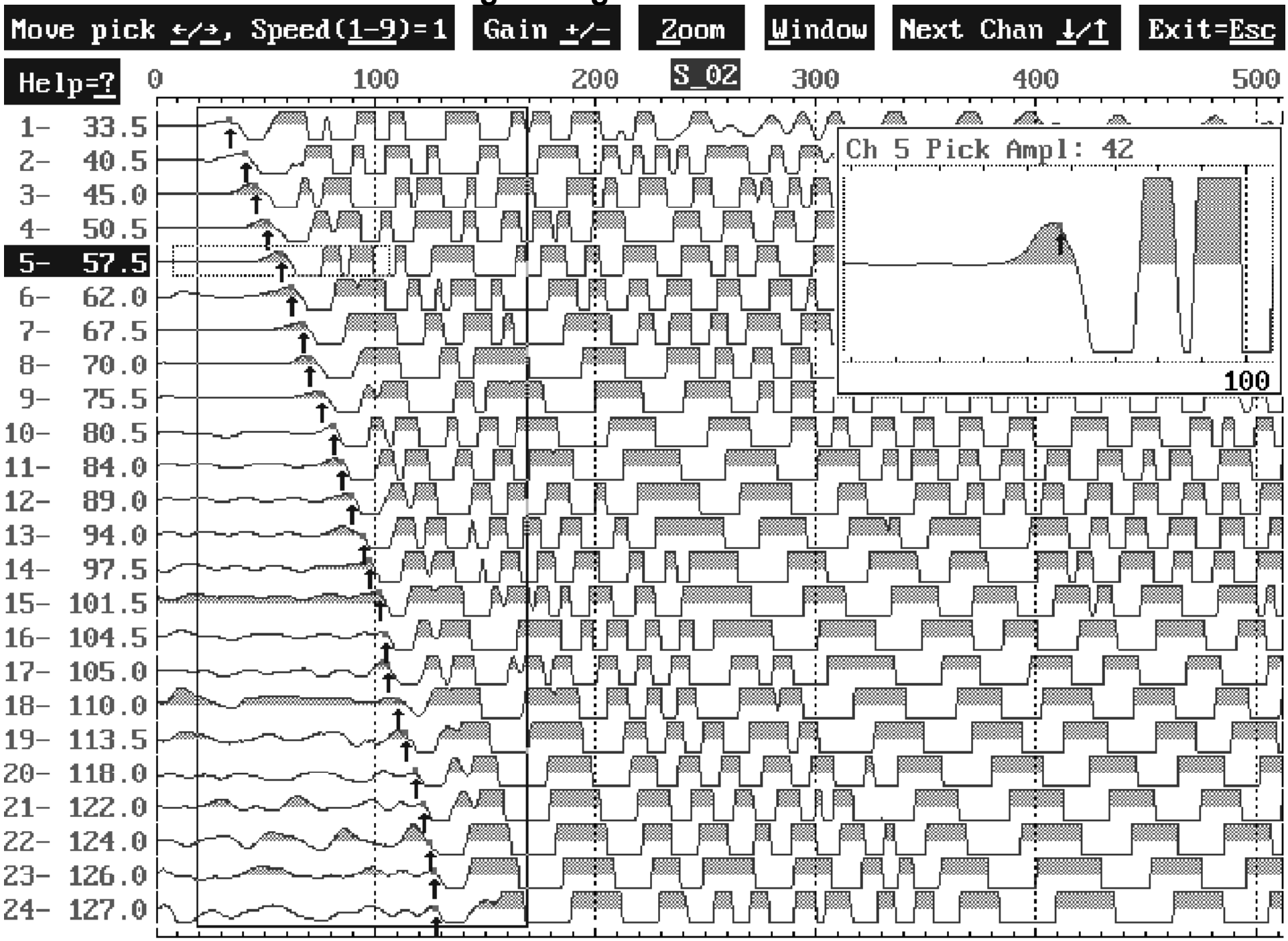

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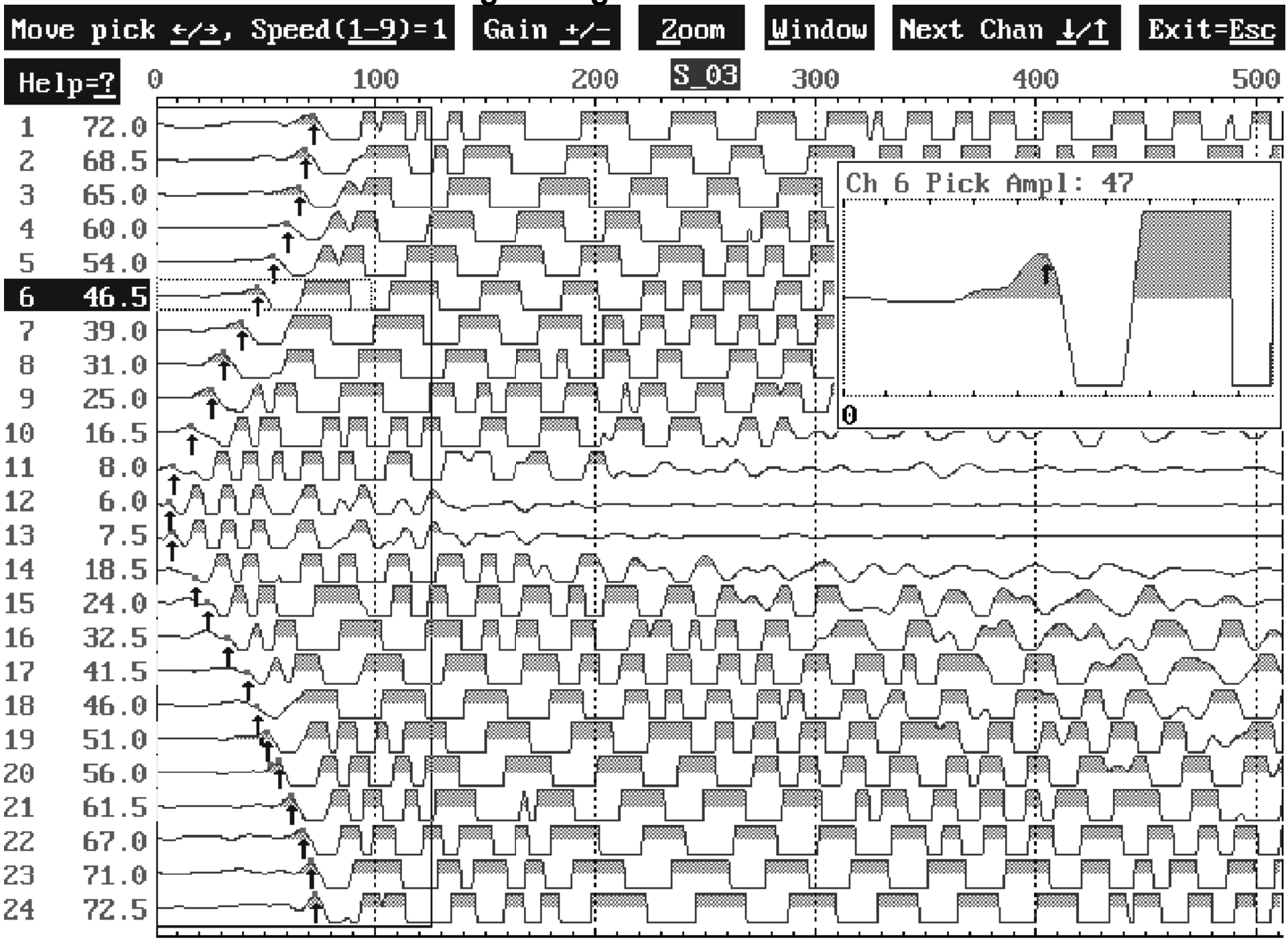

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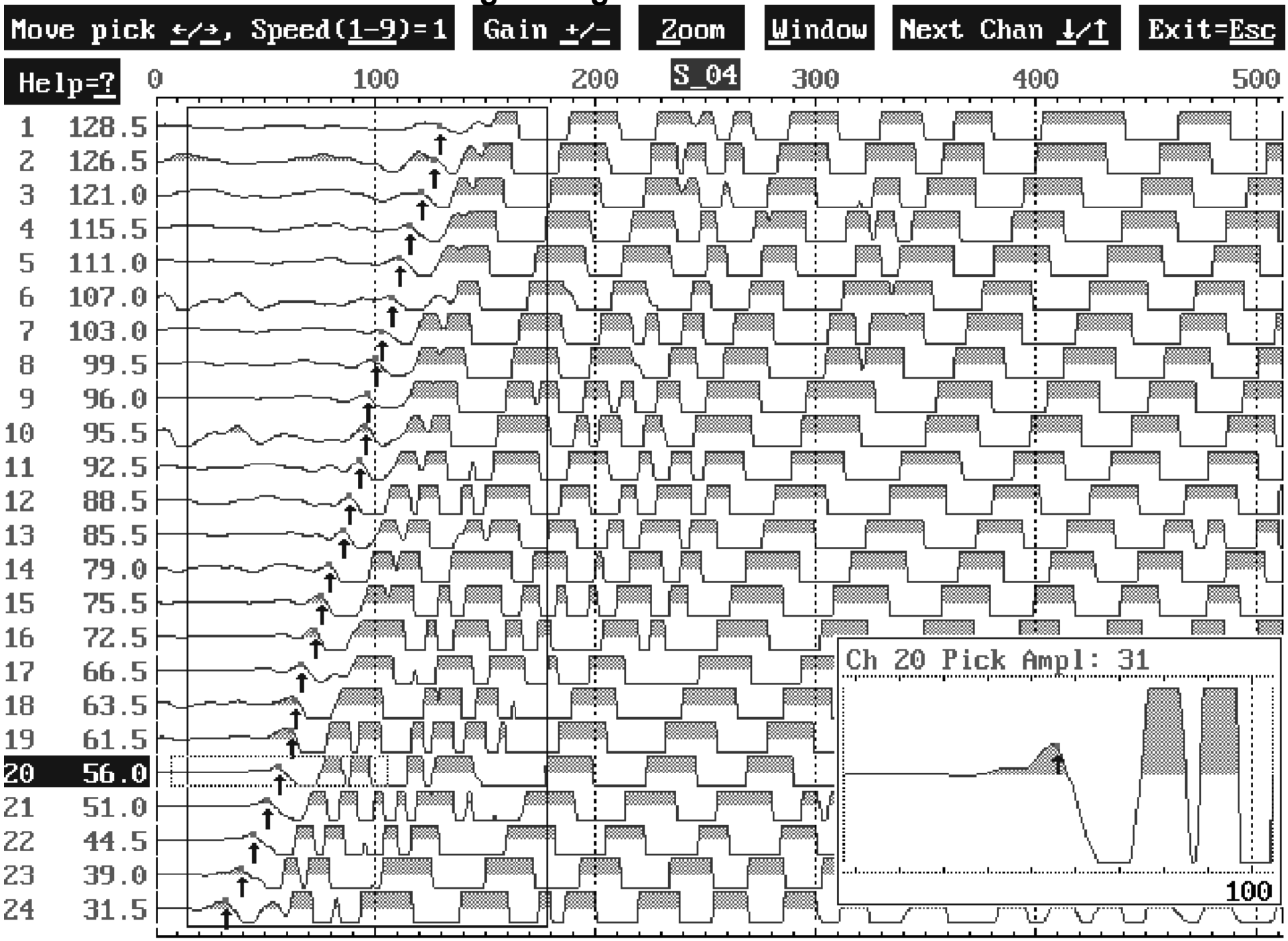

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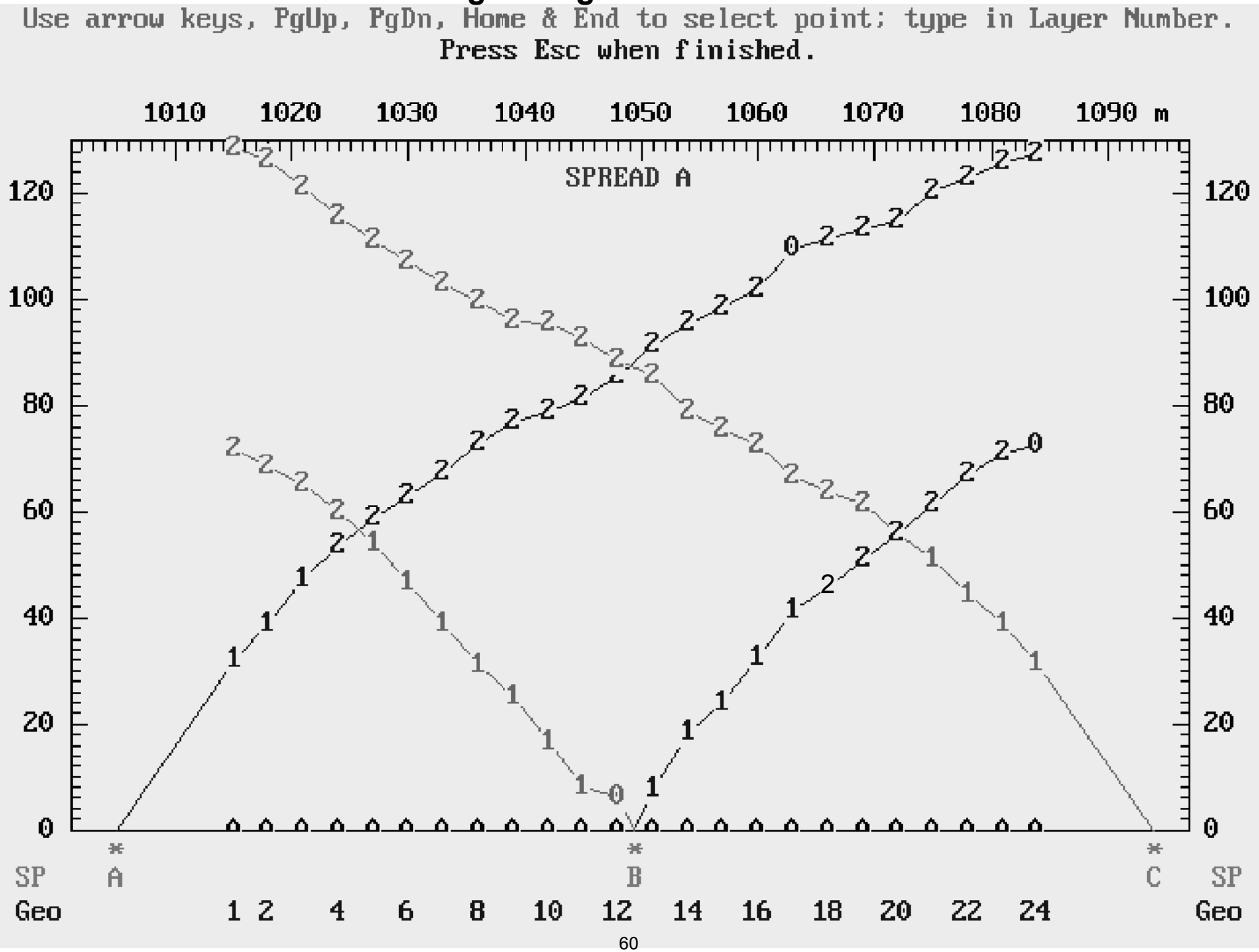

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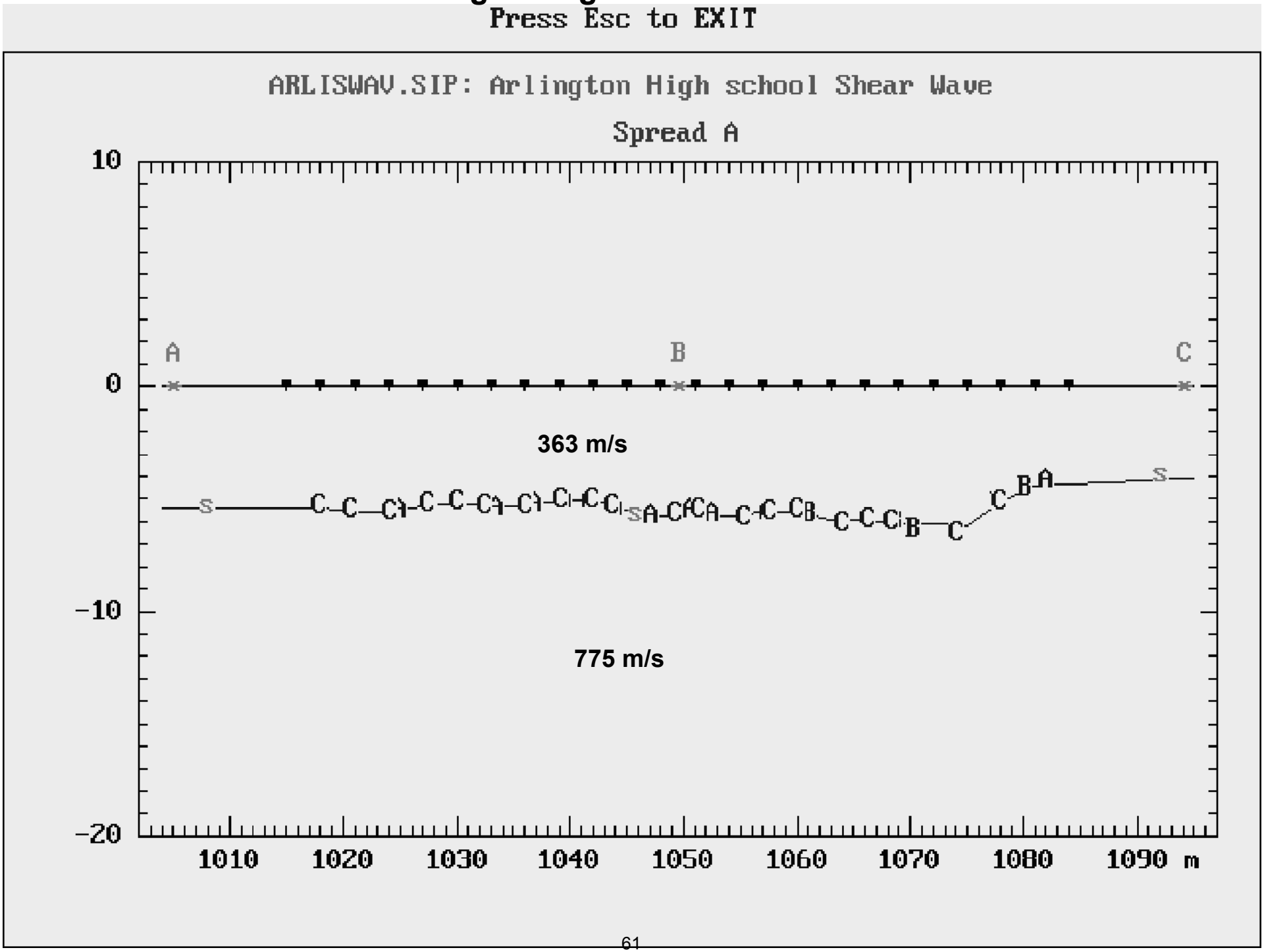

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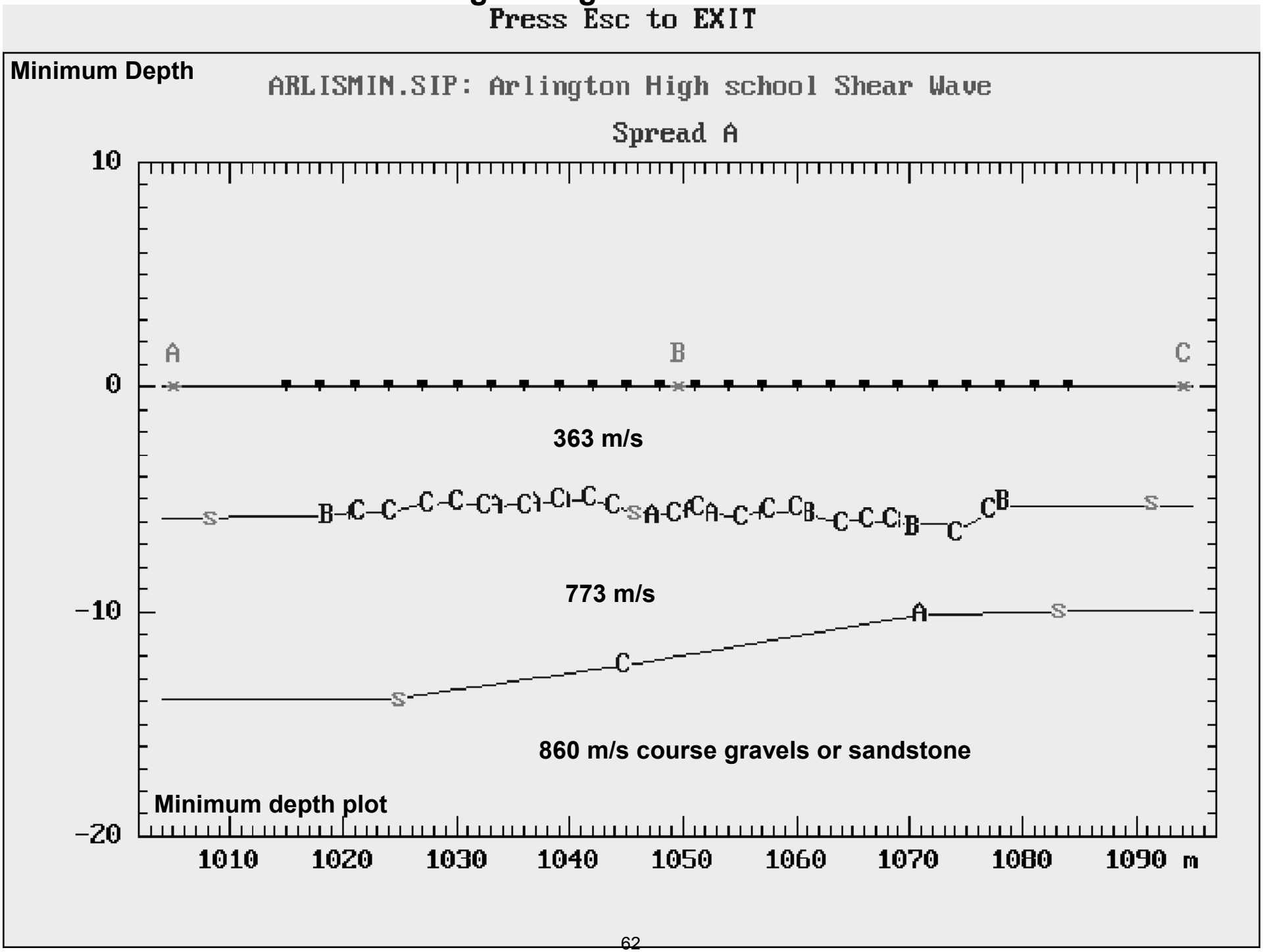
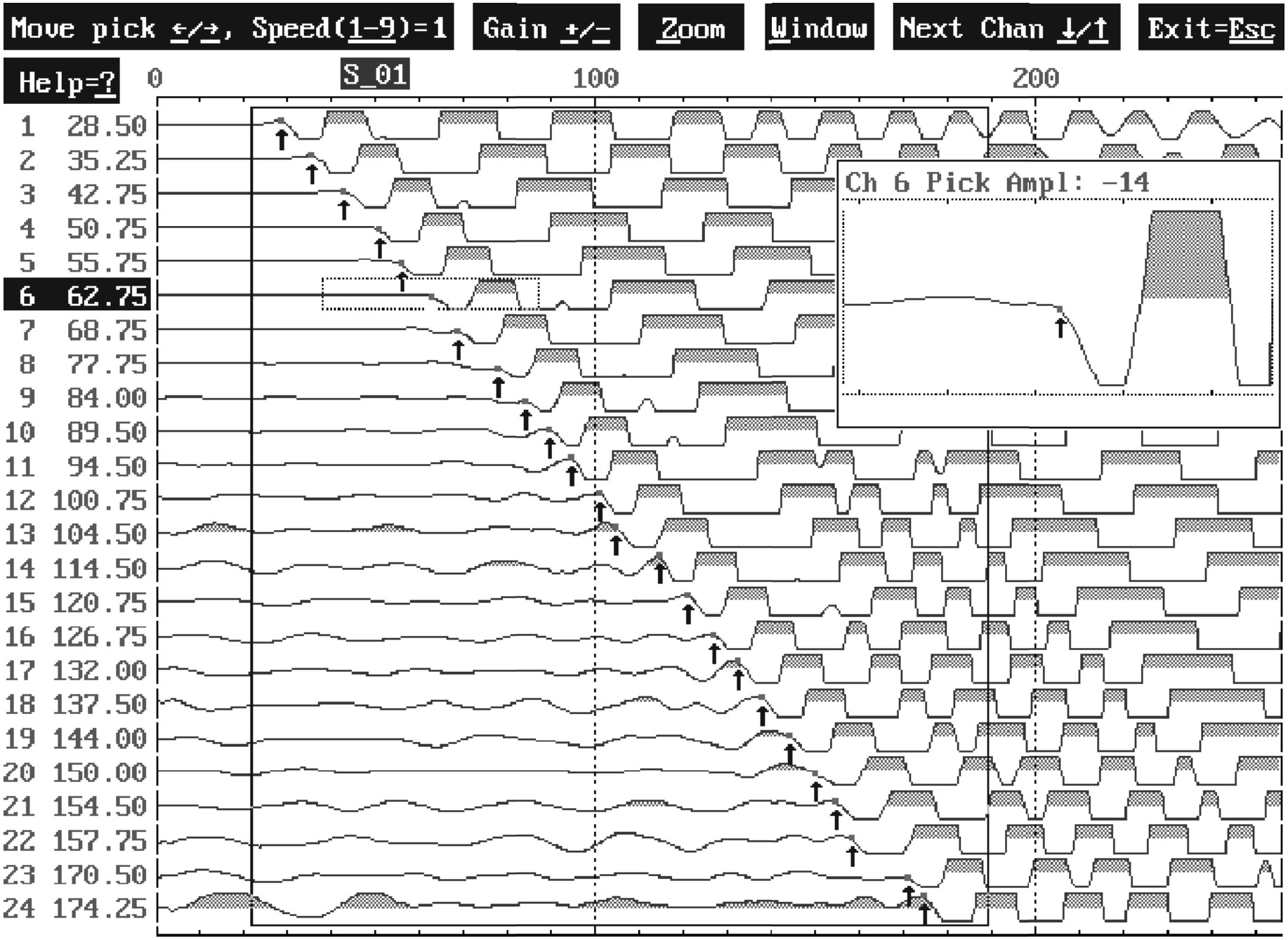


Bald Road S-wave



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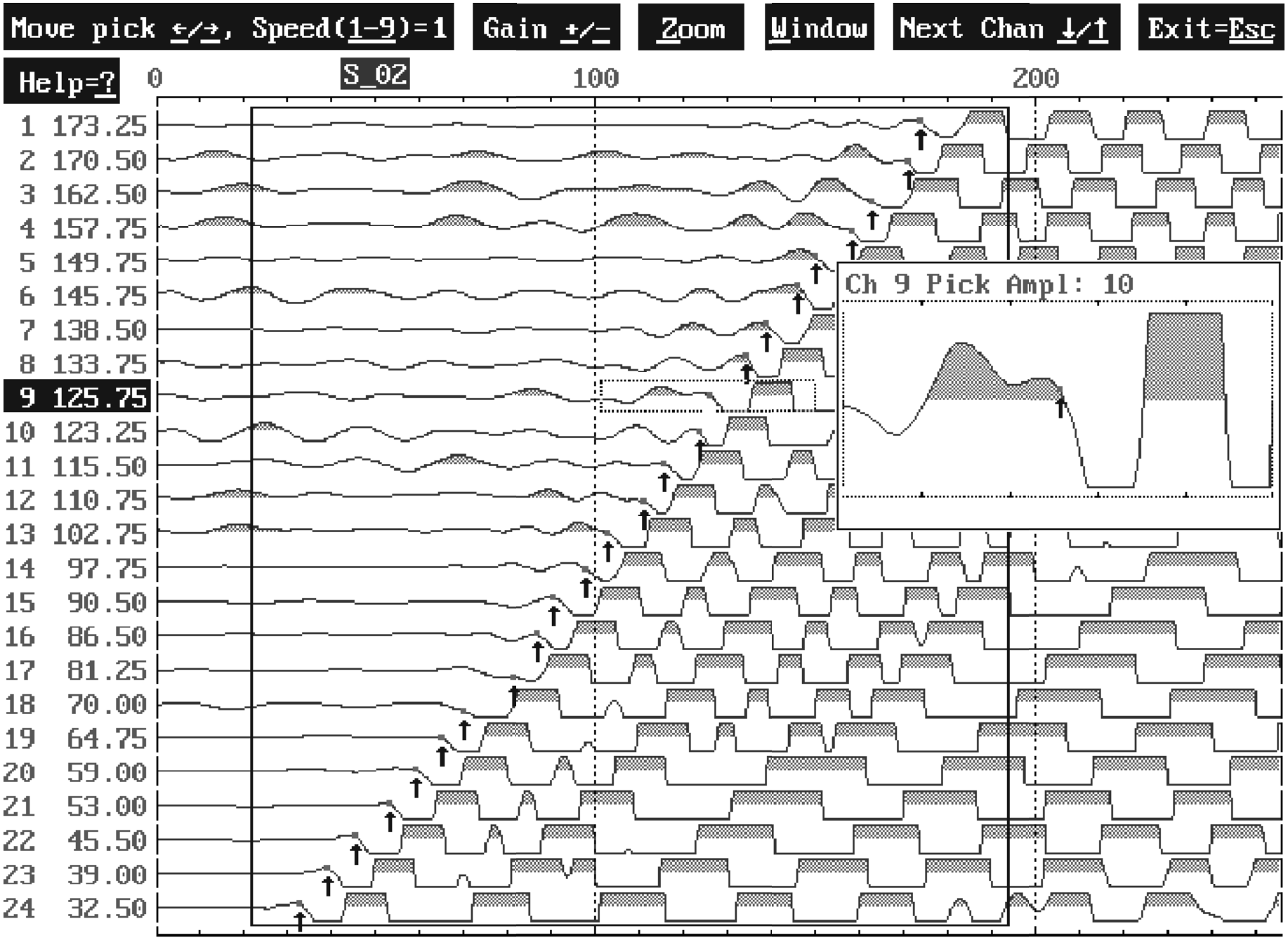

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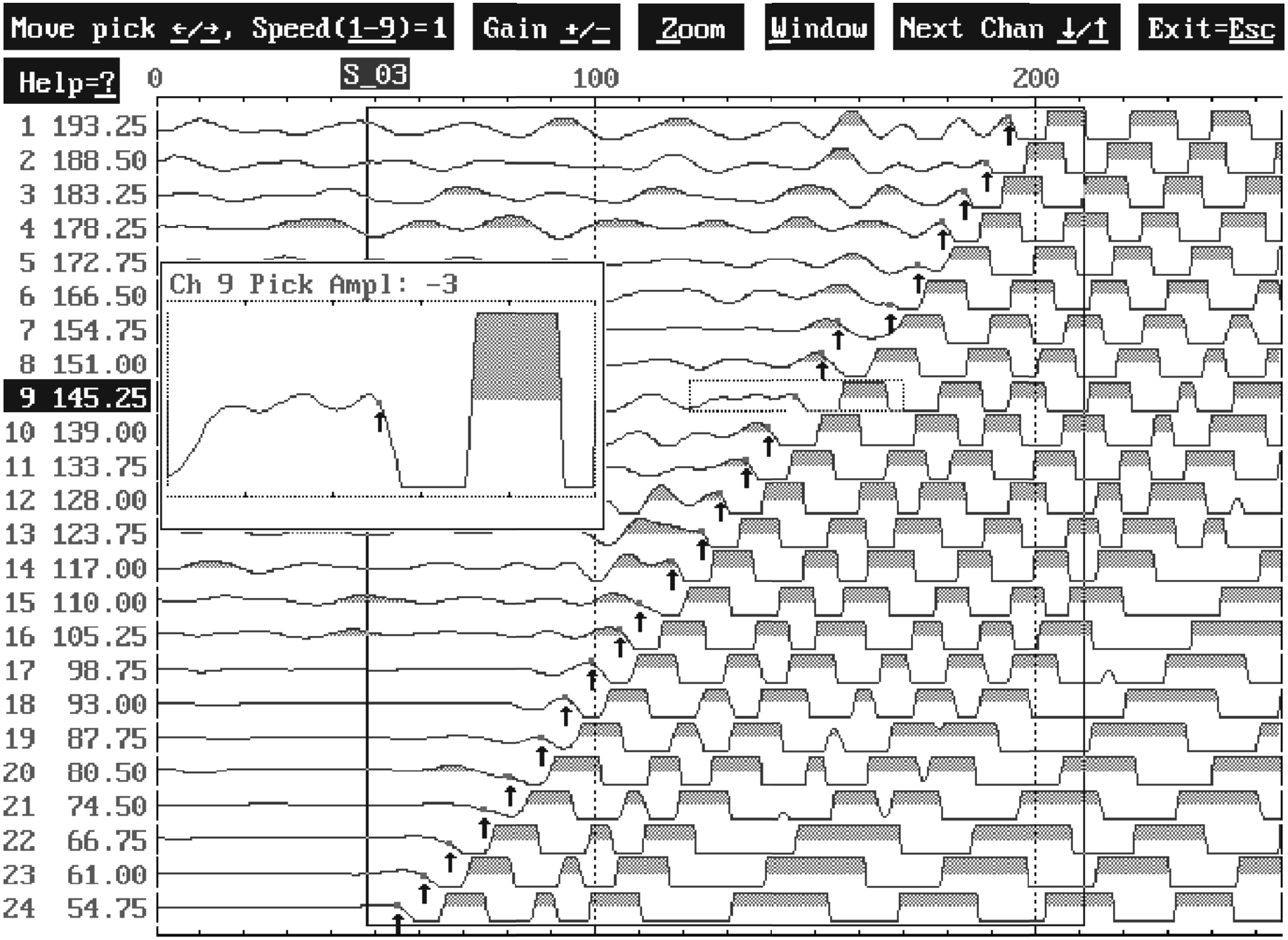

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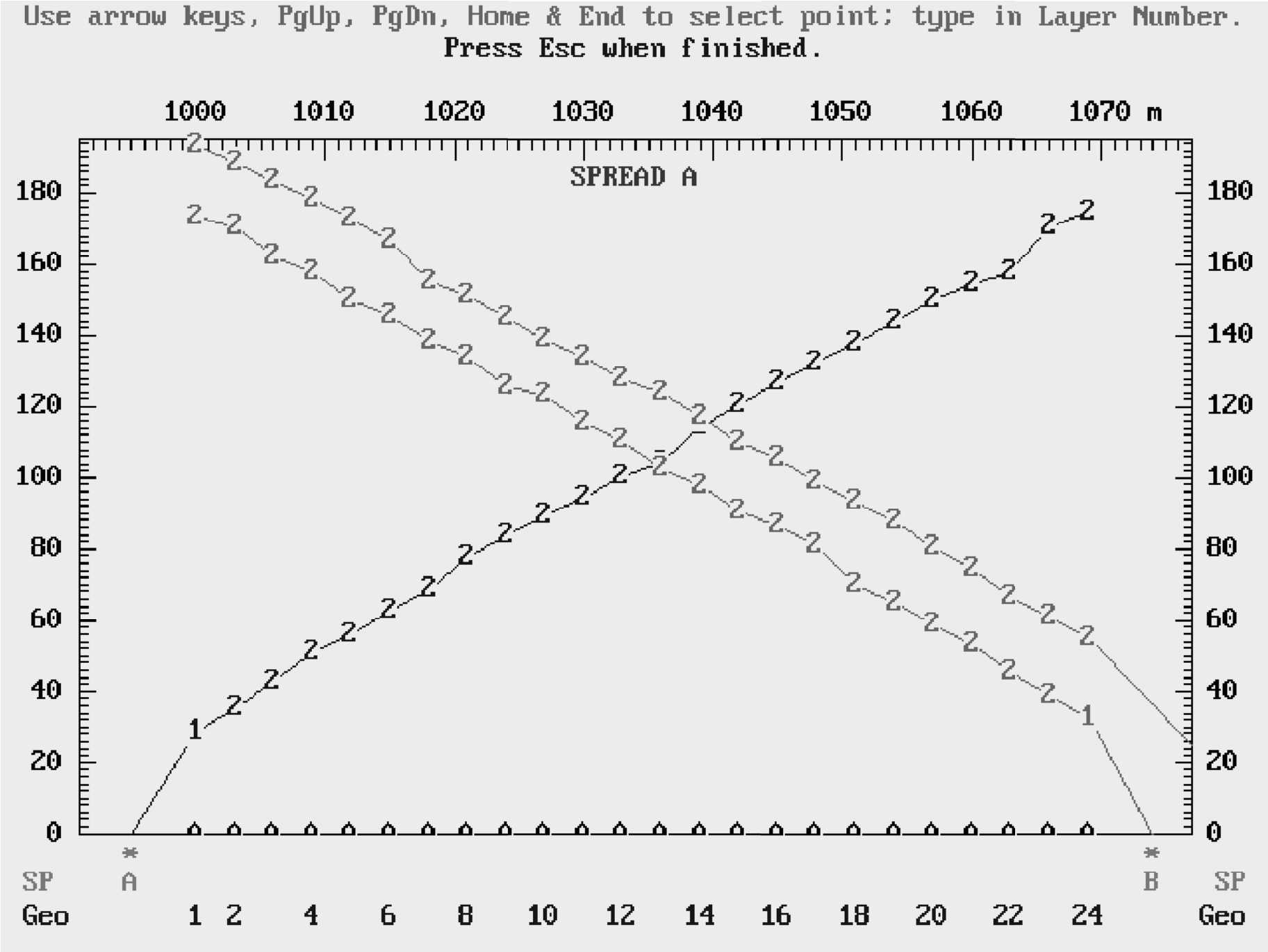

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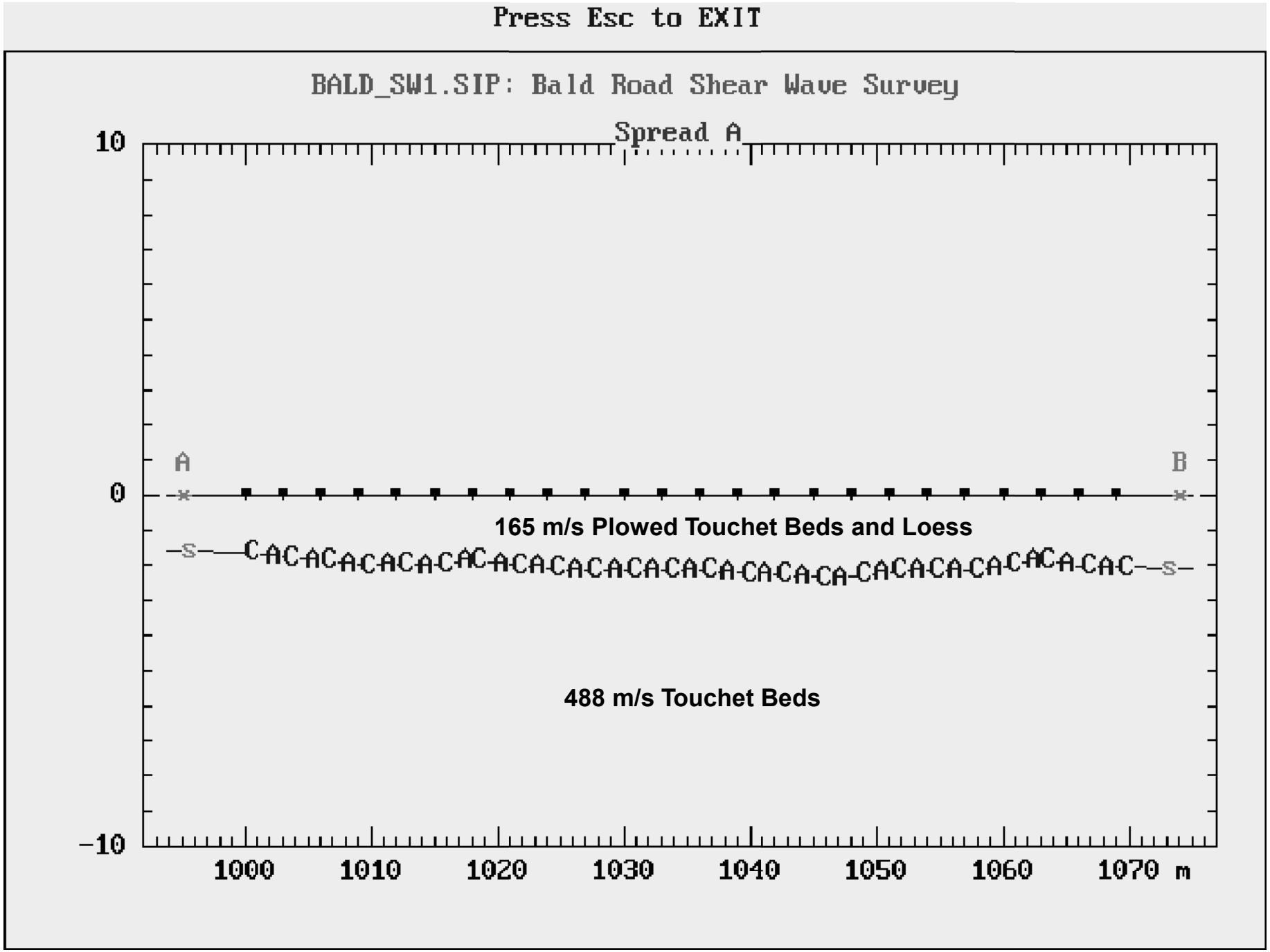

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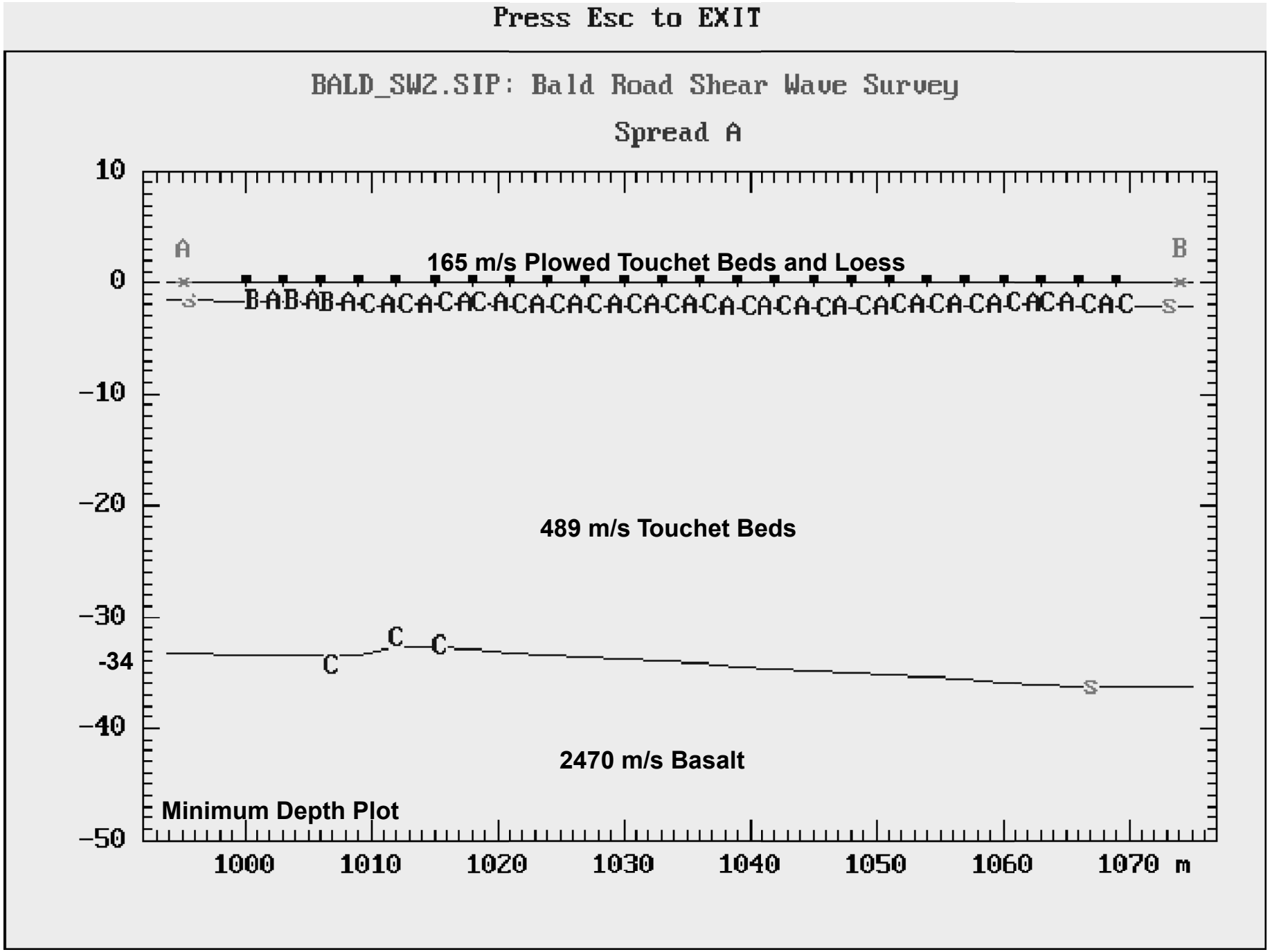
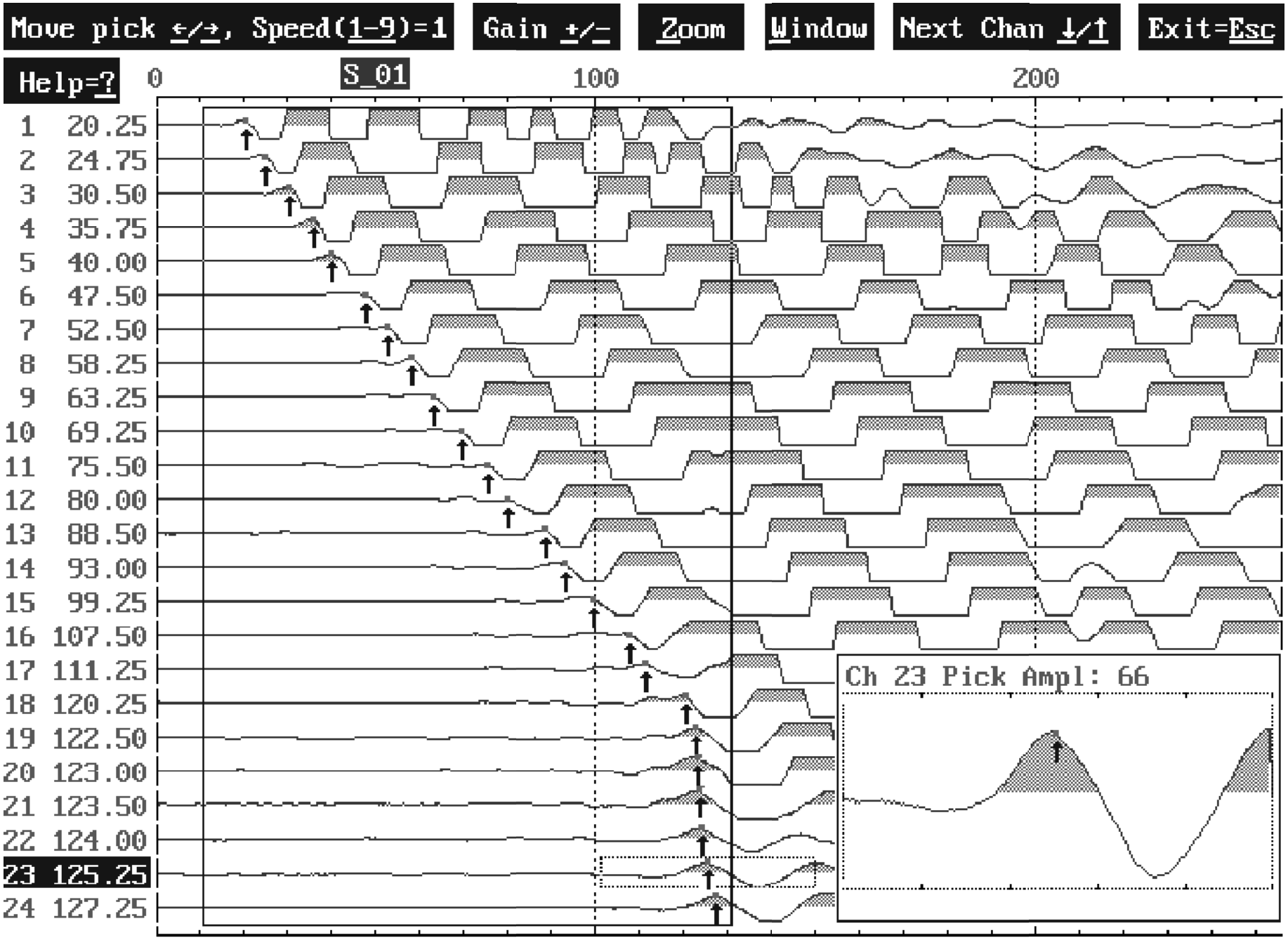


Barker Road South S-wave



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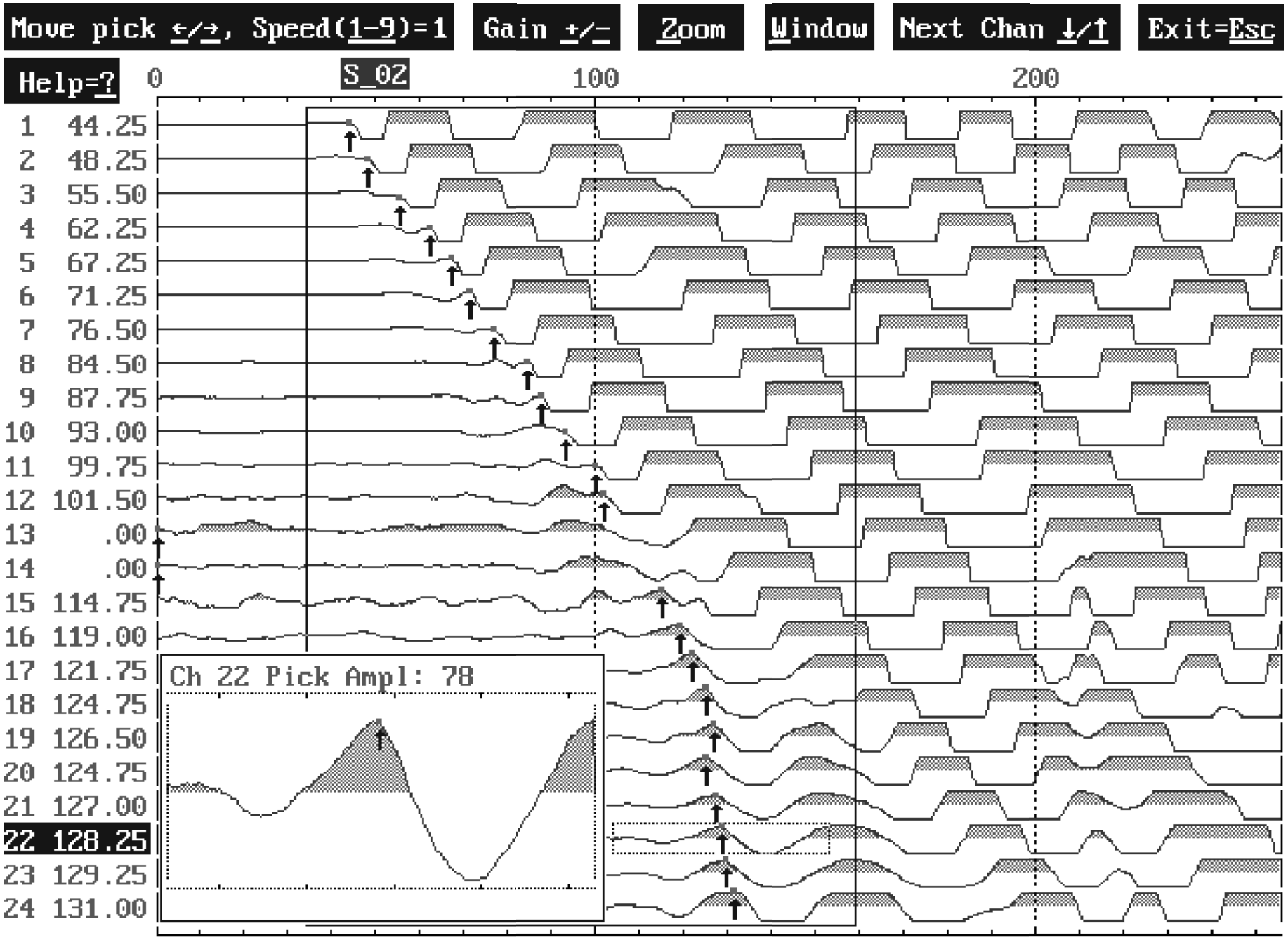

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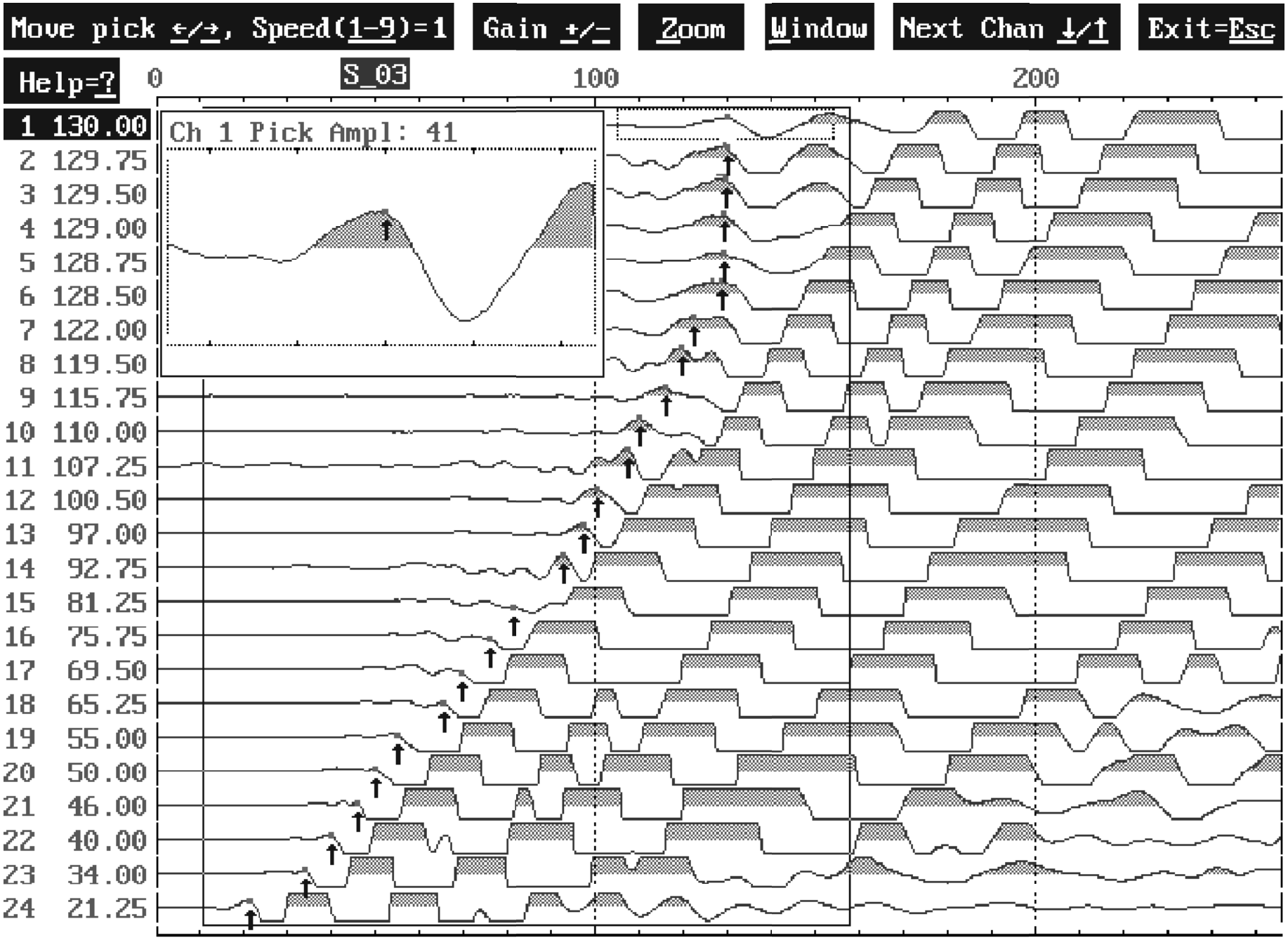

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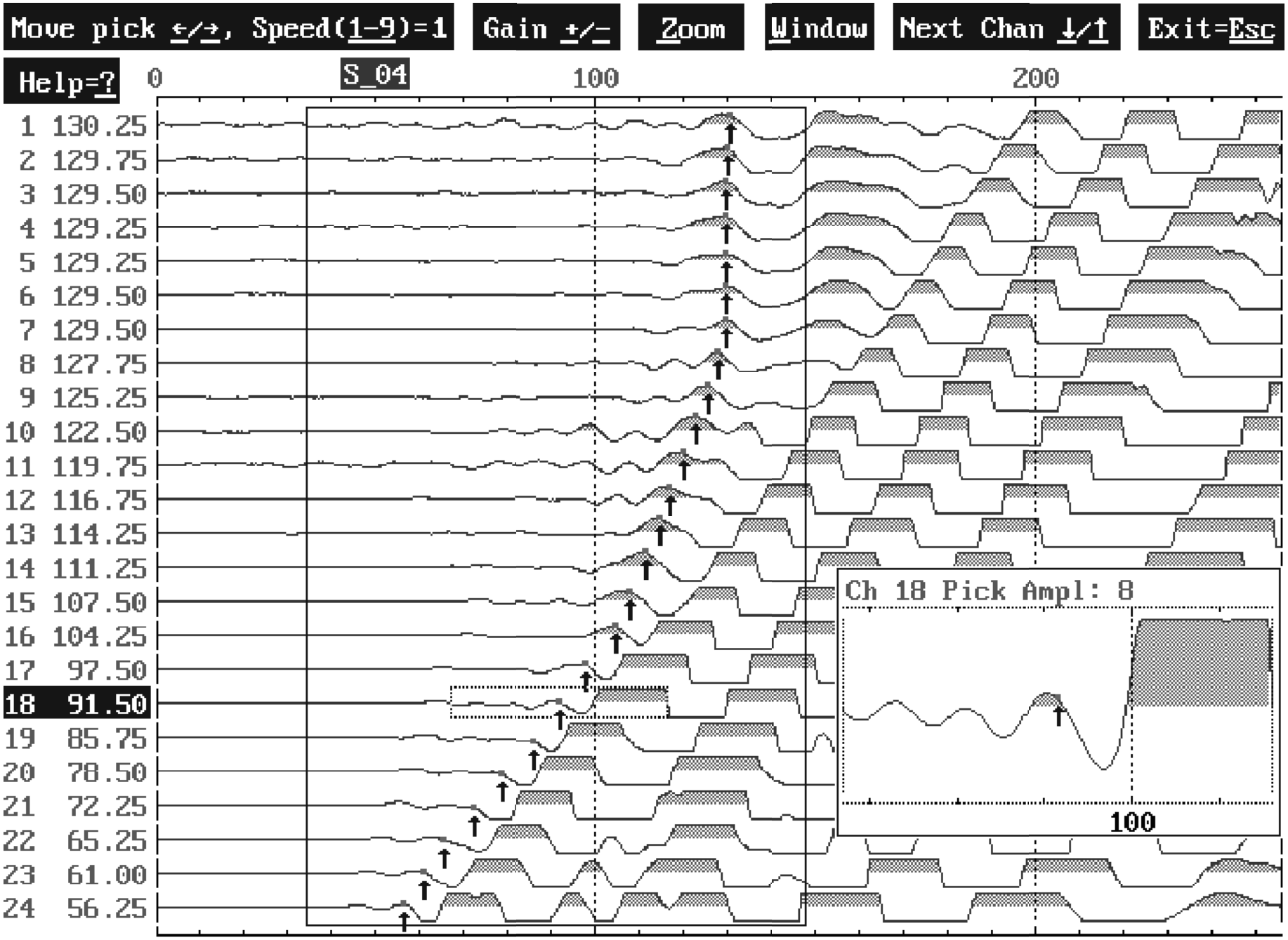

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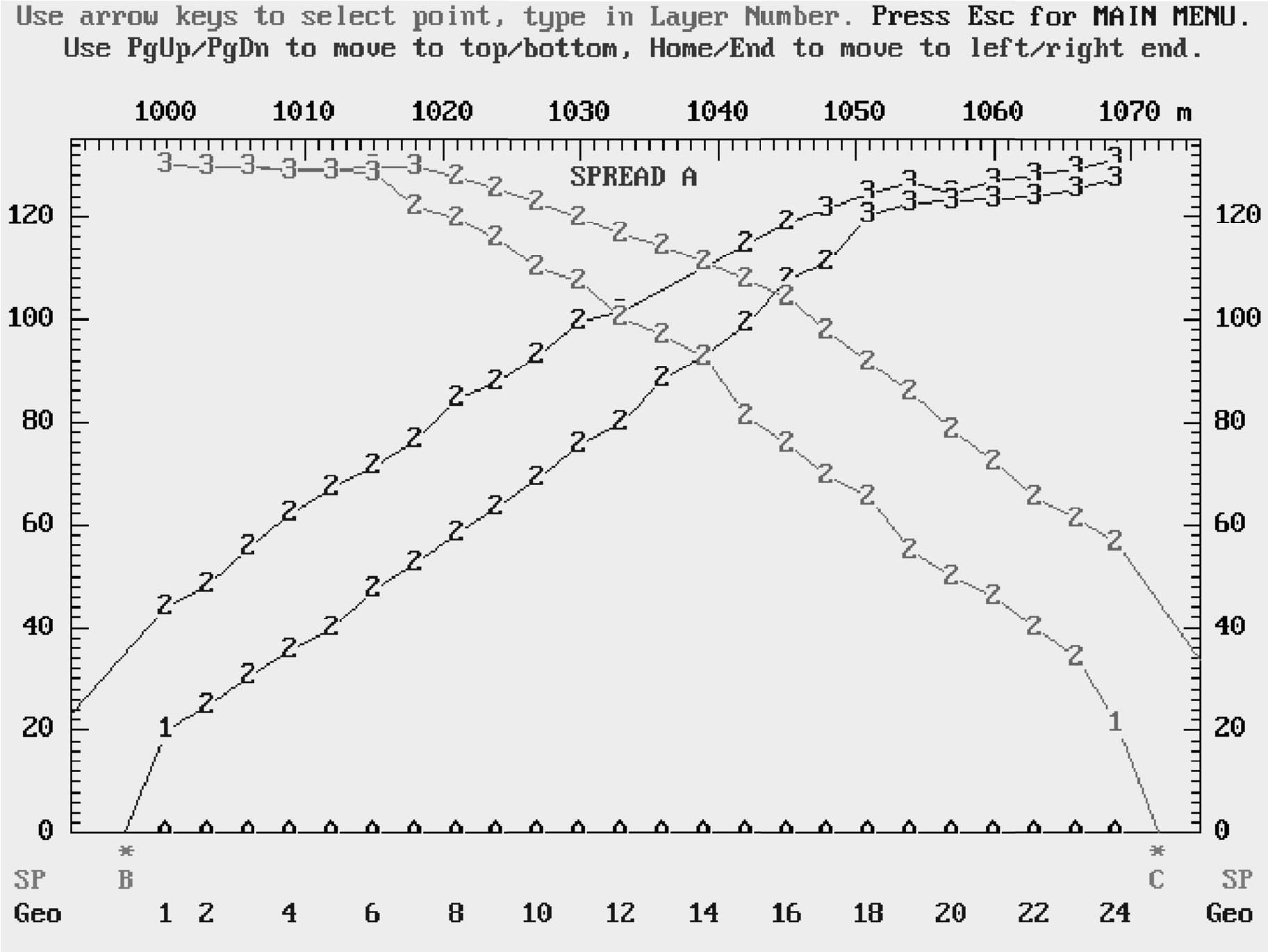

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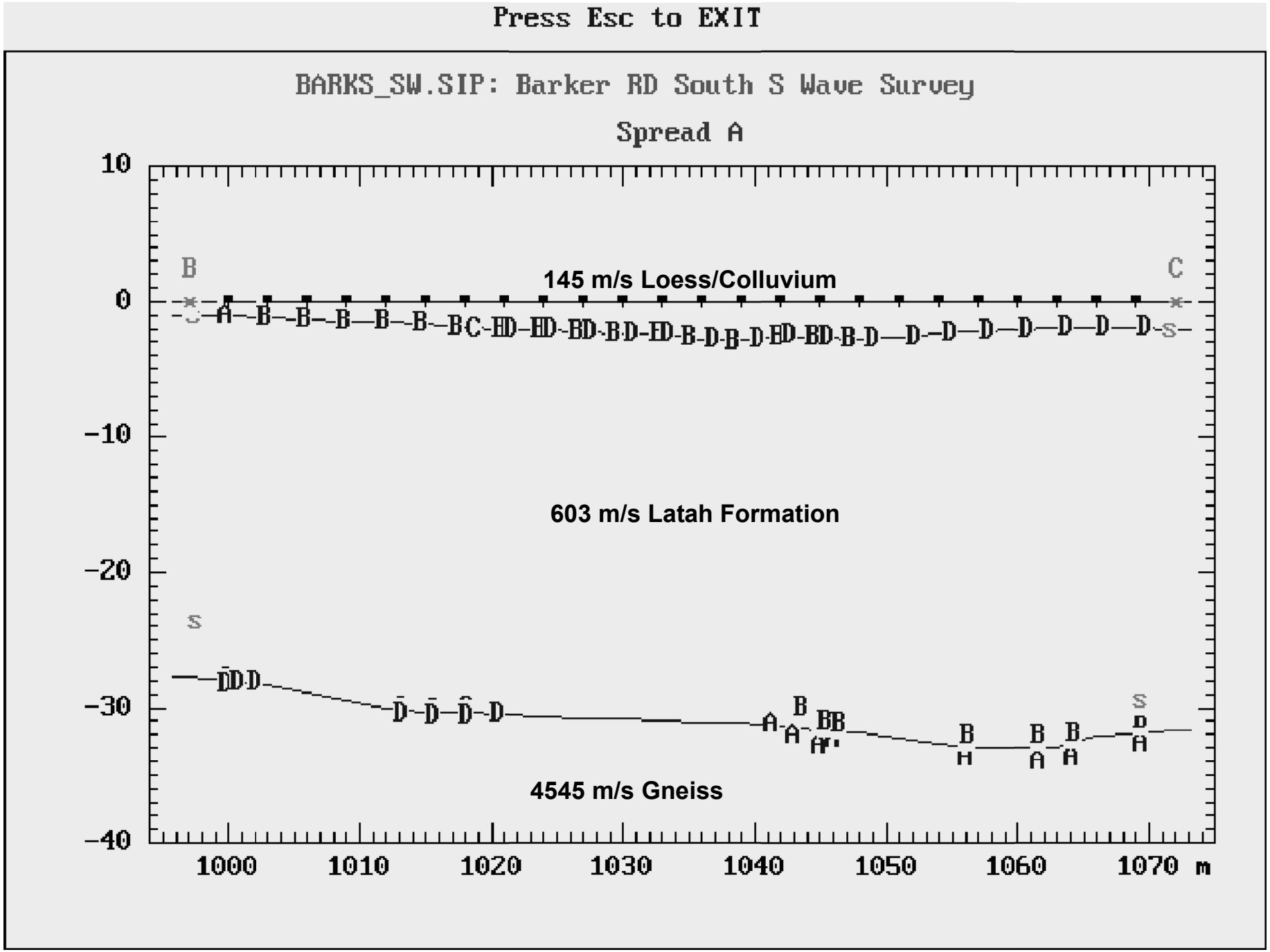
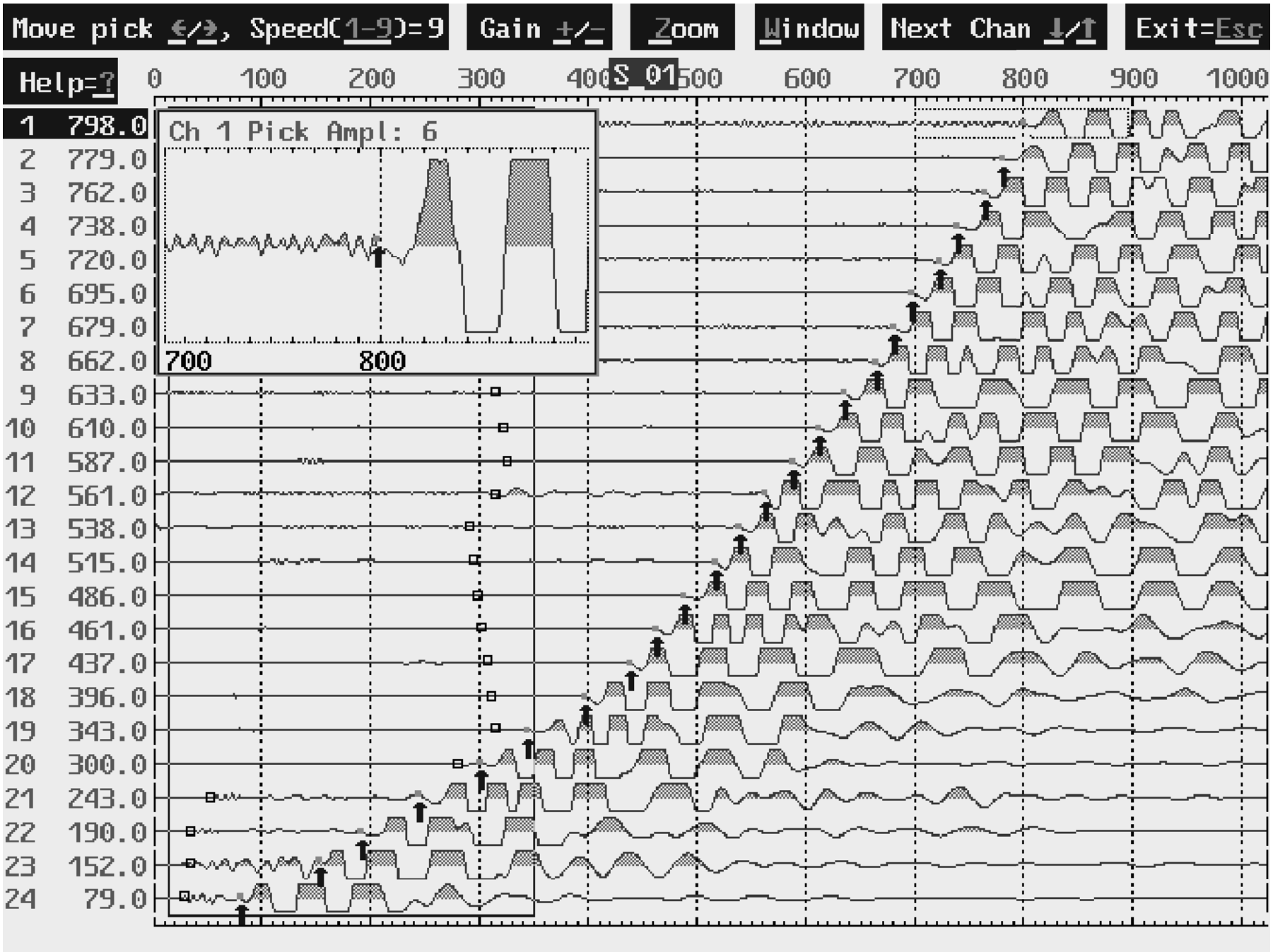


Barlow Point RD S-wave



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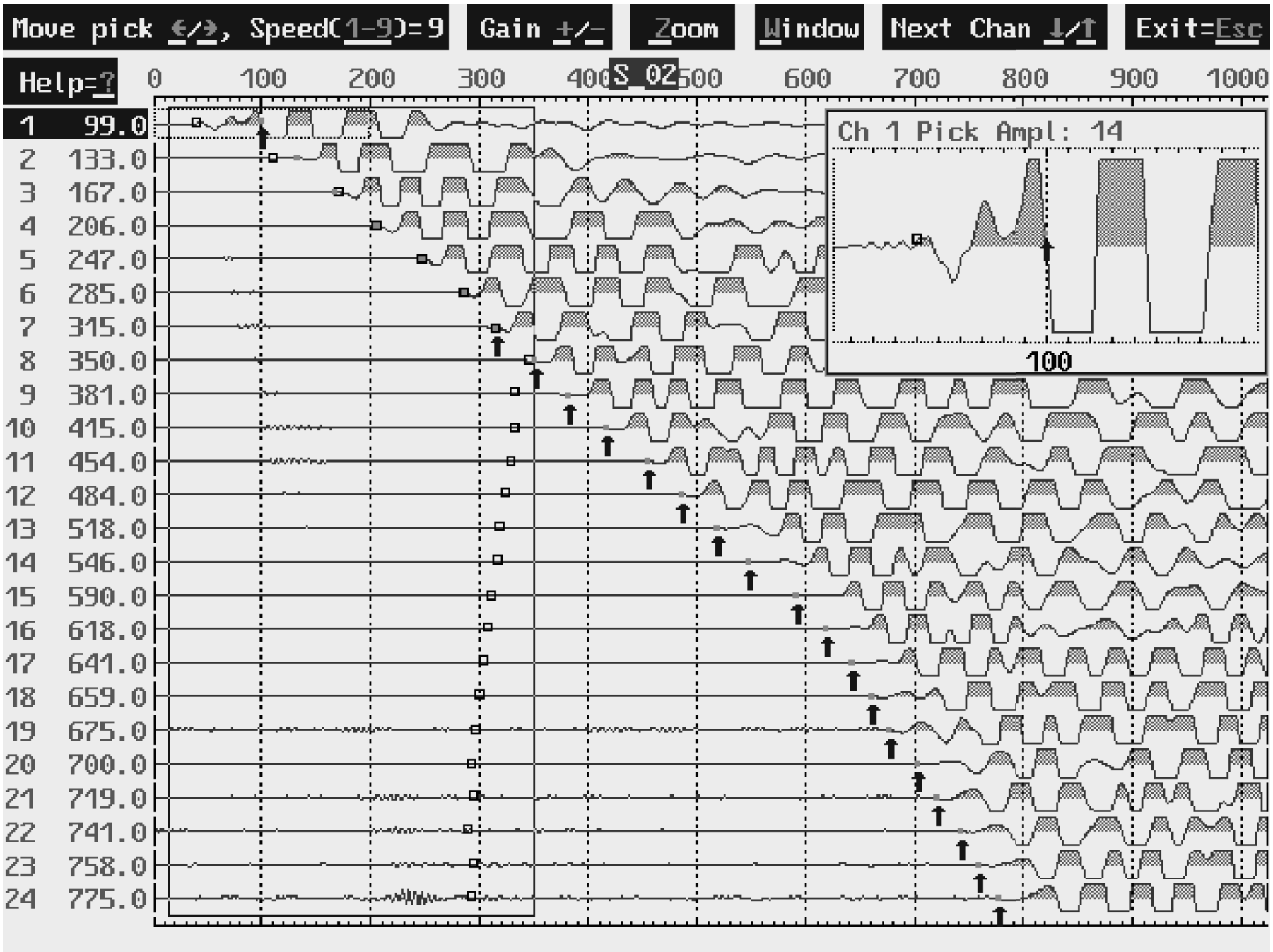

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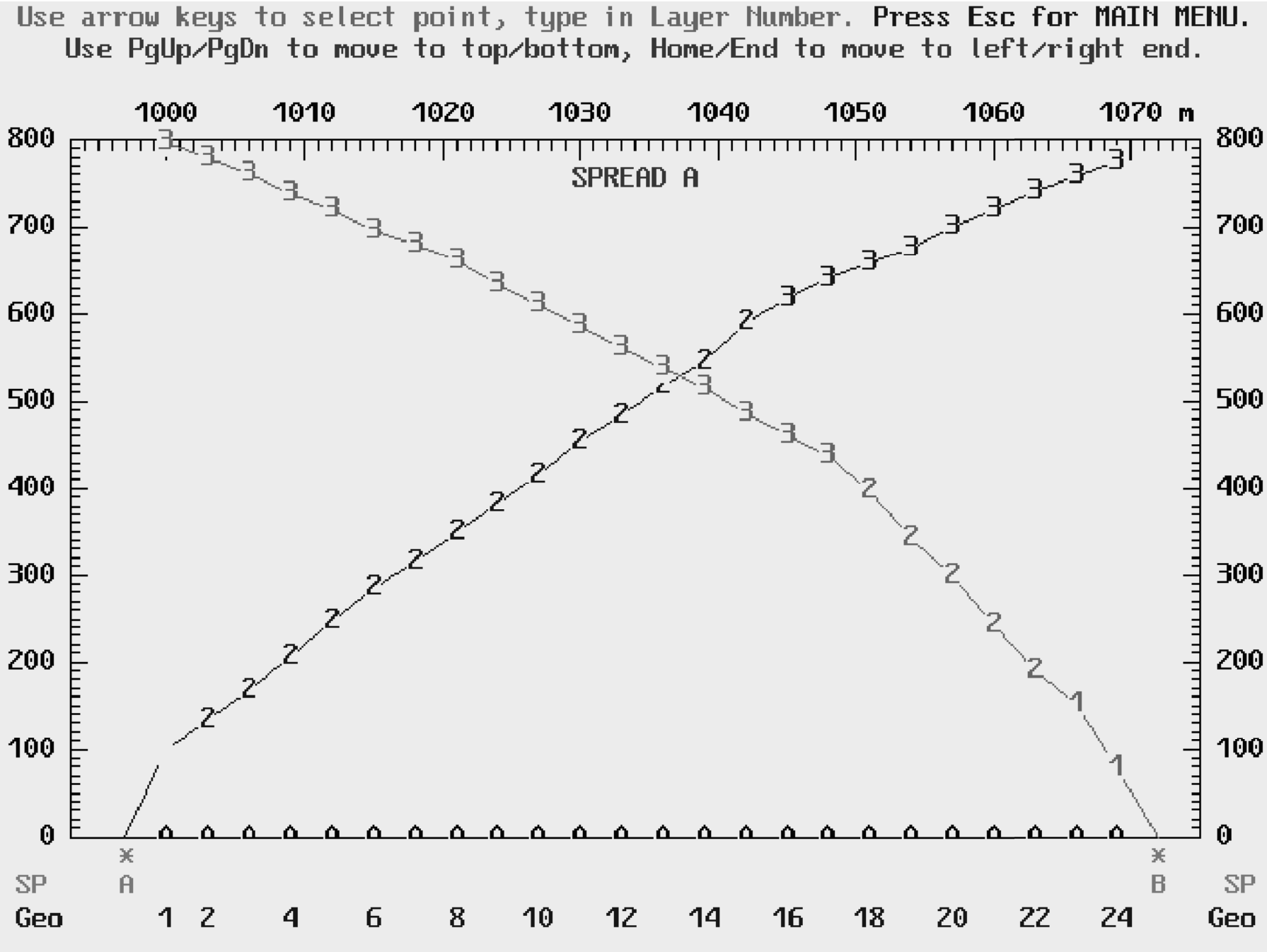

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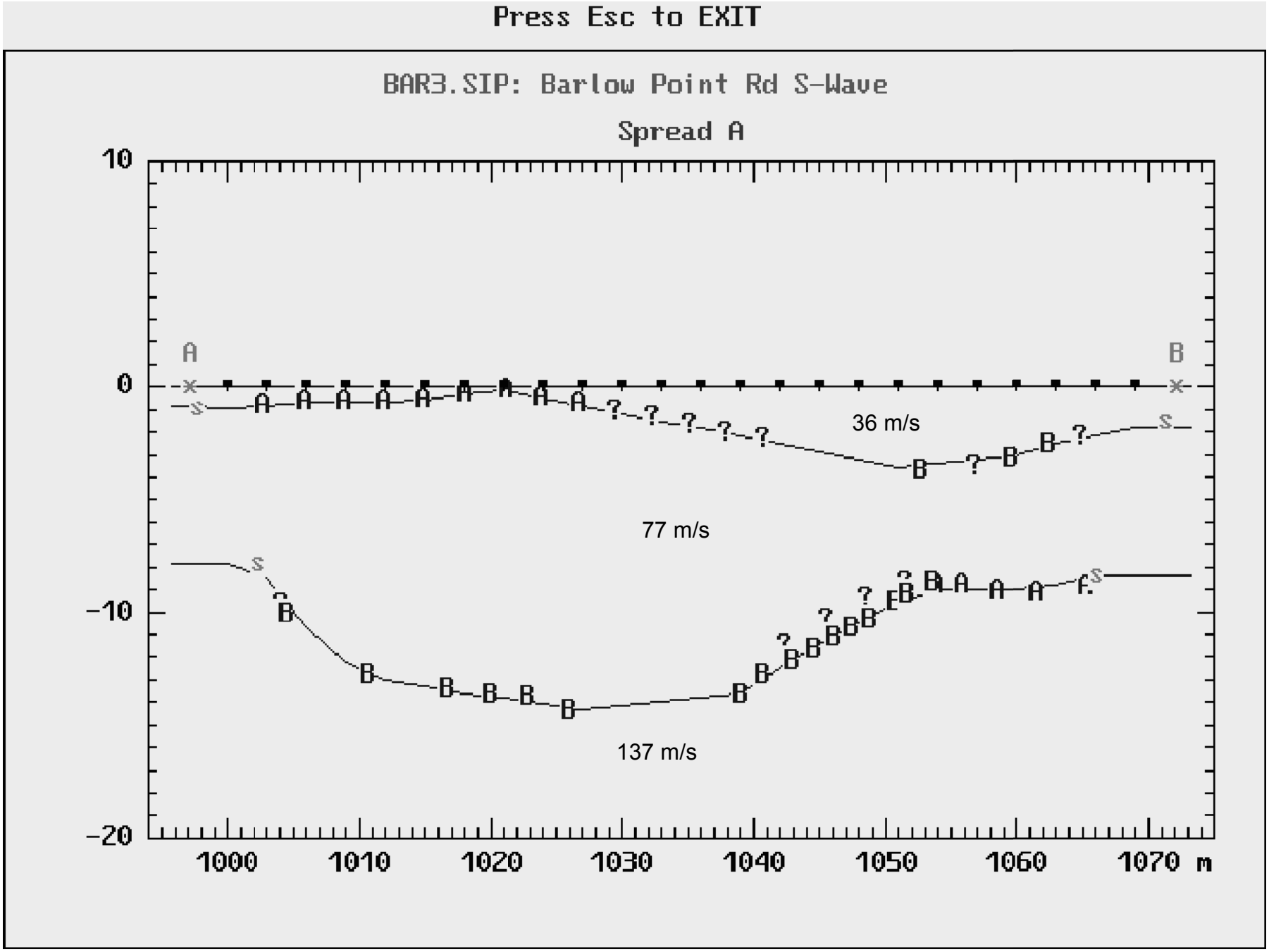

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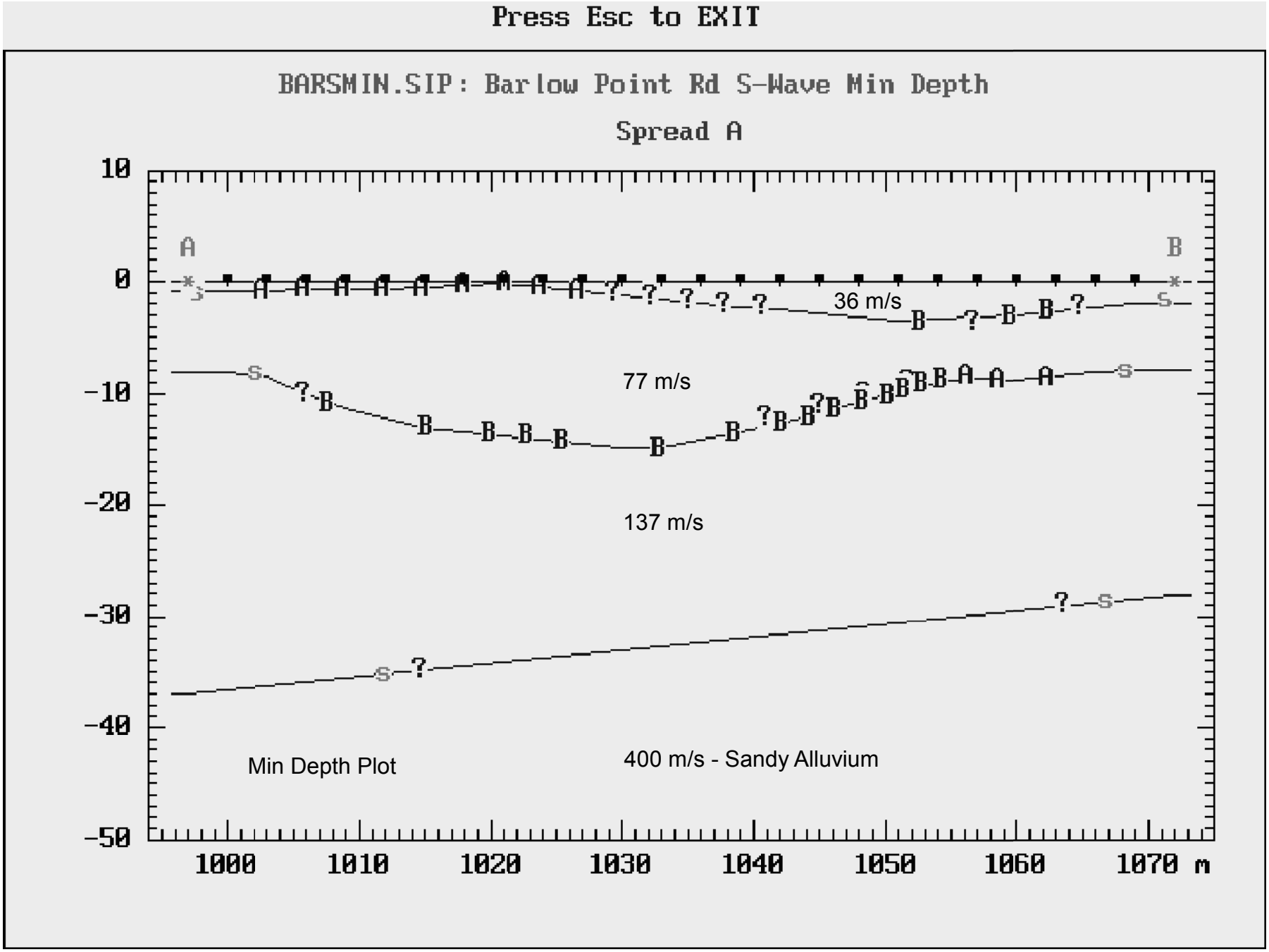
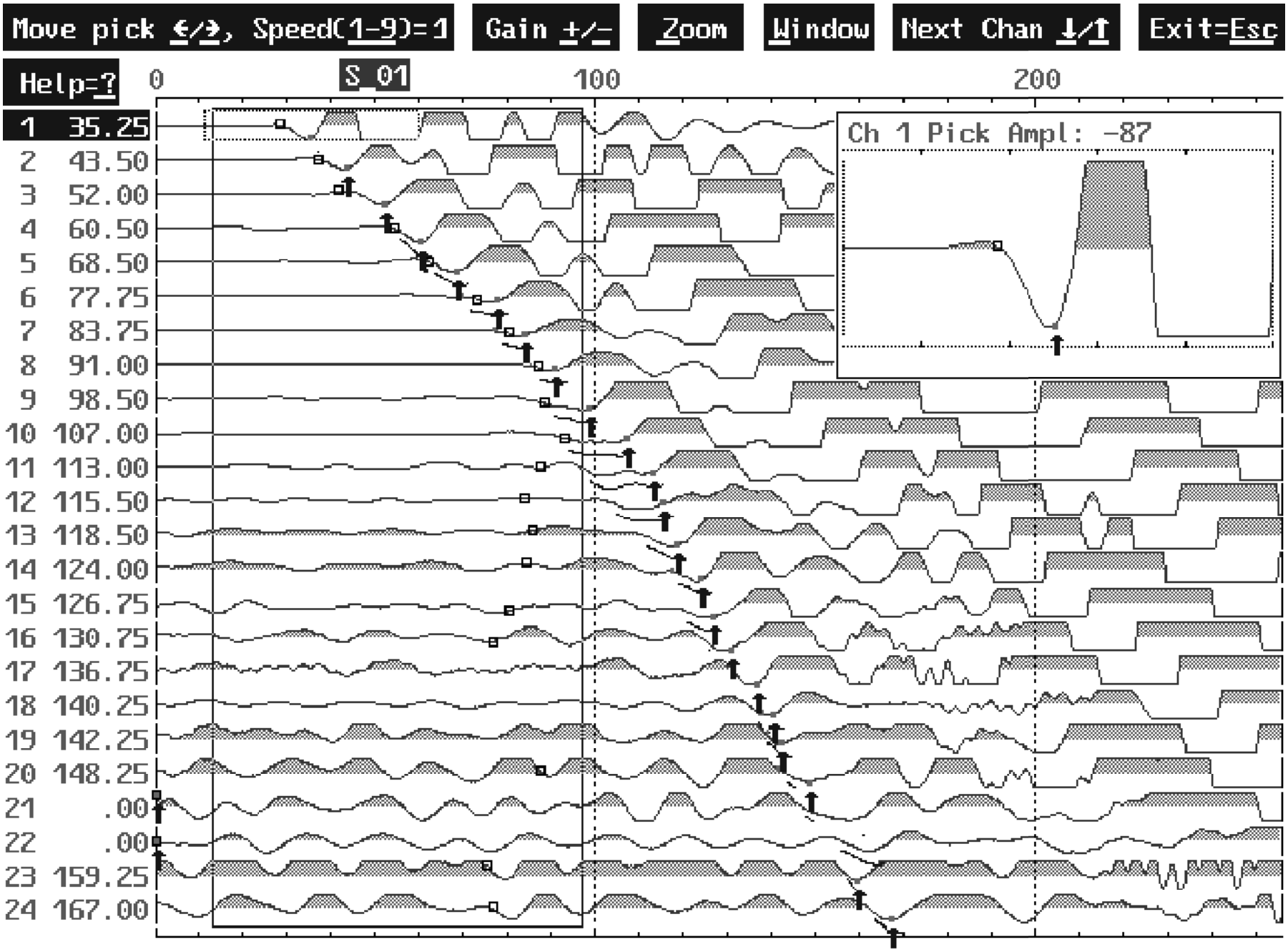
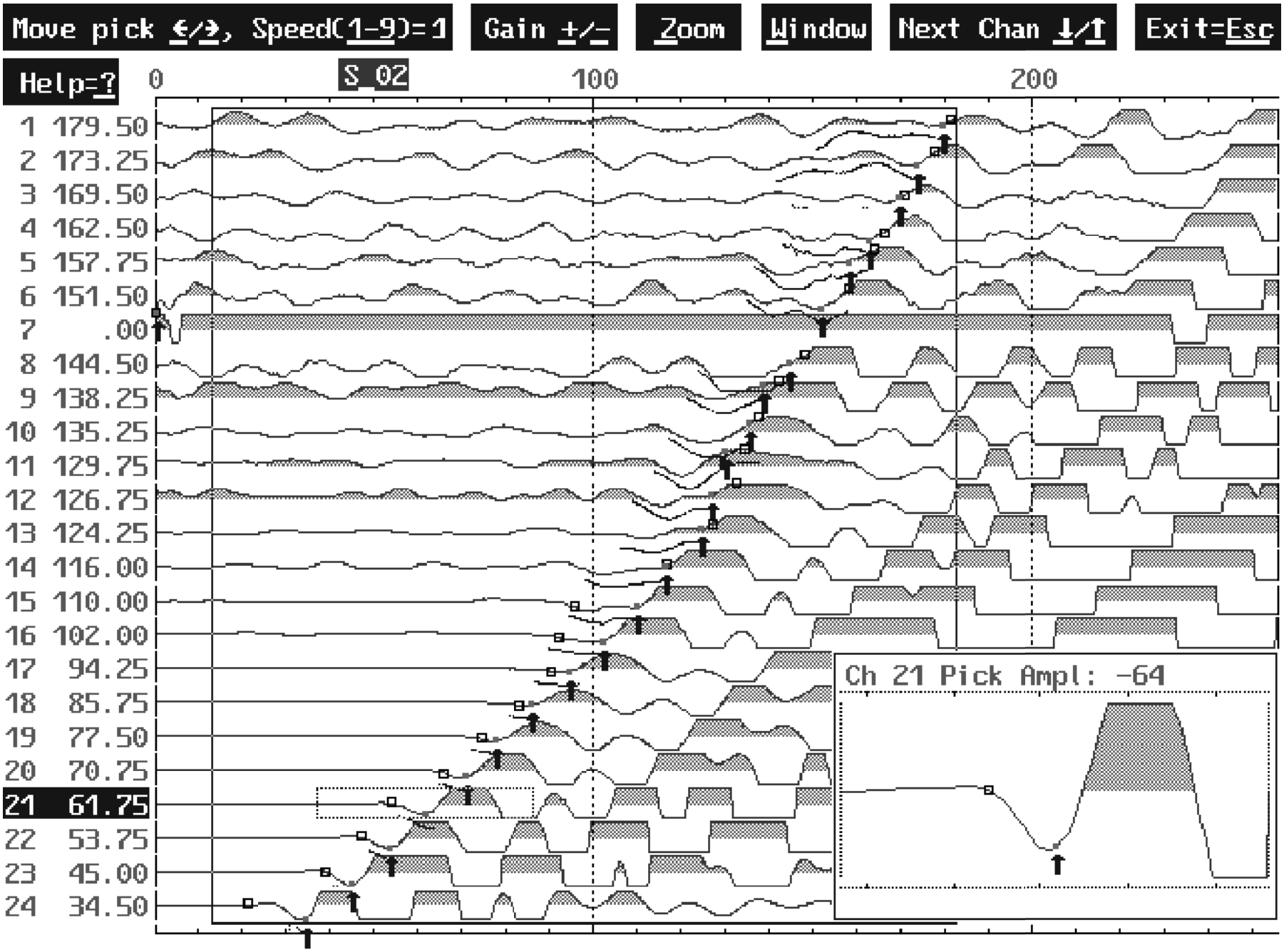


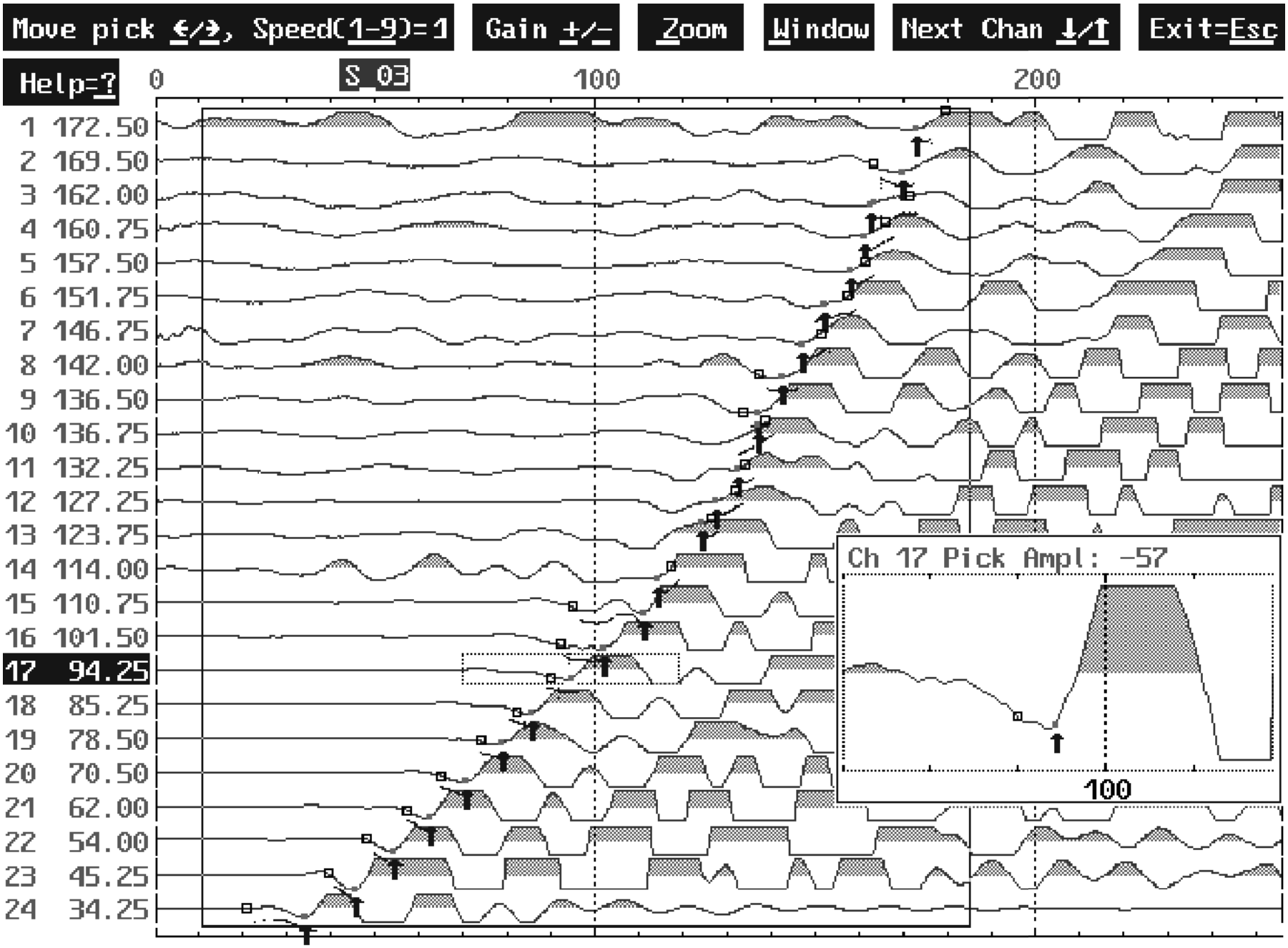
Big George S-wave



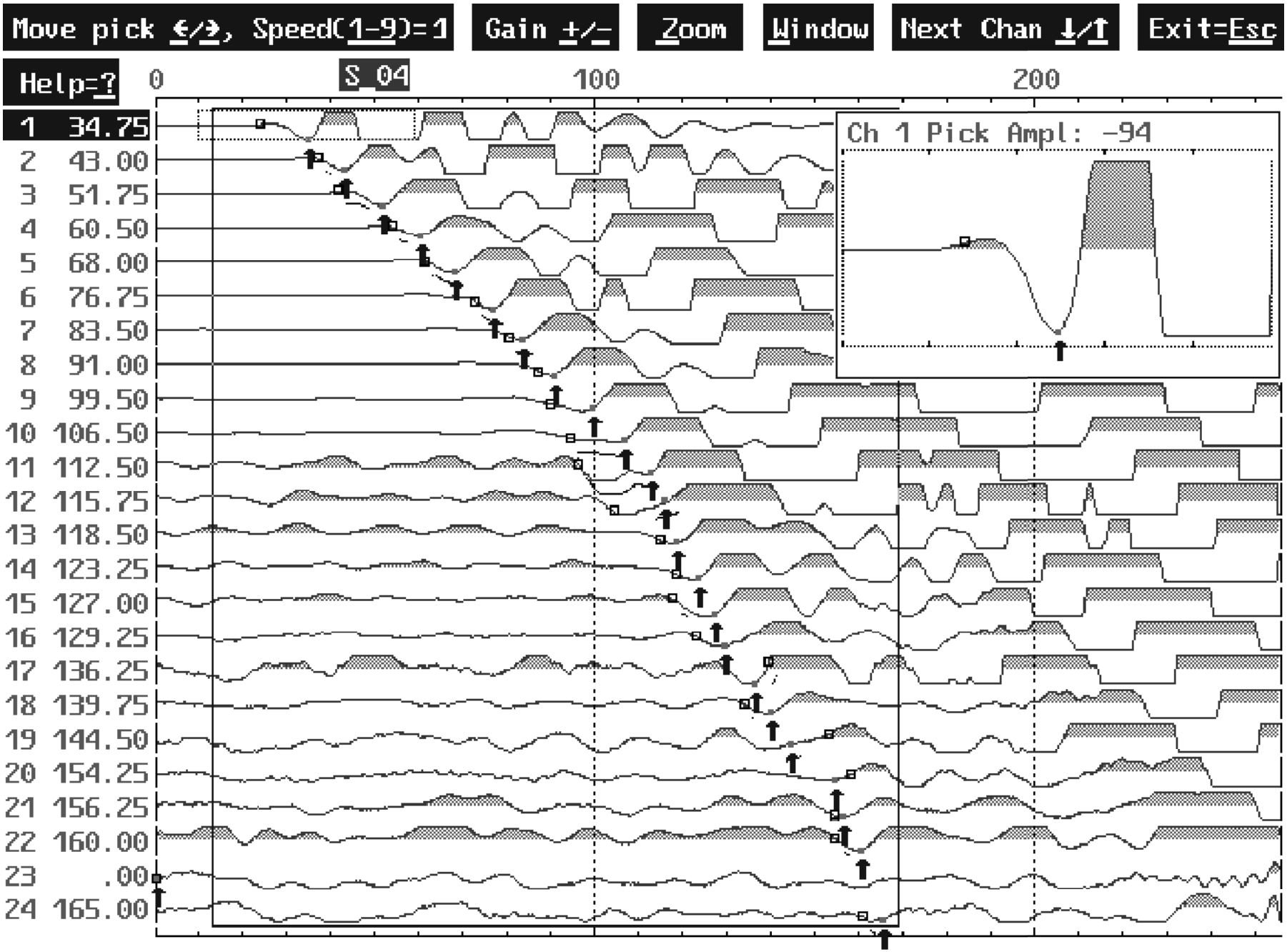
Big George S-wave



Big George S-wave



Big George S-wave



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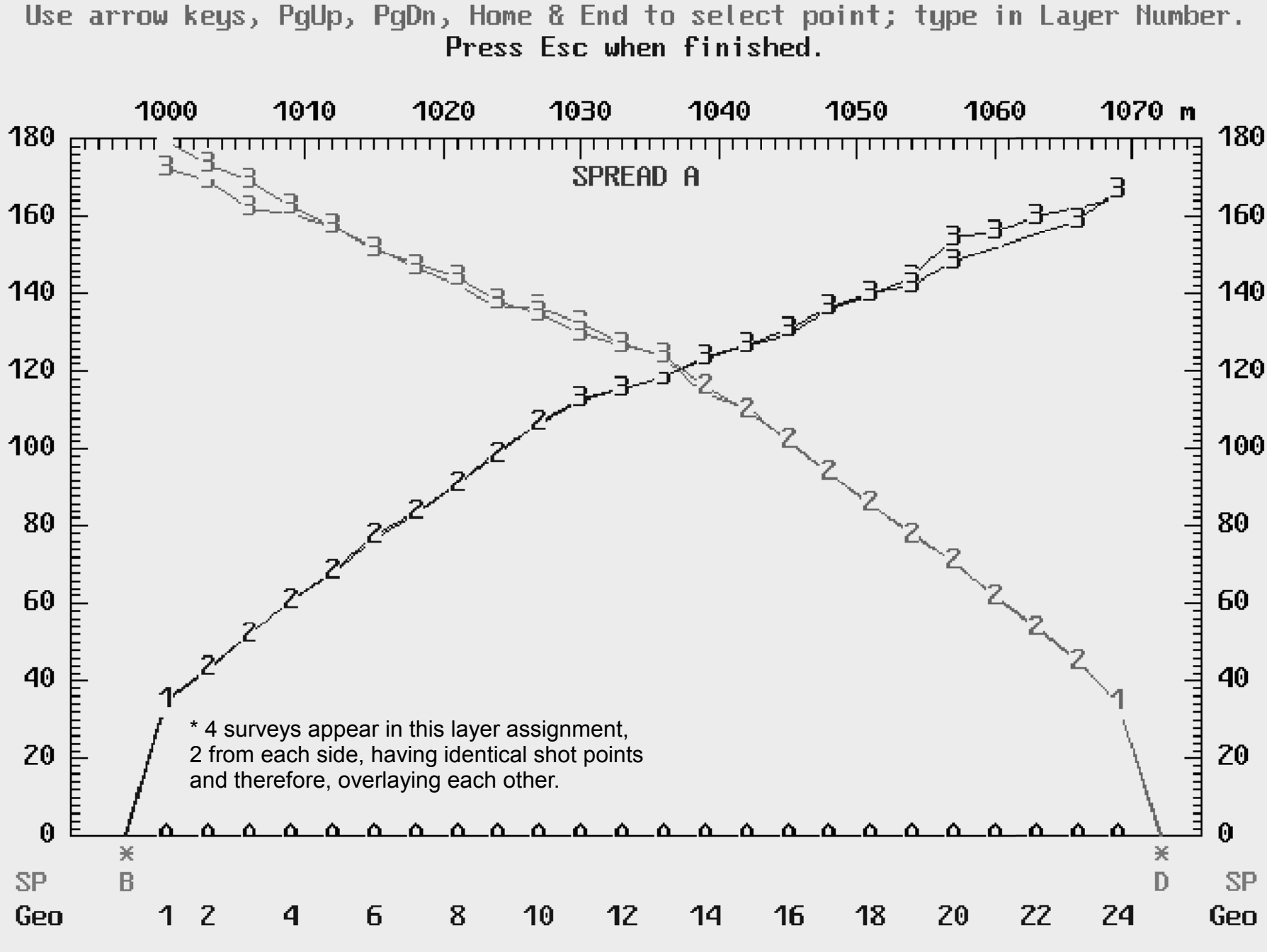

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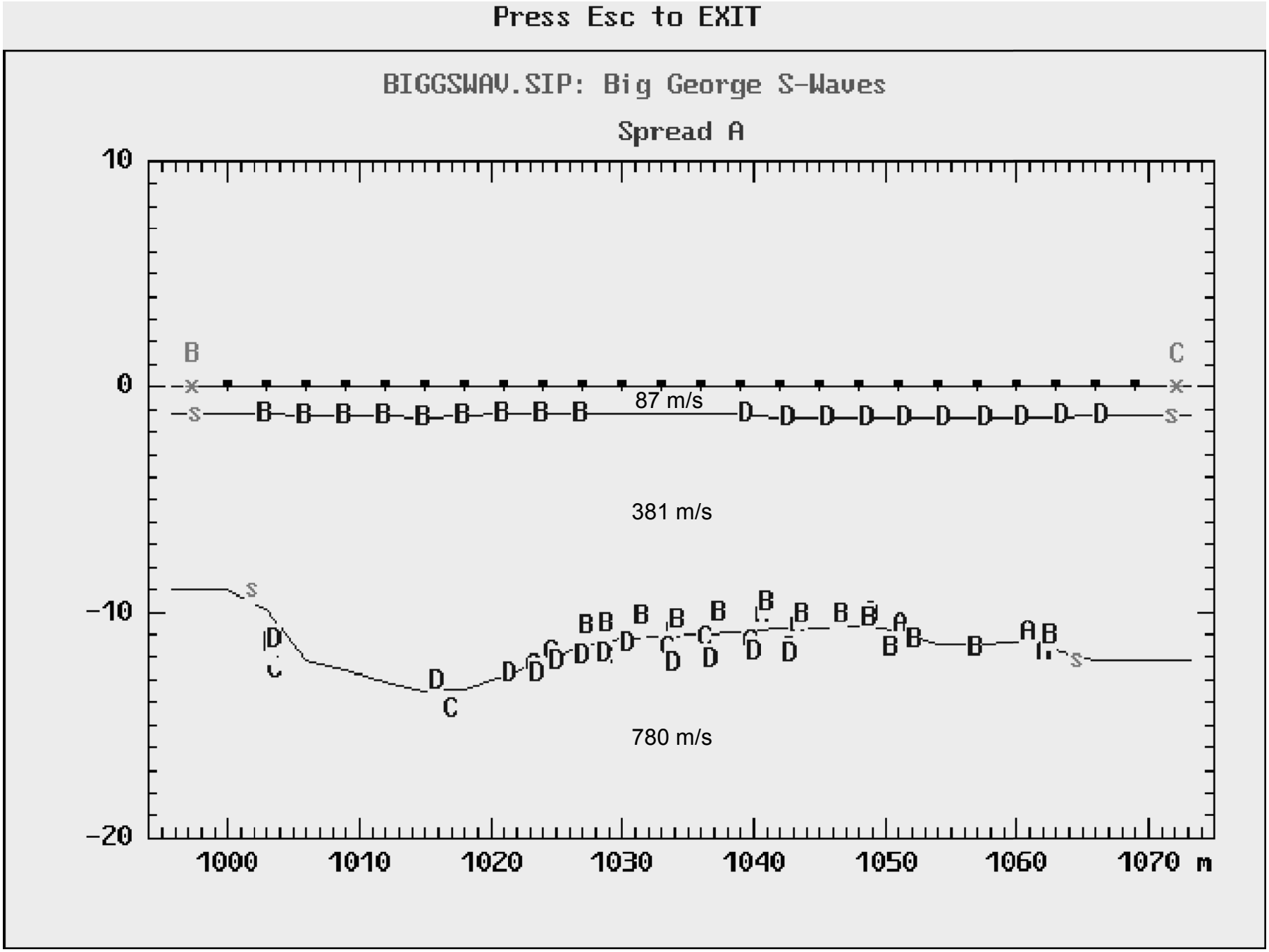

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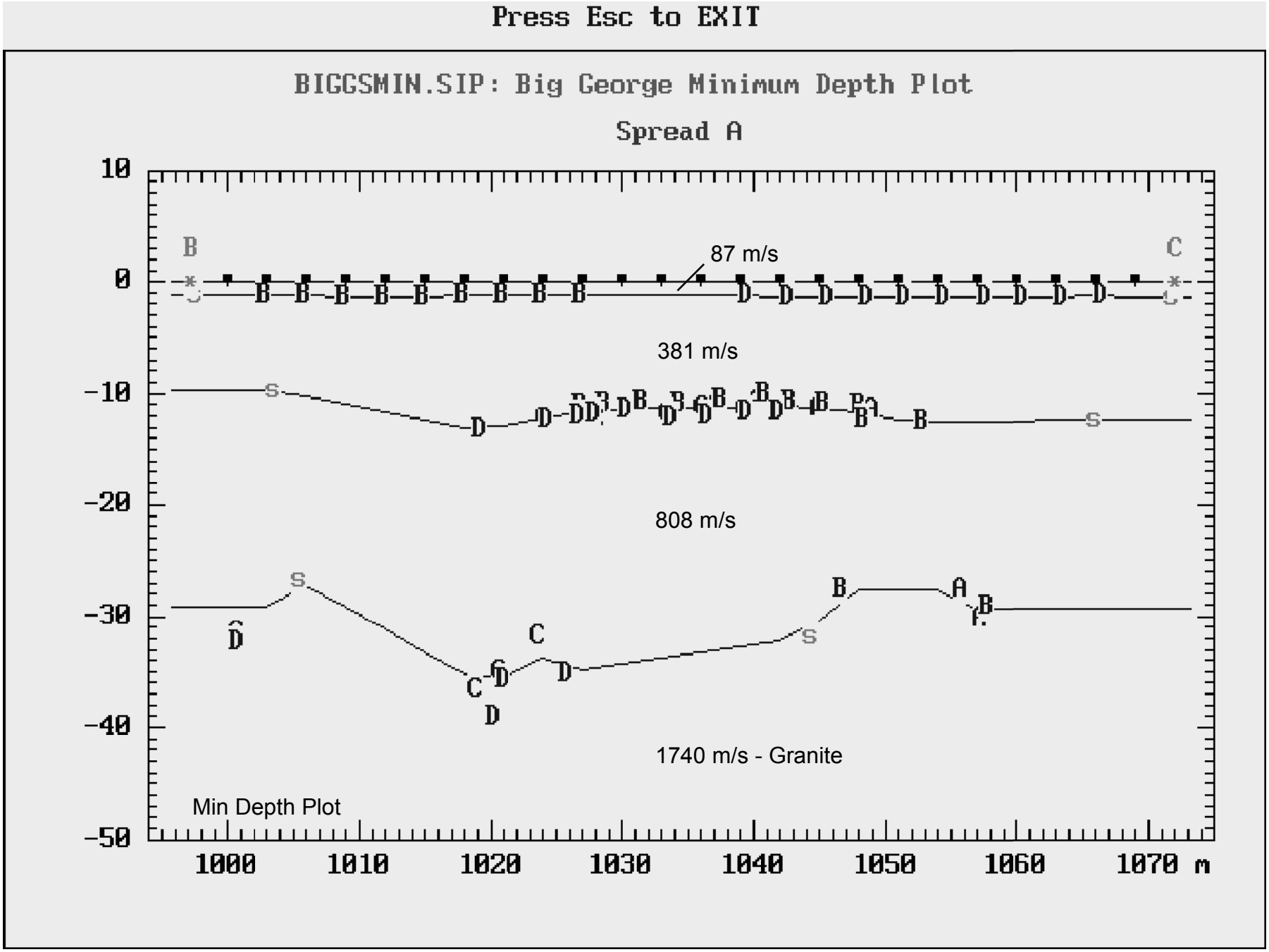

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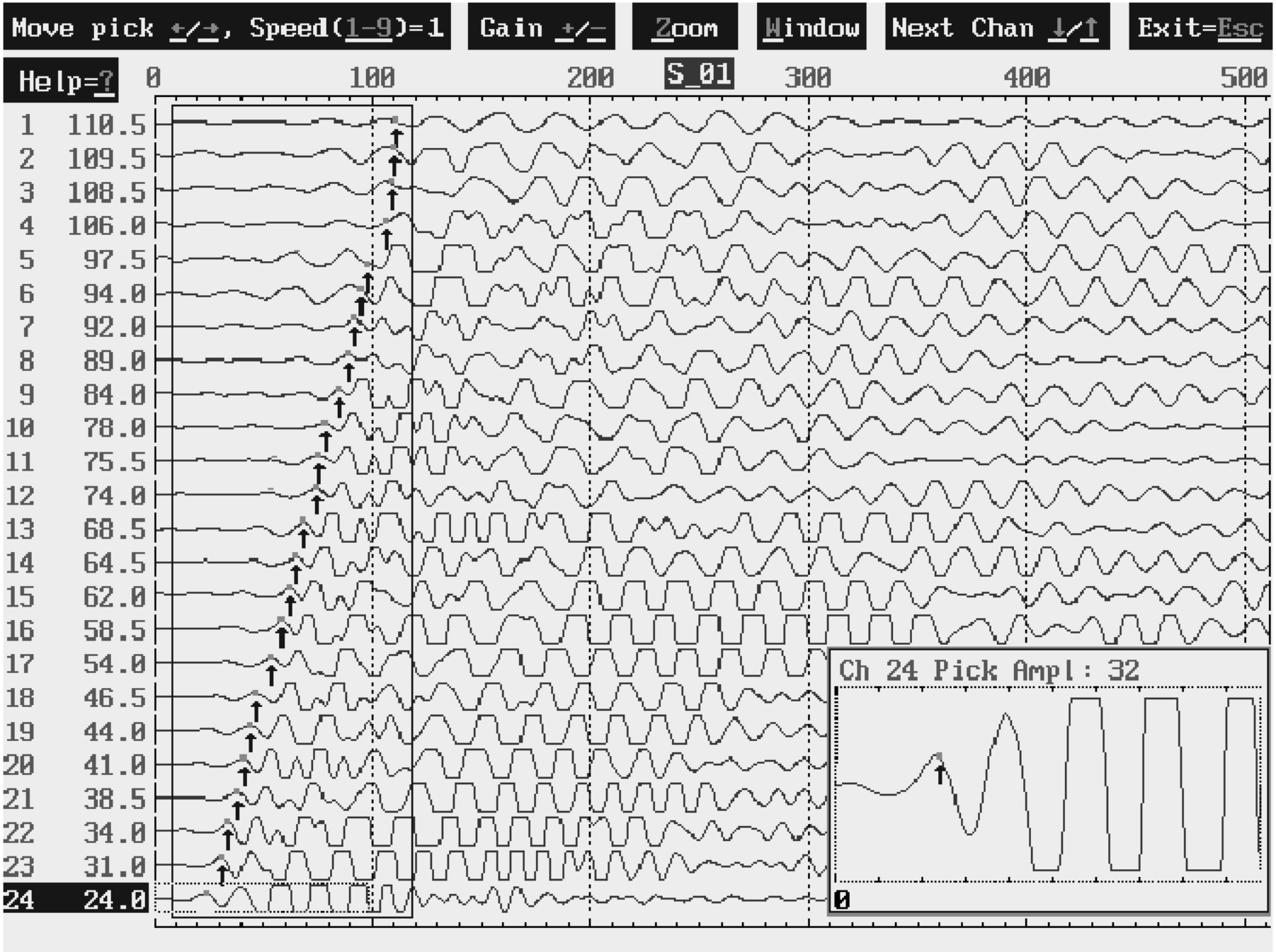

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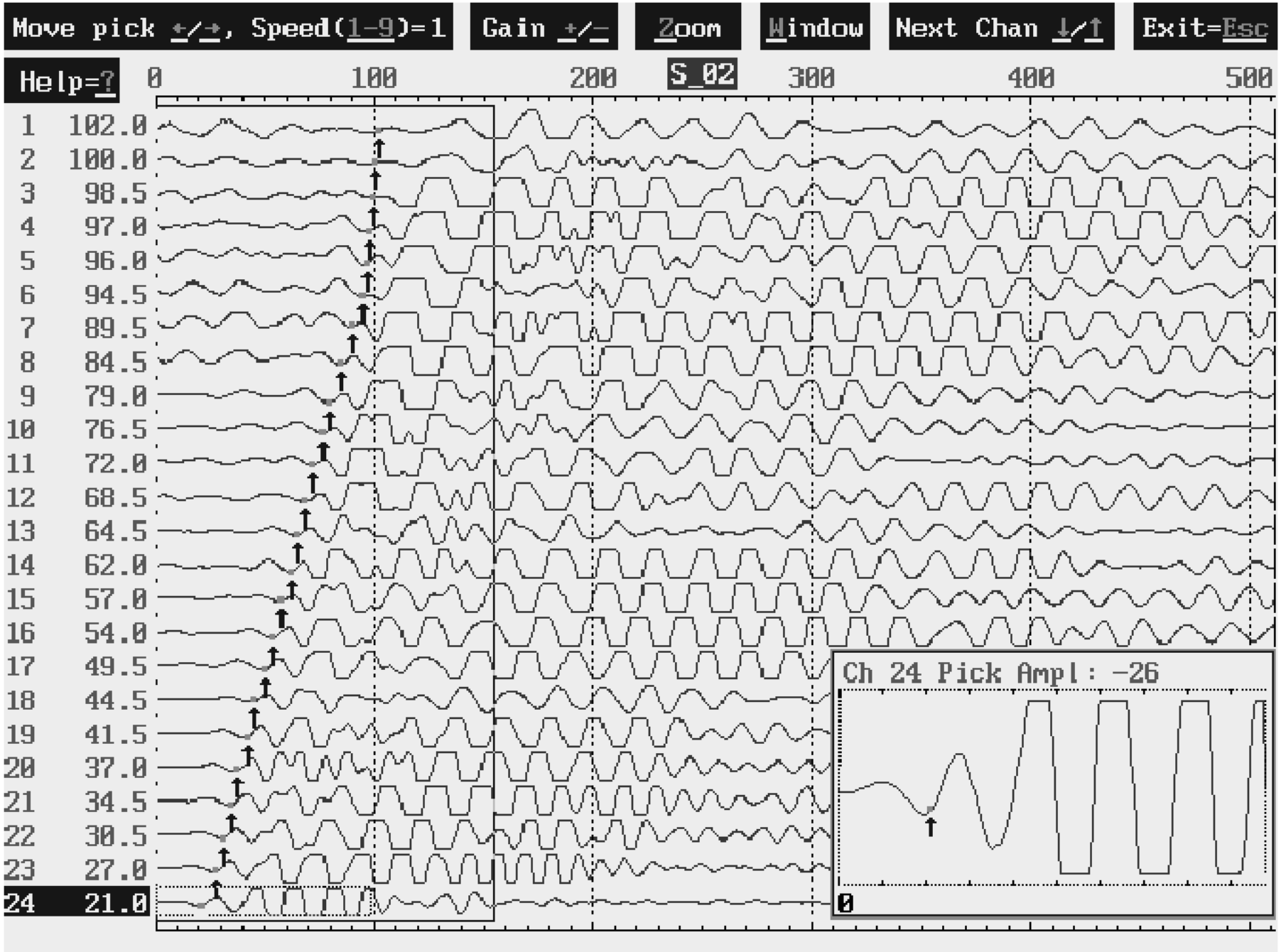

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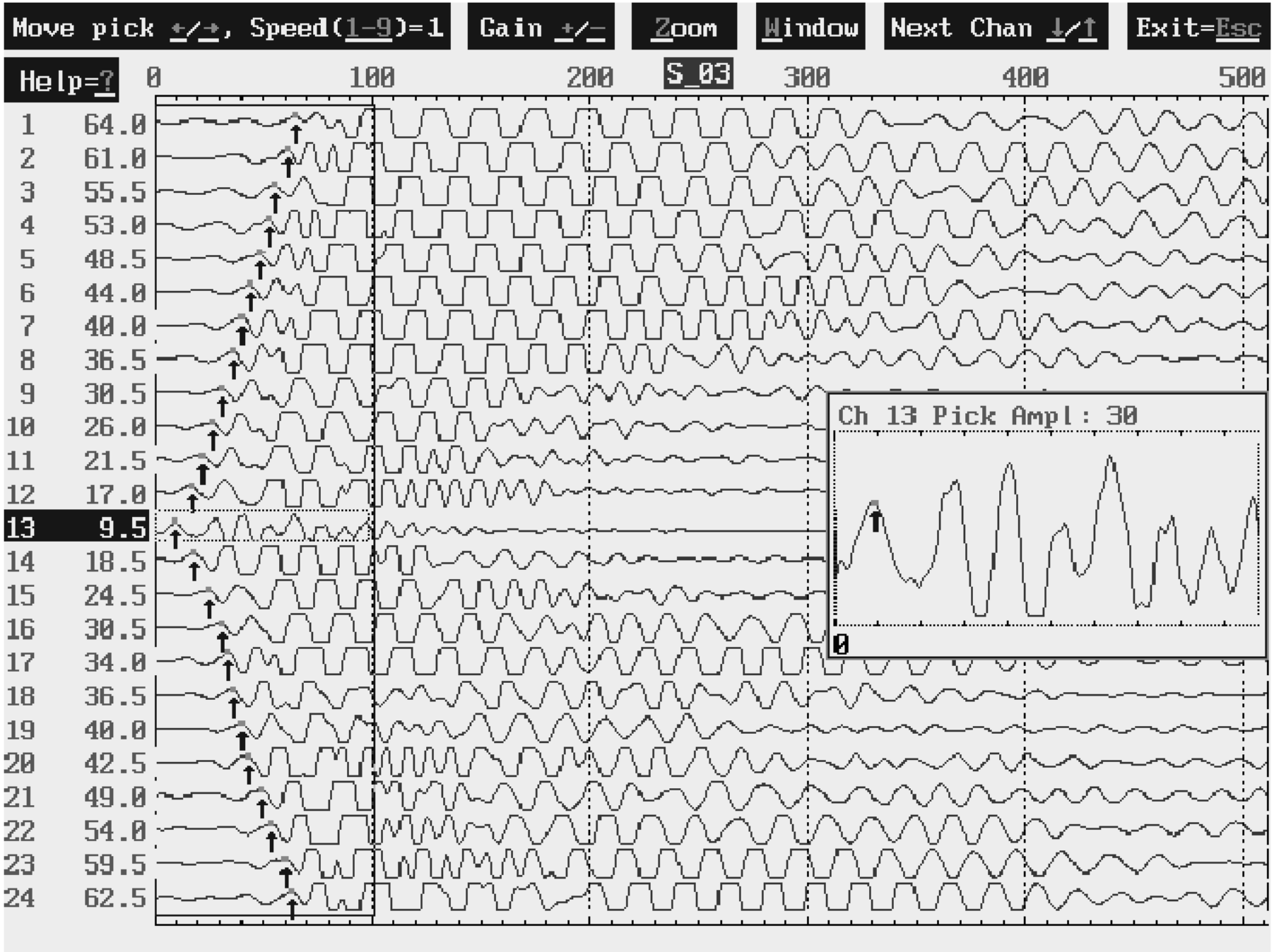

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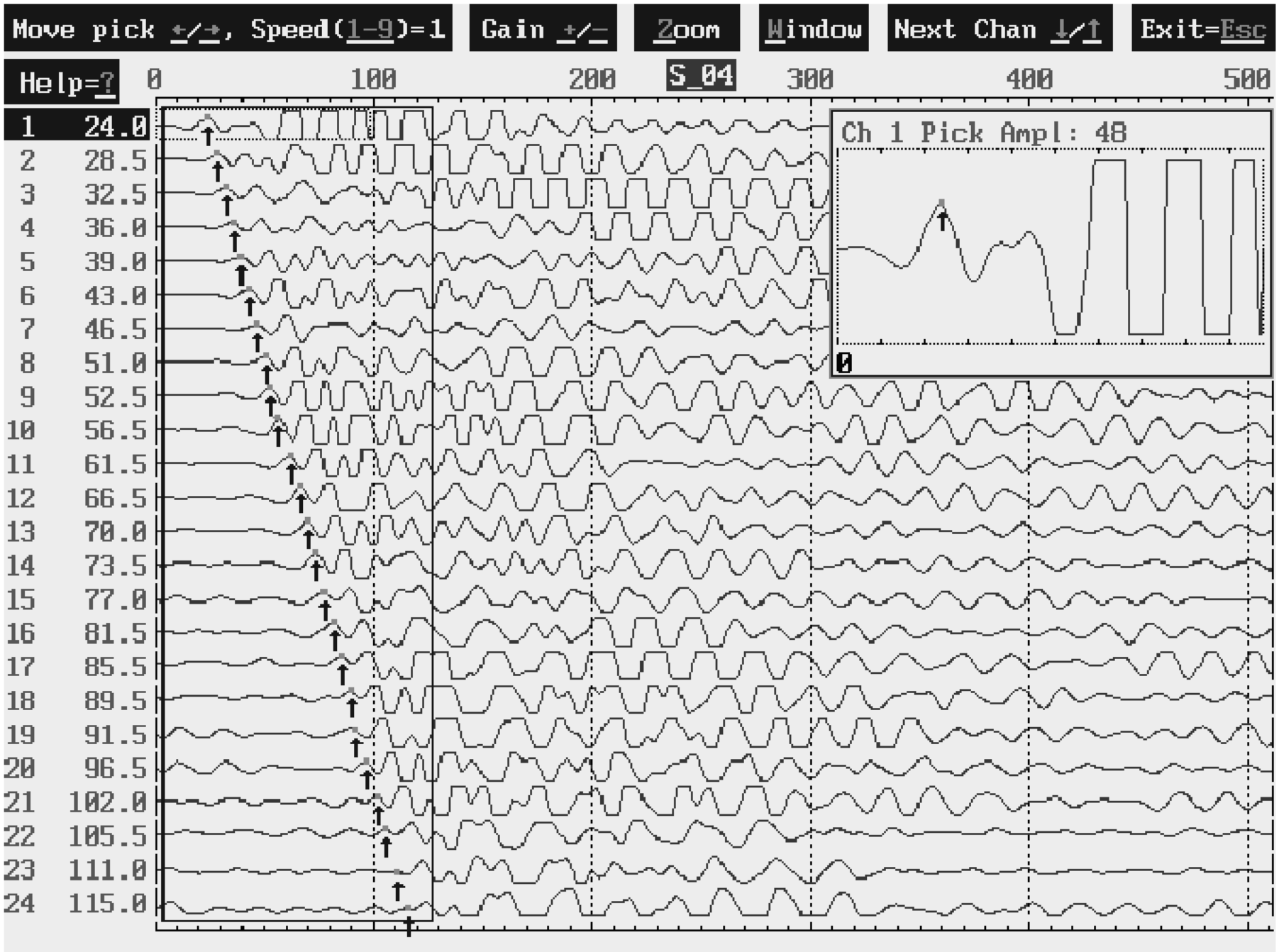

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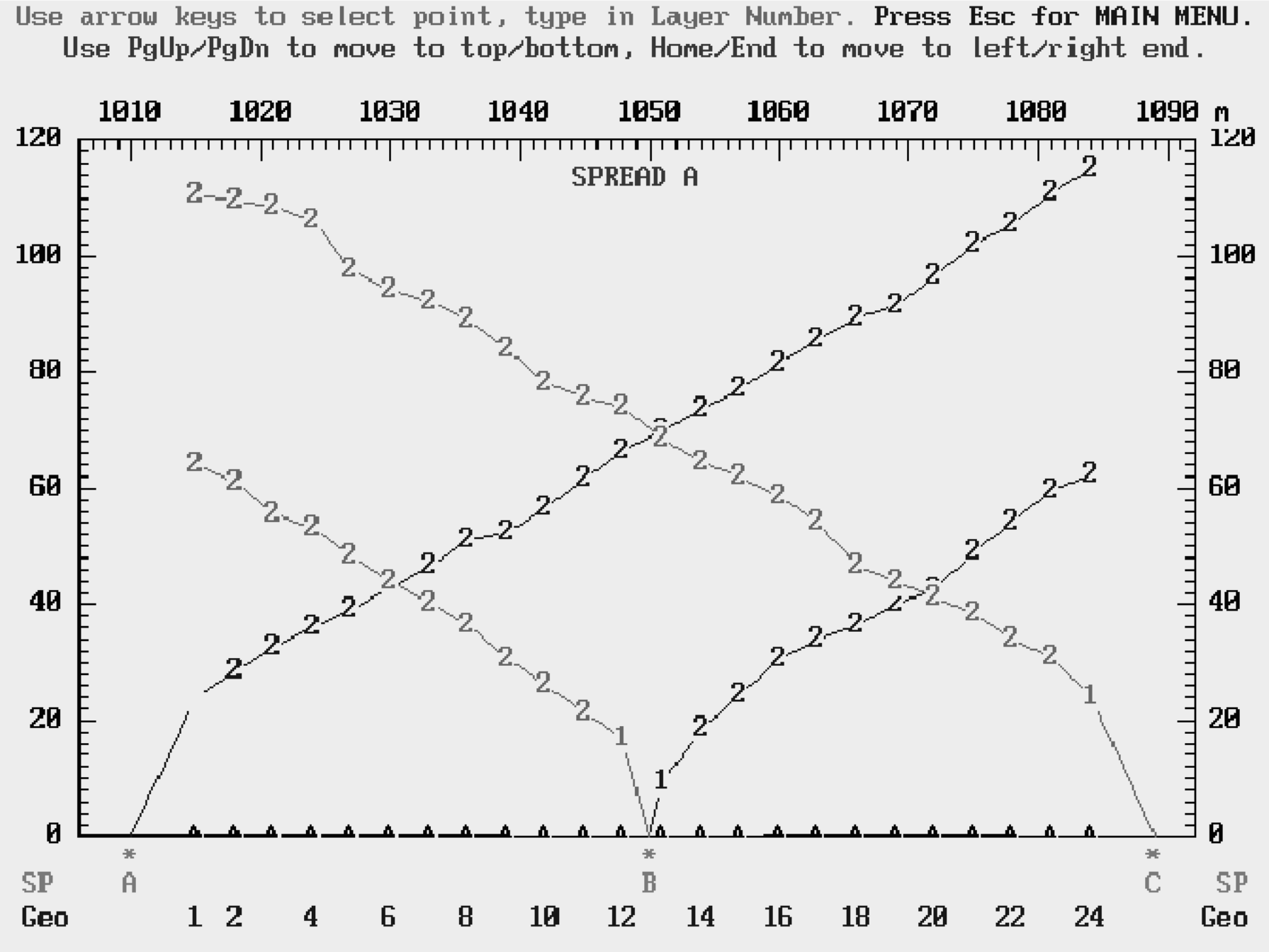

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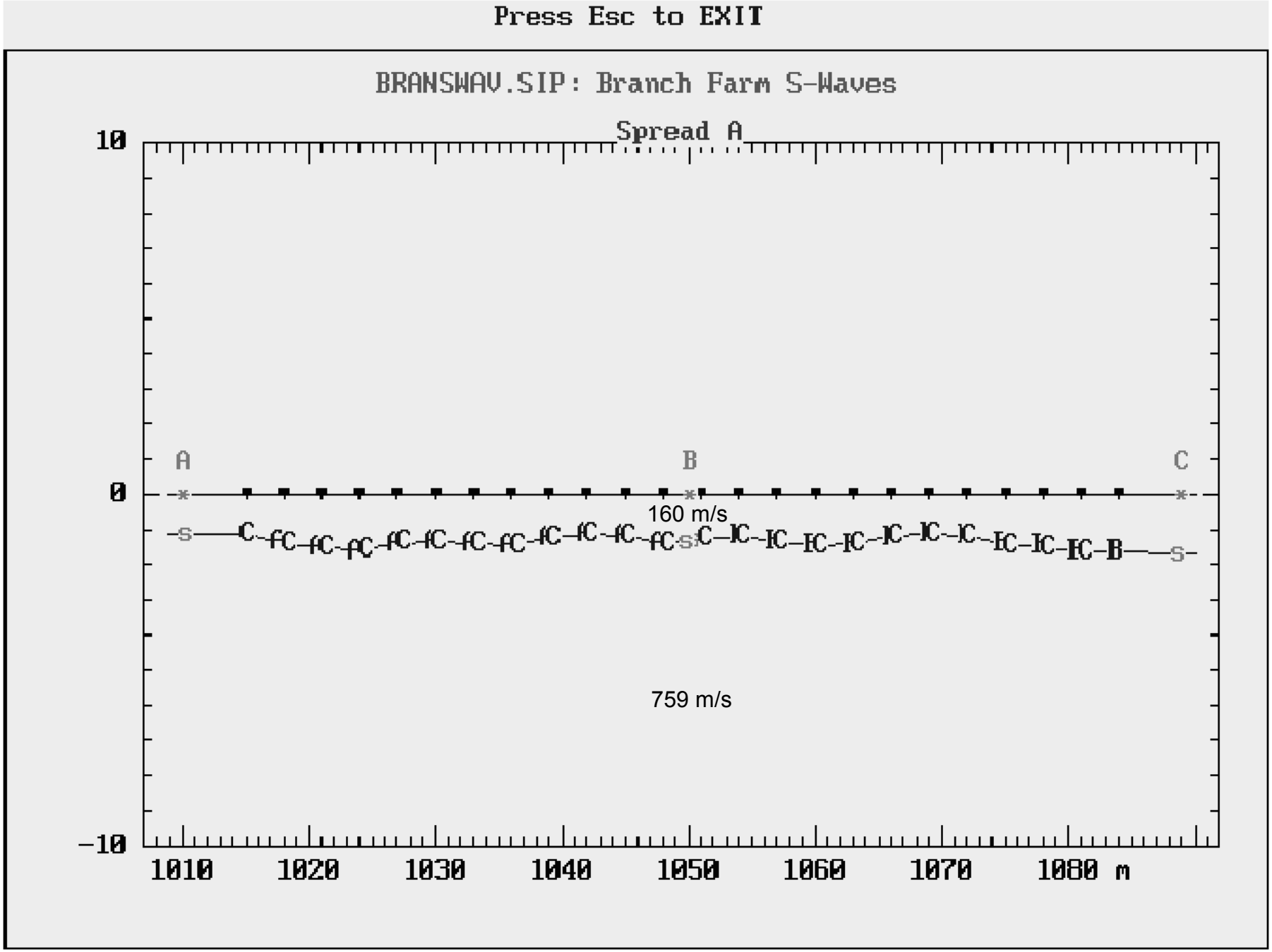

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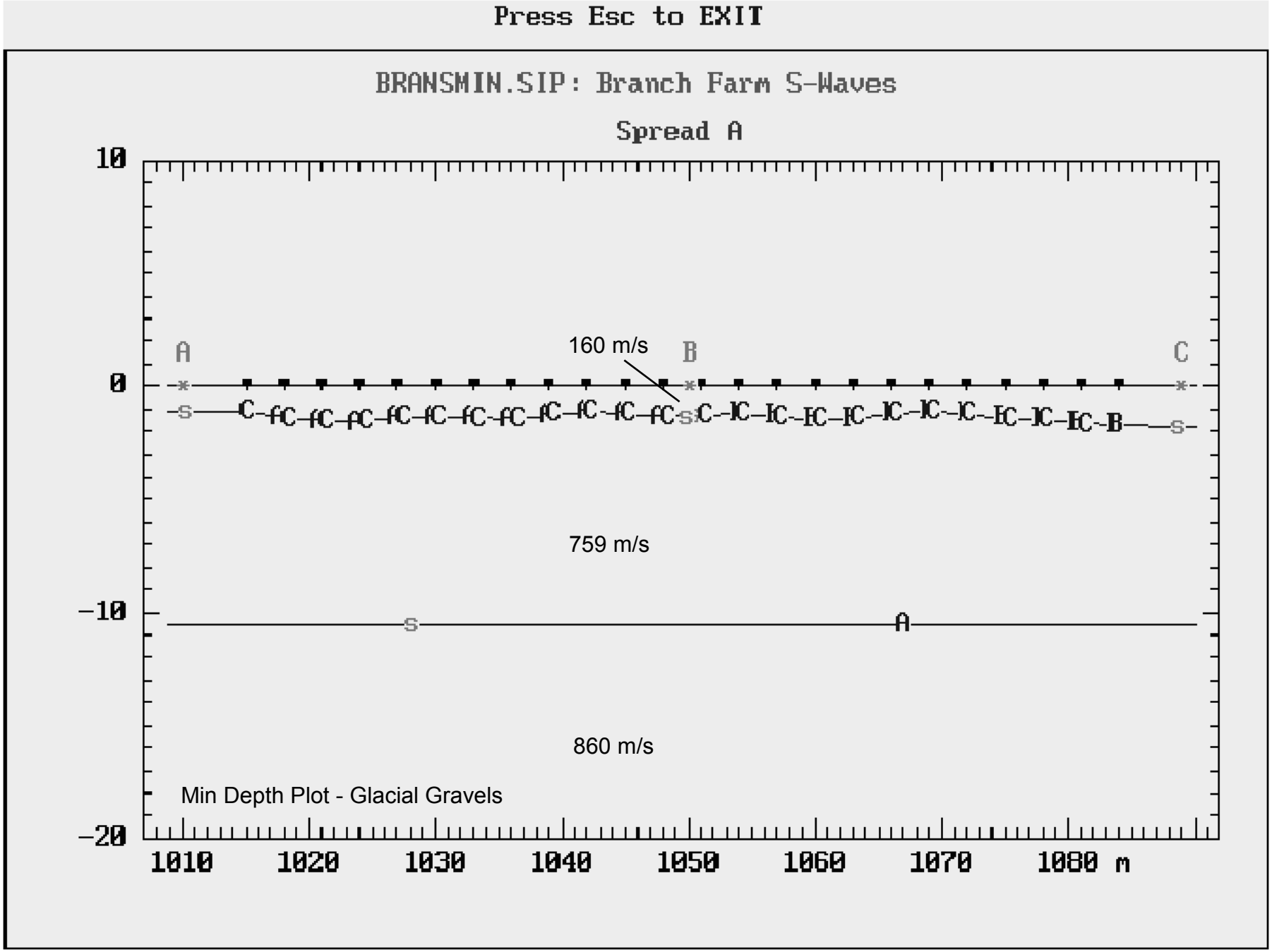

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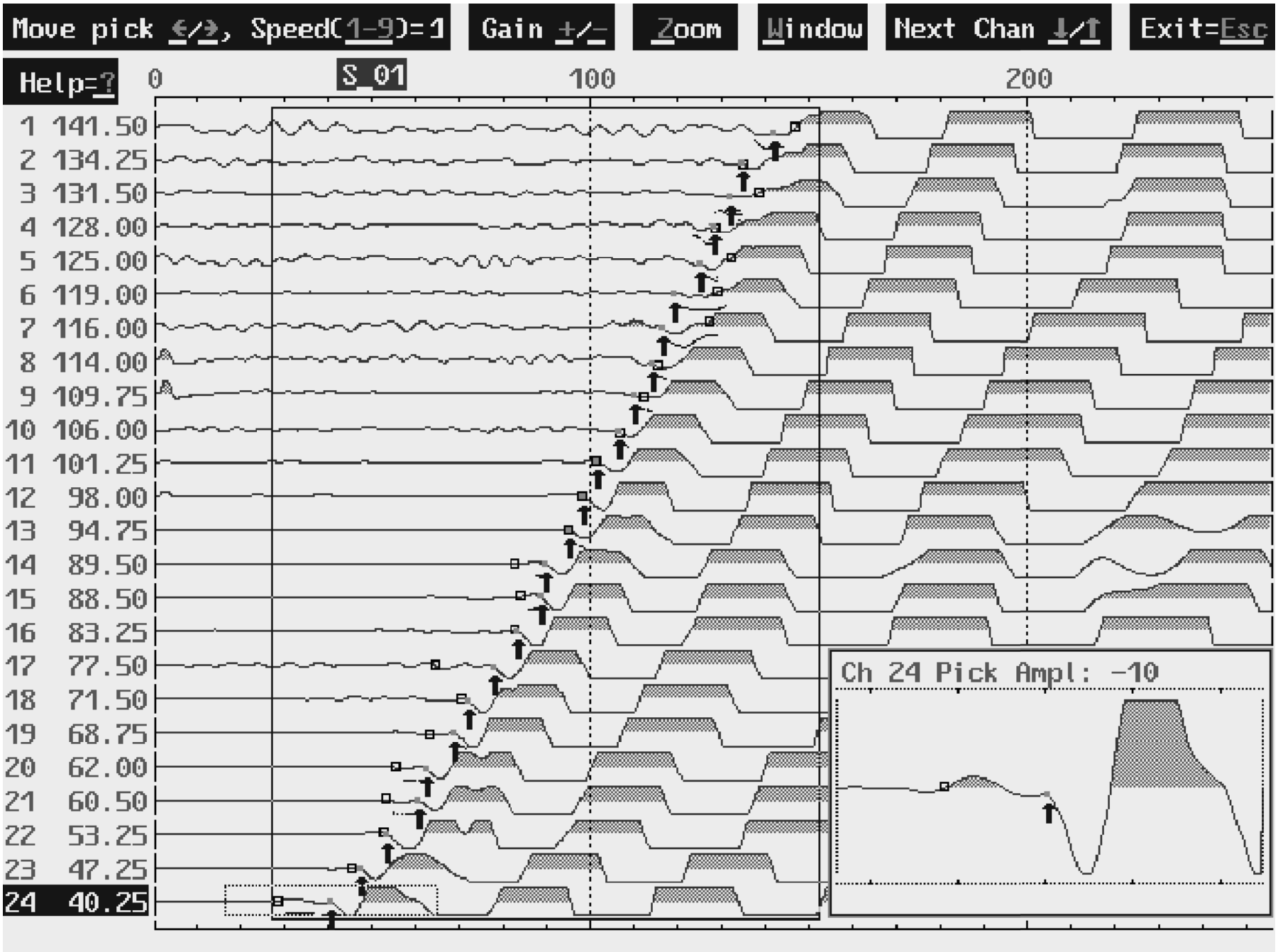

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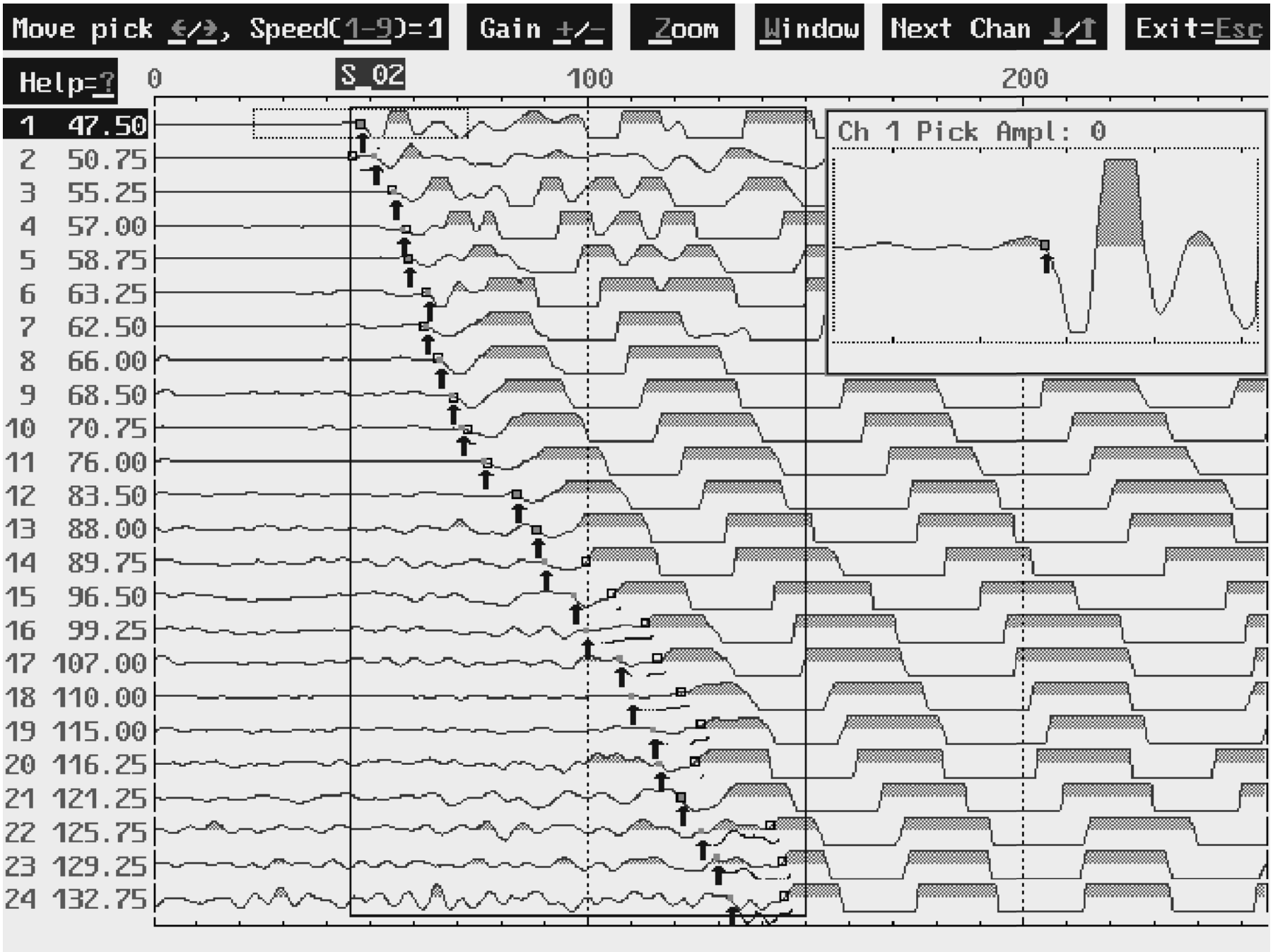

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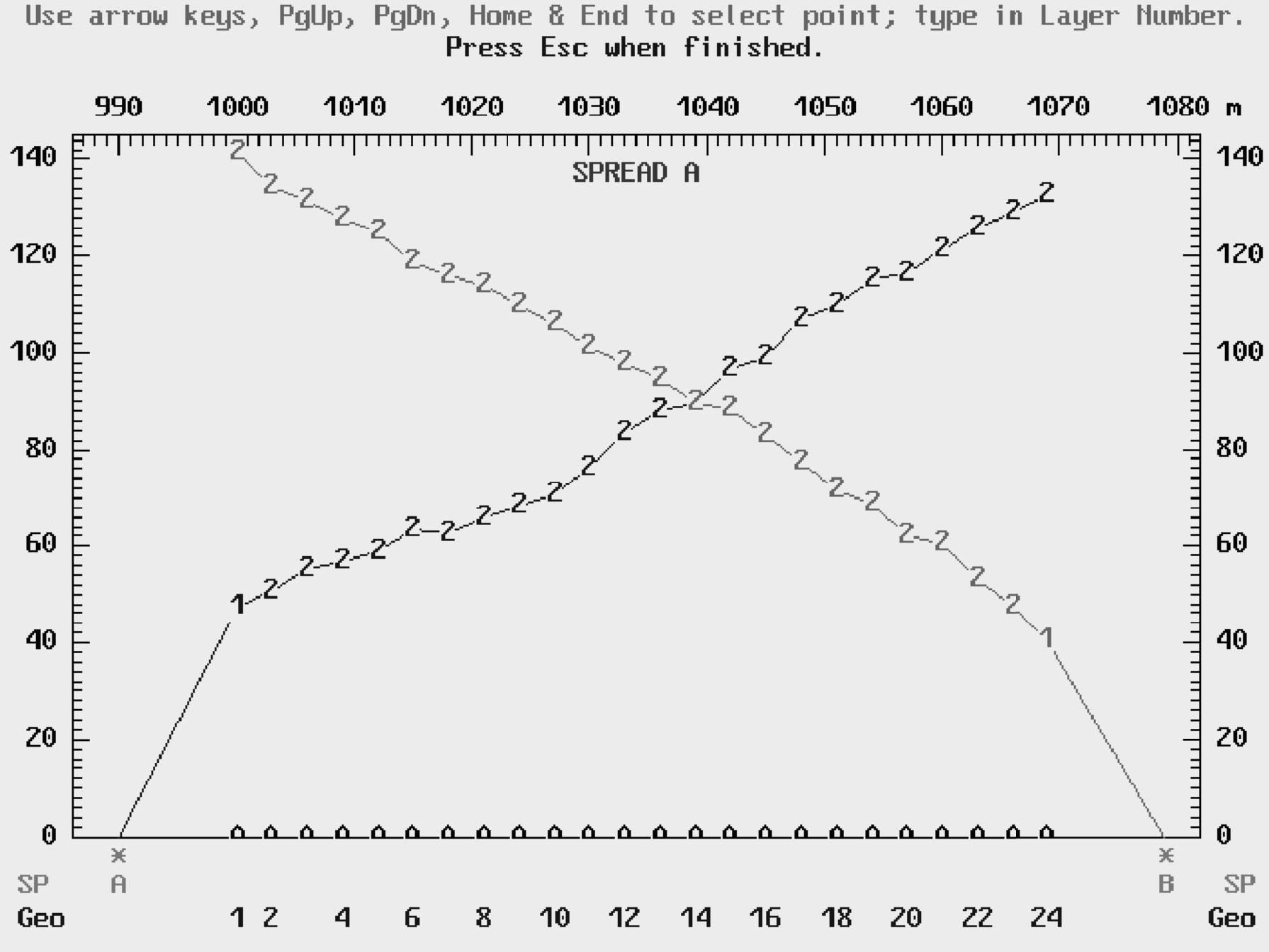

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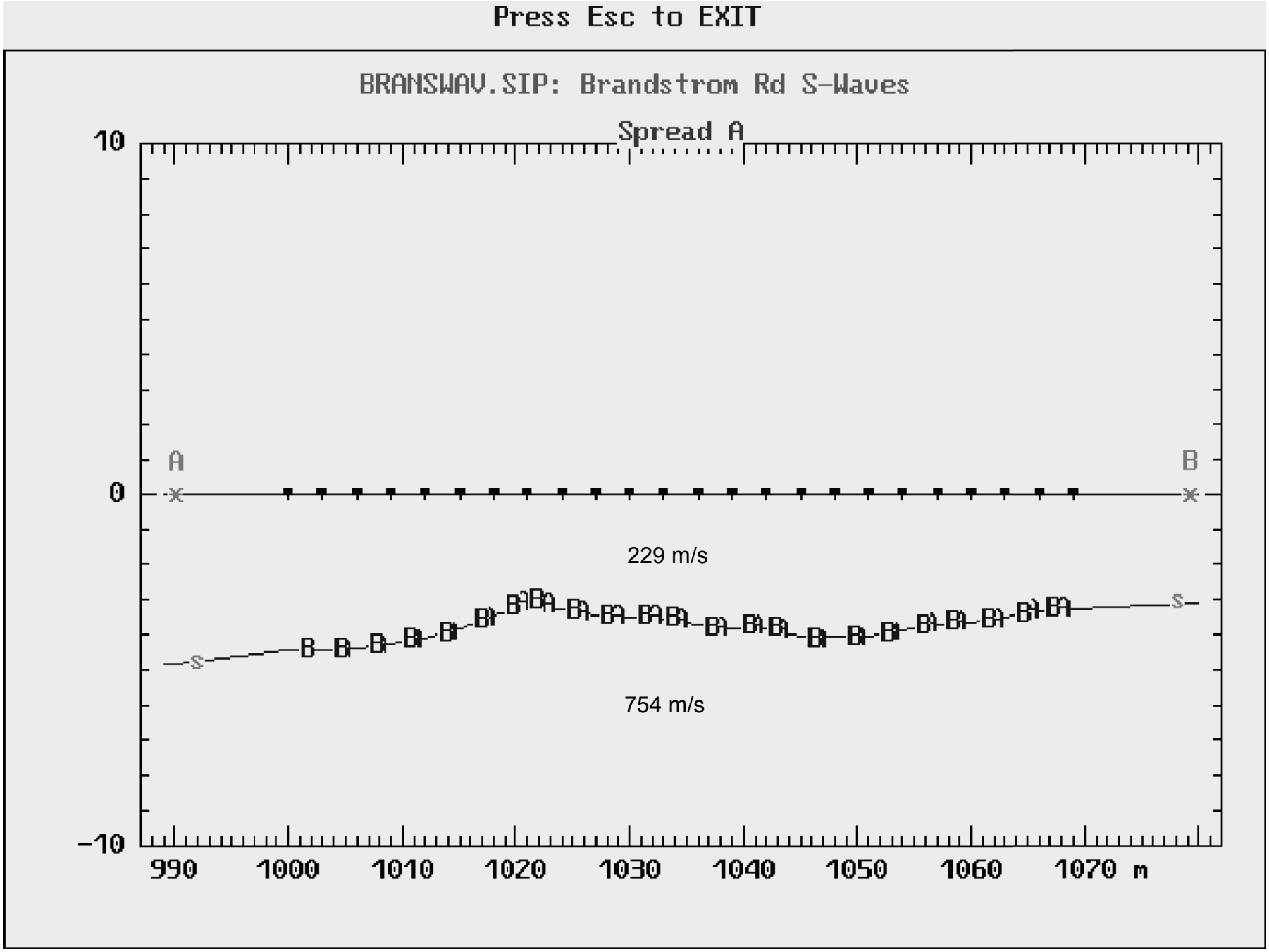

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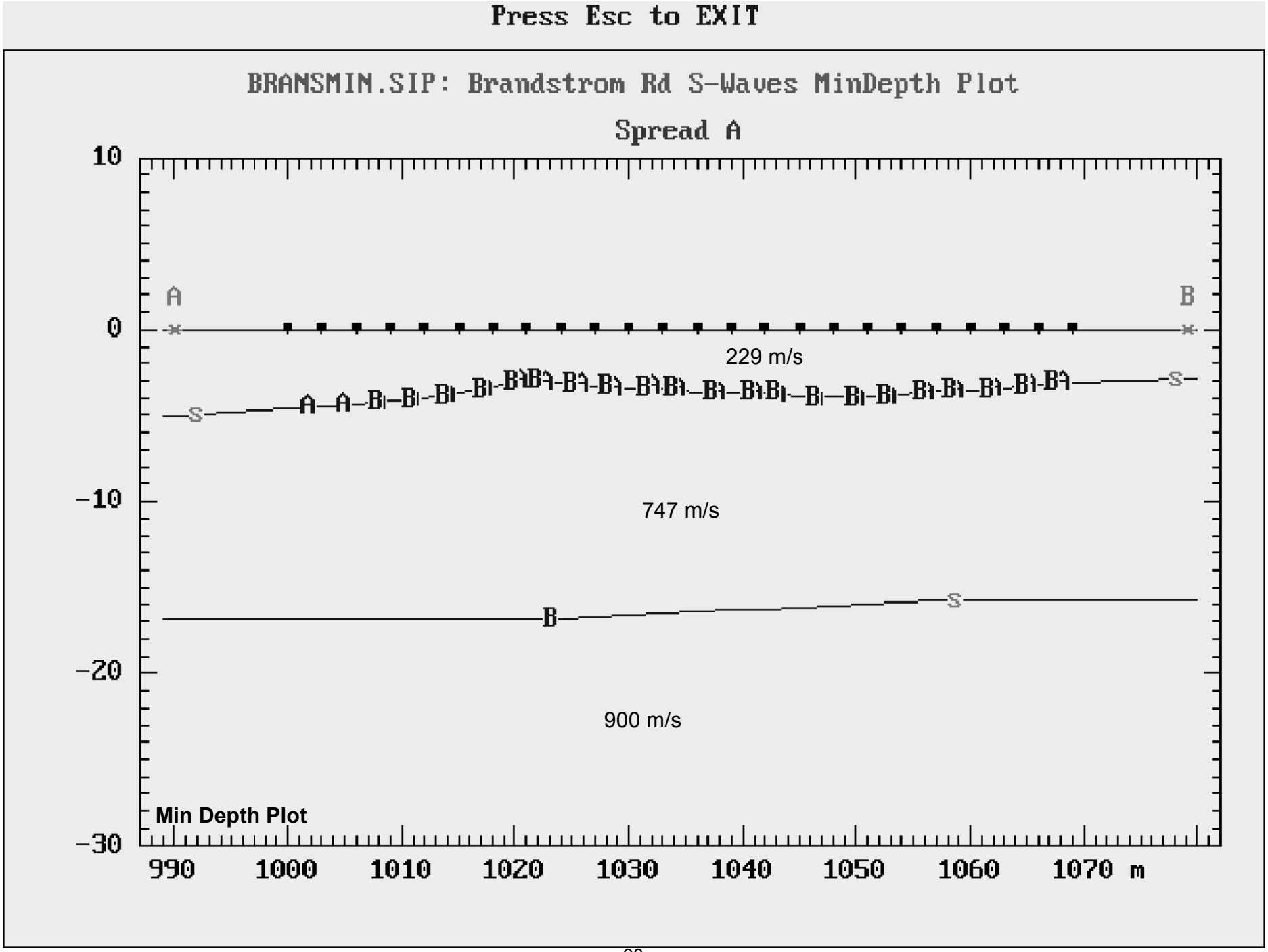

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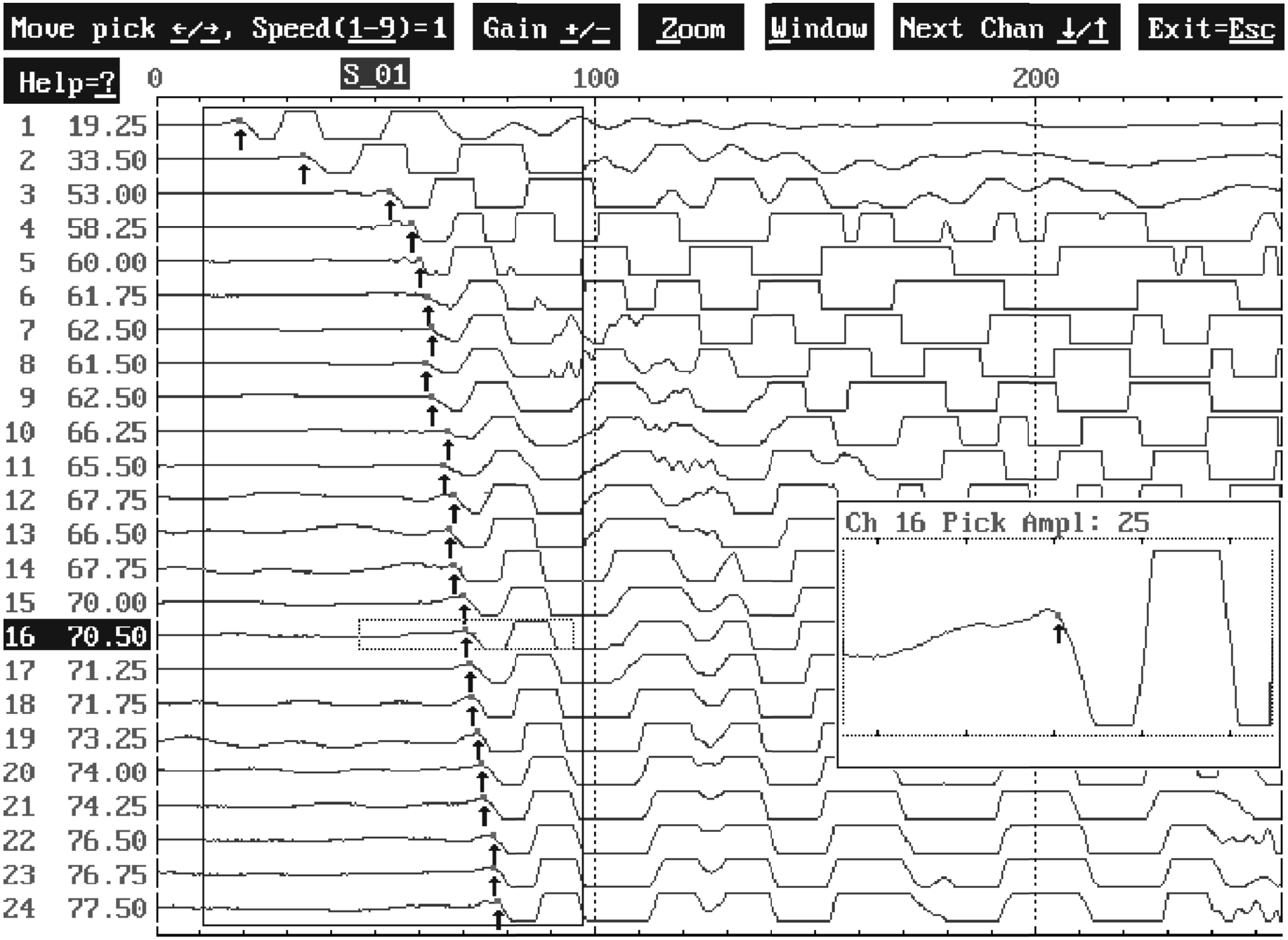

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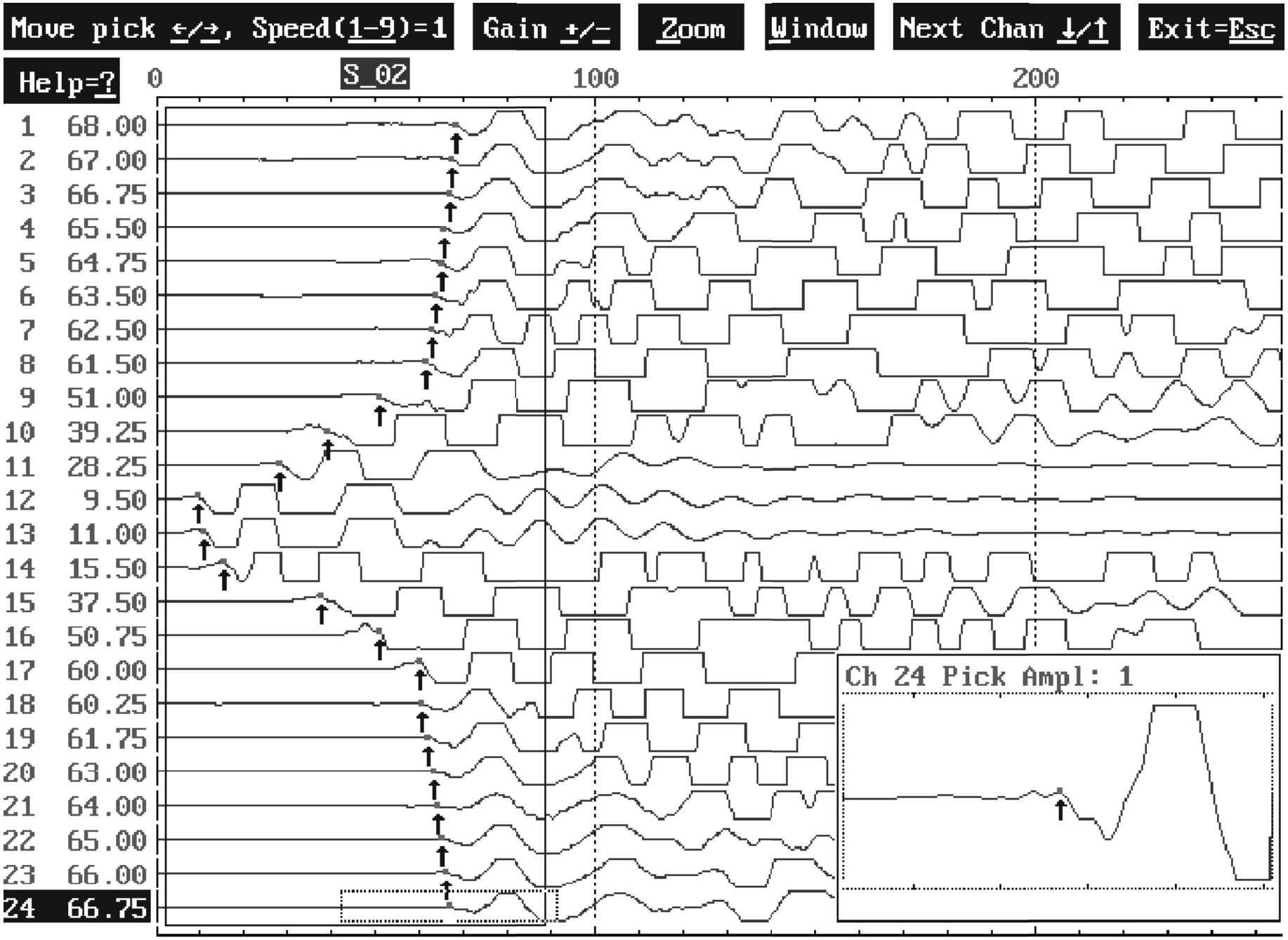

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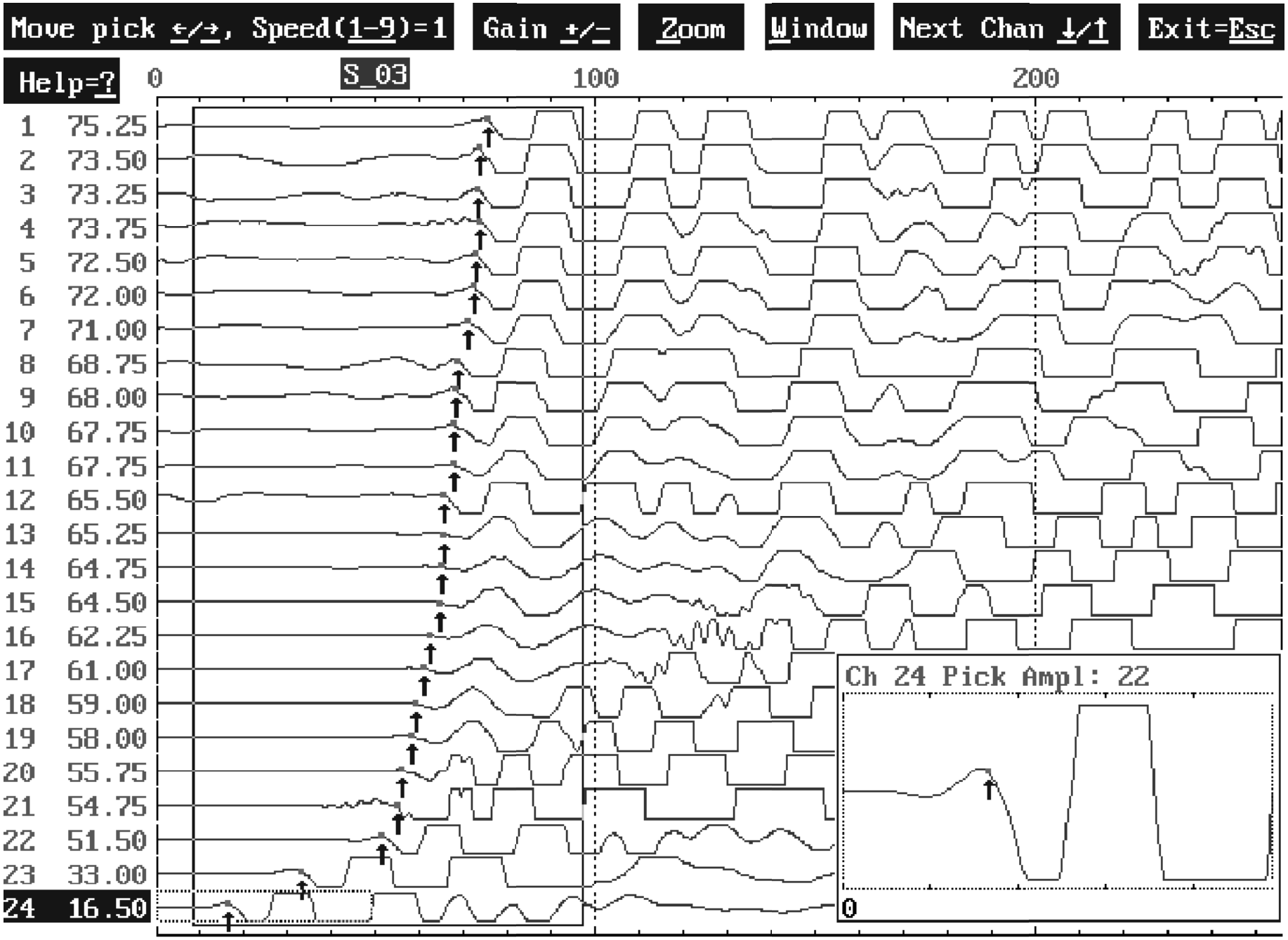

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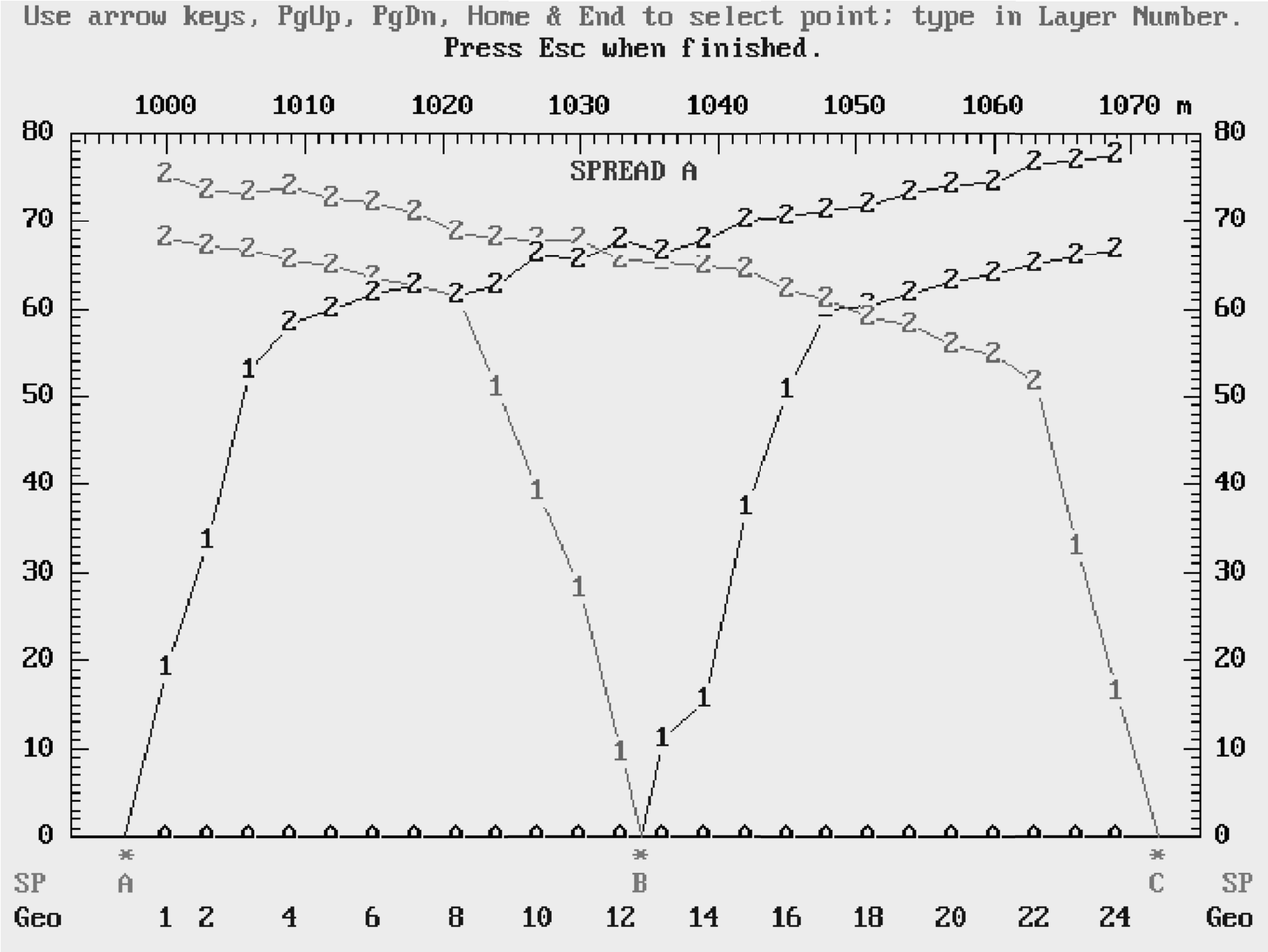

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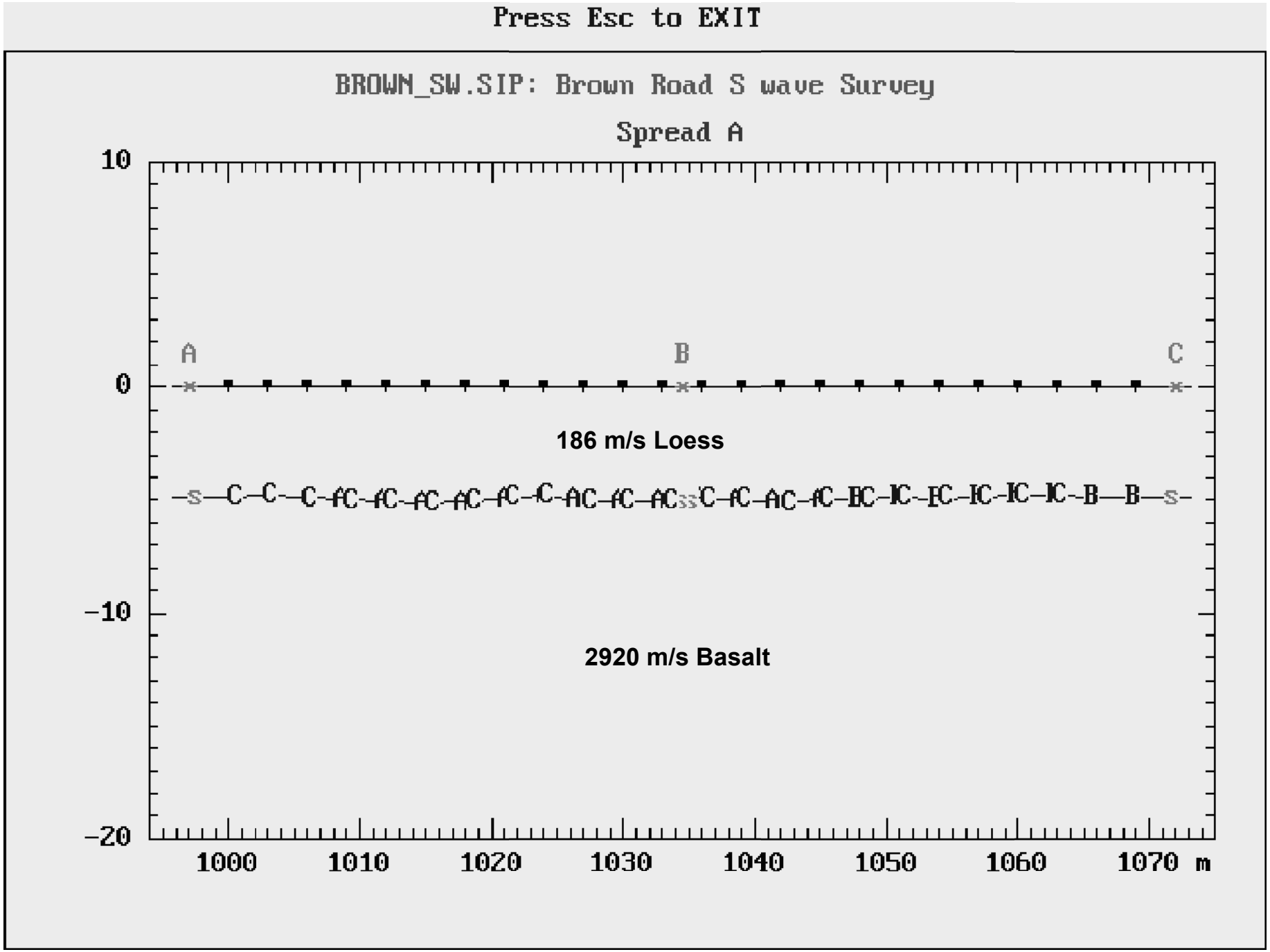

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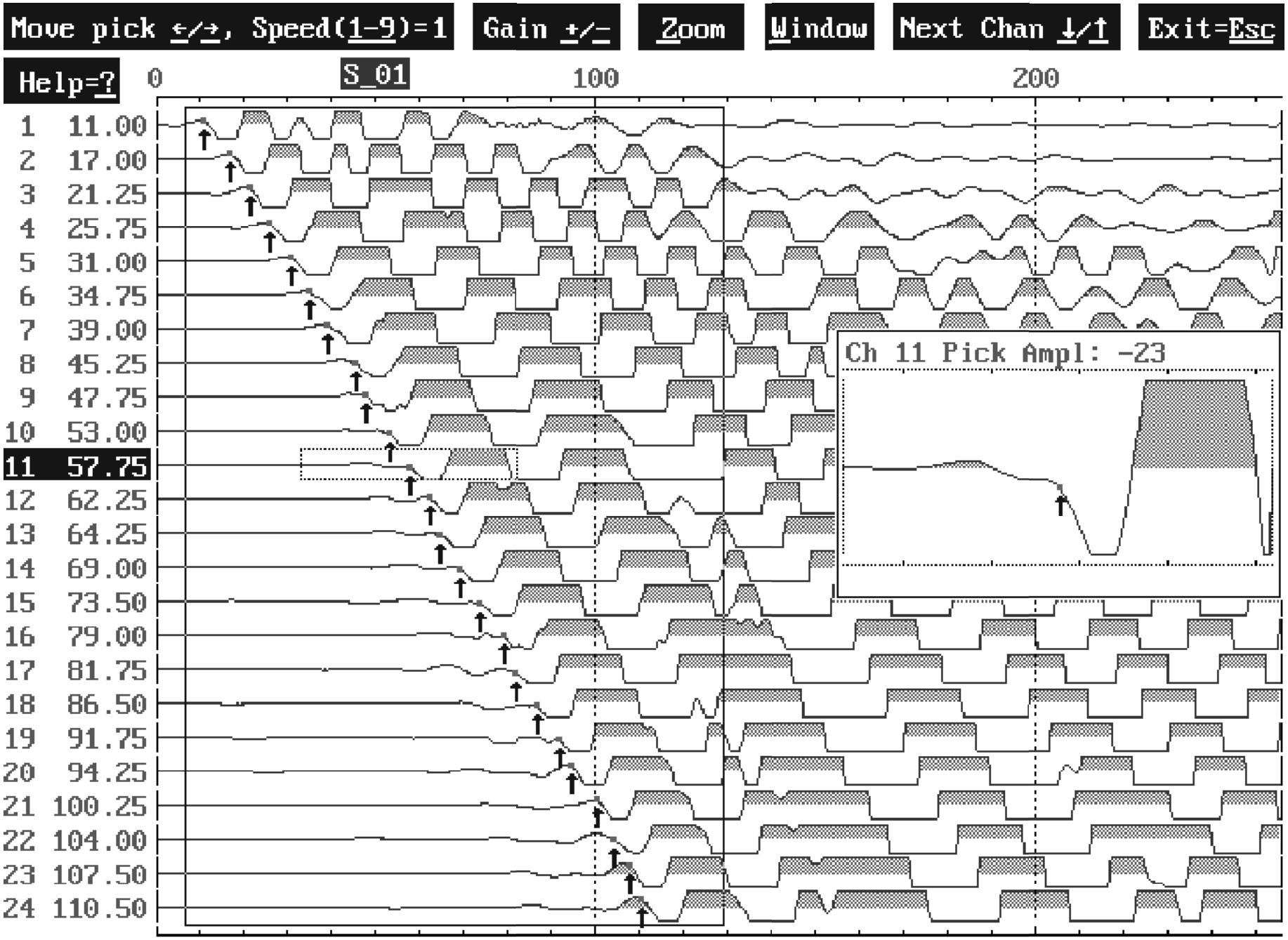

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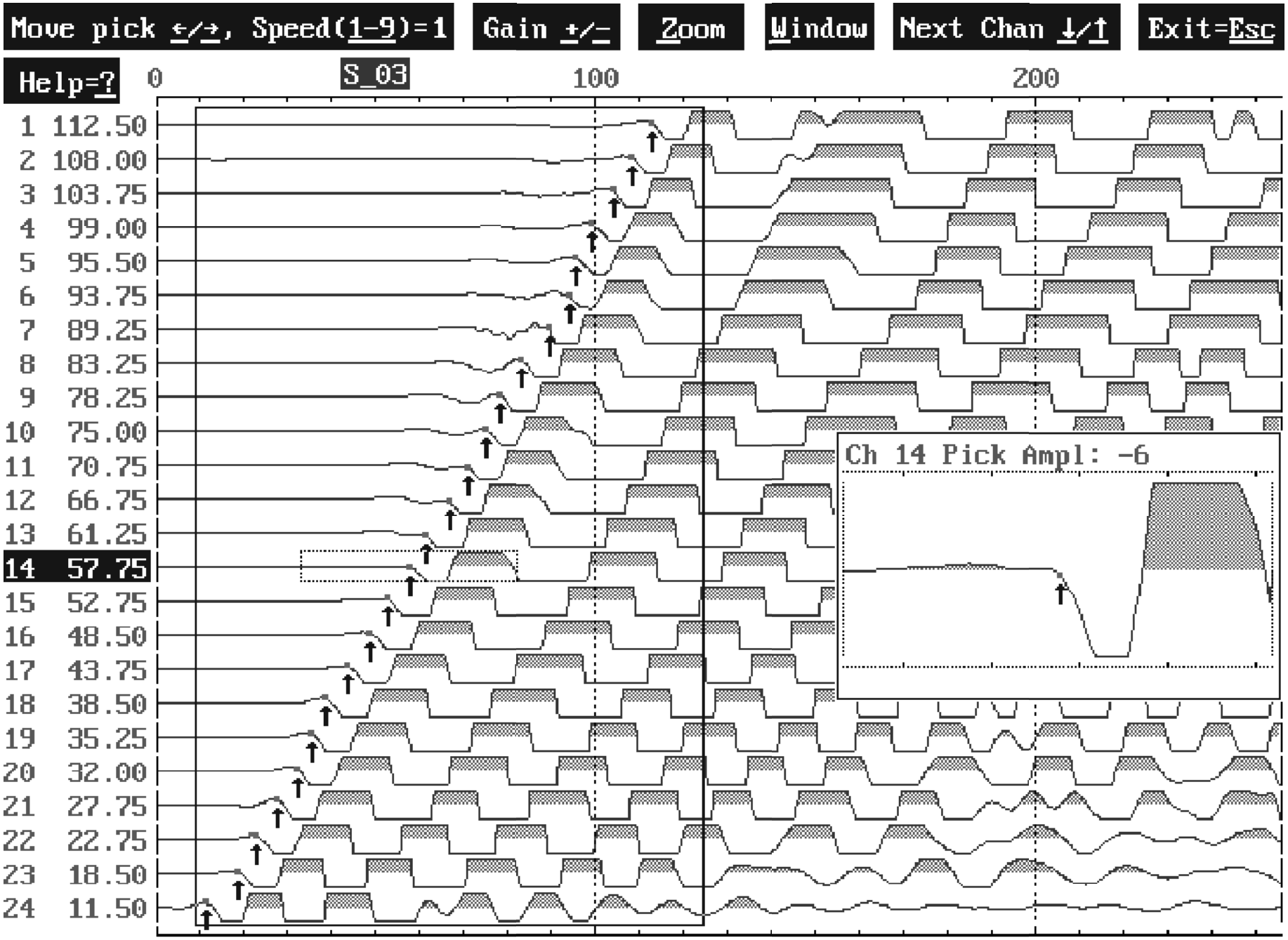

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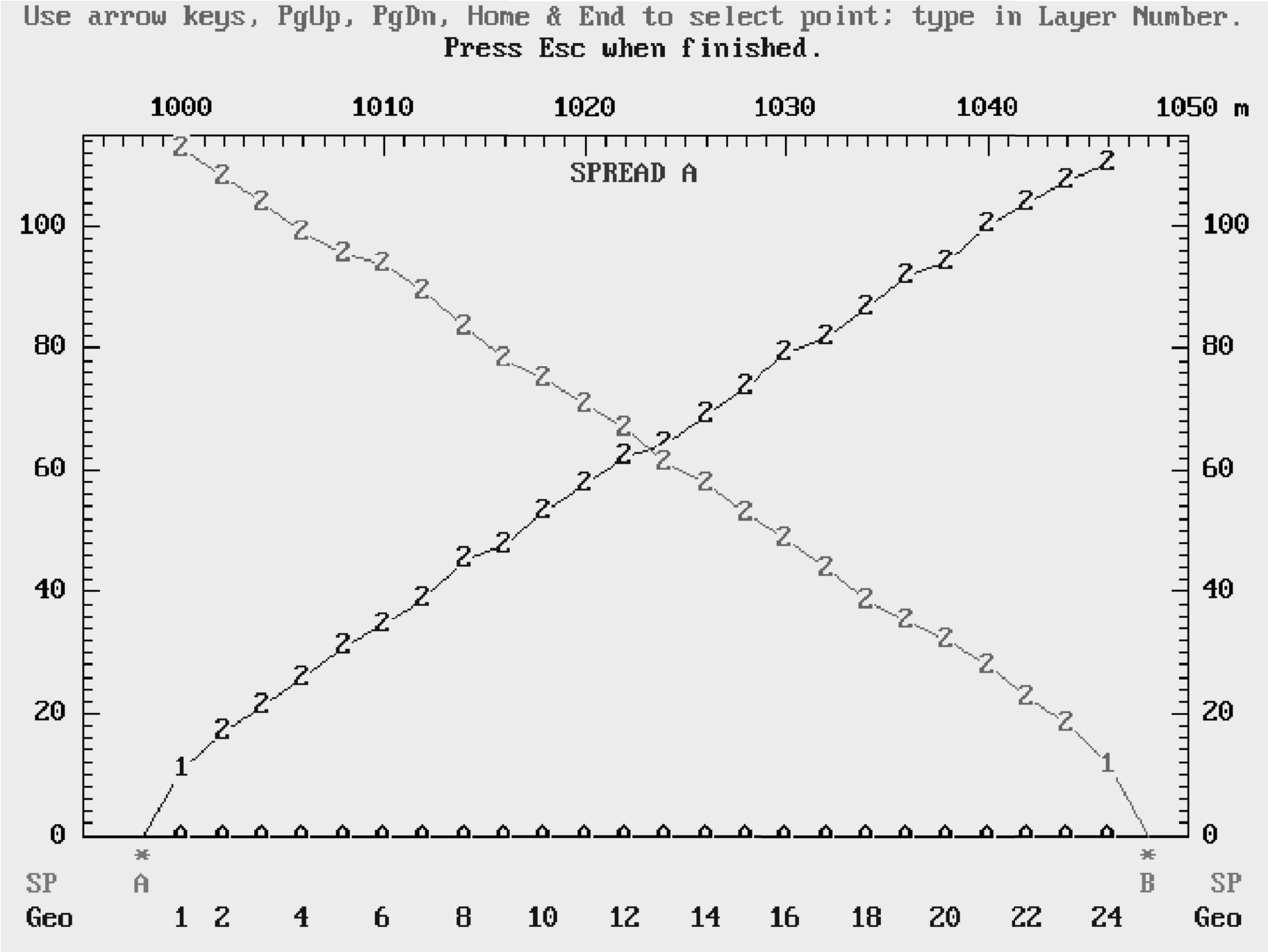

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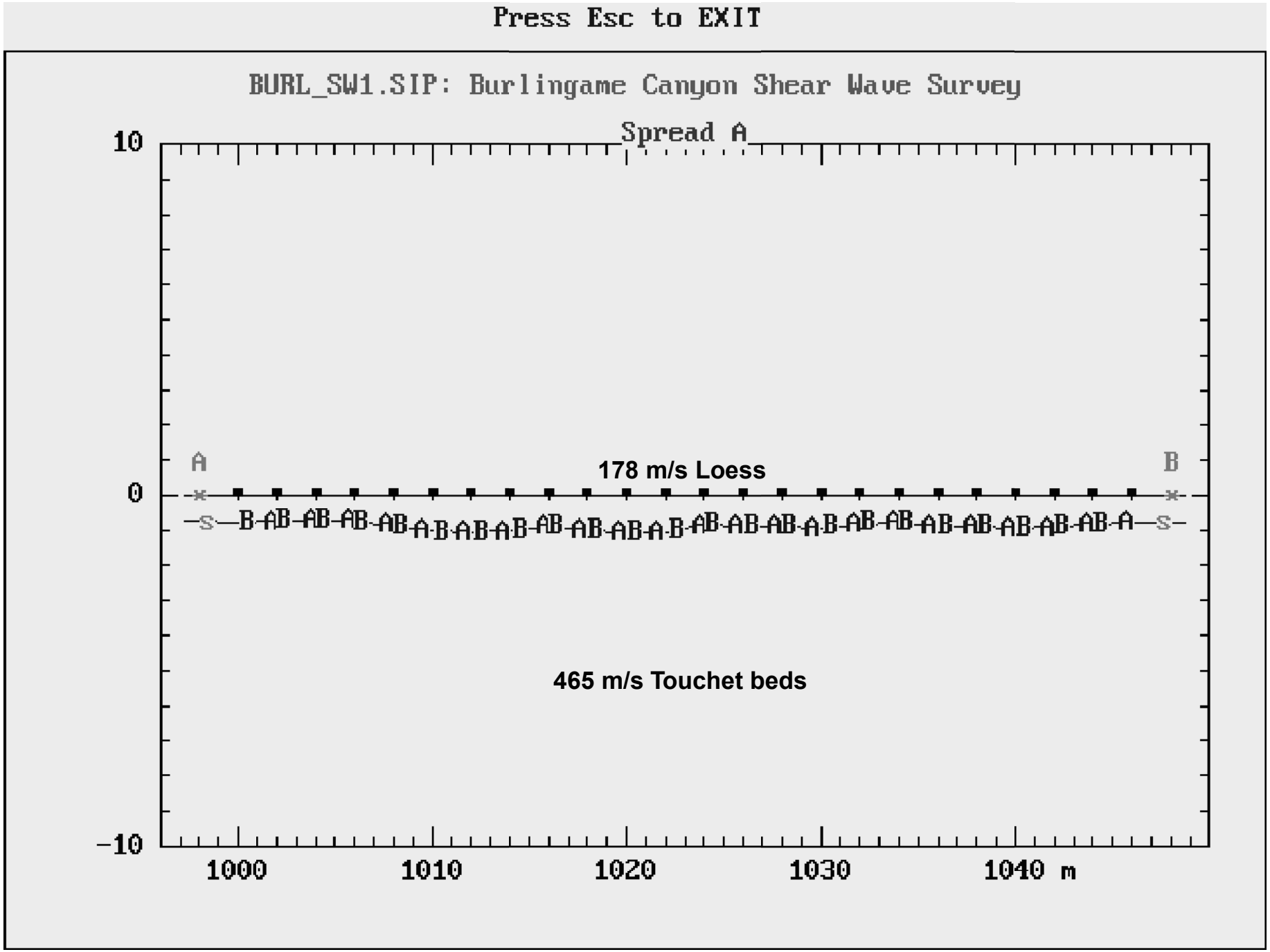

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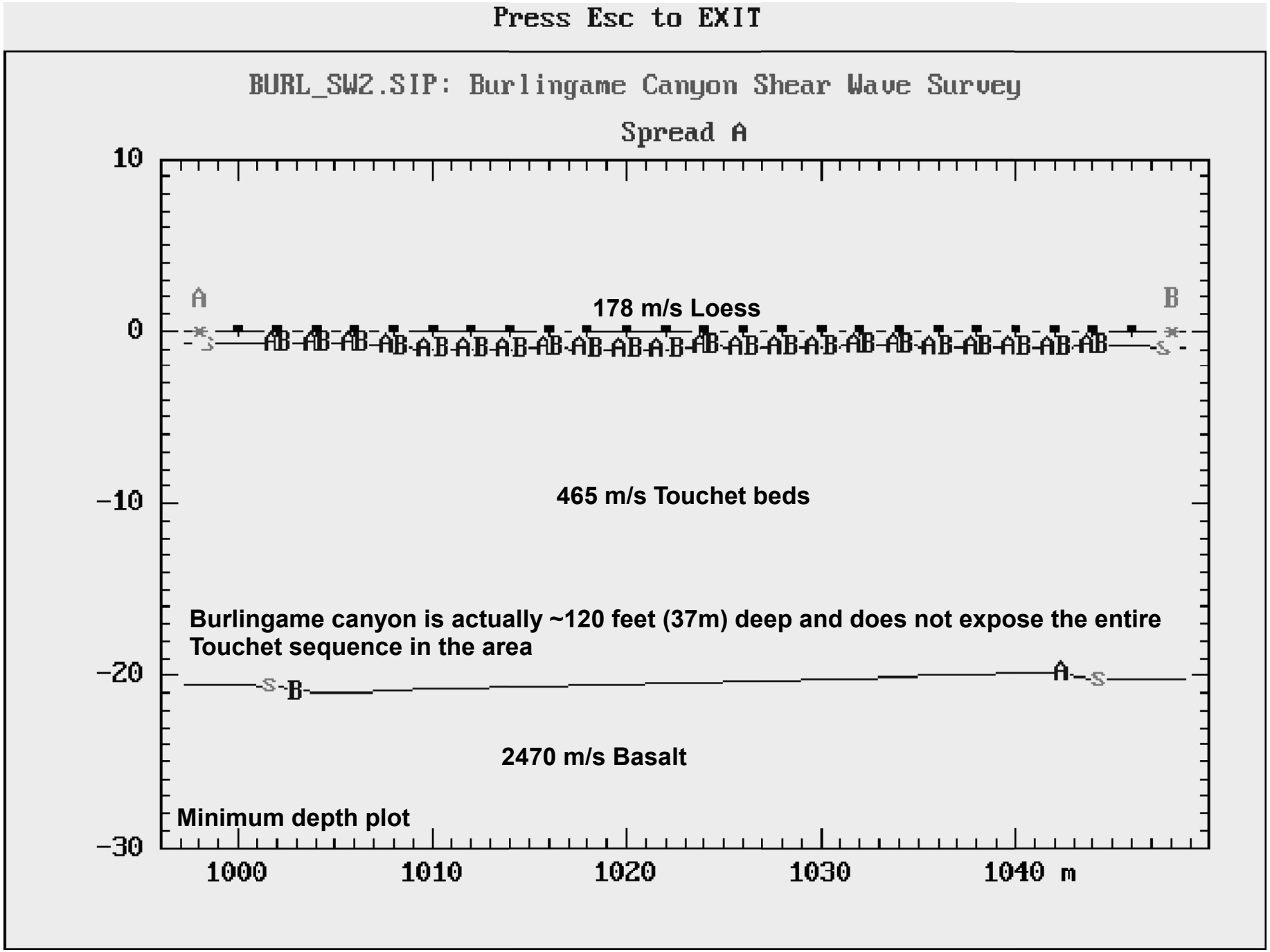

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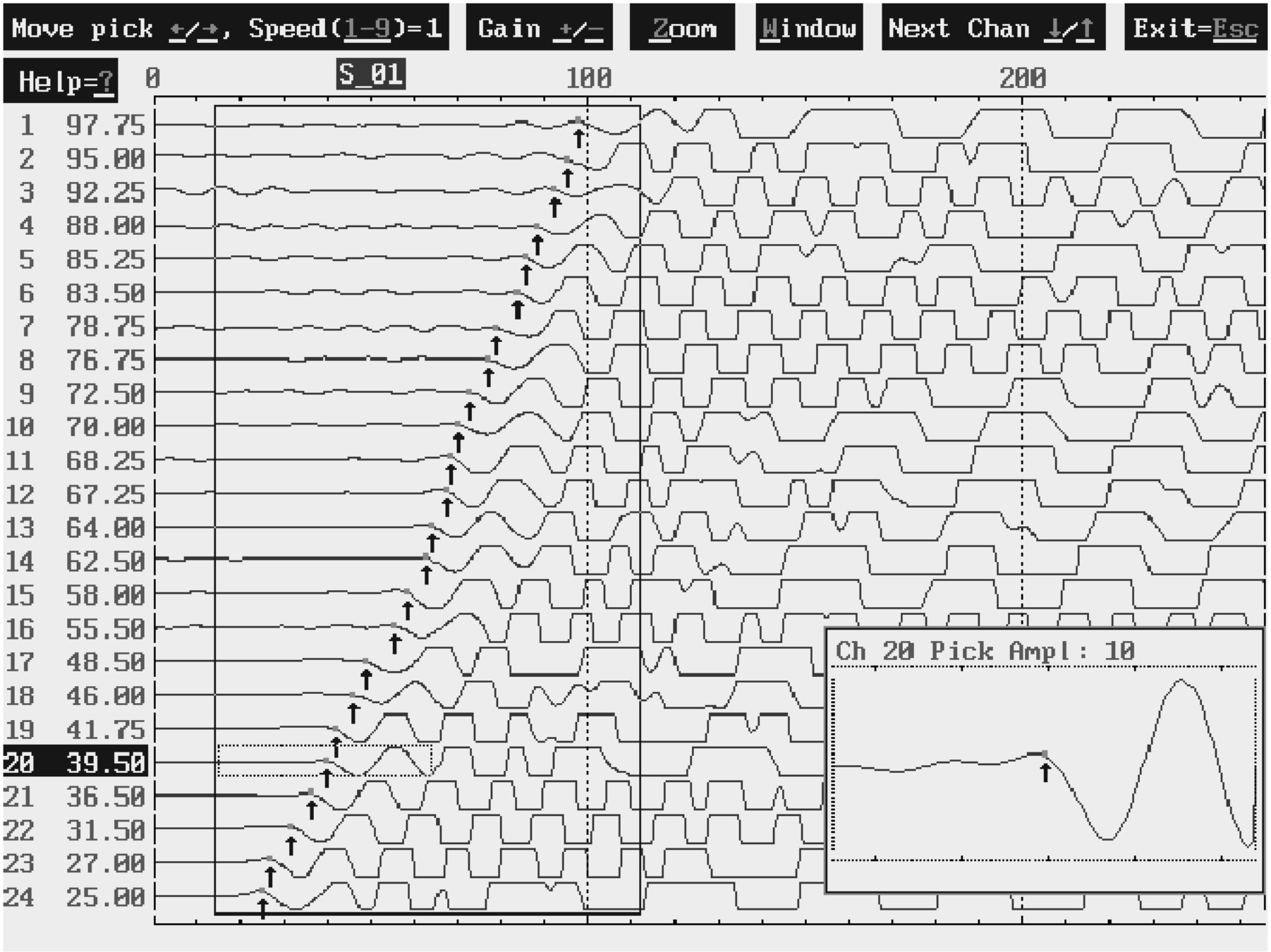

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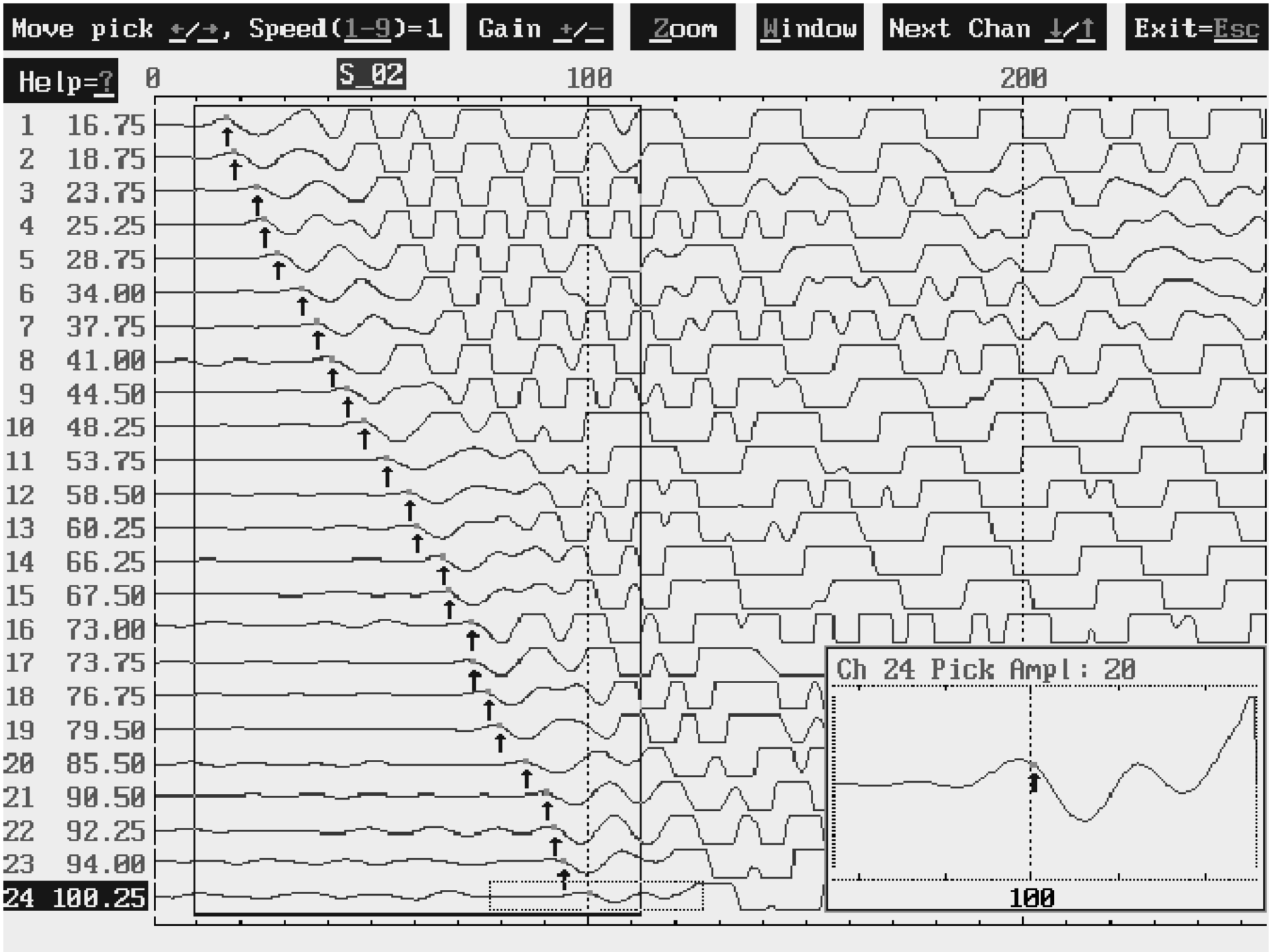

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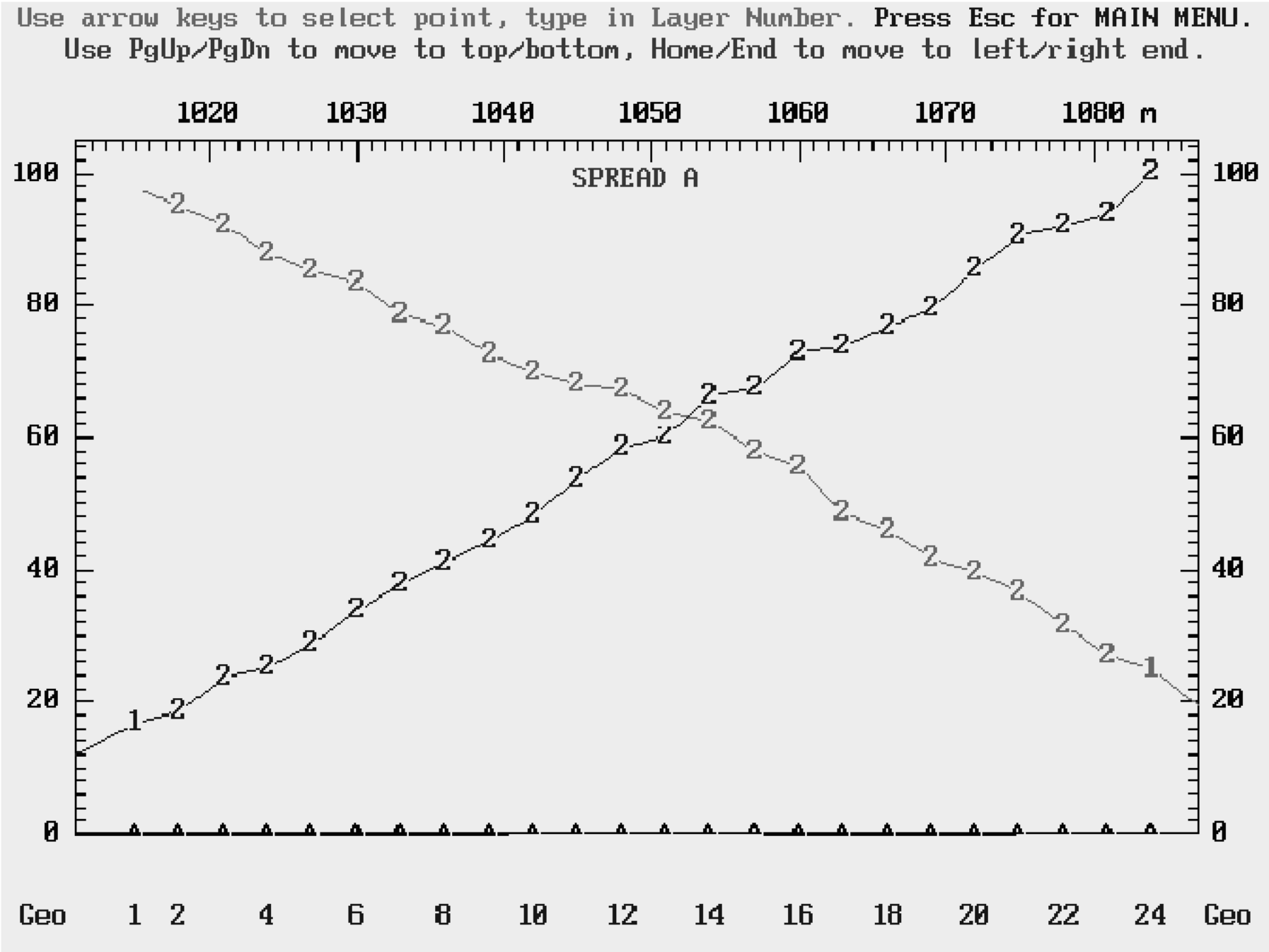

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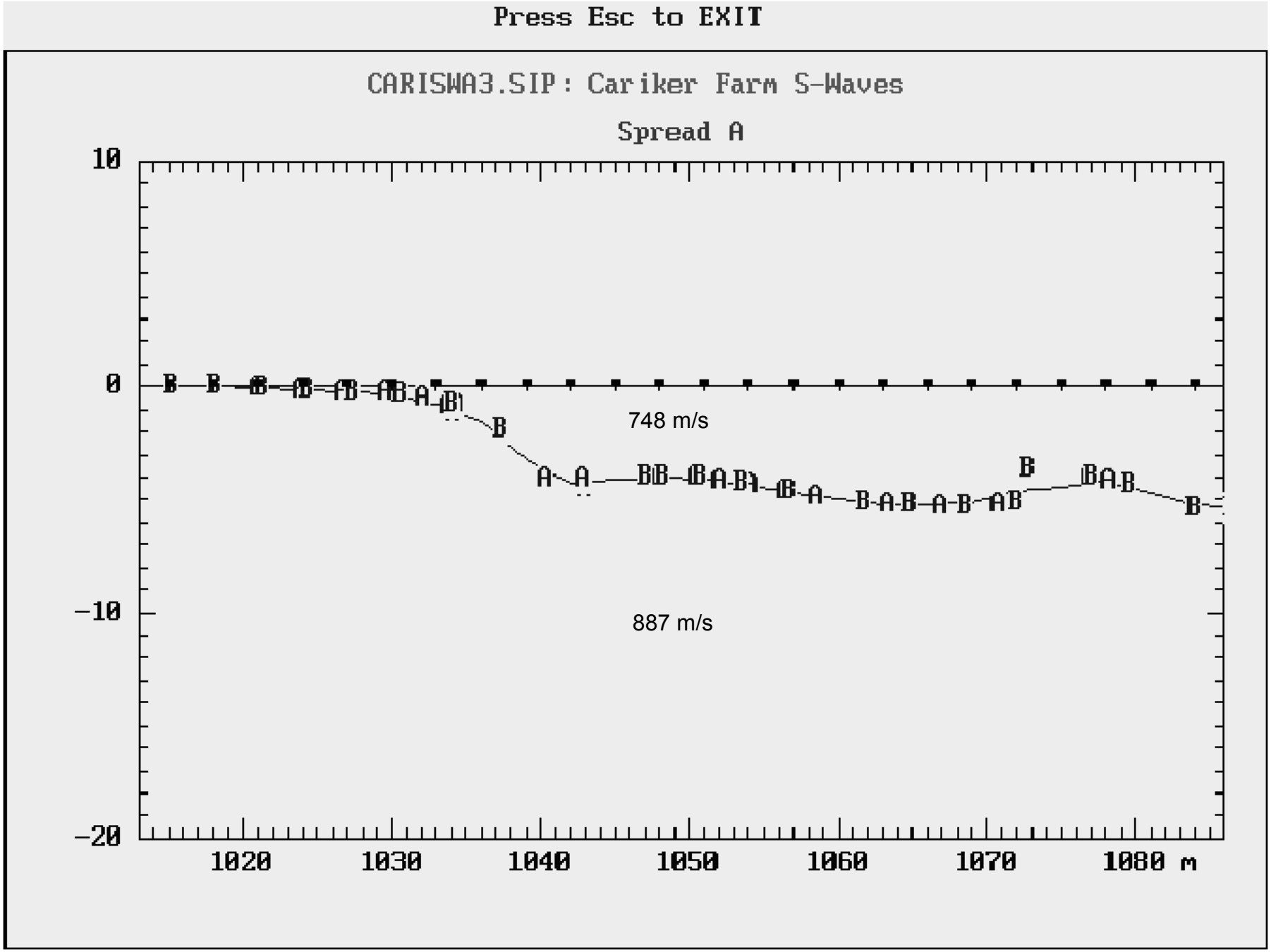

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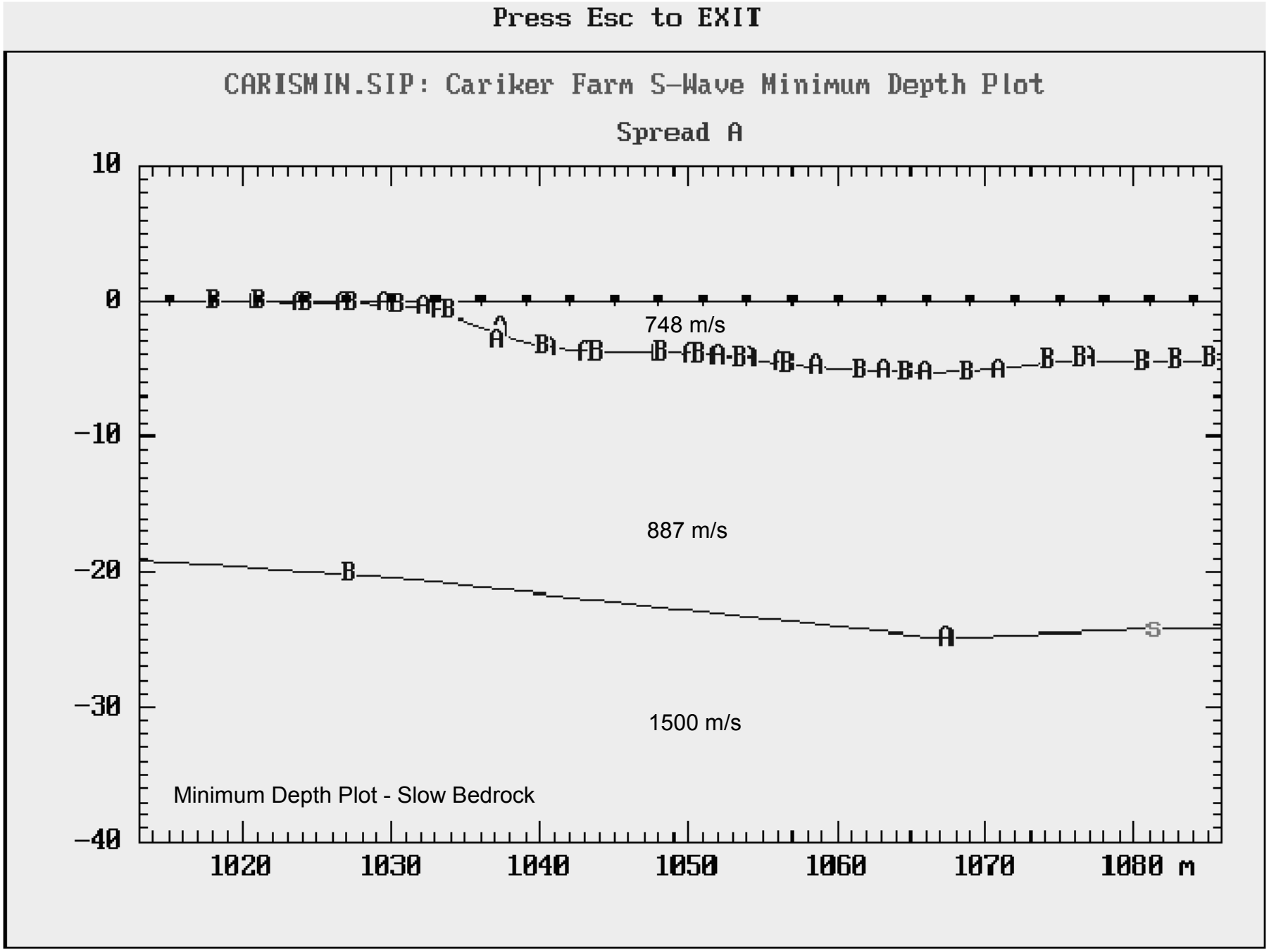

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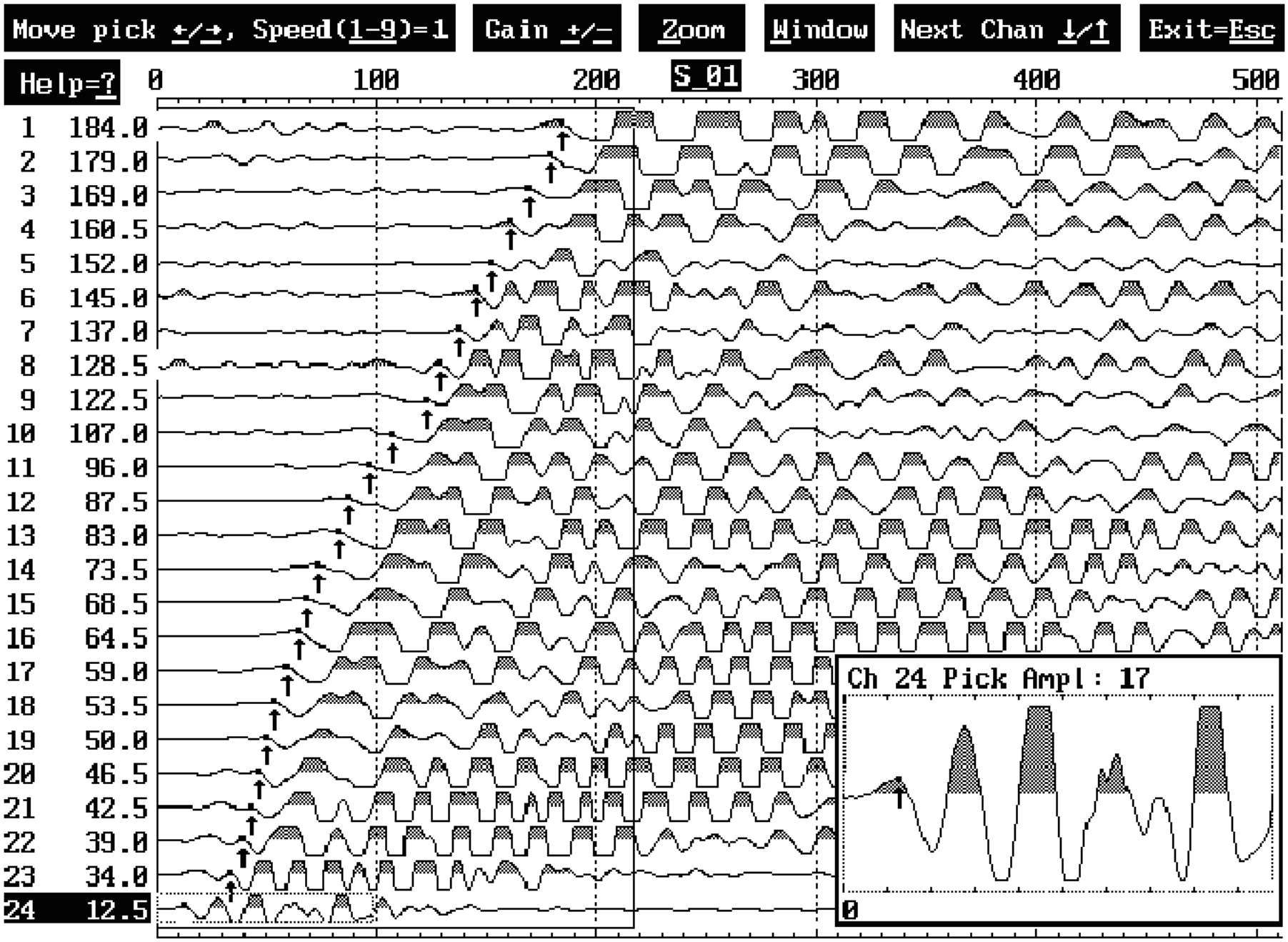

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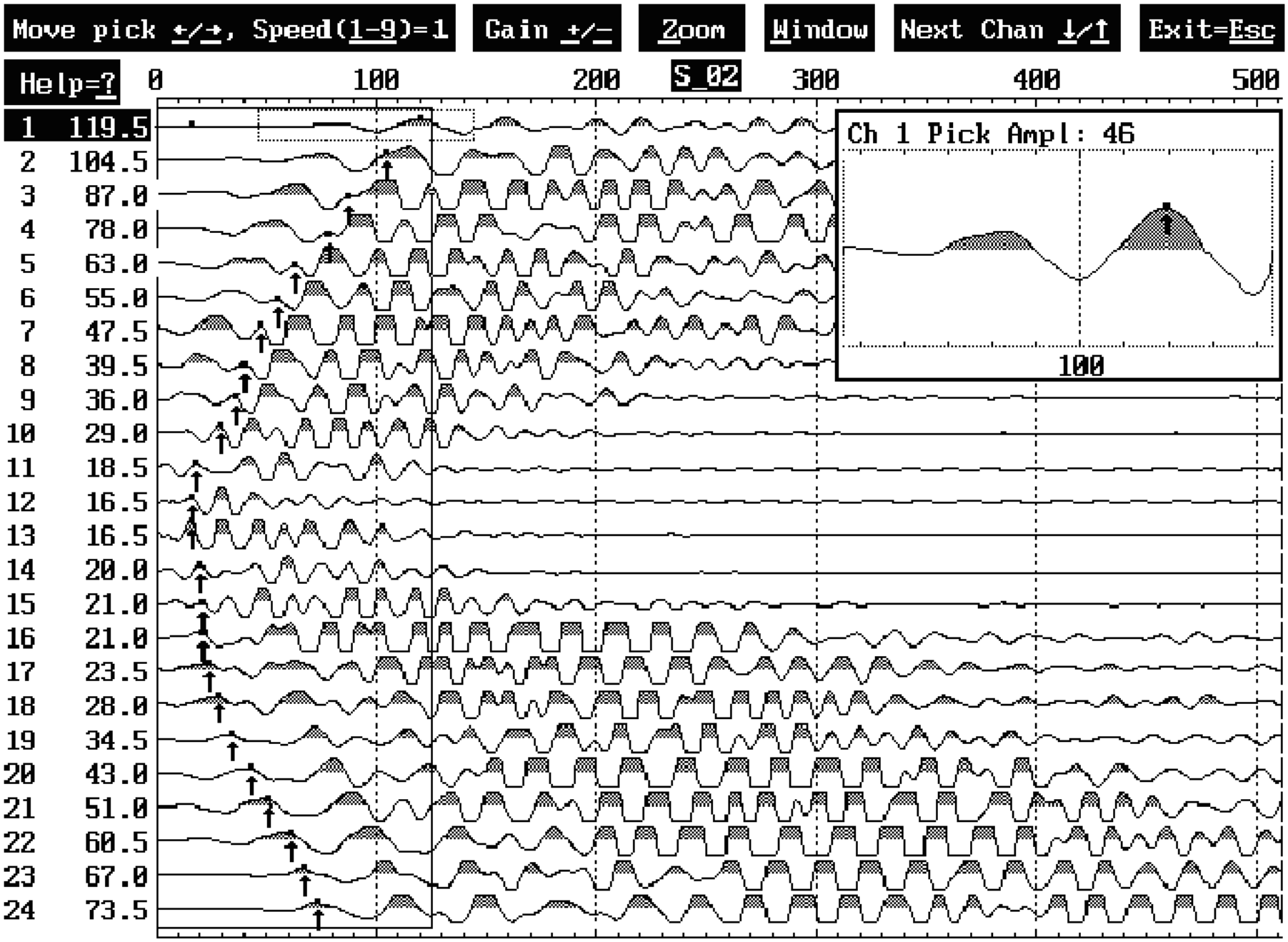

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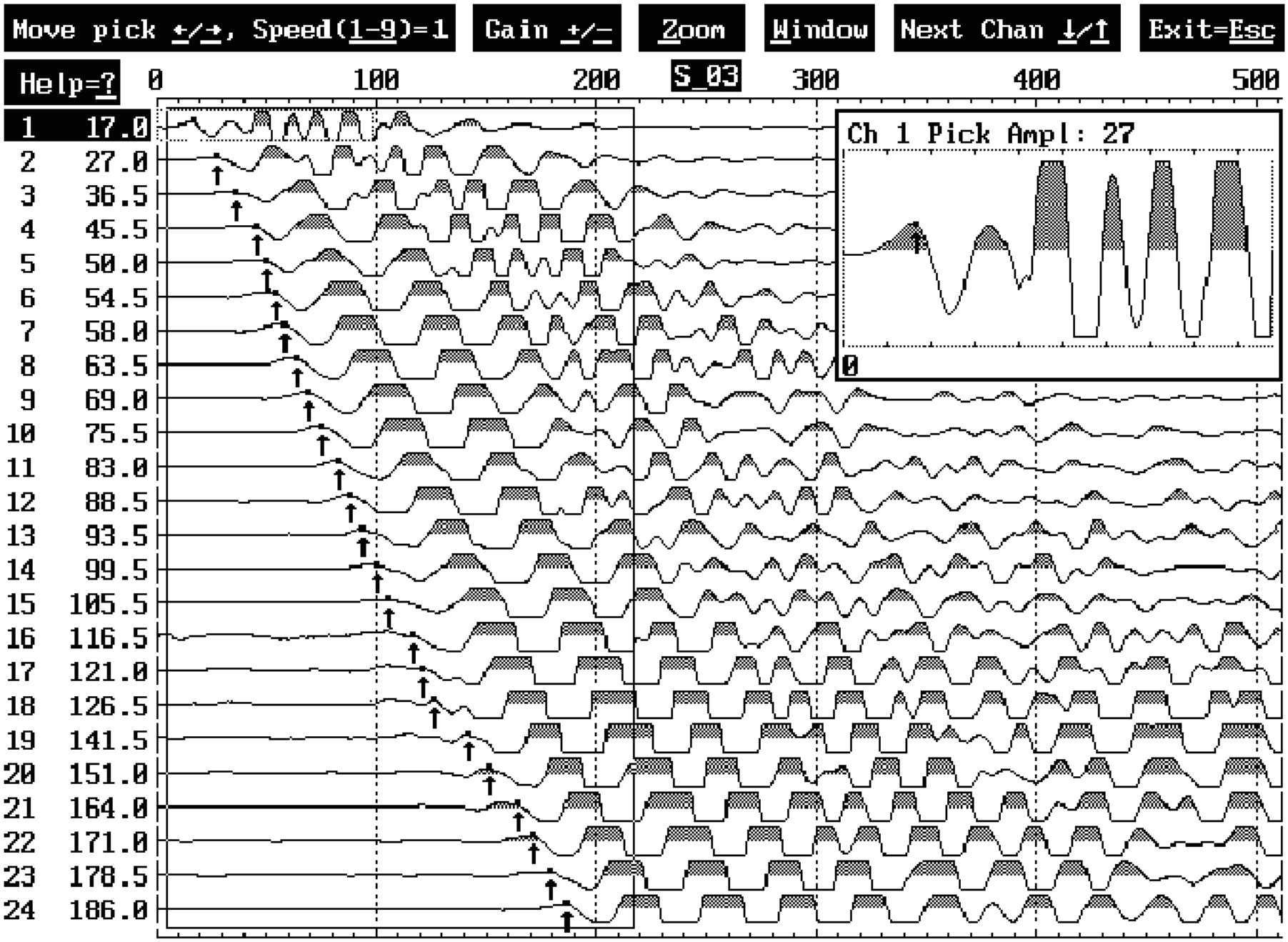

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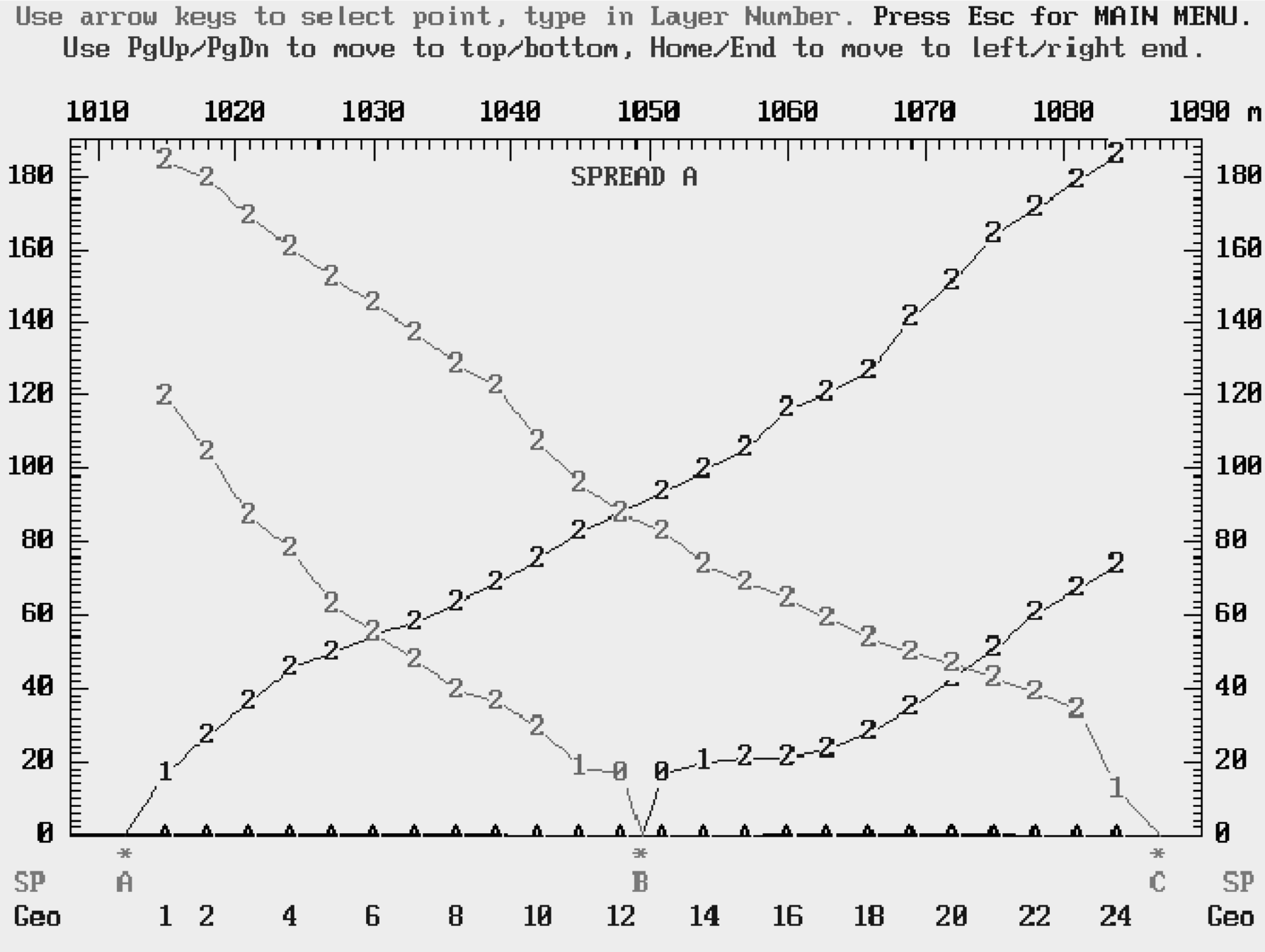

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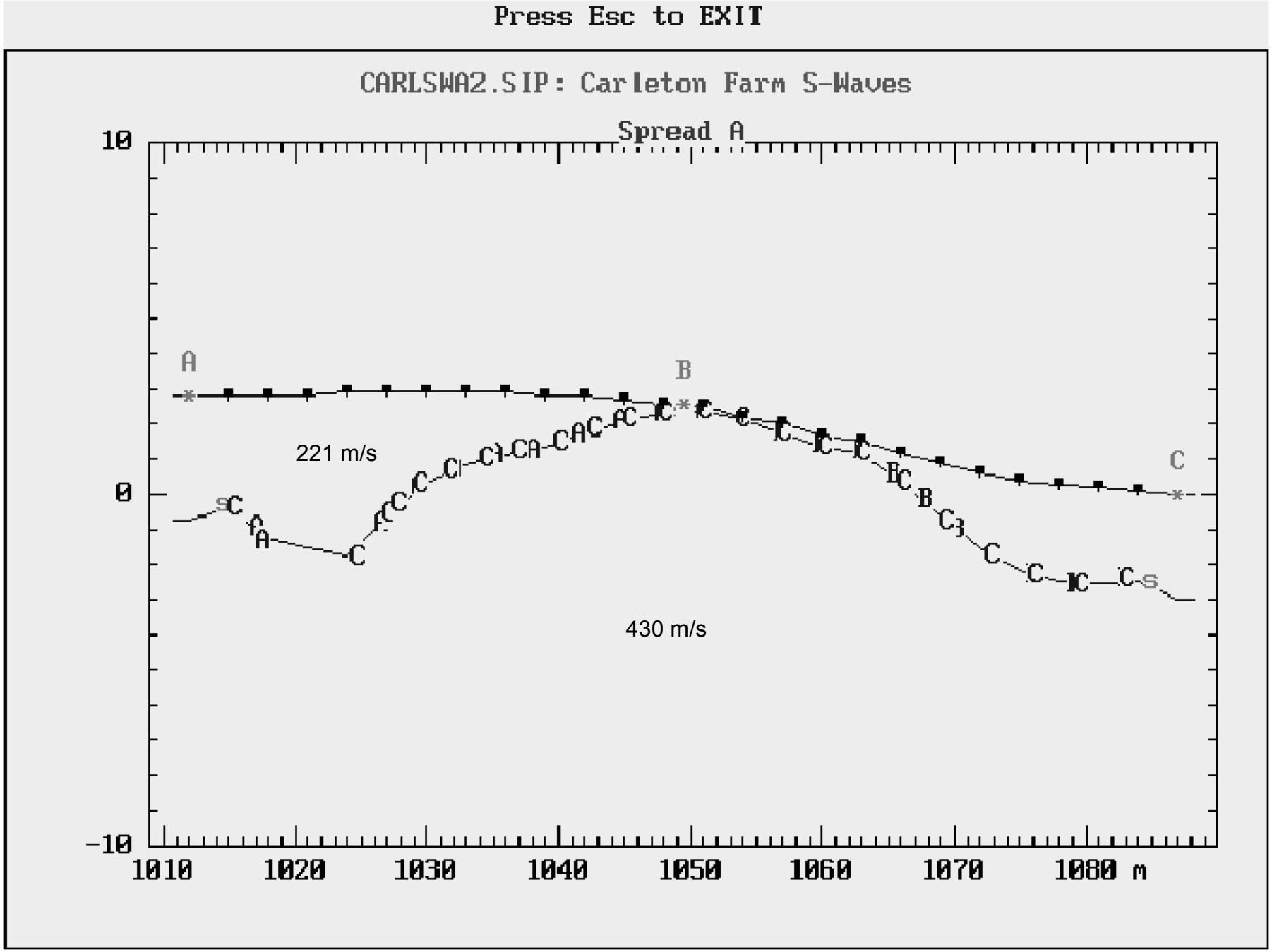

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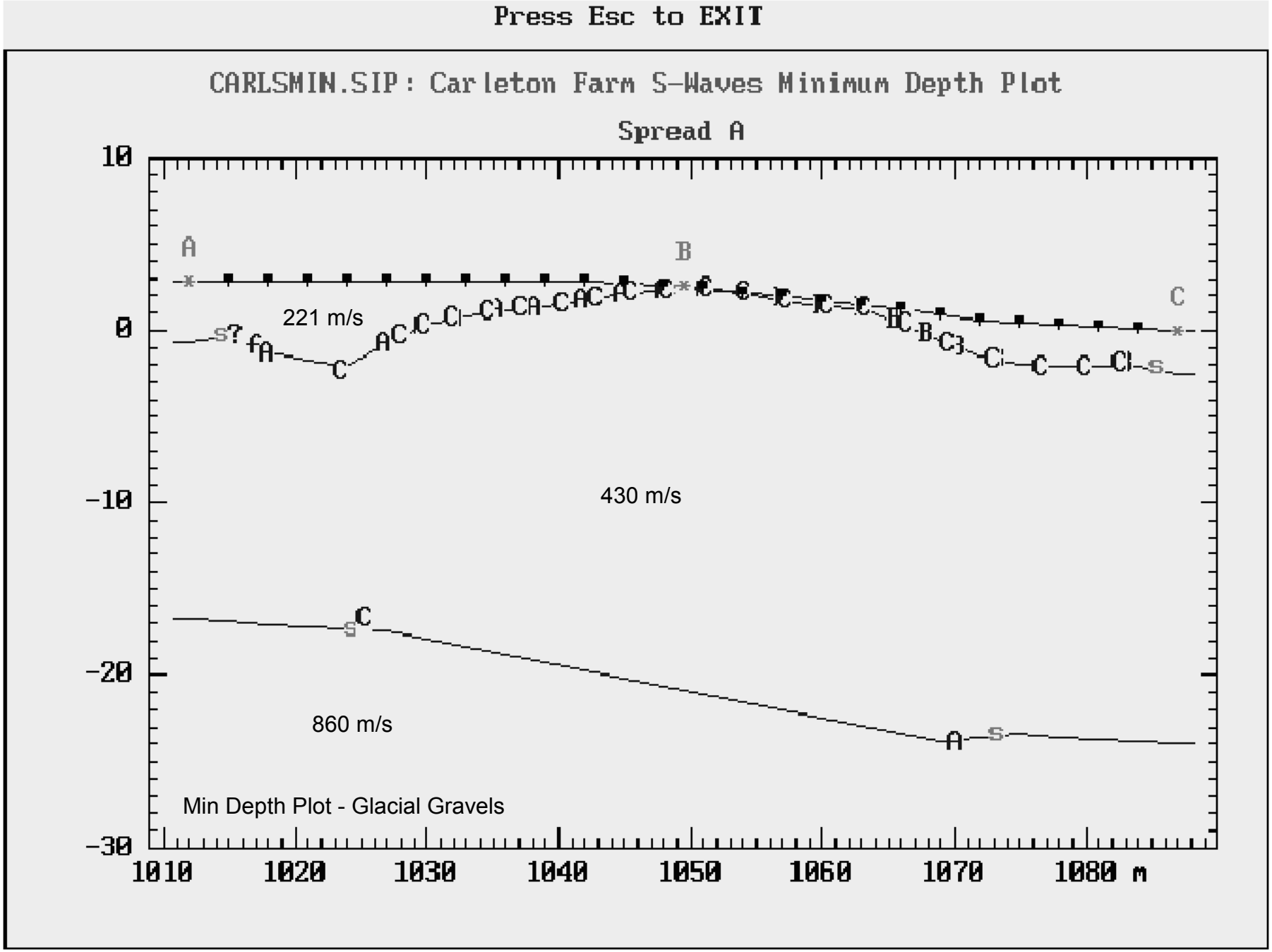
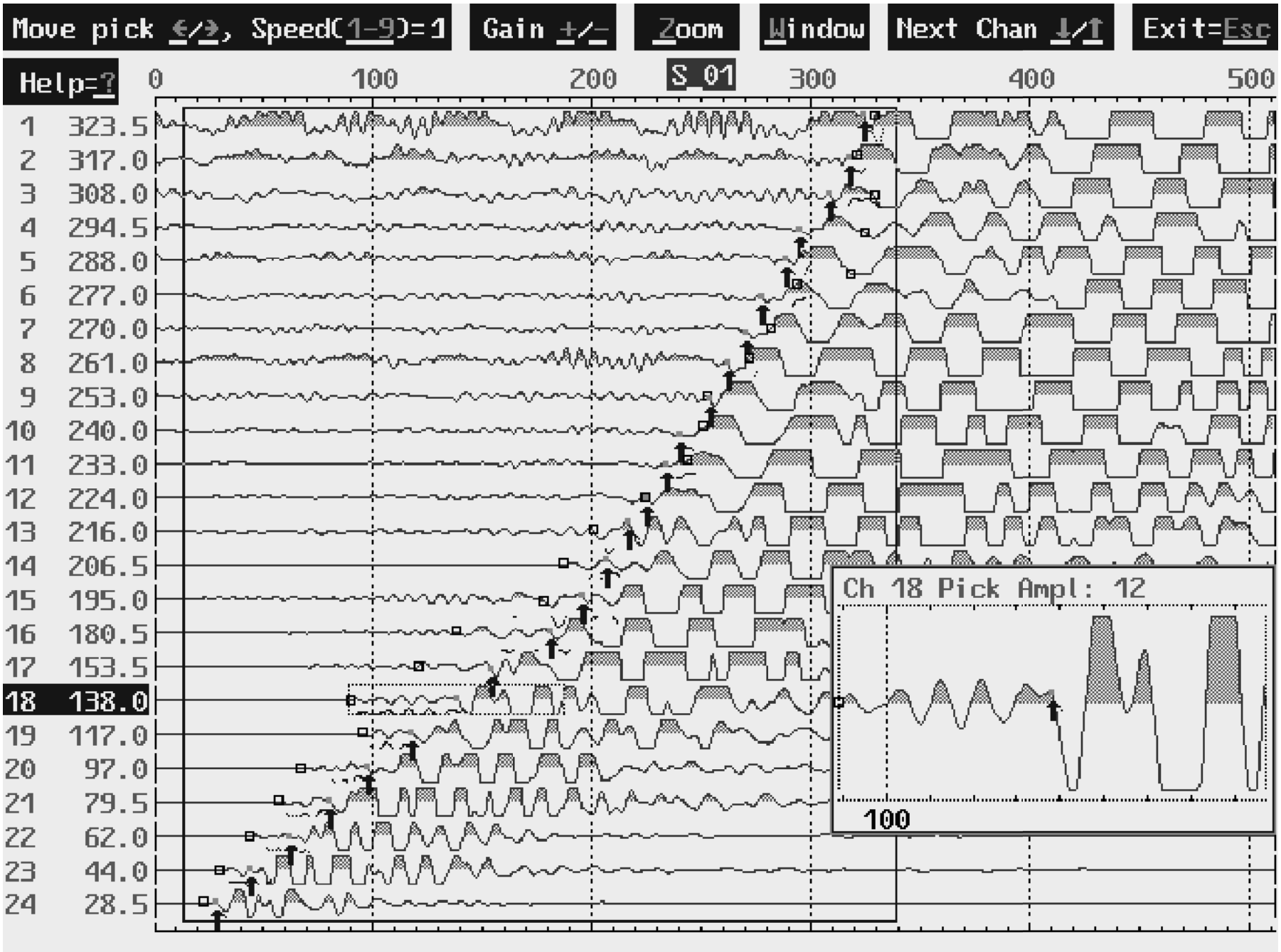


Cascade Middle School S-wave



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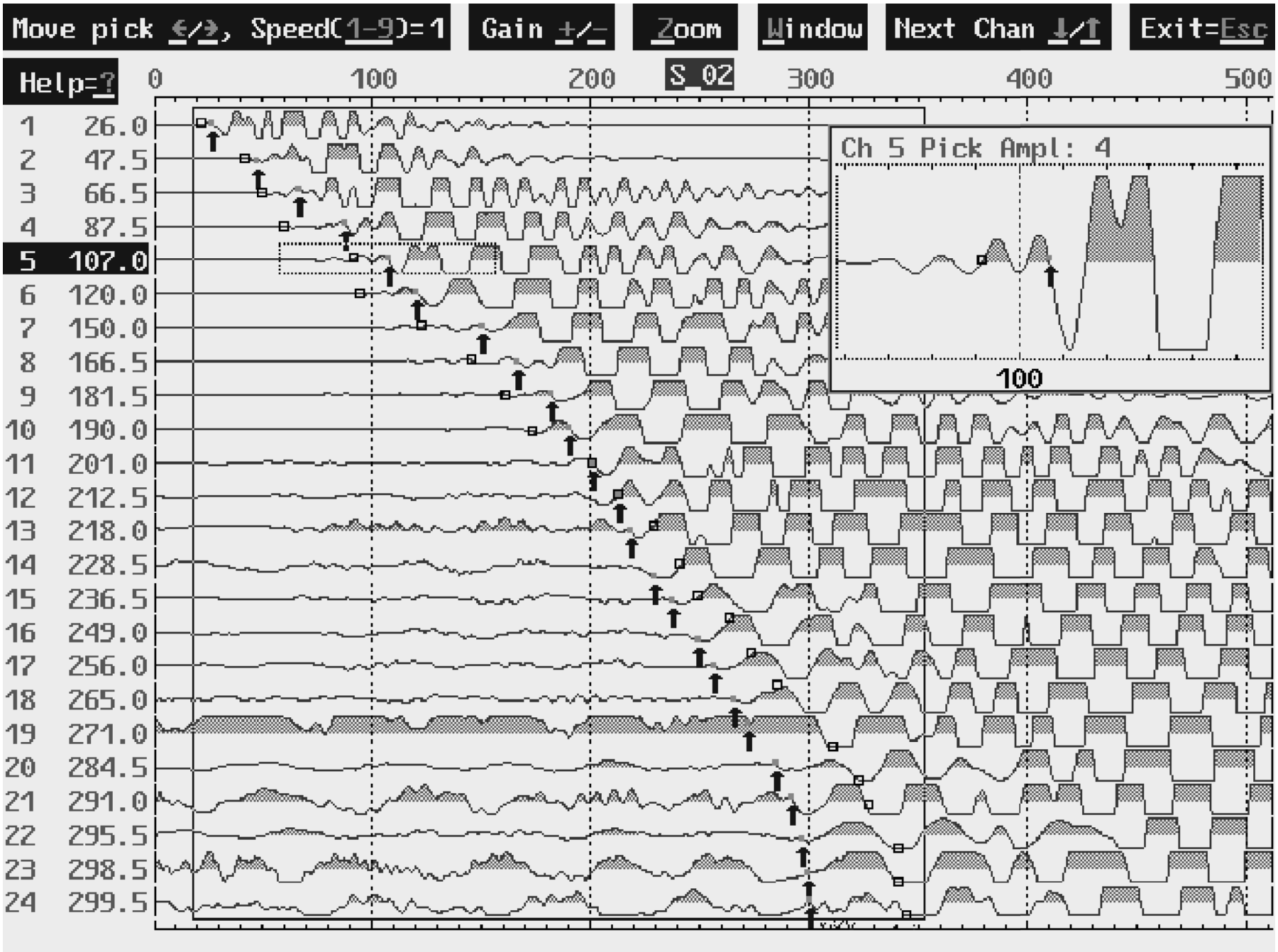

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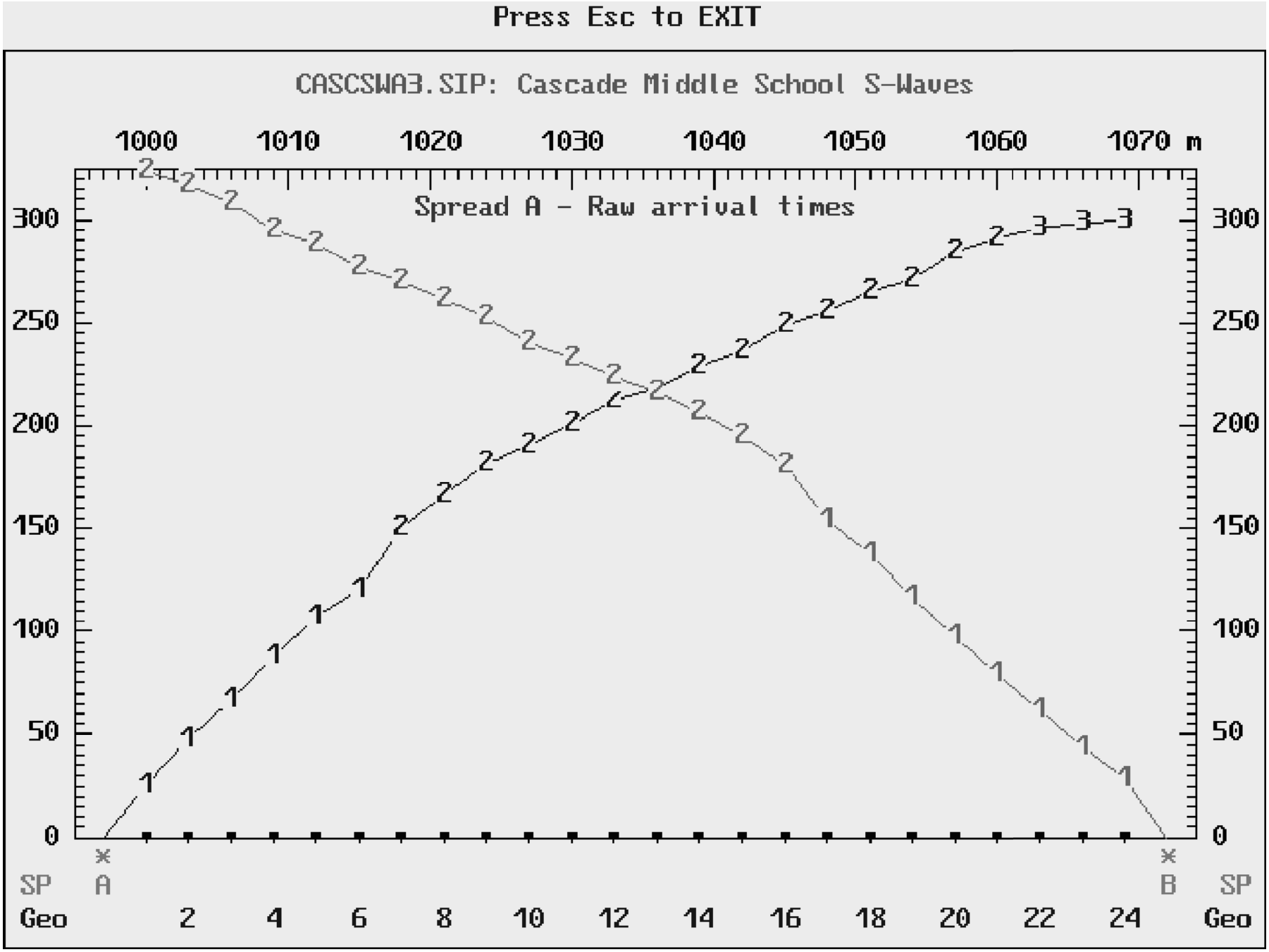

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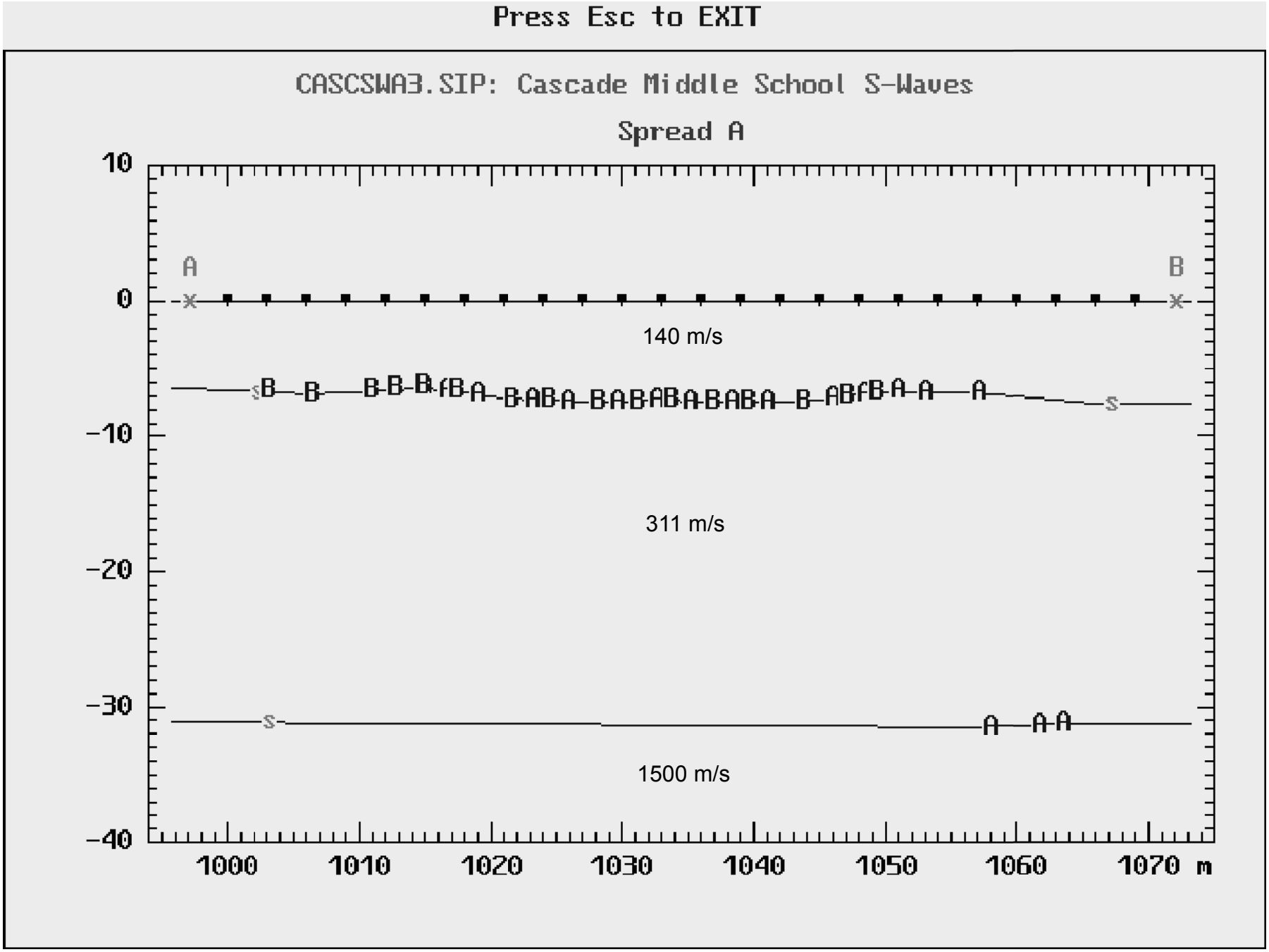
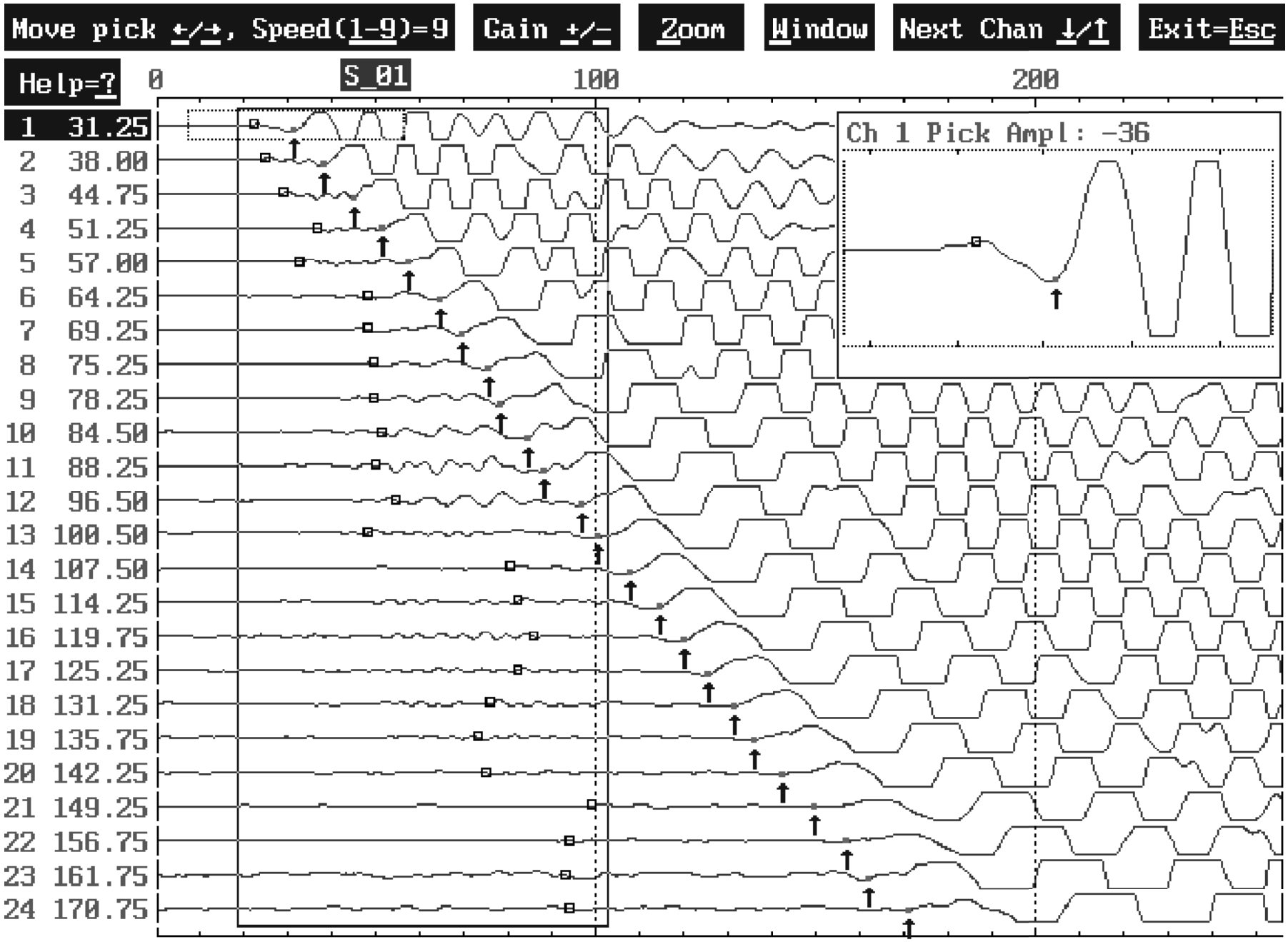


Cascade View Elementary S-wave



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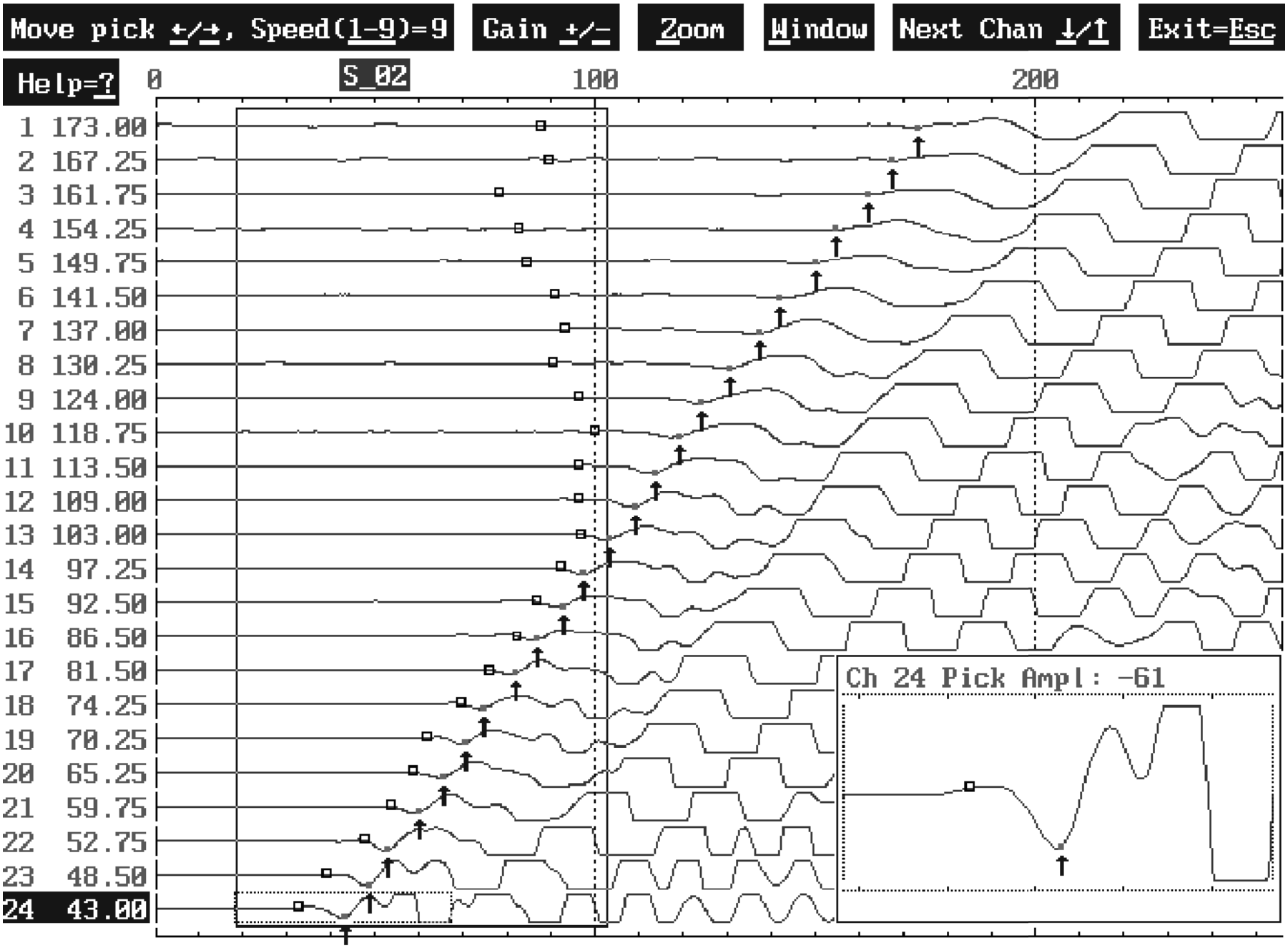

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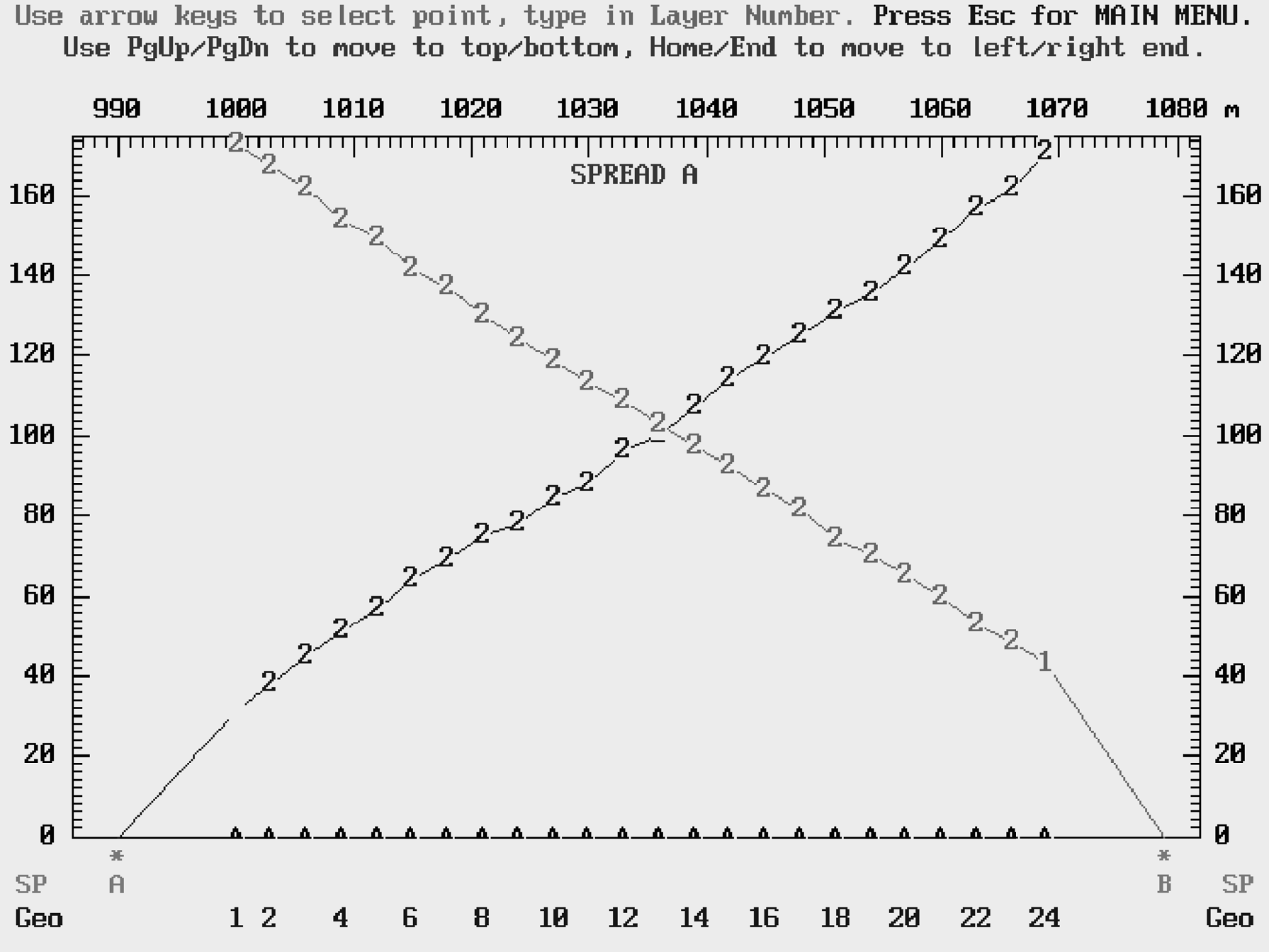

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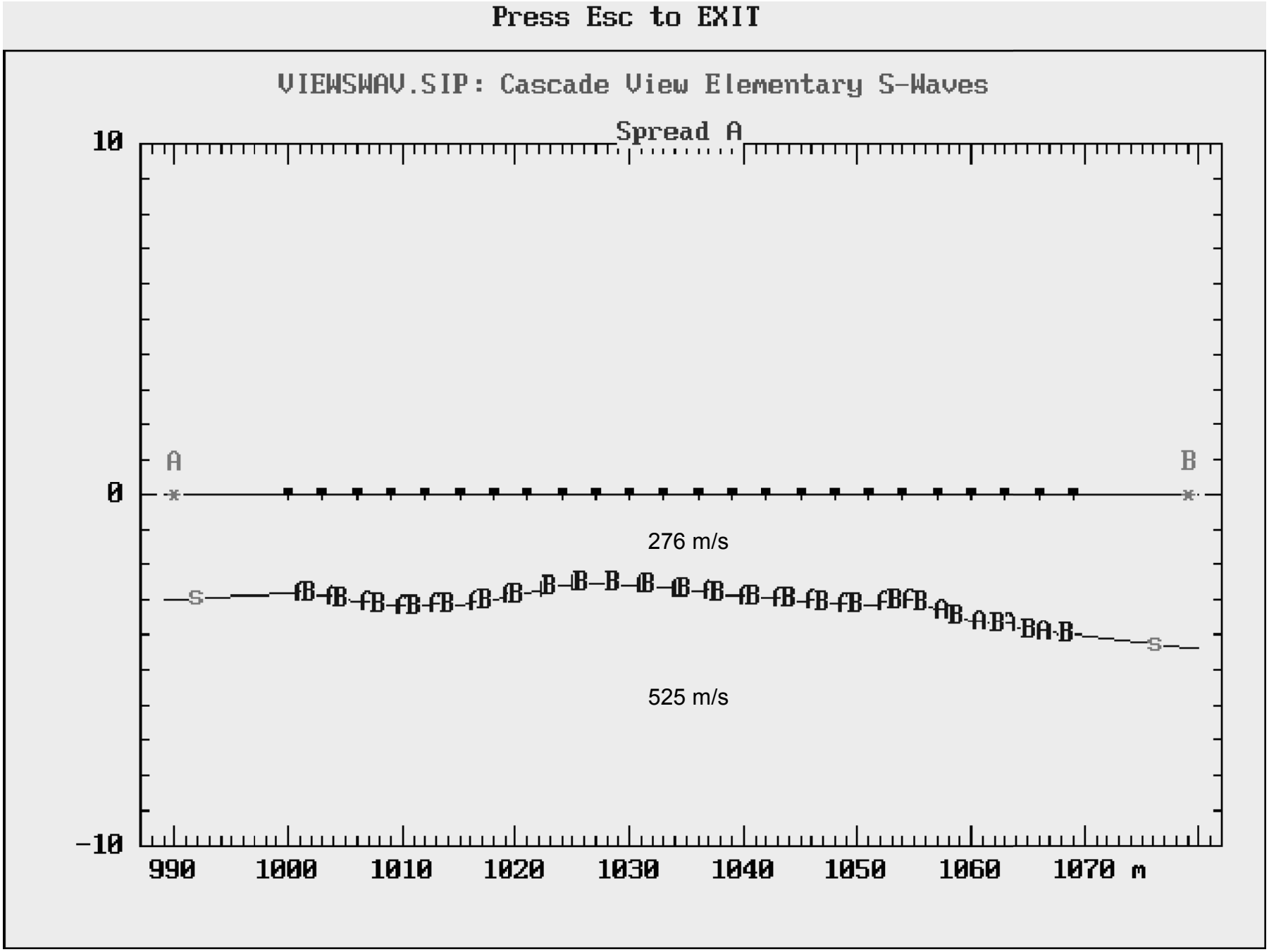

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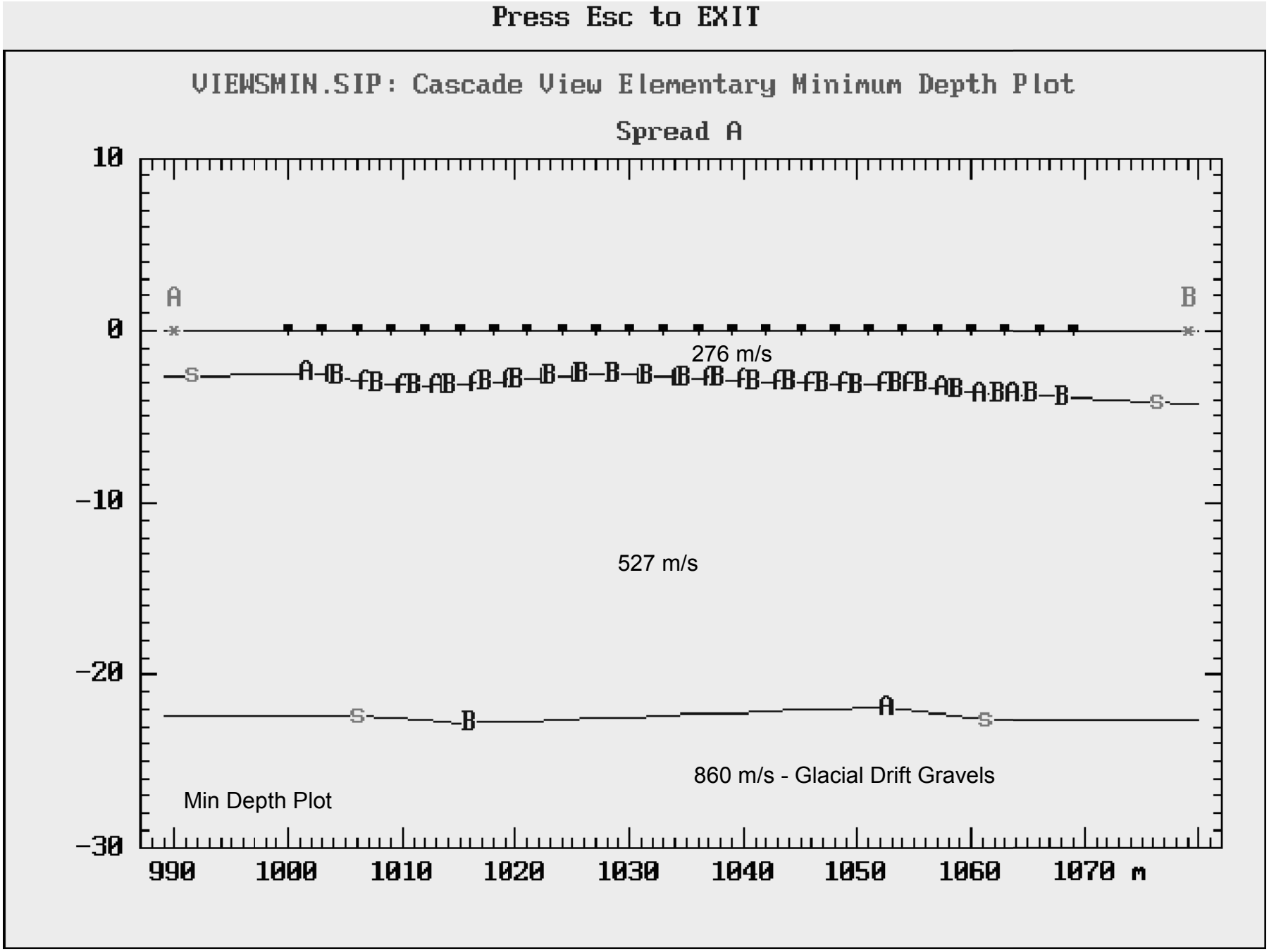
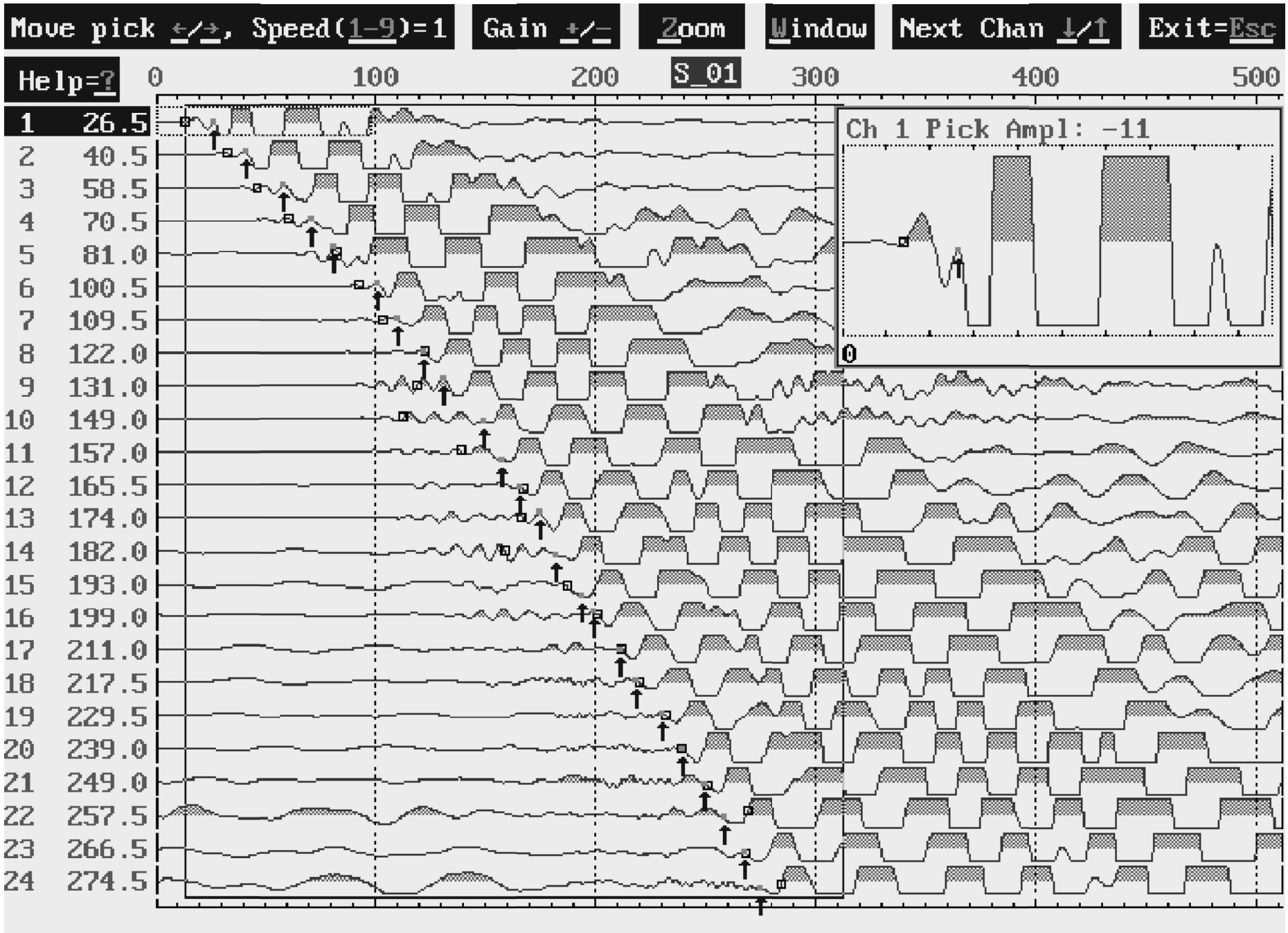
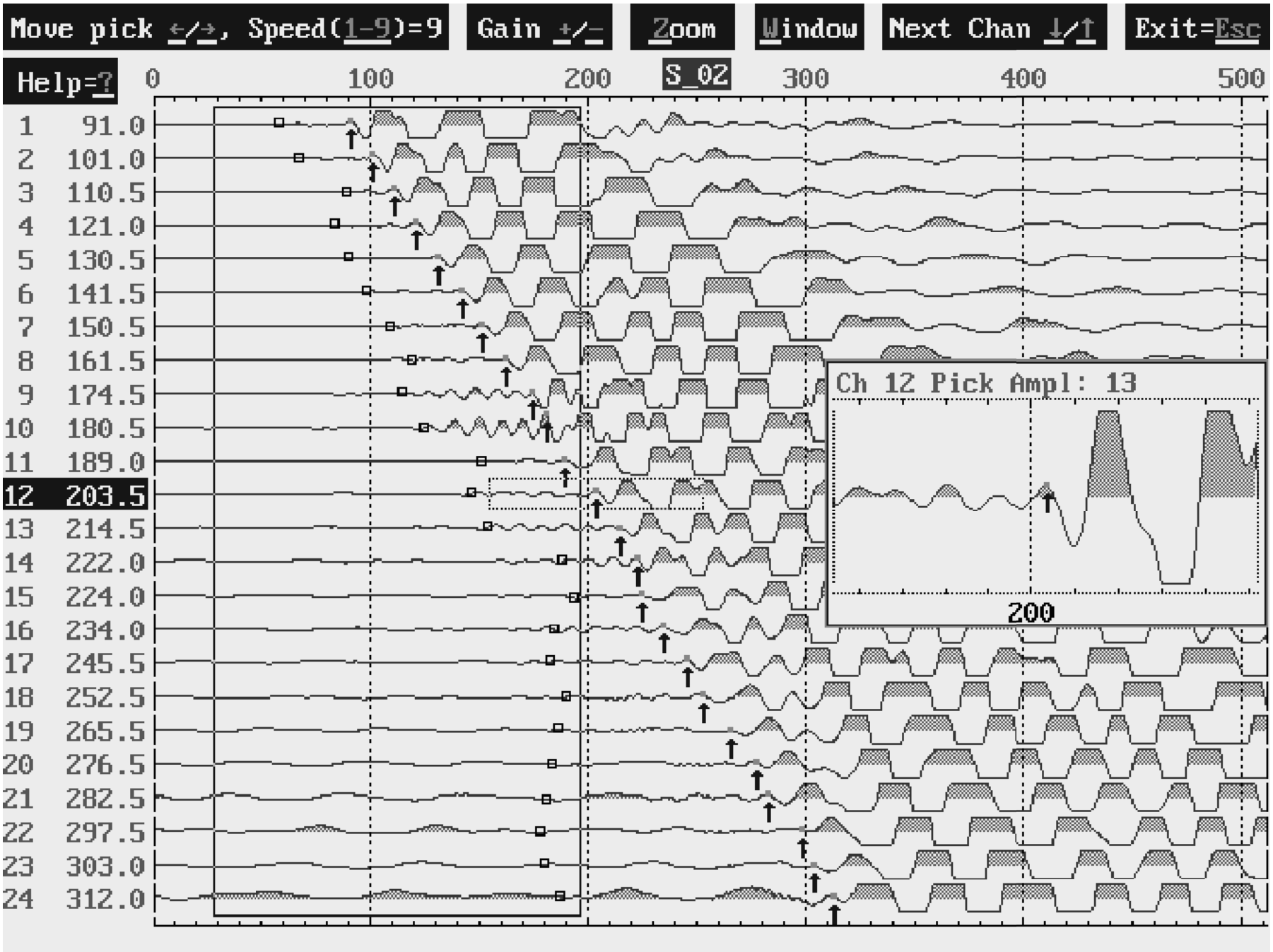


Cavlar Lumber S-wave



Cavlar Lumber S-wave



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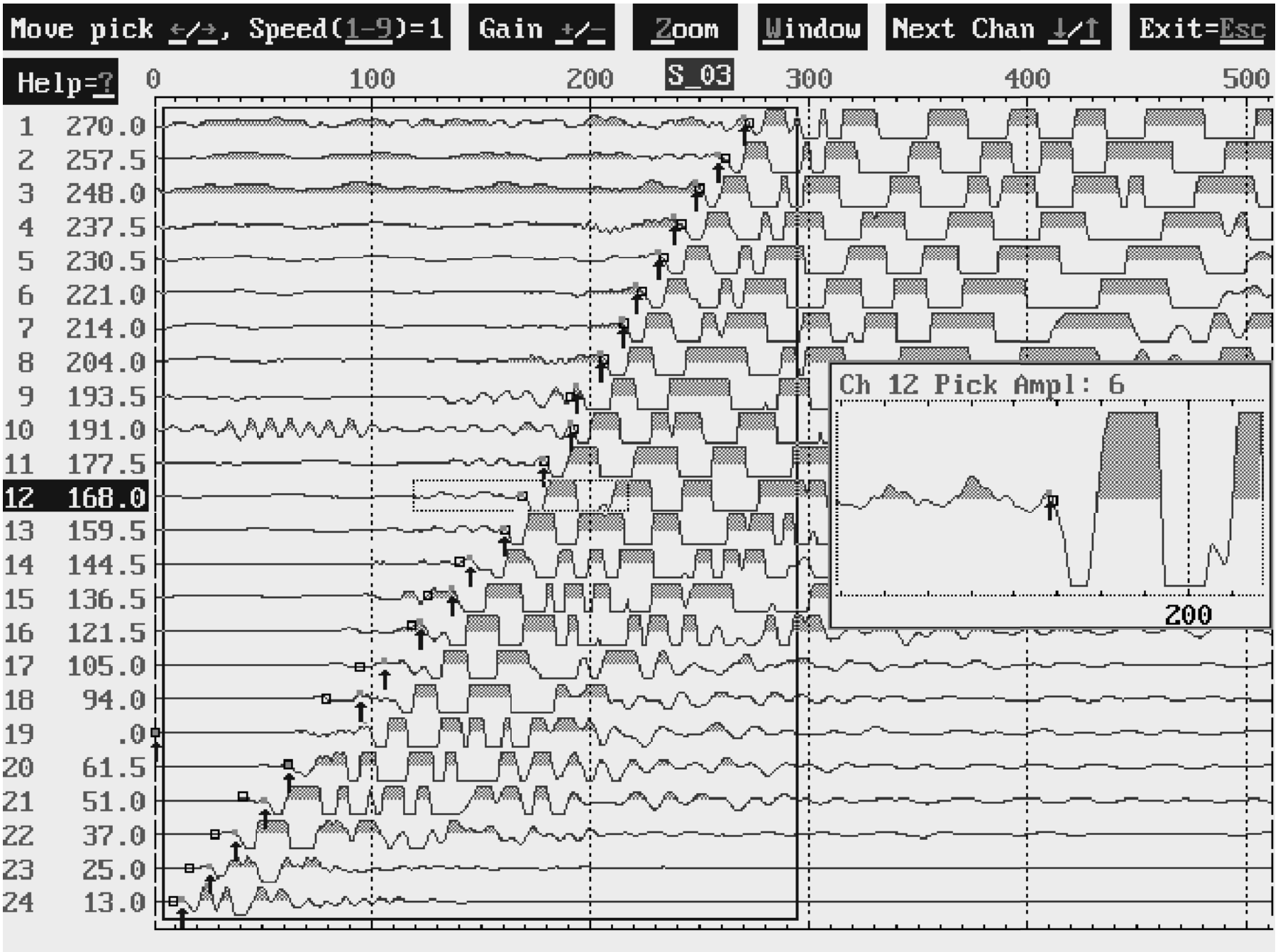

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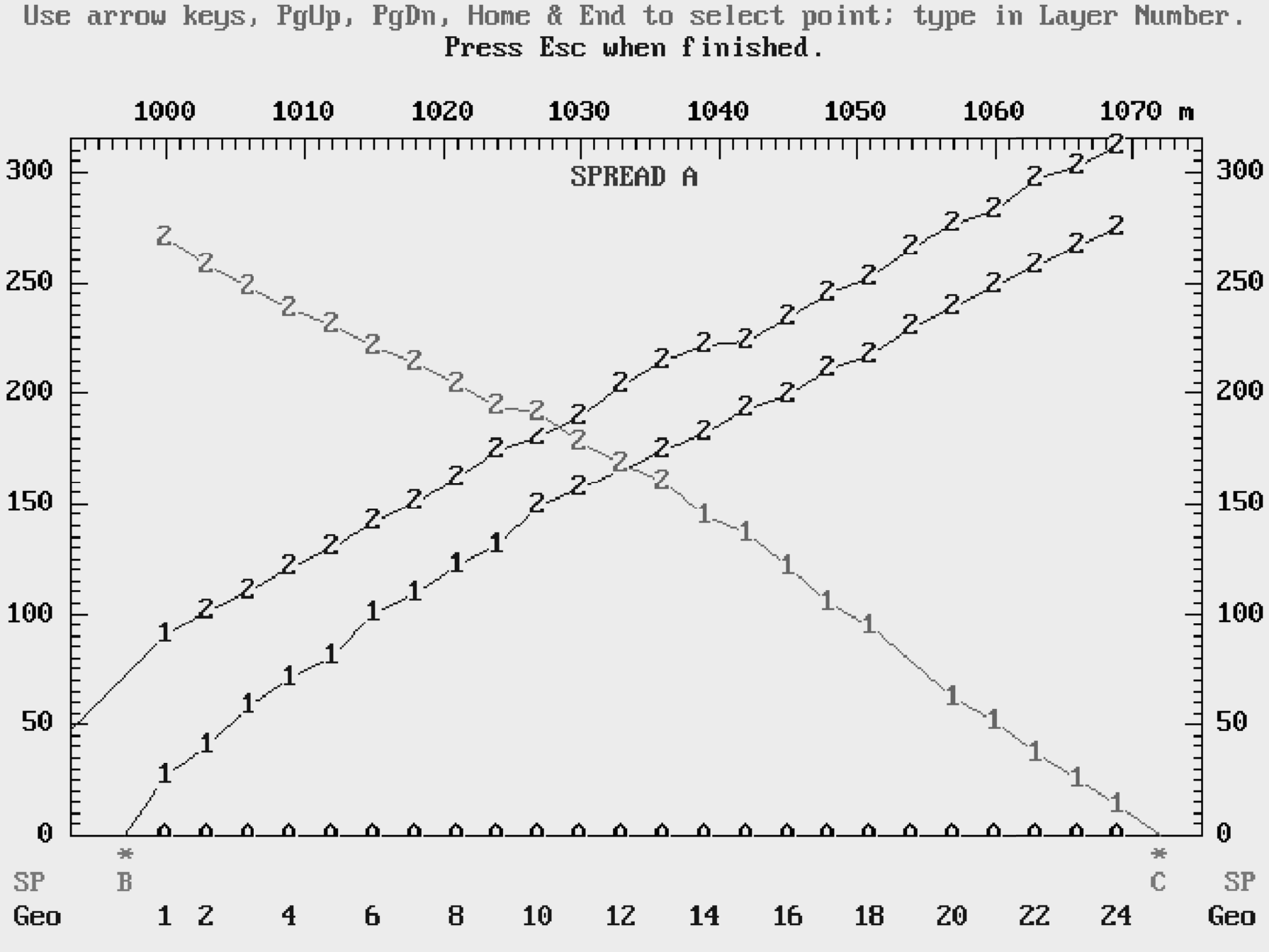

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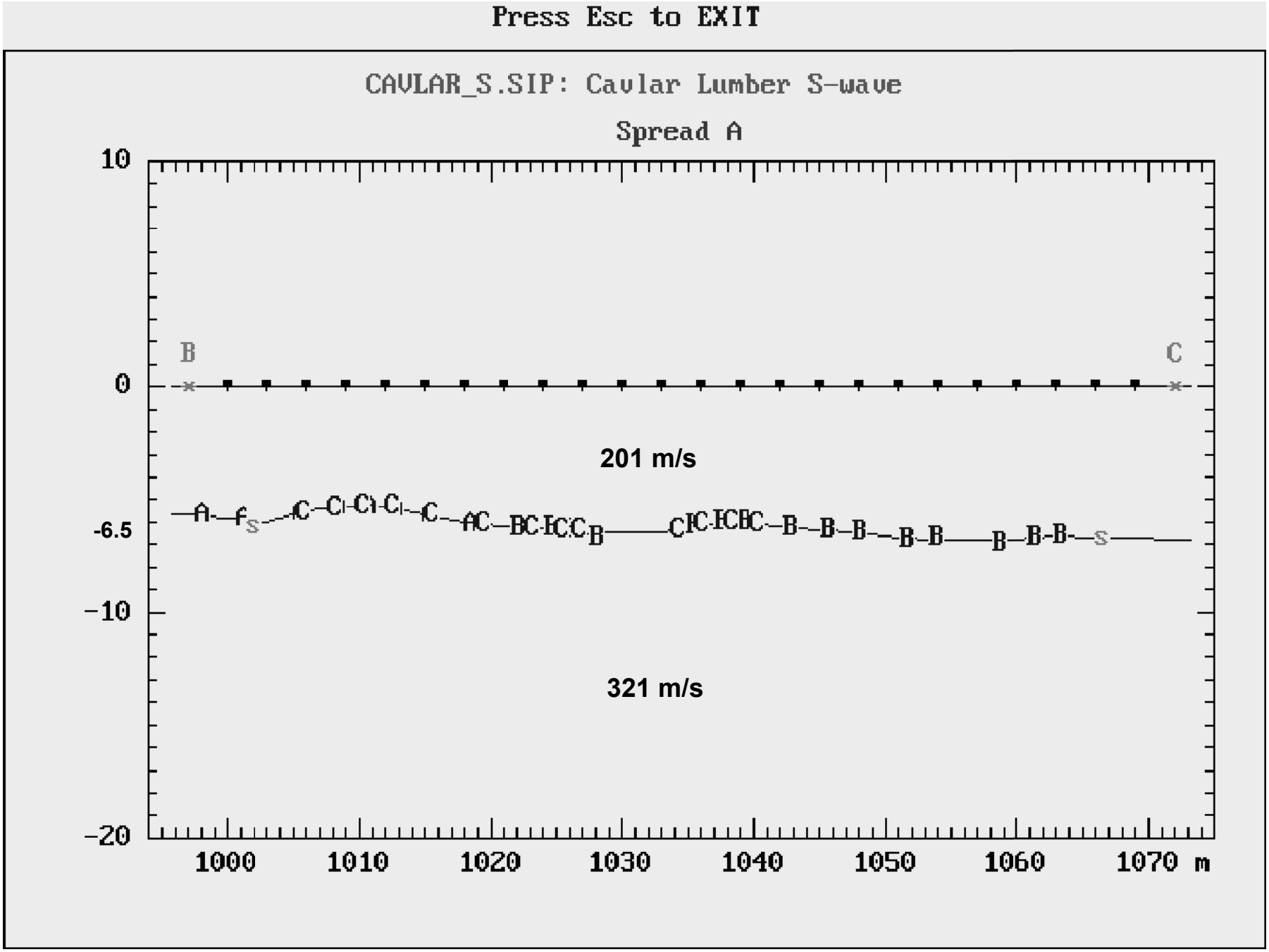

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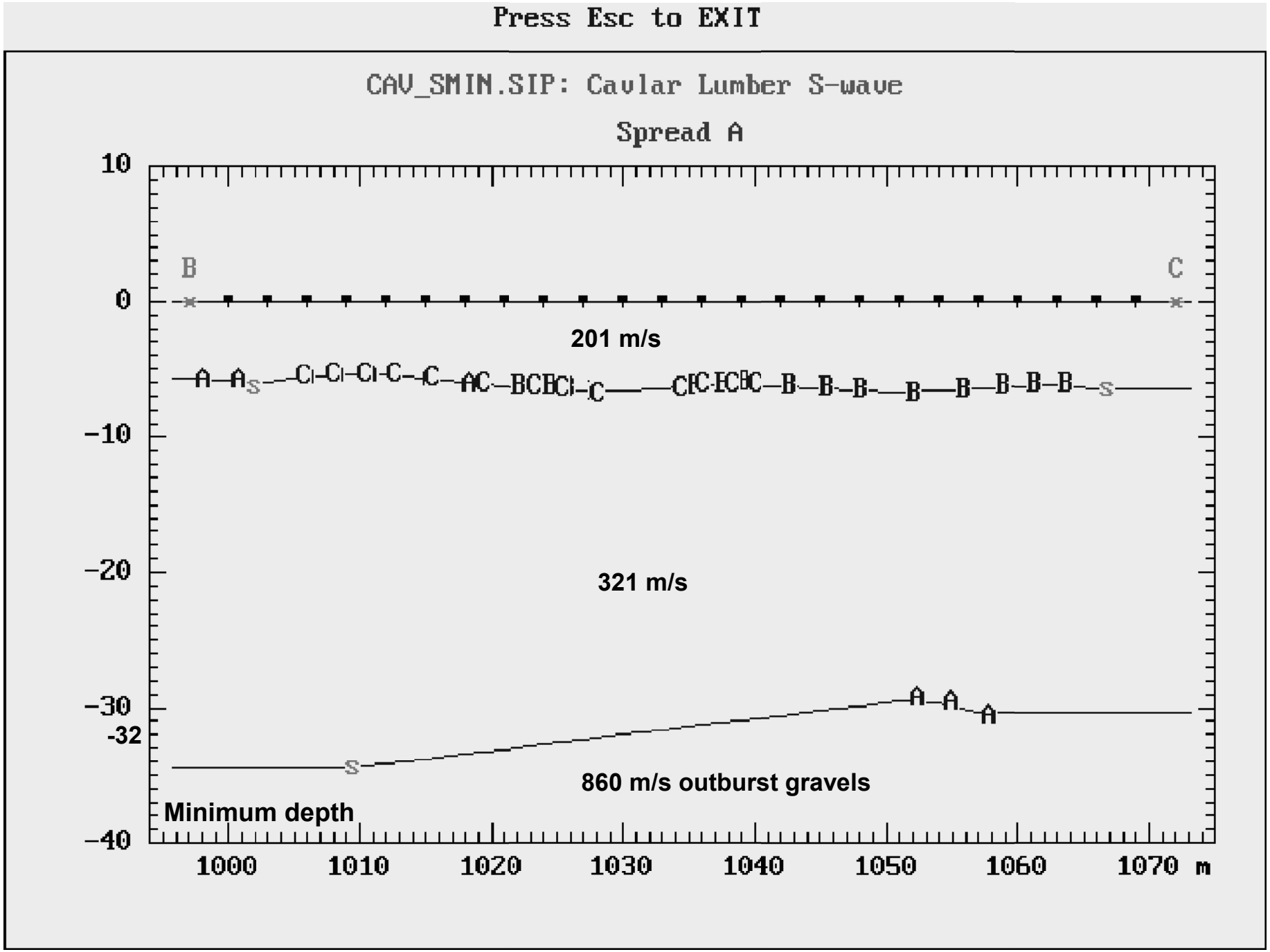
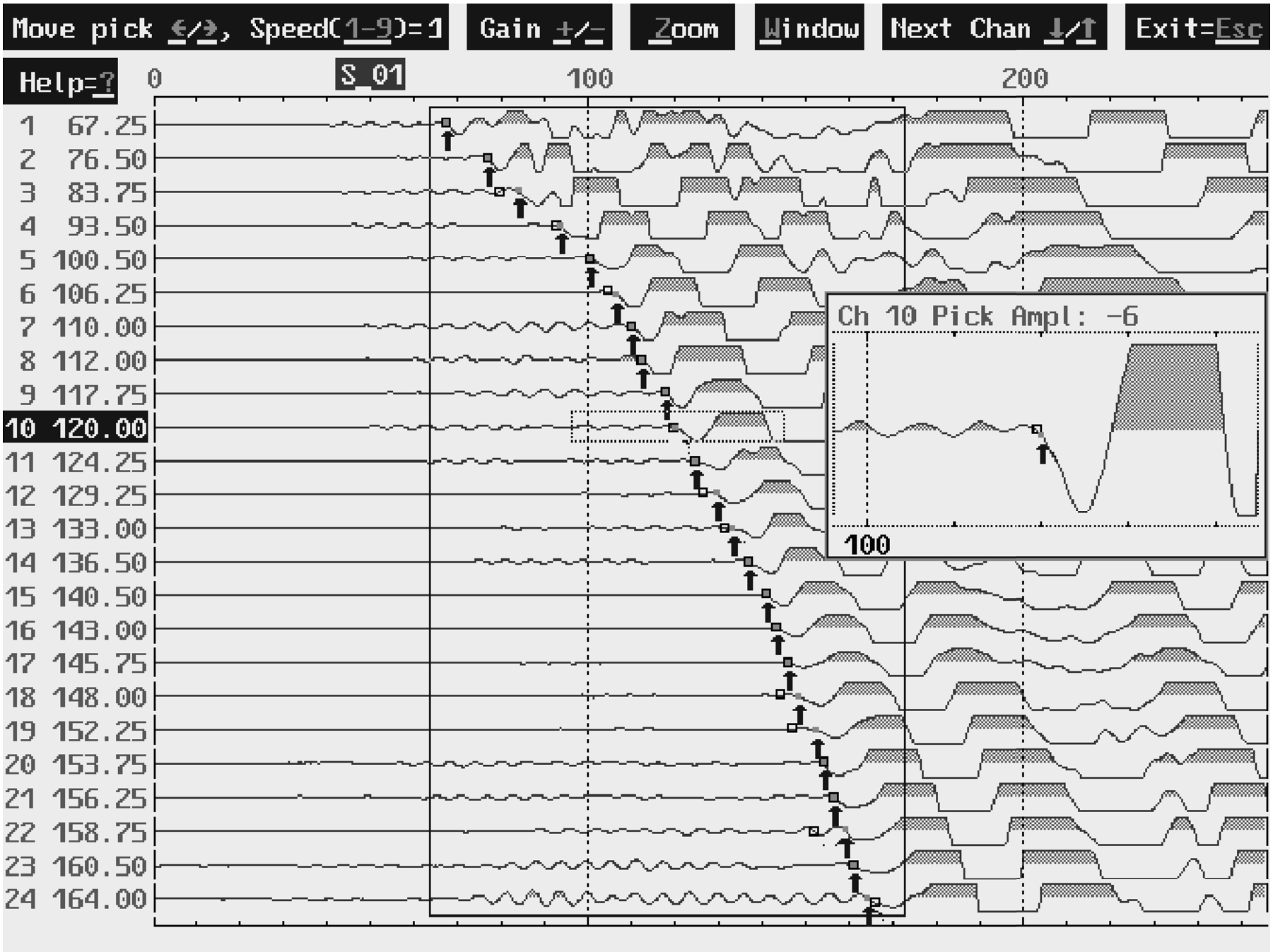


Cedarhome Elementary S-wave



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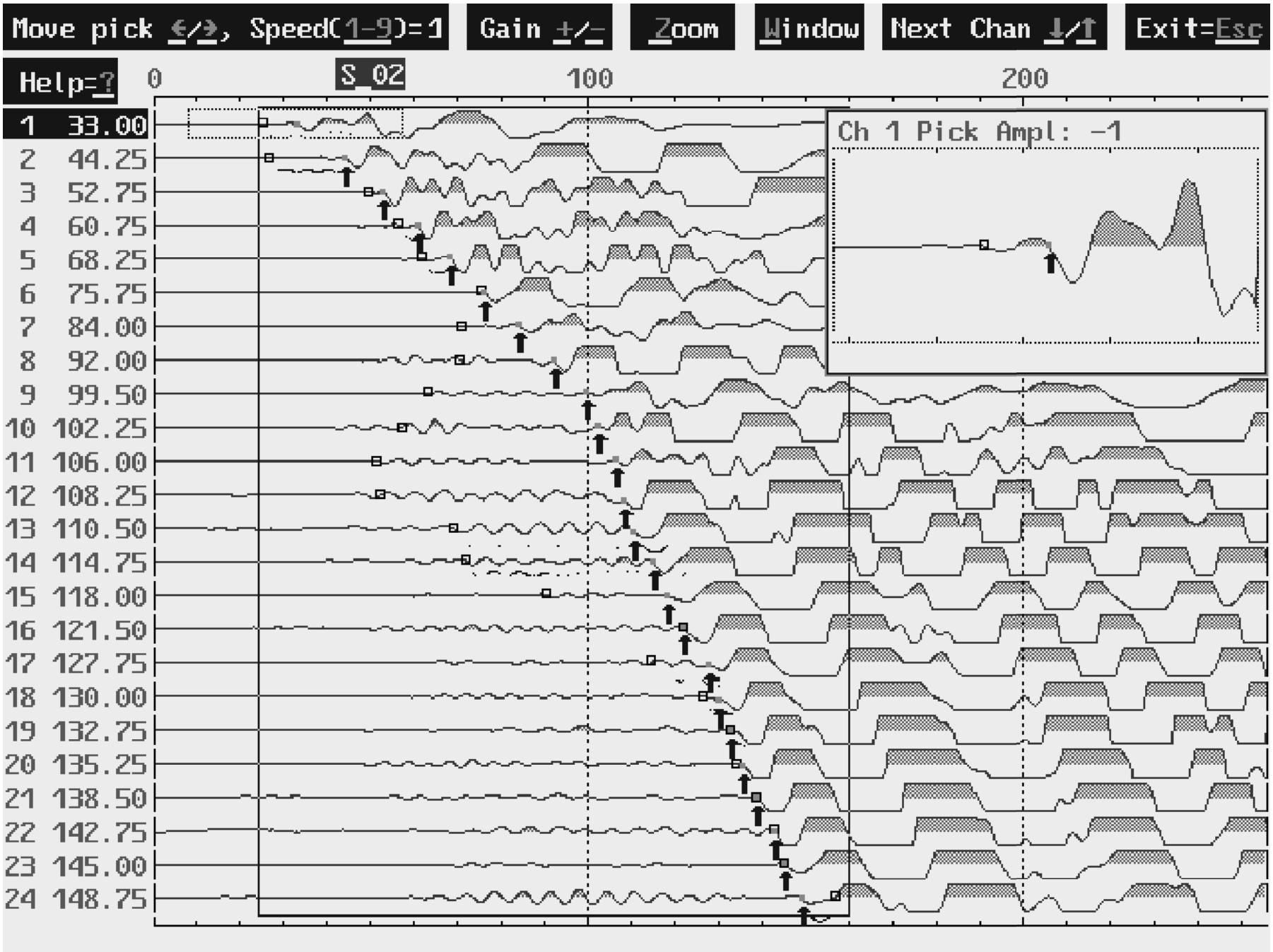

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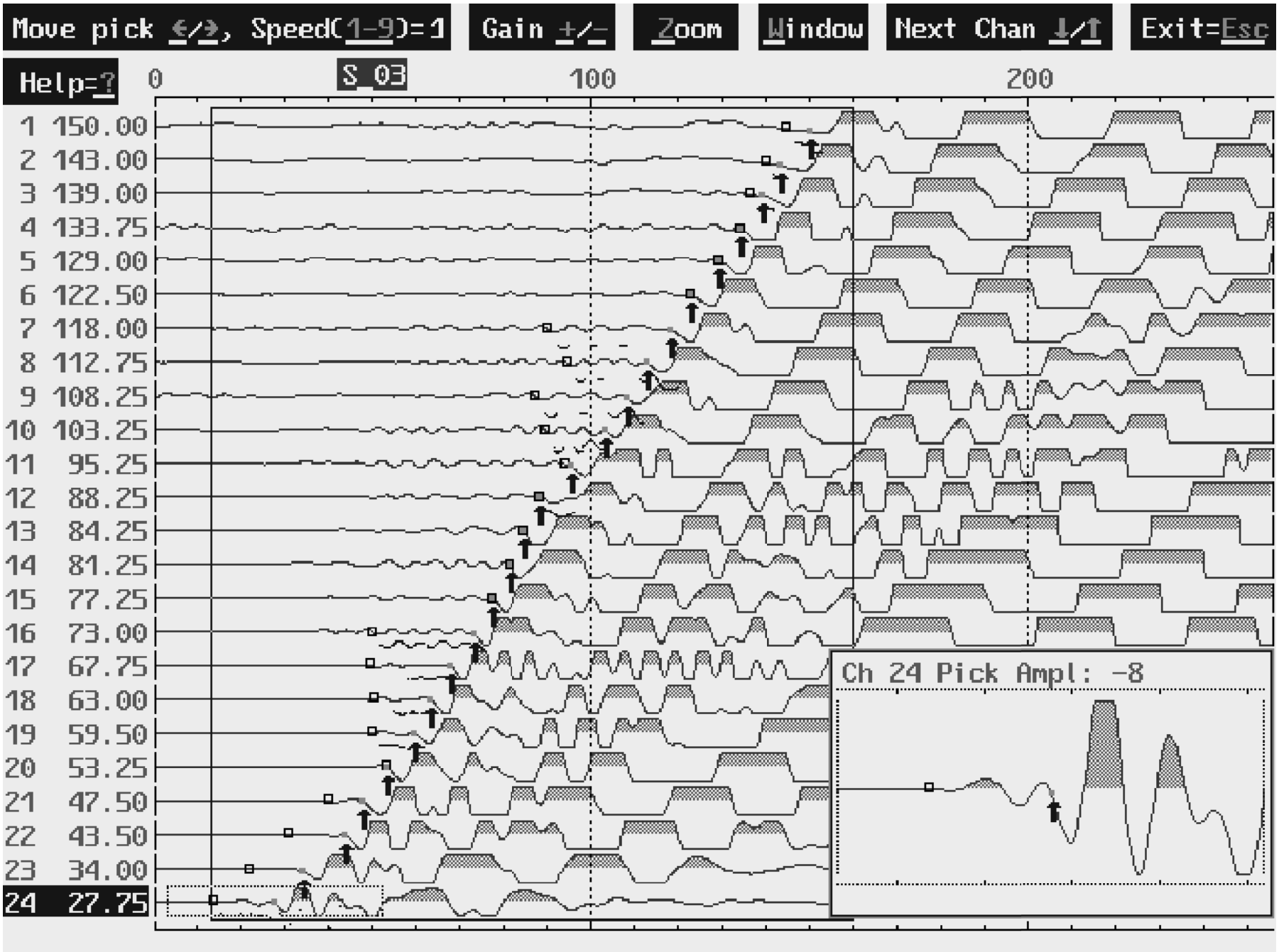

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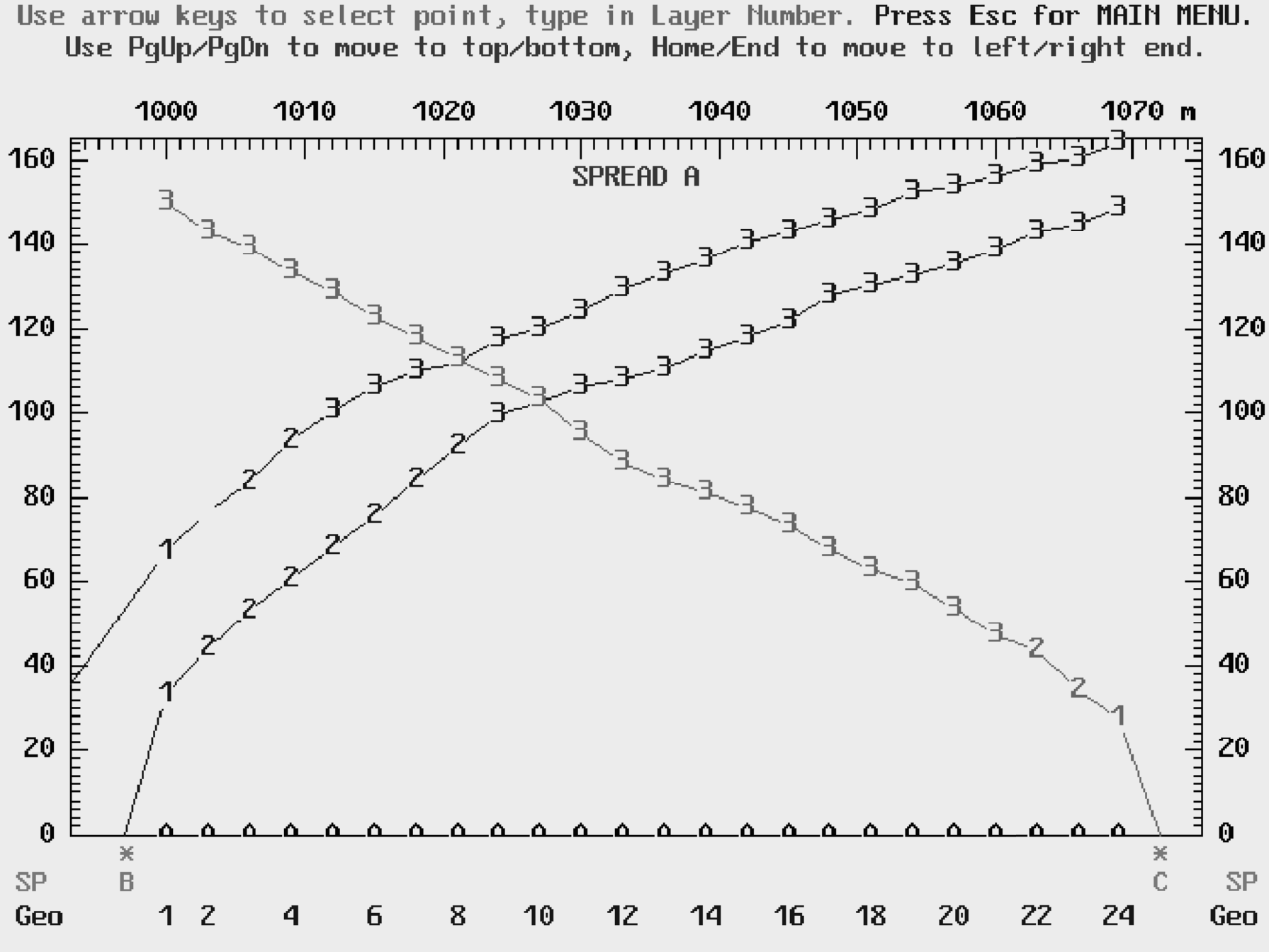

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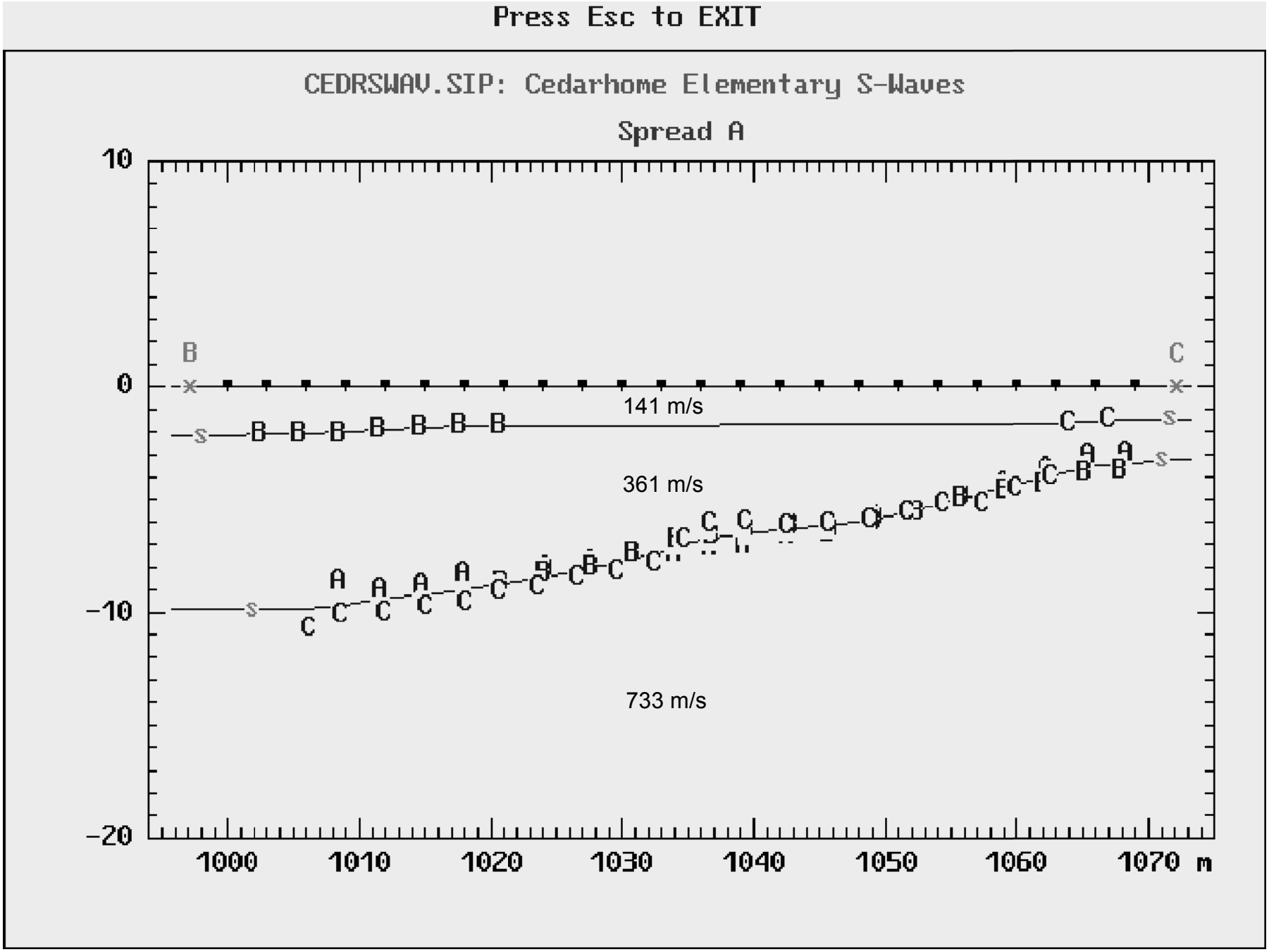

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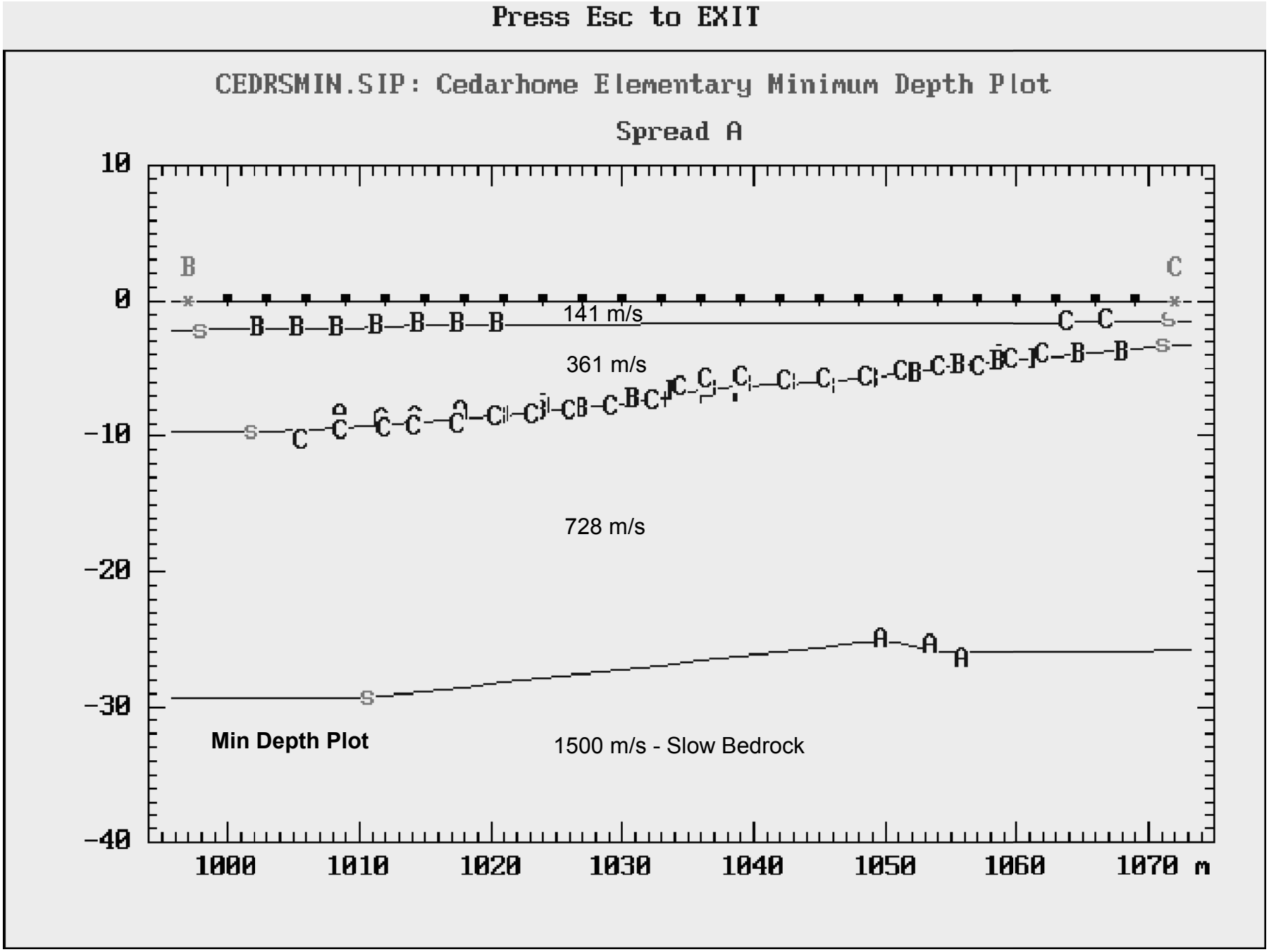
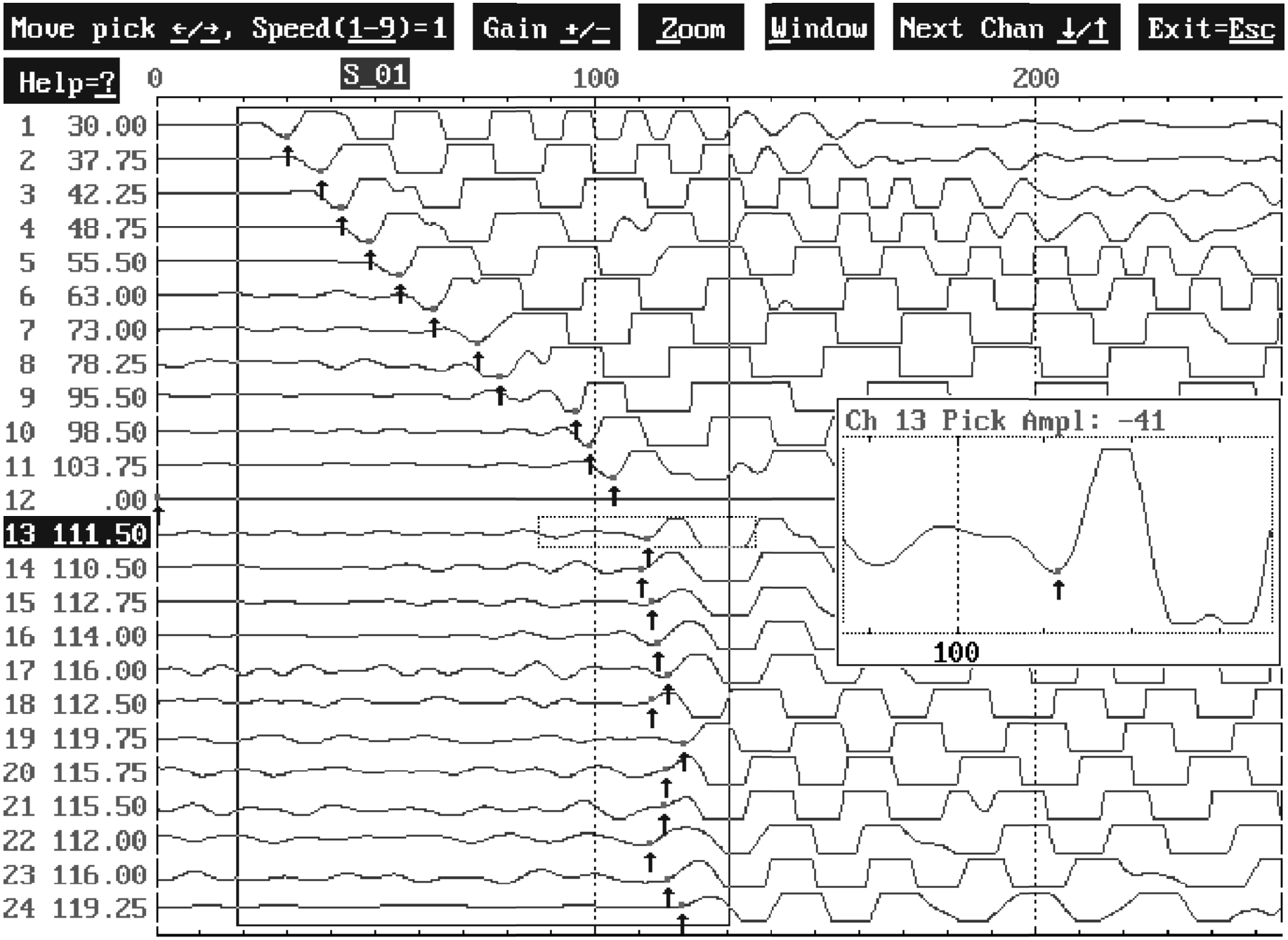


Clear Lake S-wave



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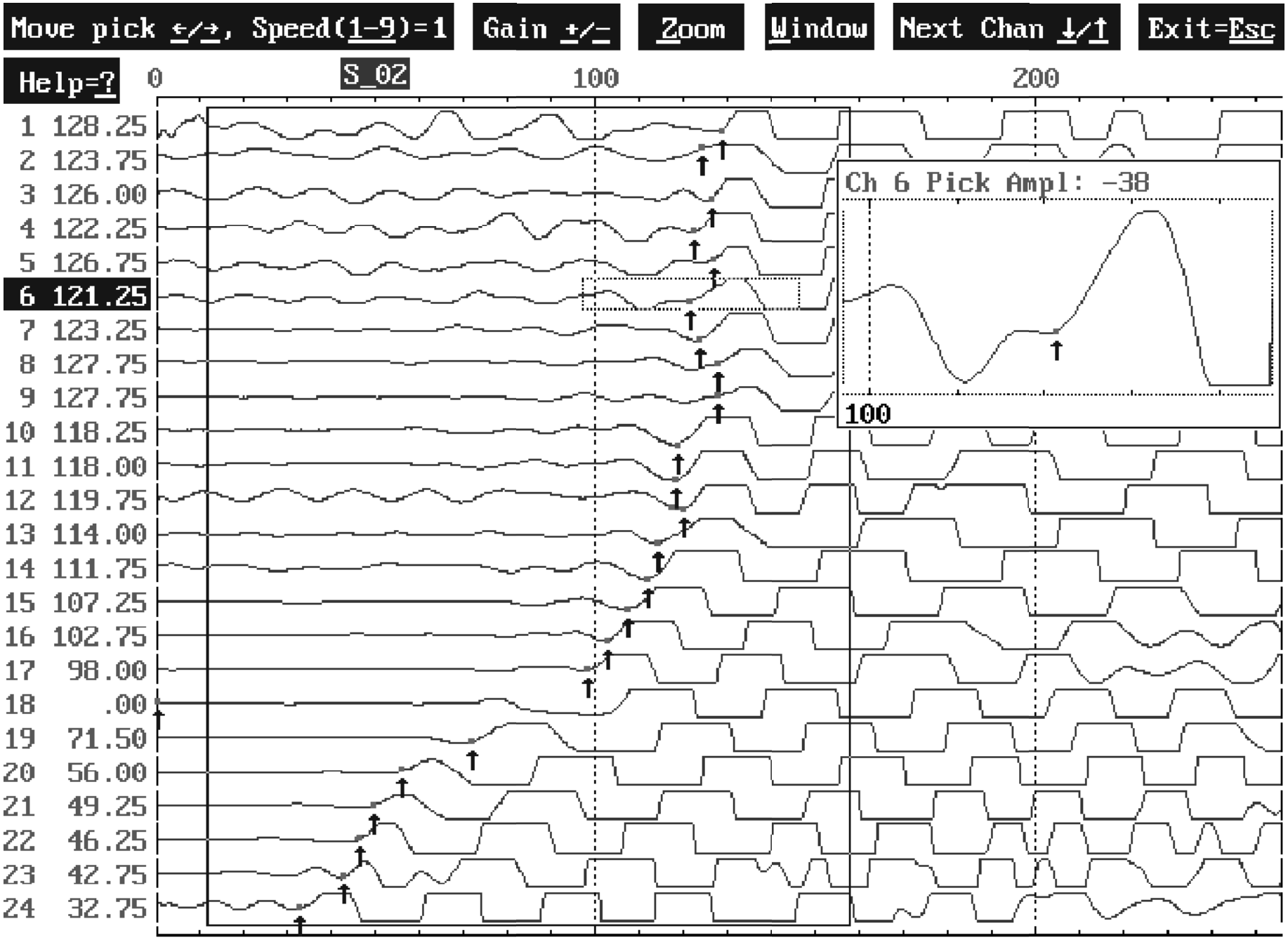

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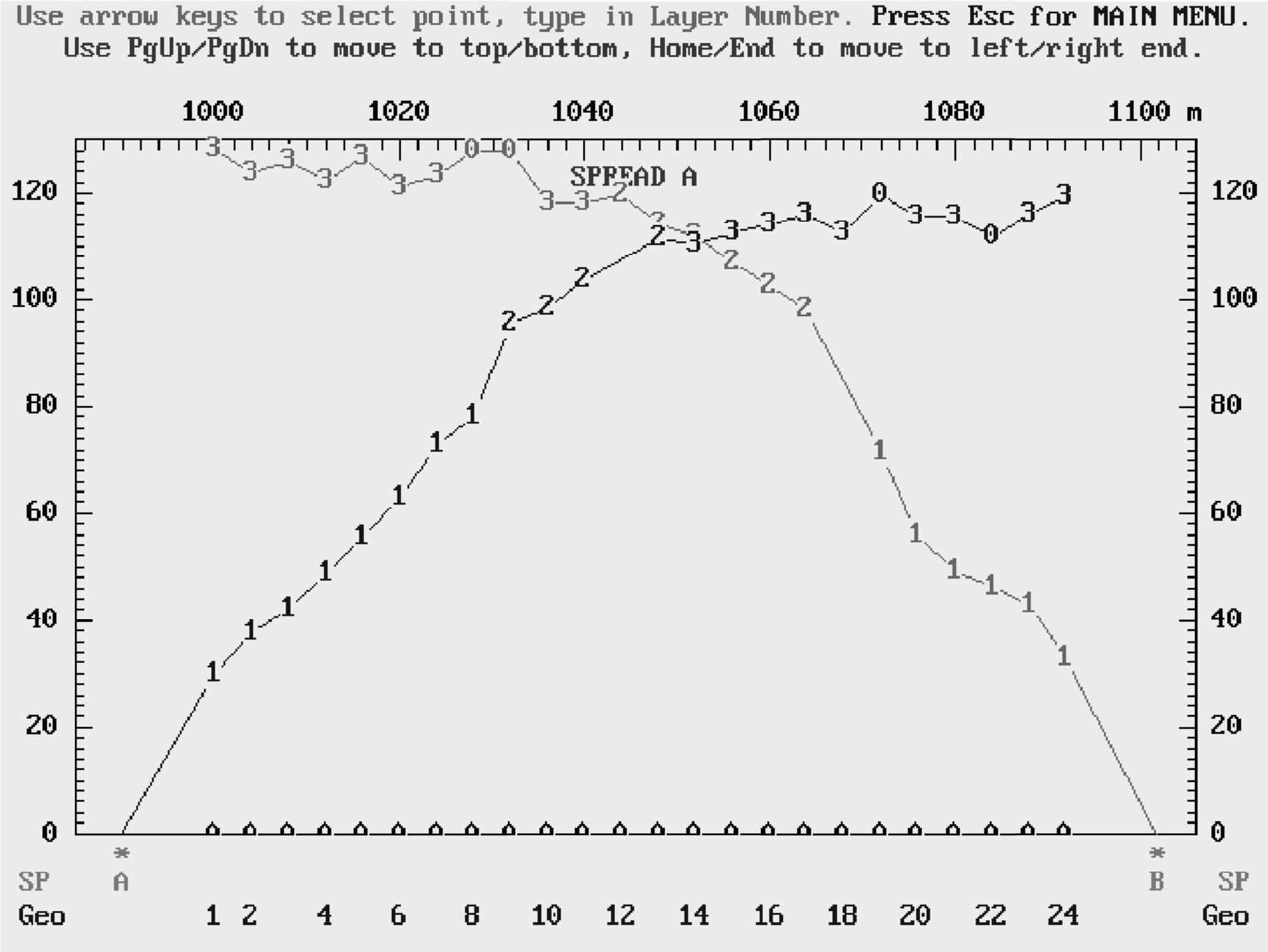

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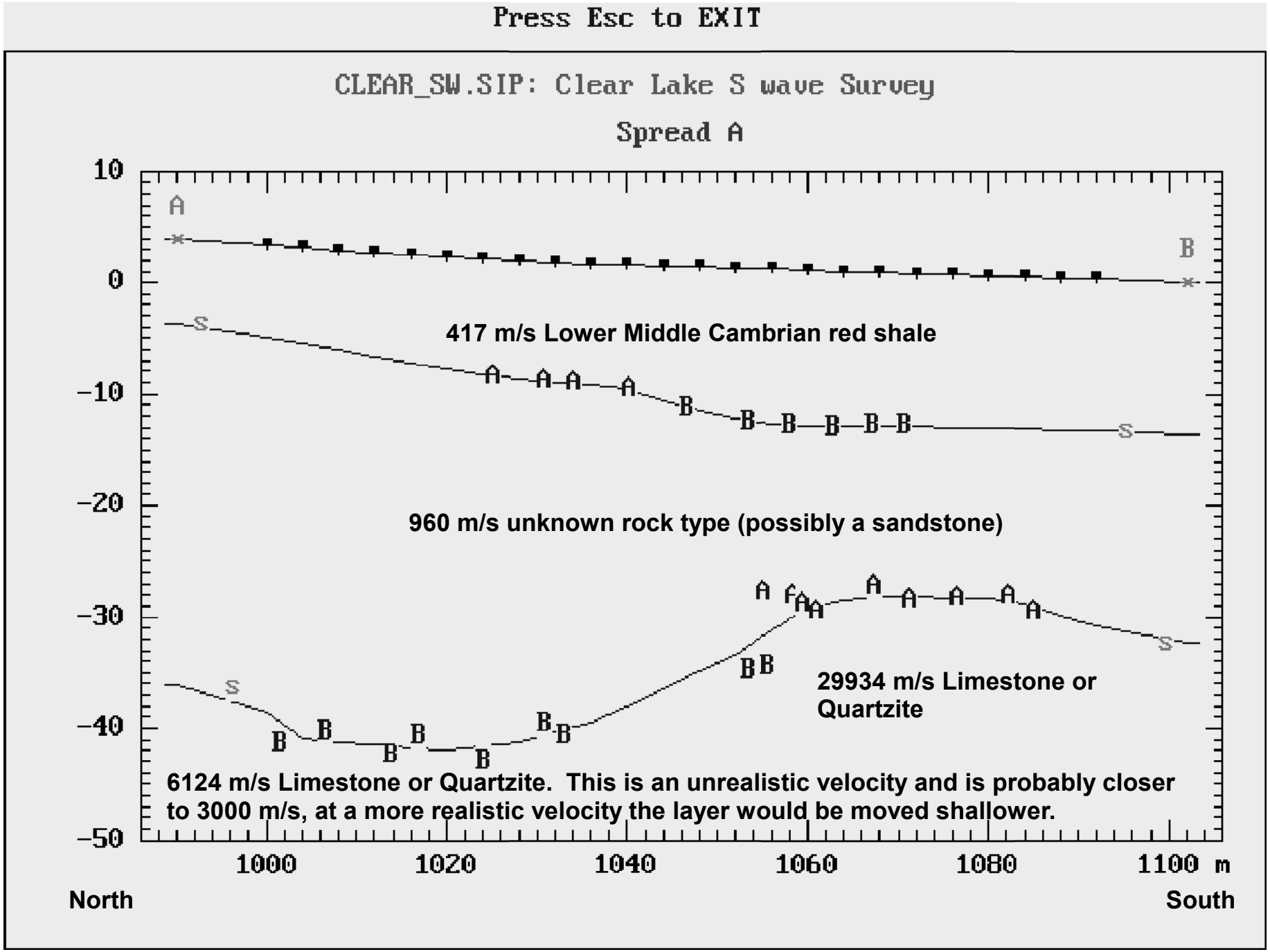

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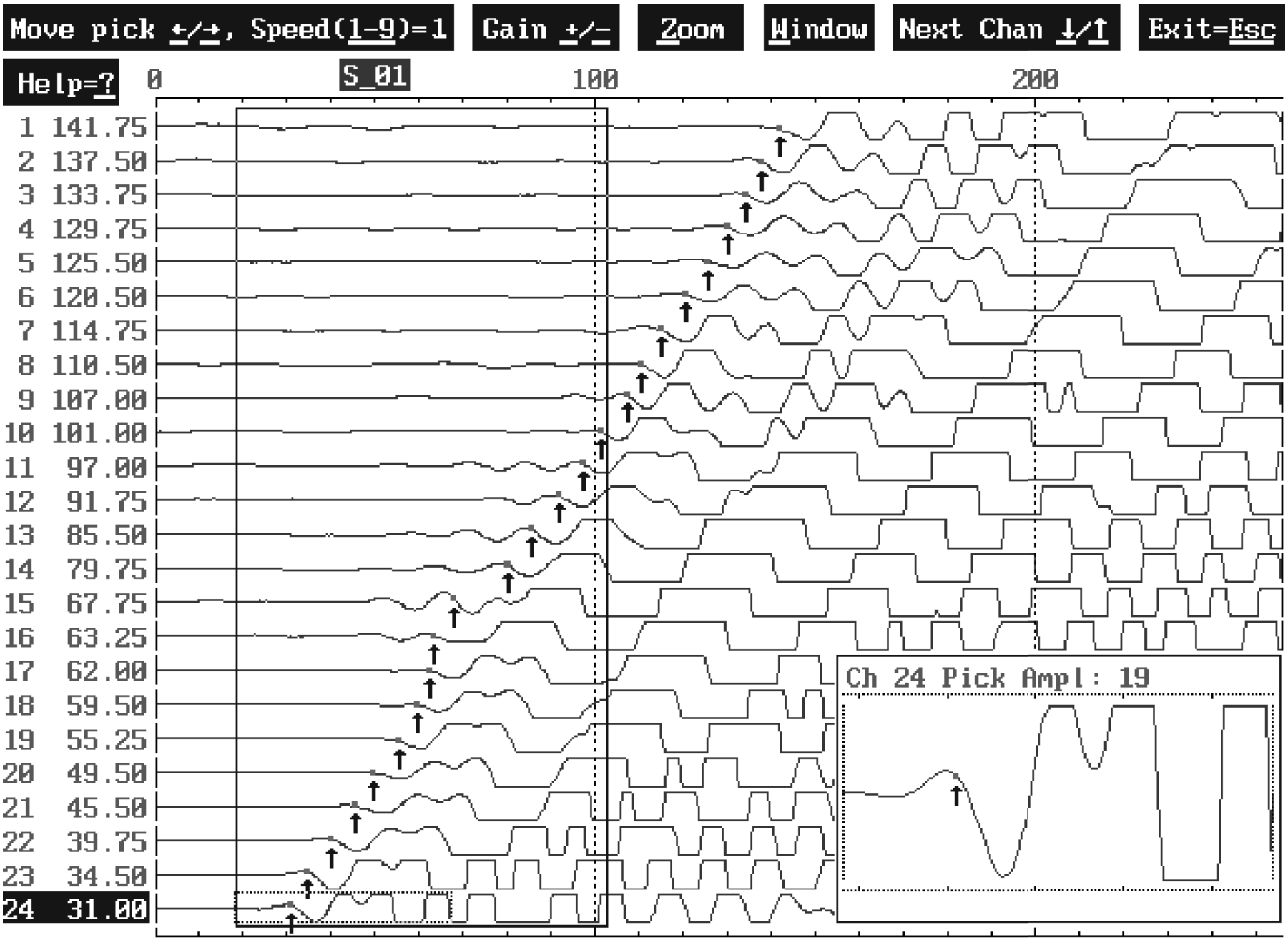

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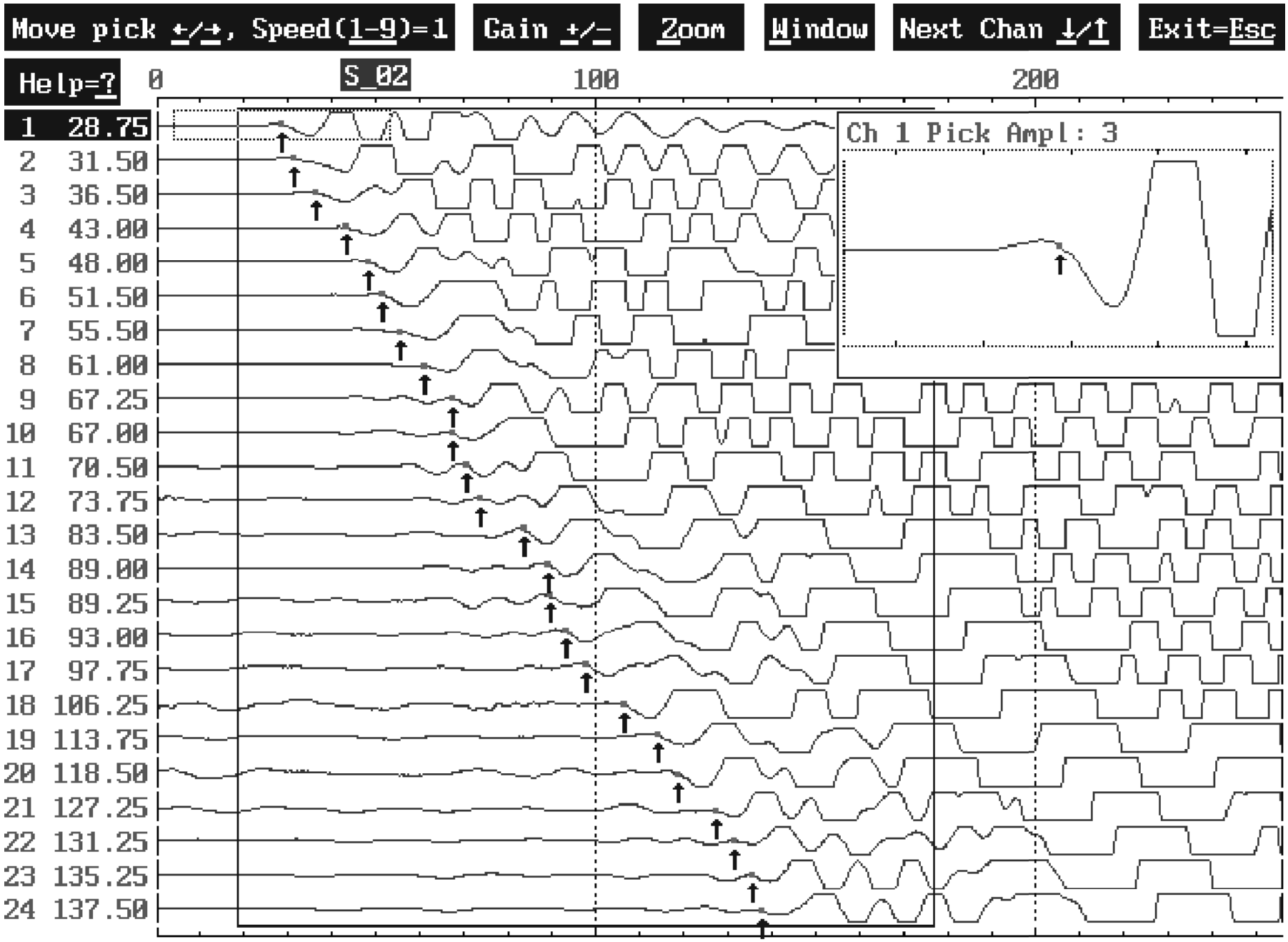

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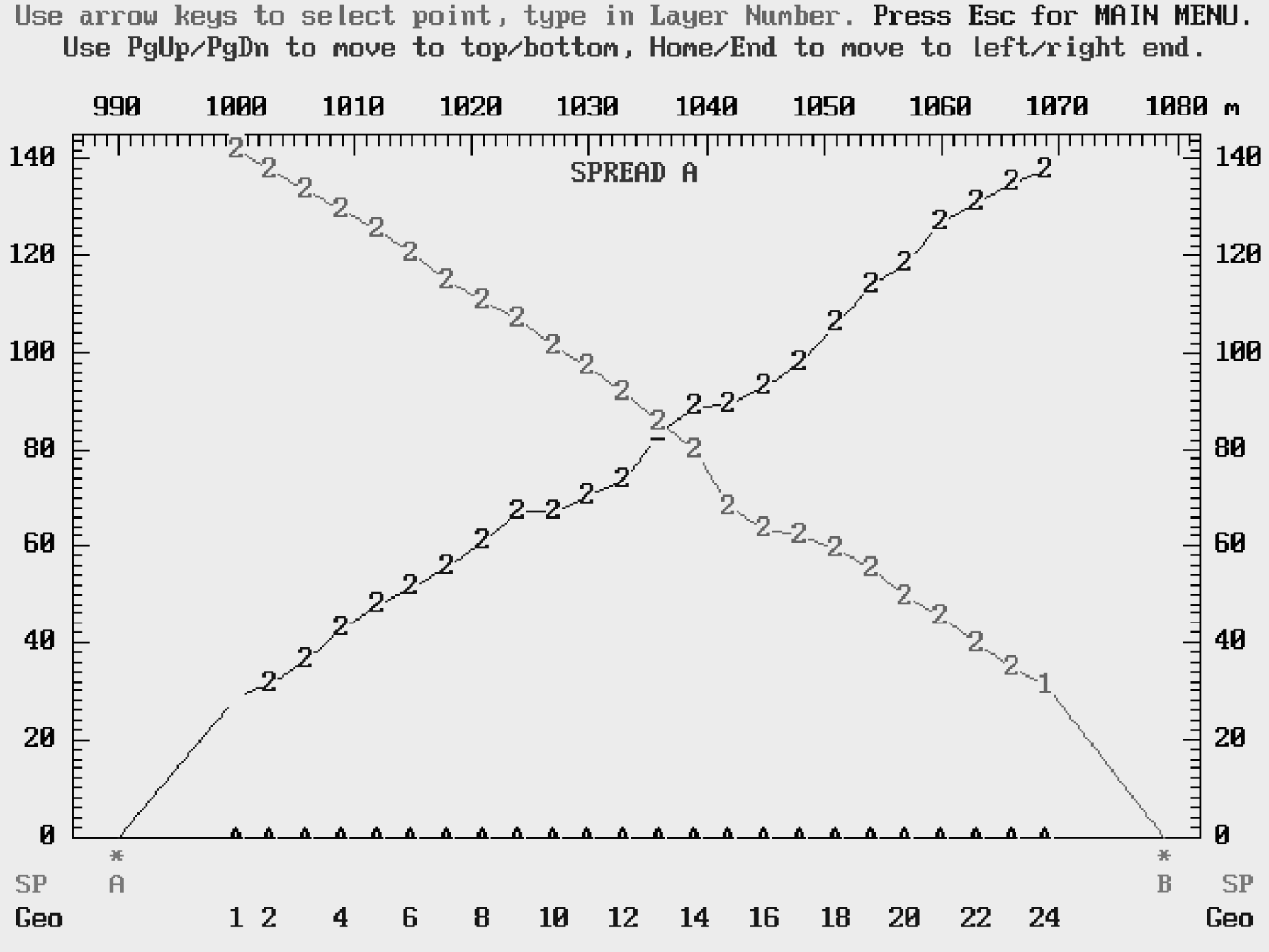

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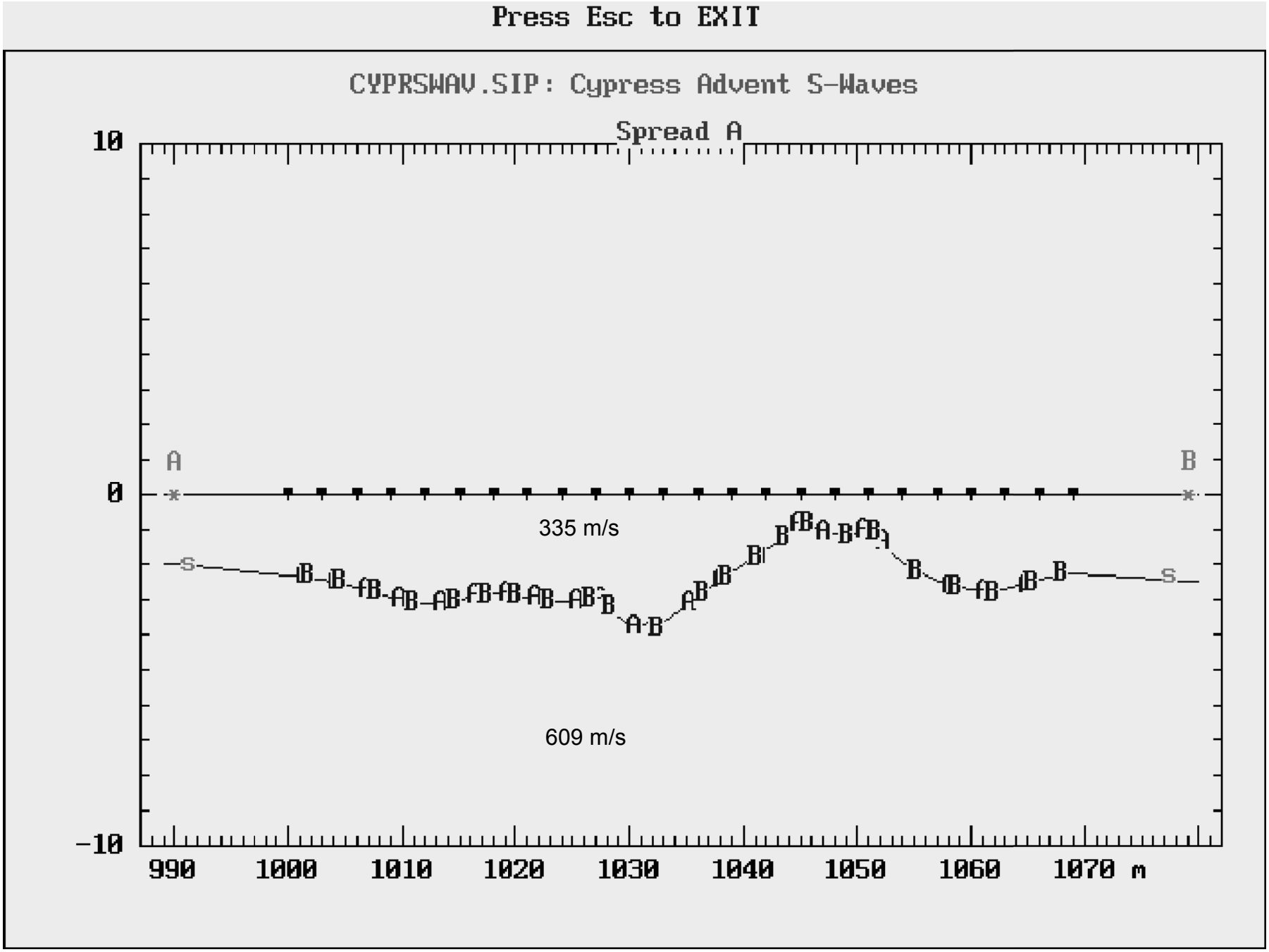

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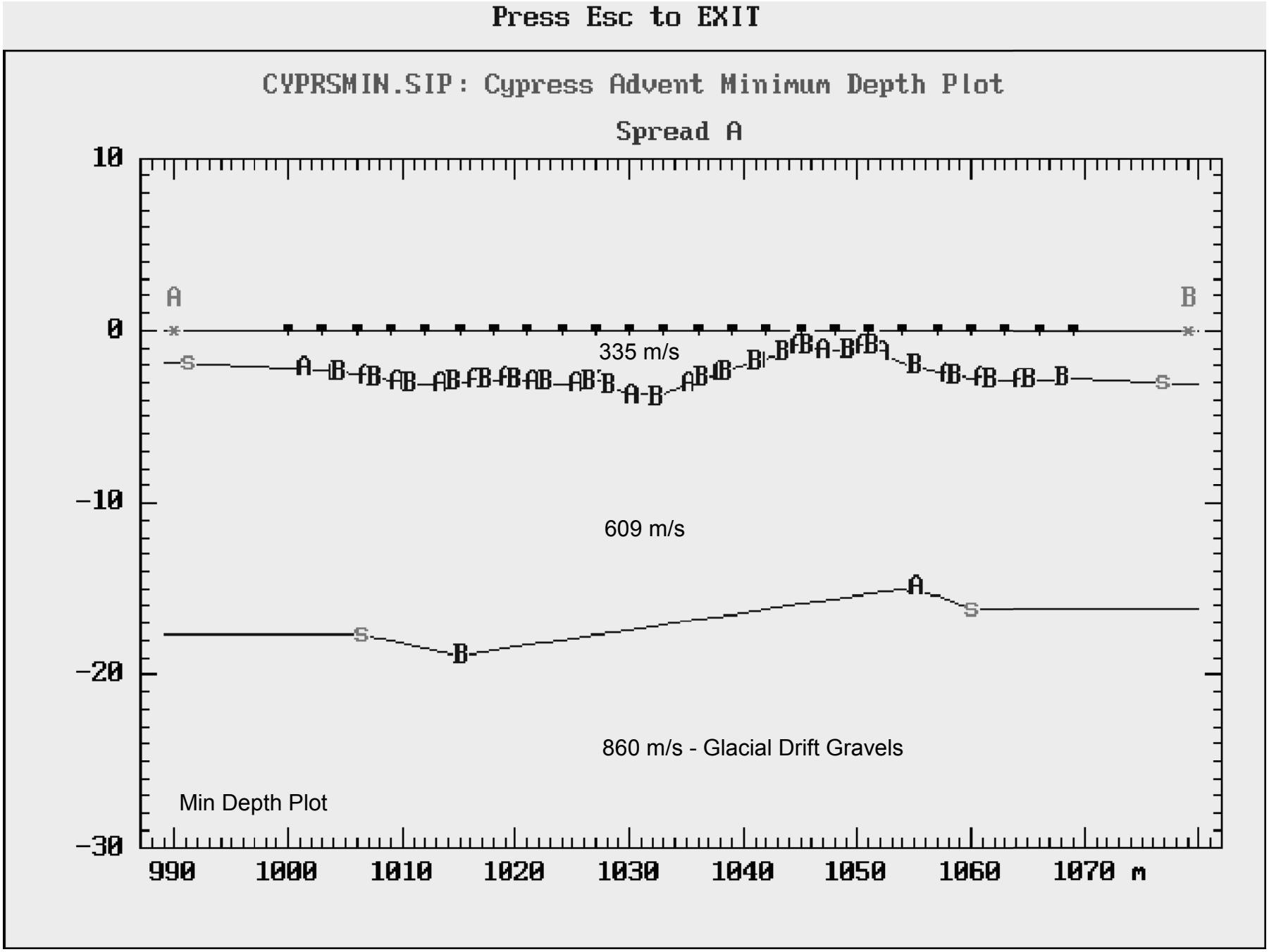

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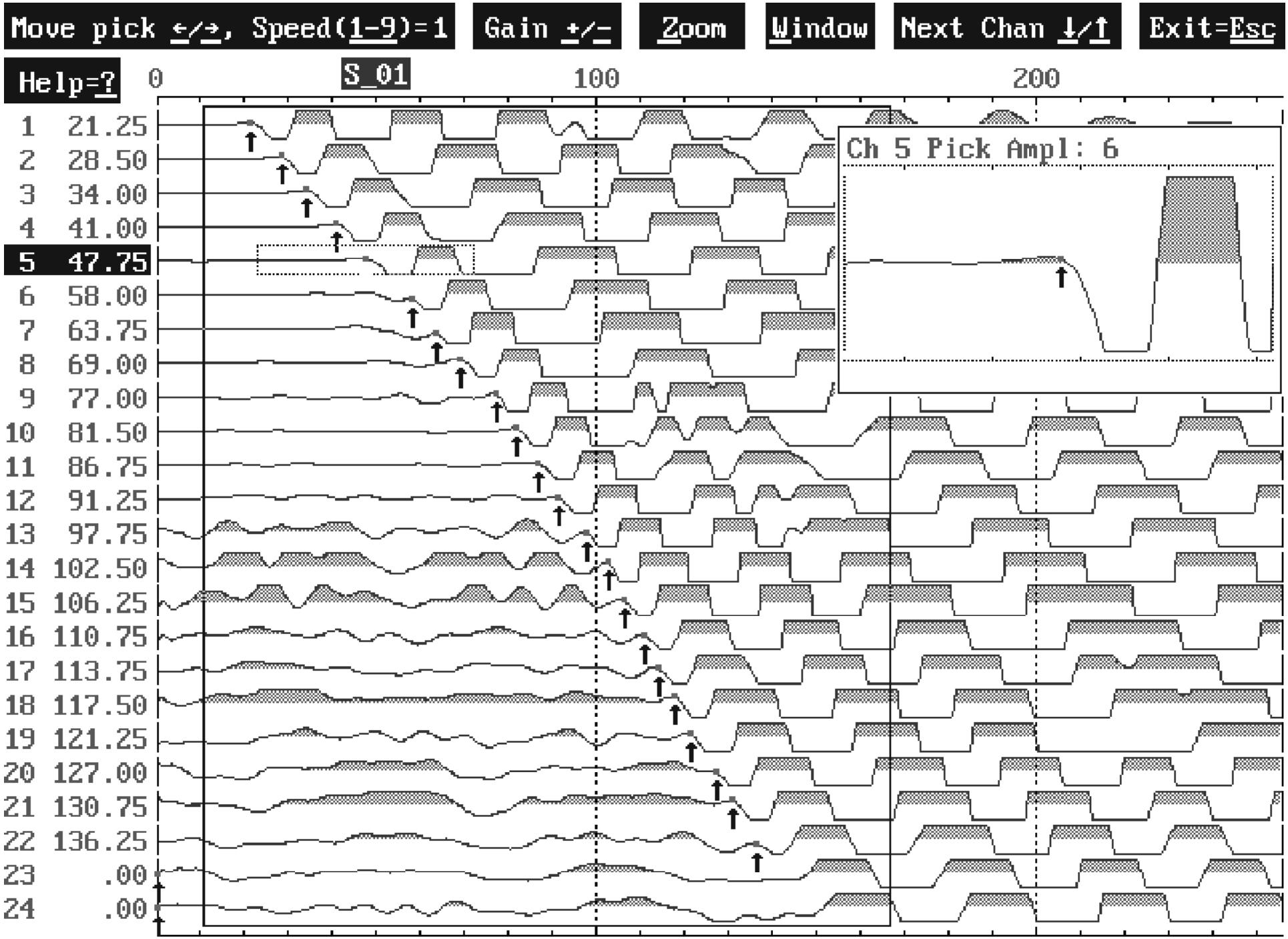

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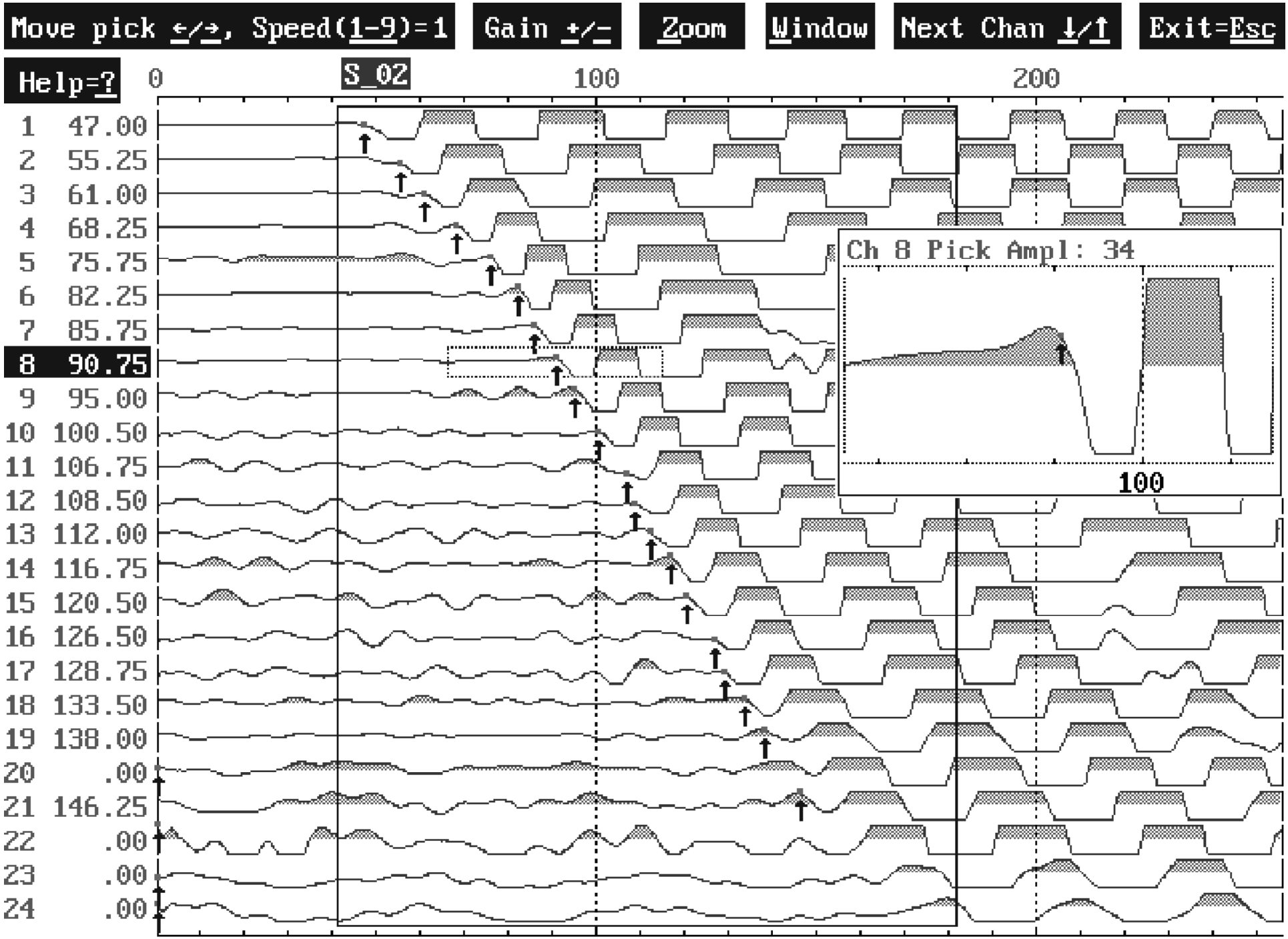

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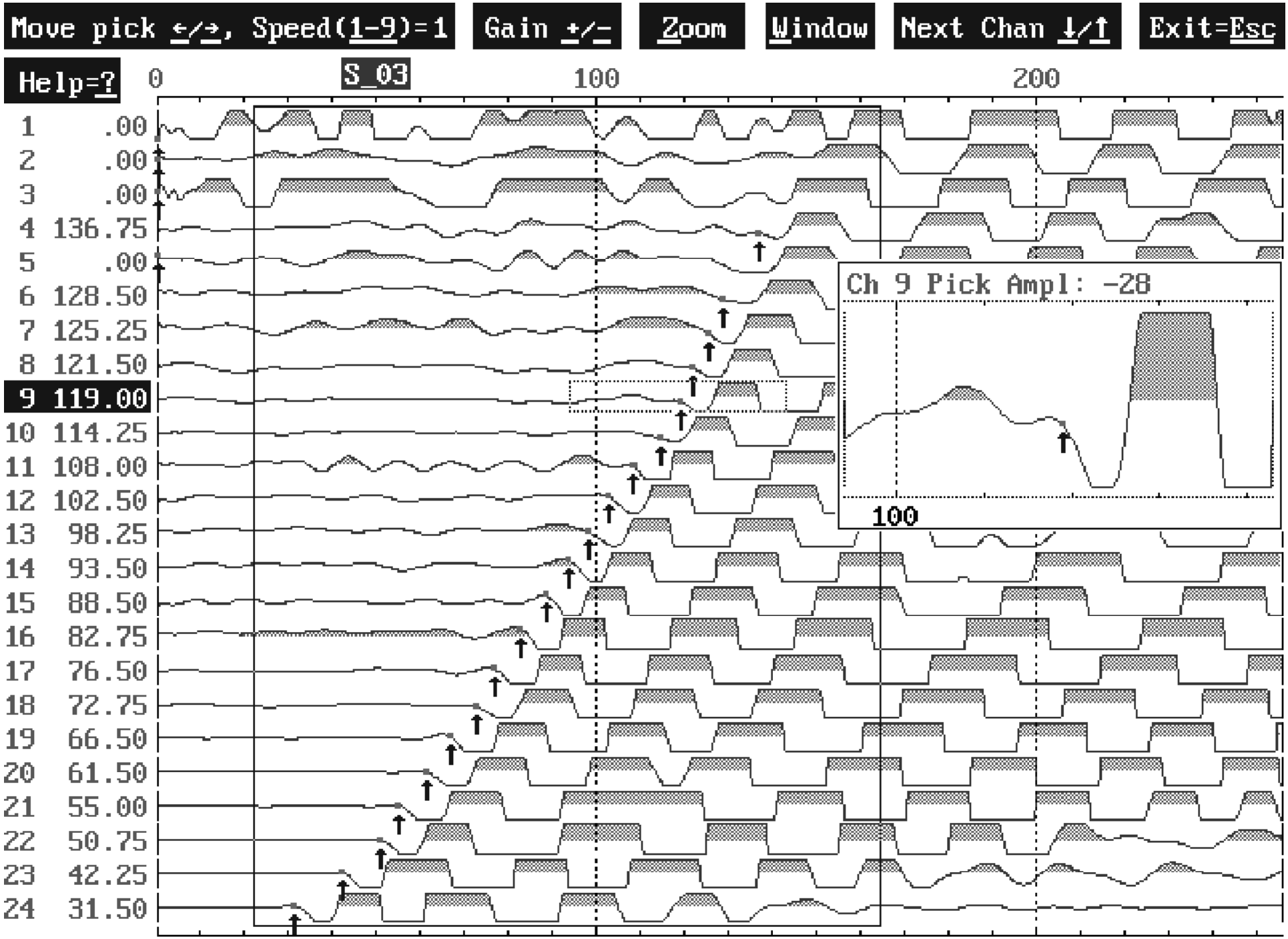

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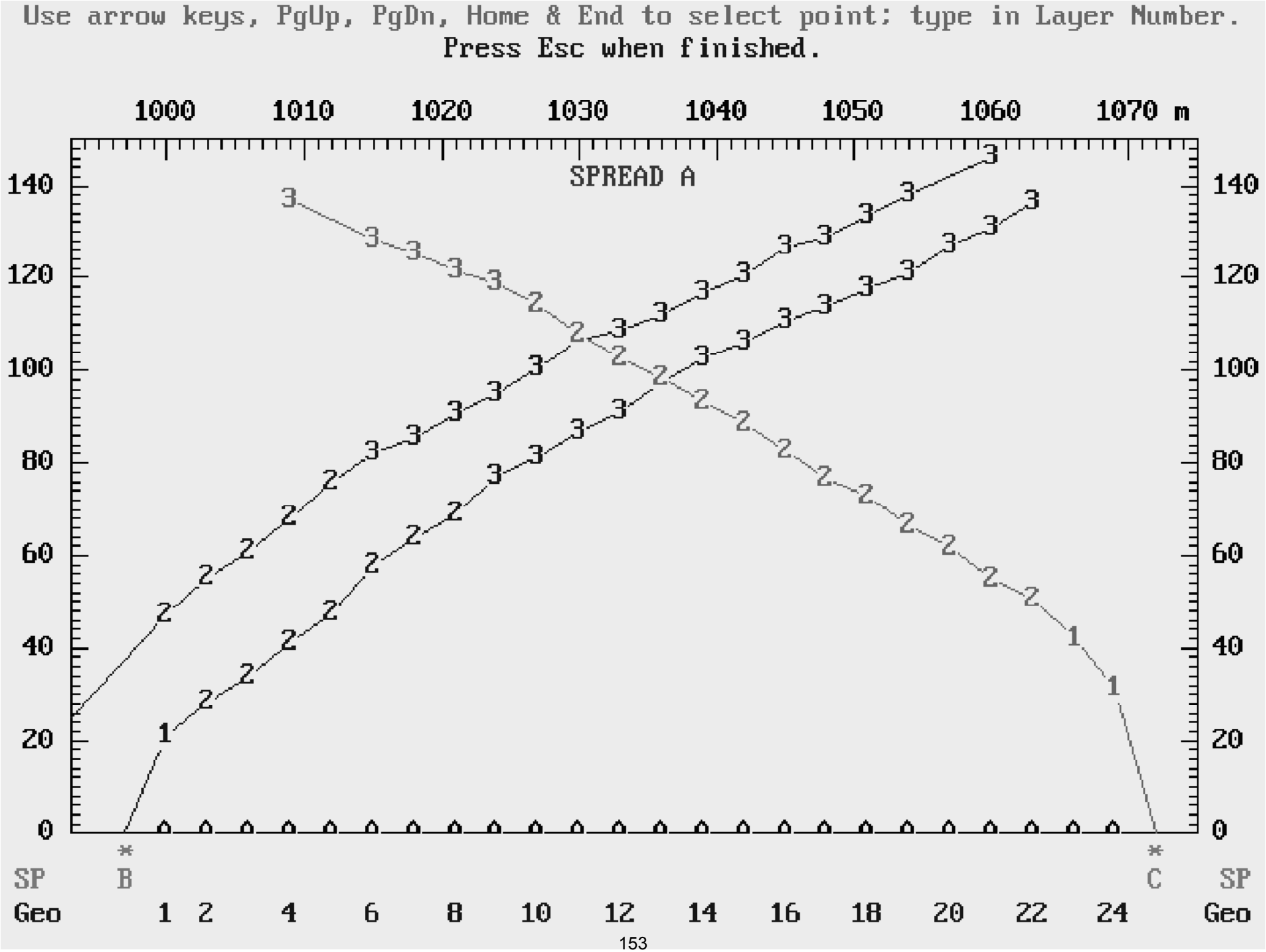

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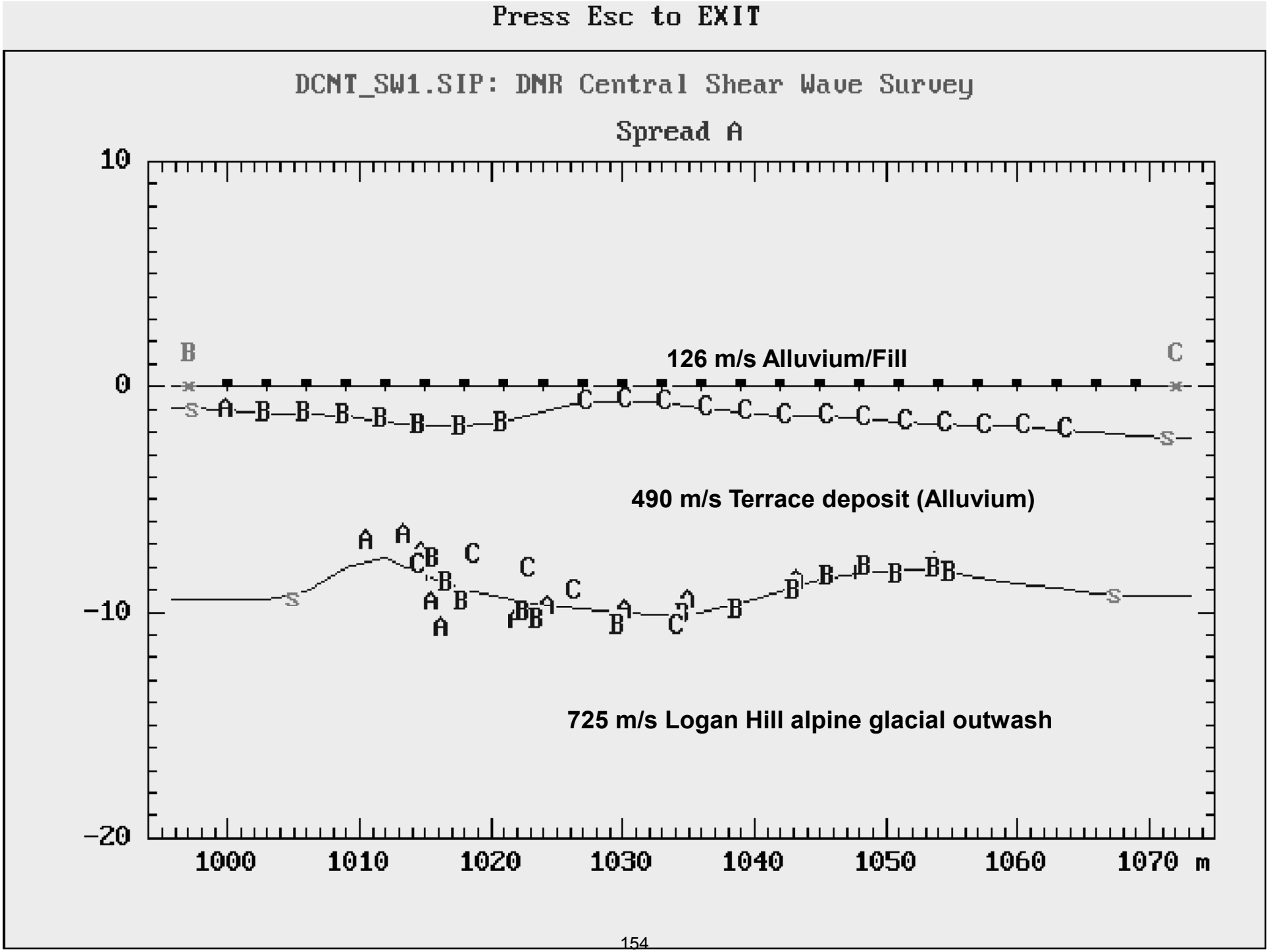

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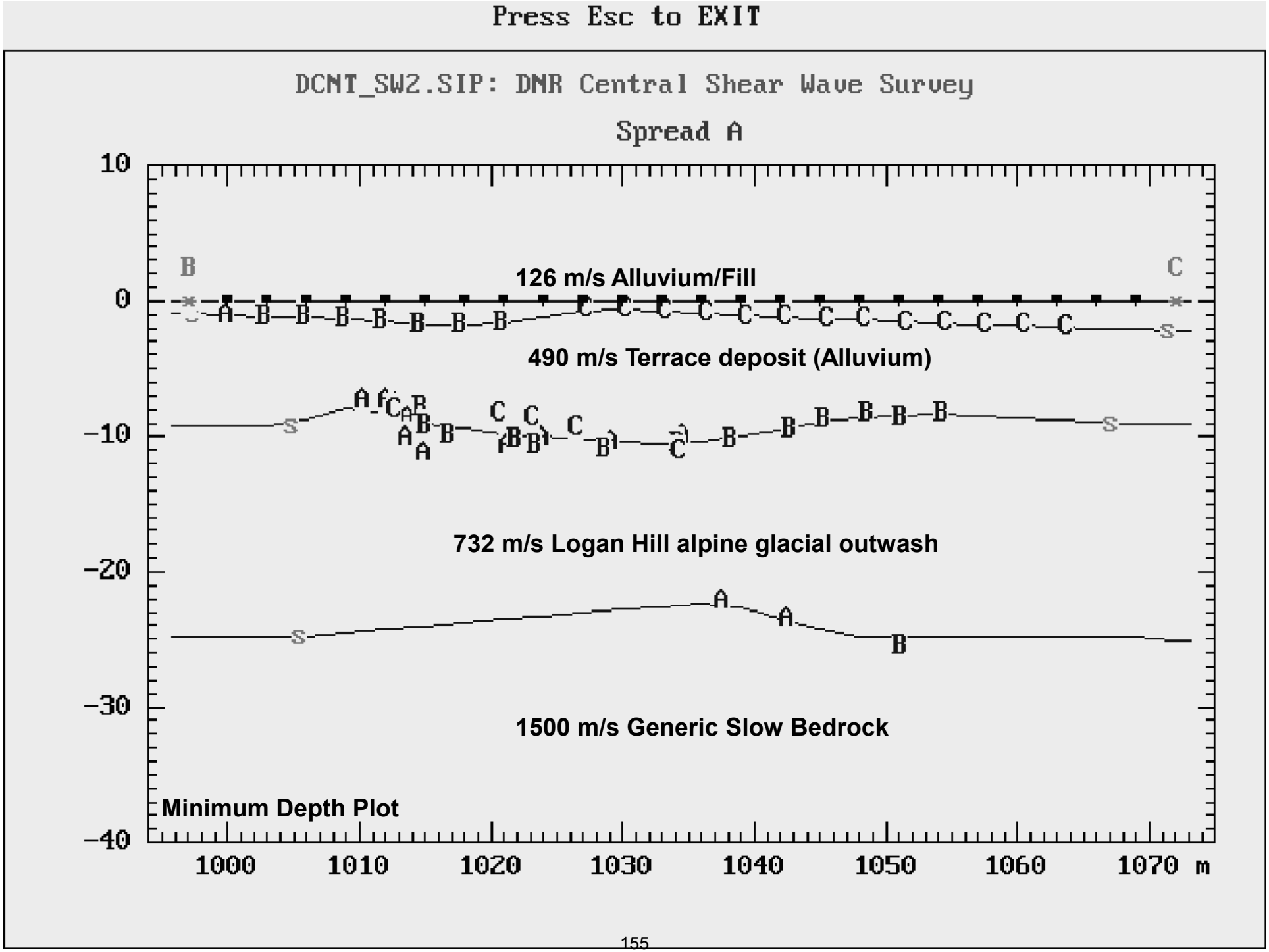

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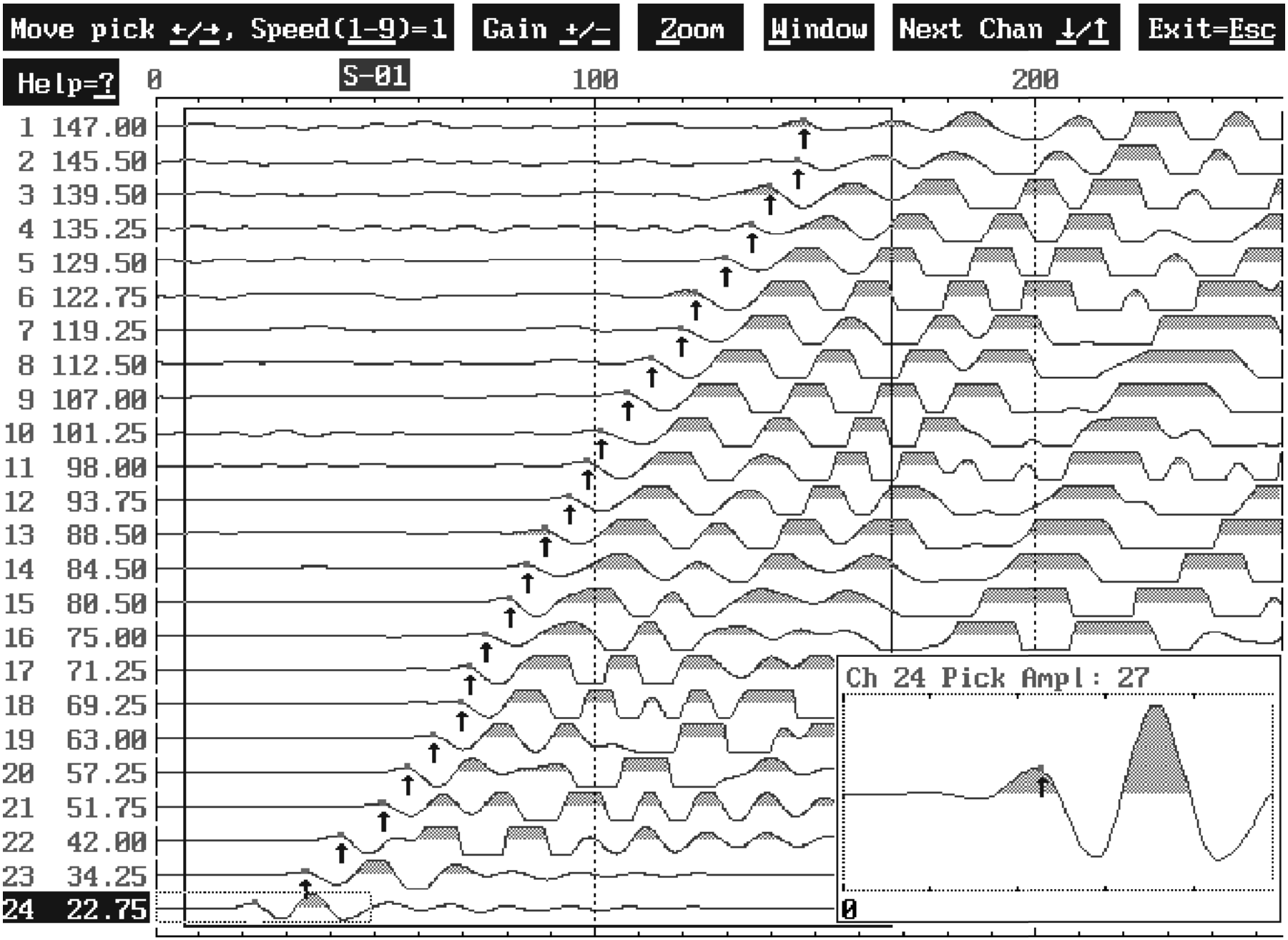

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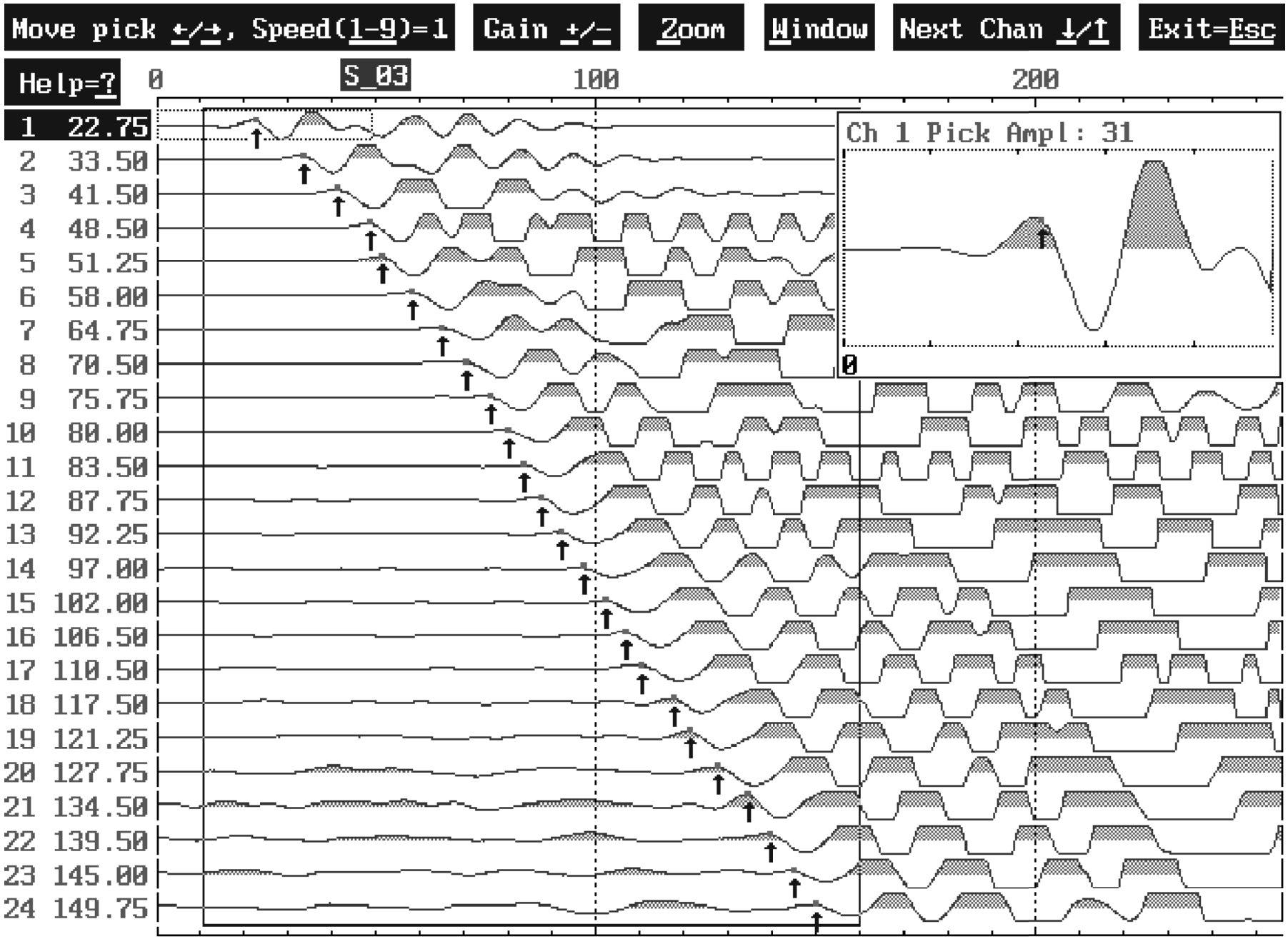

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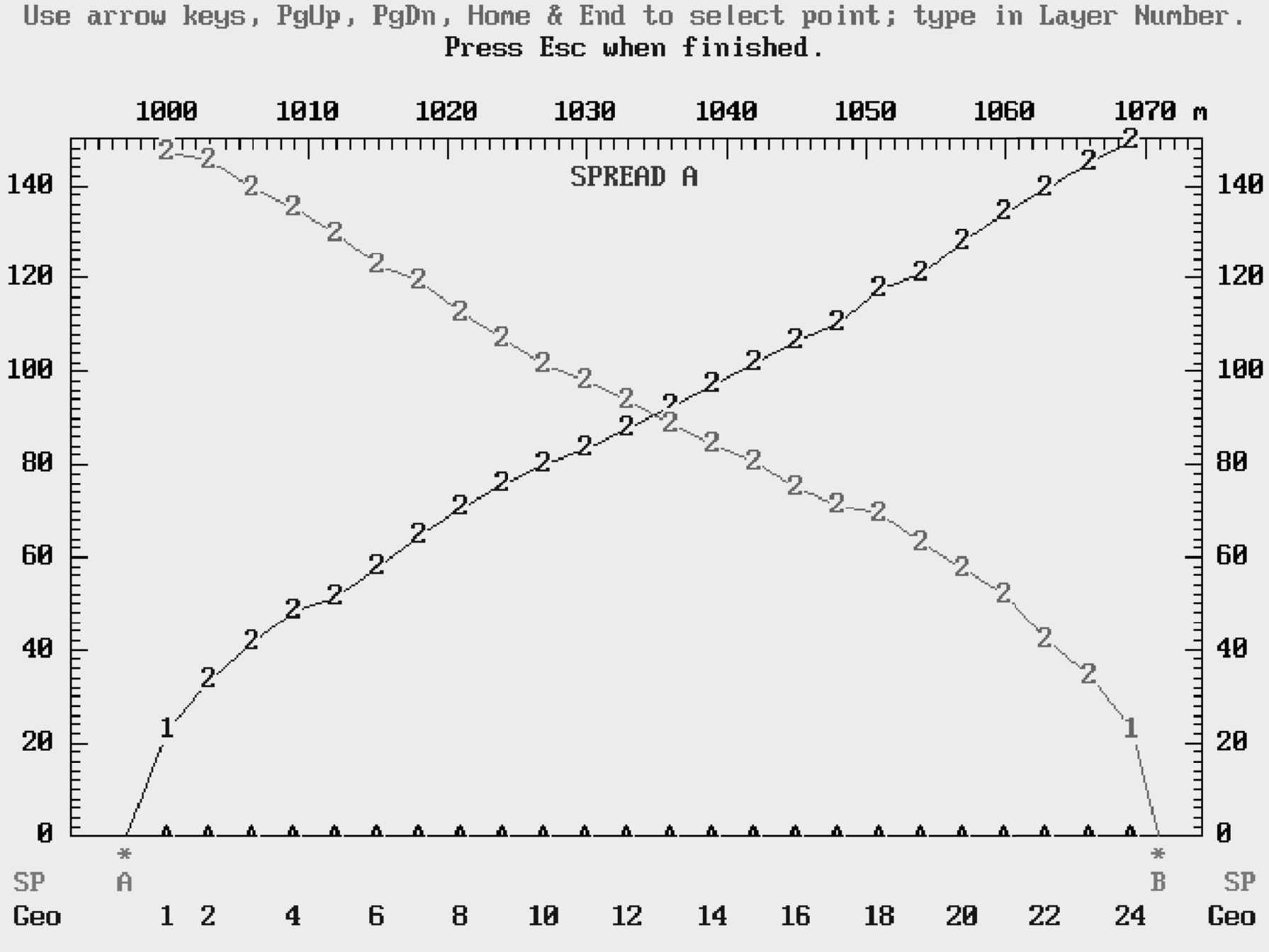

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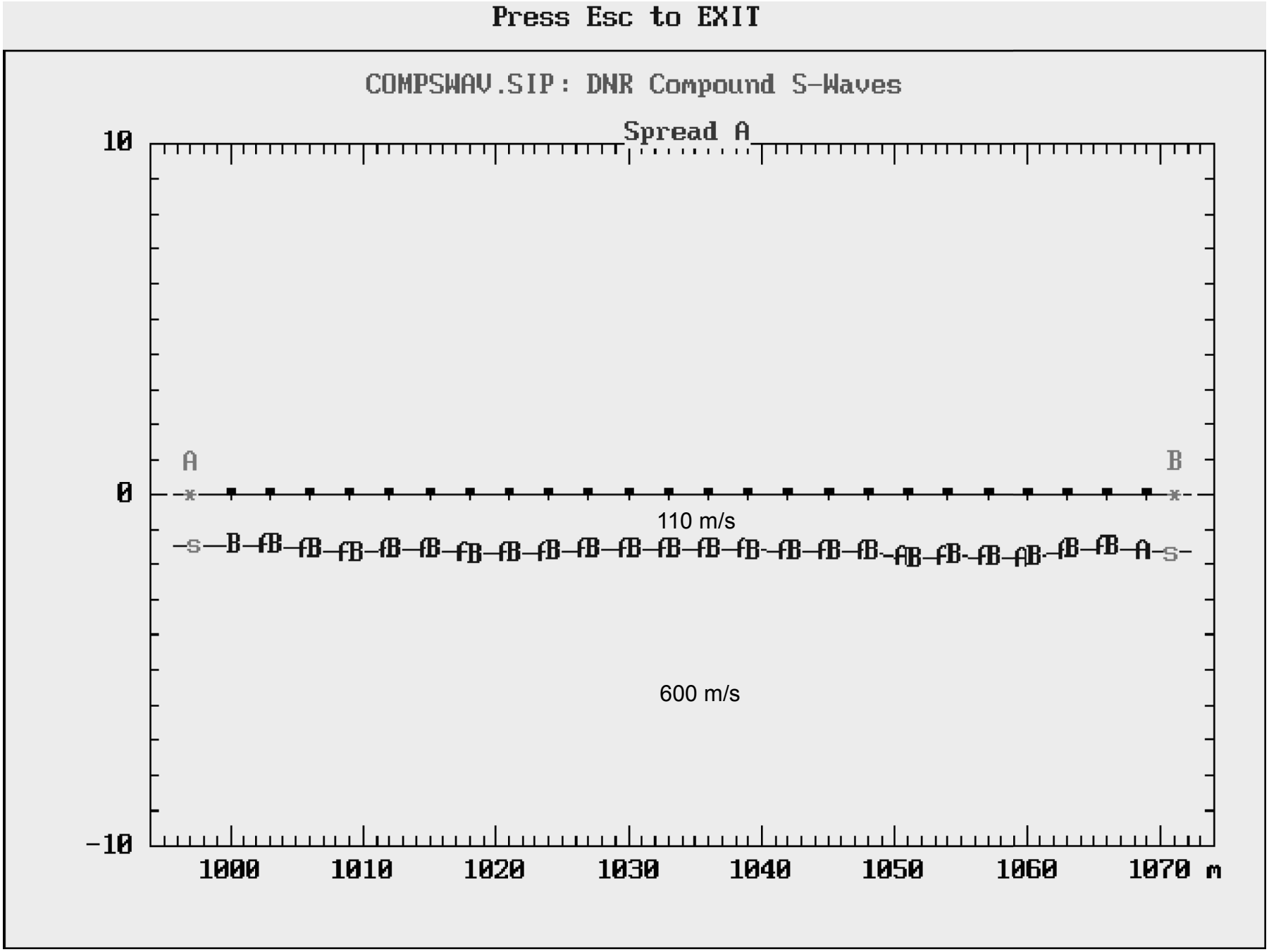

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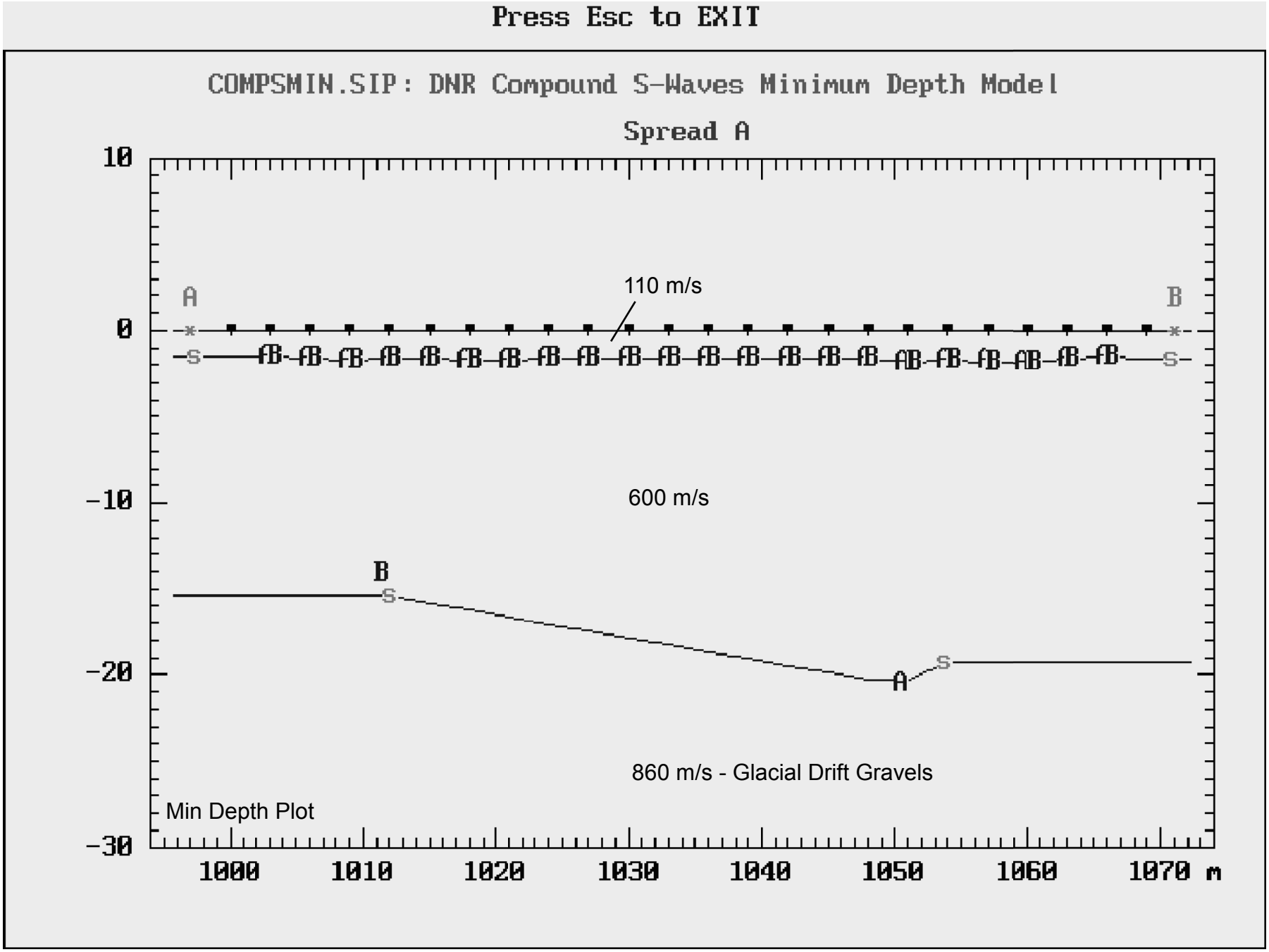

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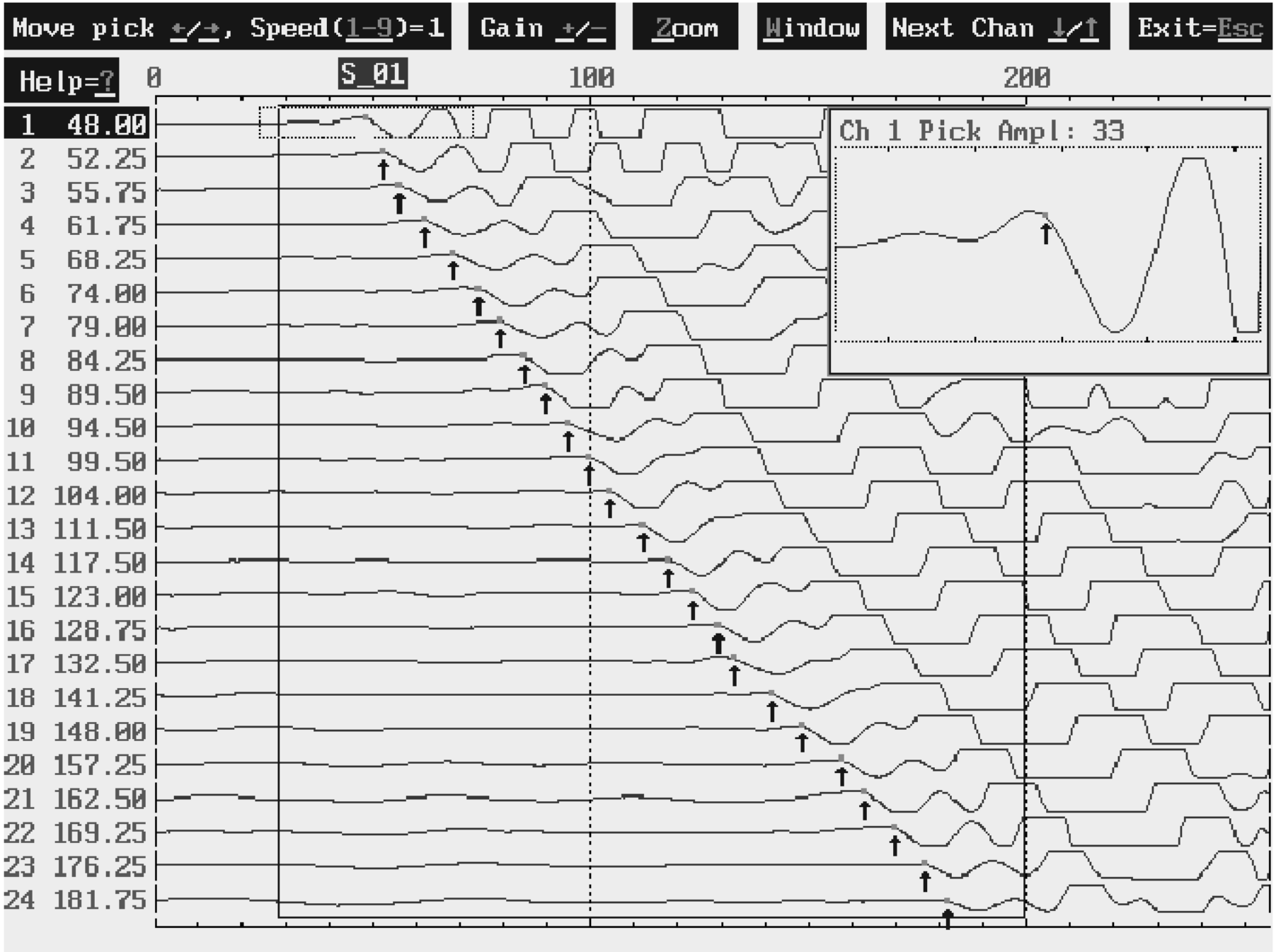

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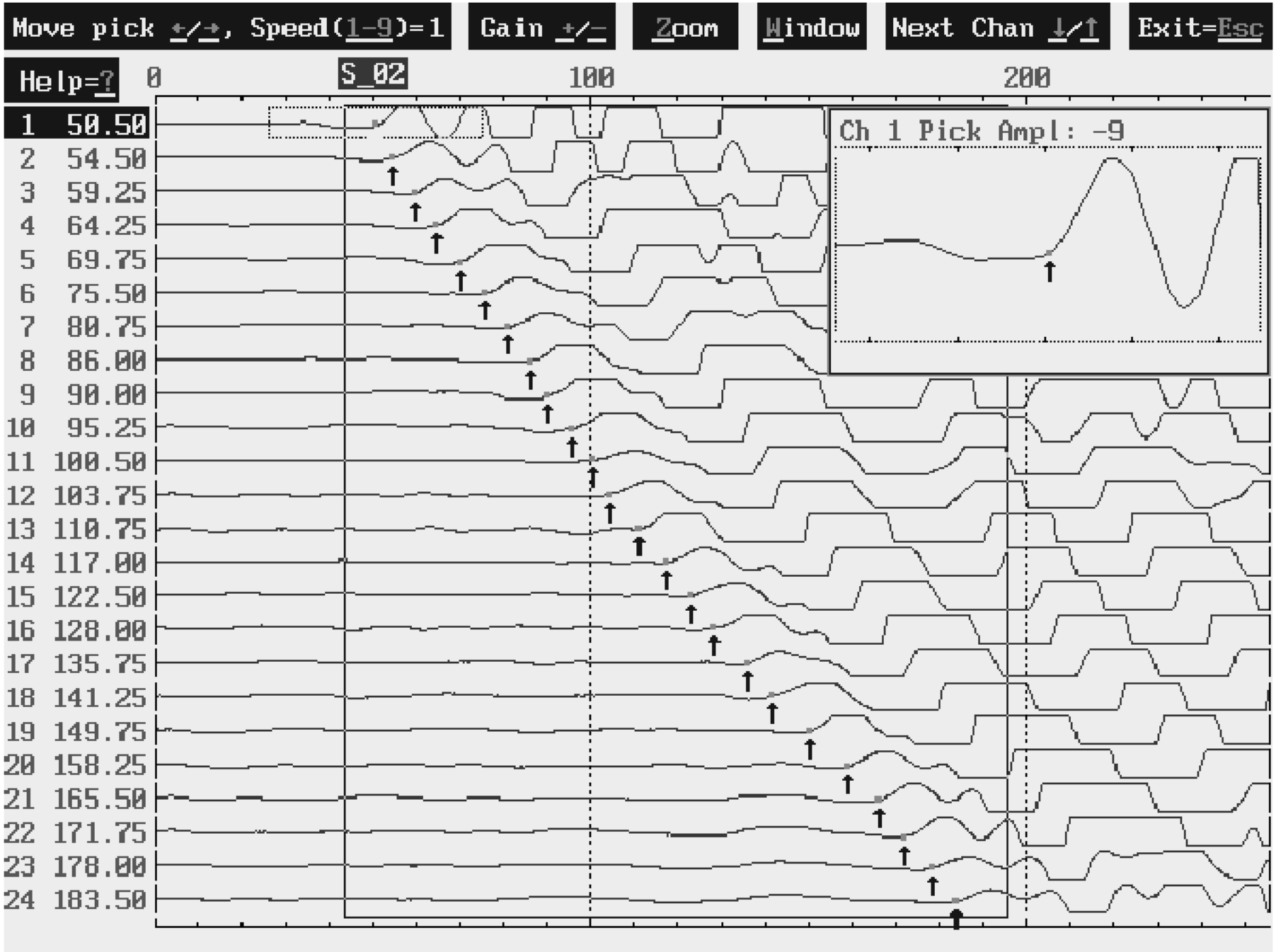

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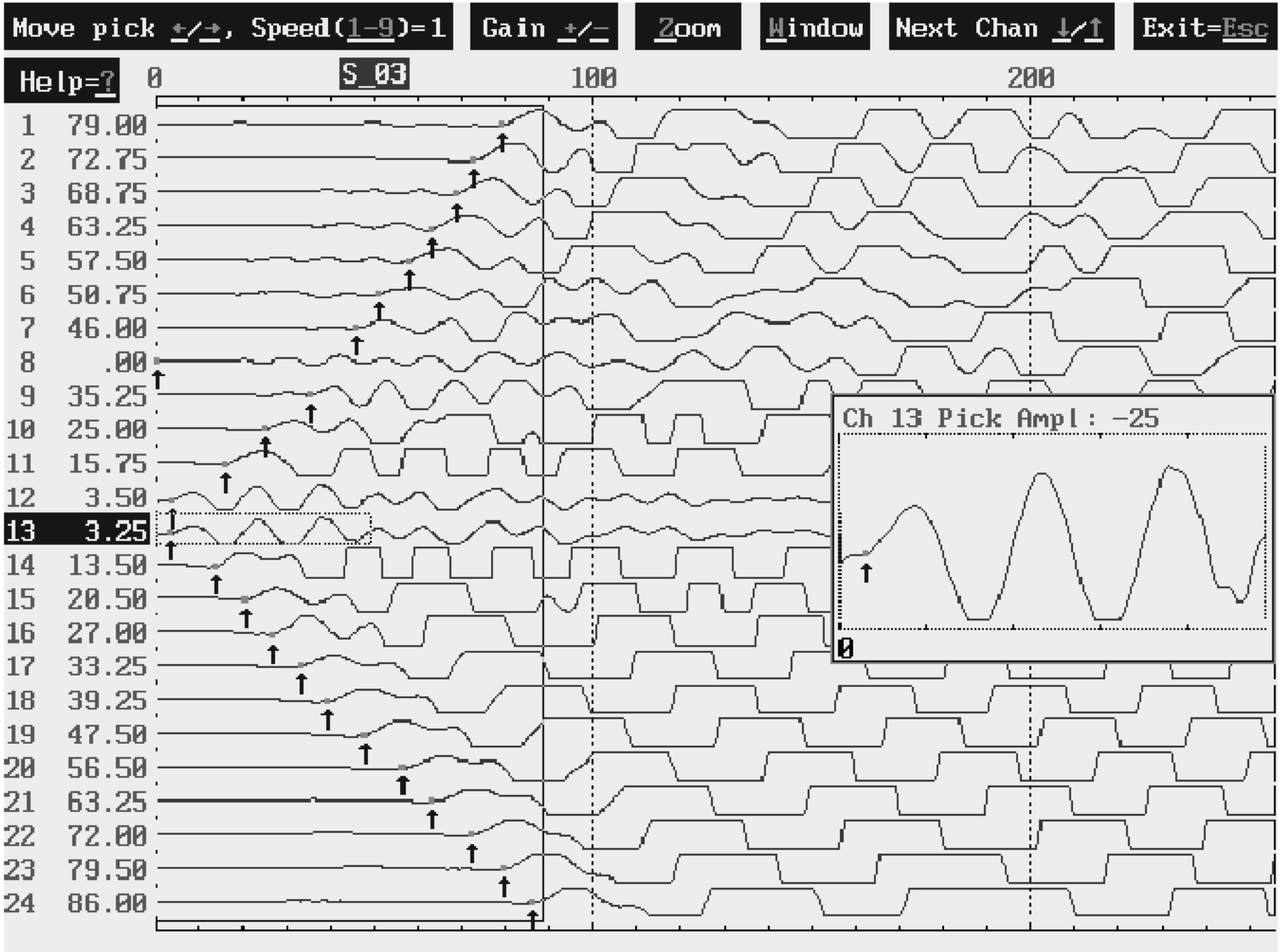

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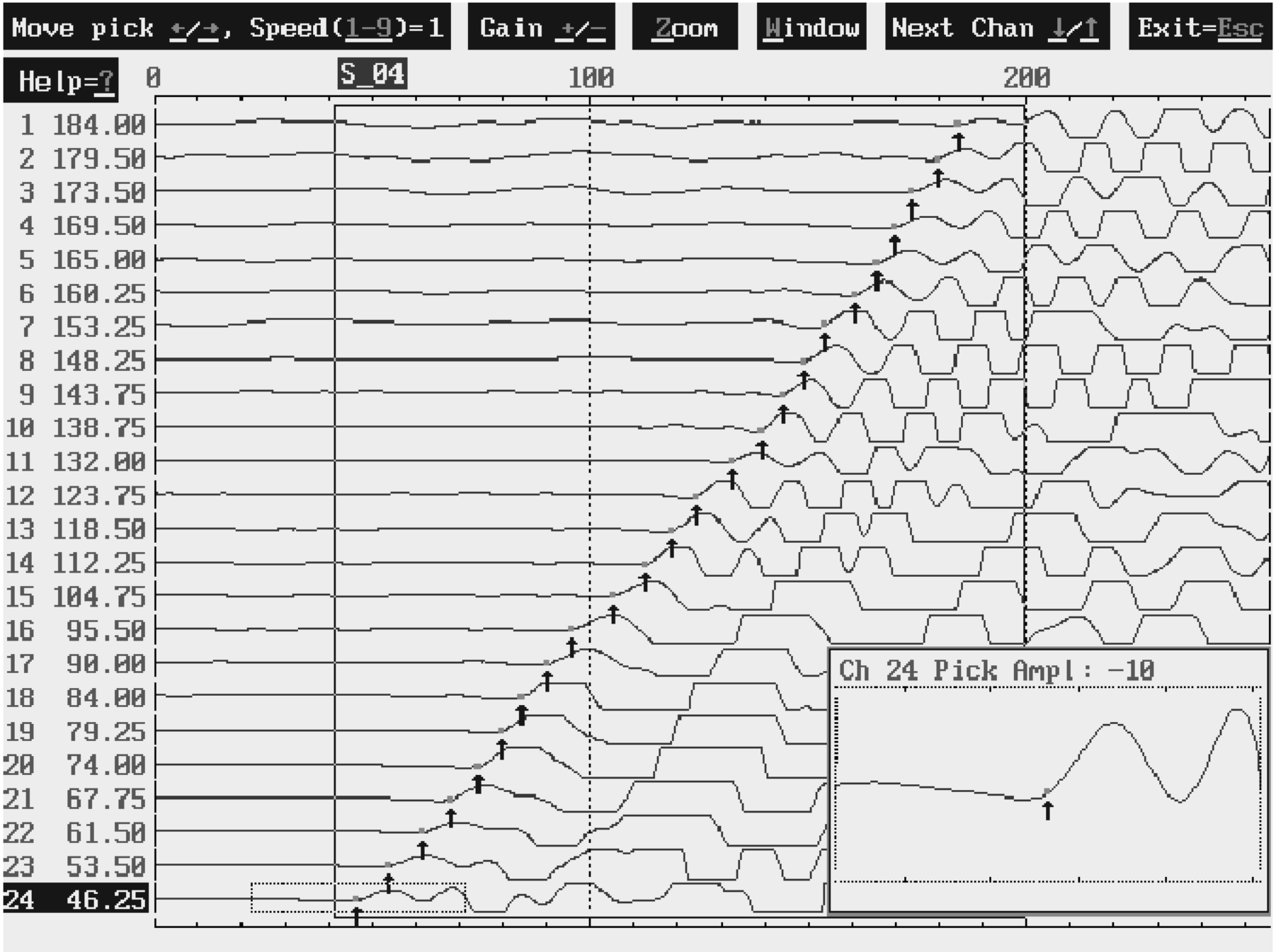

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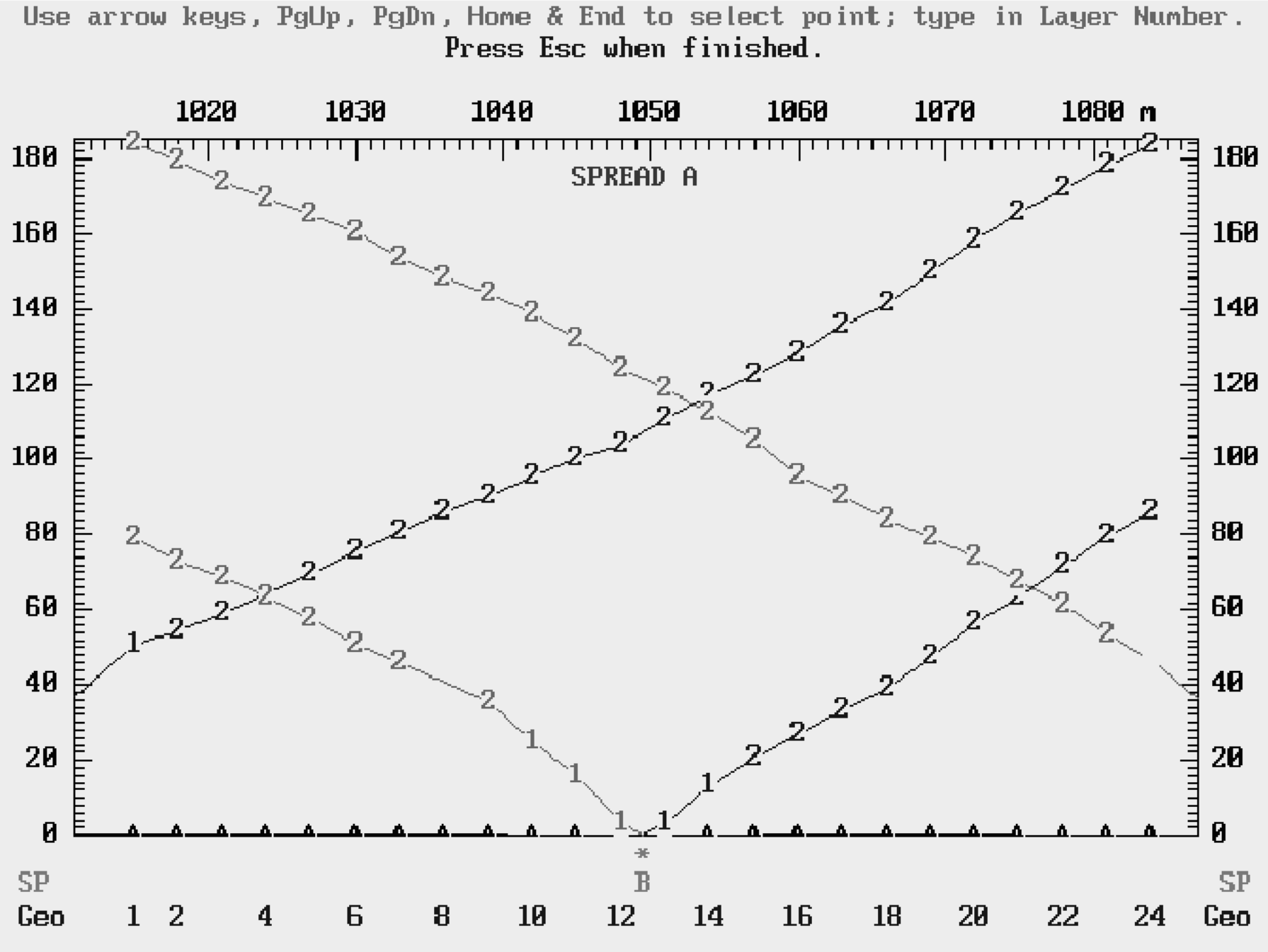

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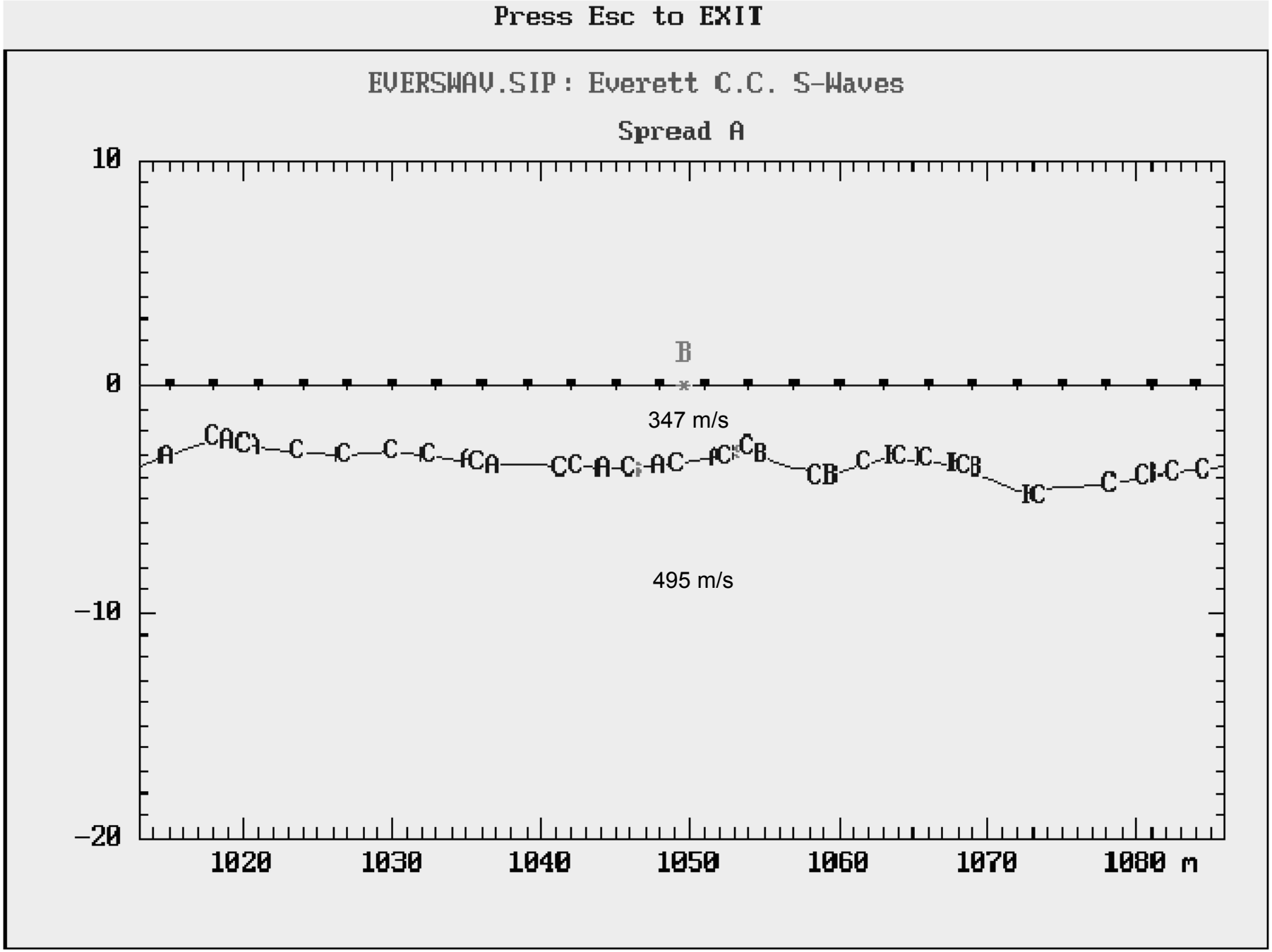

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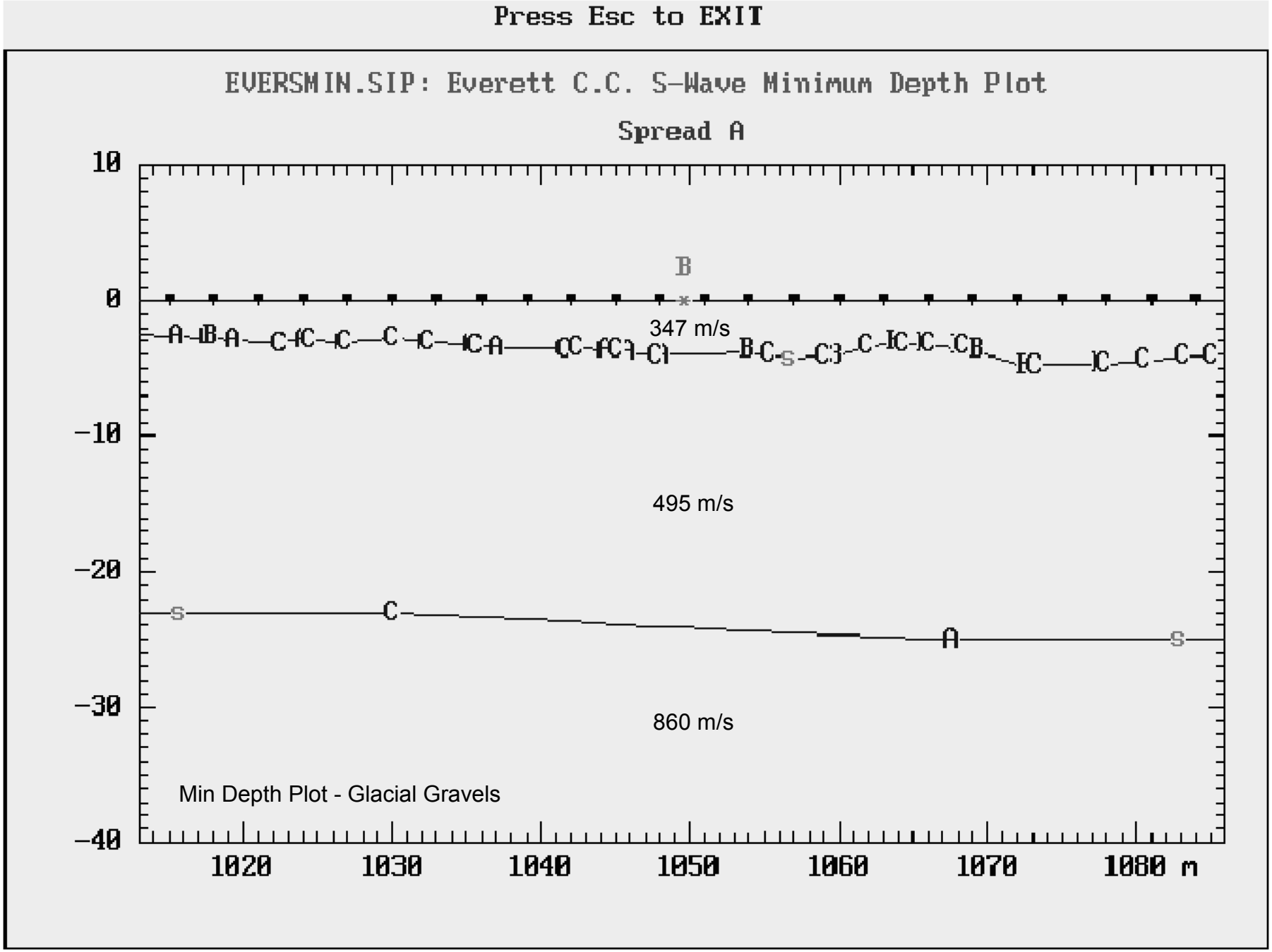

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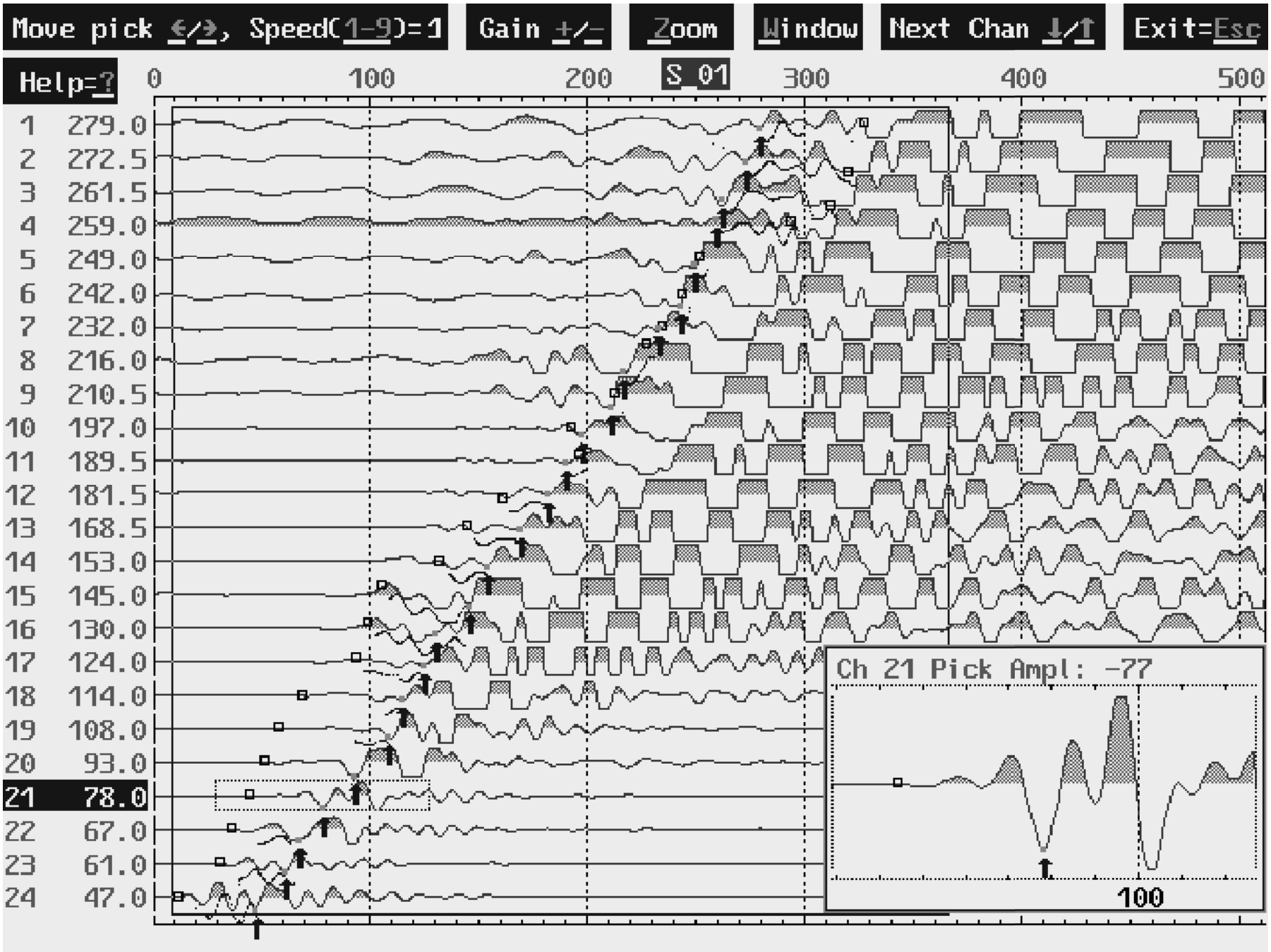

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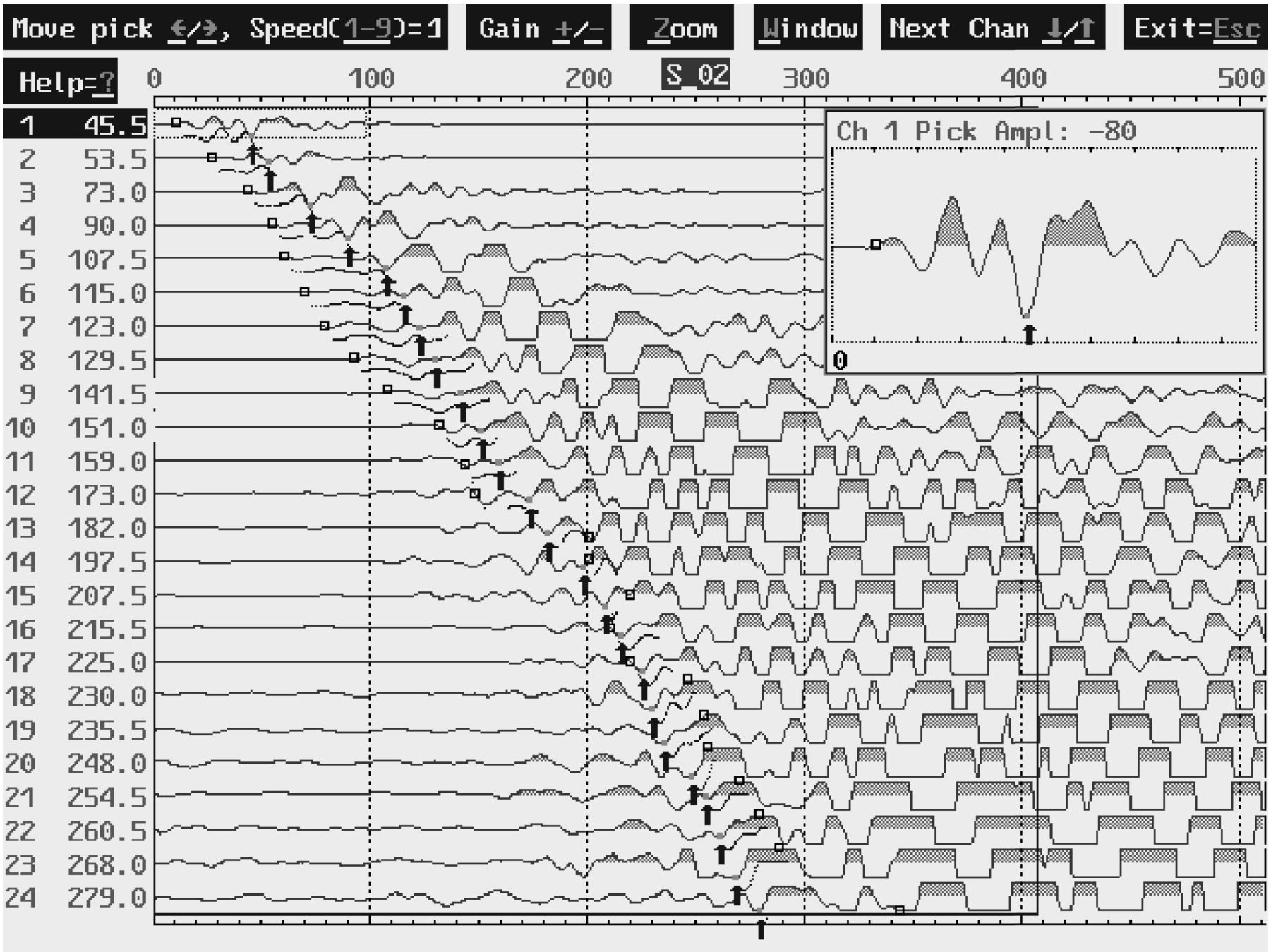

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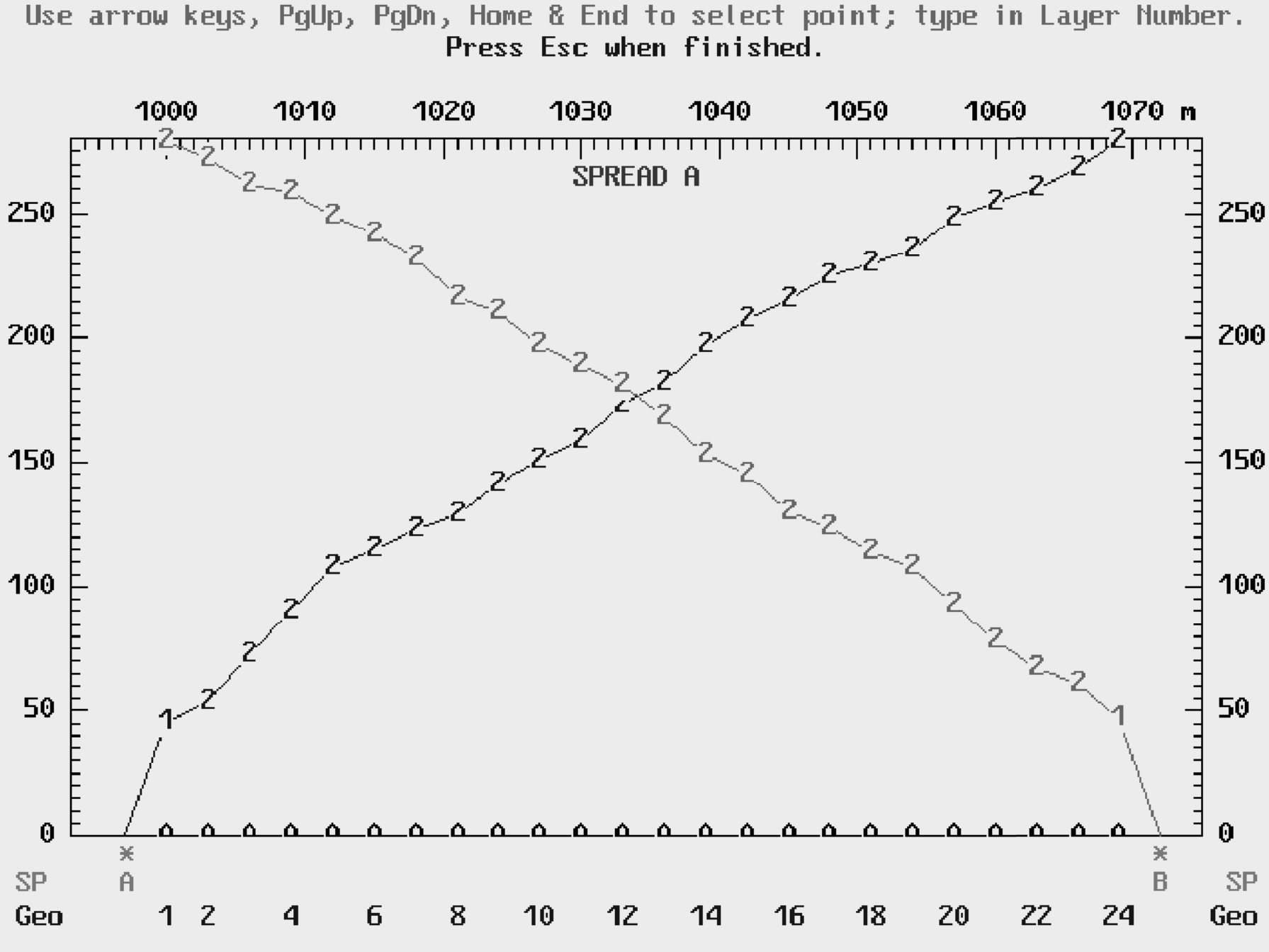

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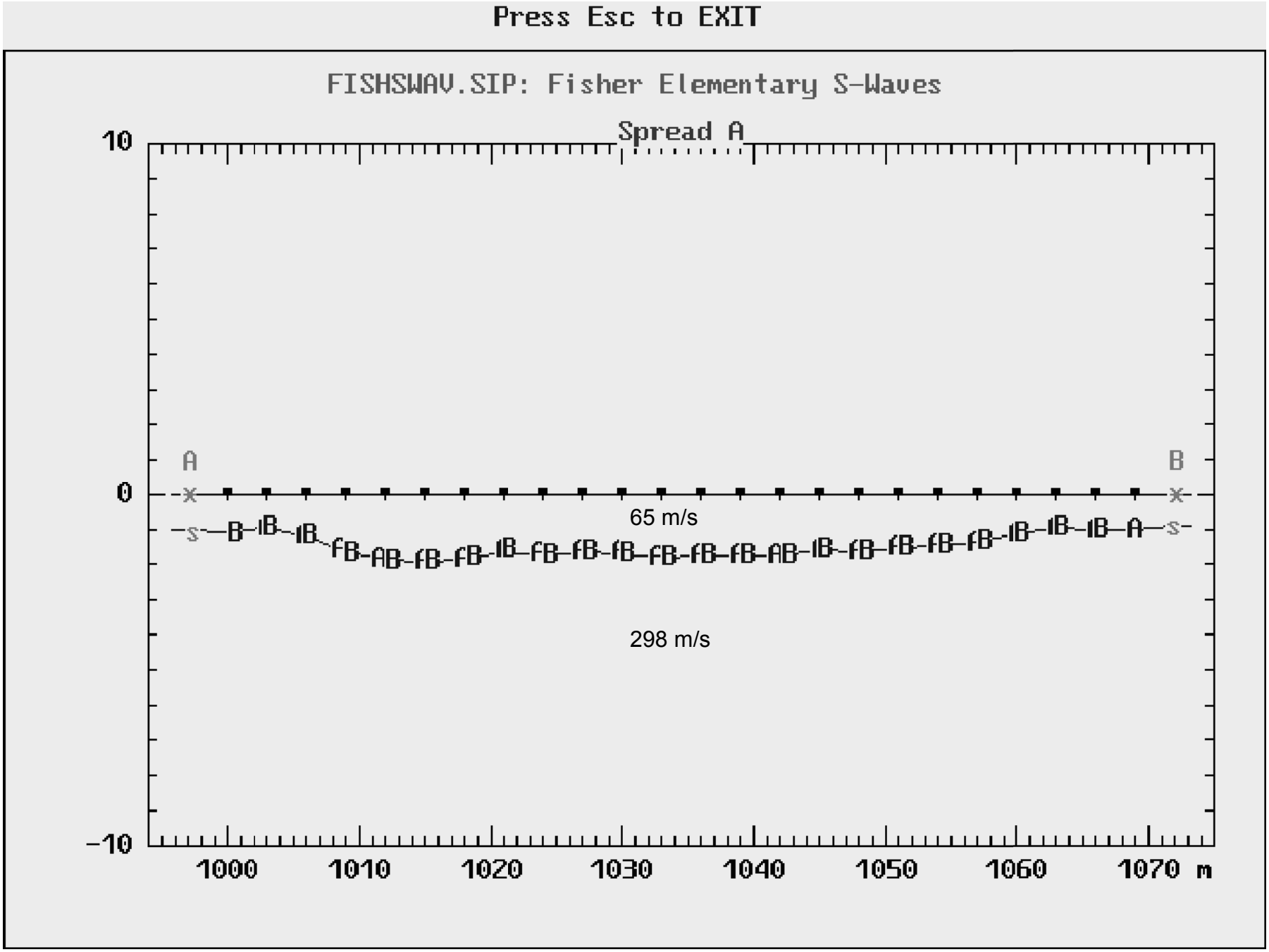

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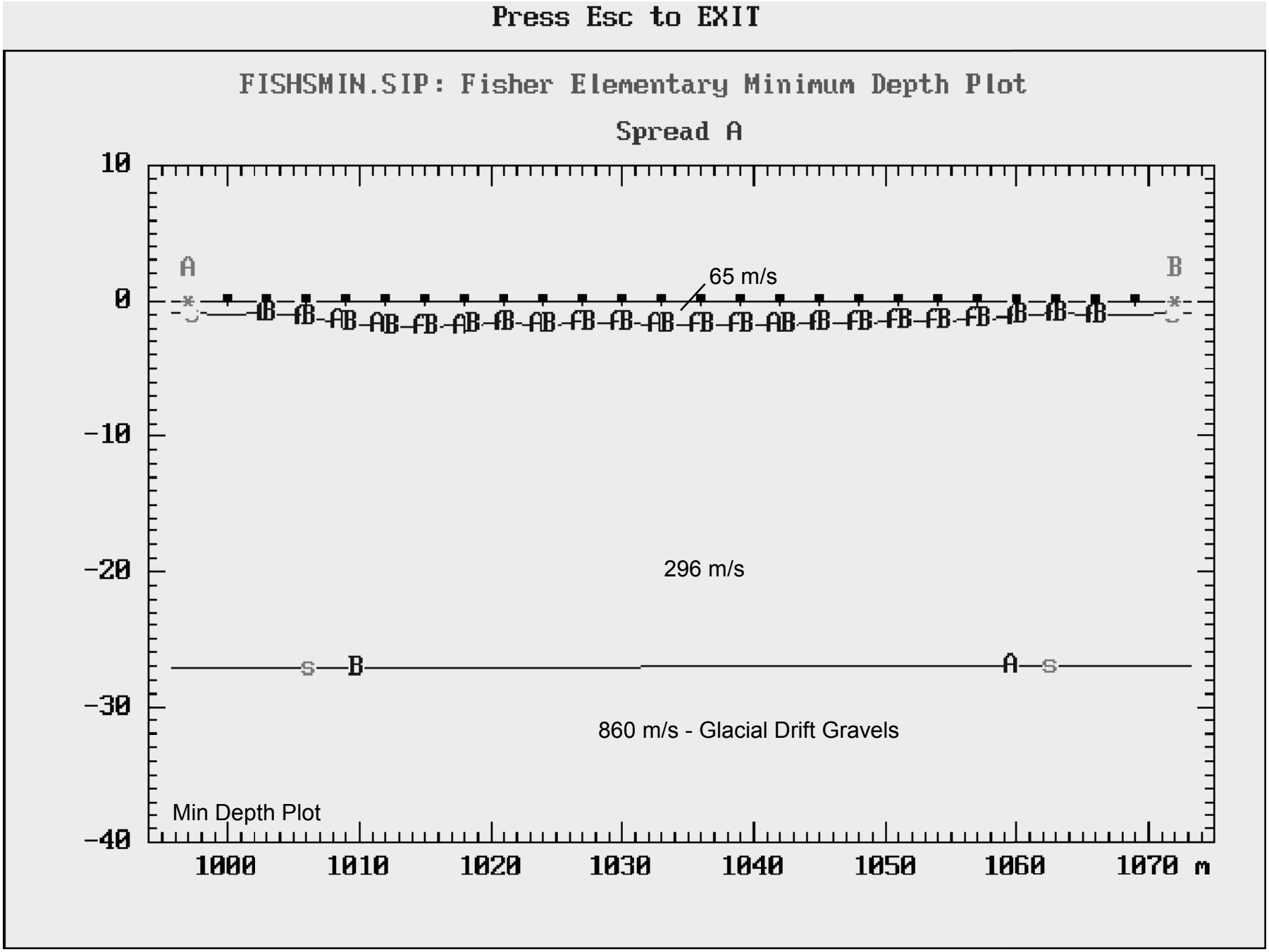

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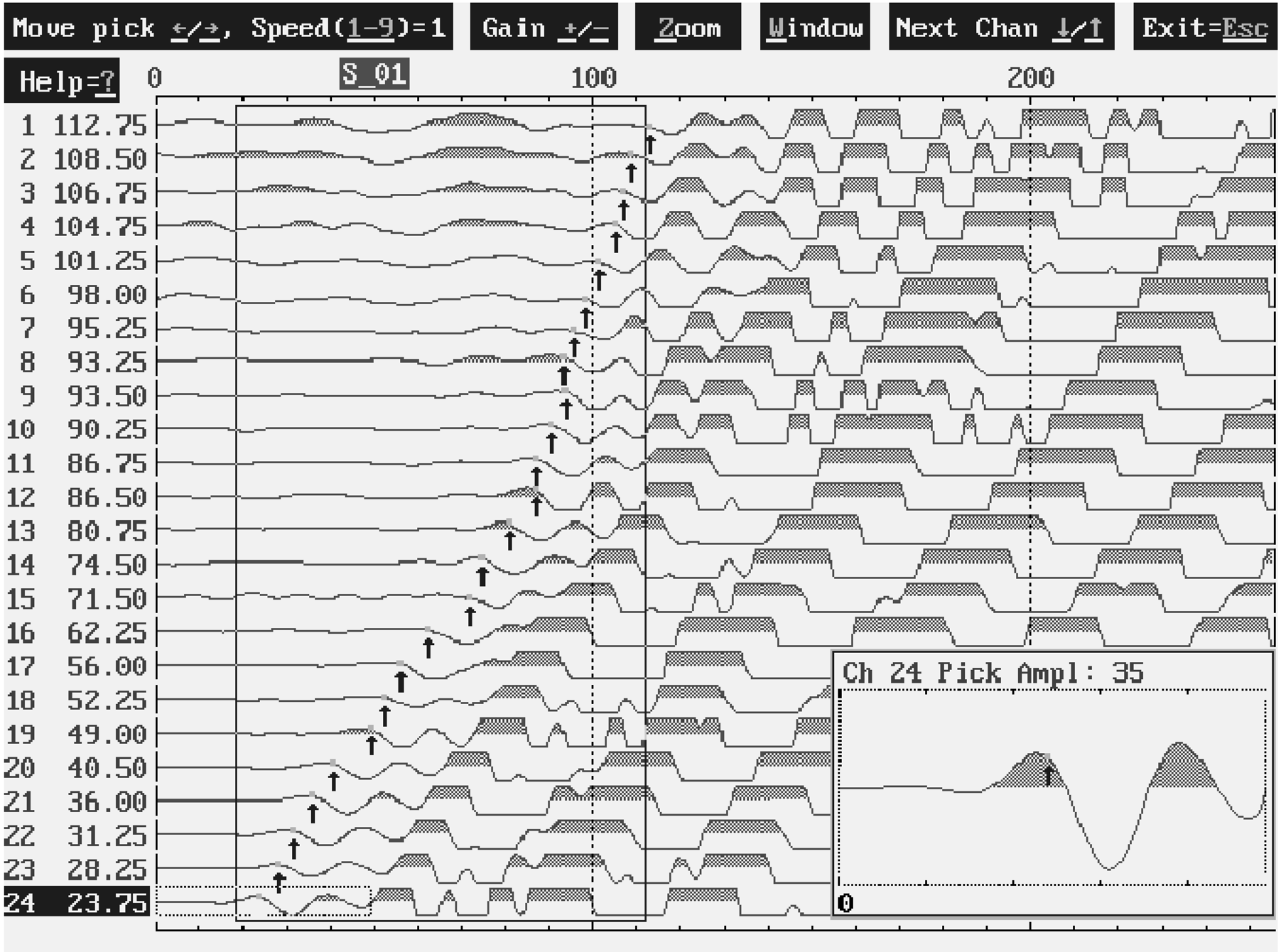

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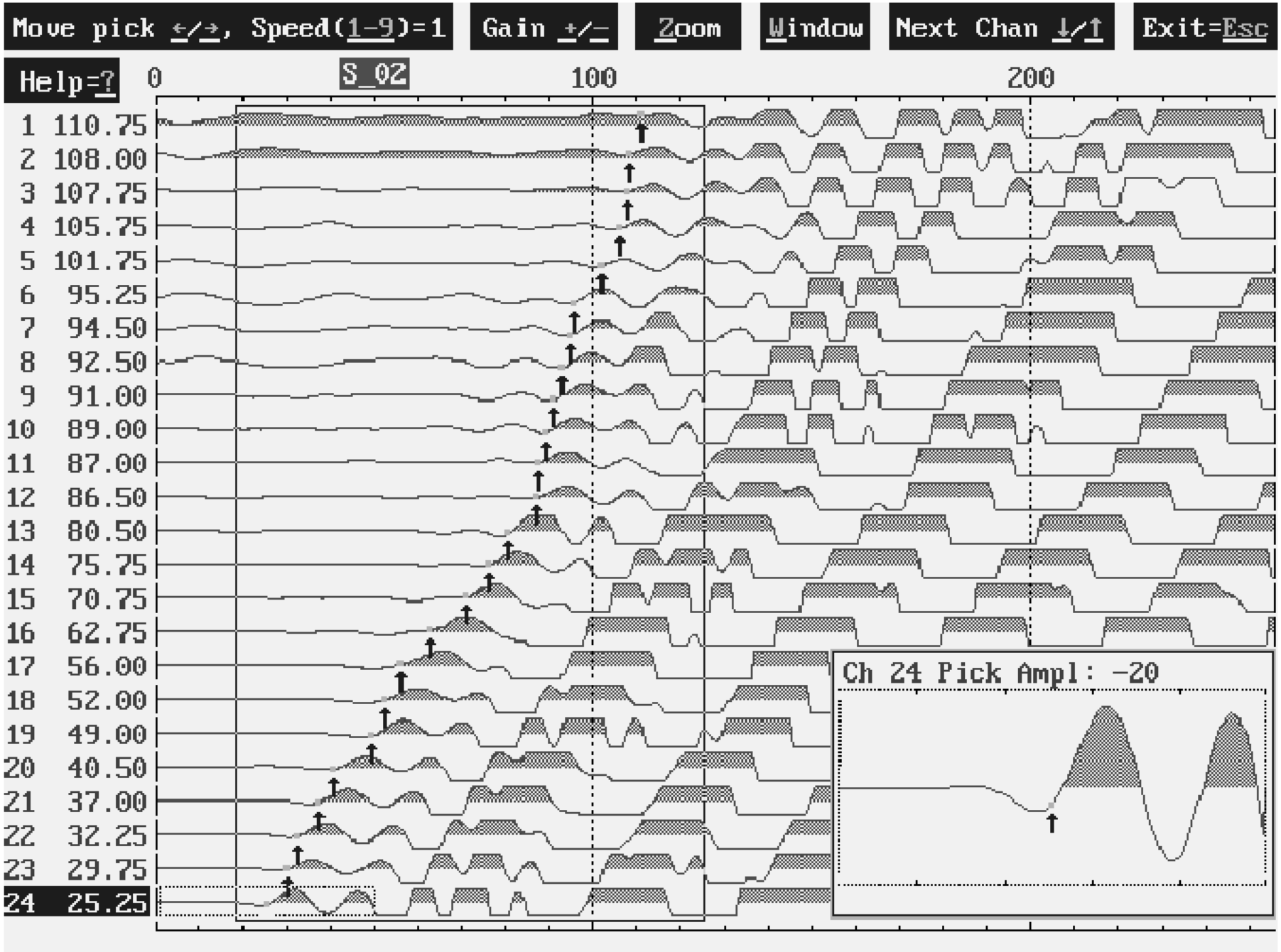

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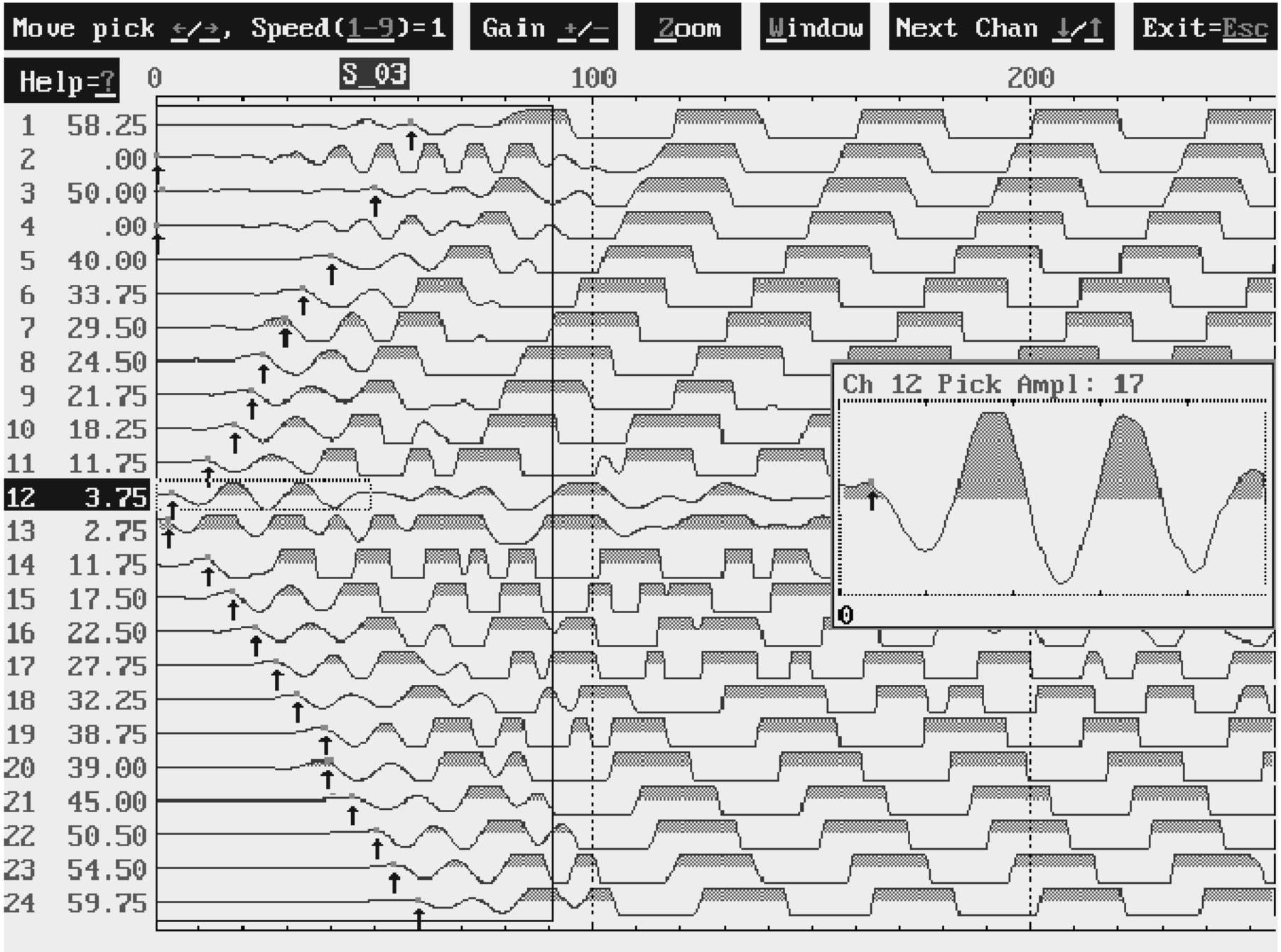

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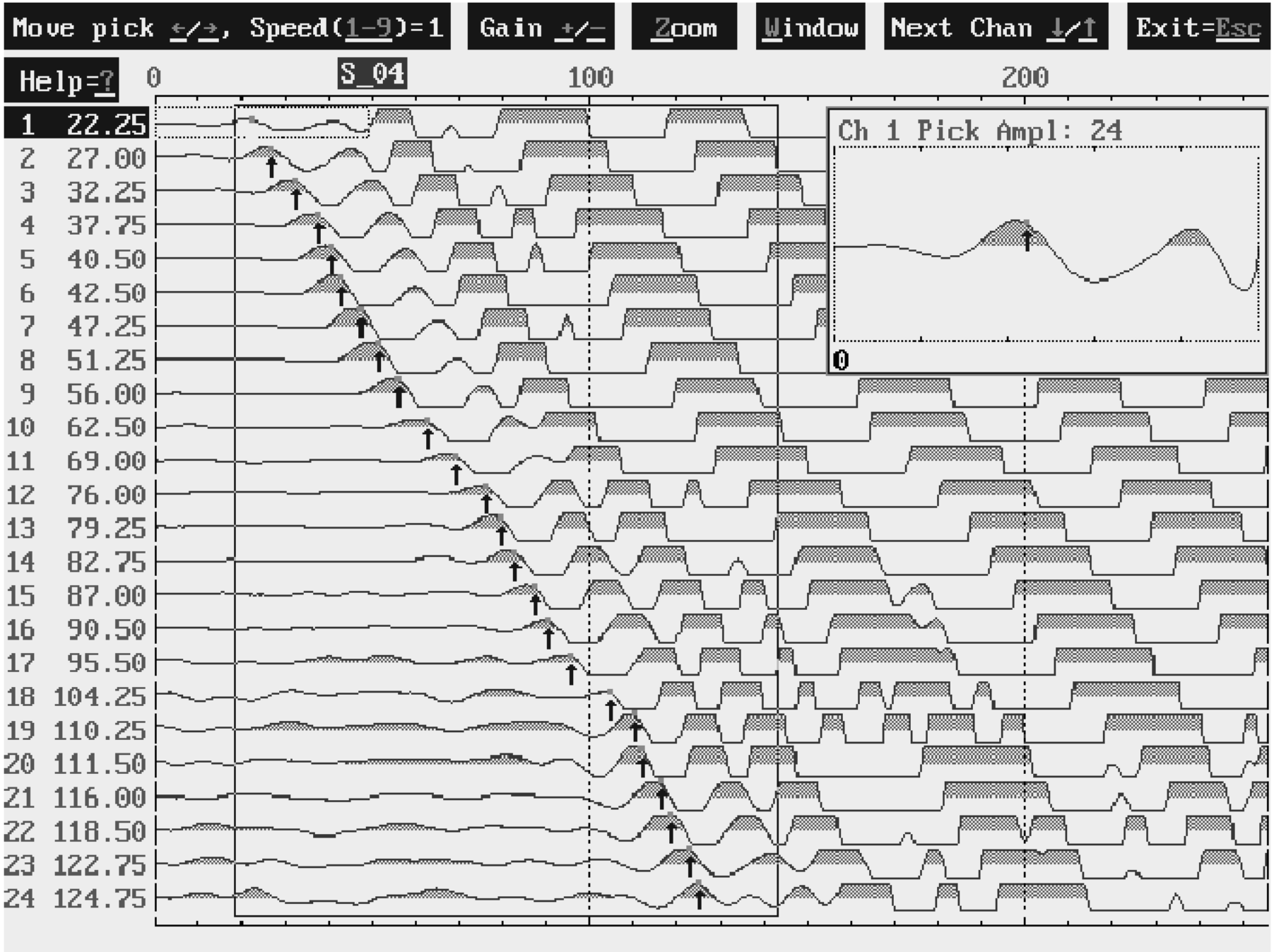

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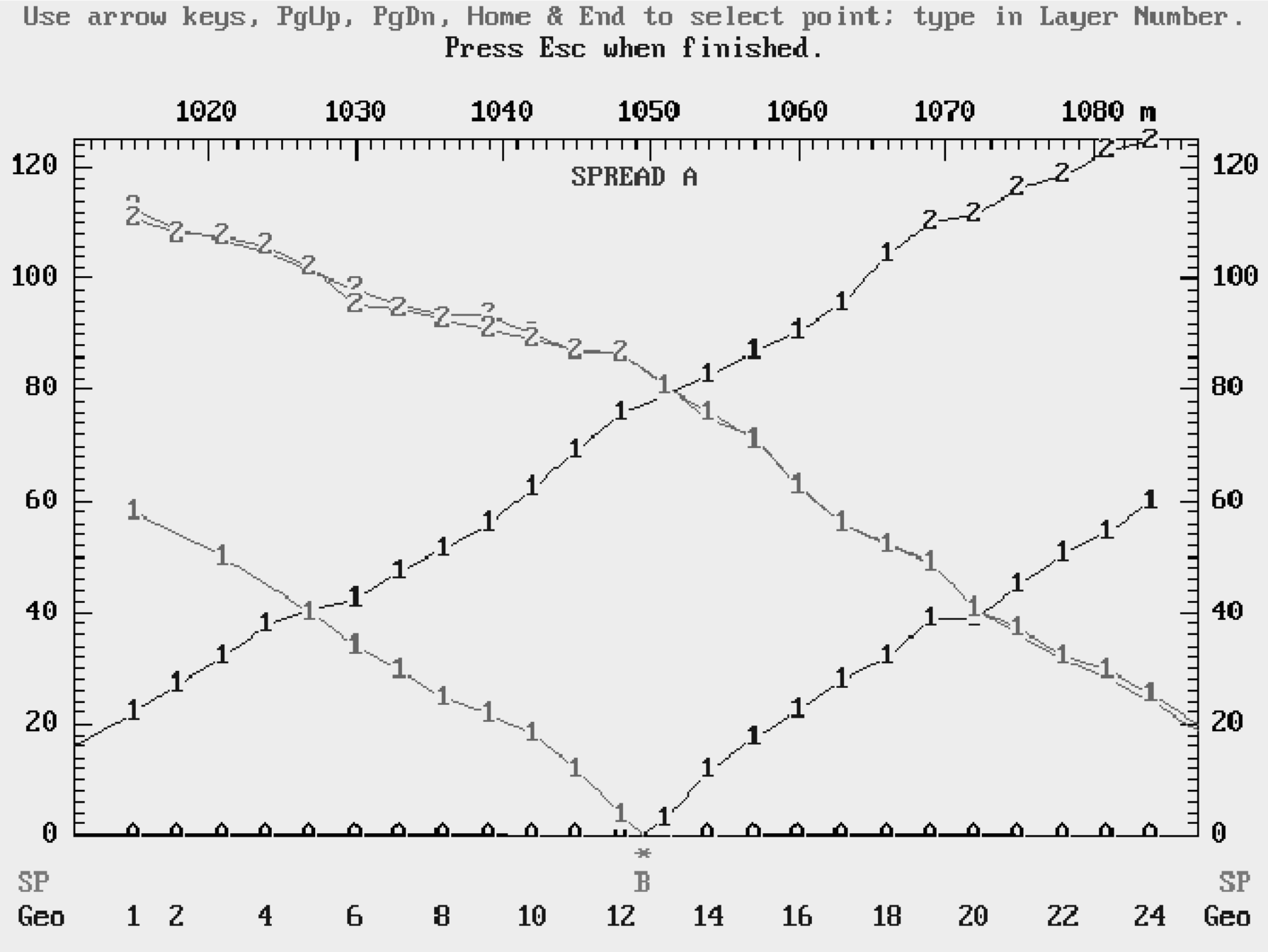

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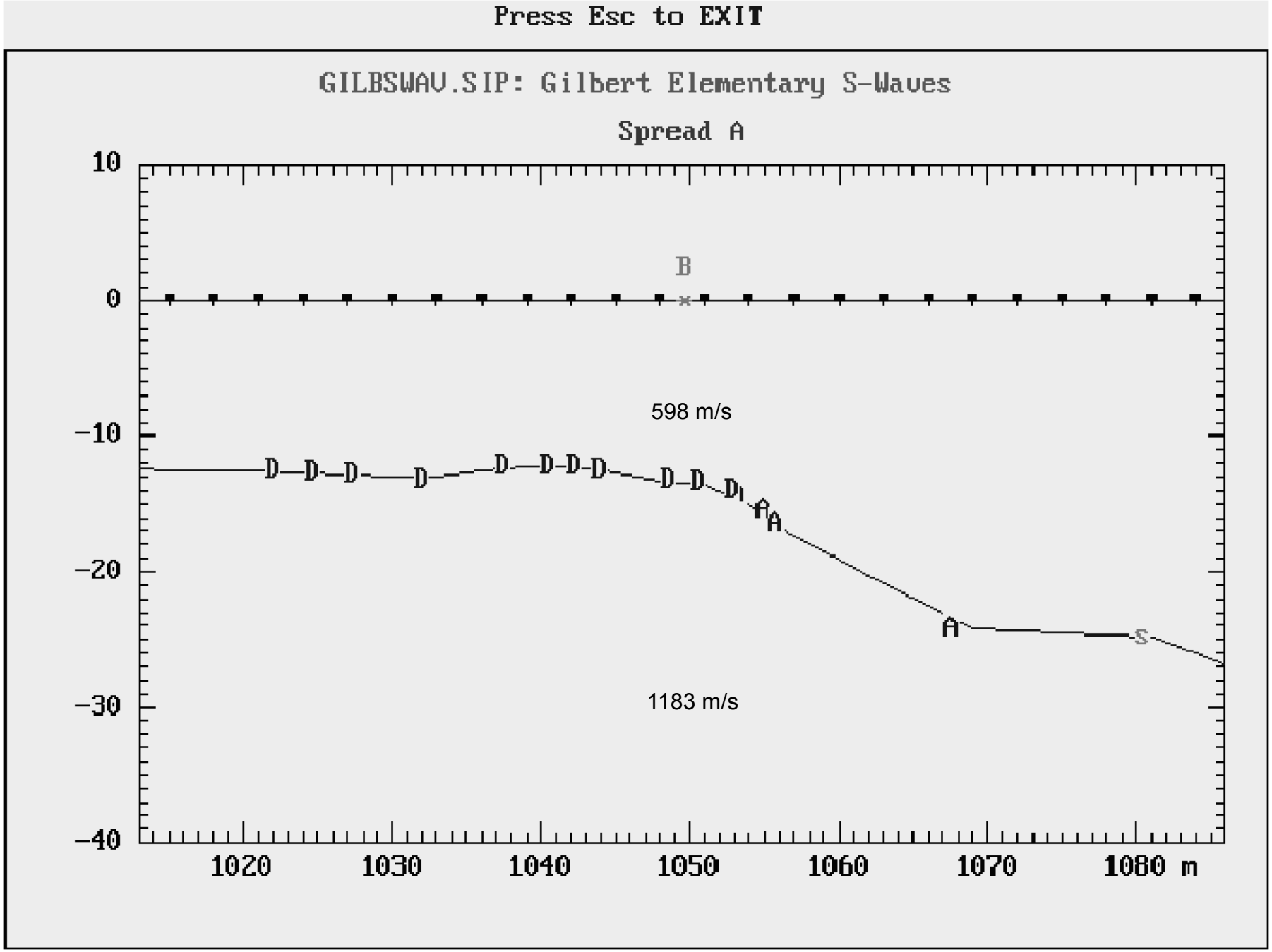

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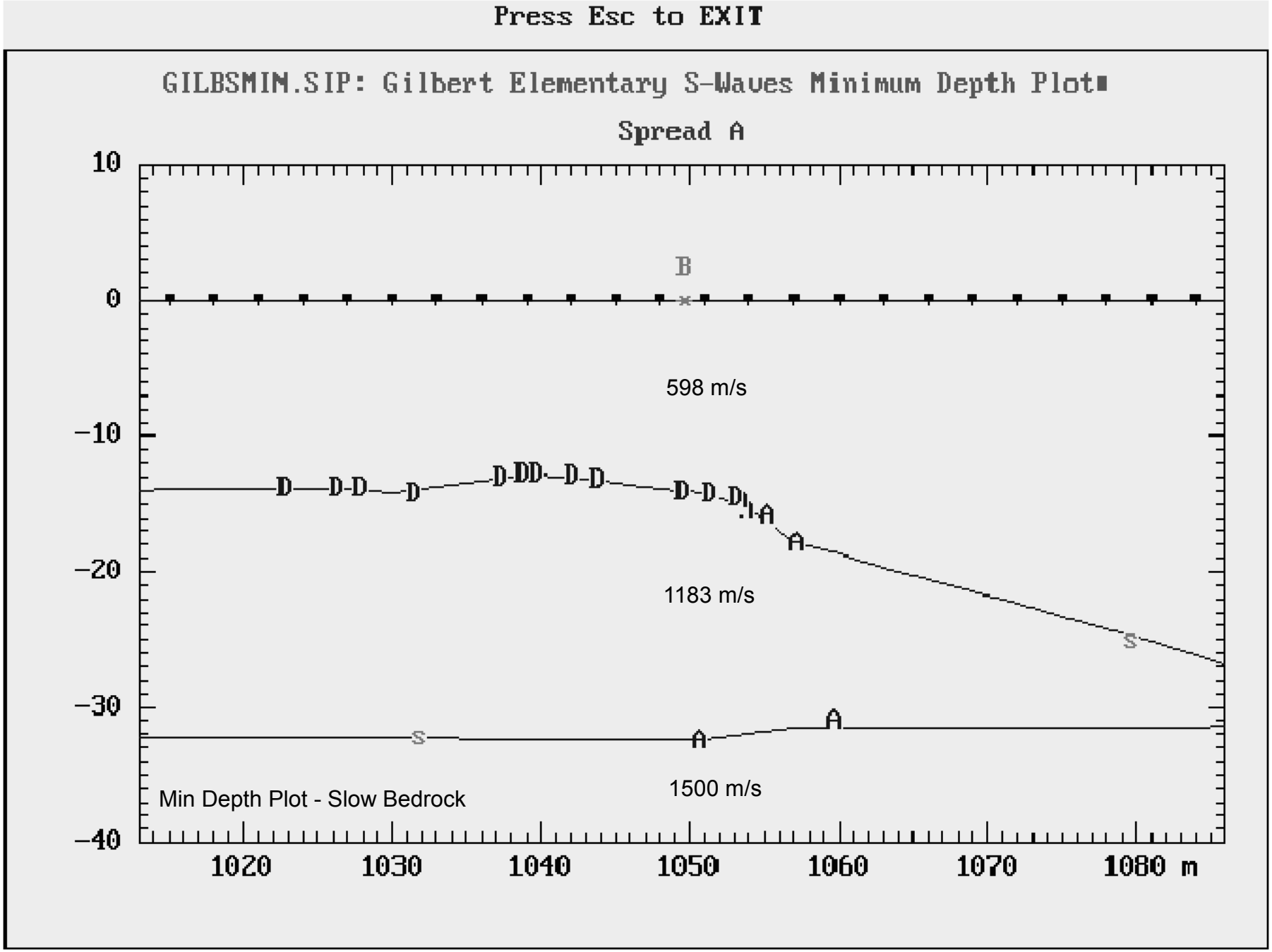

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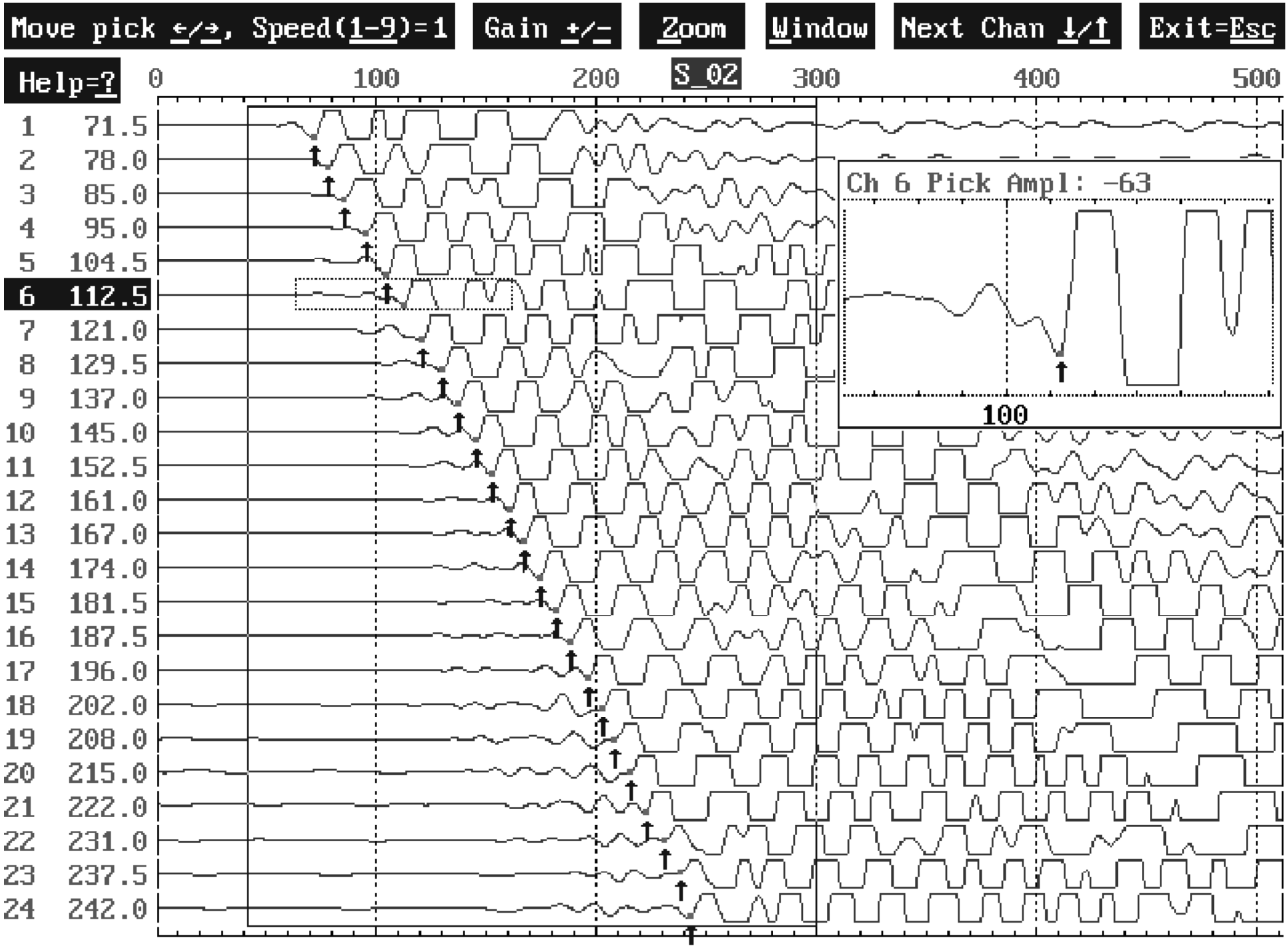

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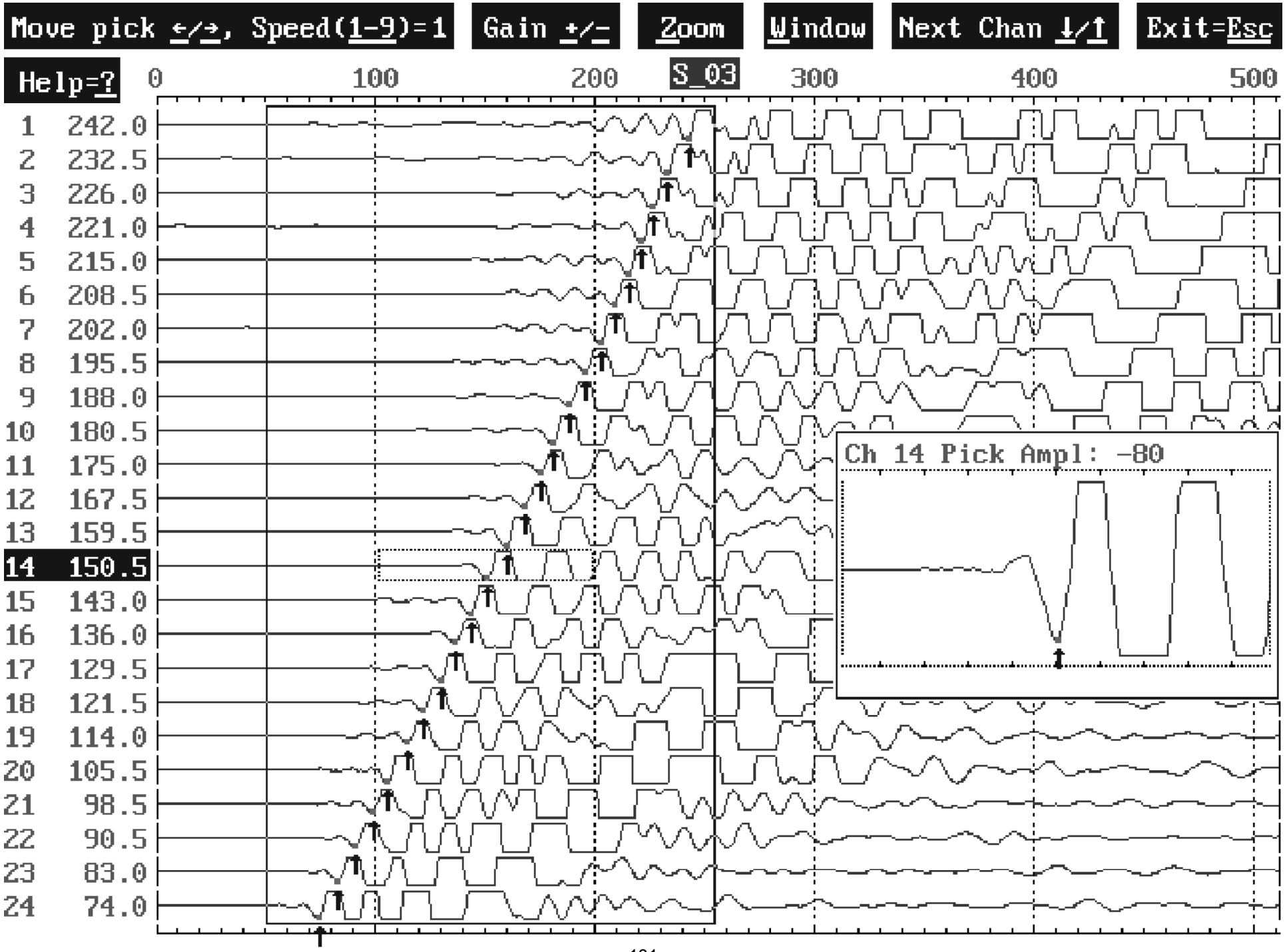

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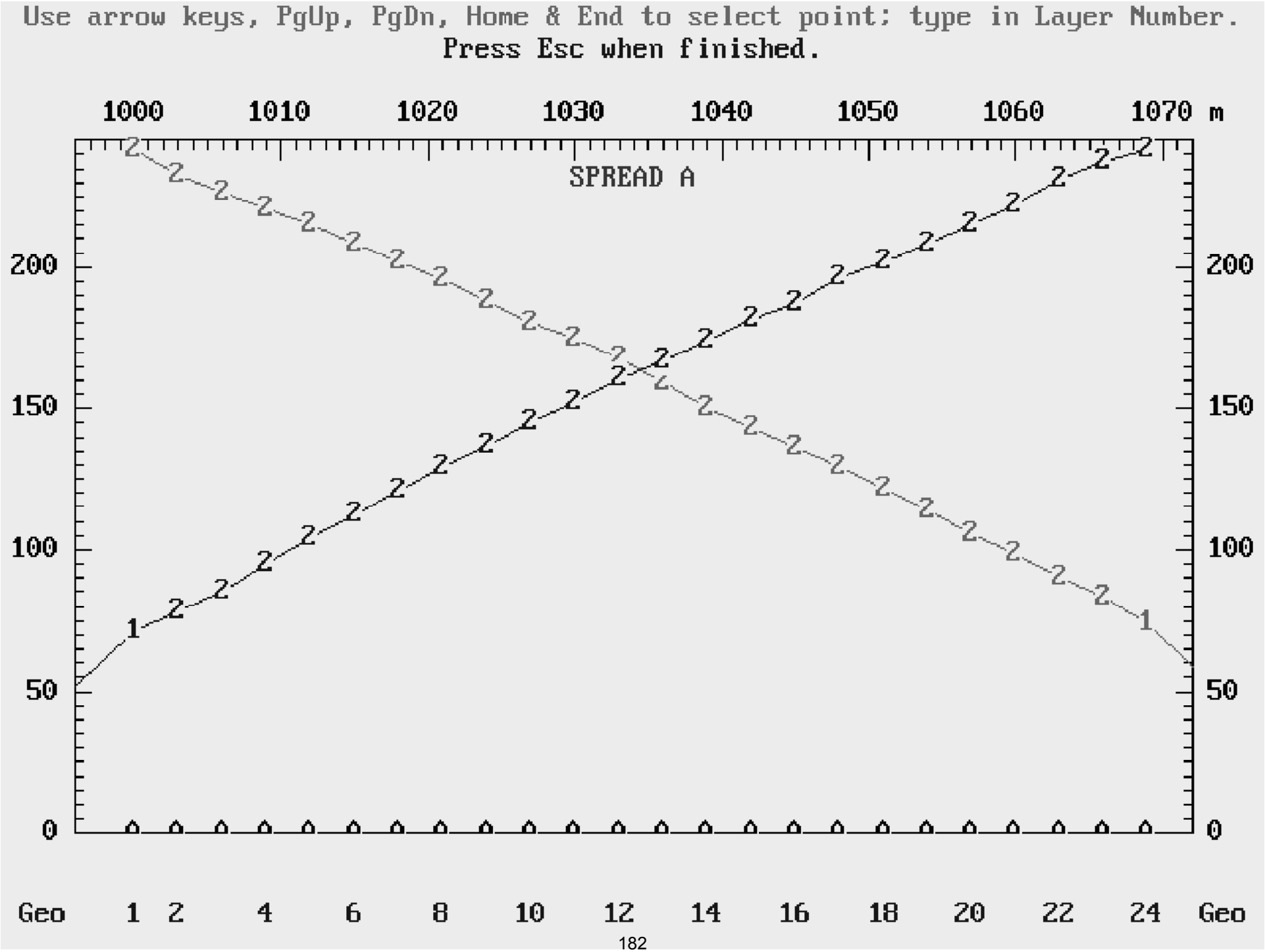

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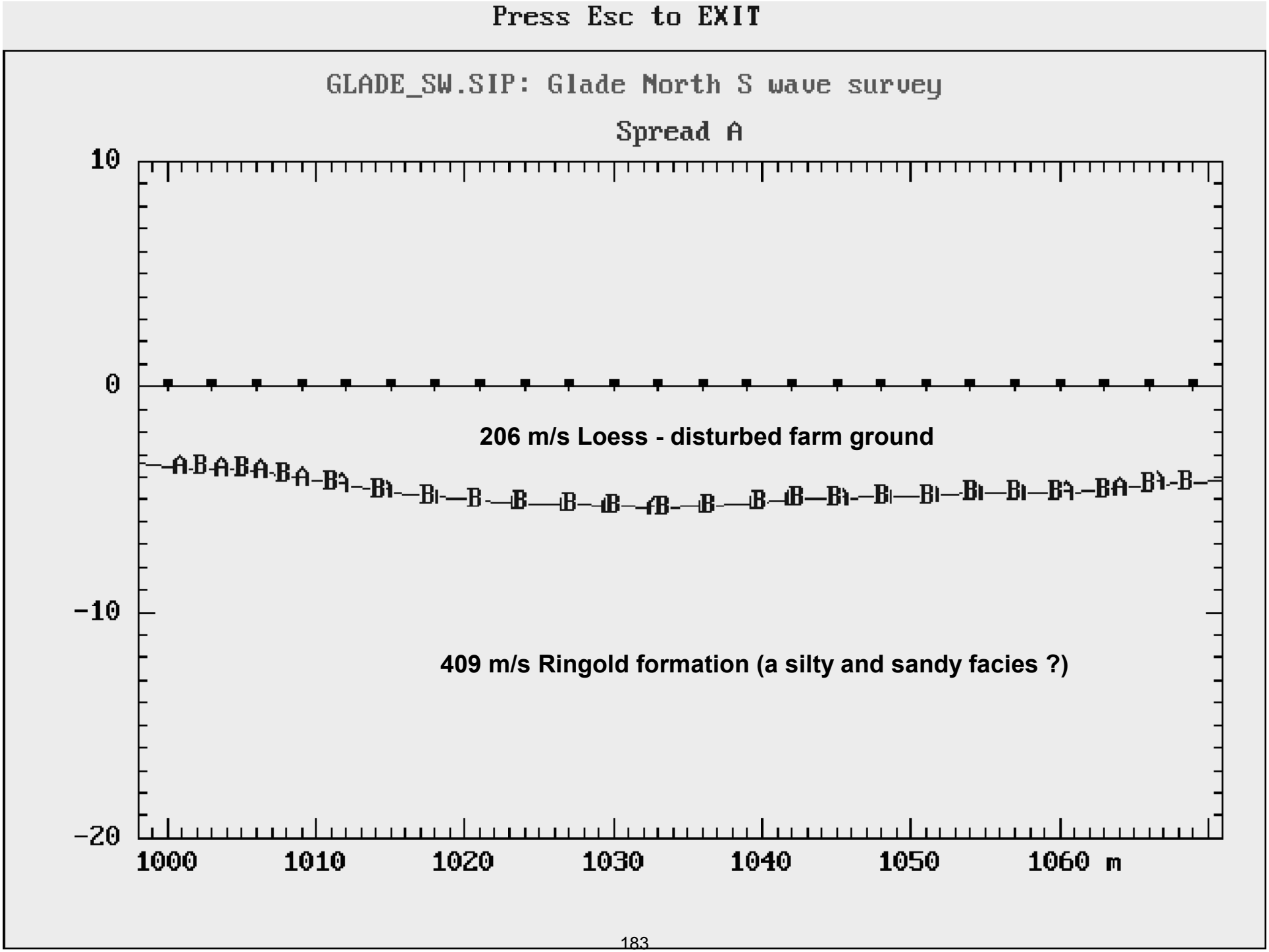
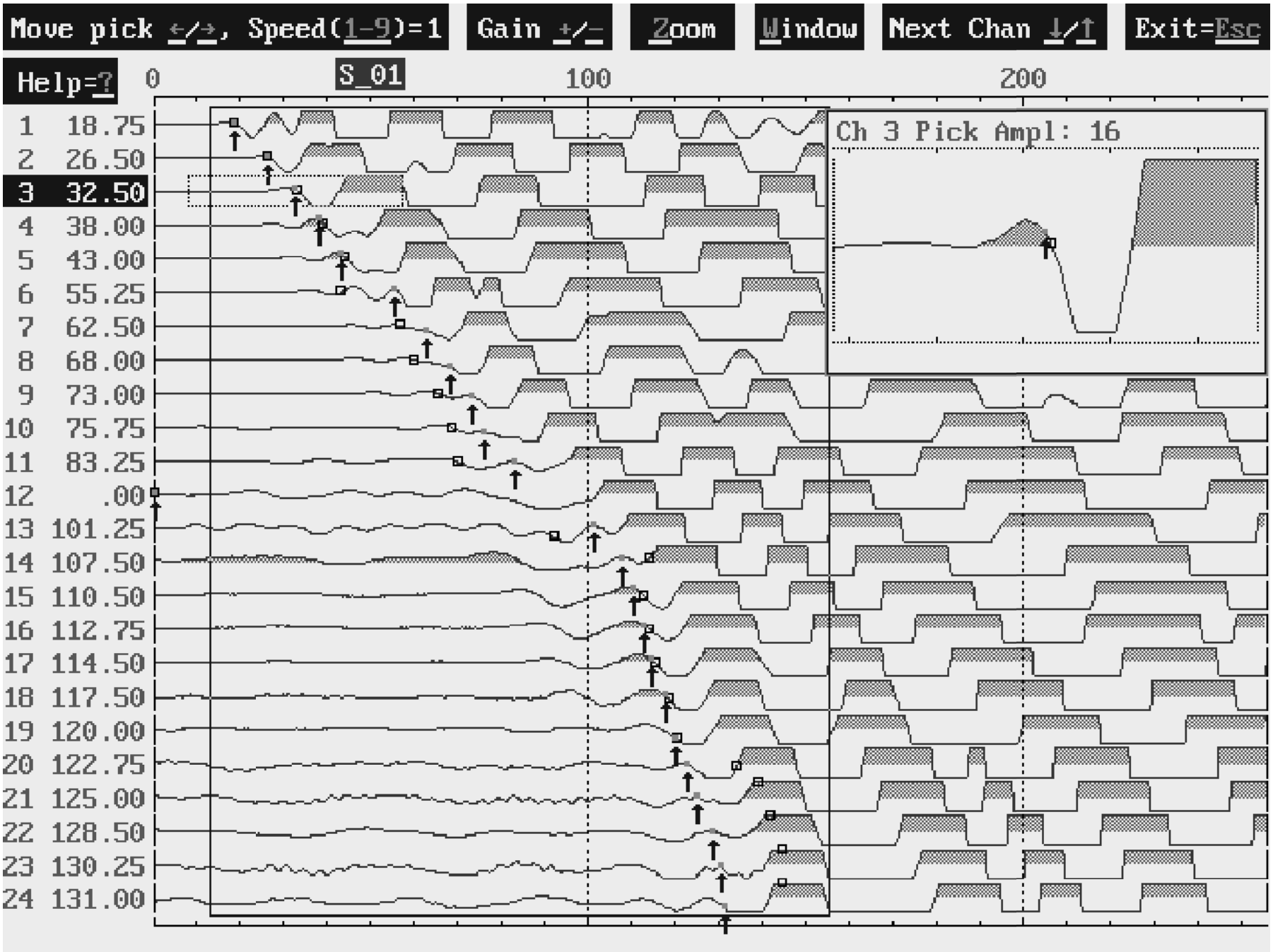


Half Moon S-wave



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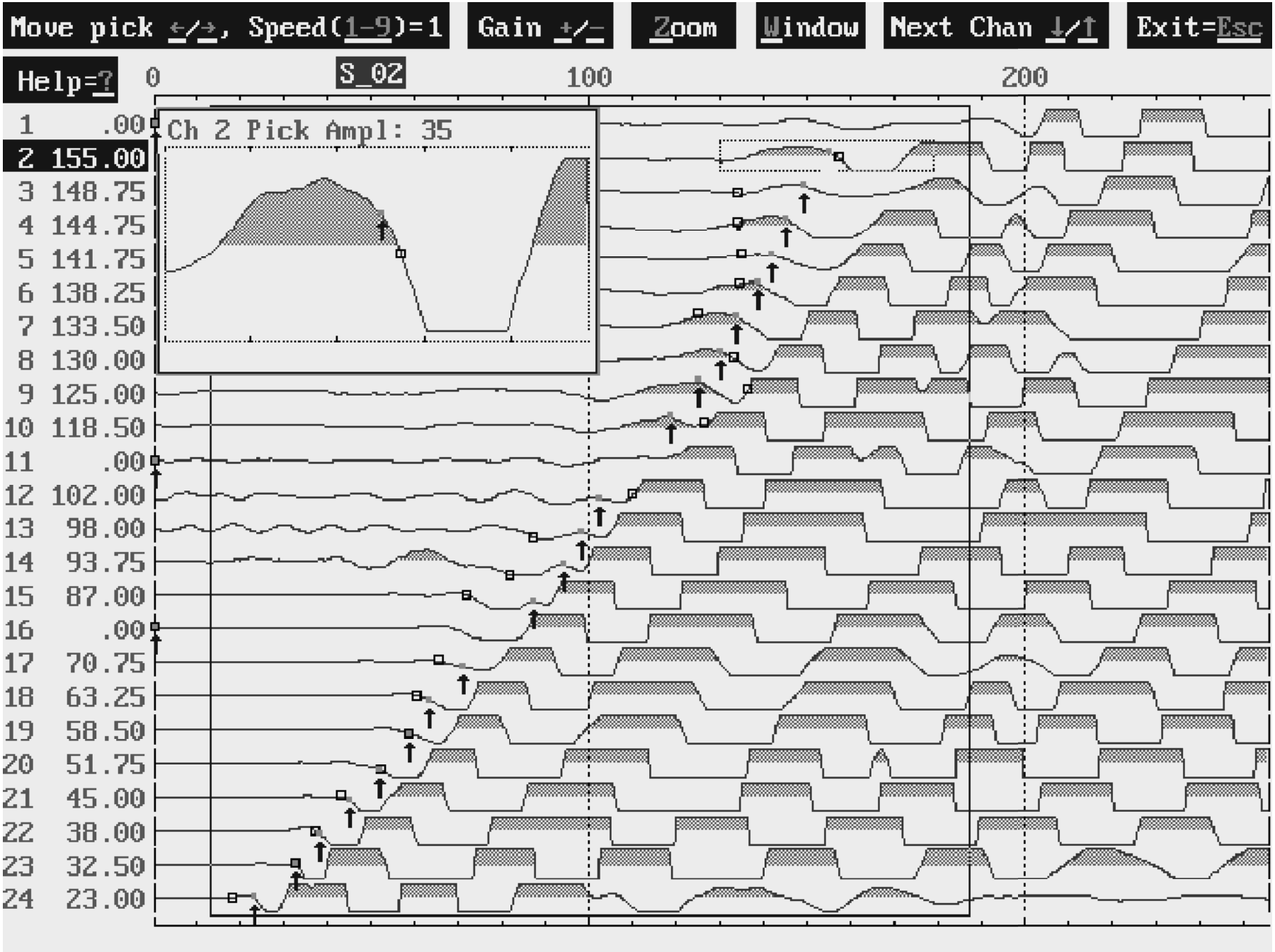

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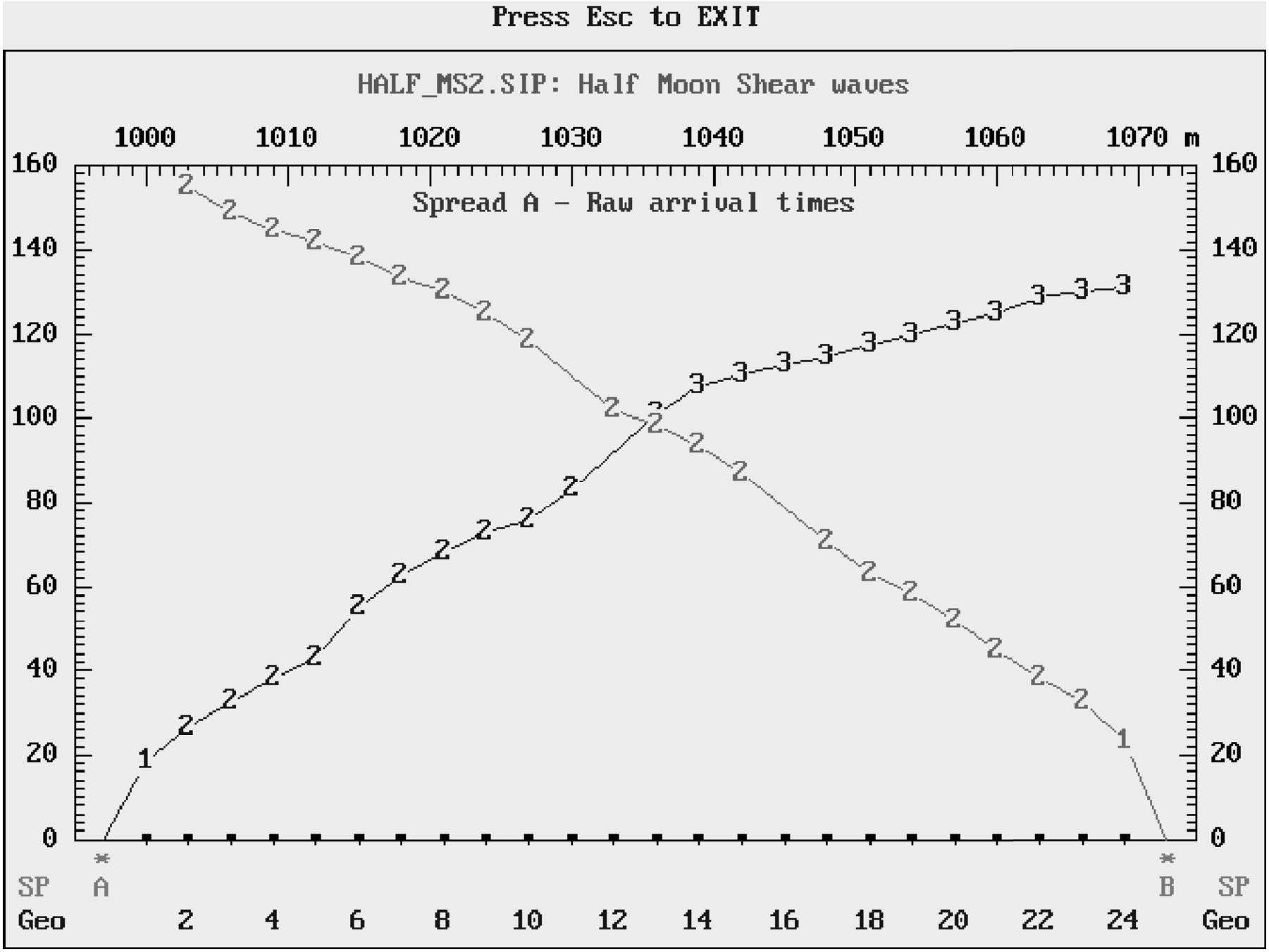

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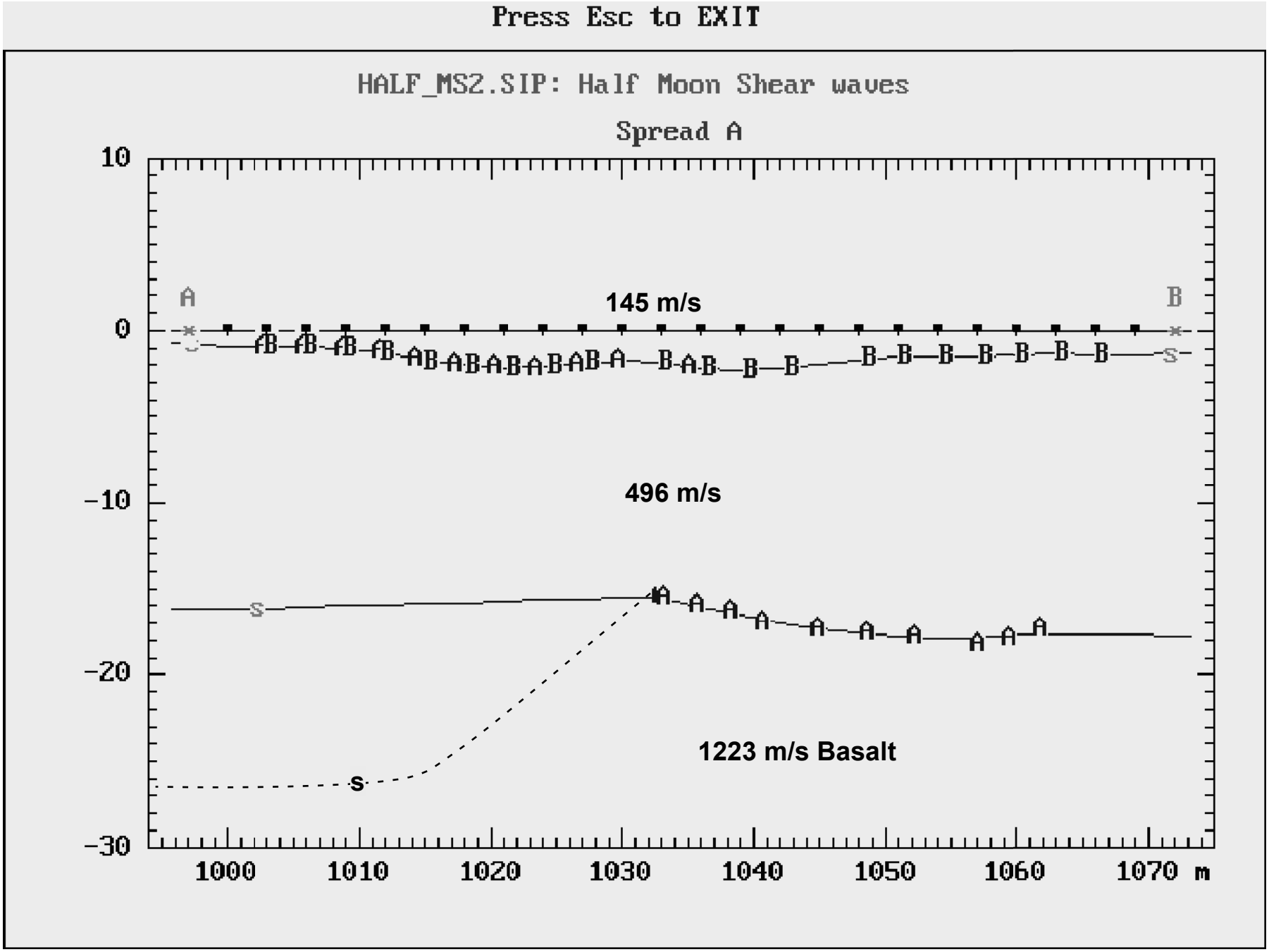
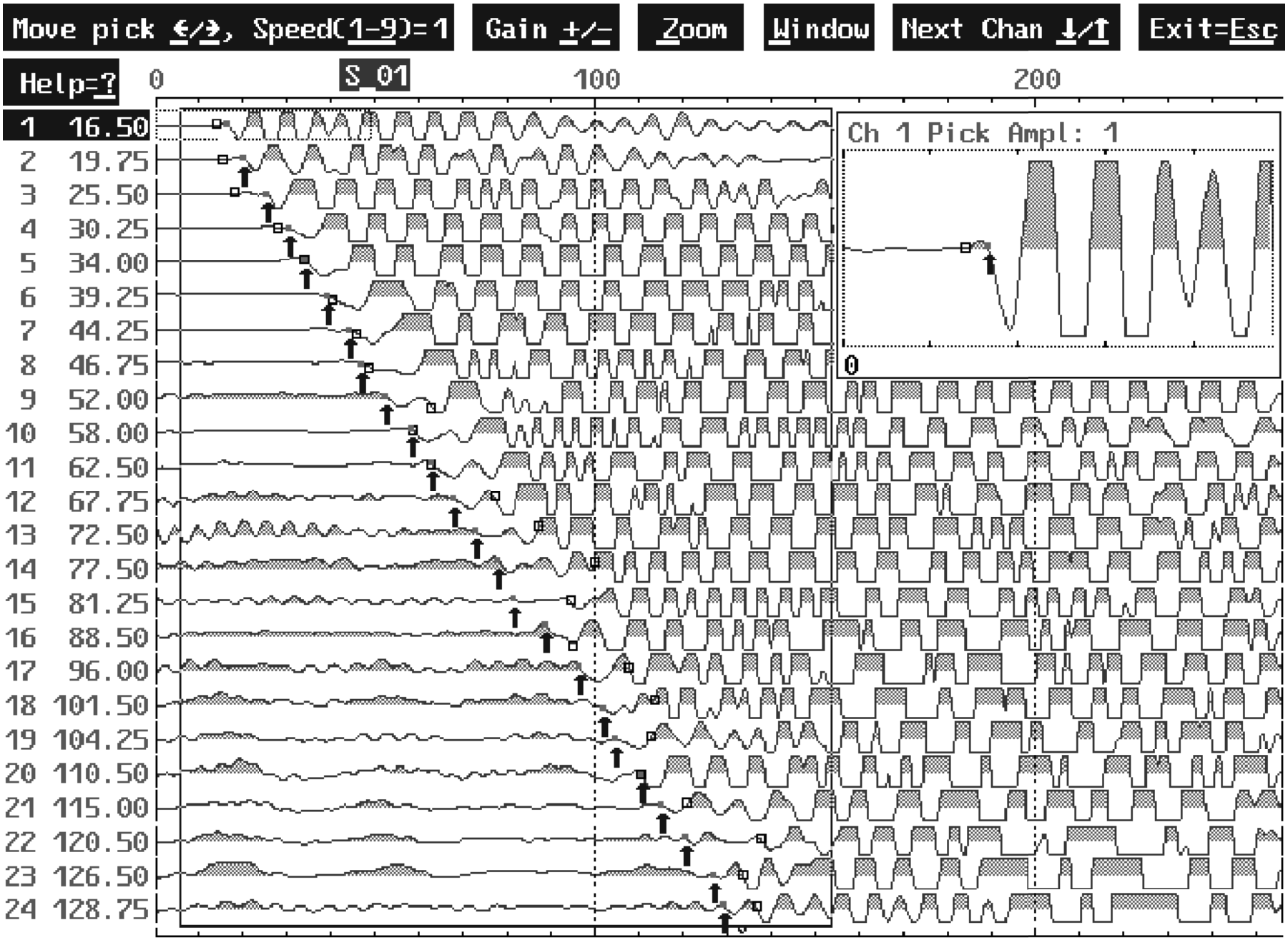


Hanford 100K S-wave



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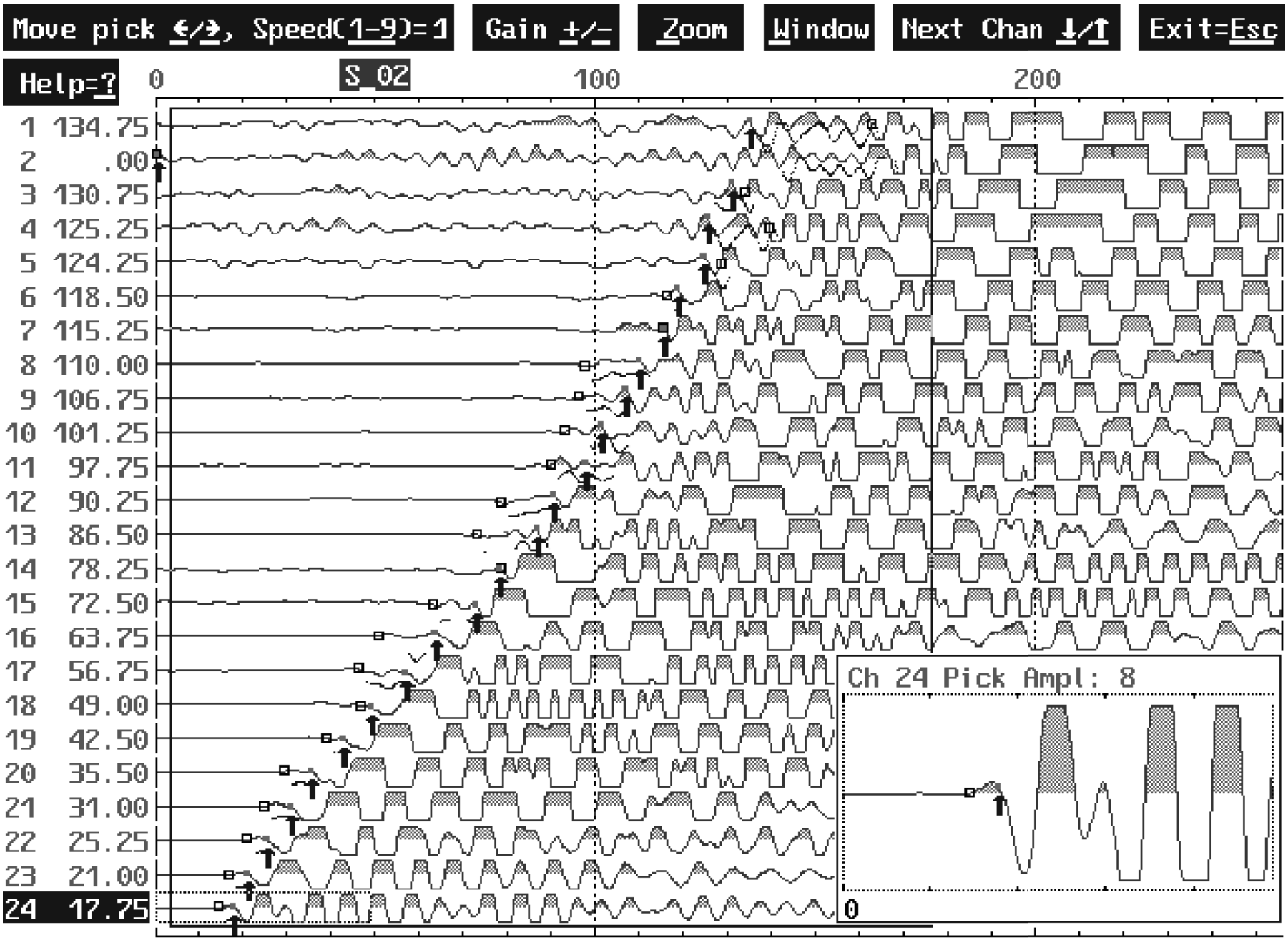

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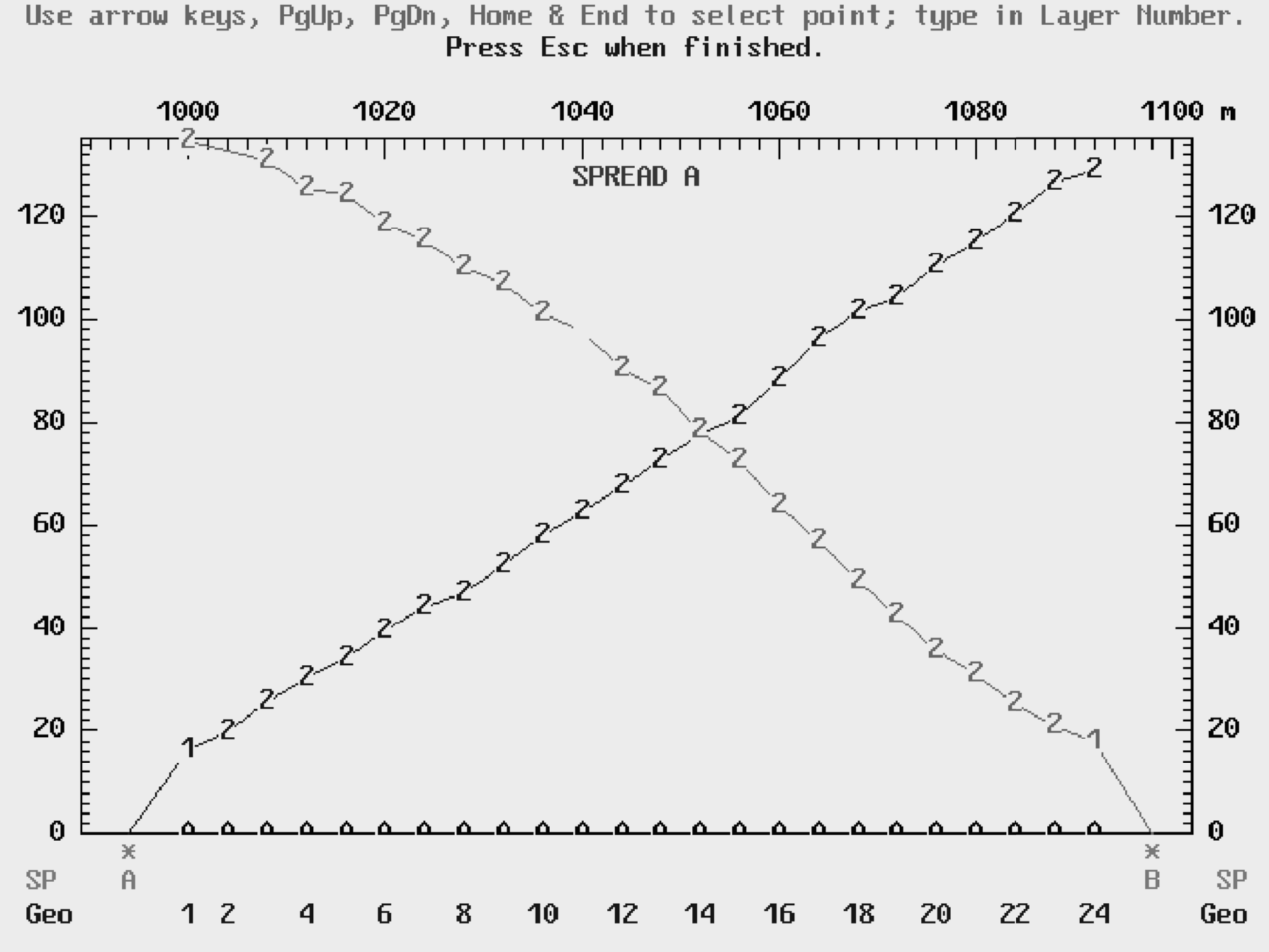

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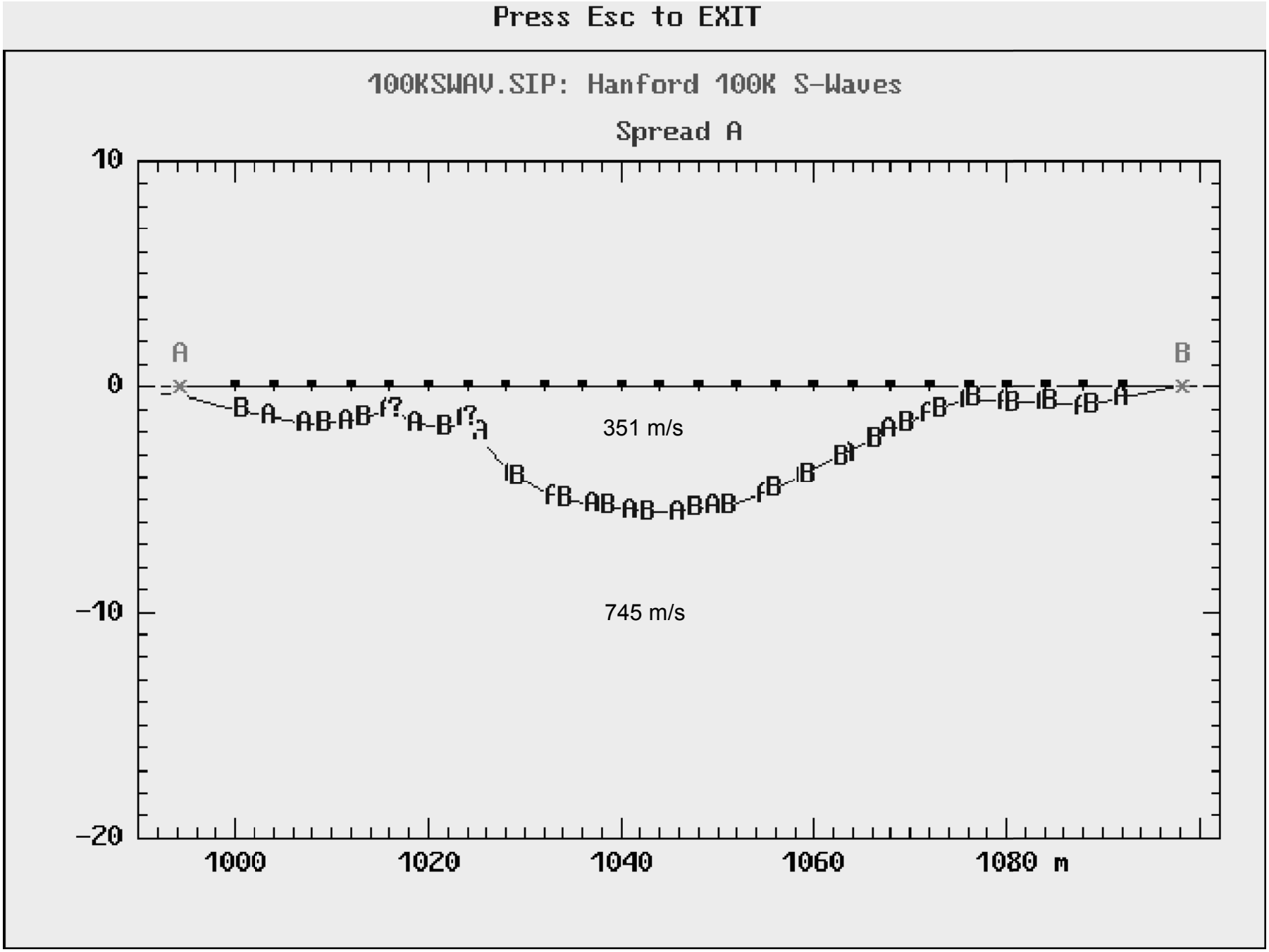

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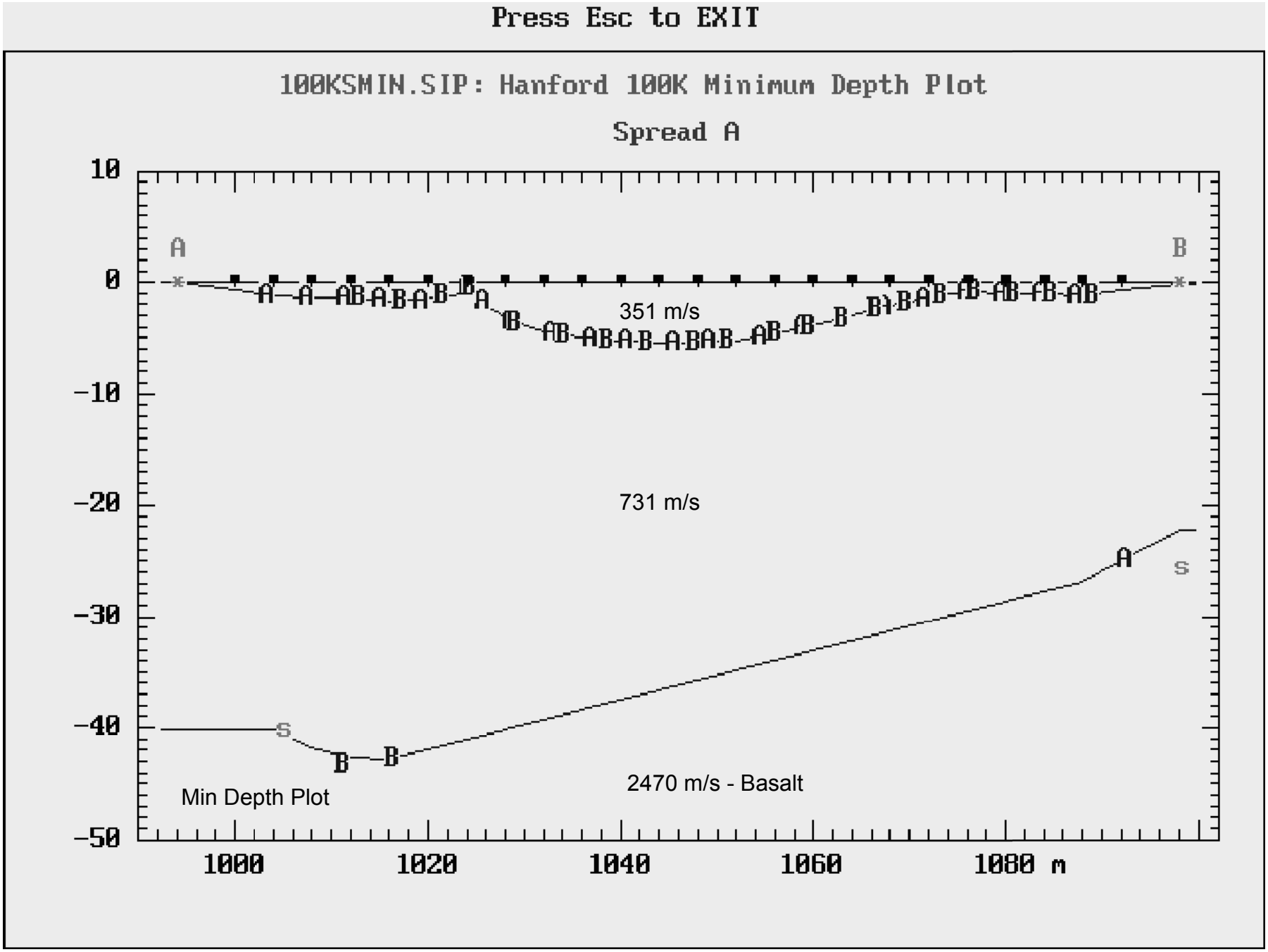

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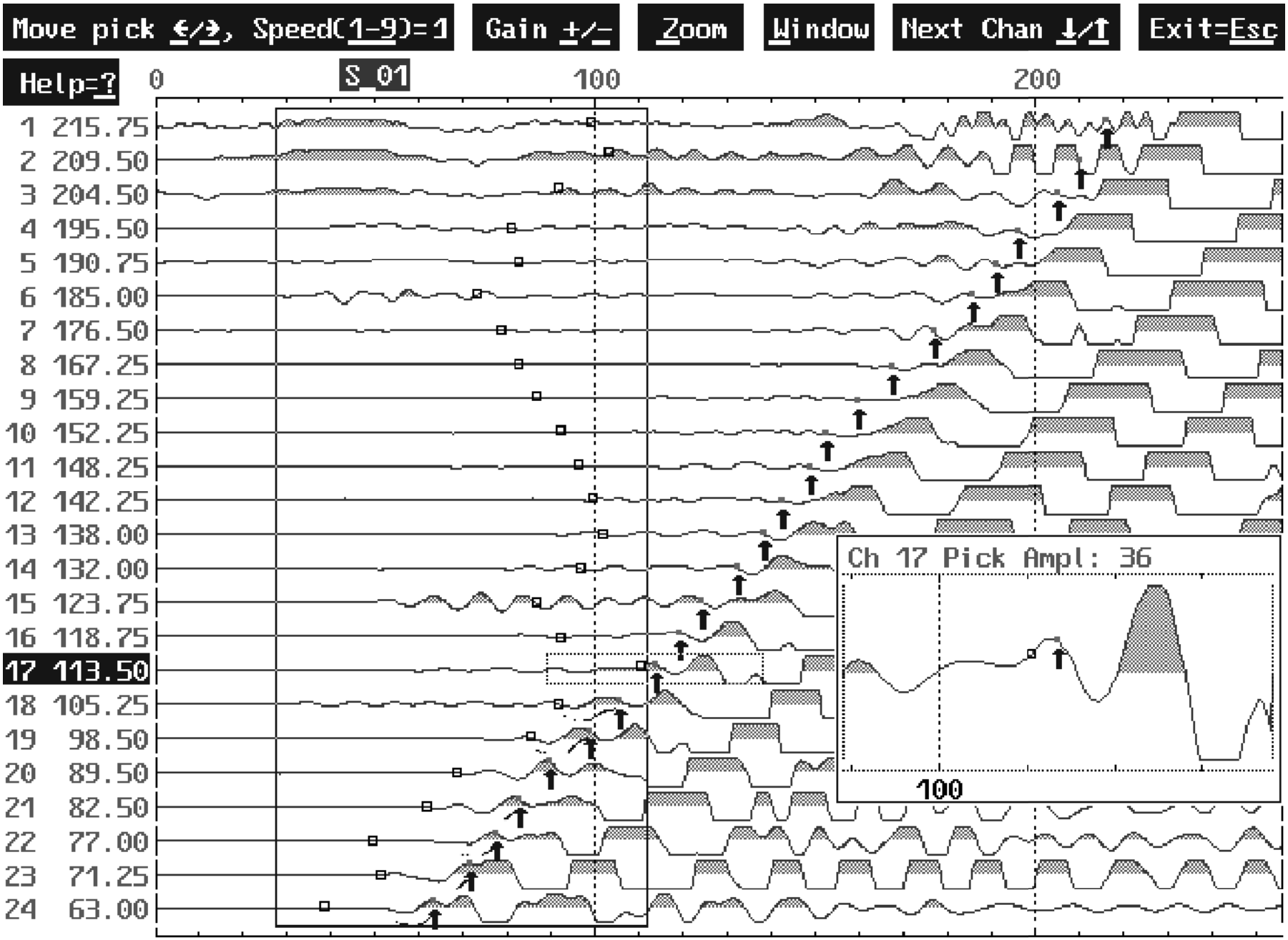

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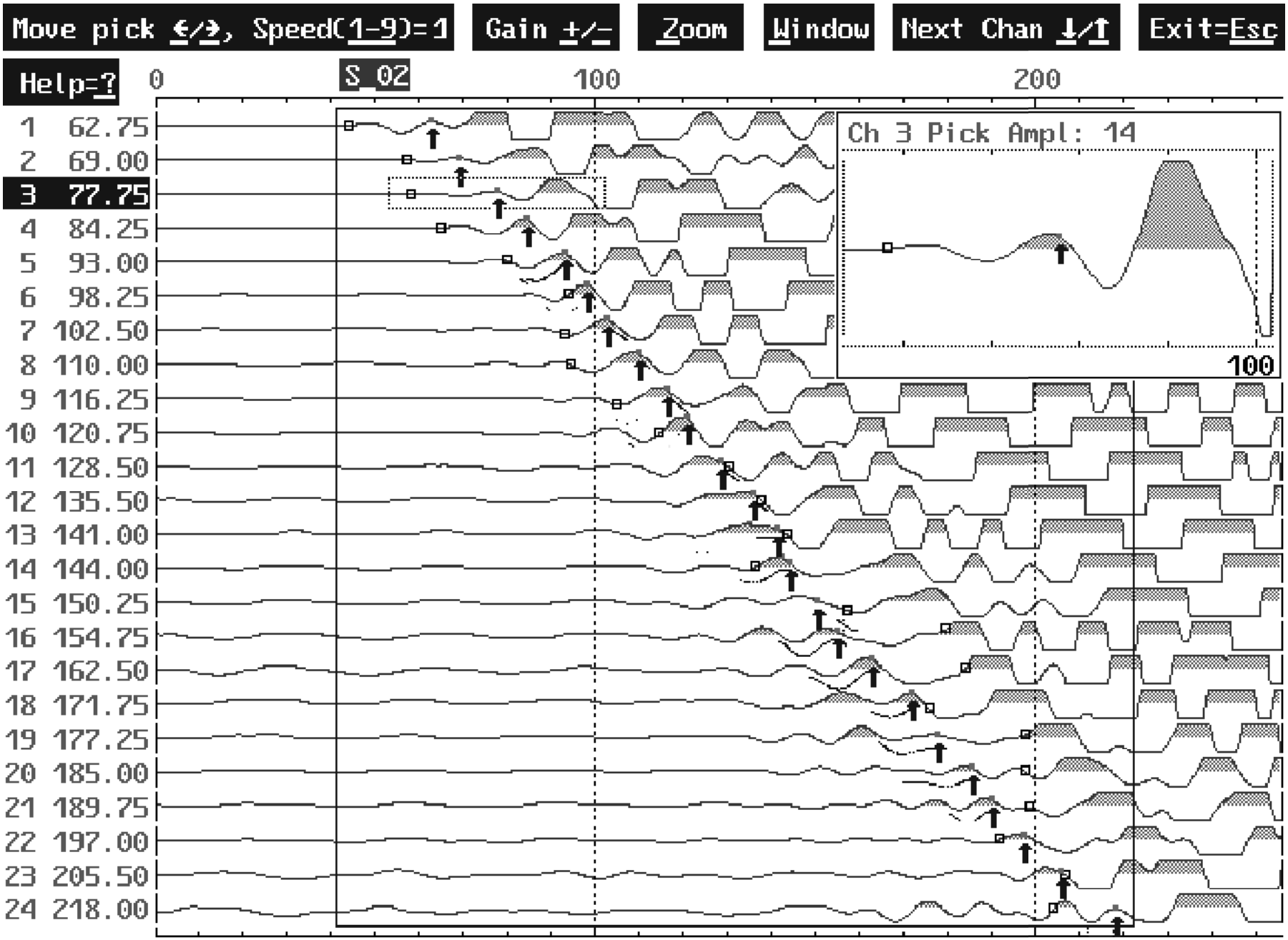

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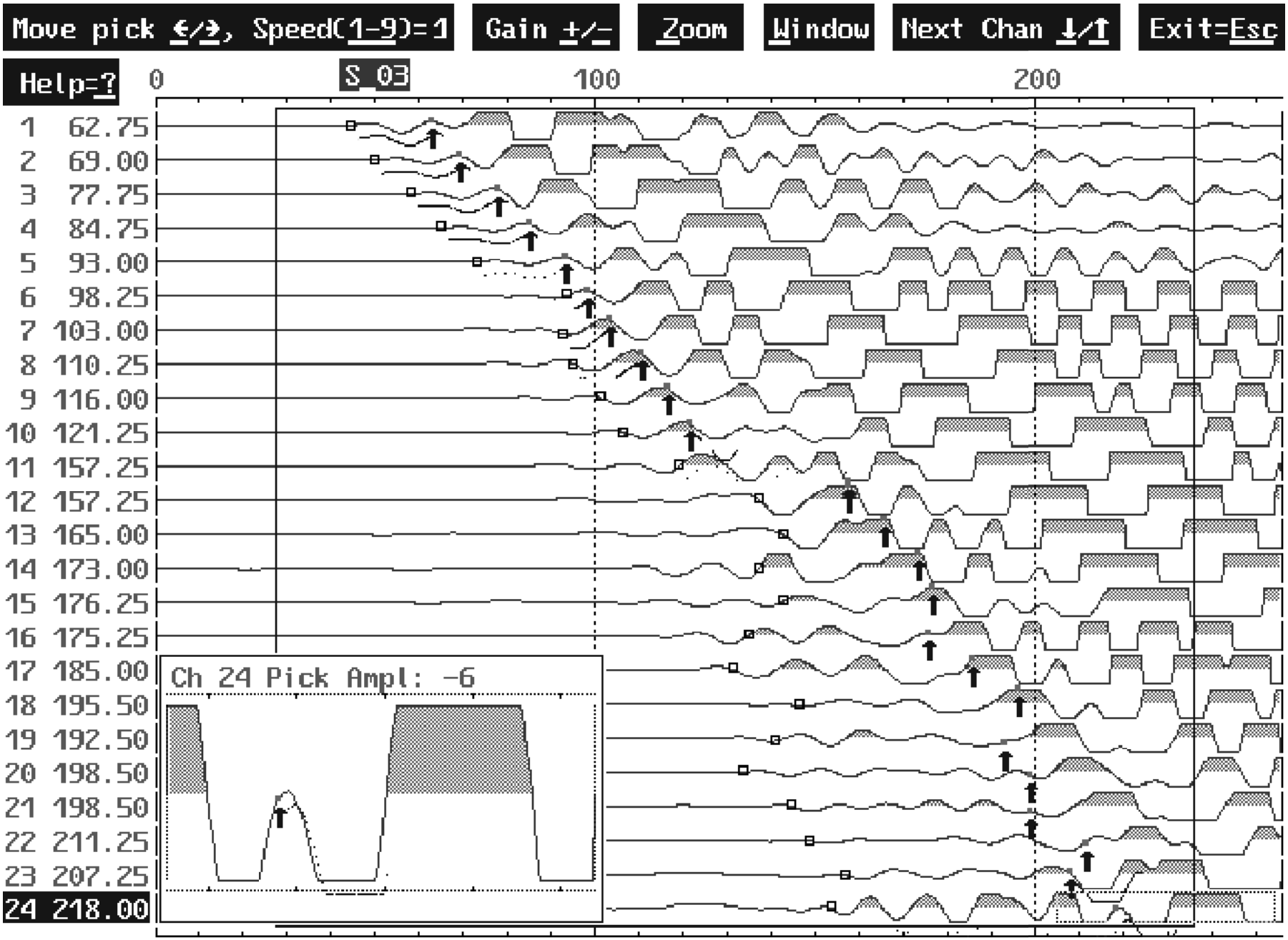

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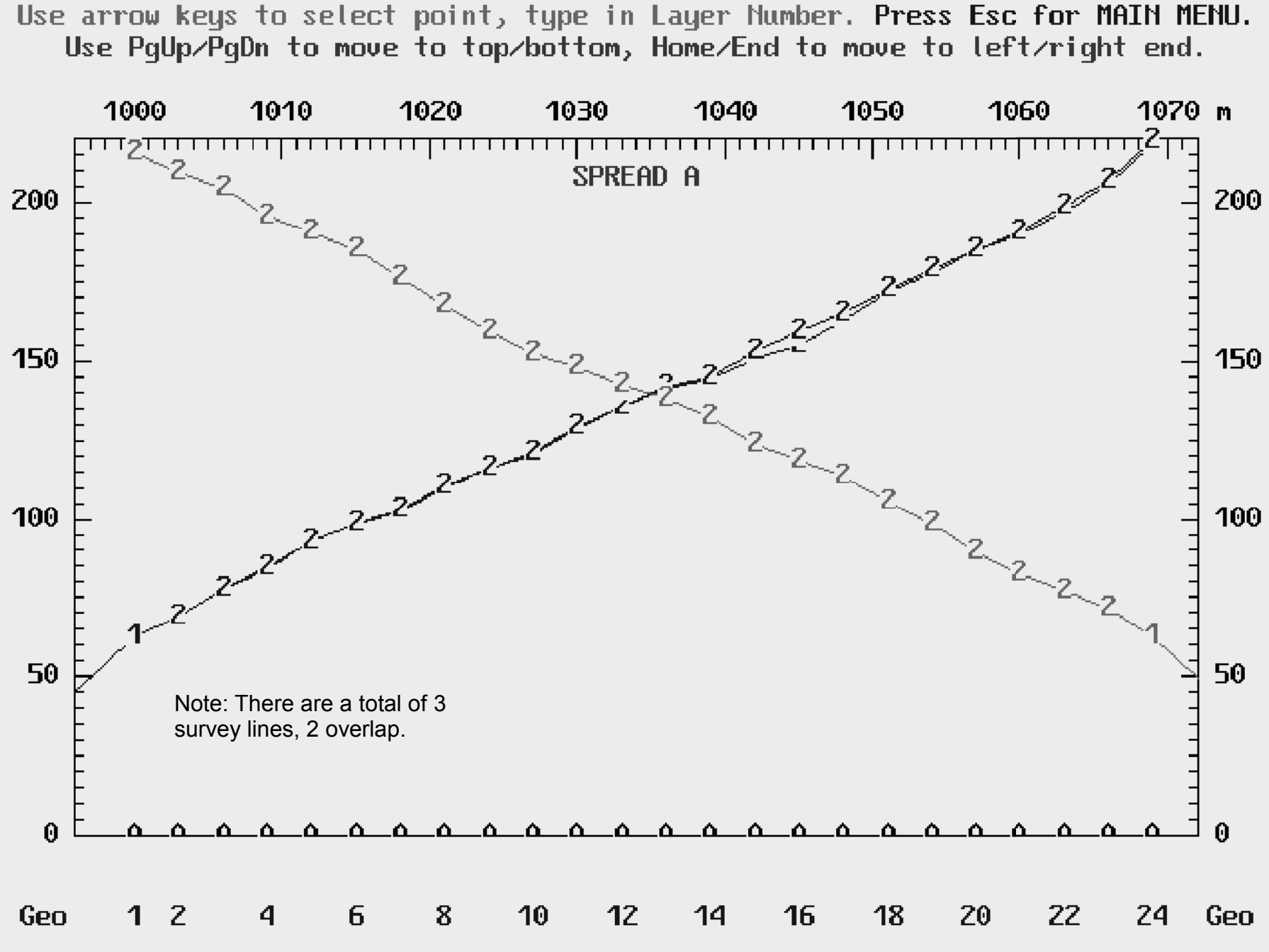

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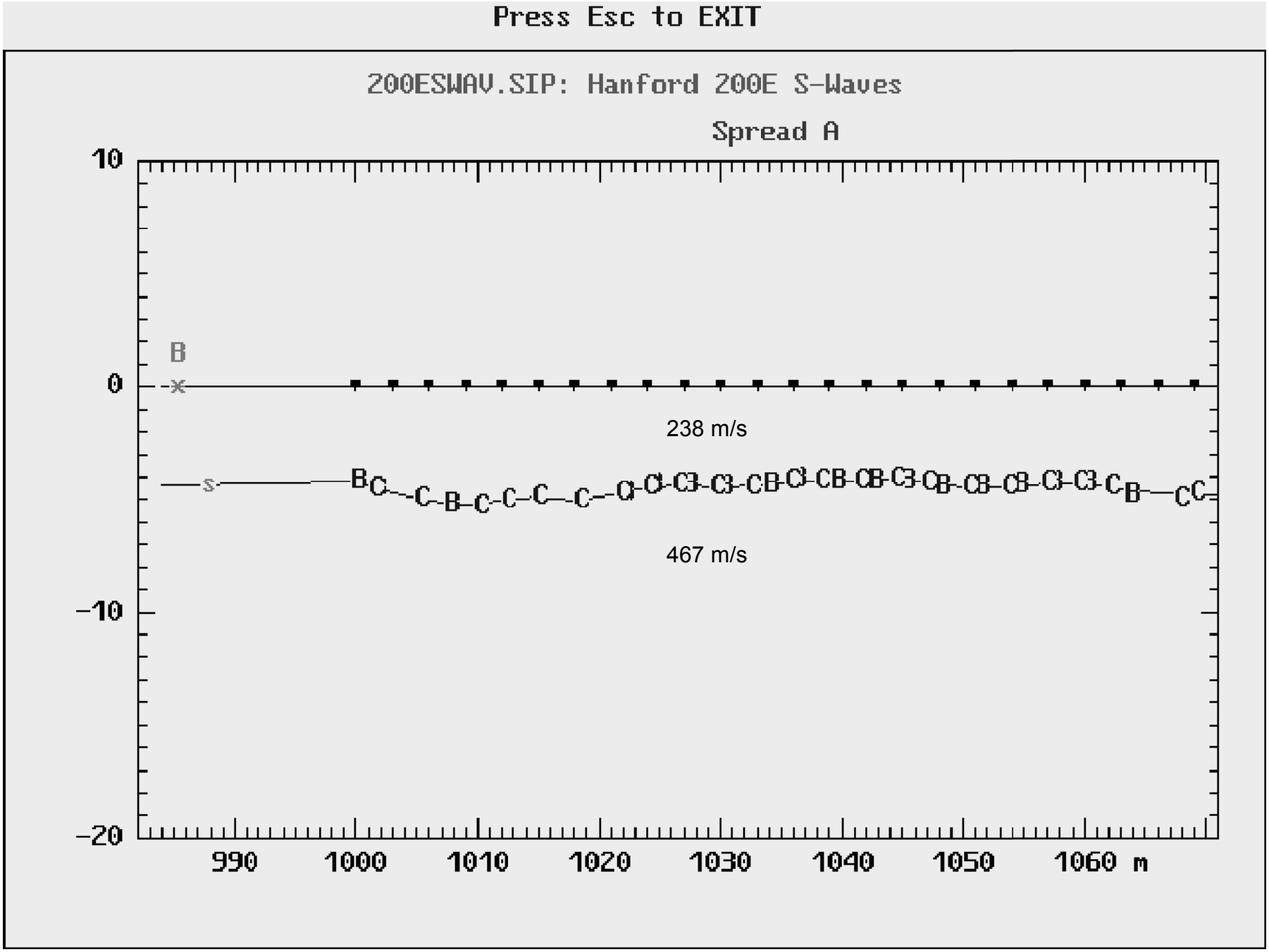

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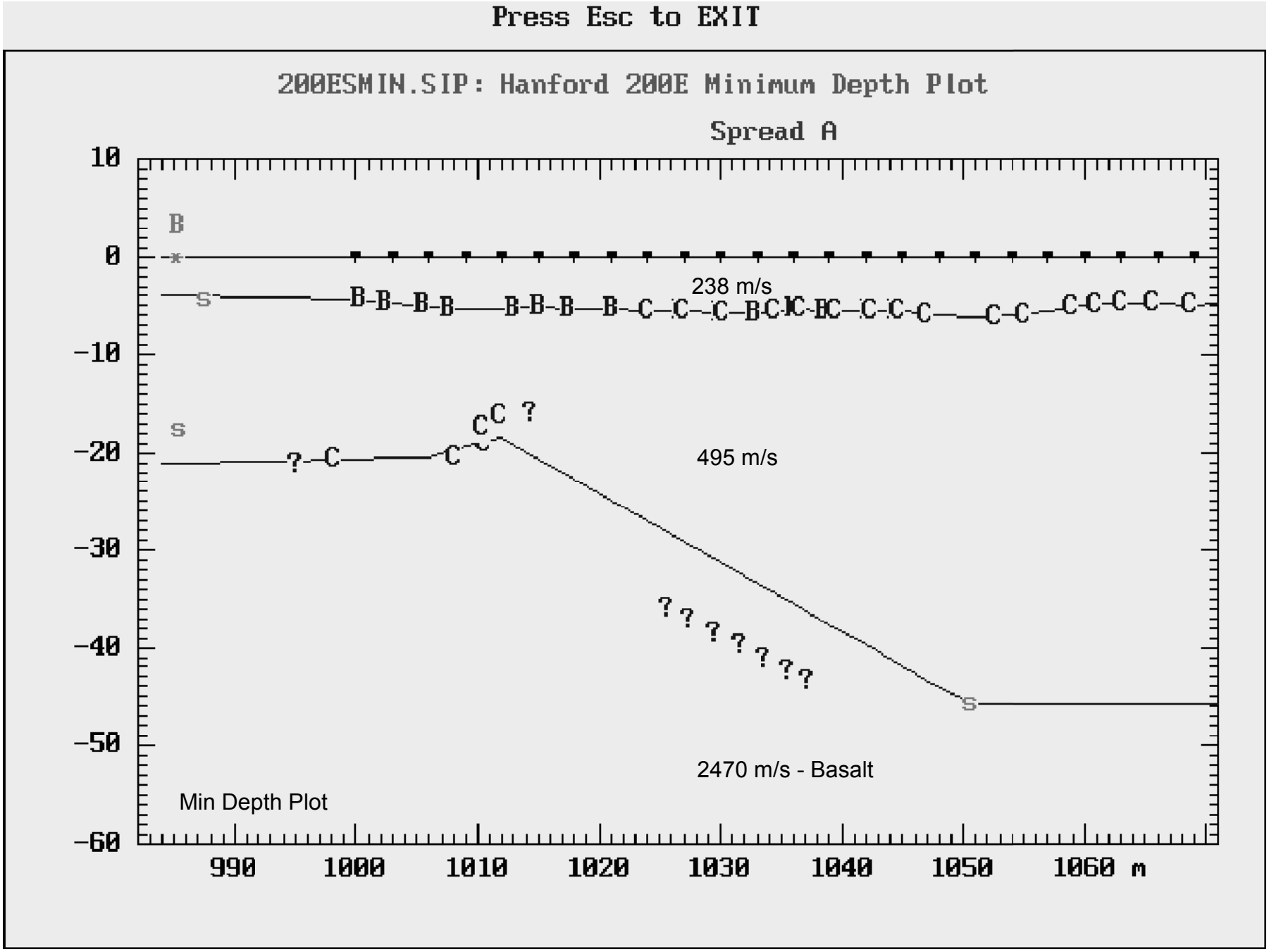

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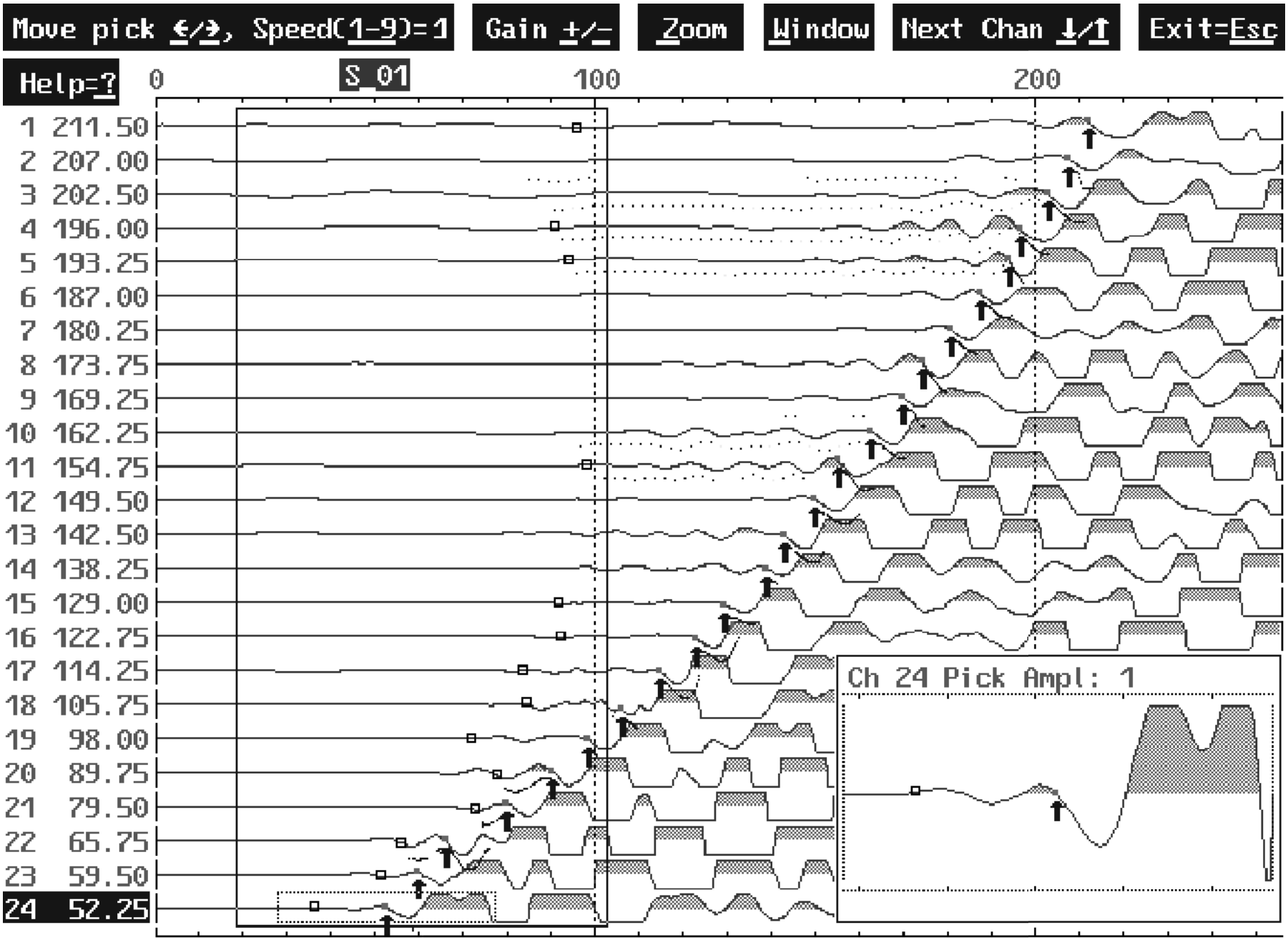

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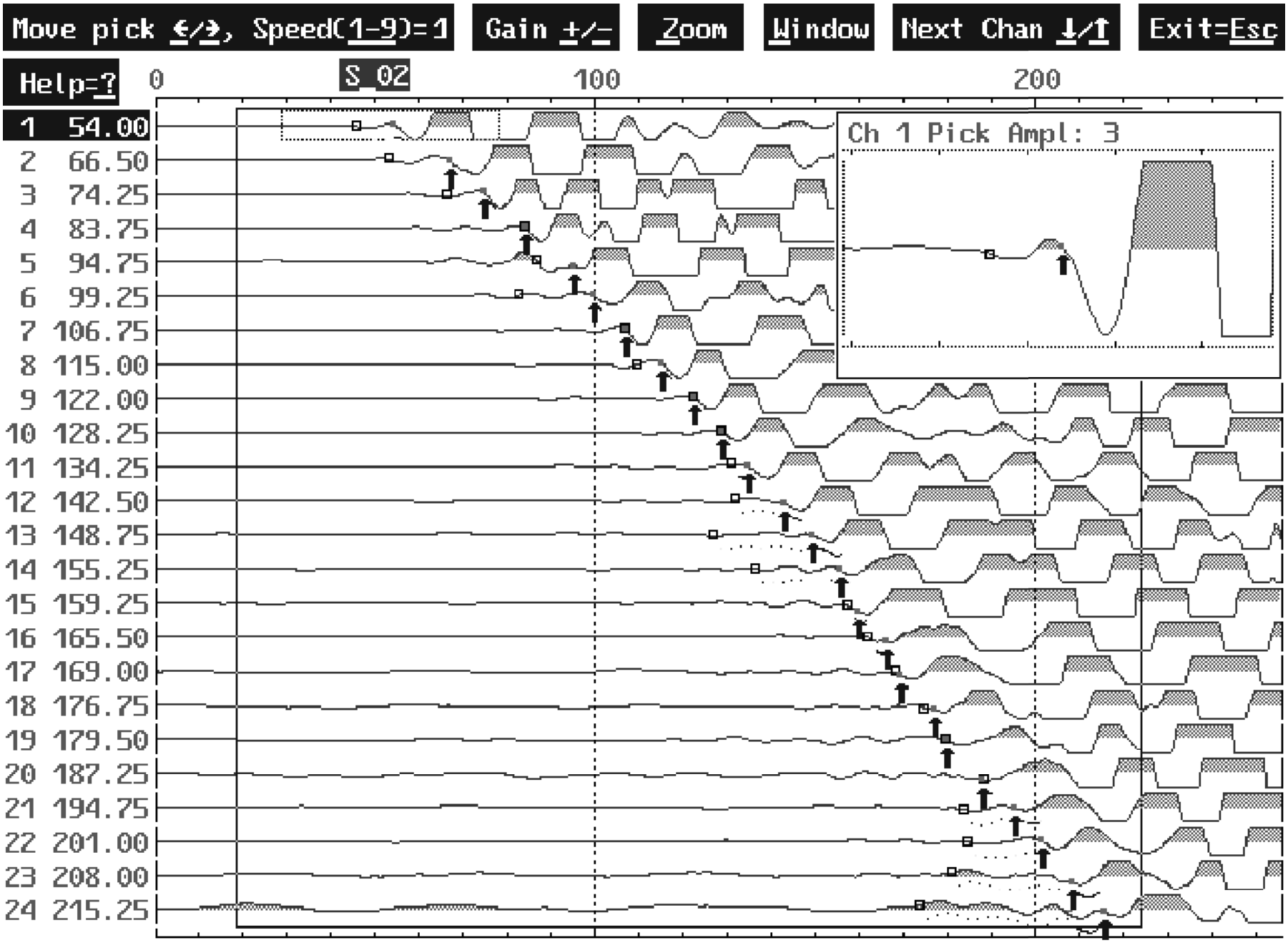

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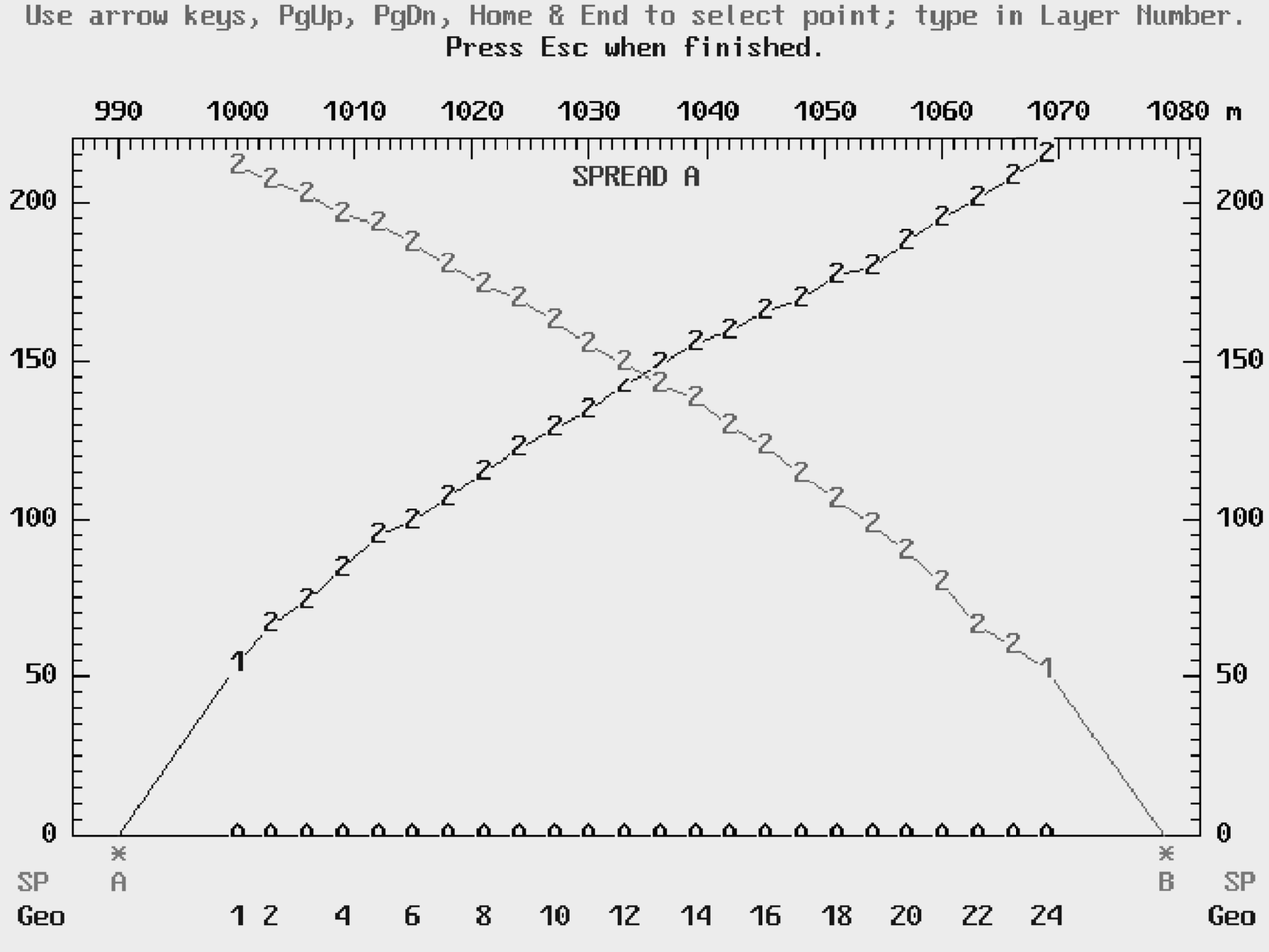

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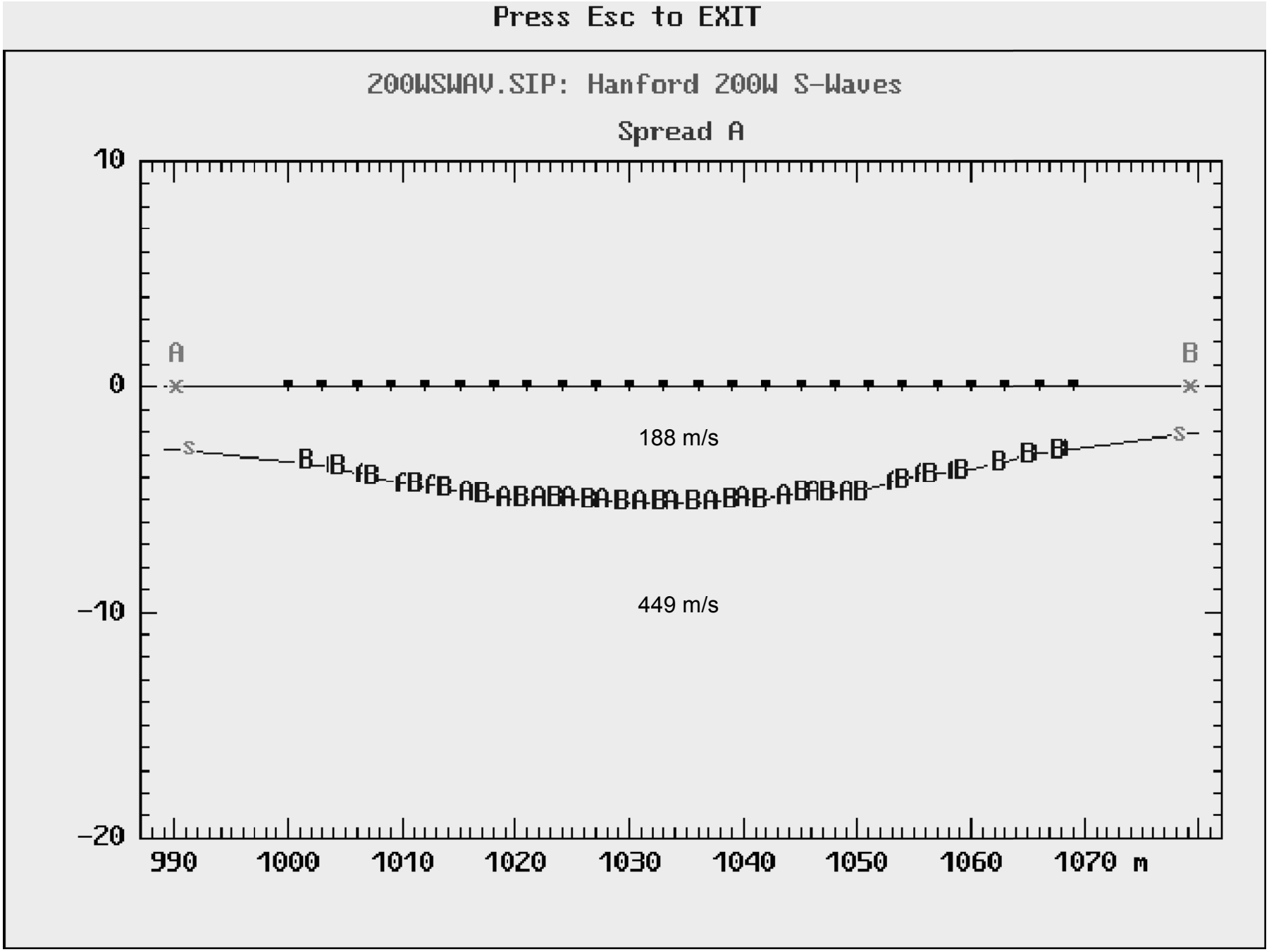

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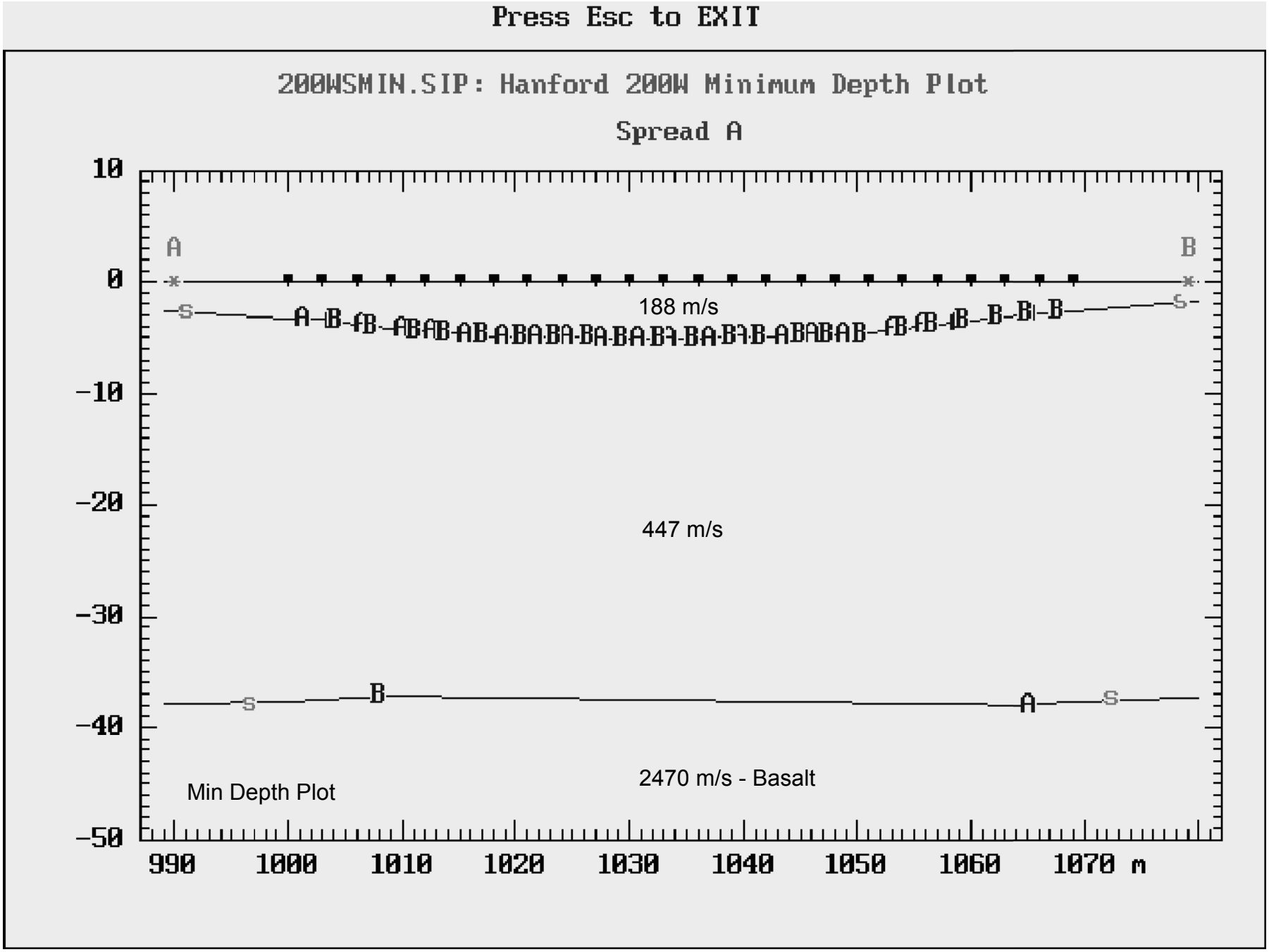

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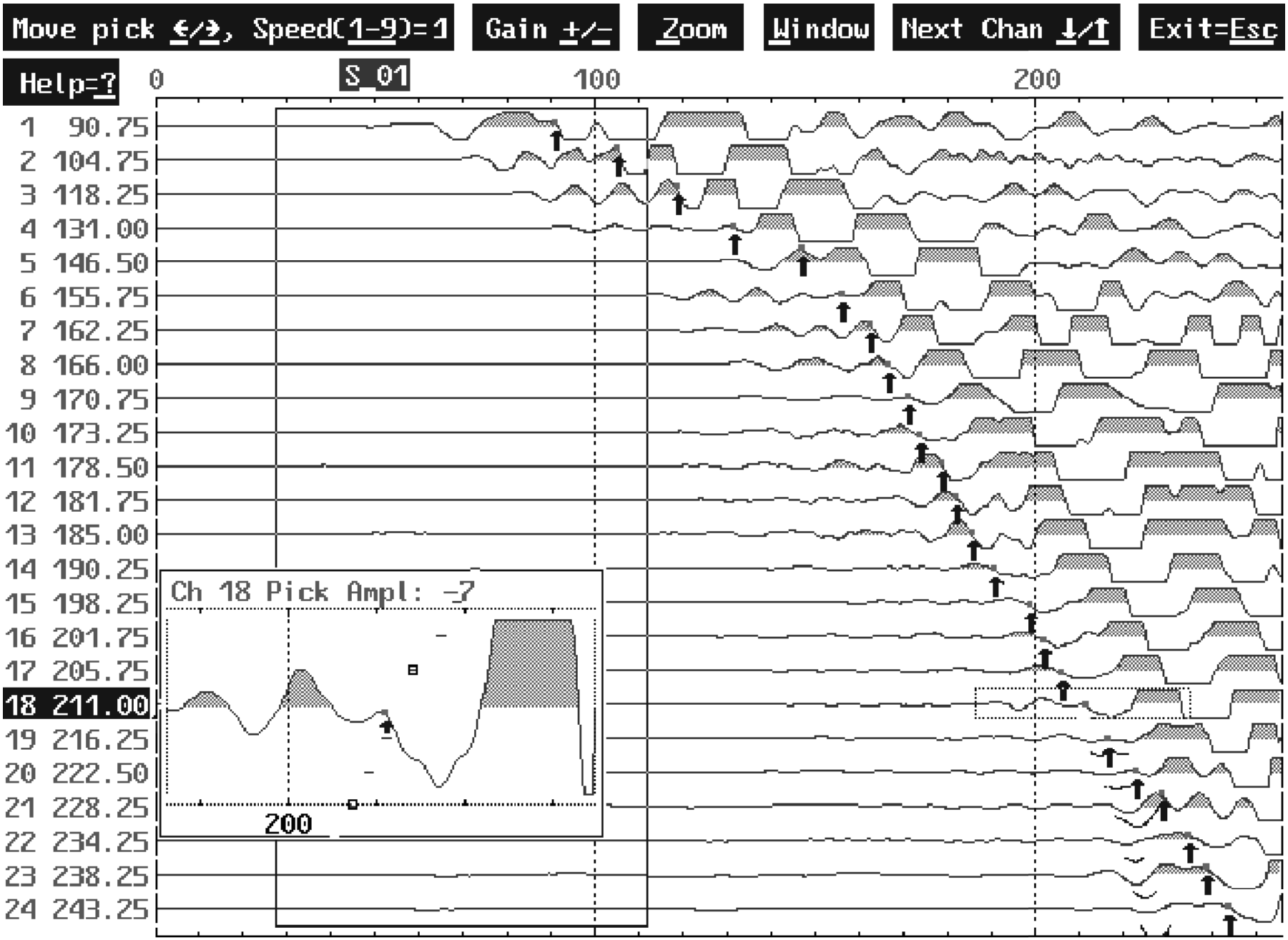

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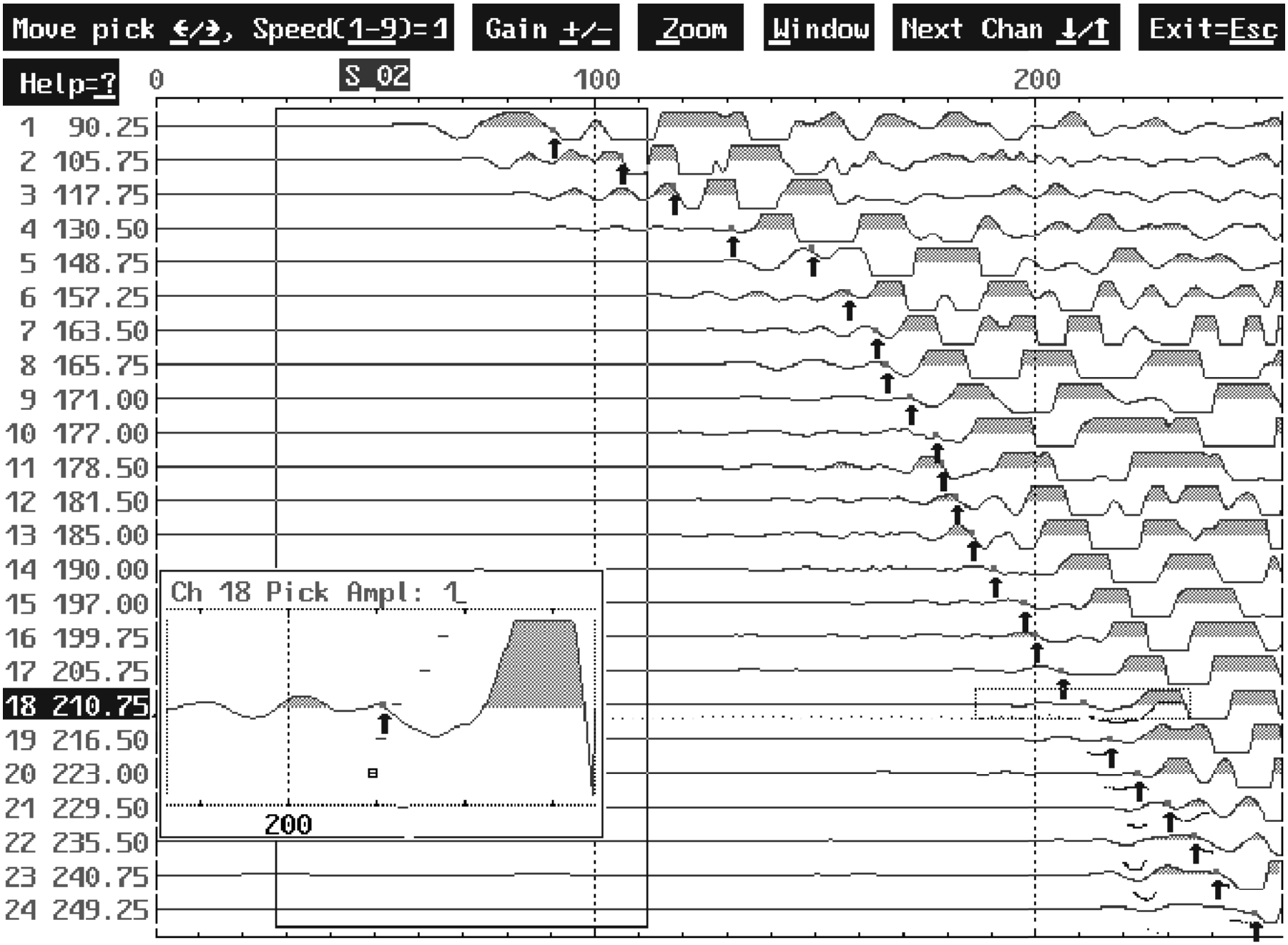

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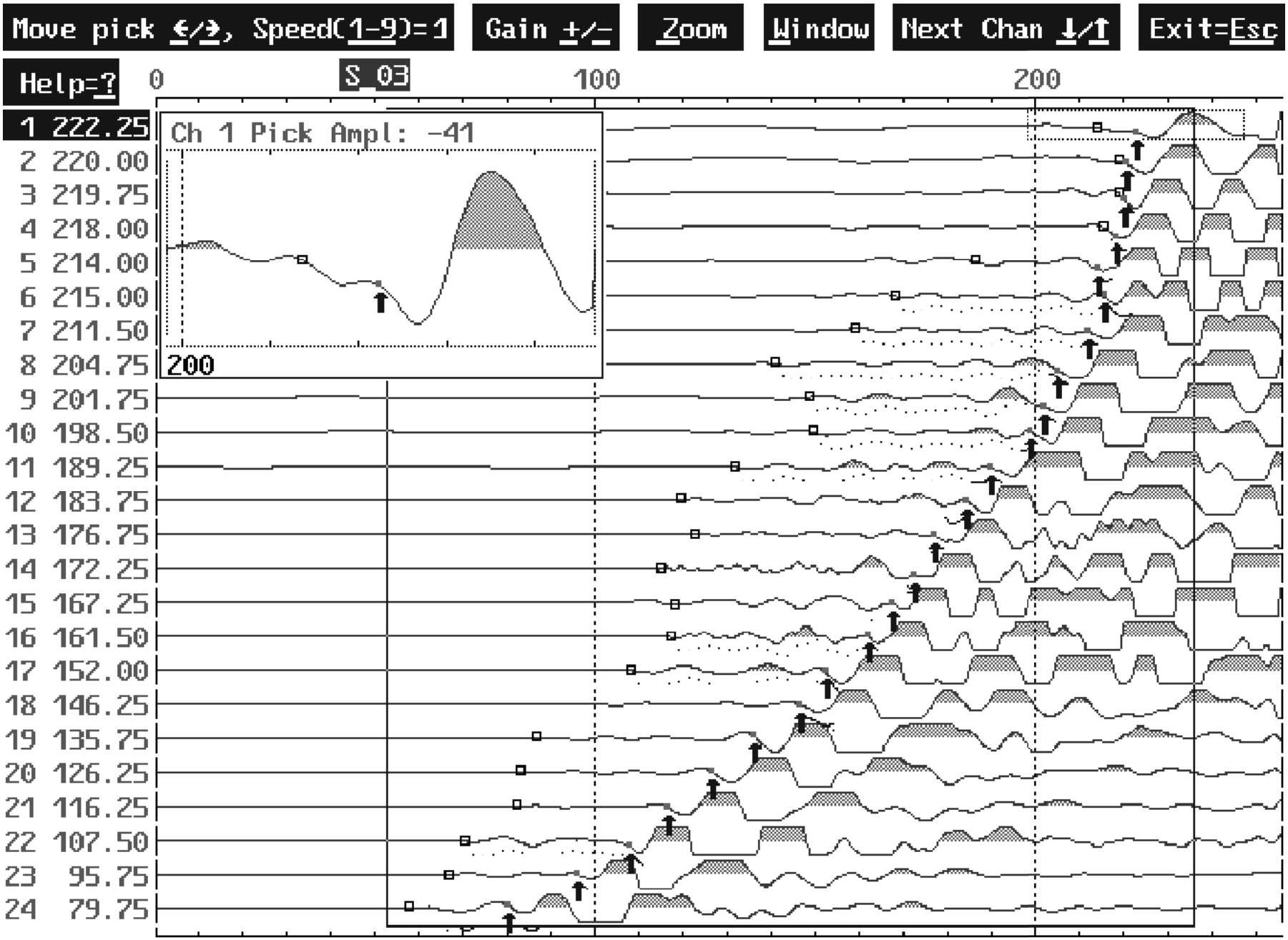

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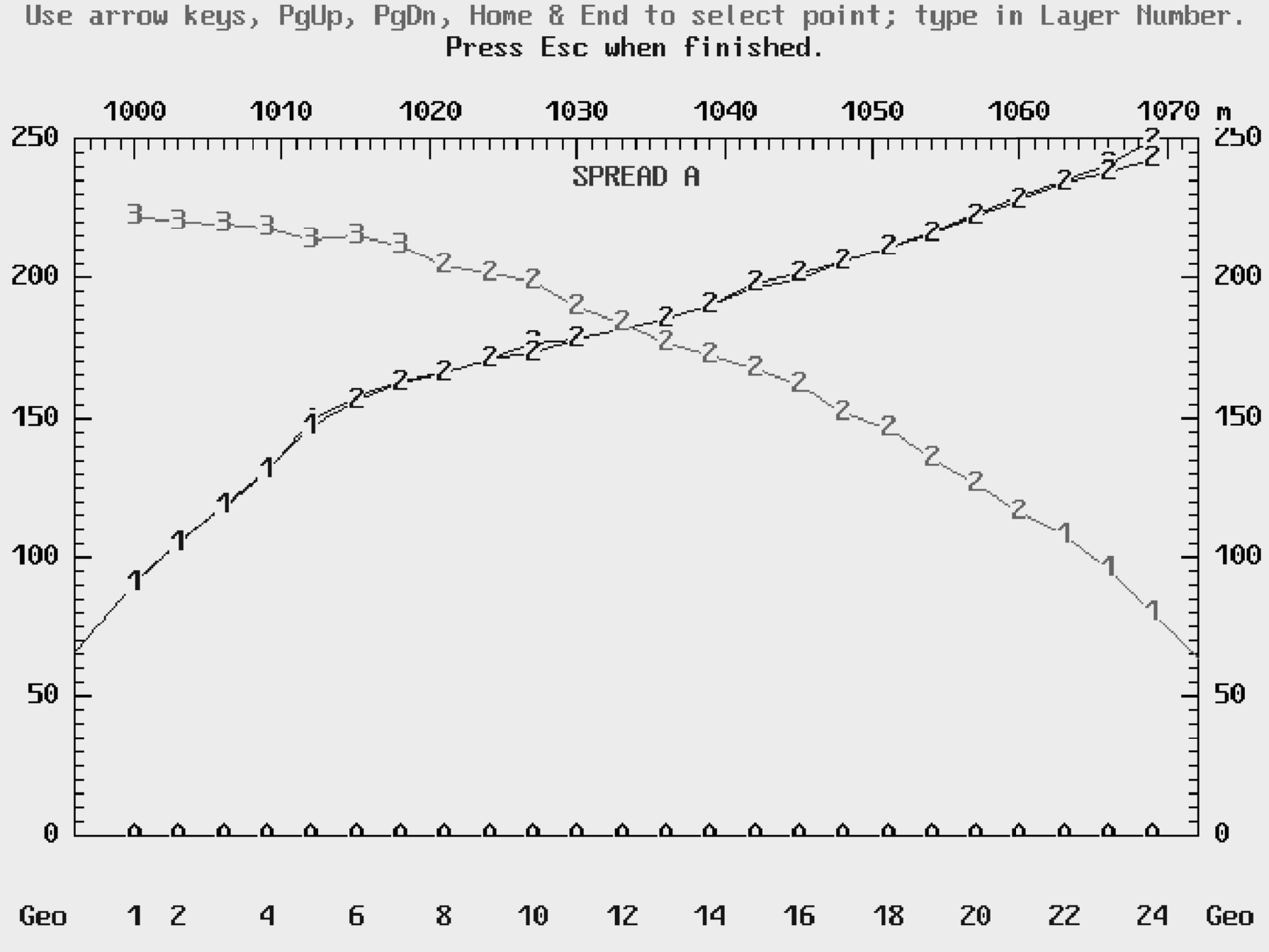

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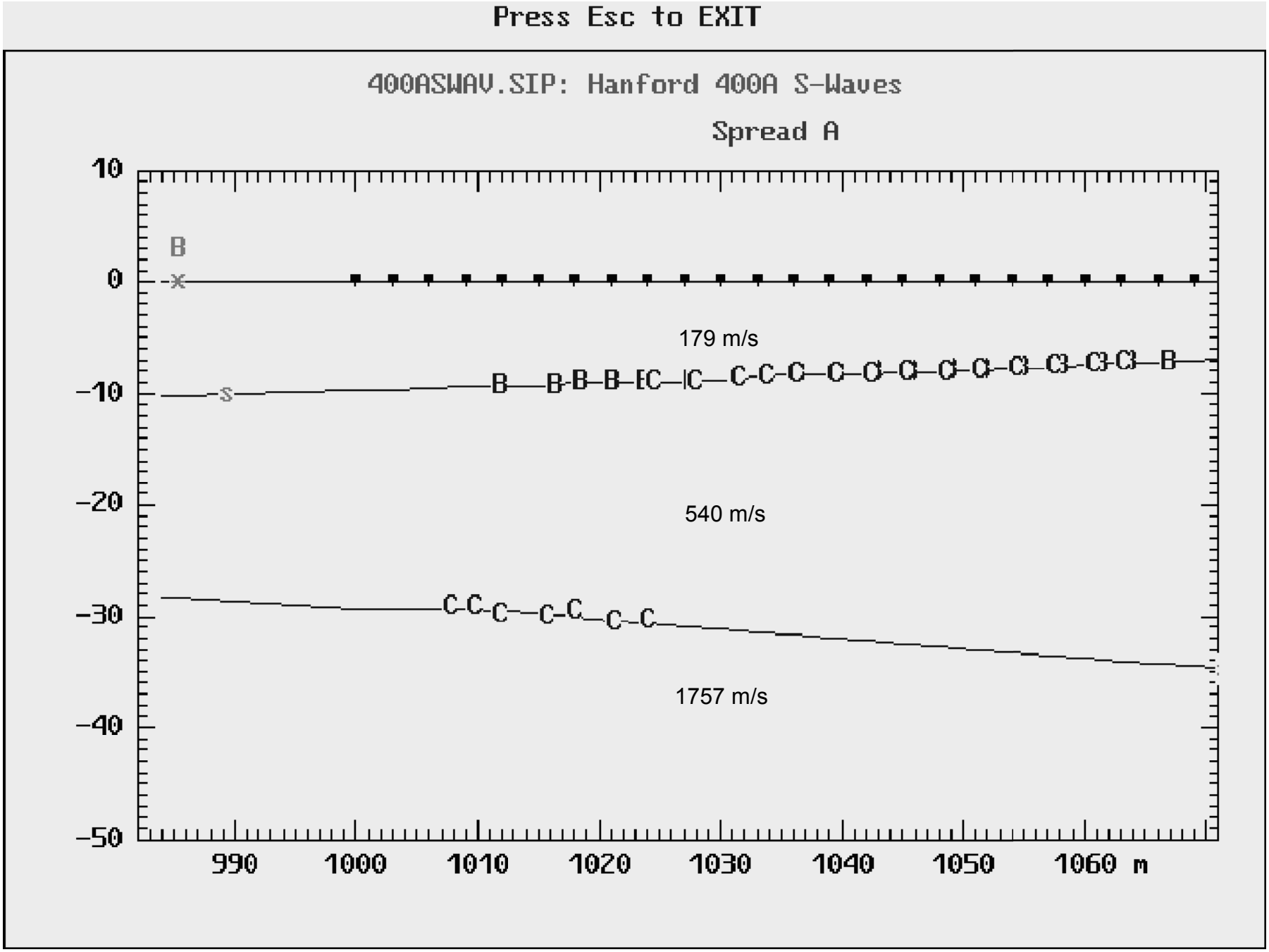

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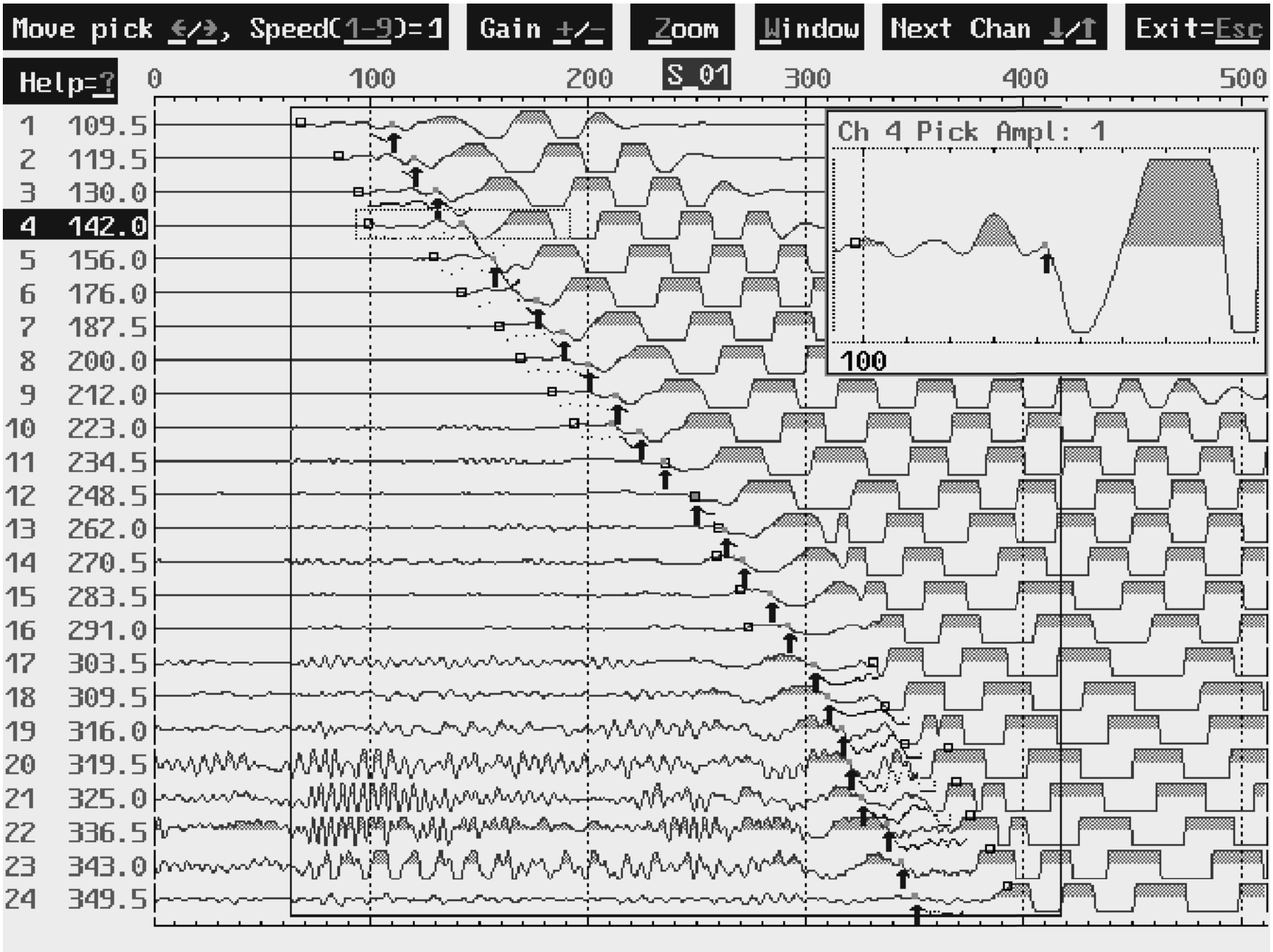

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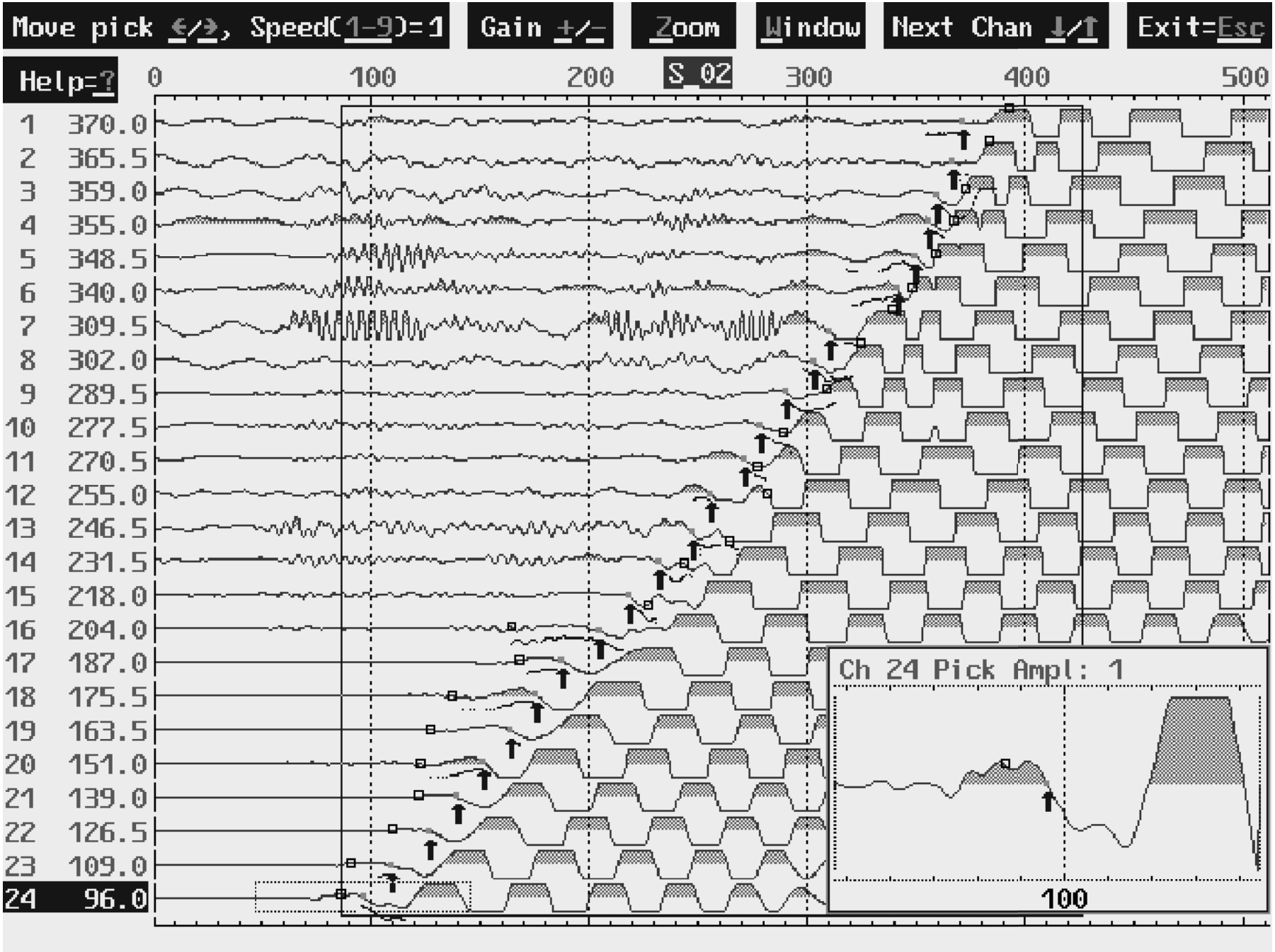

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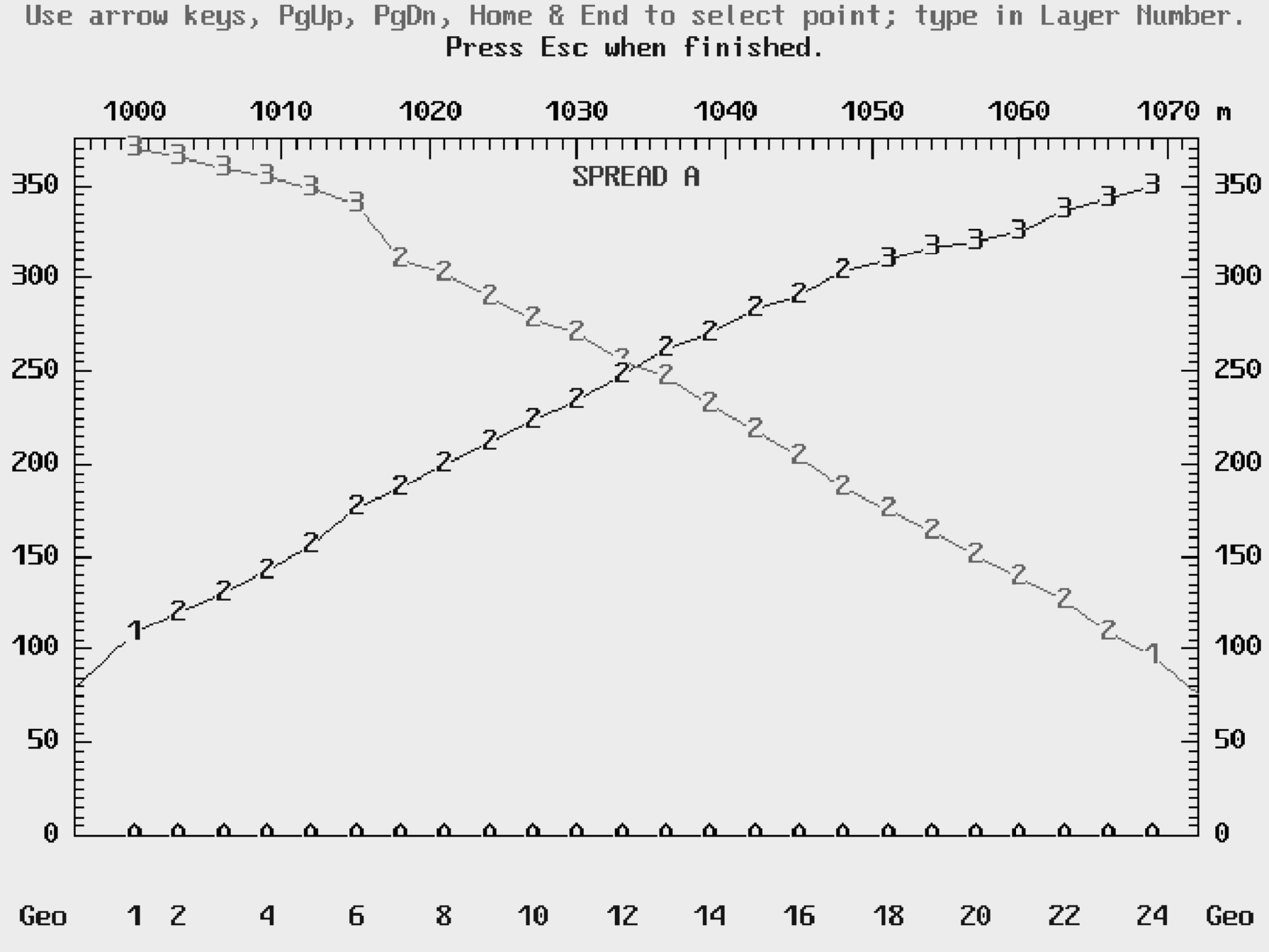

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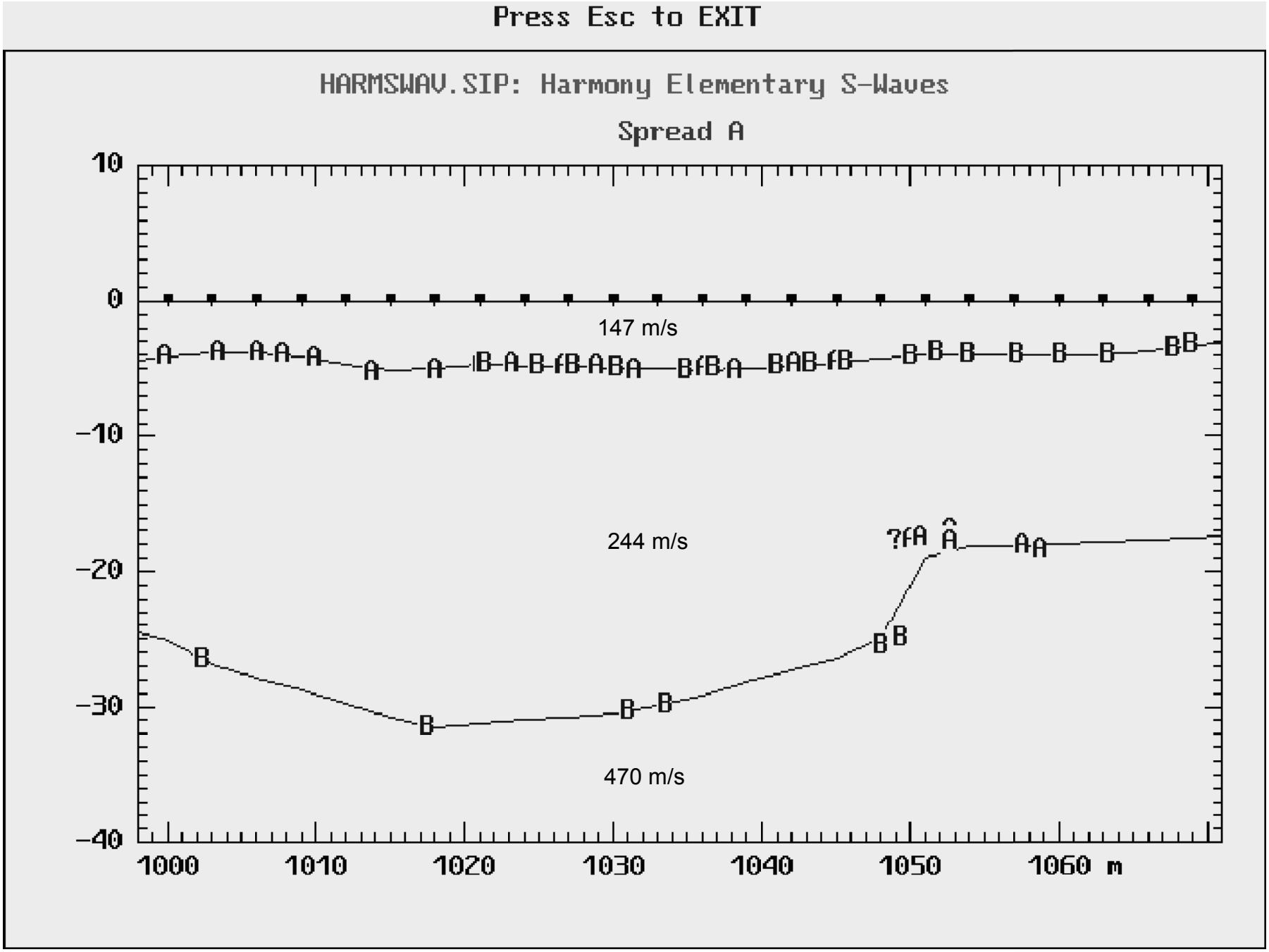

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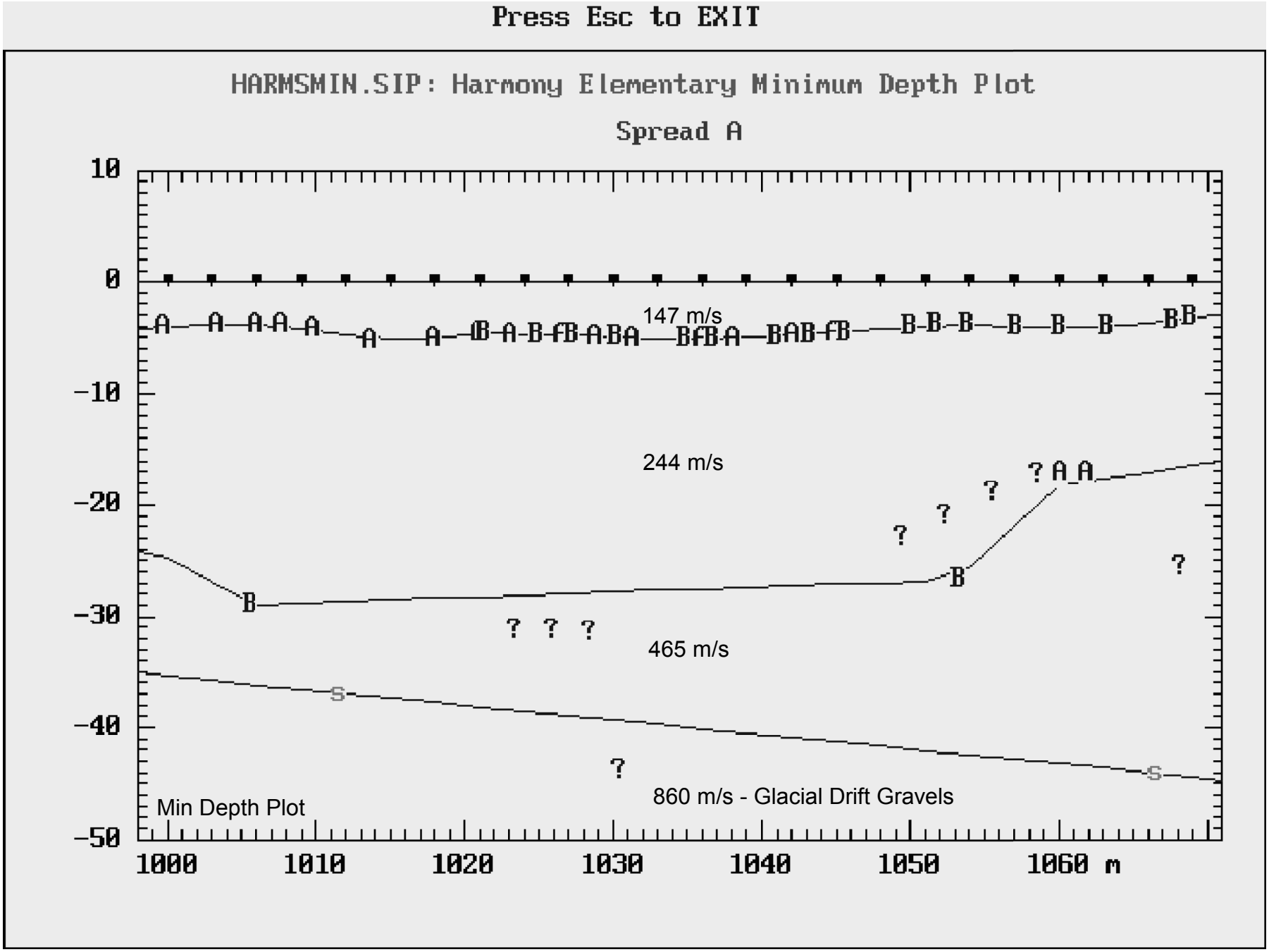

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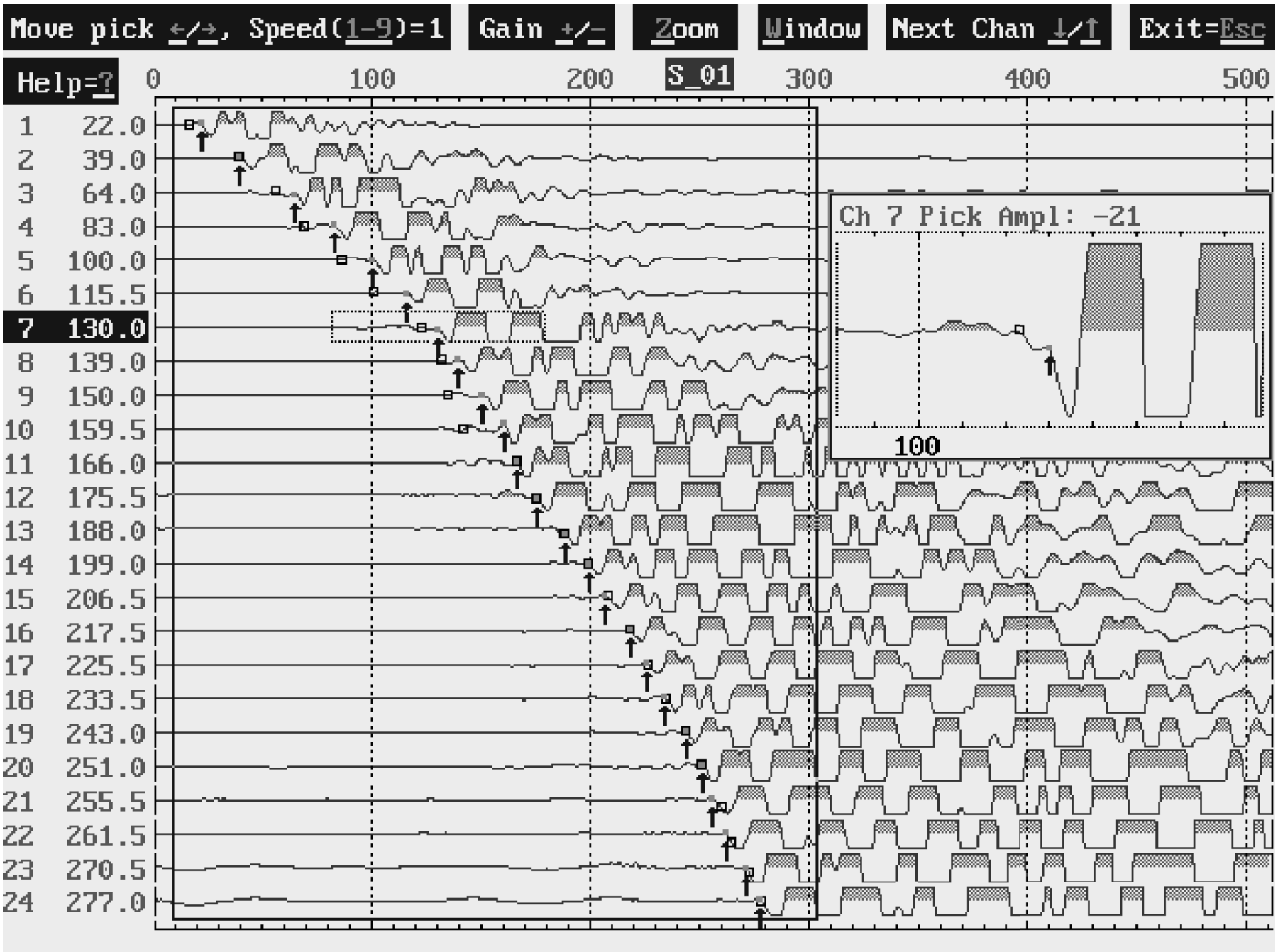

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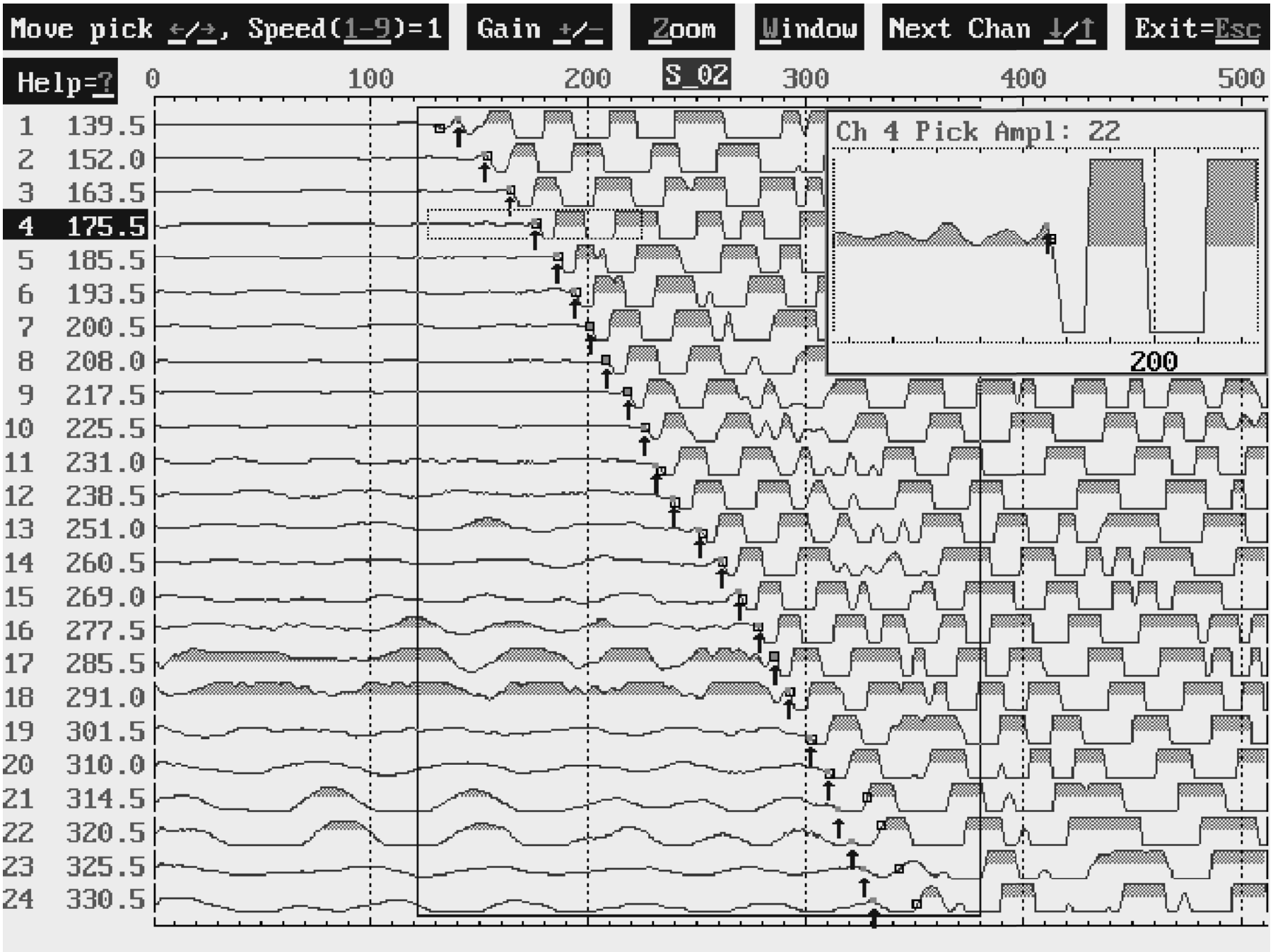

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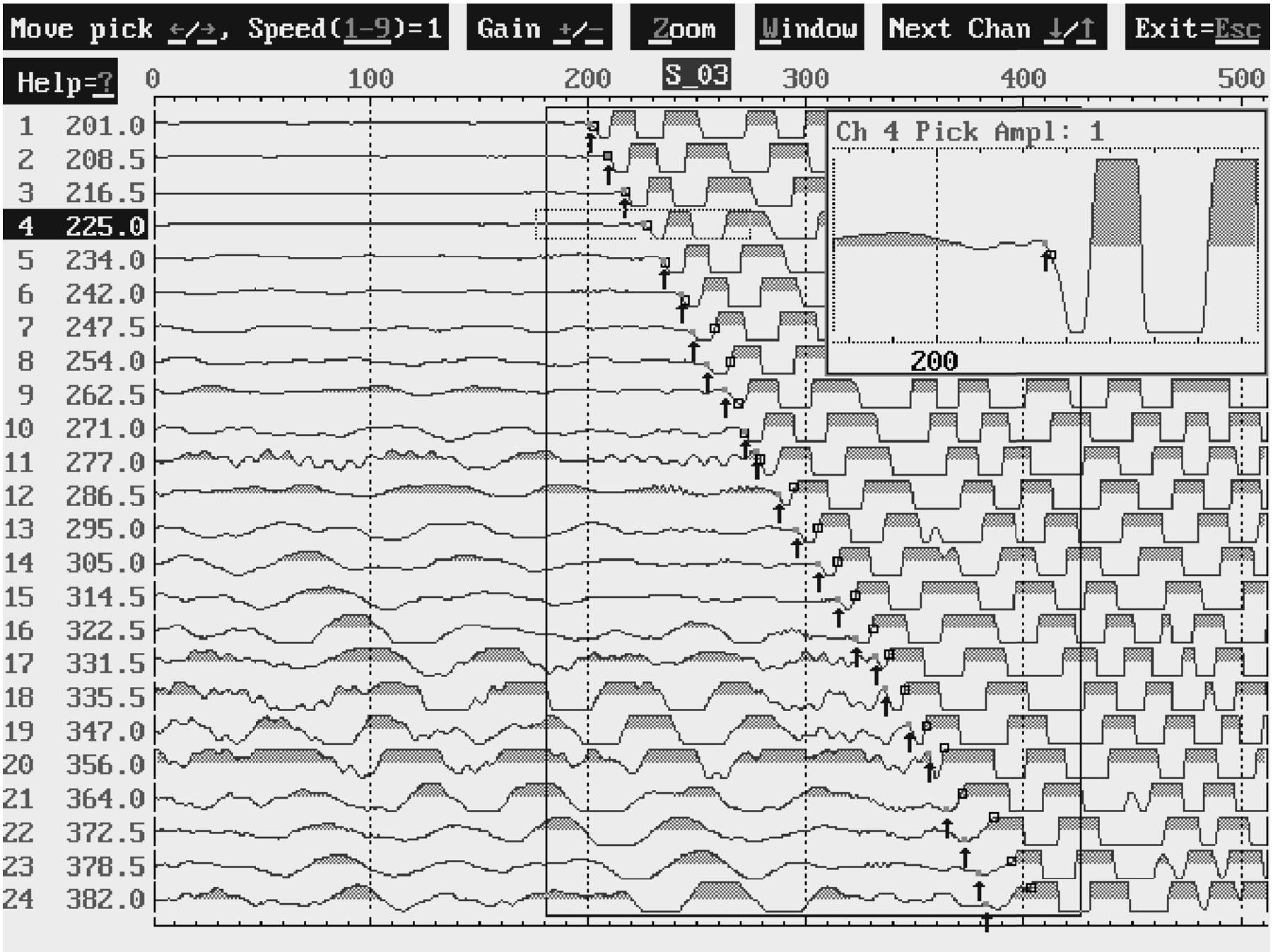

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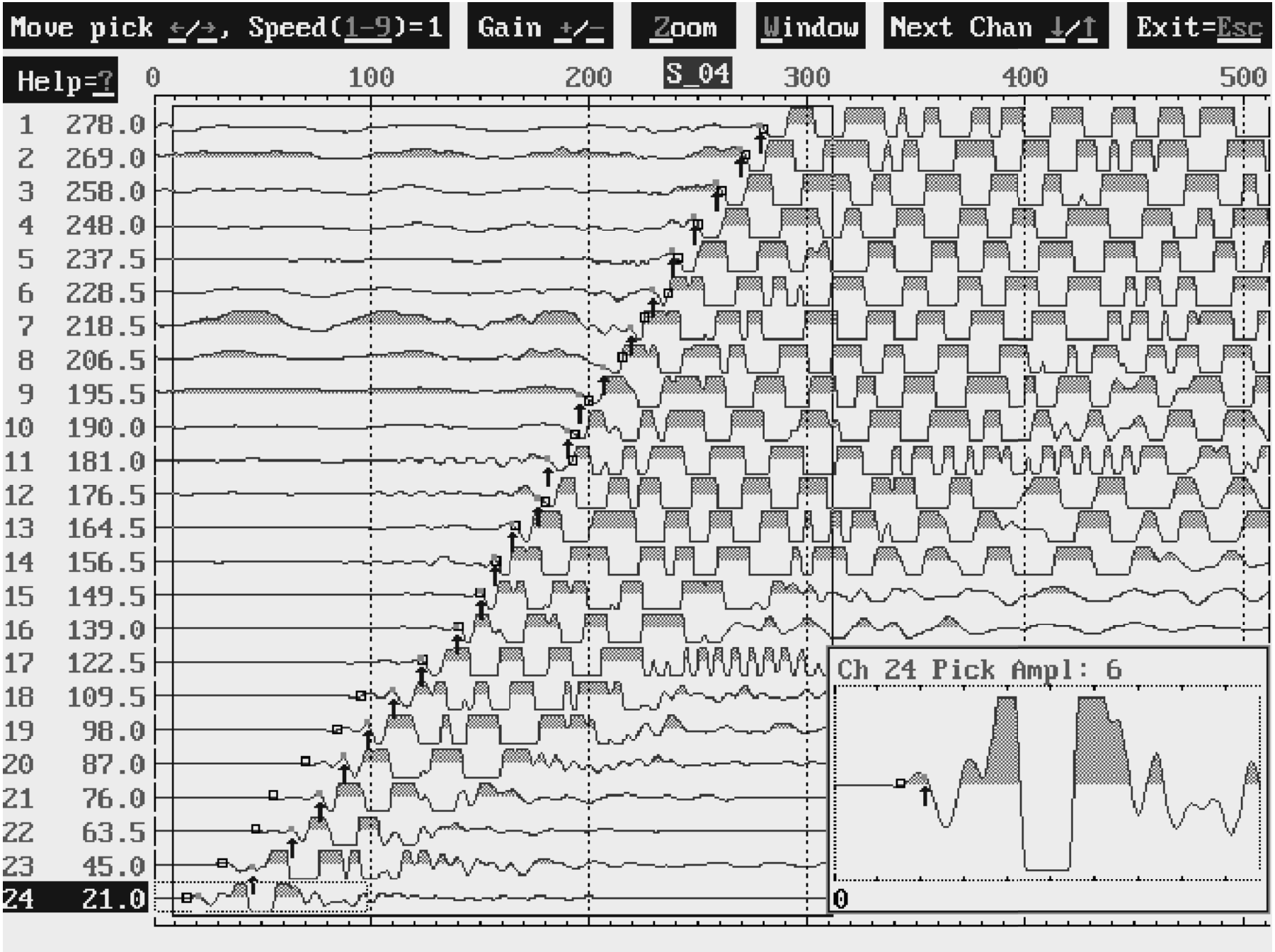

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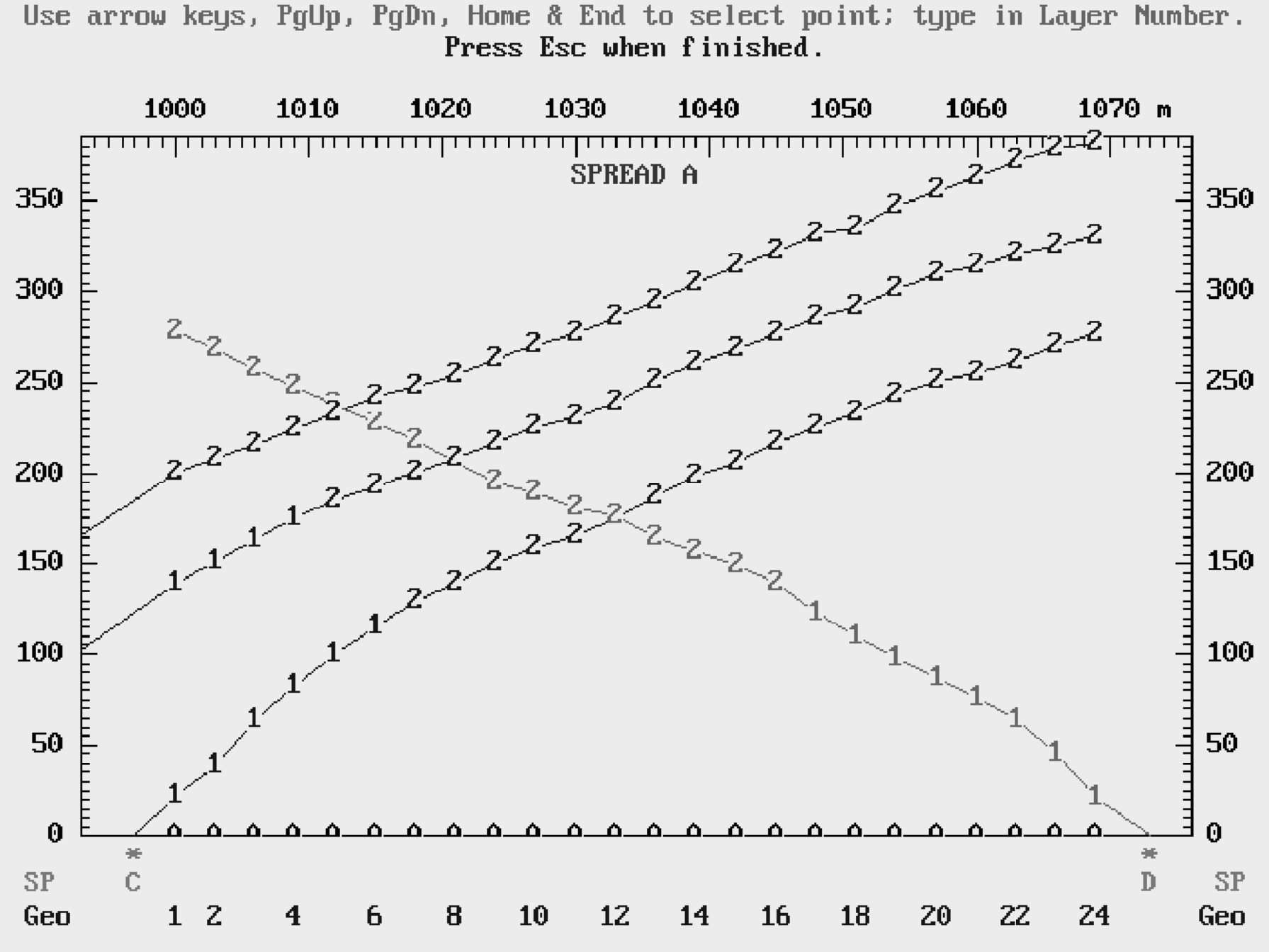

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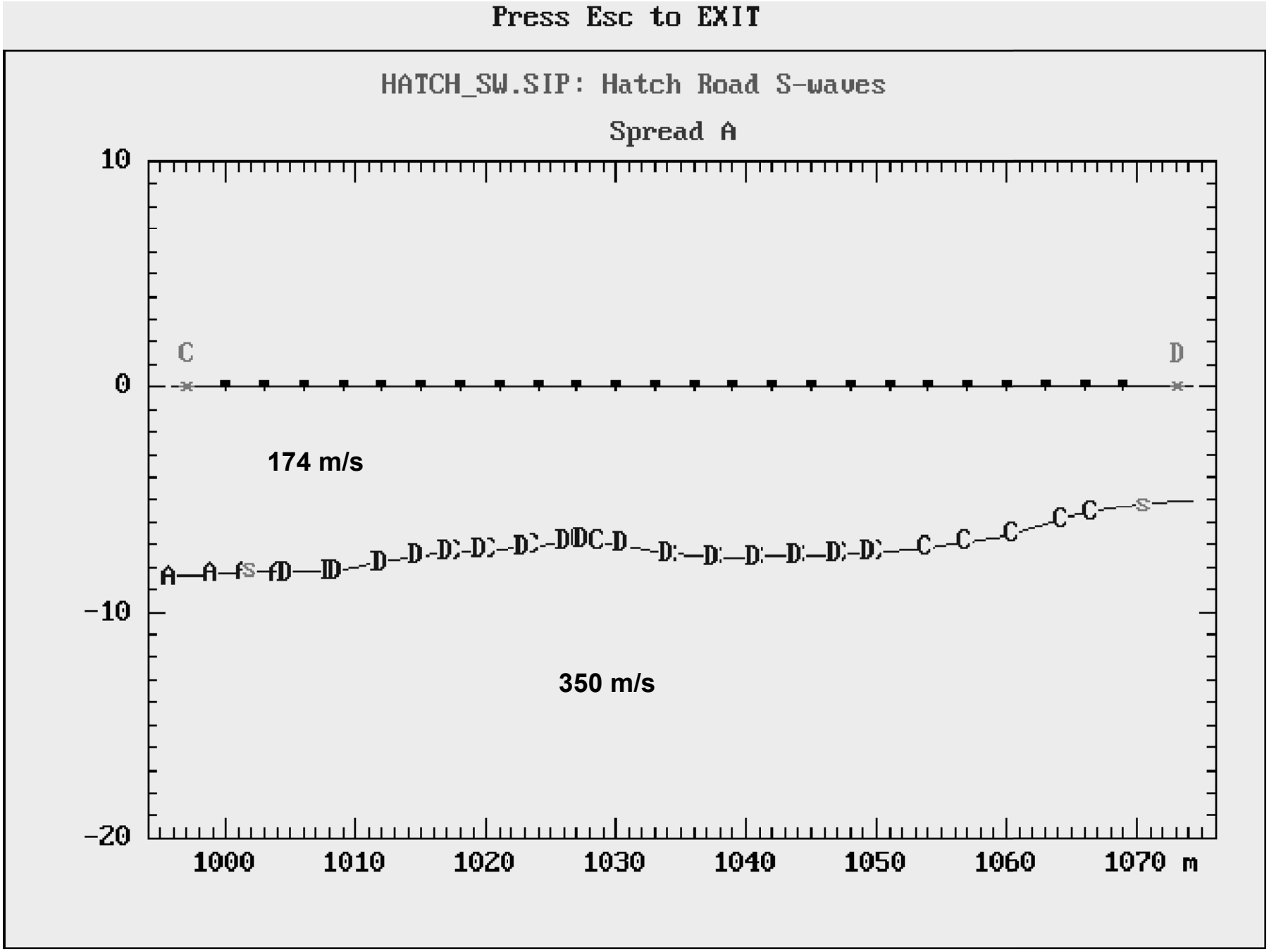

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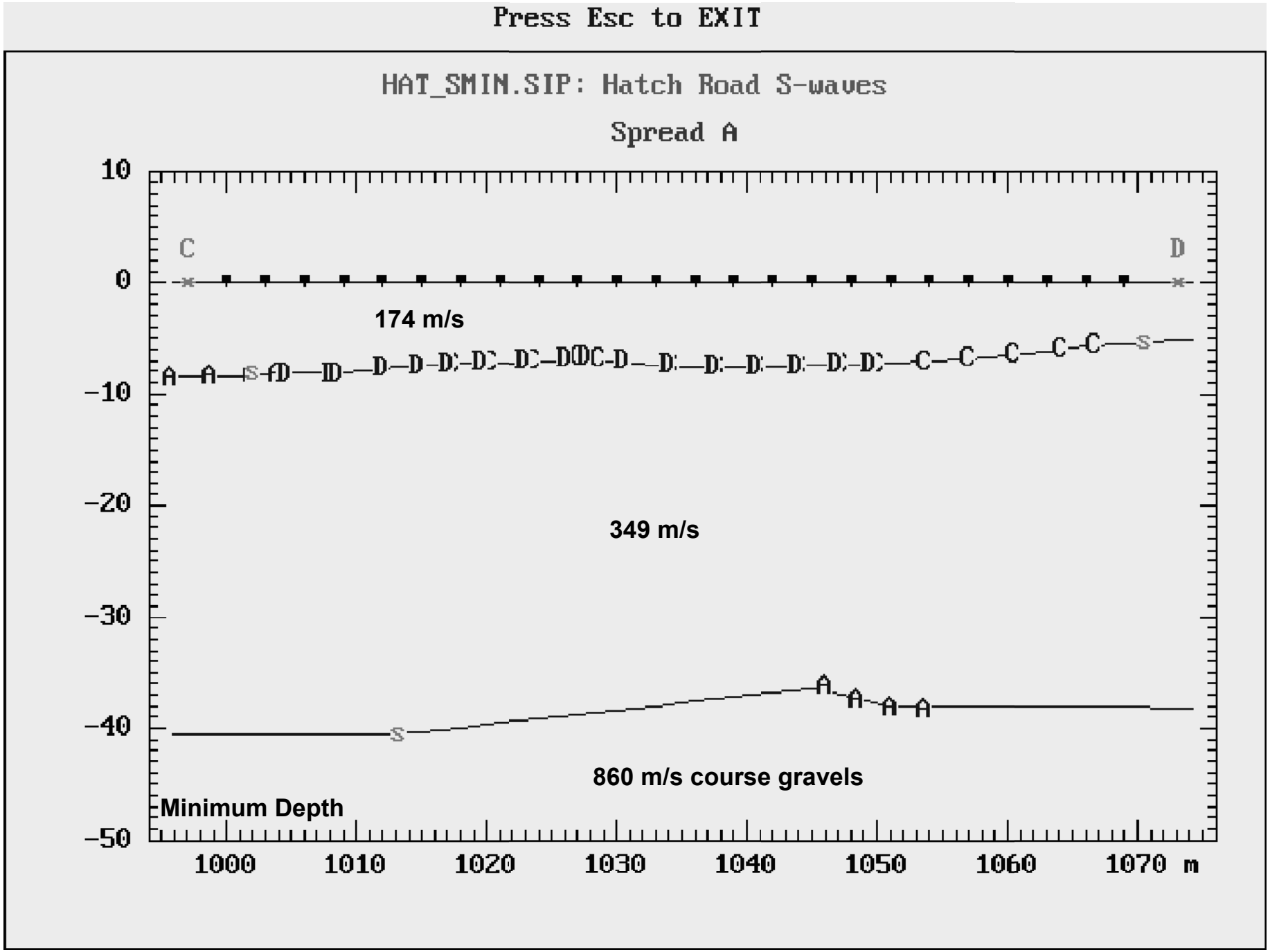

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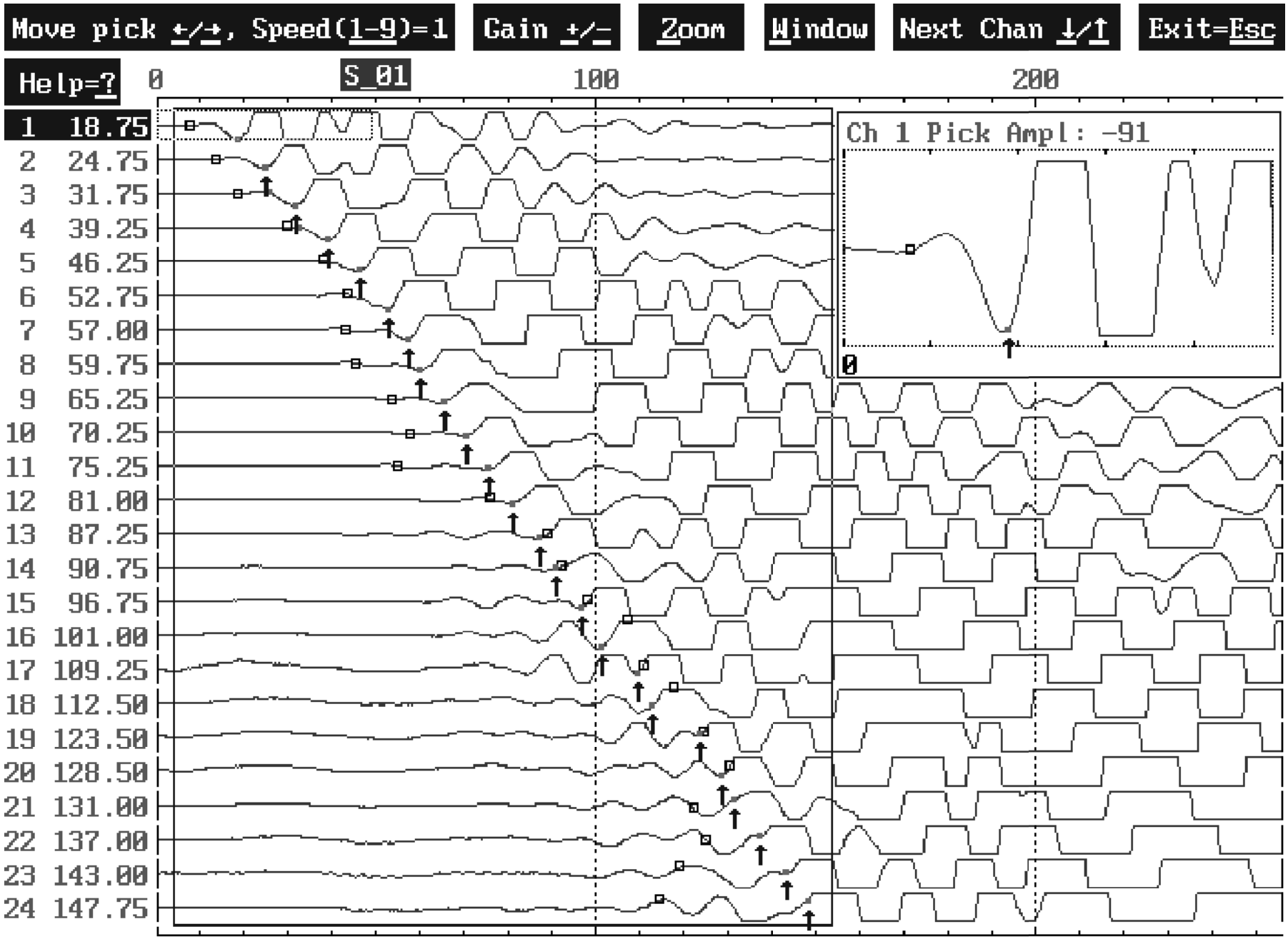

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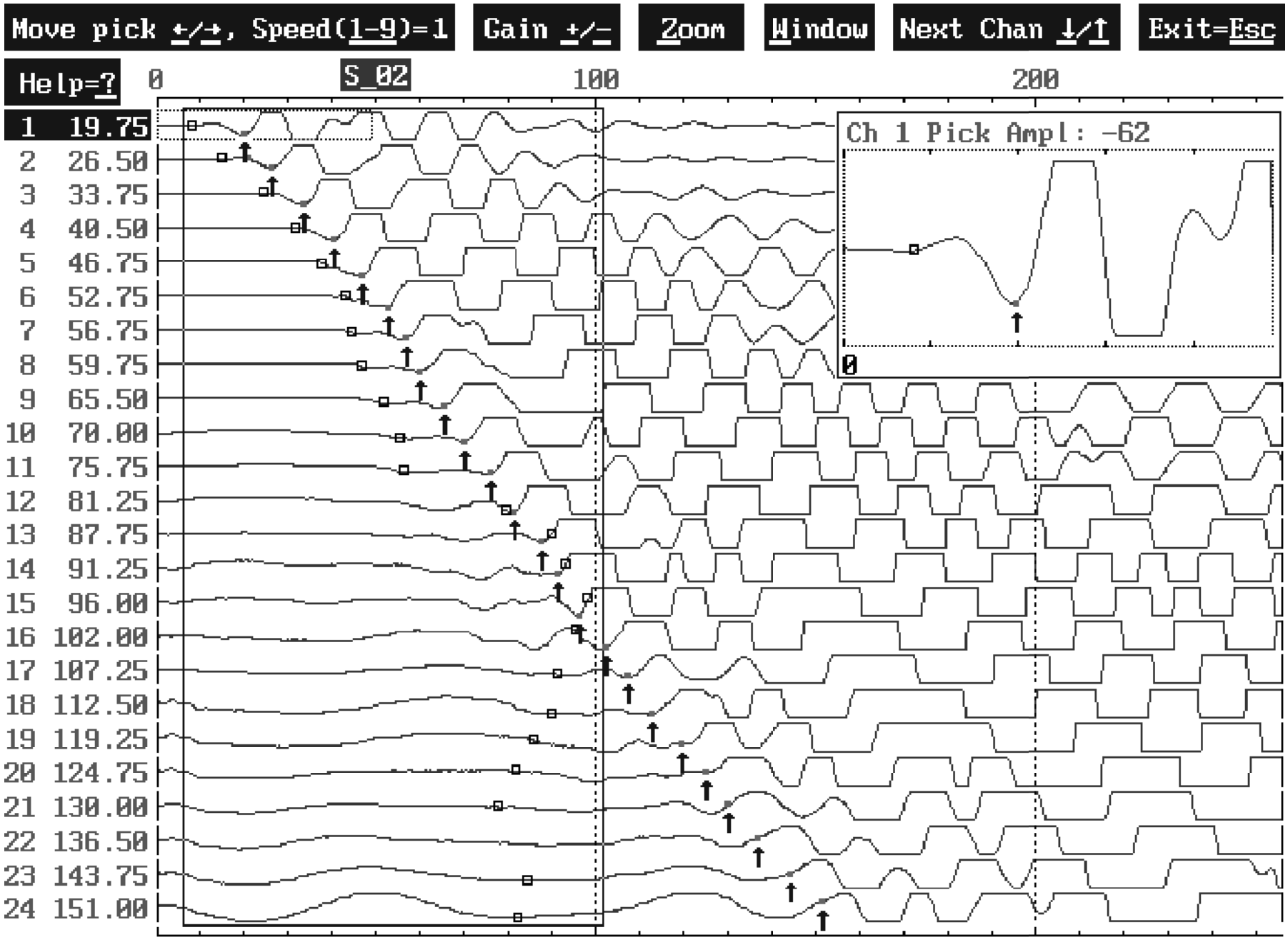

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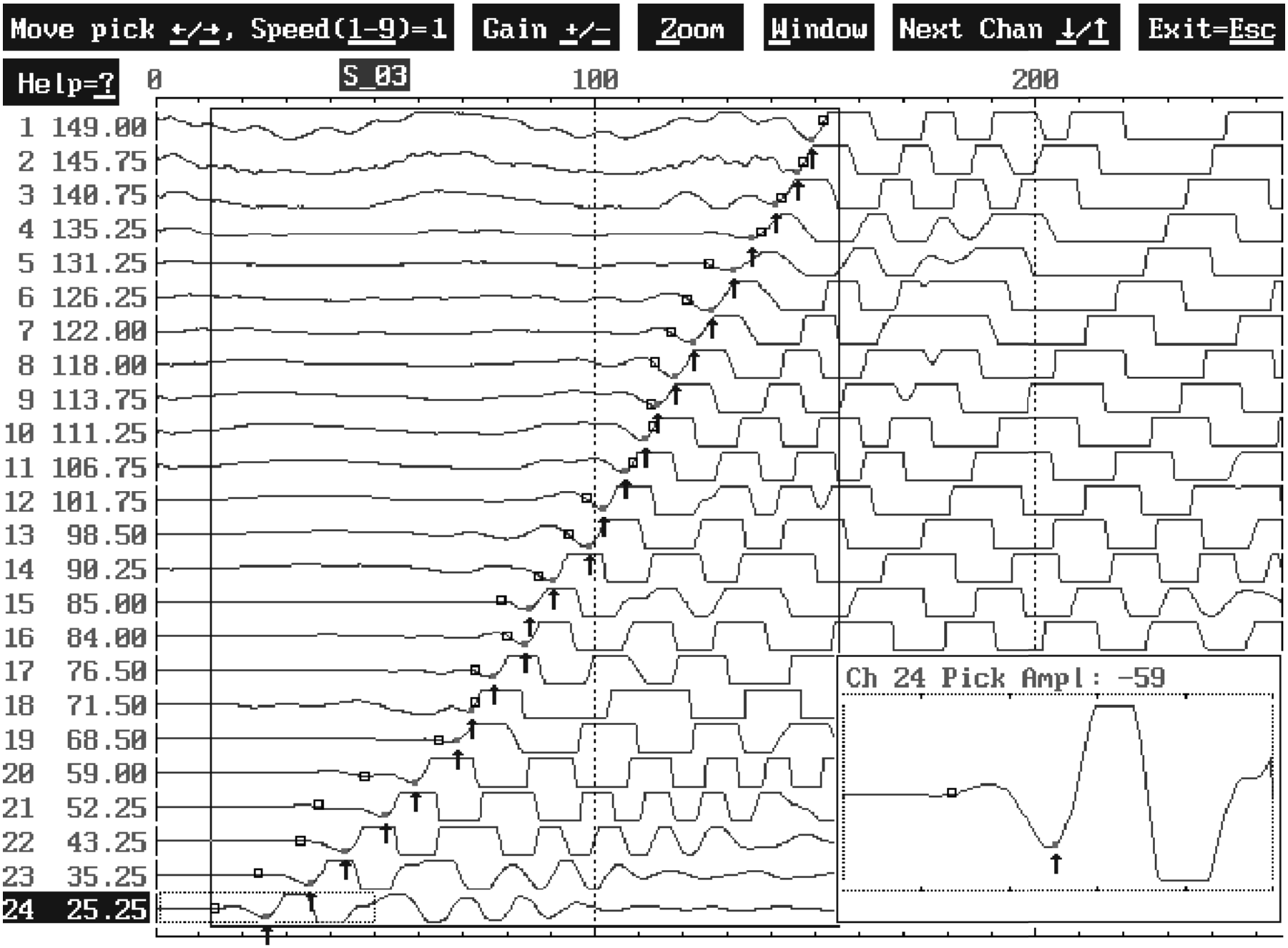

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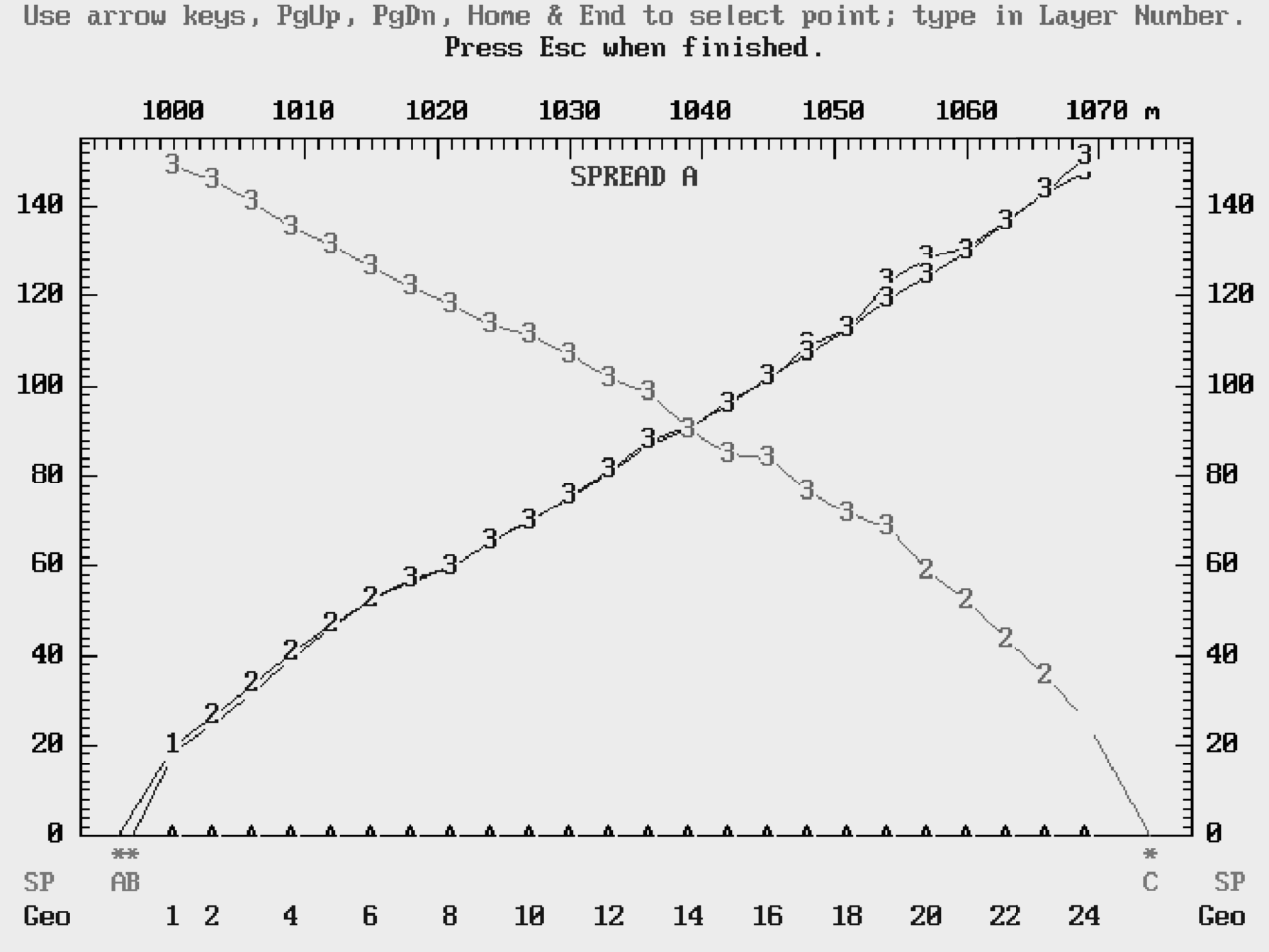

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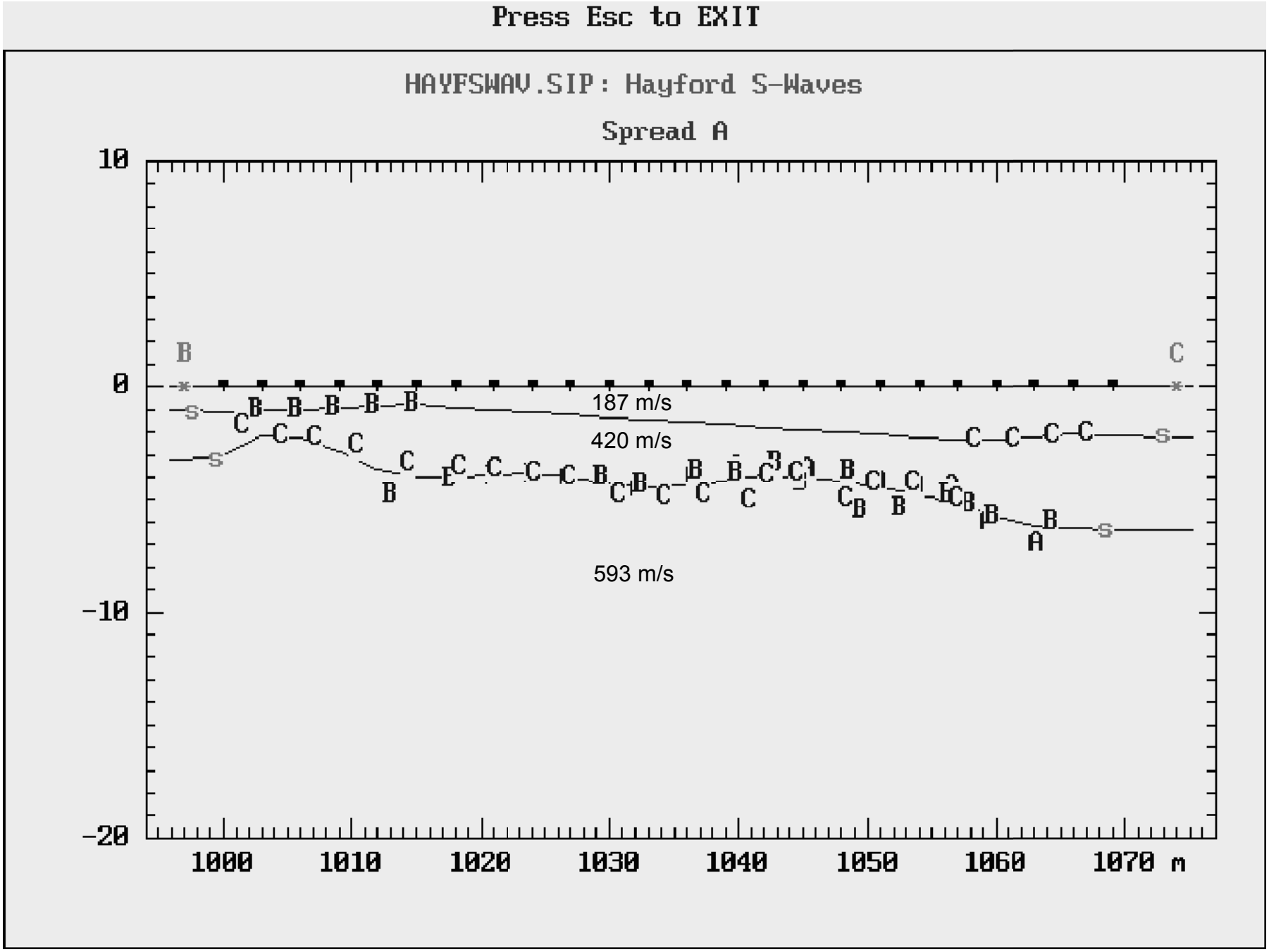

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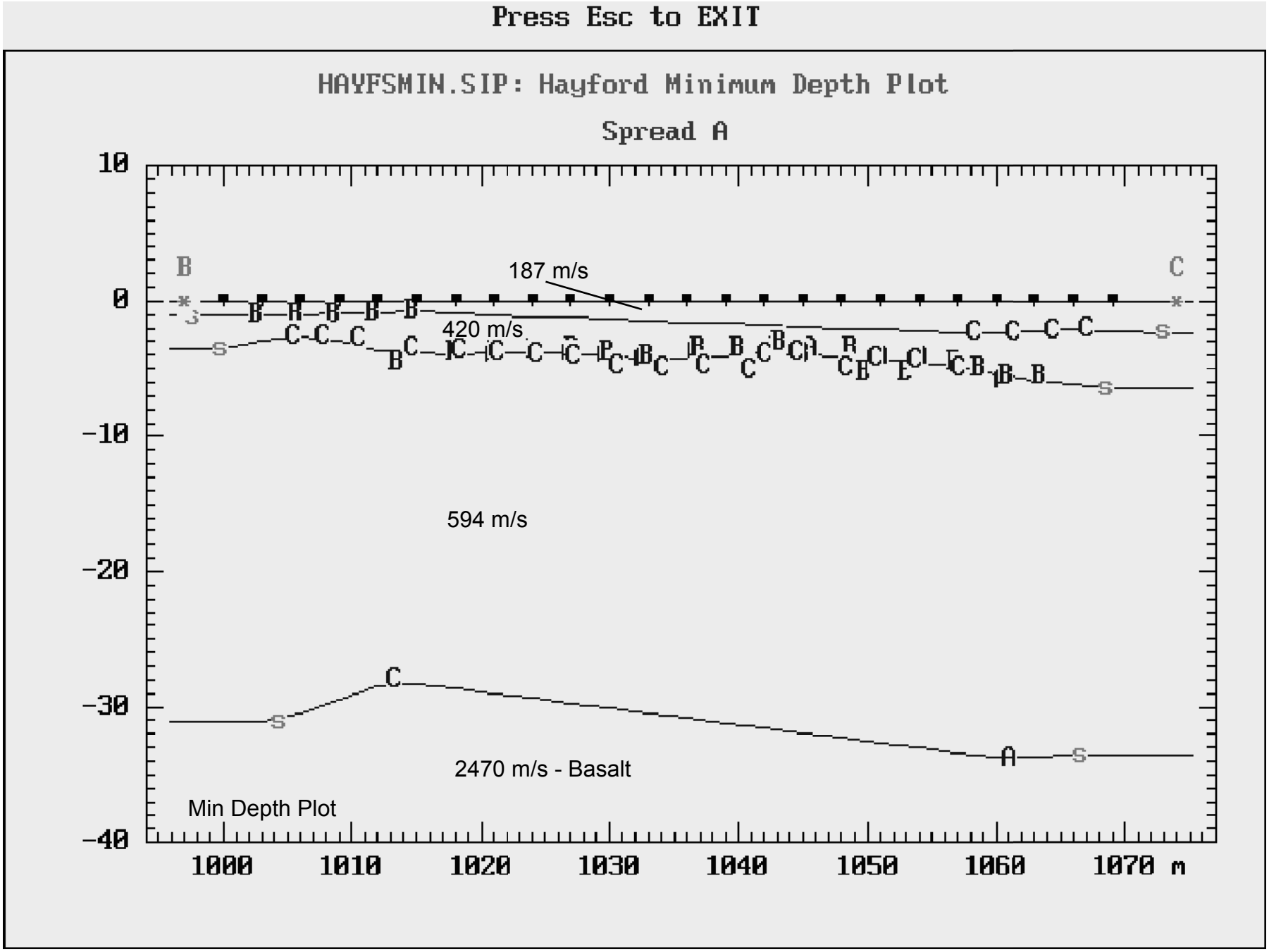

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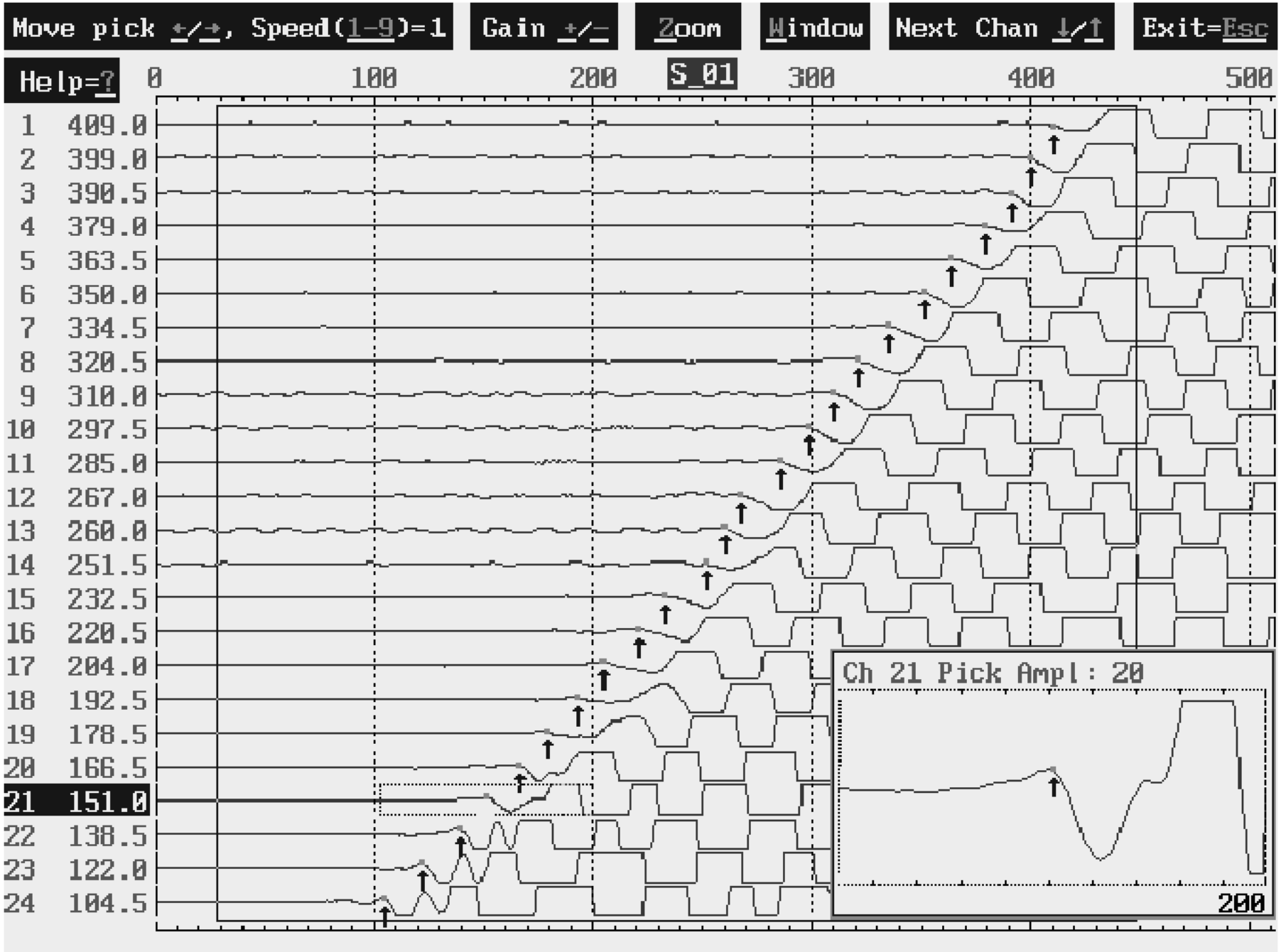

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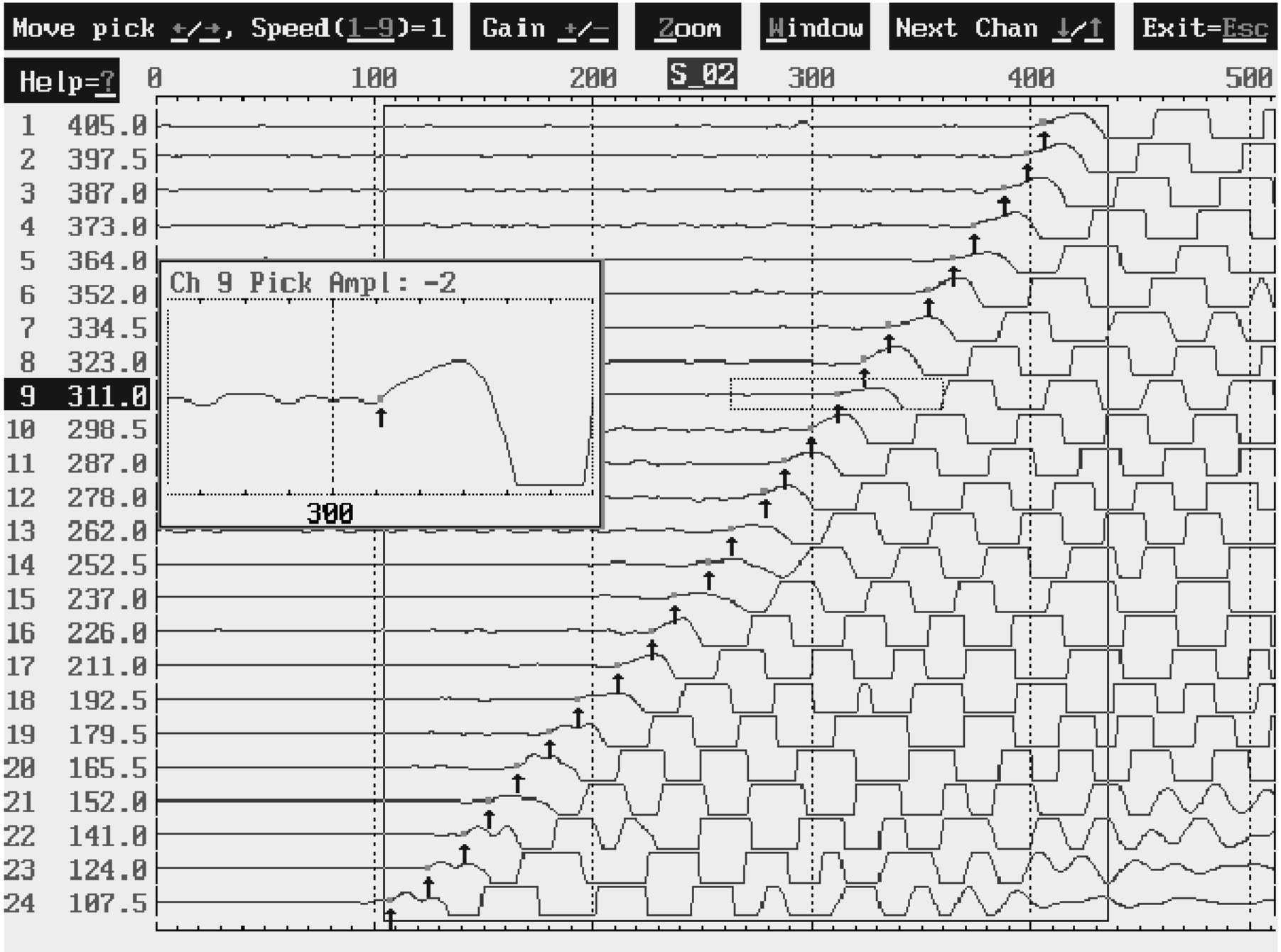

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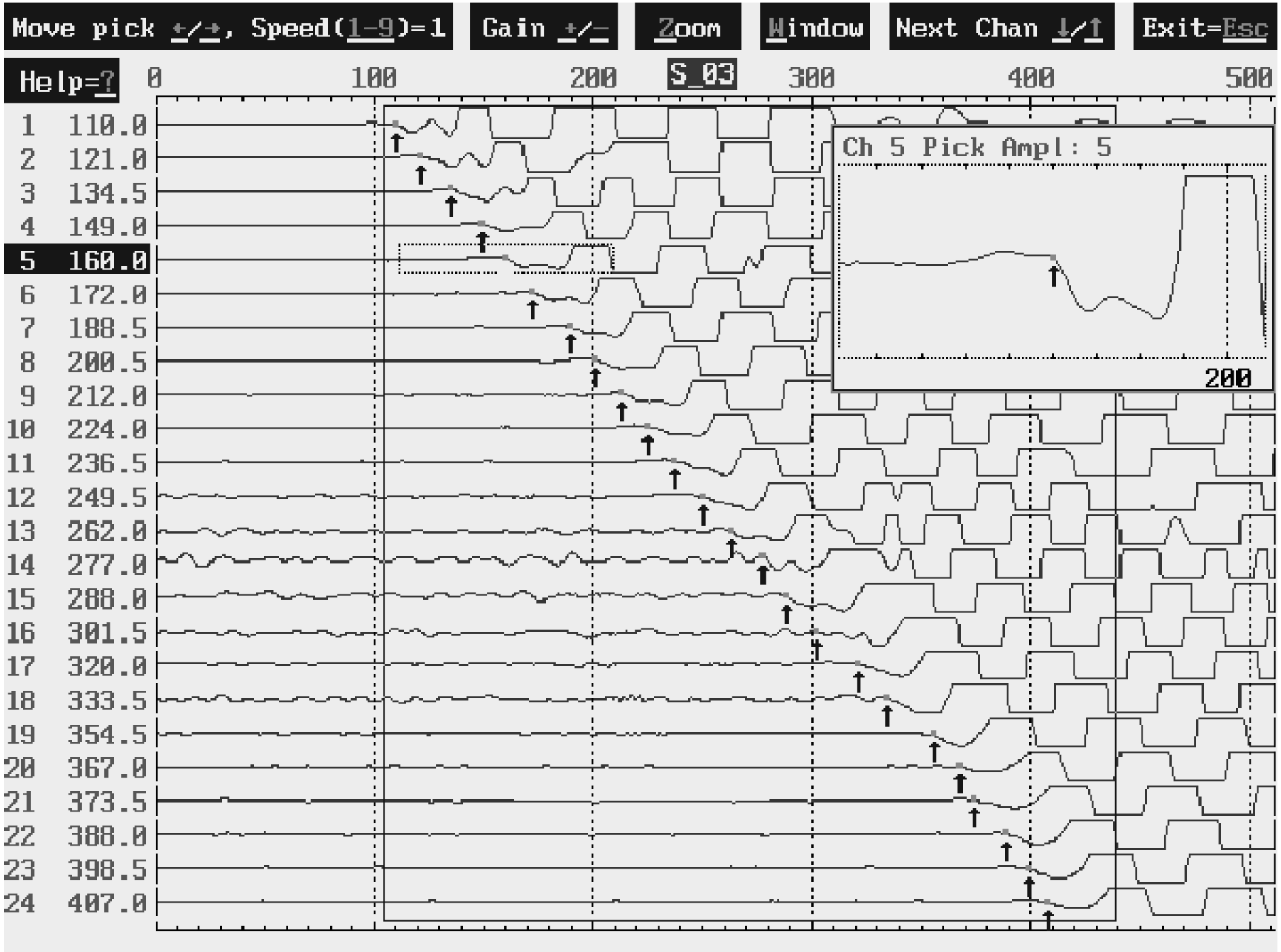

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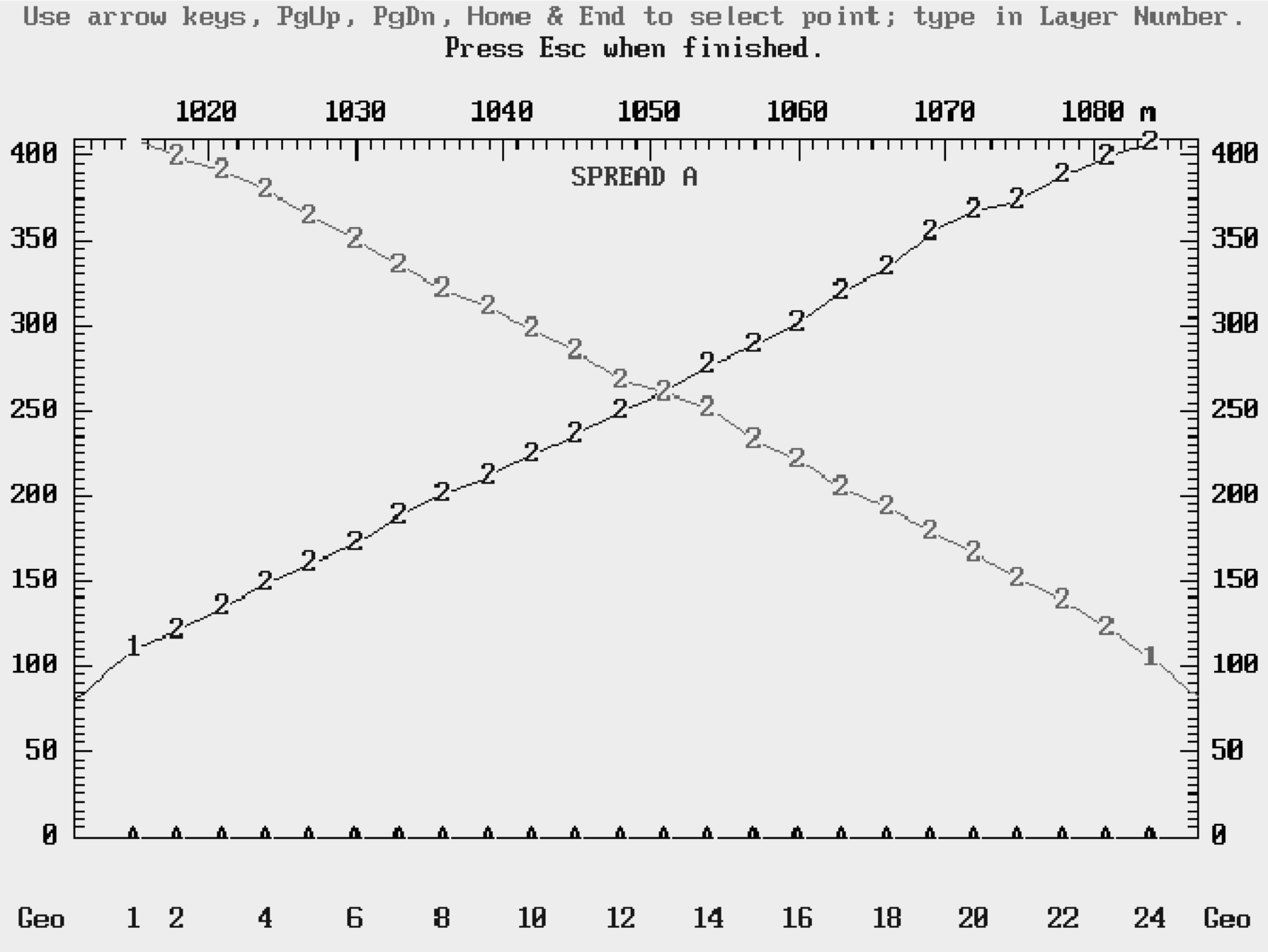

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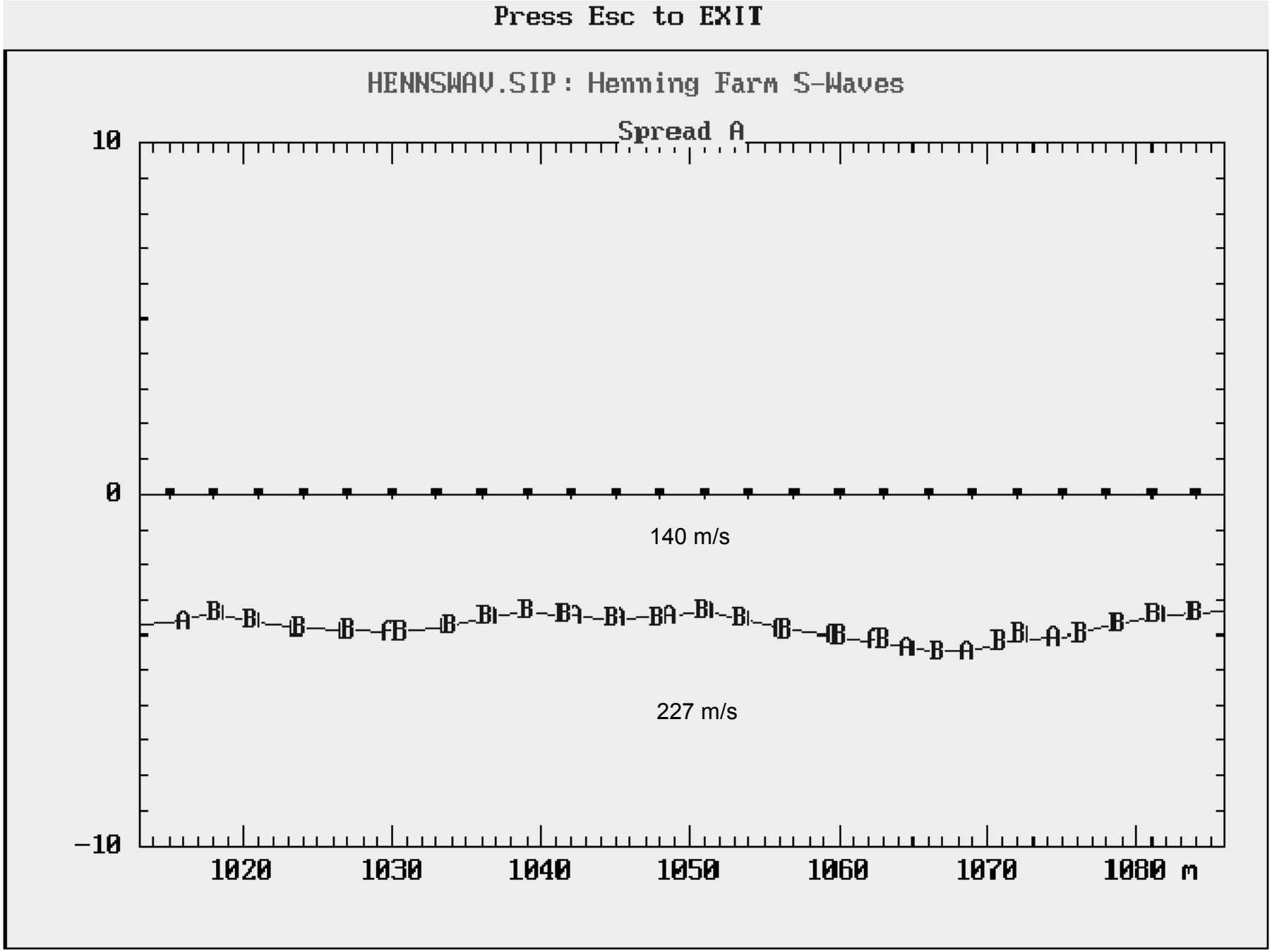

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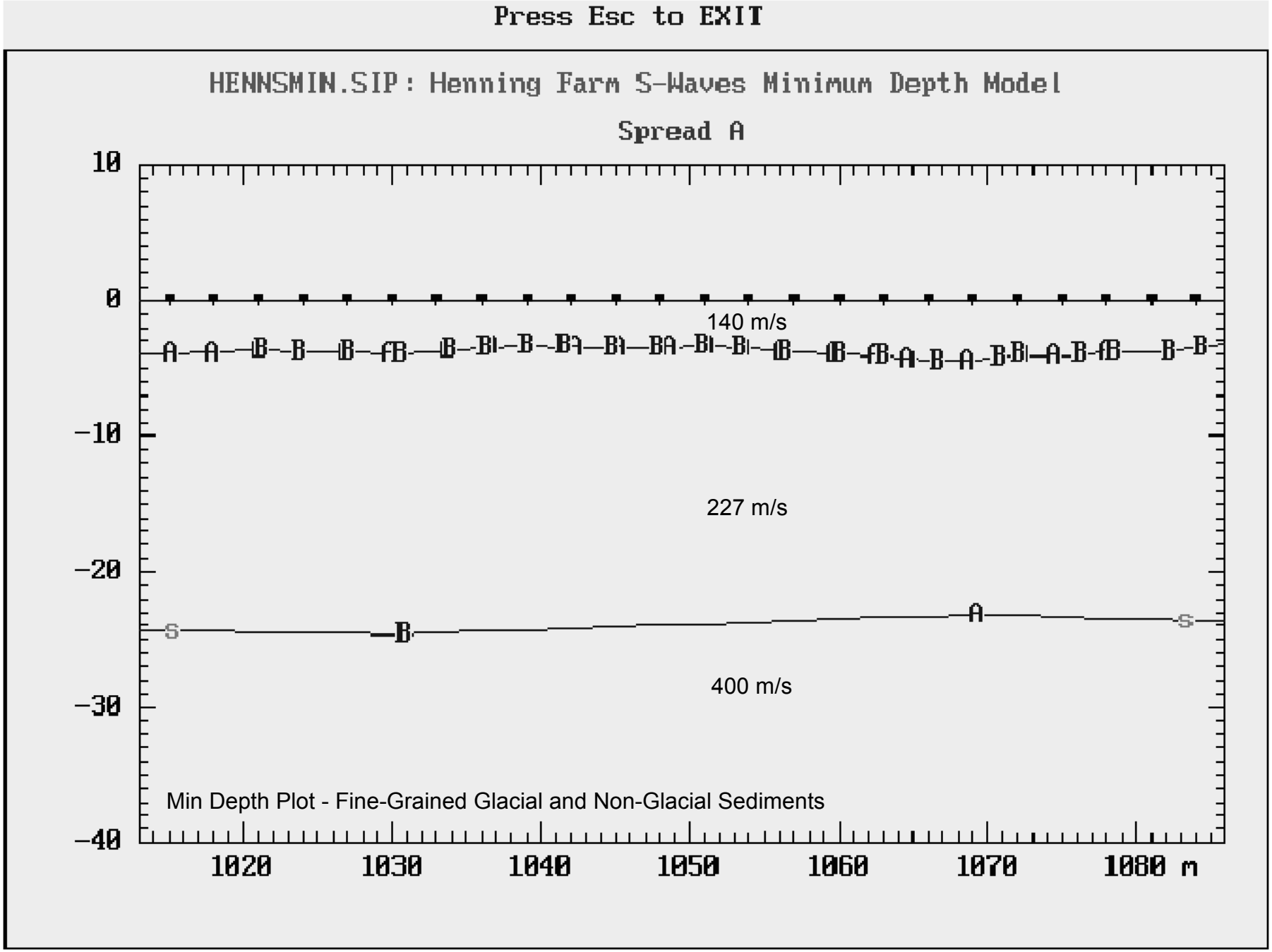

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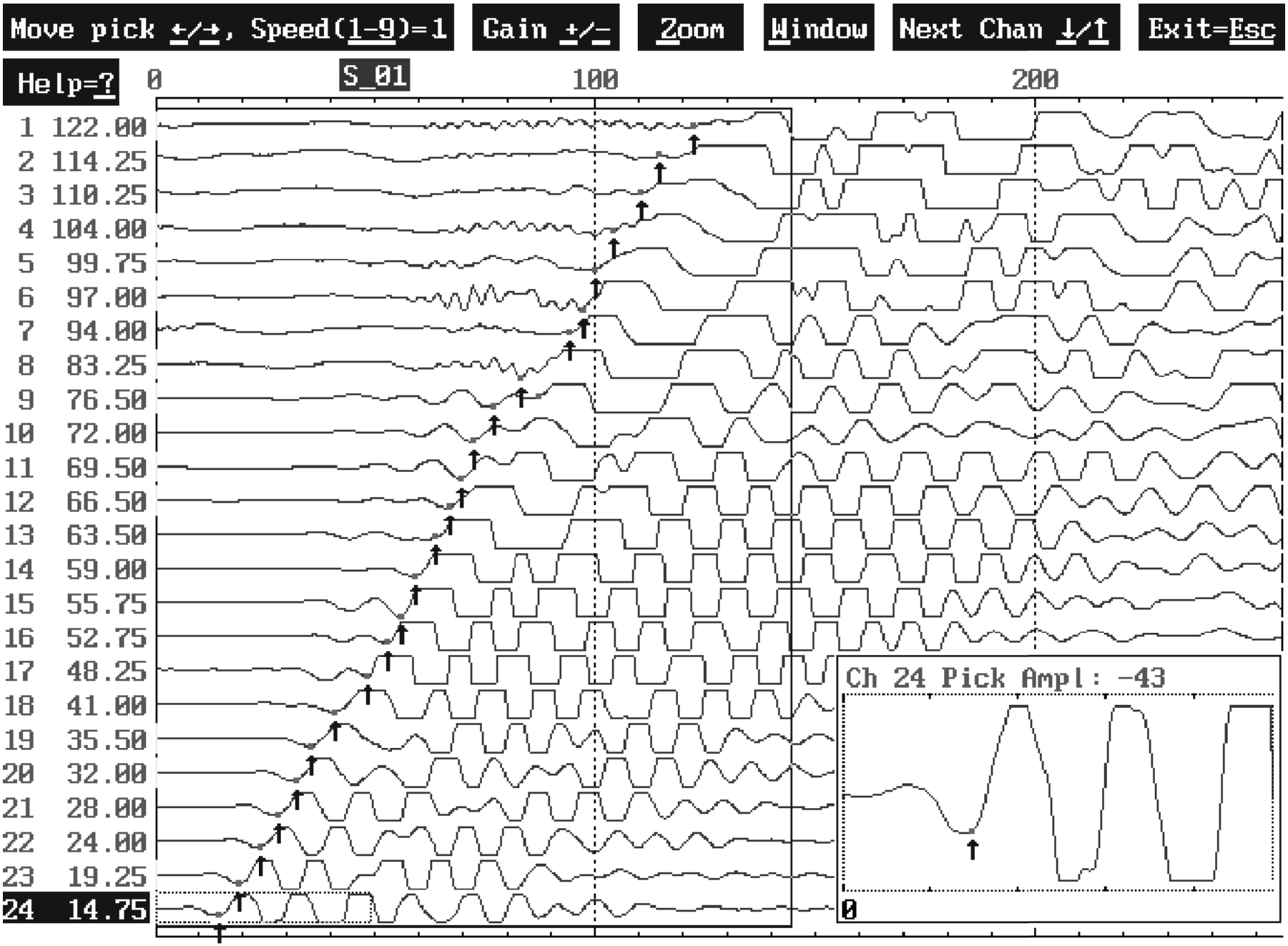

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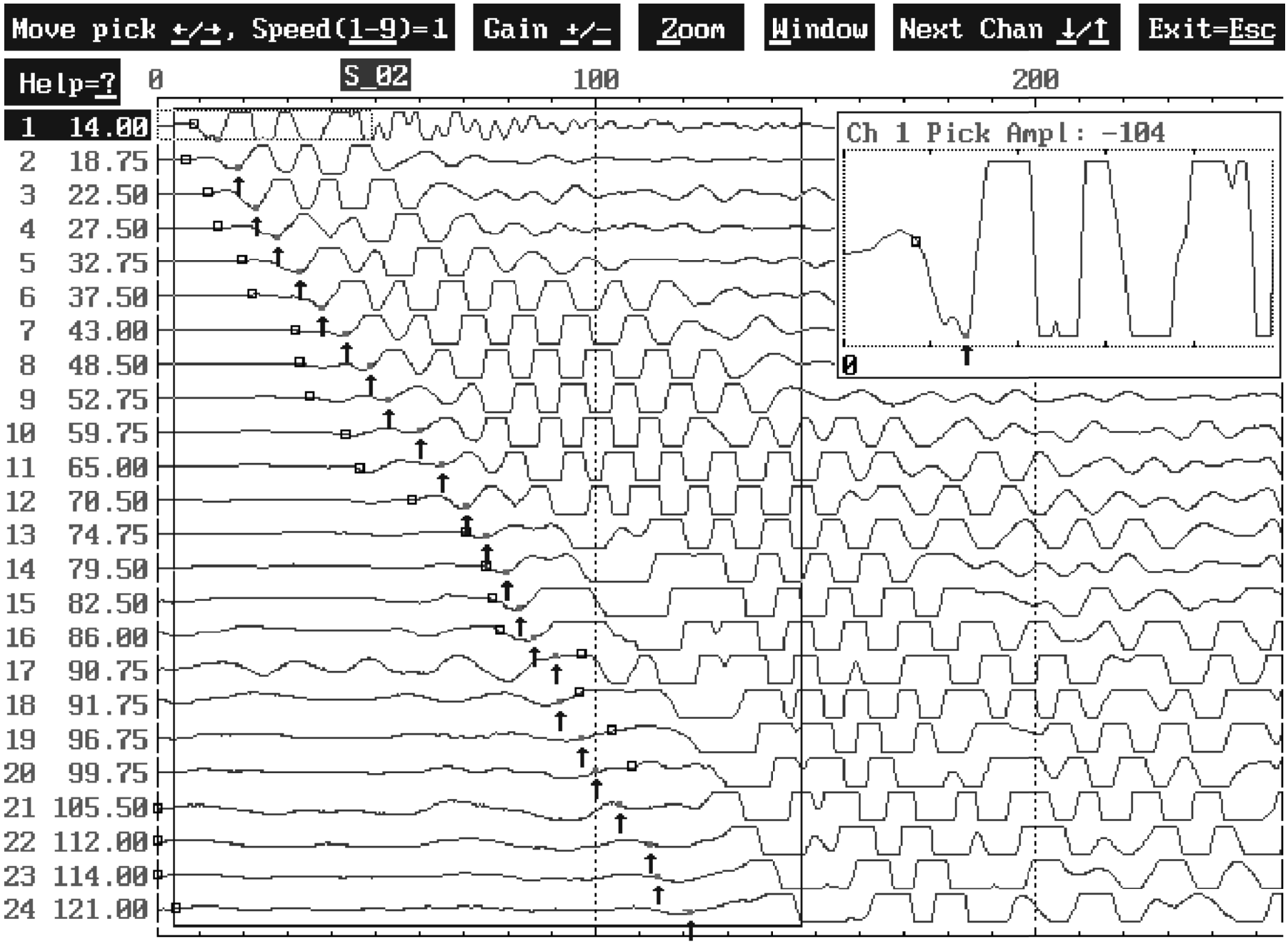

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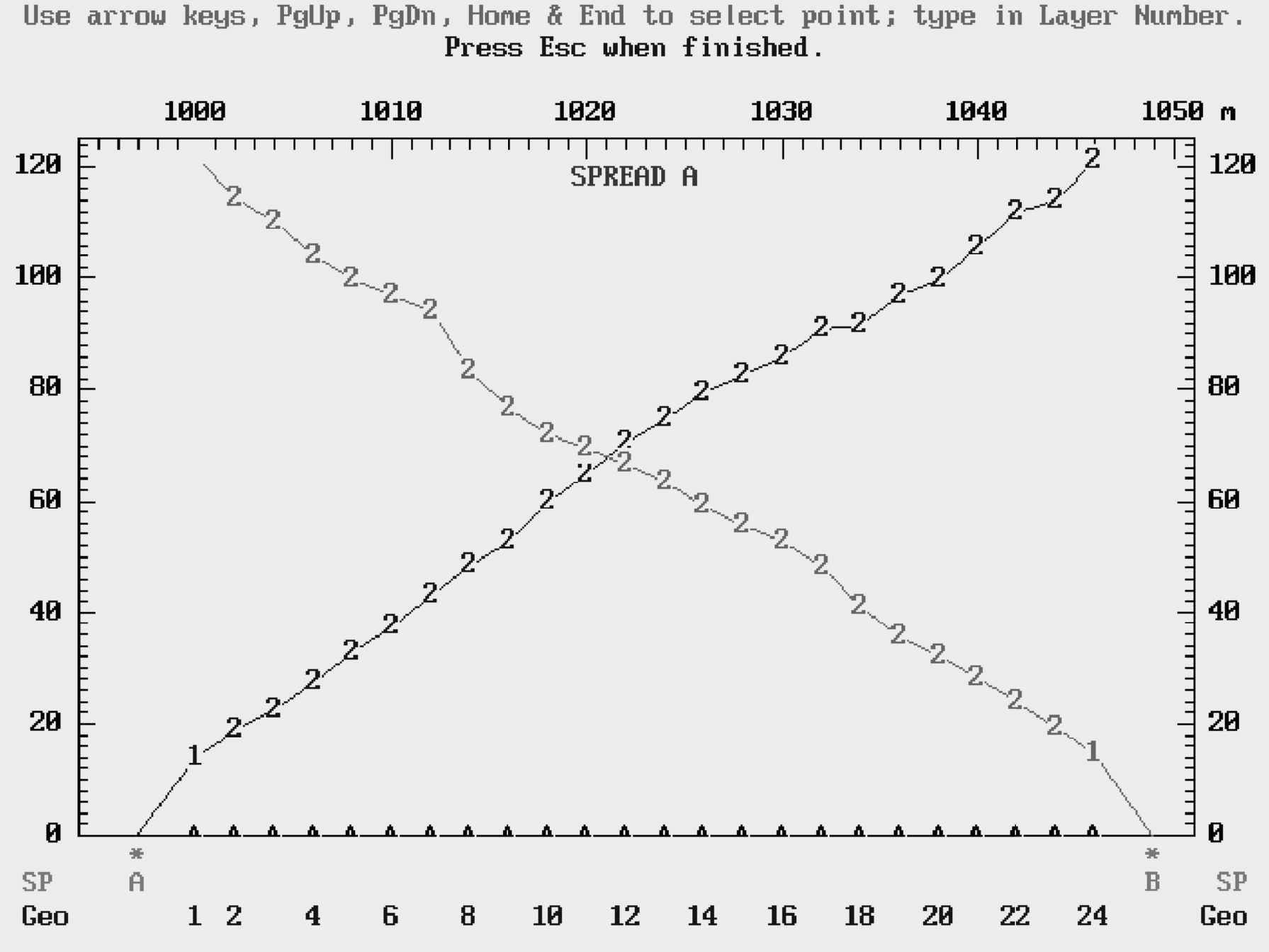

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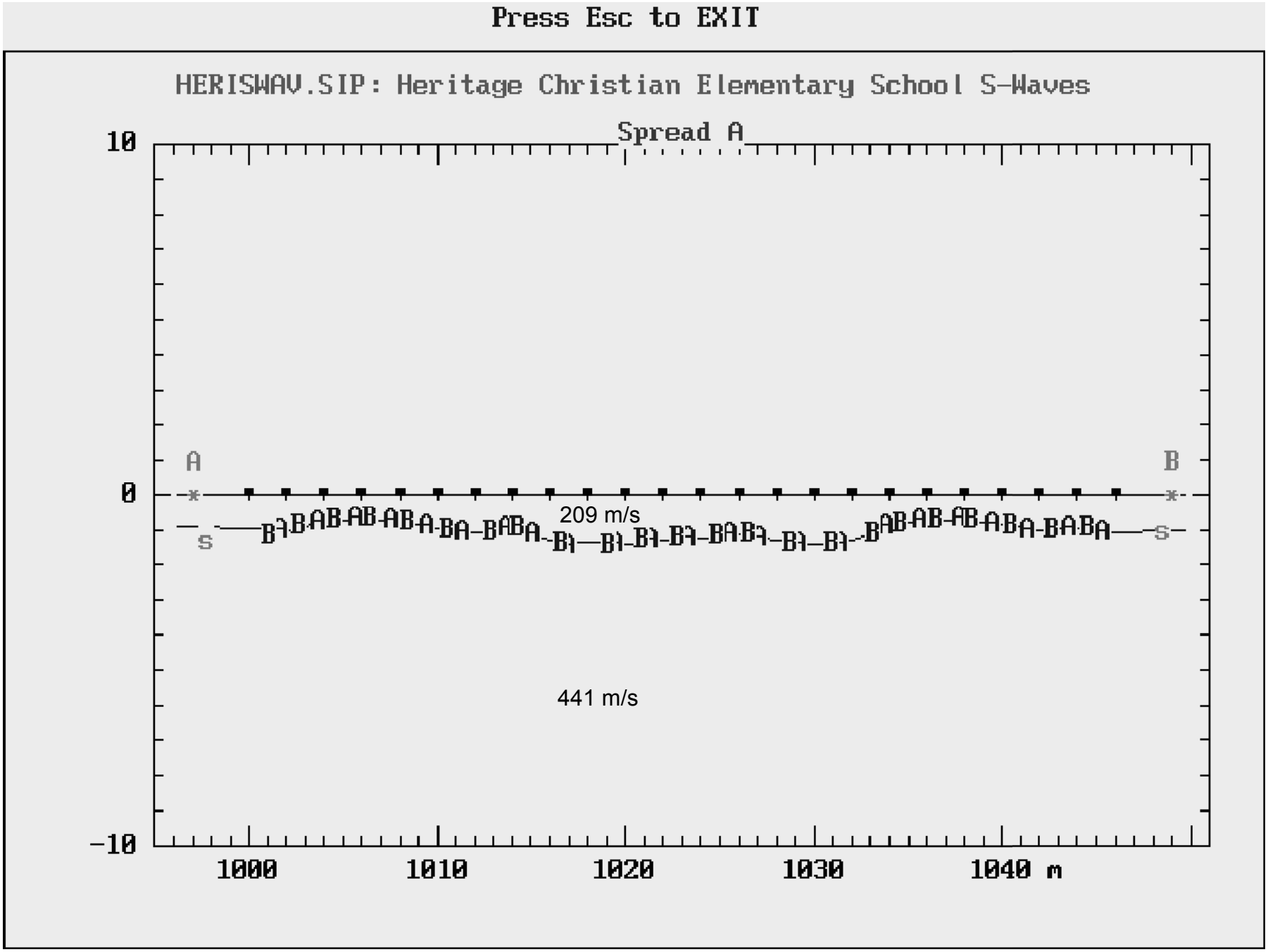

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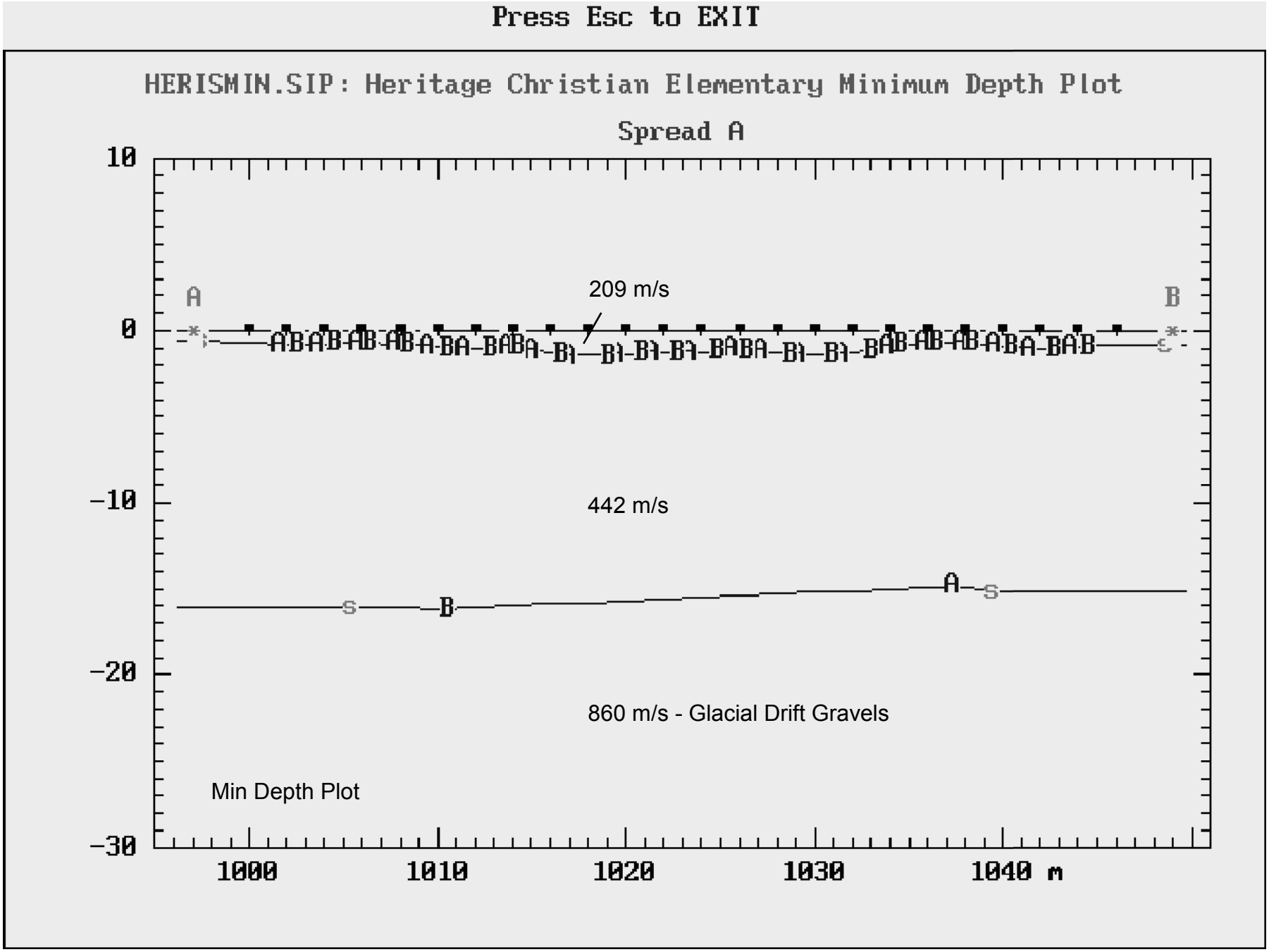

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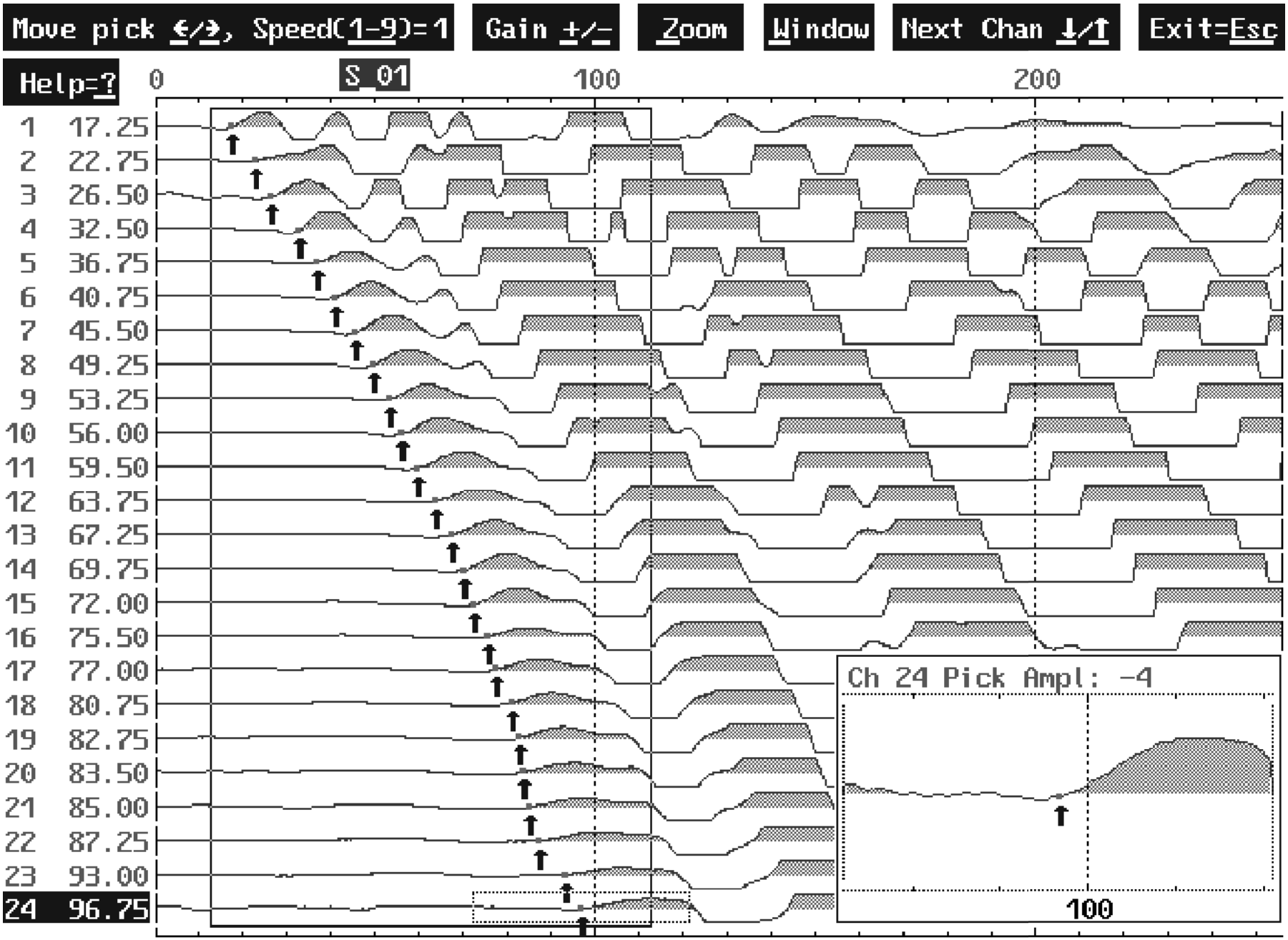

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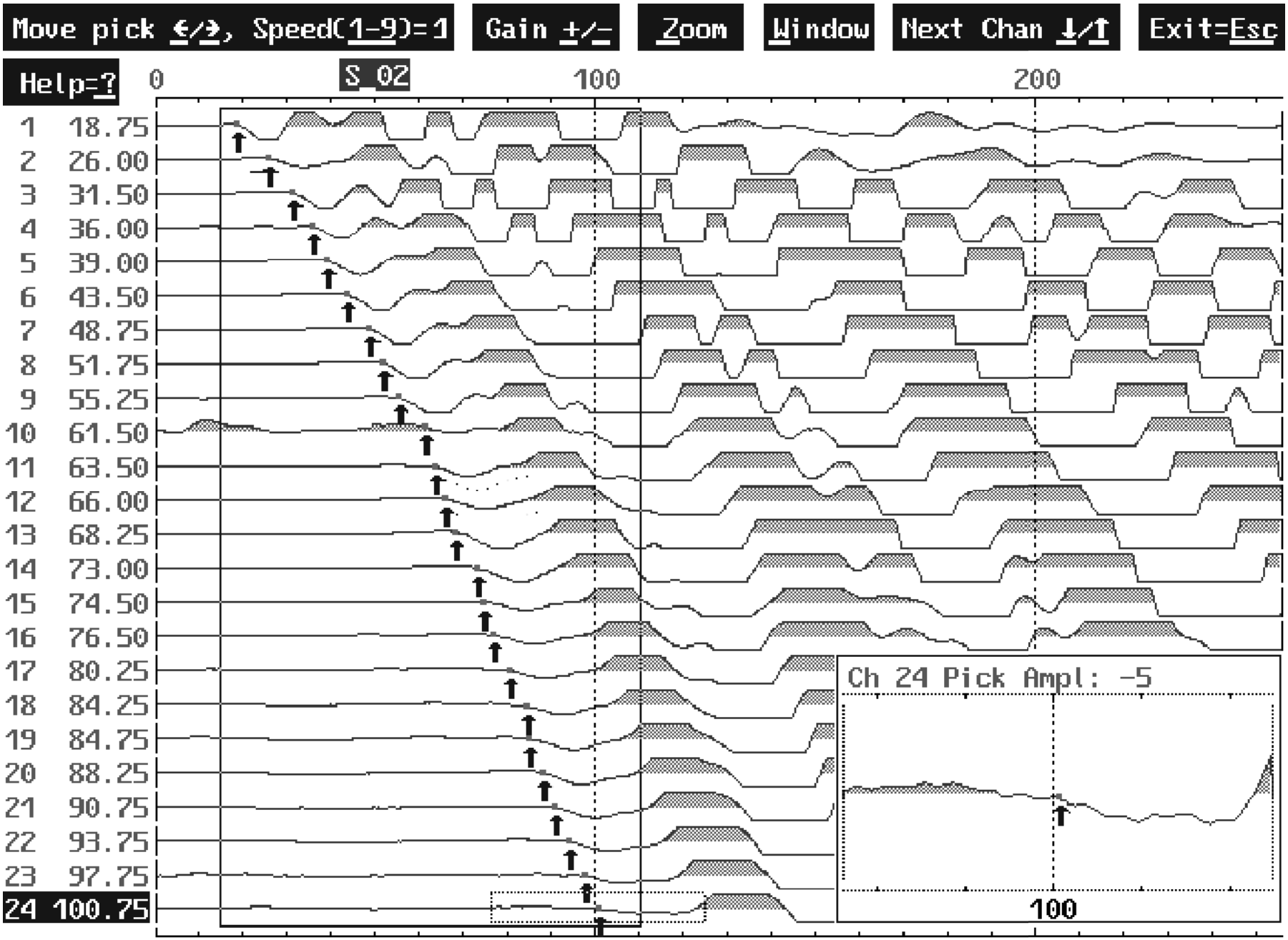

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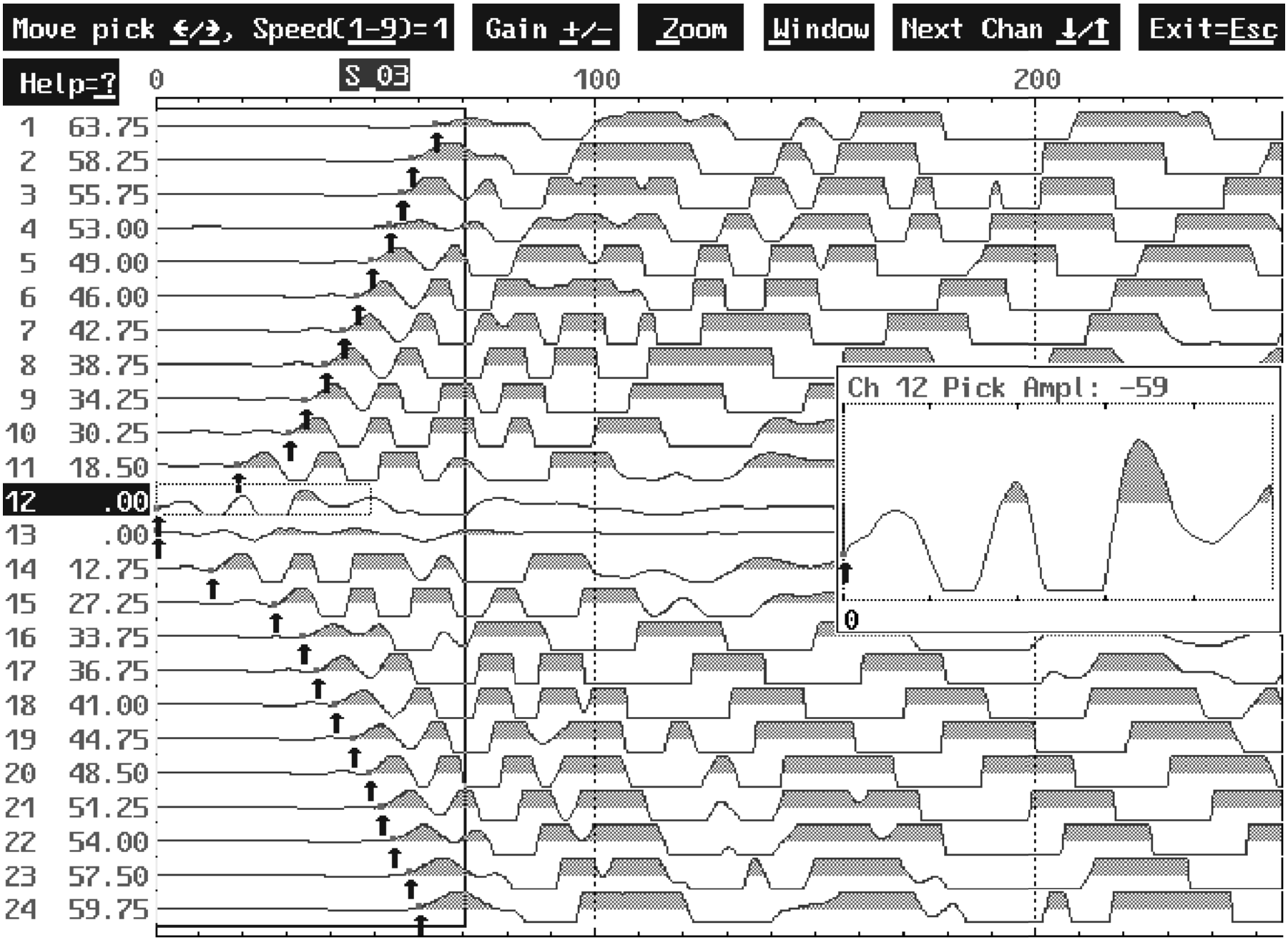

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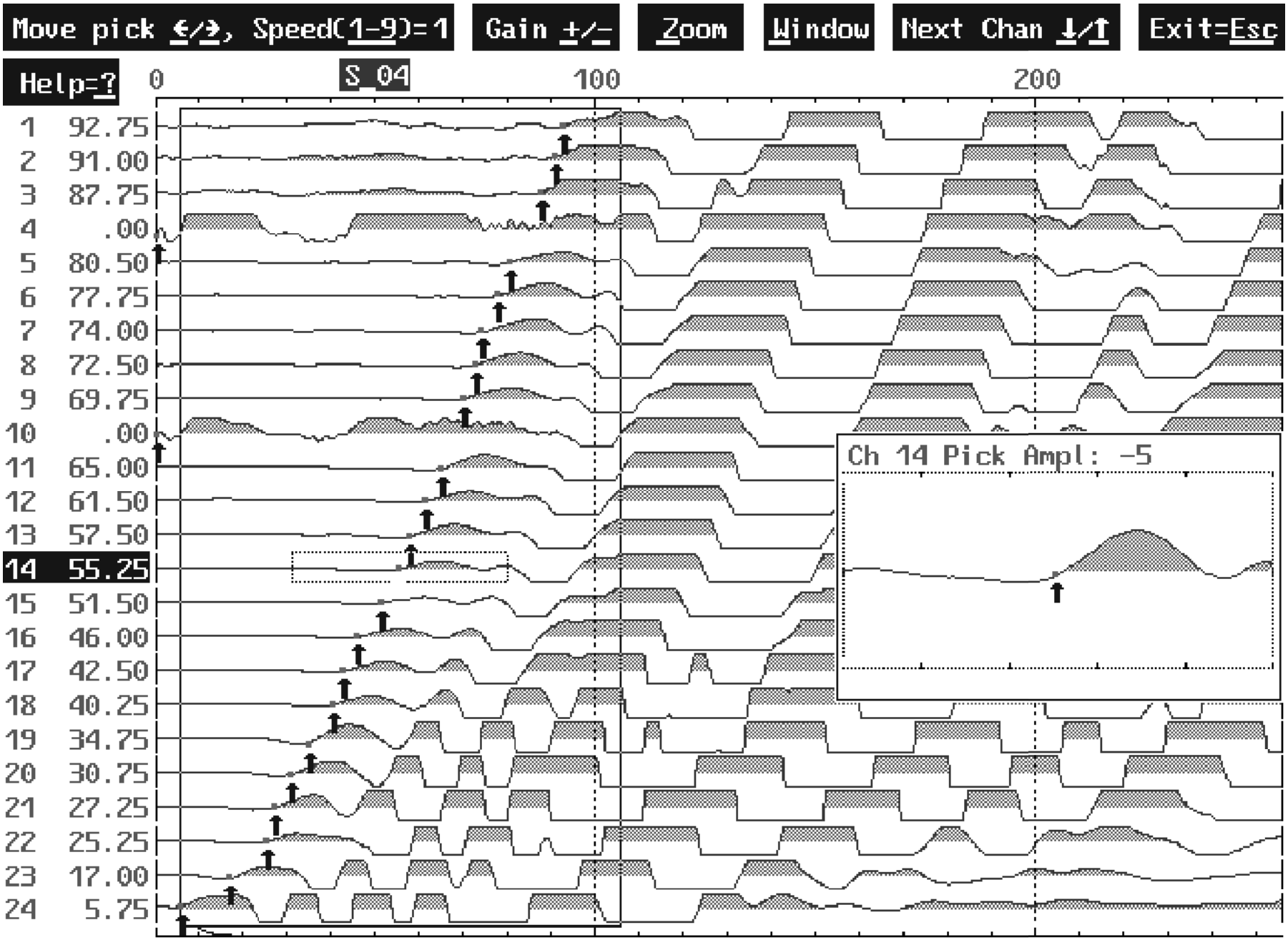

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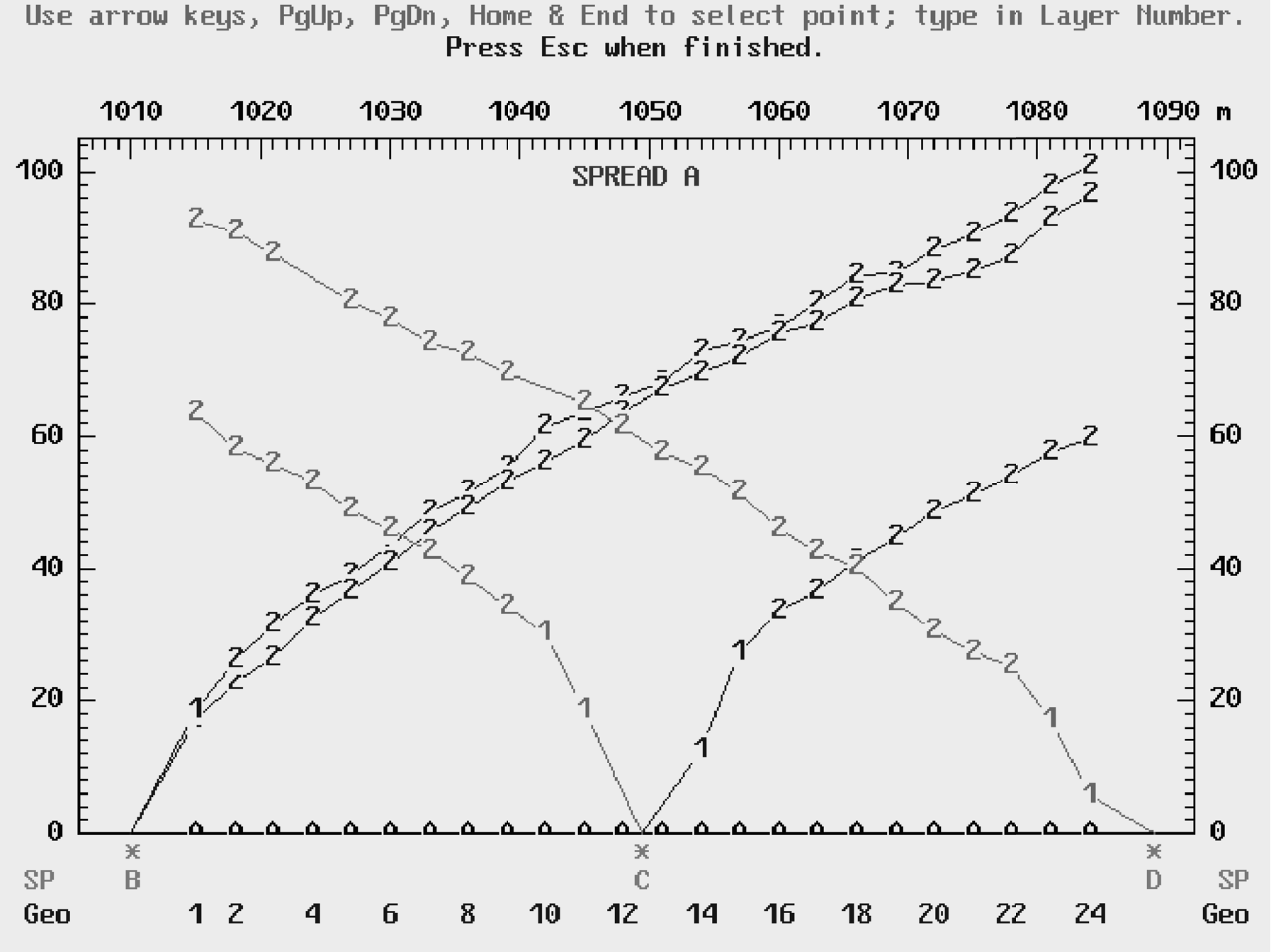

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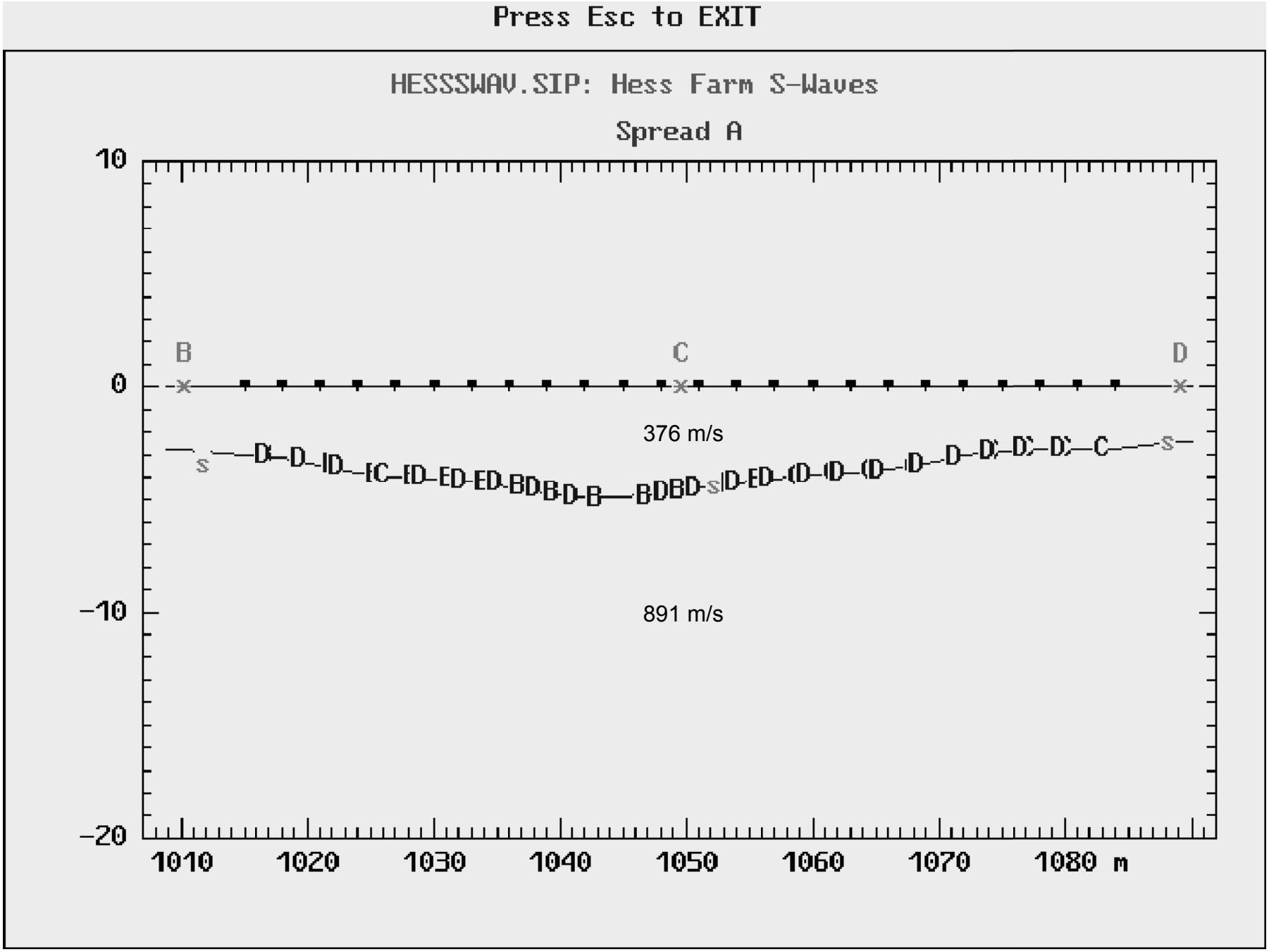

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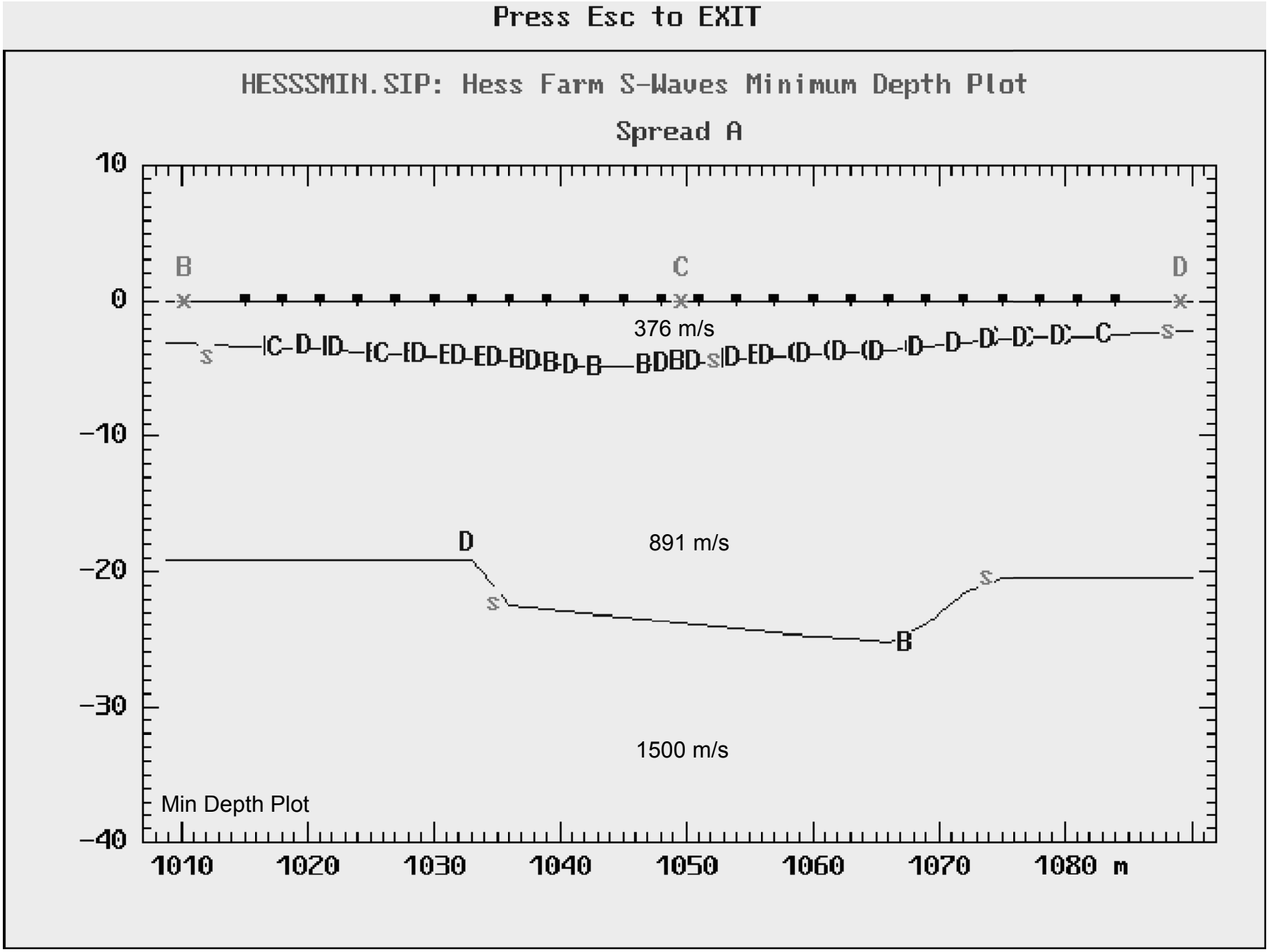

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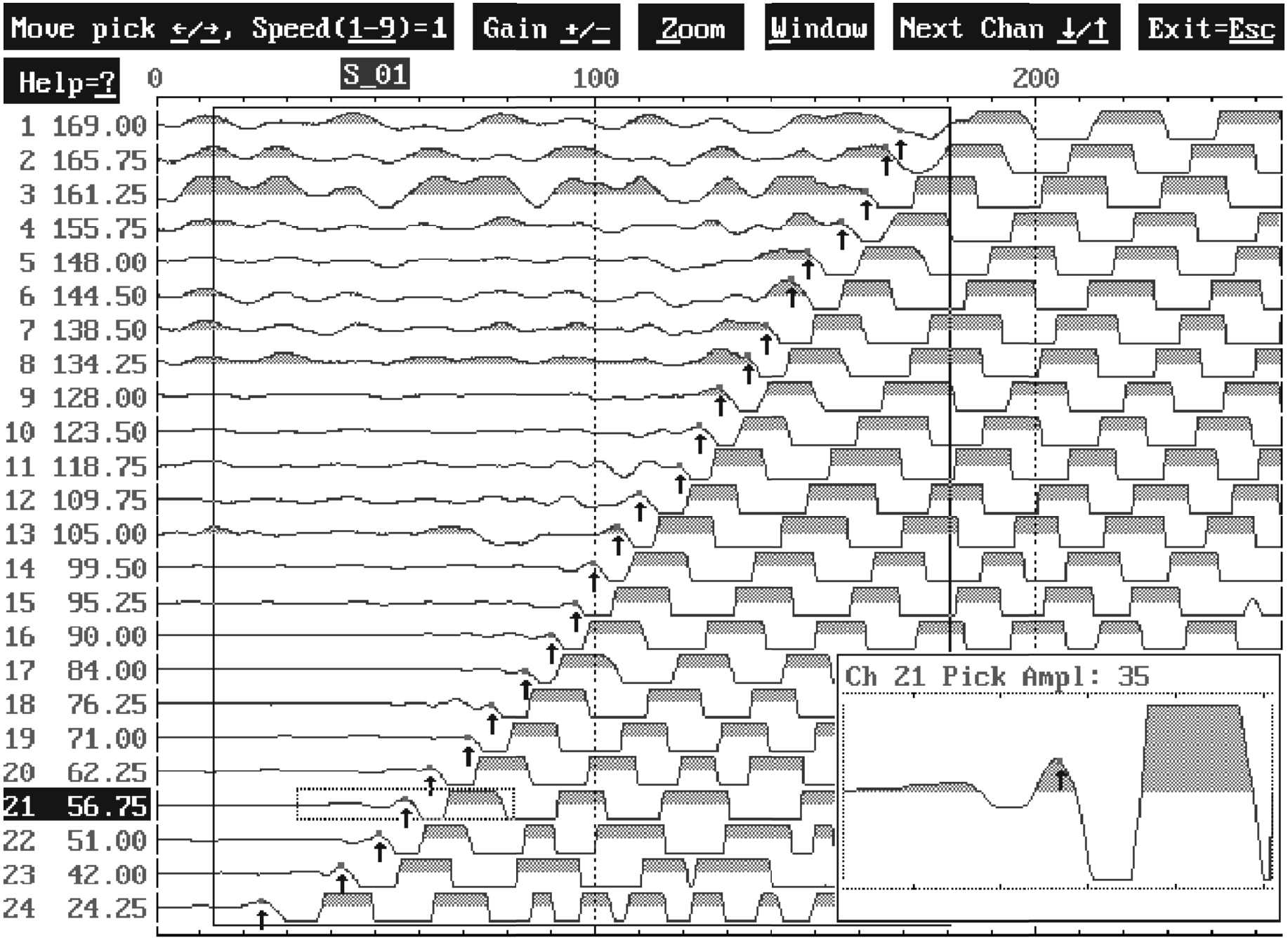

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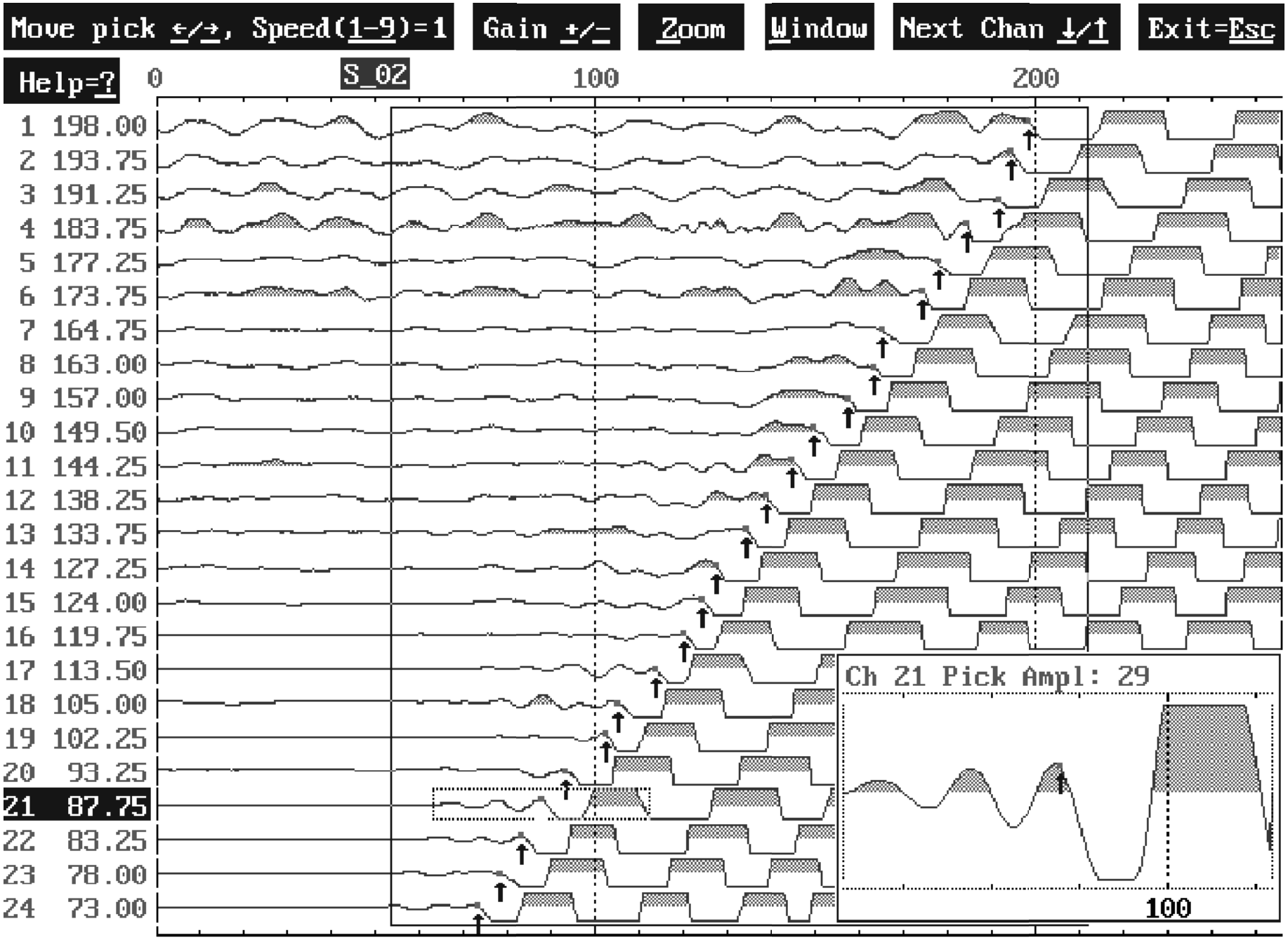

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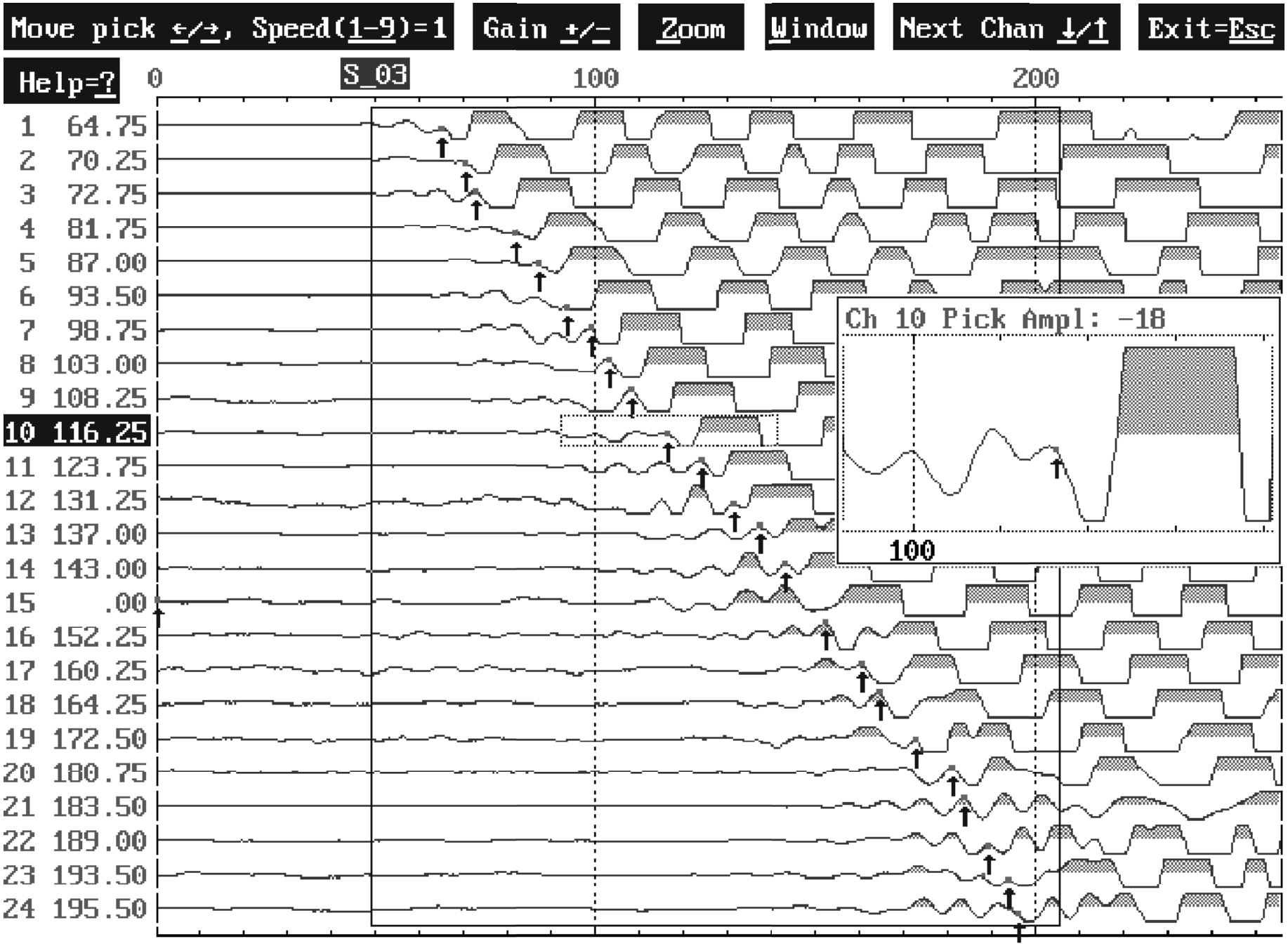

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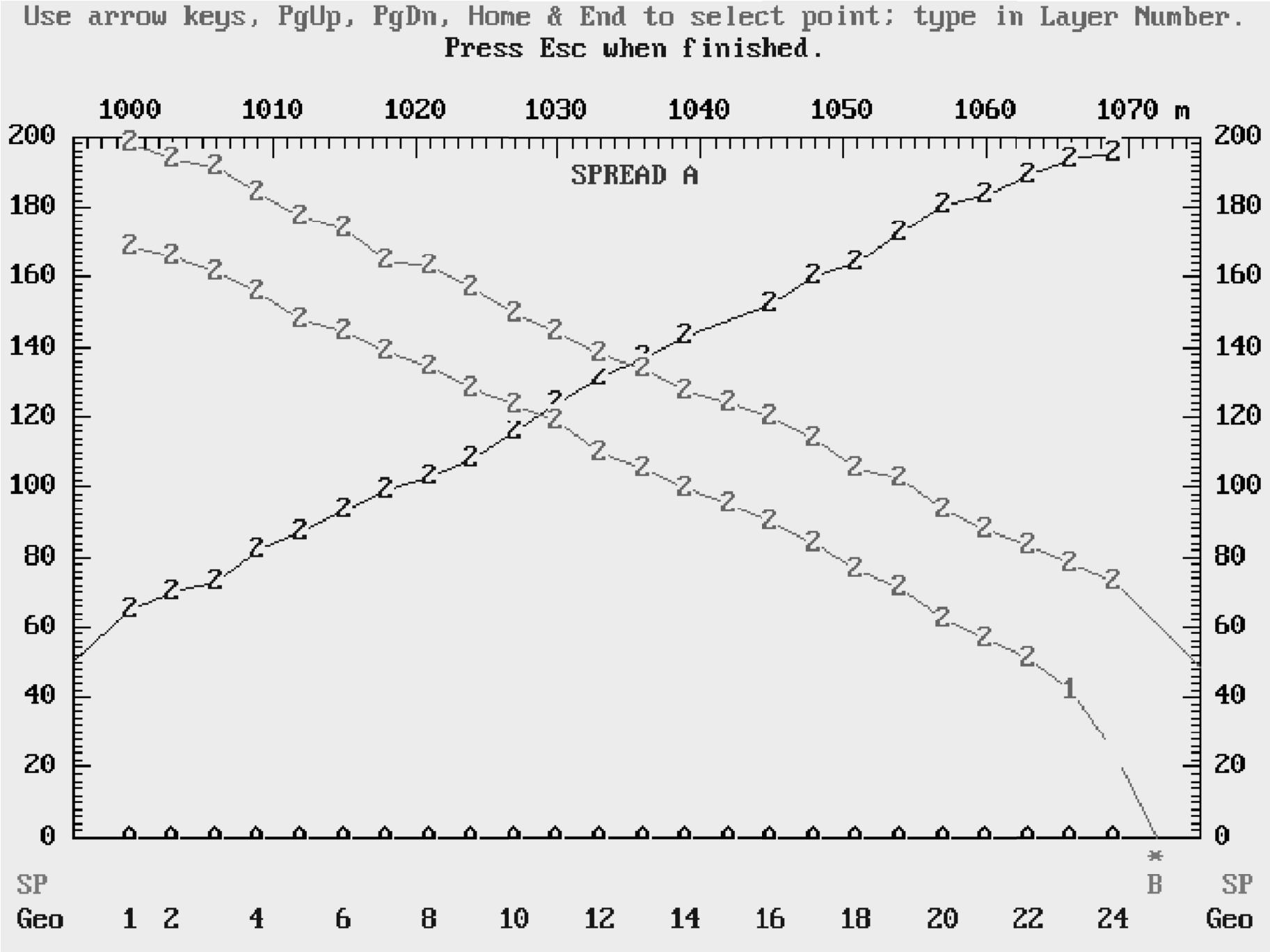

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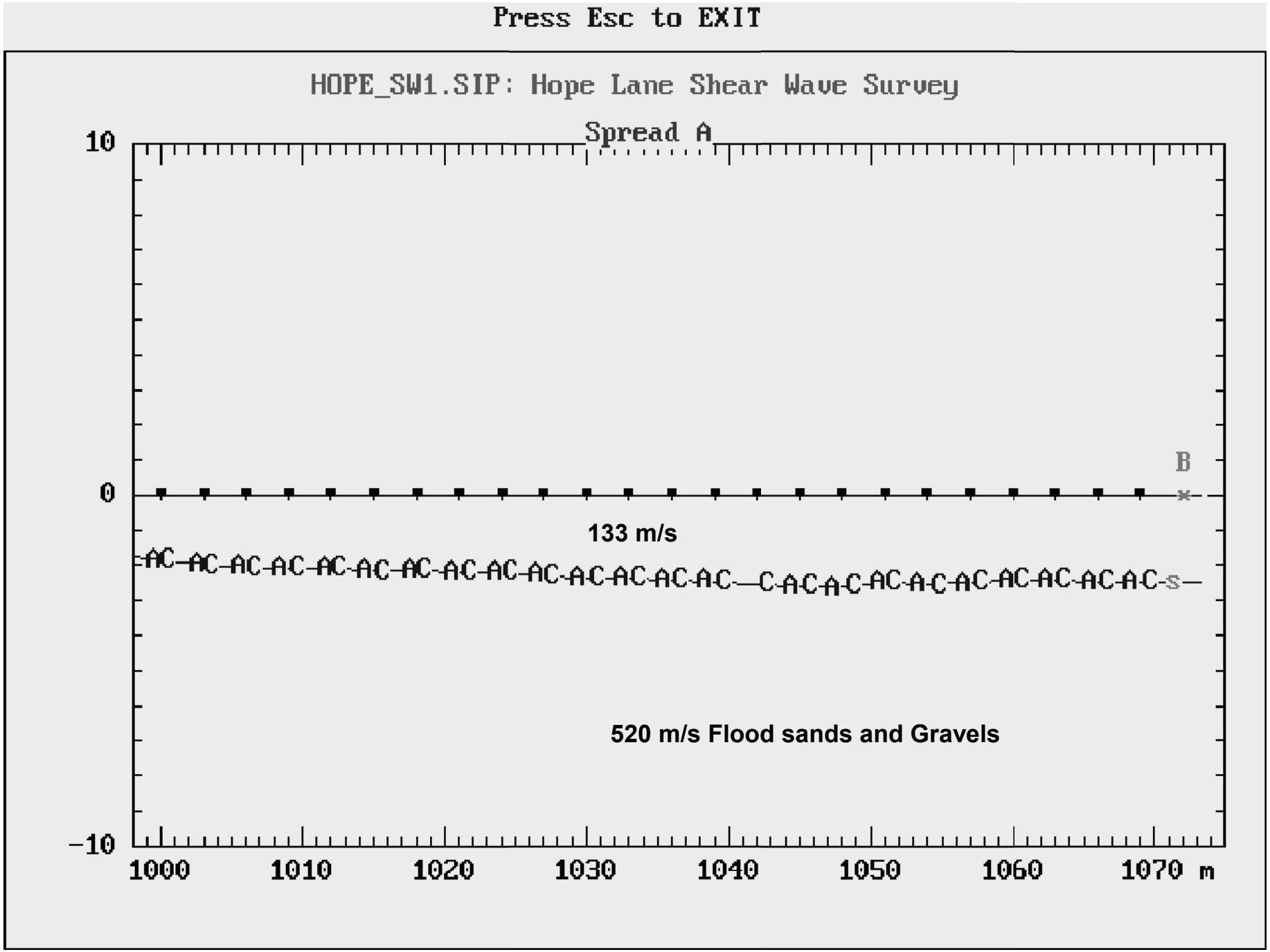

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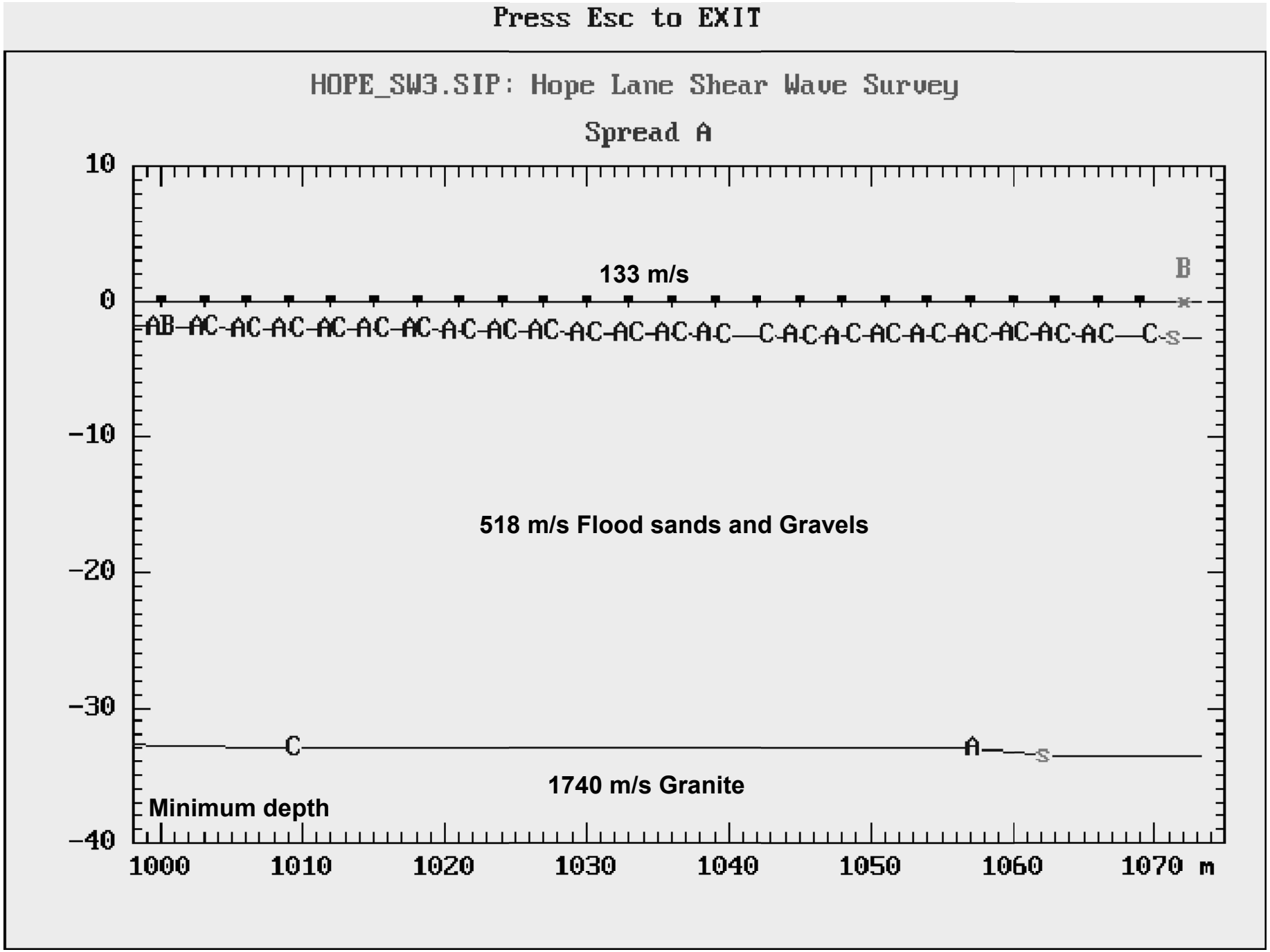

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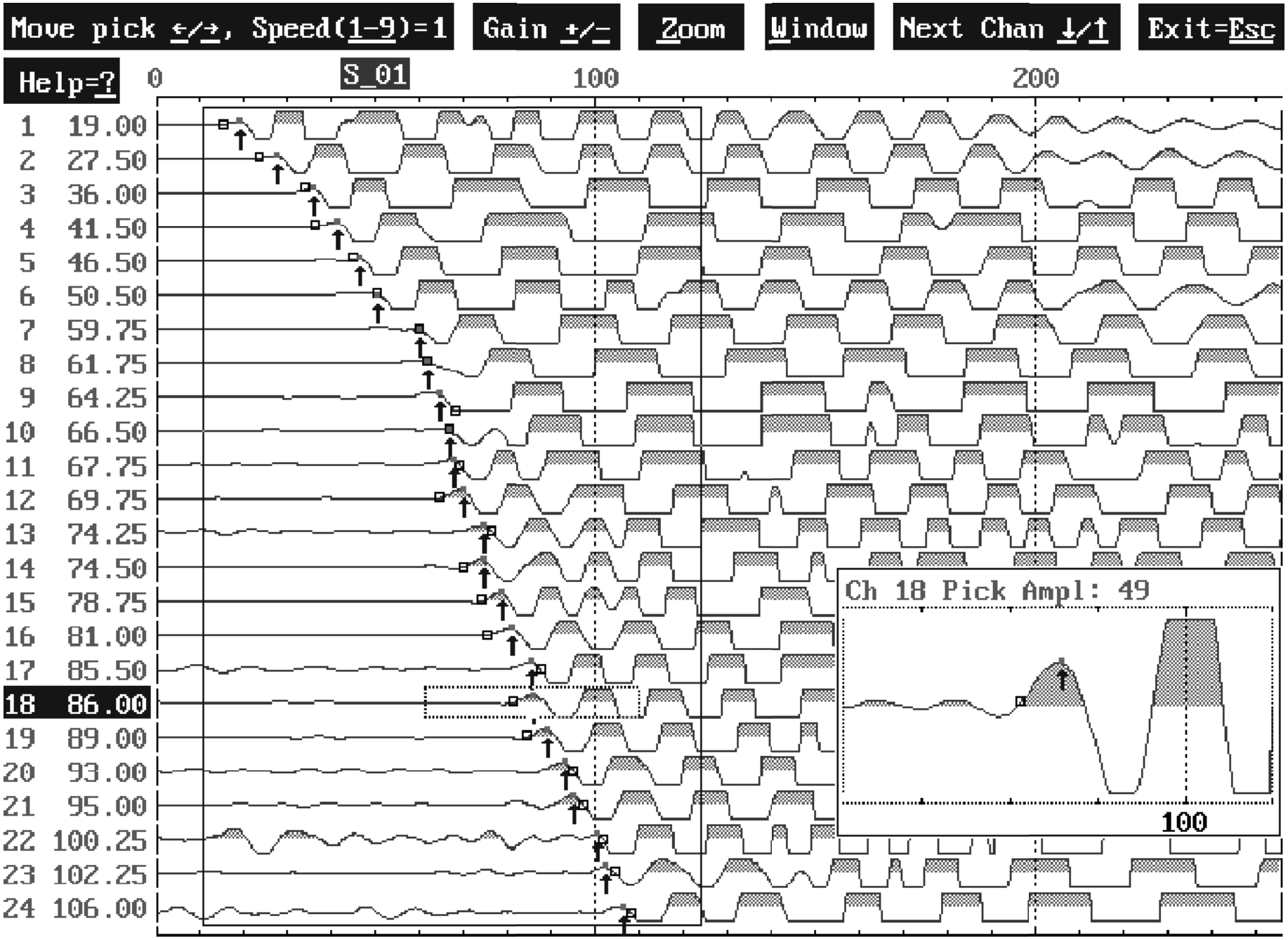

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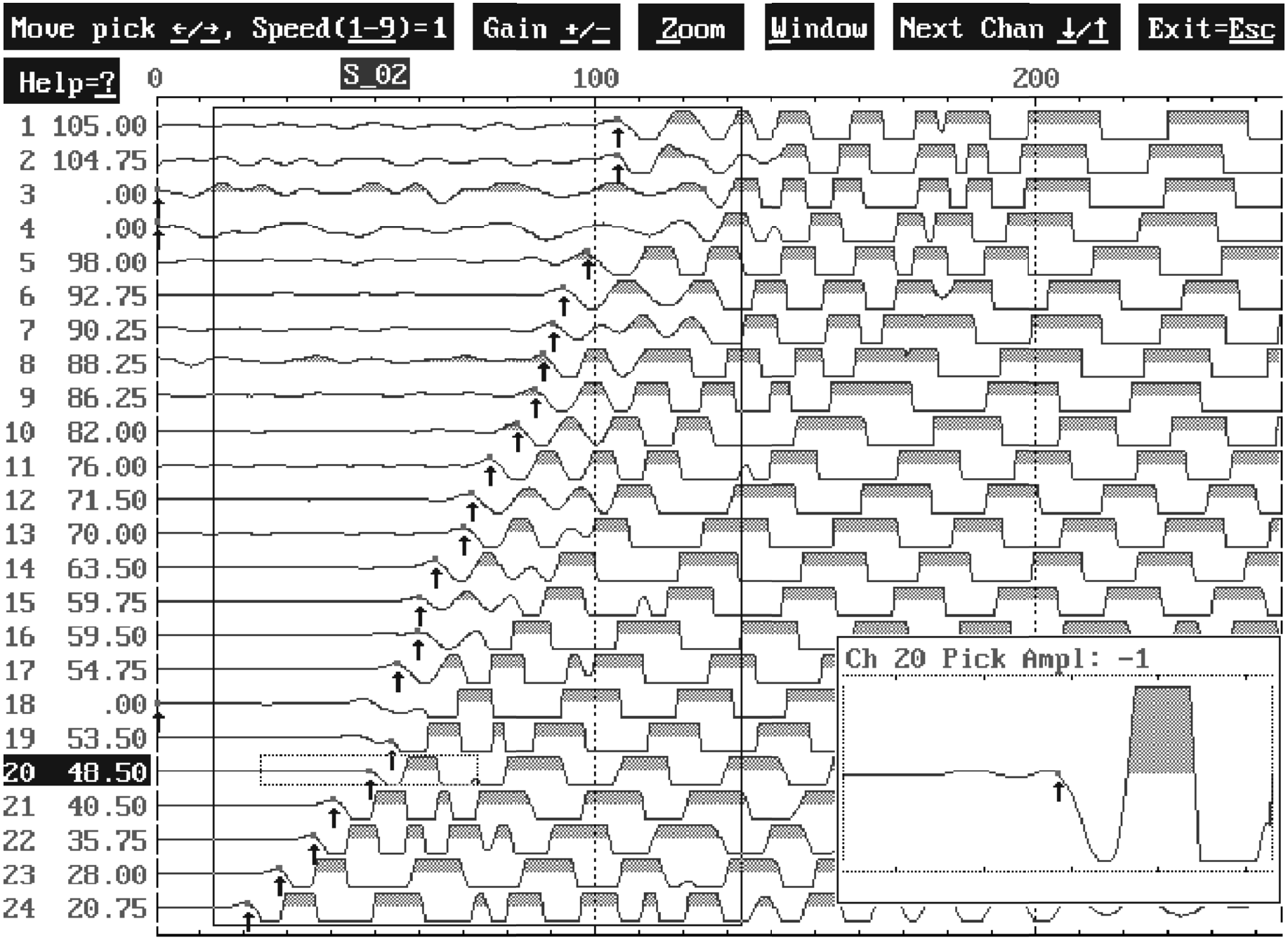

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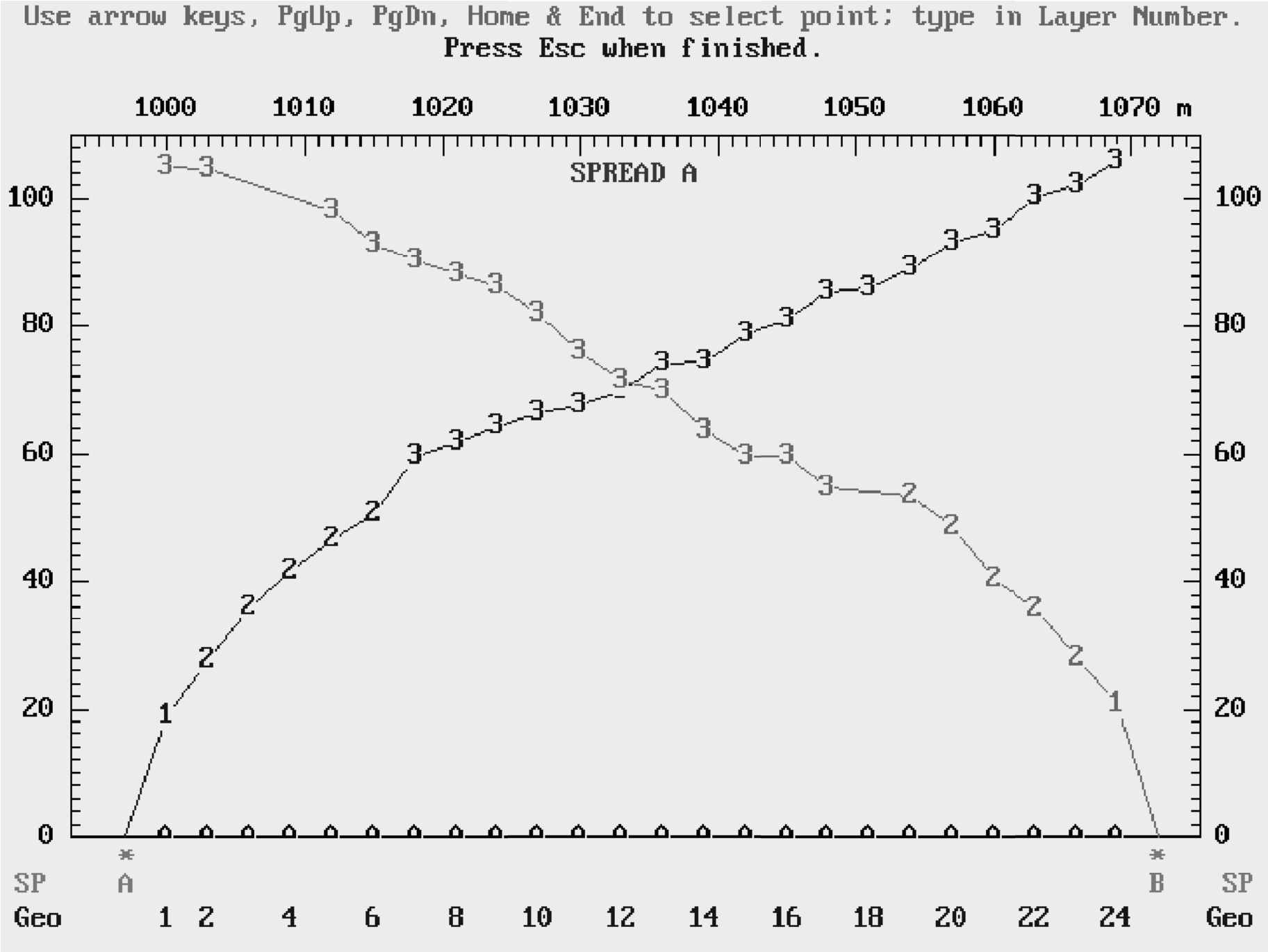

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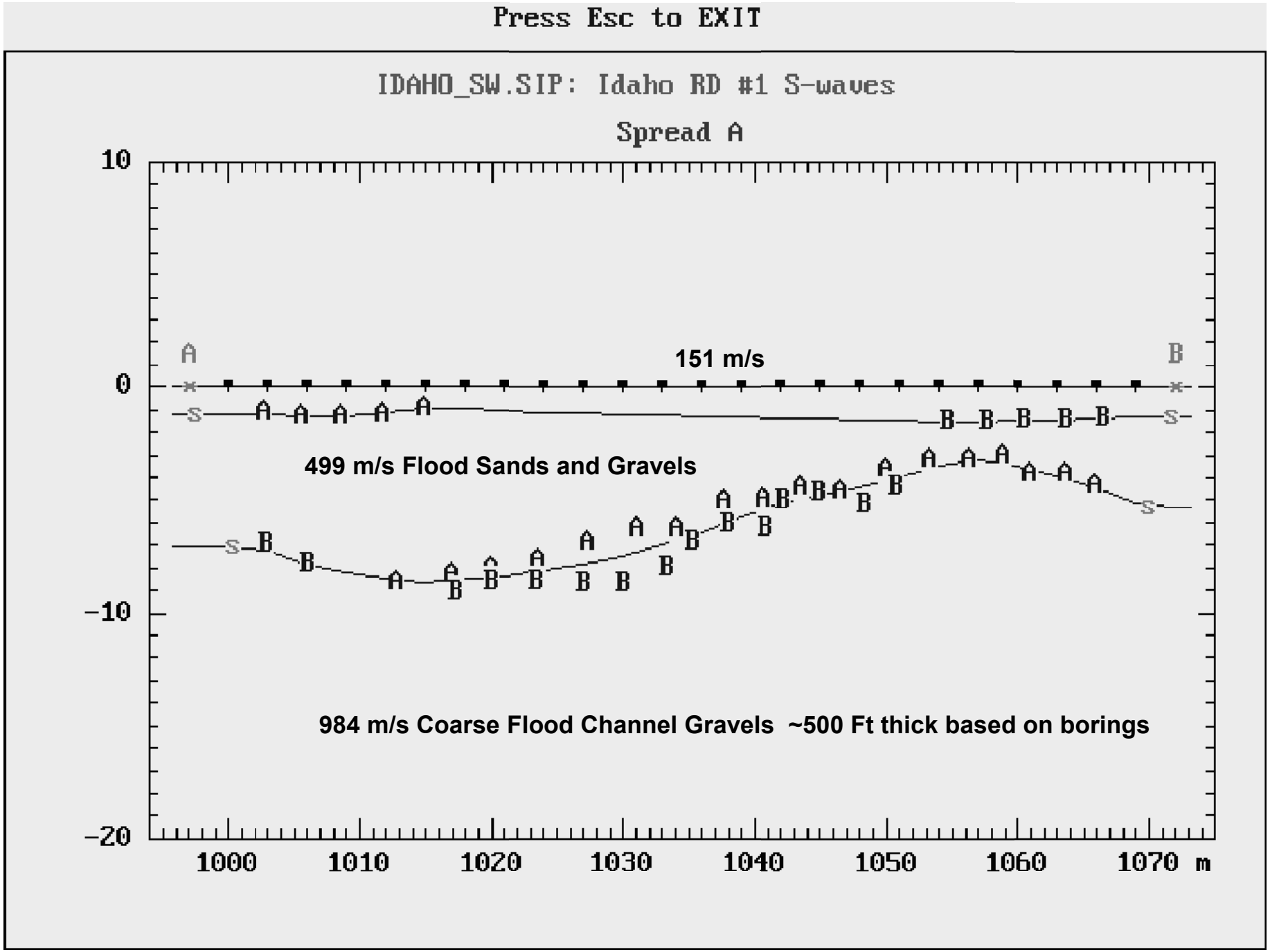

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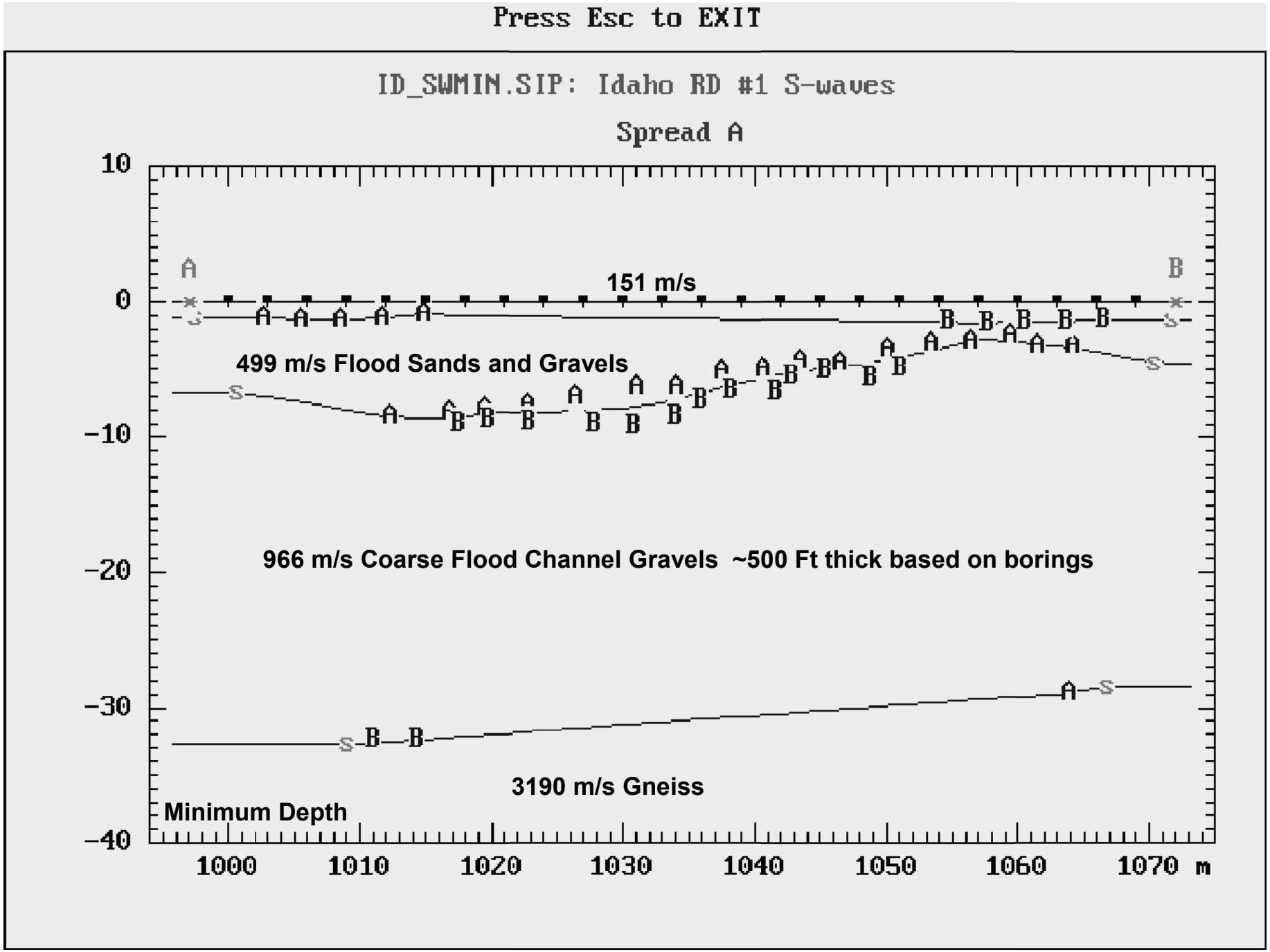
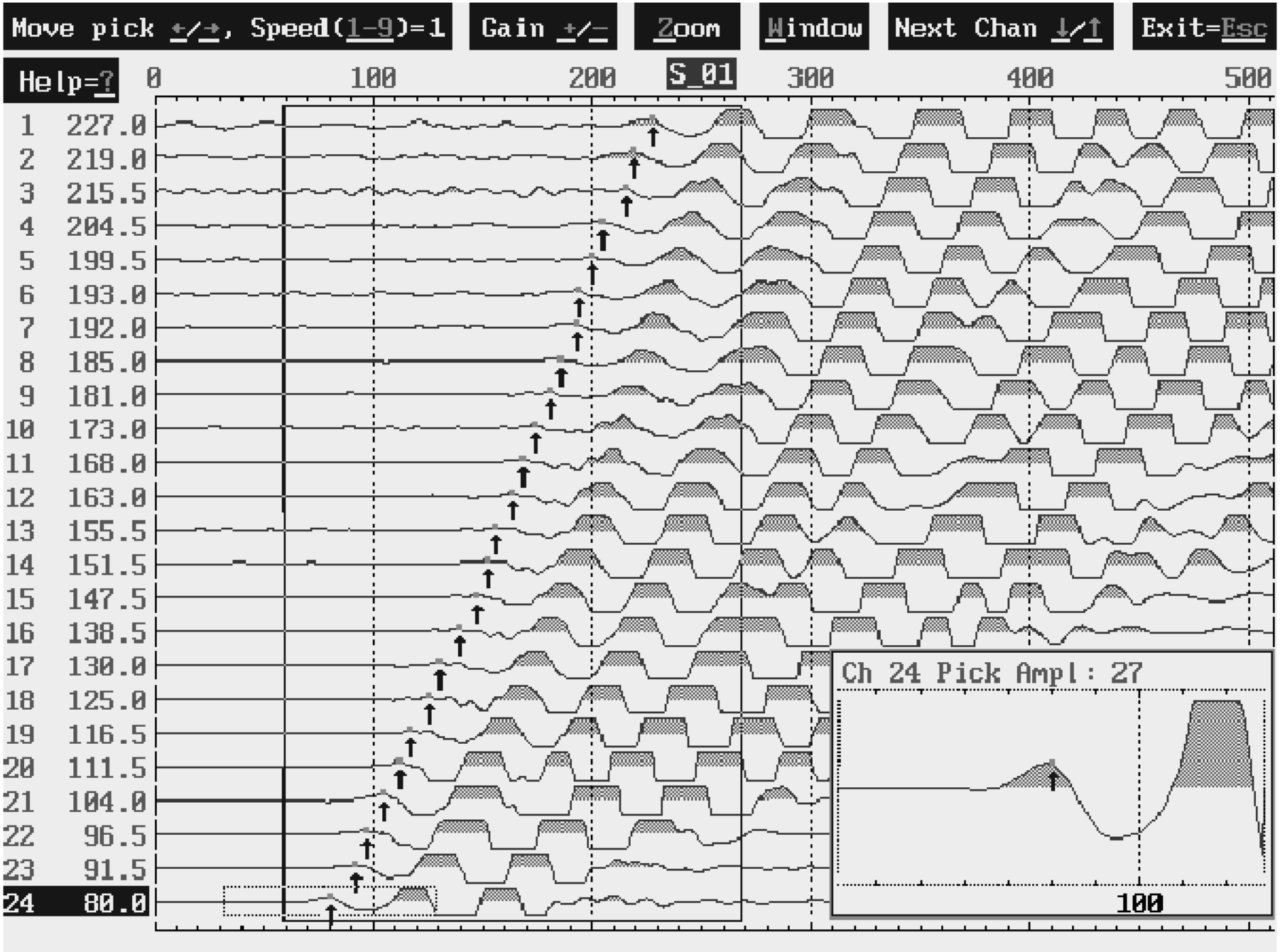
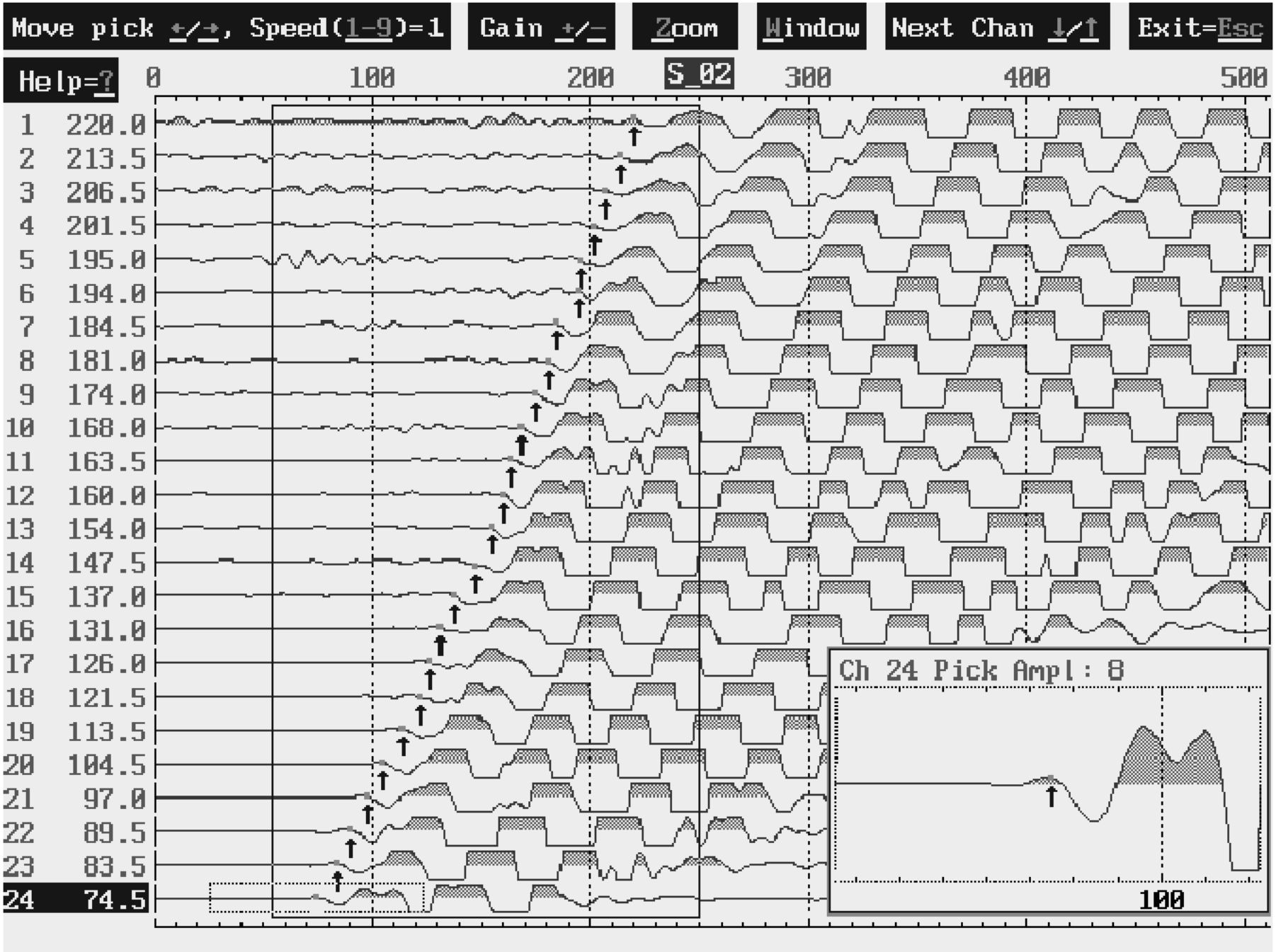


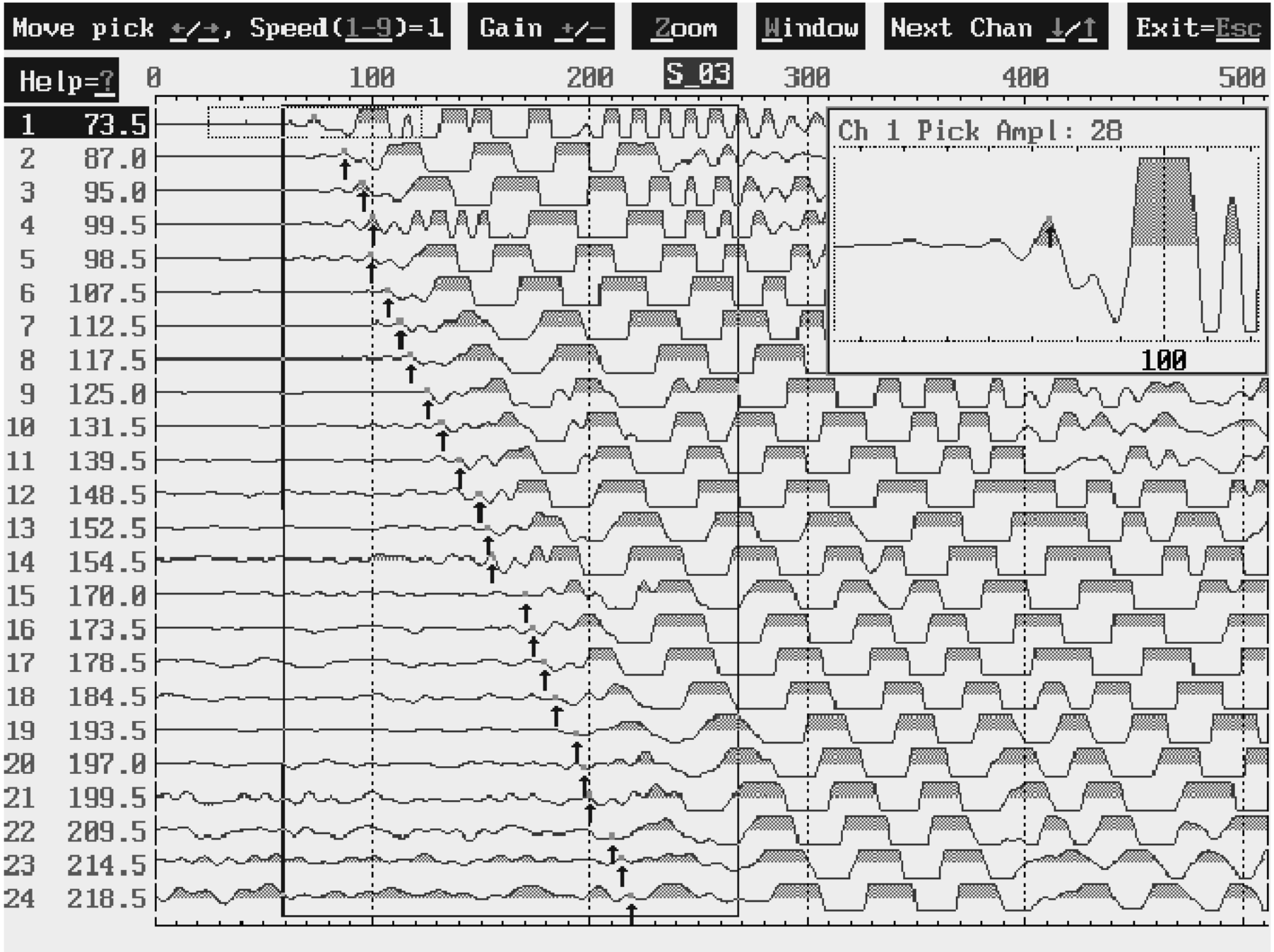
Kenmore Middle School S-wave



Kenmore Middle School S-wave



Kenmore Middle School S-wave



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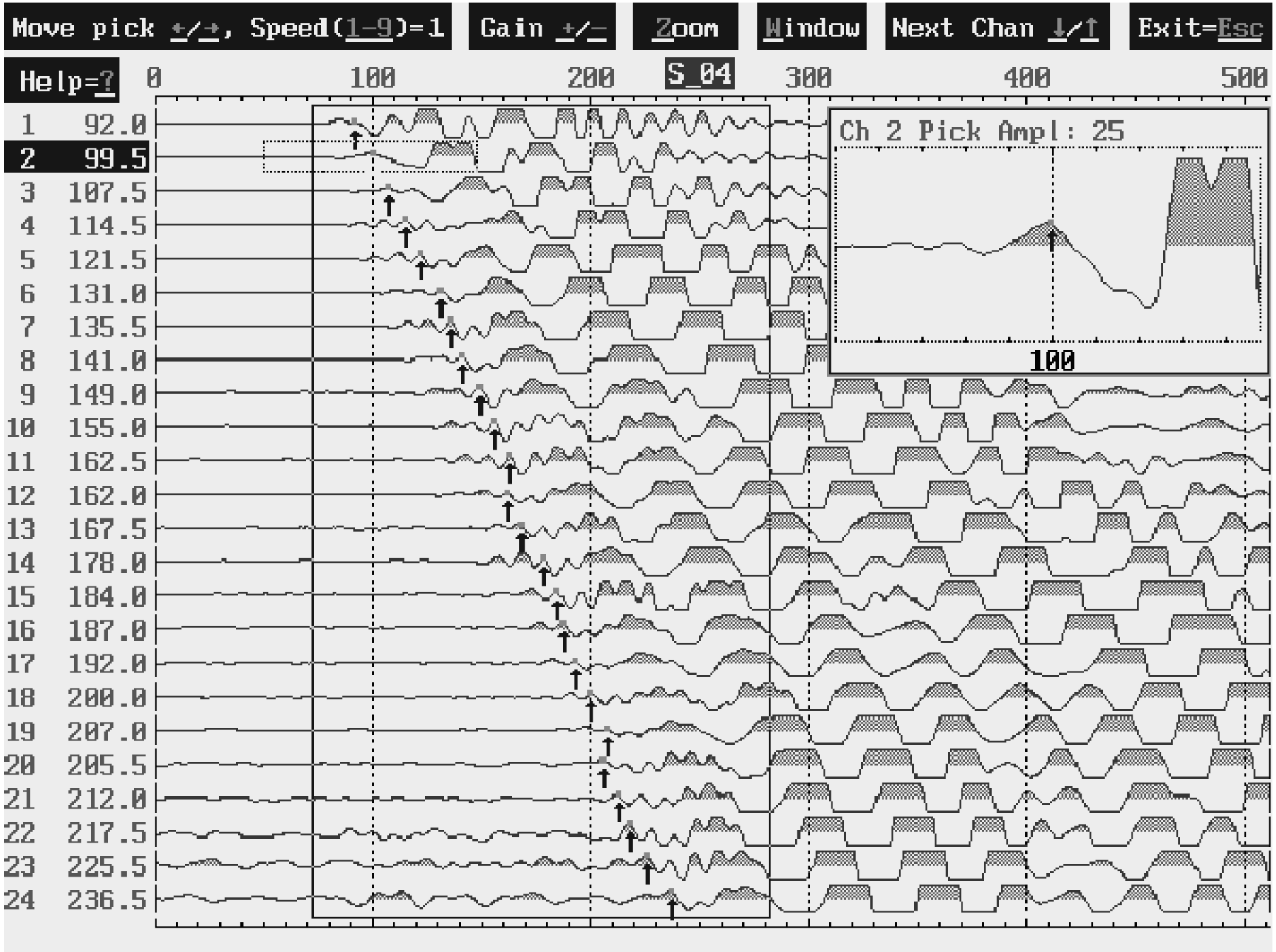

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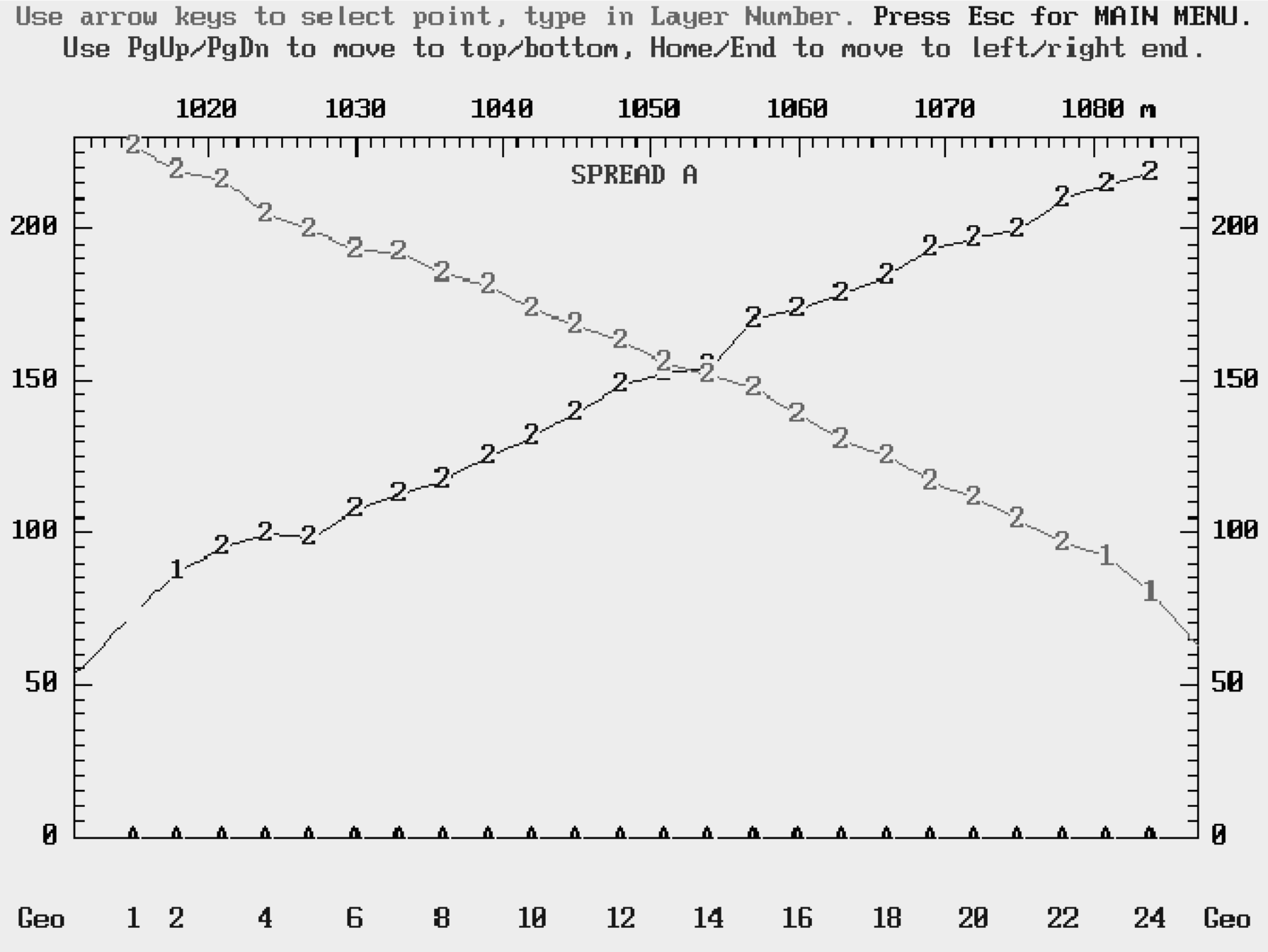

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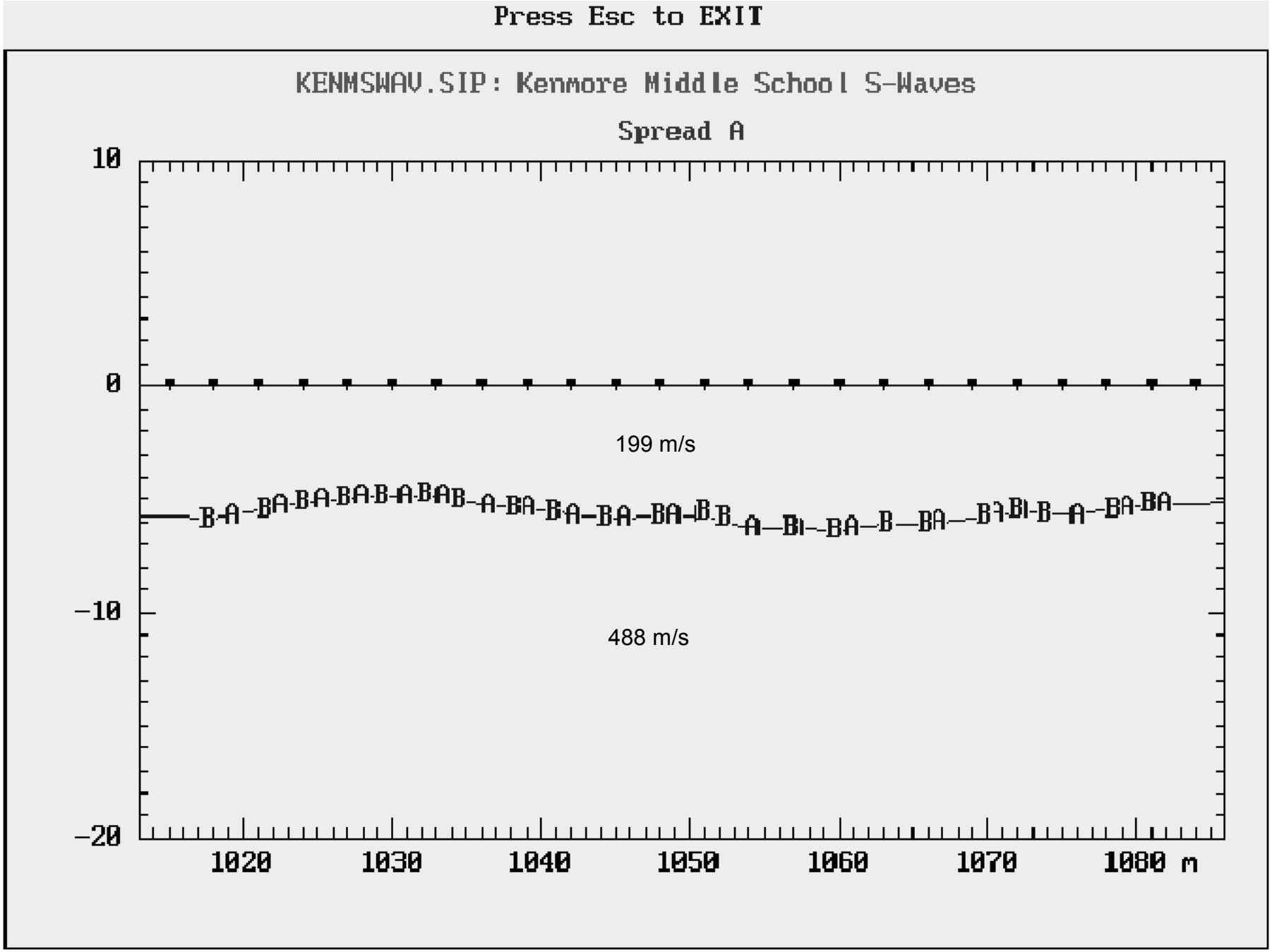

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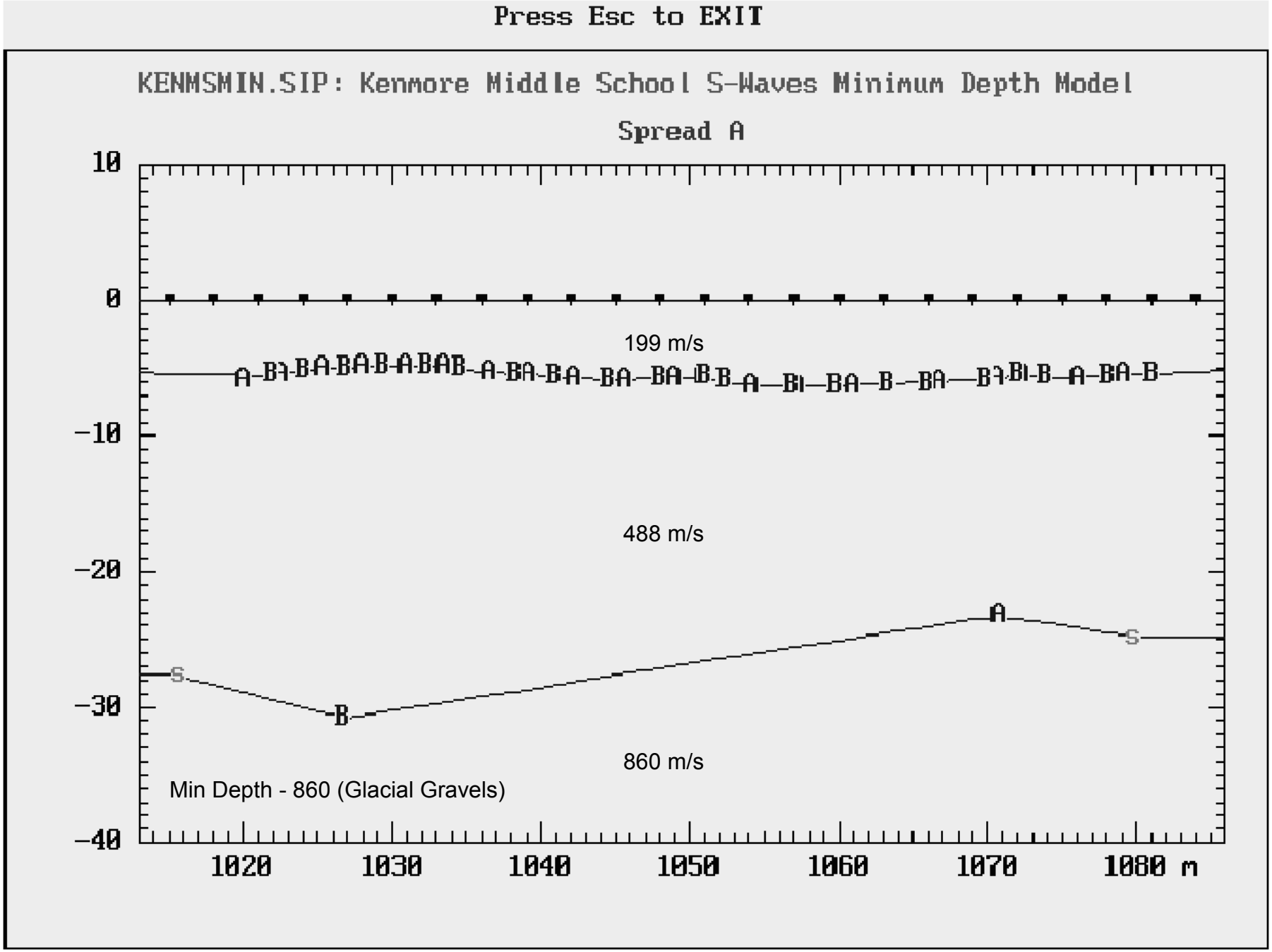
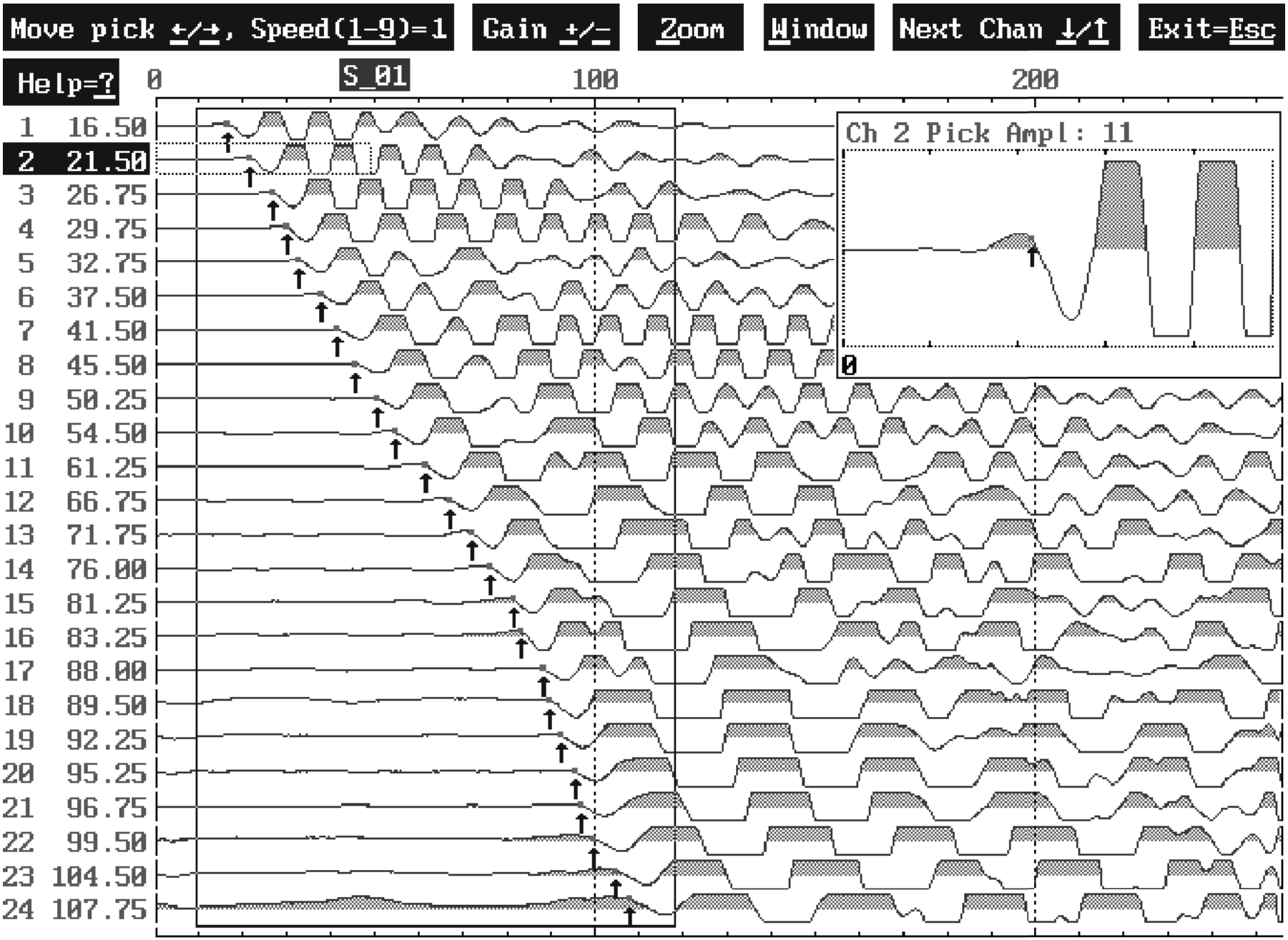


Lake Stevens Middle School S-wave



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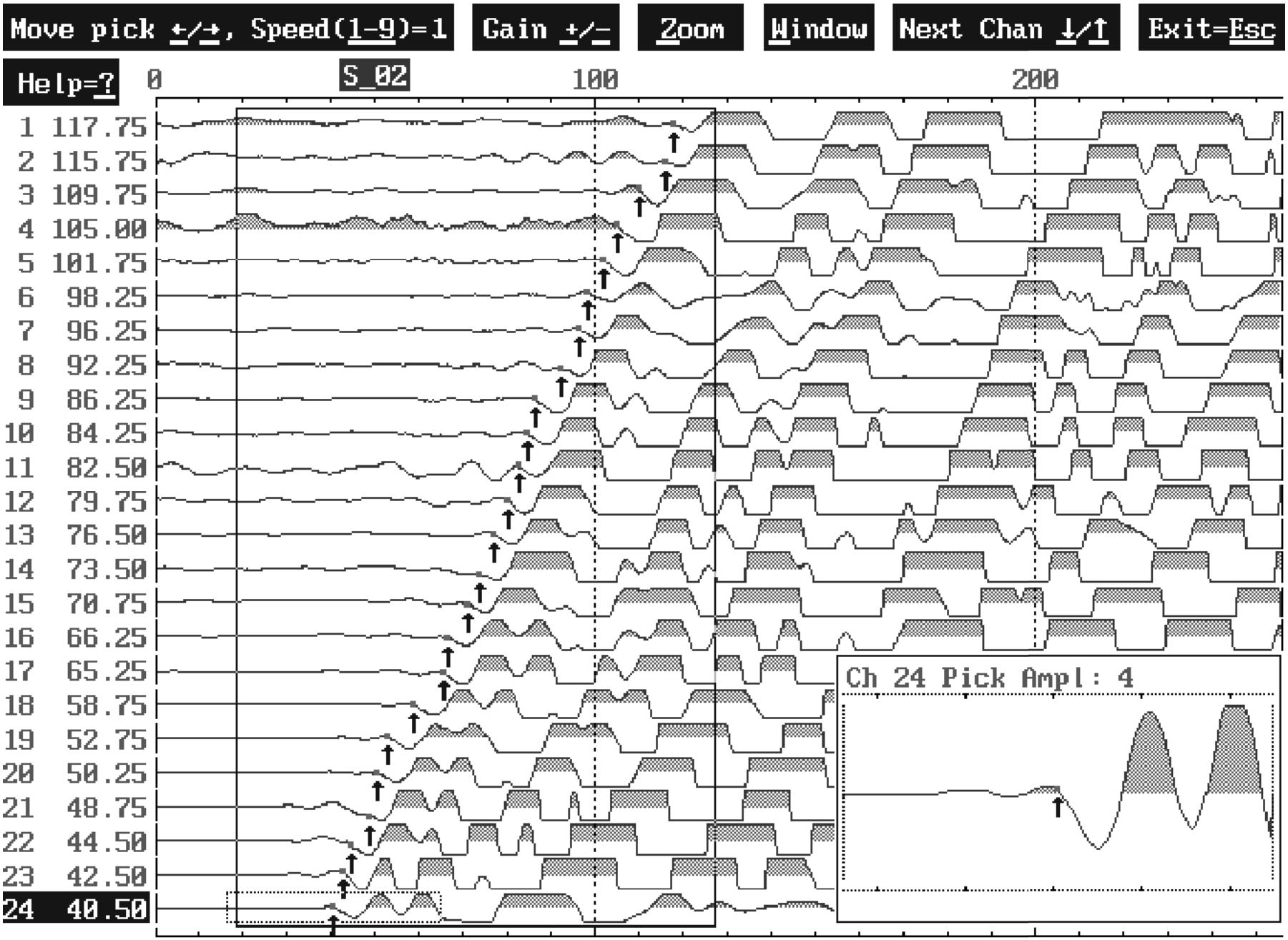

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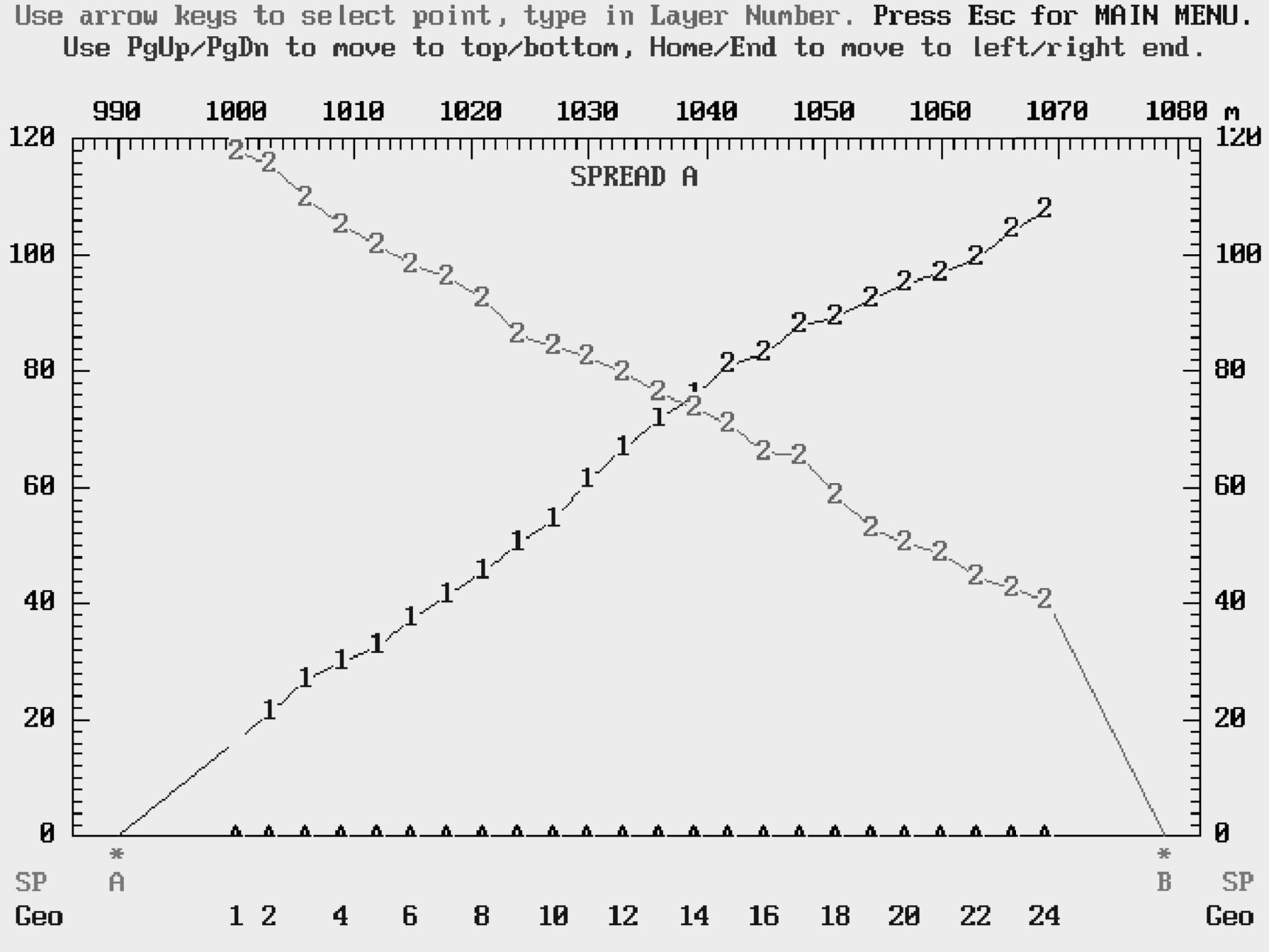

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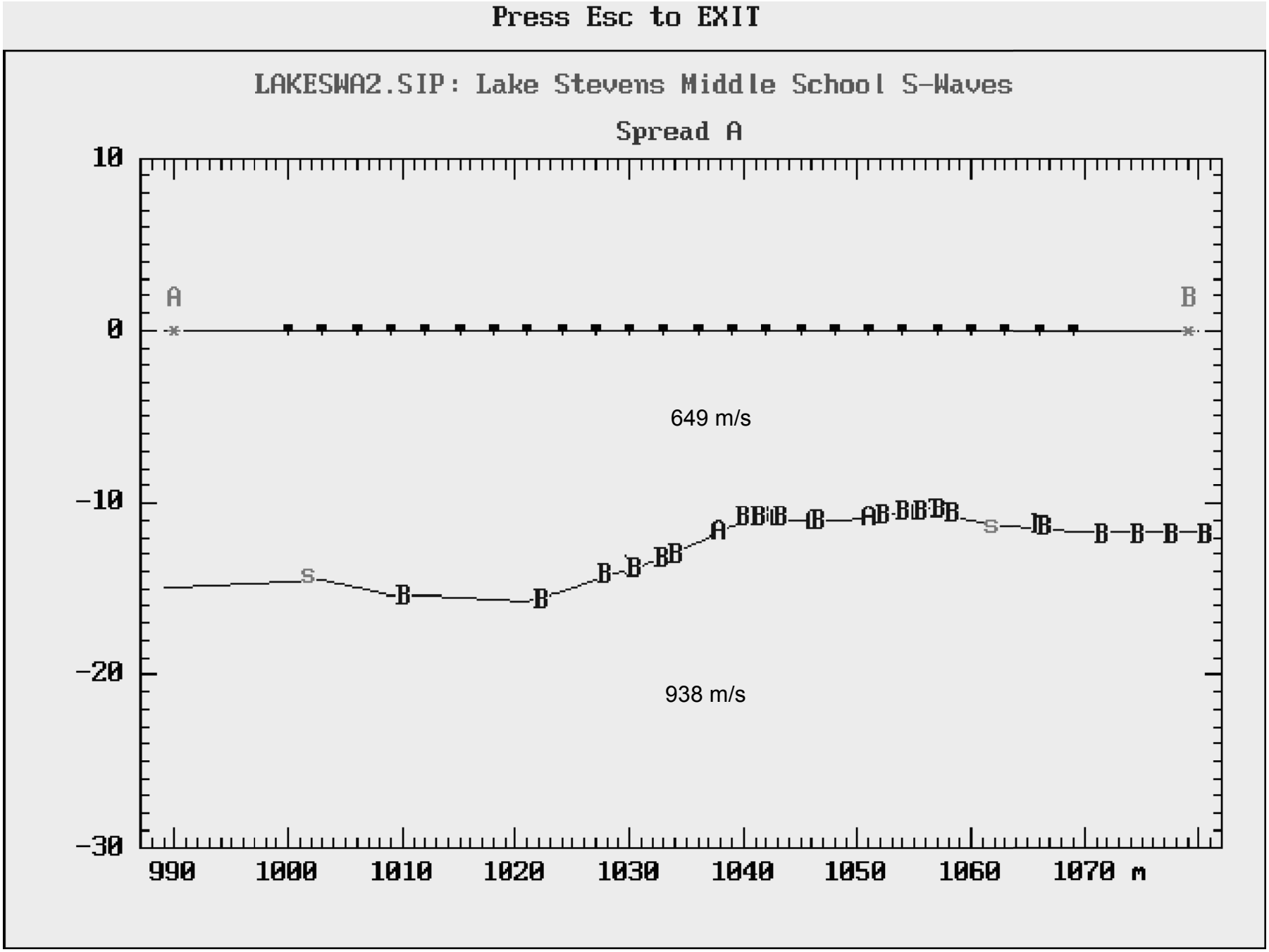

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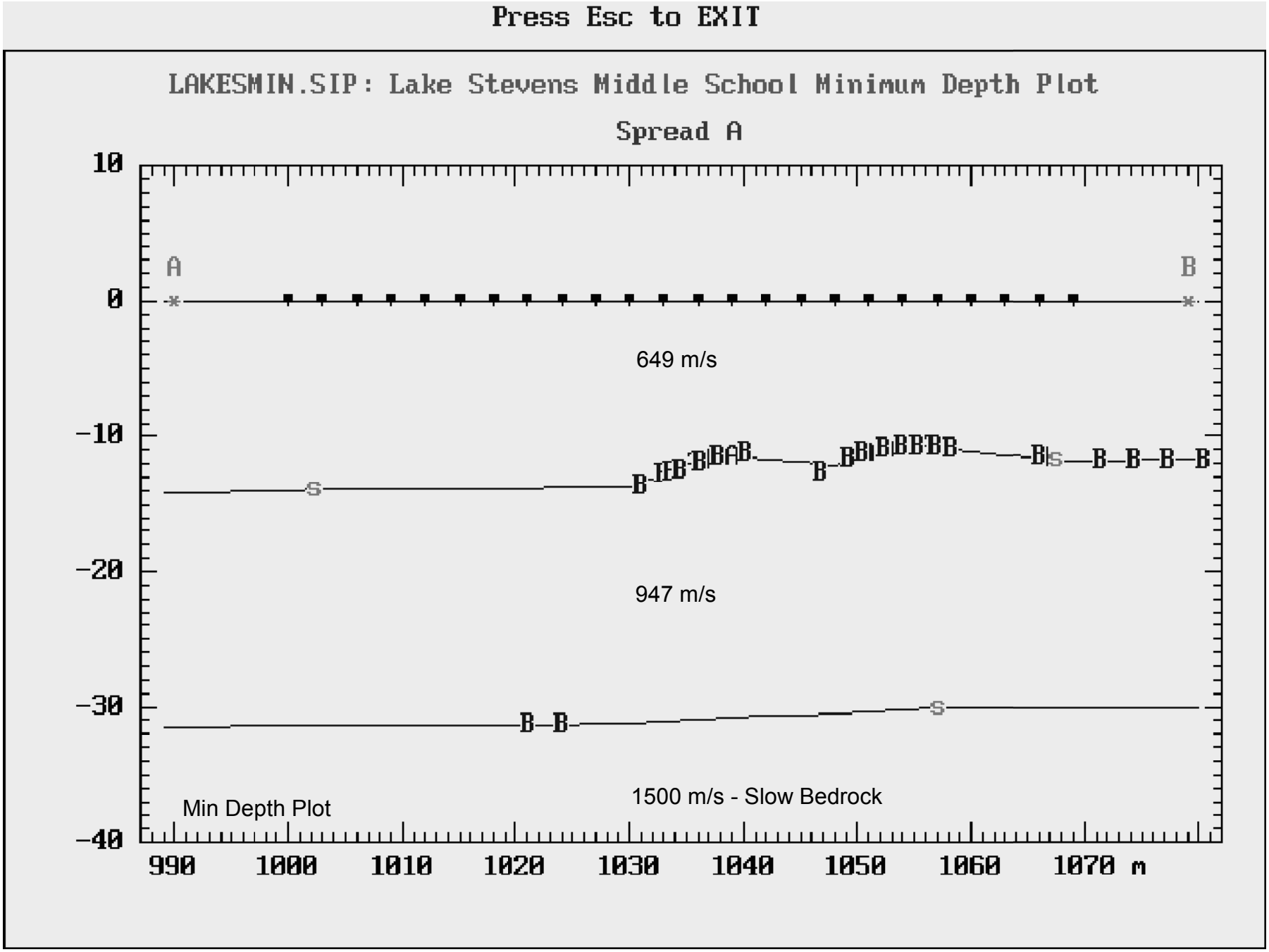
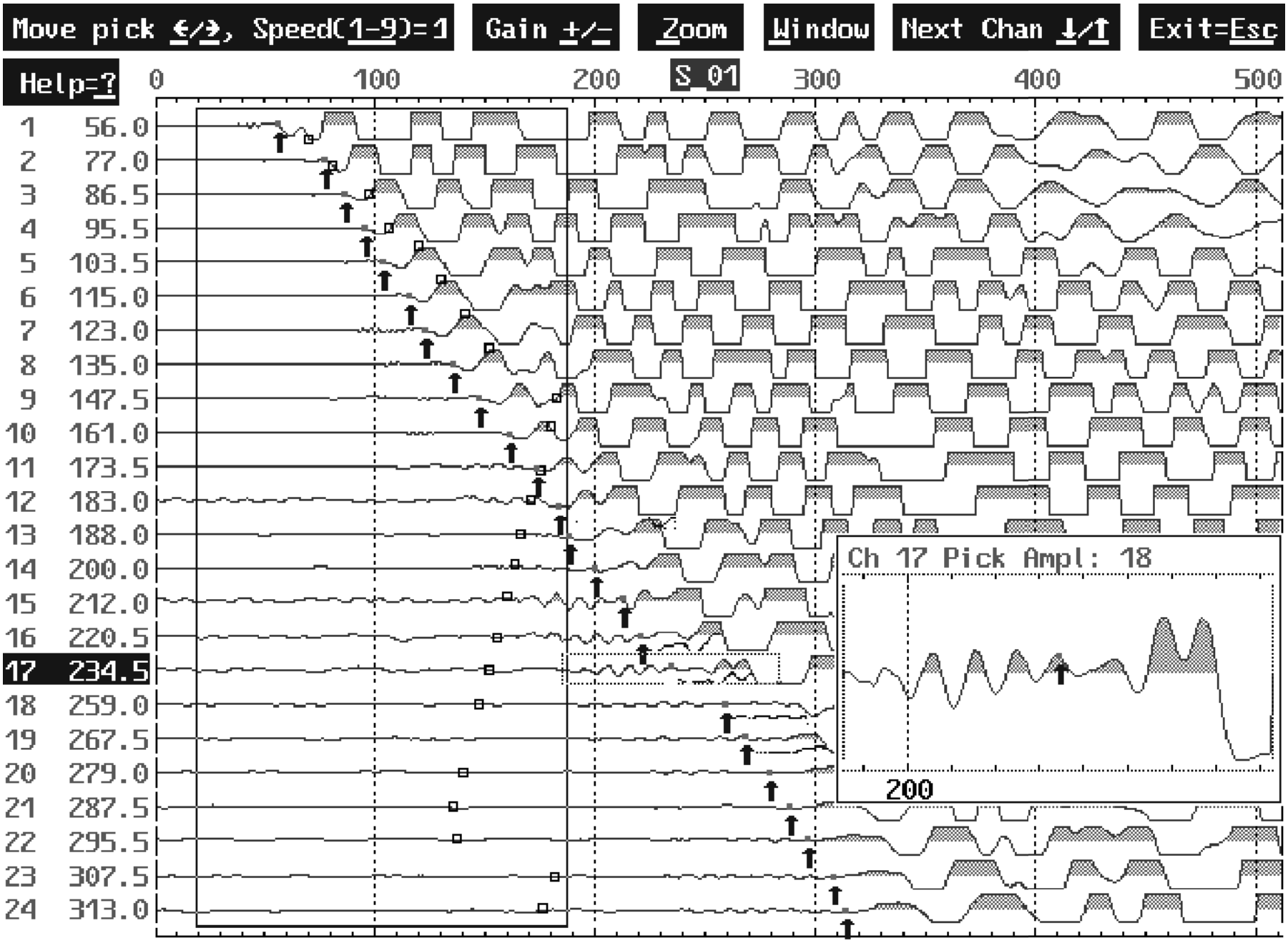


Lake Tye Park S-wave



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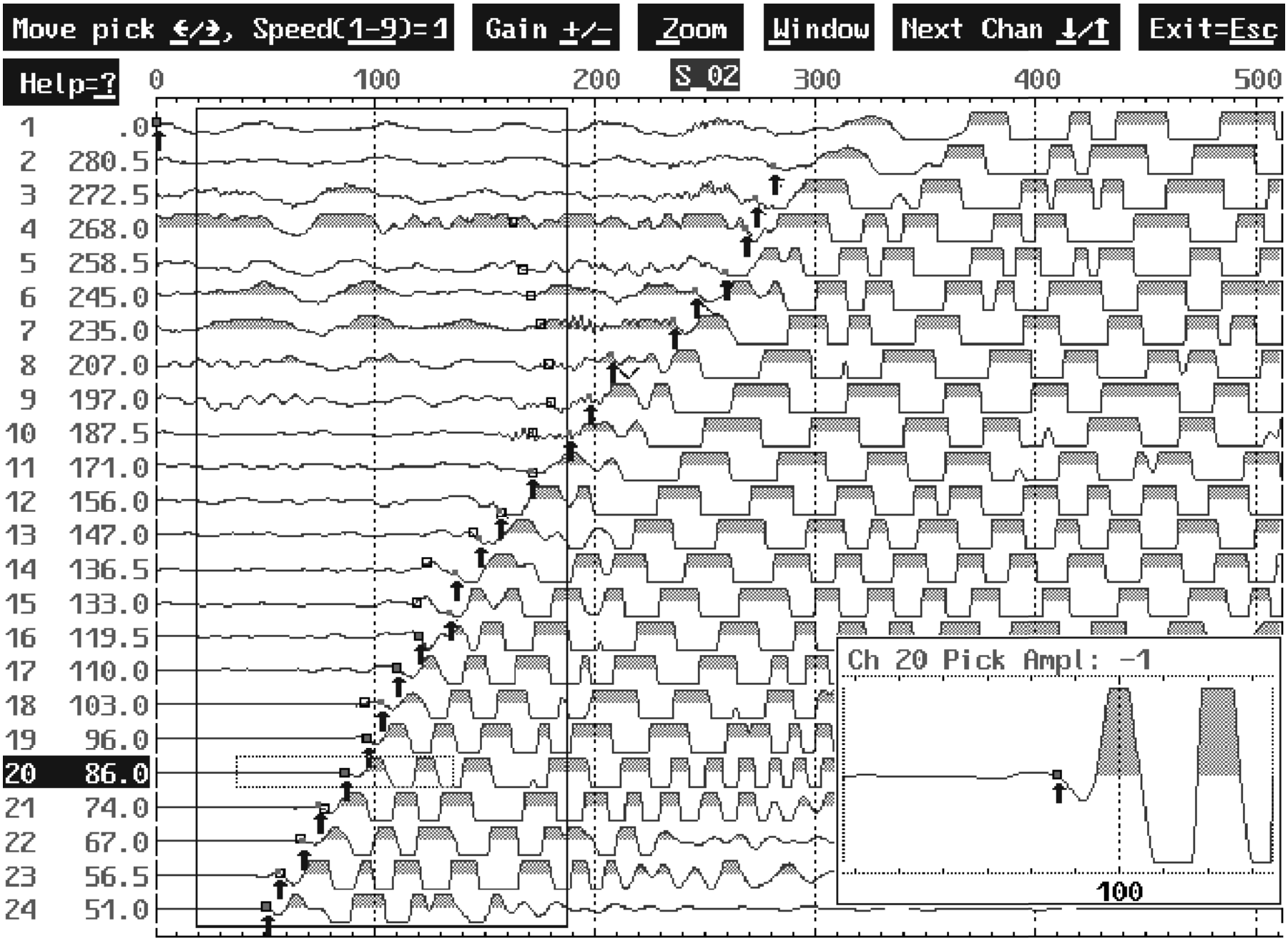

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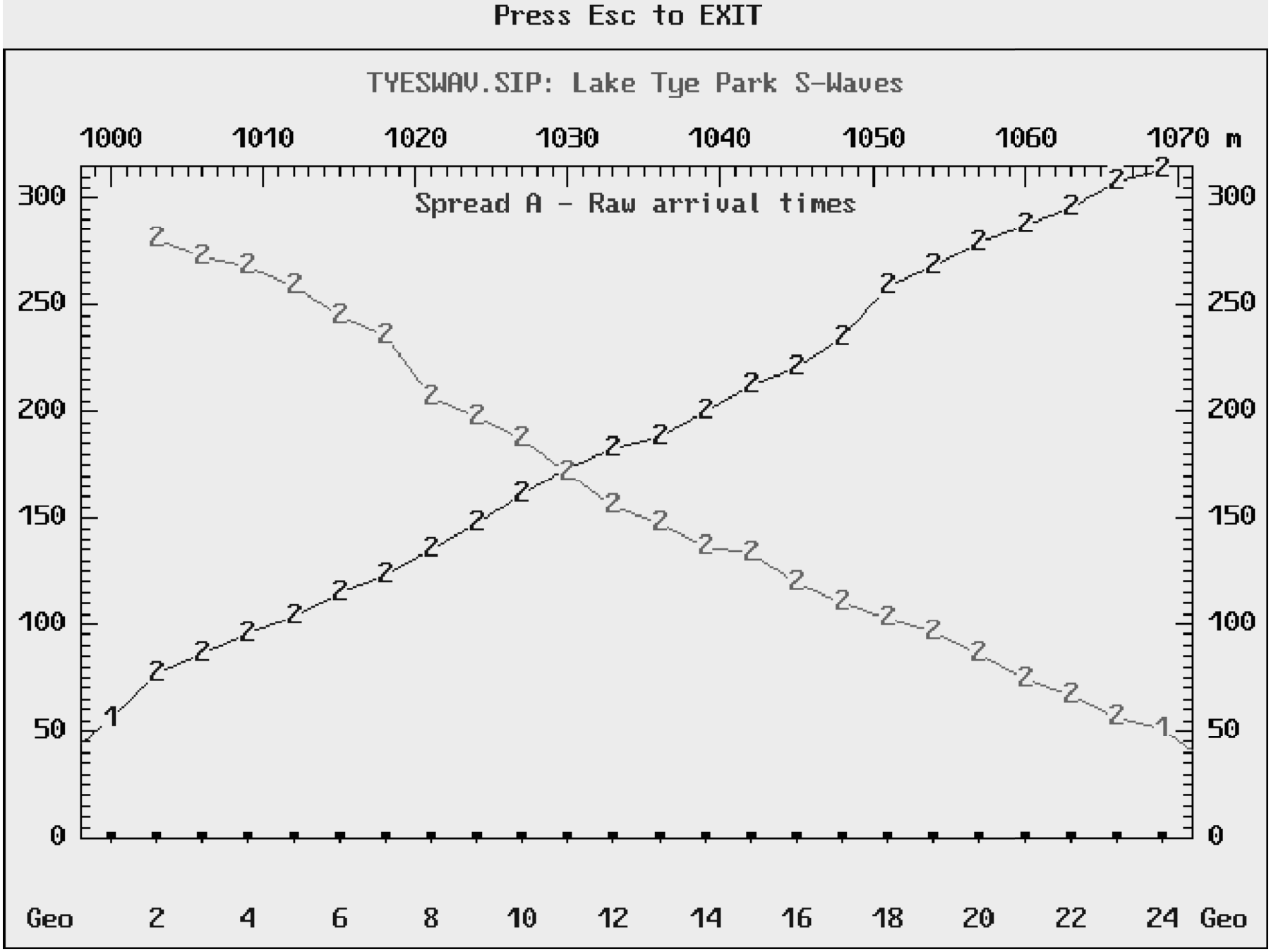

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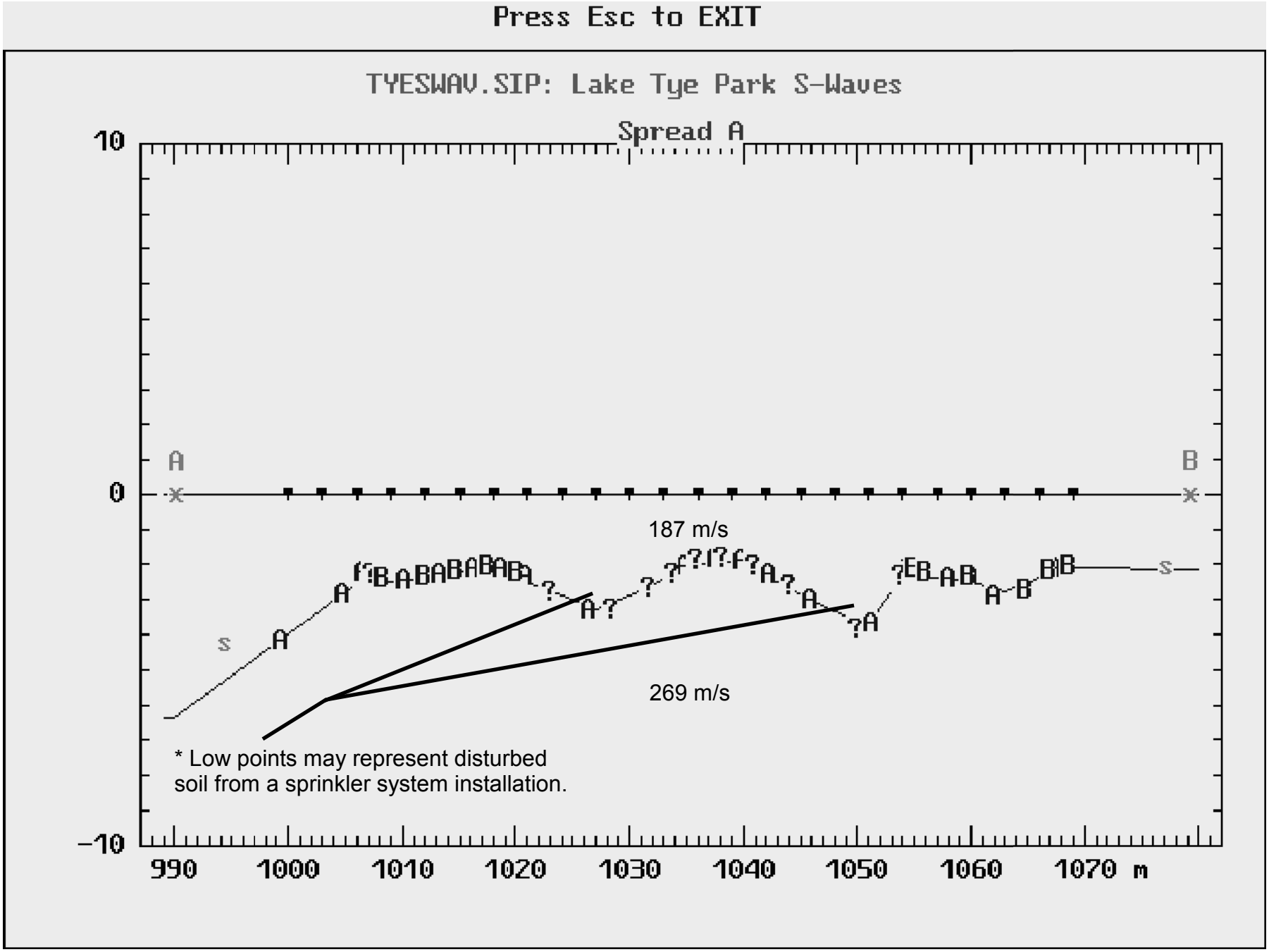

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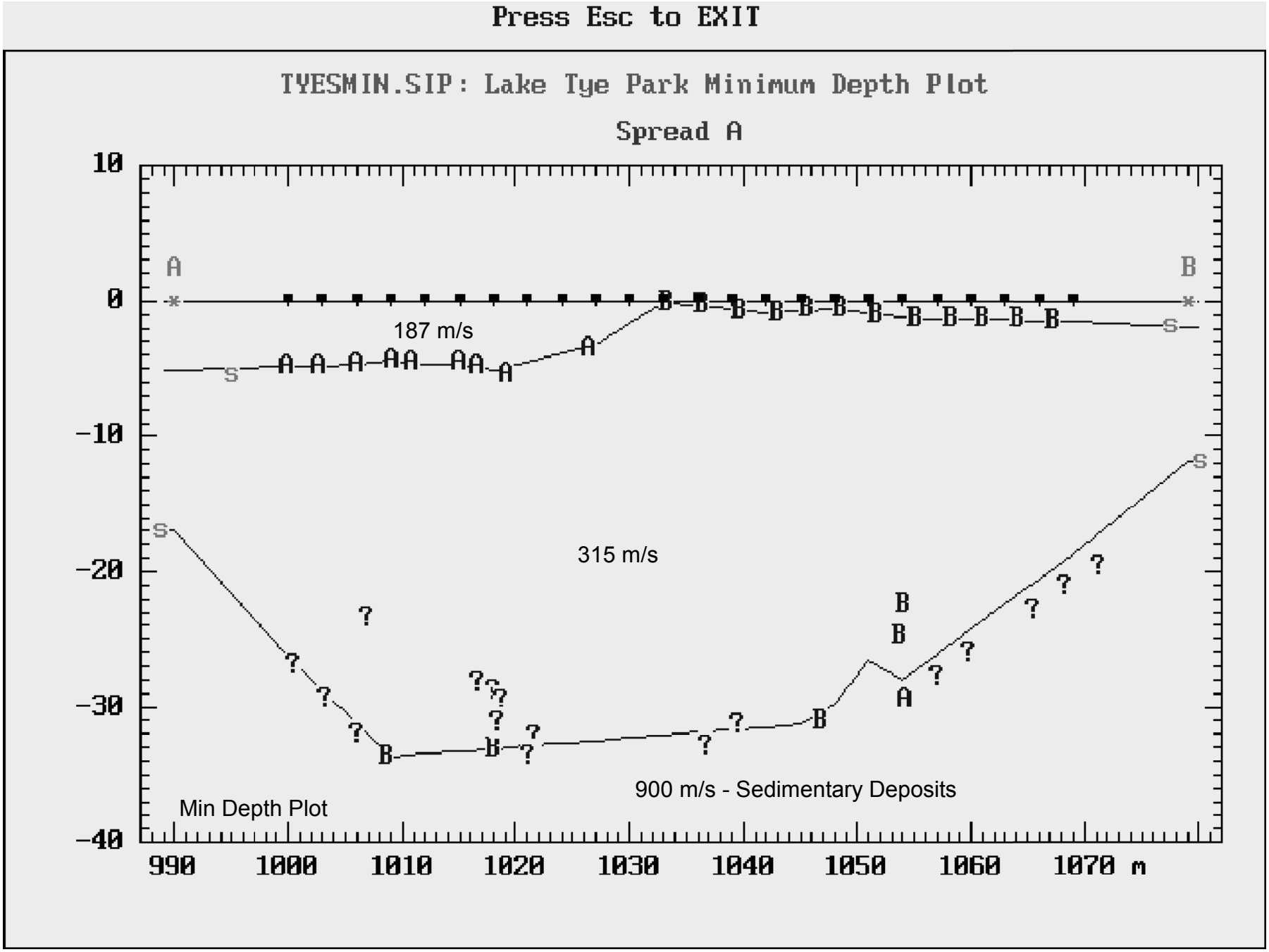
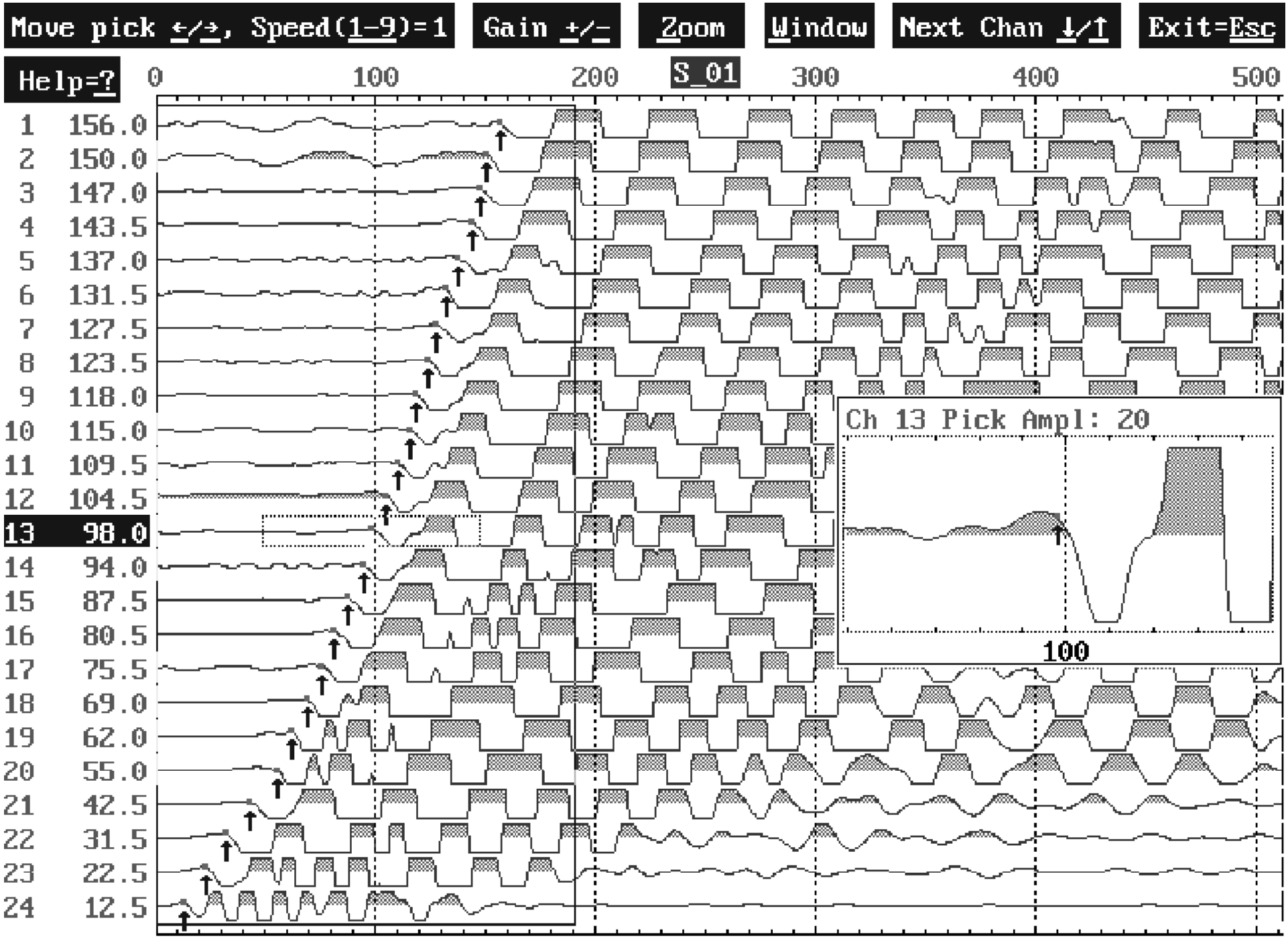


Lakewood High School S-wave



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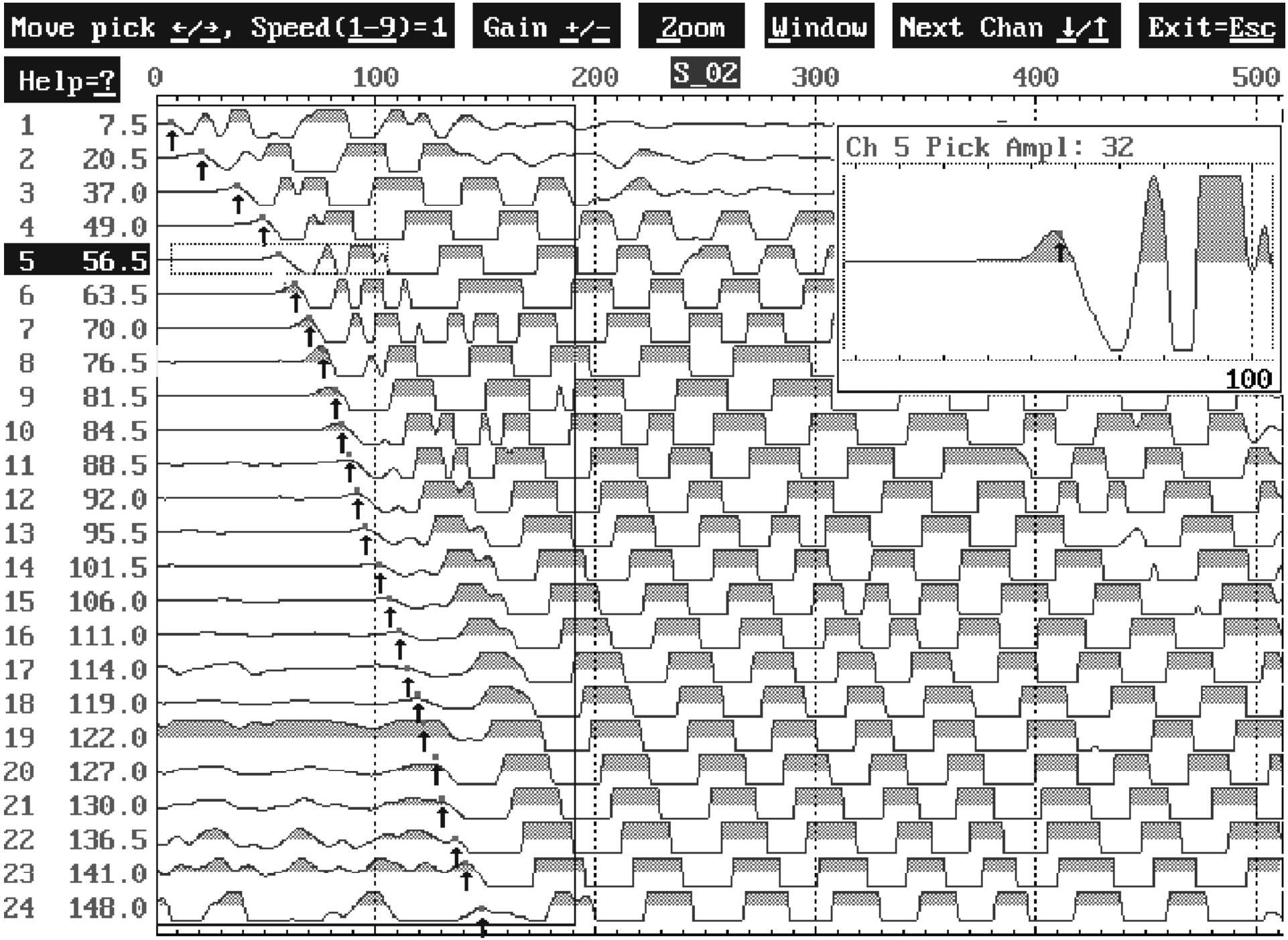

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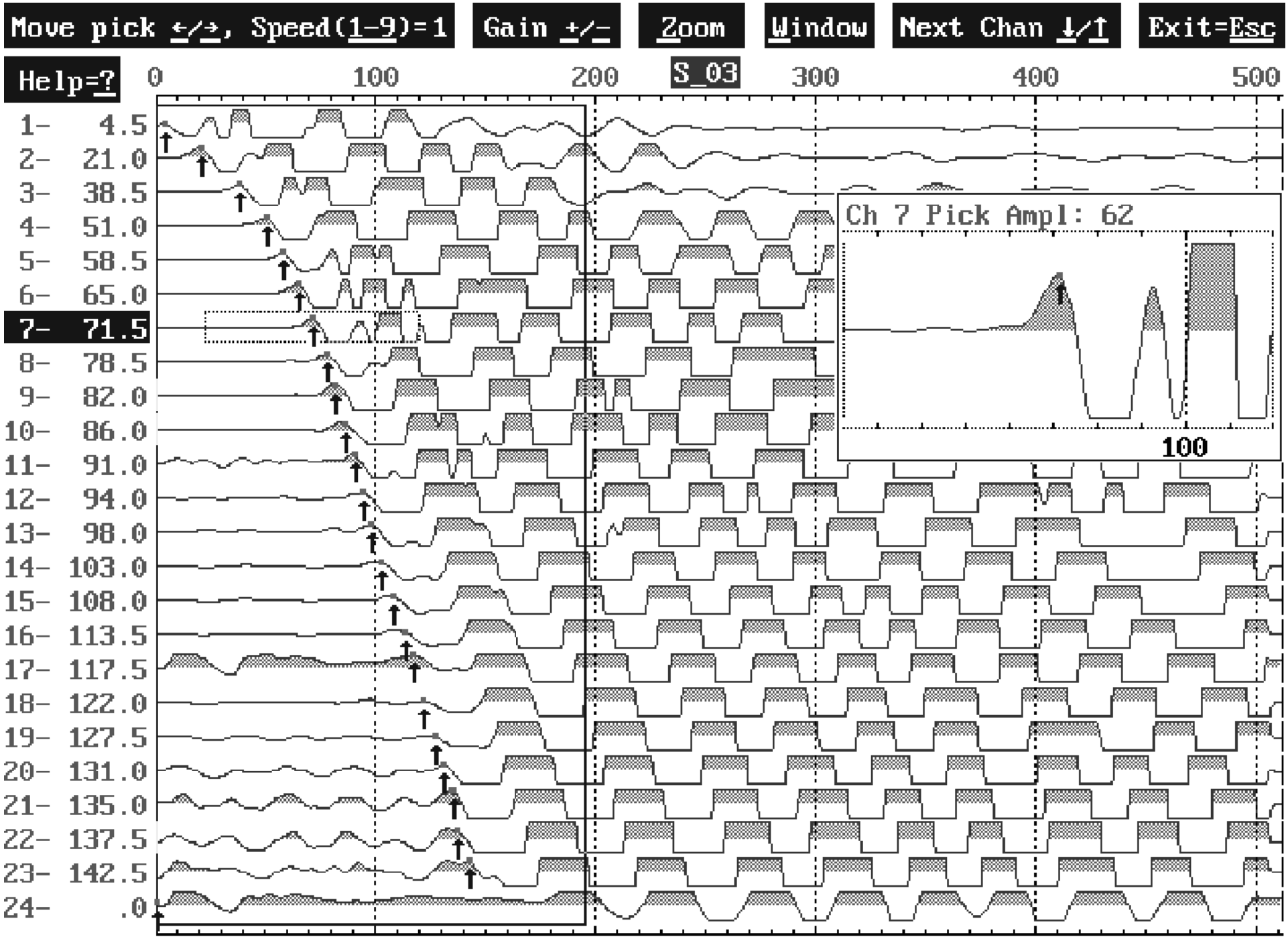

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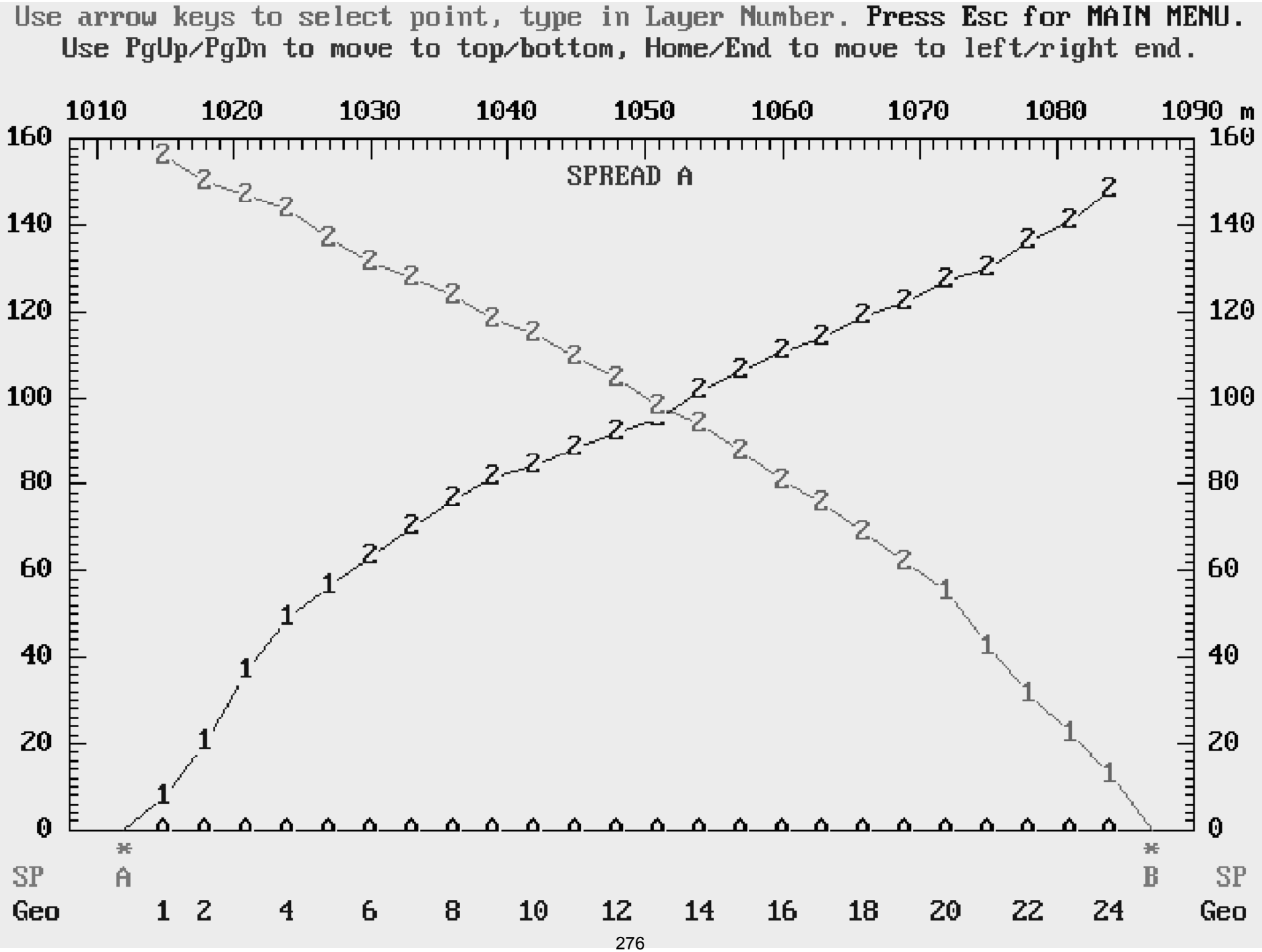

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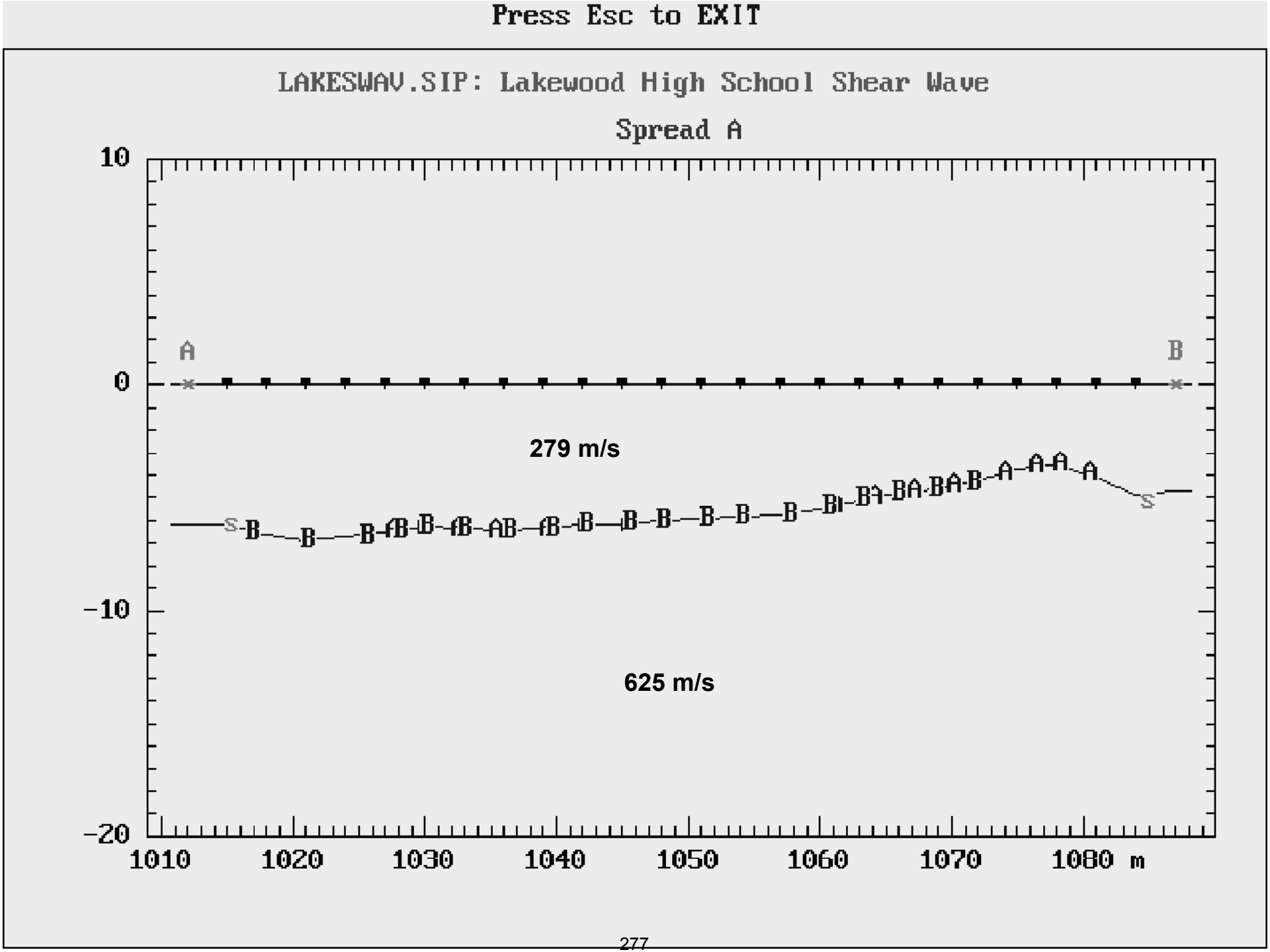

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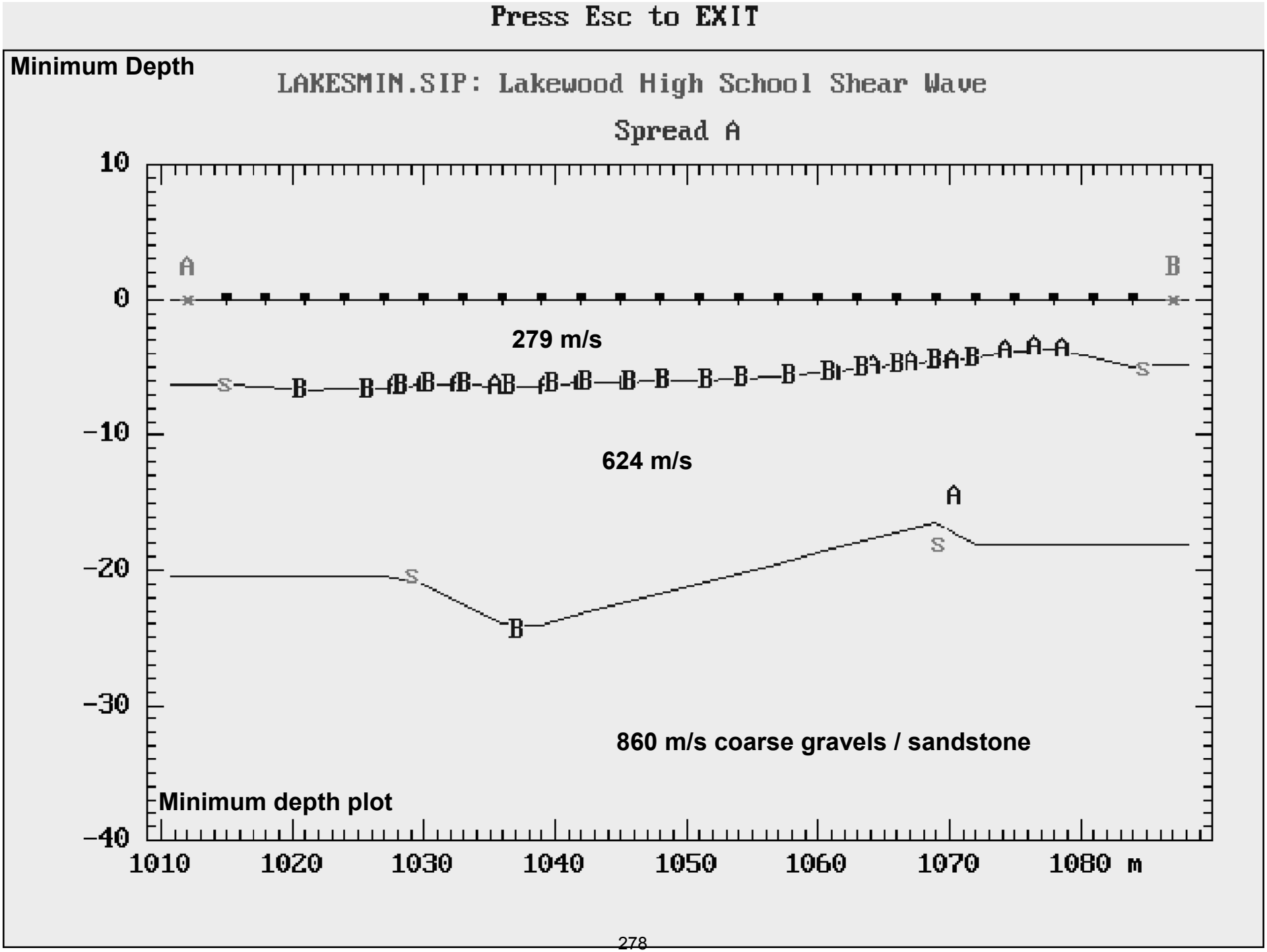
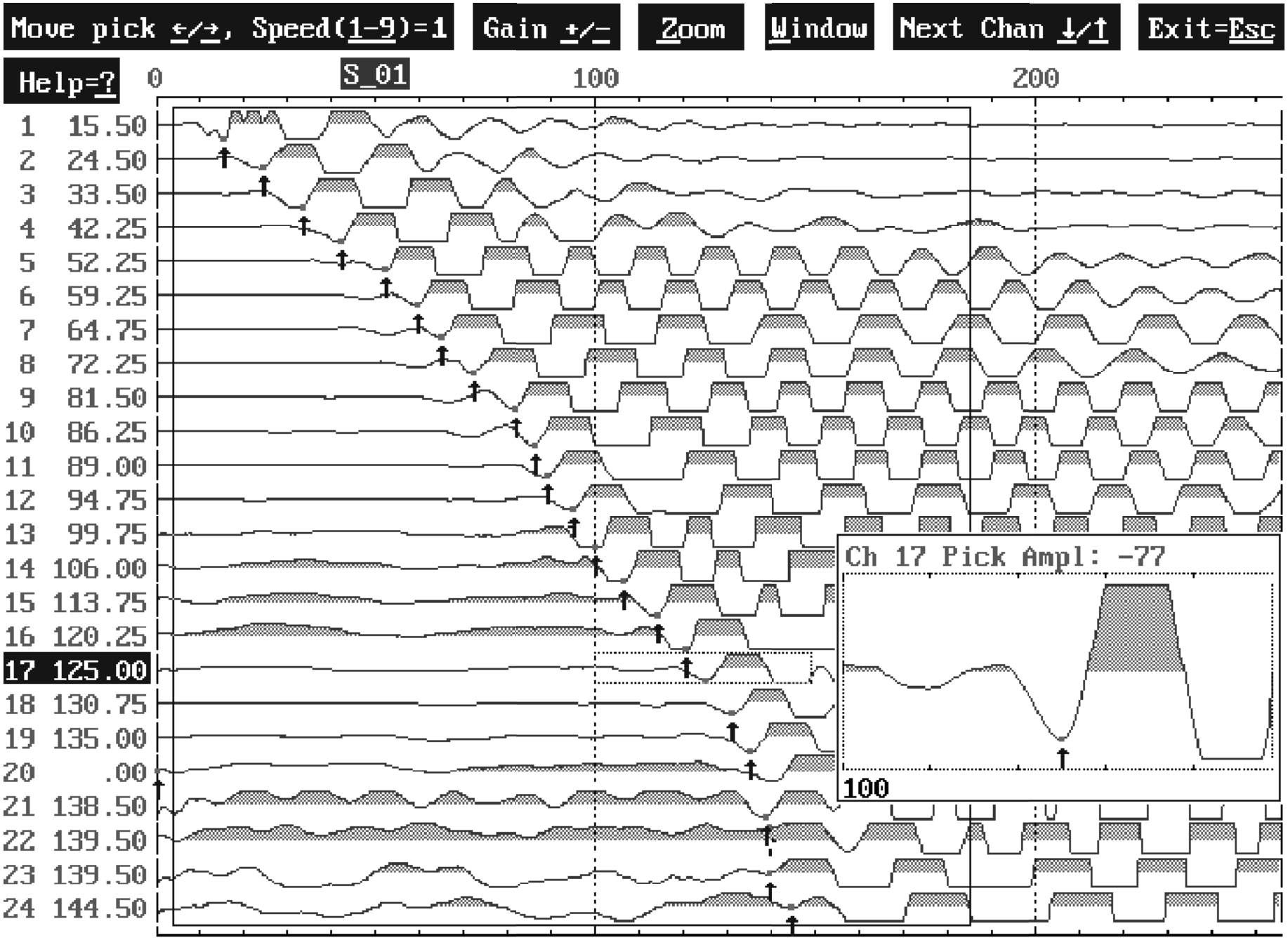


Liberty Lake S-wave



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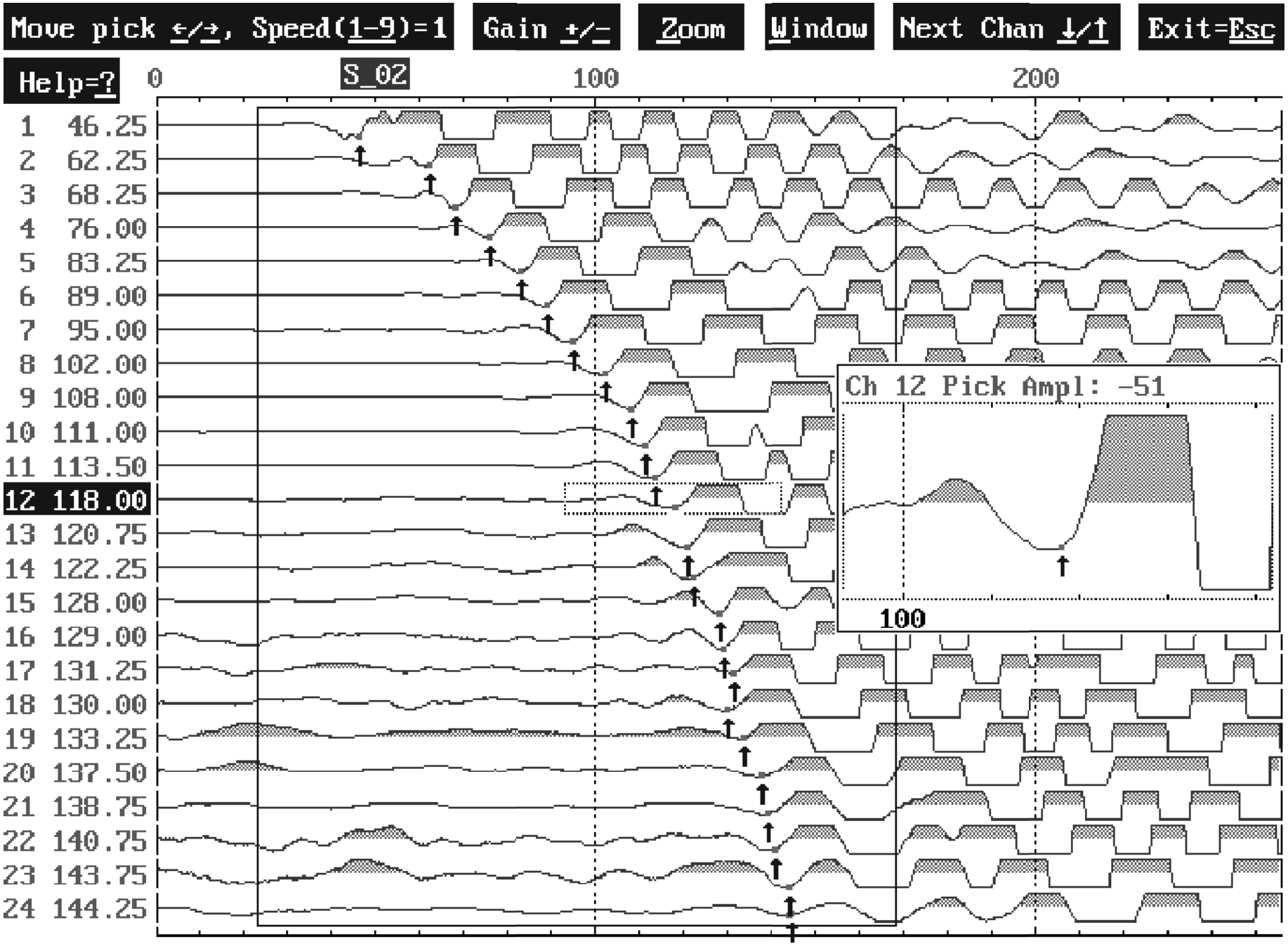

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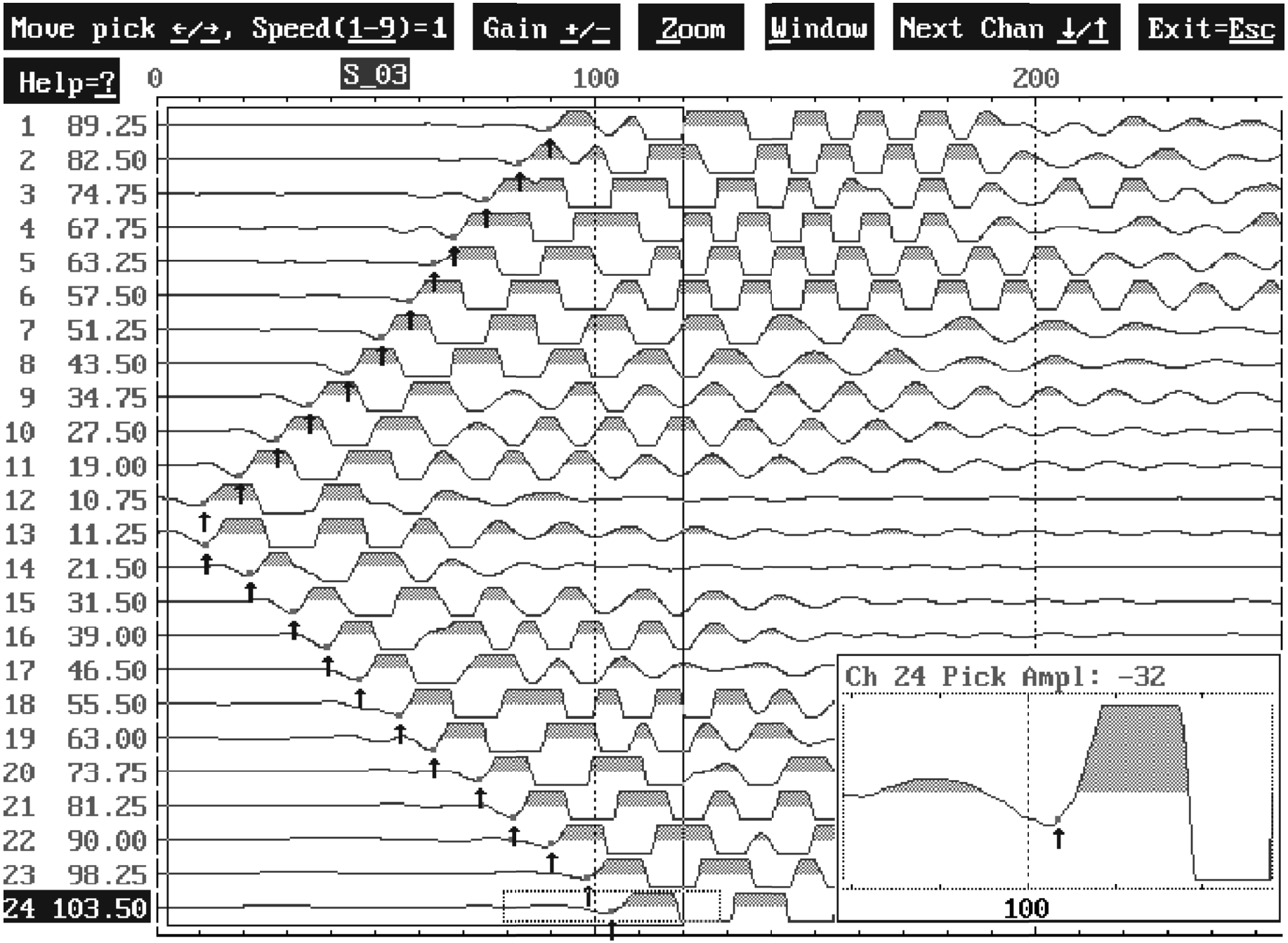

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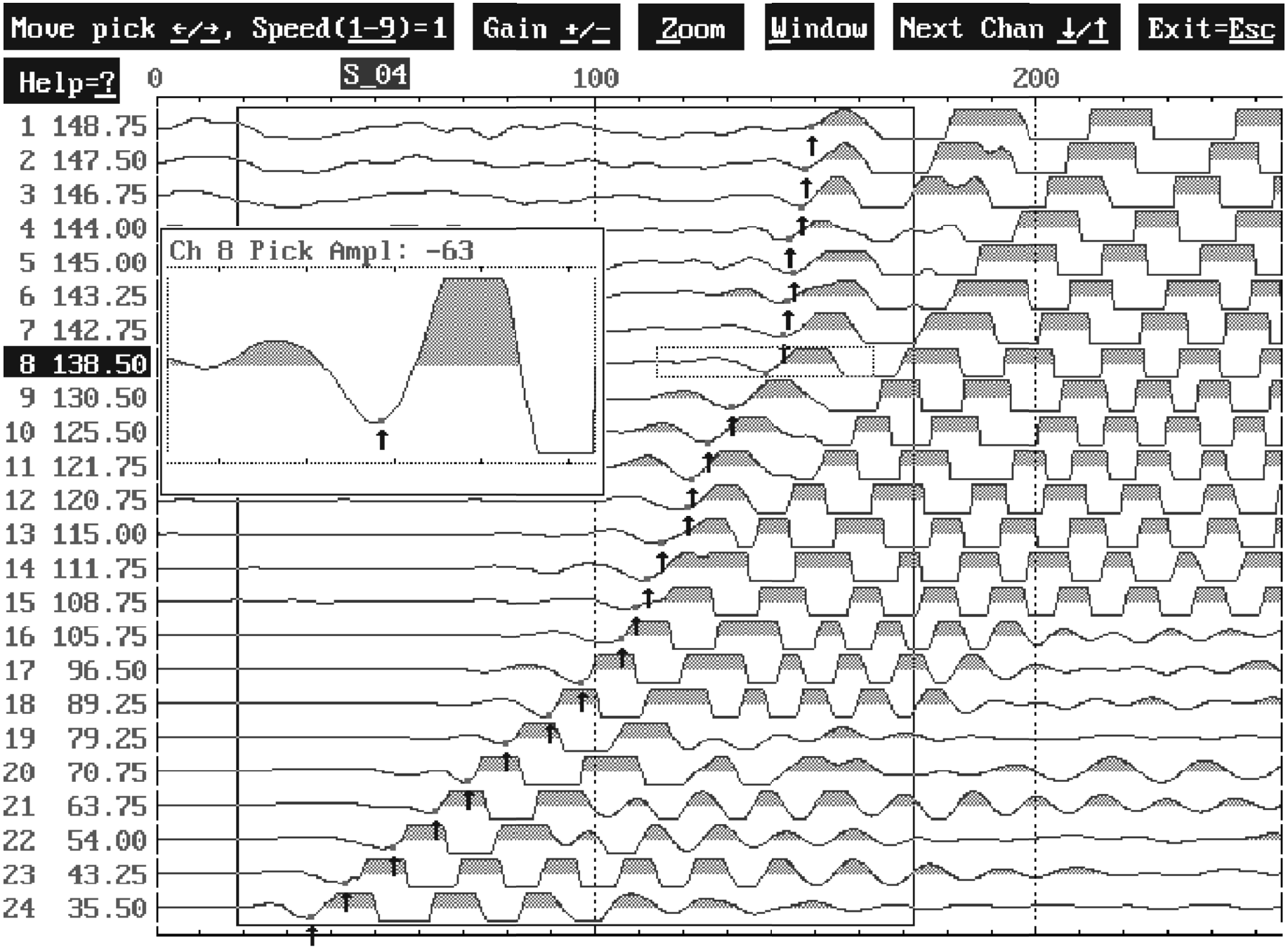

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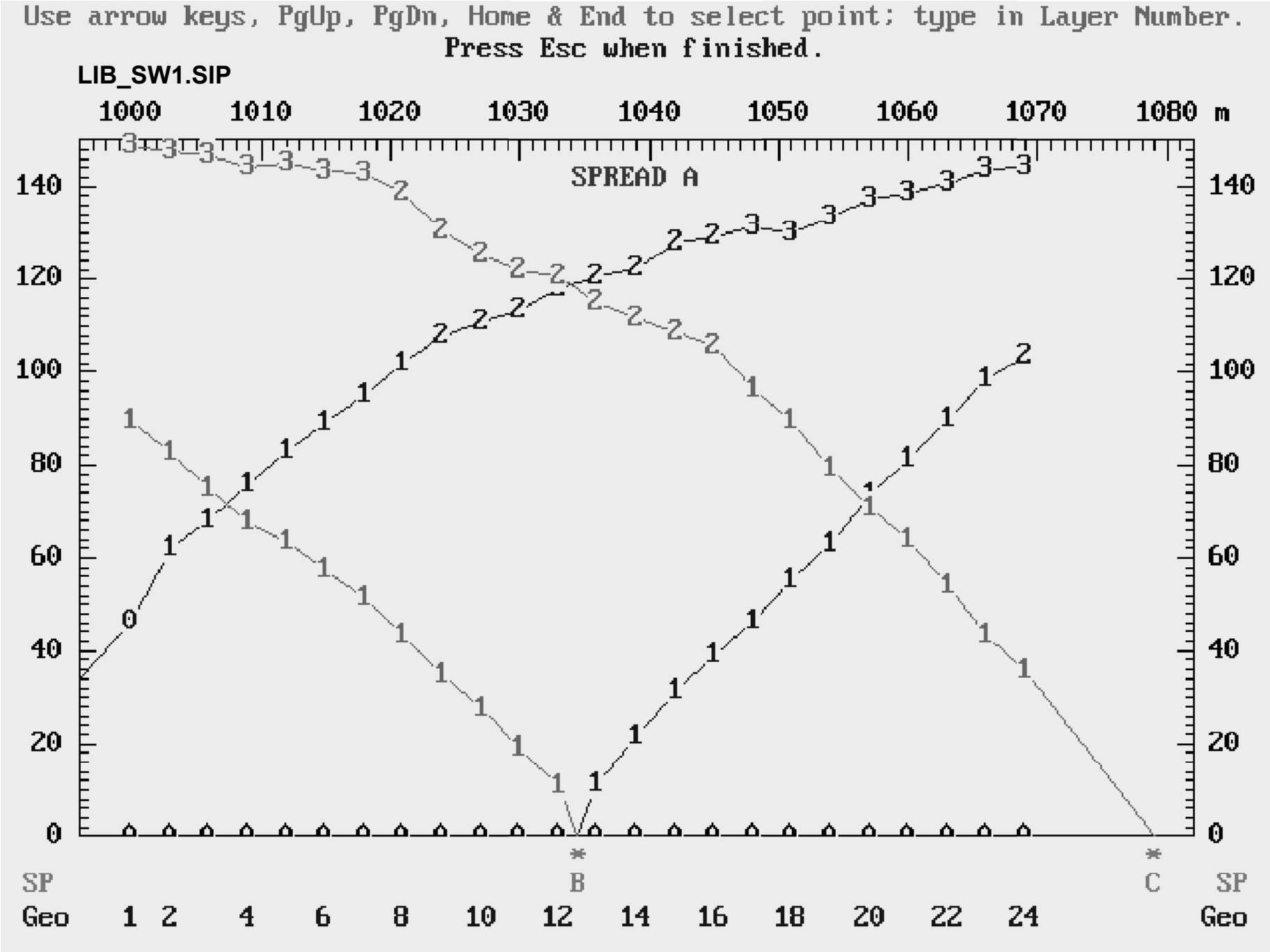

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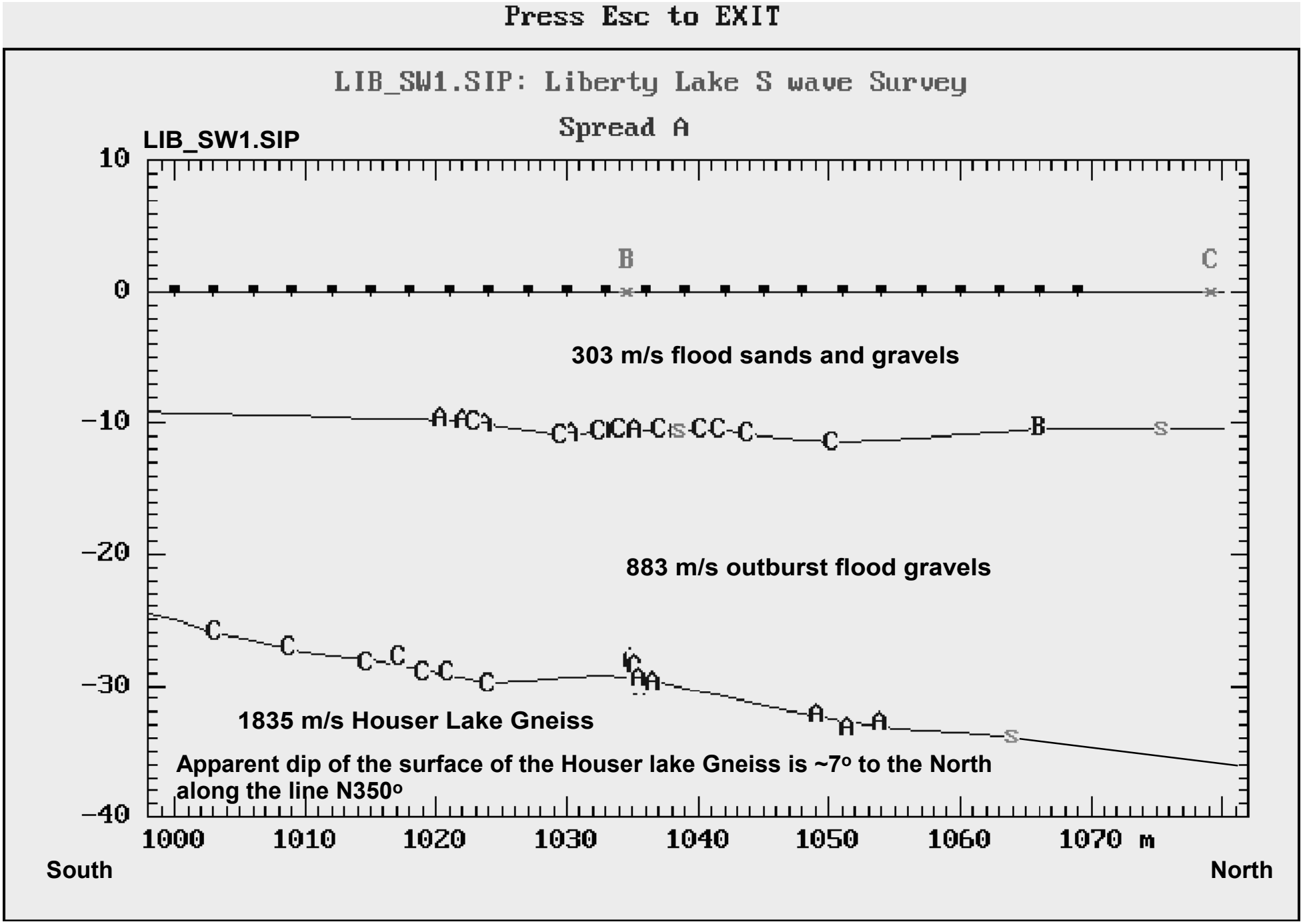
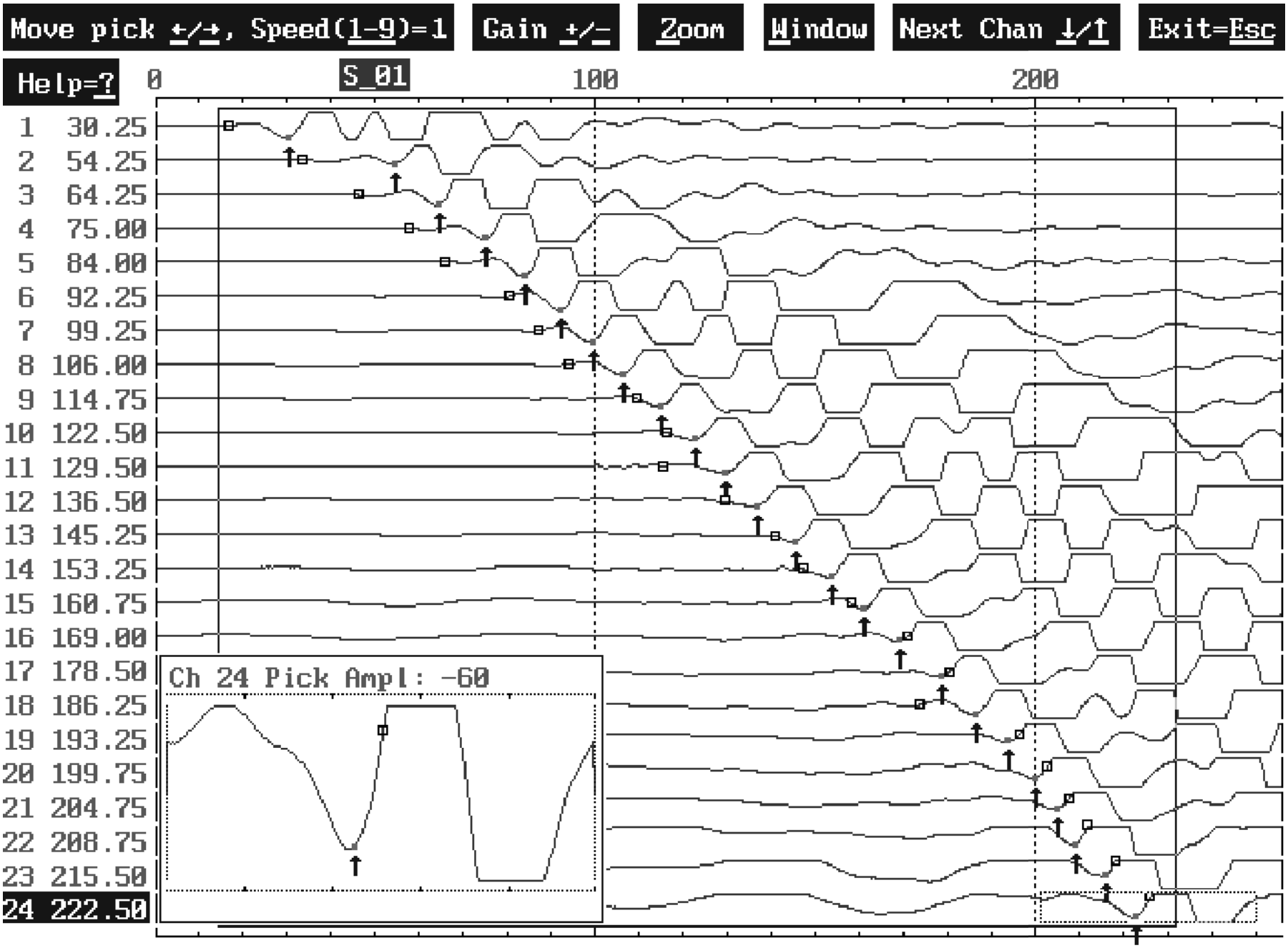


Lincoln Road S-wave



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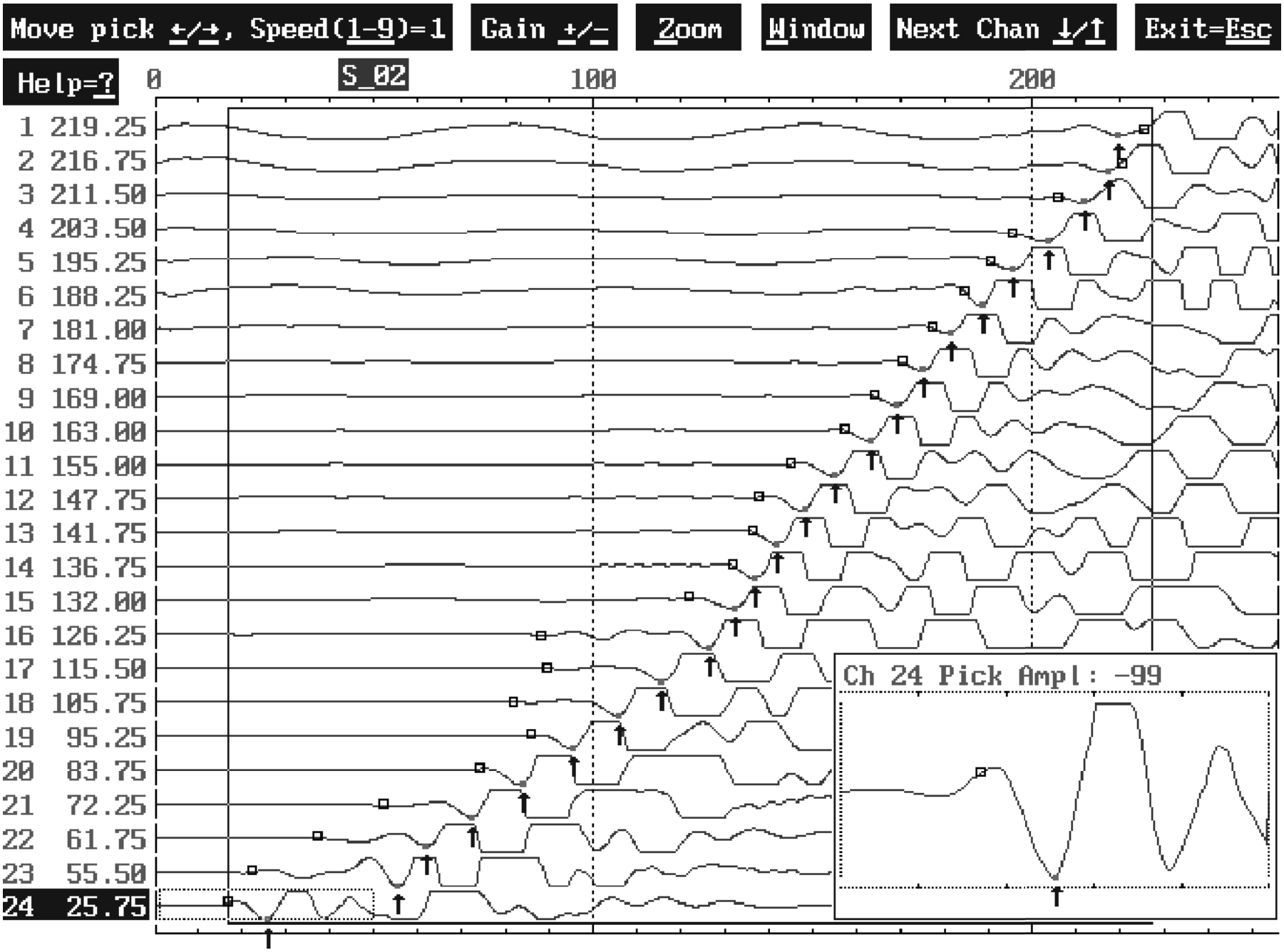

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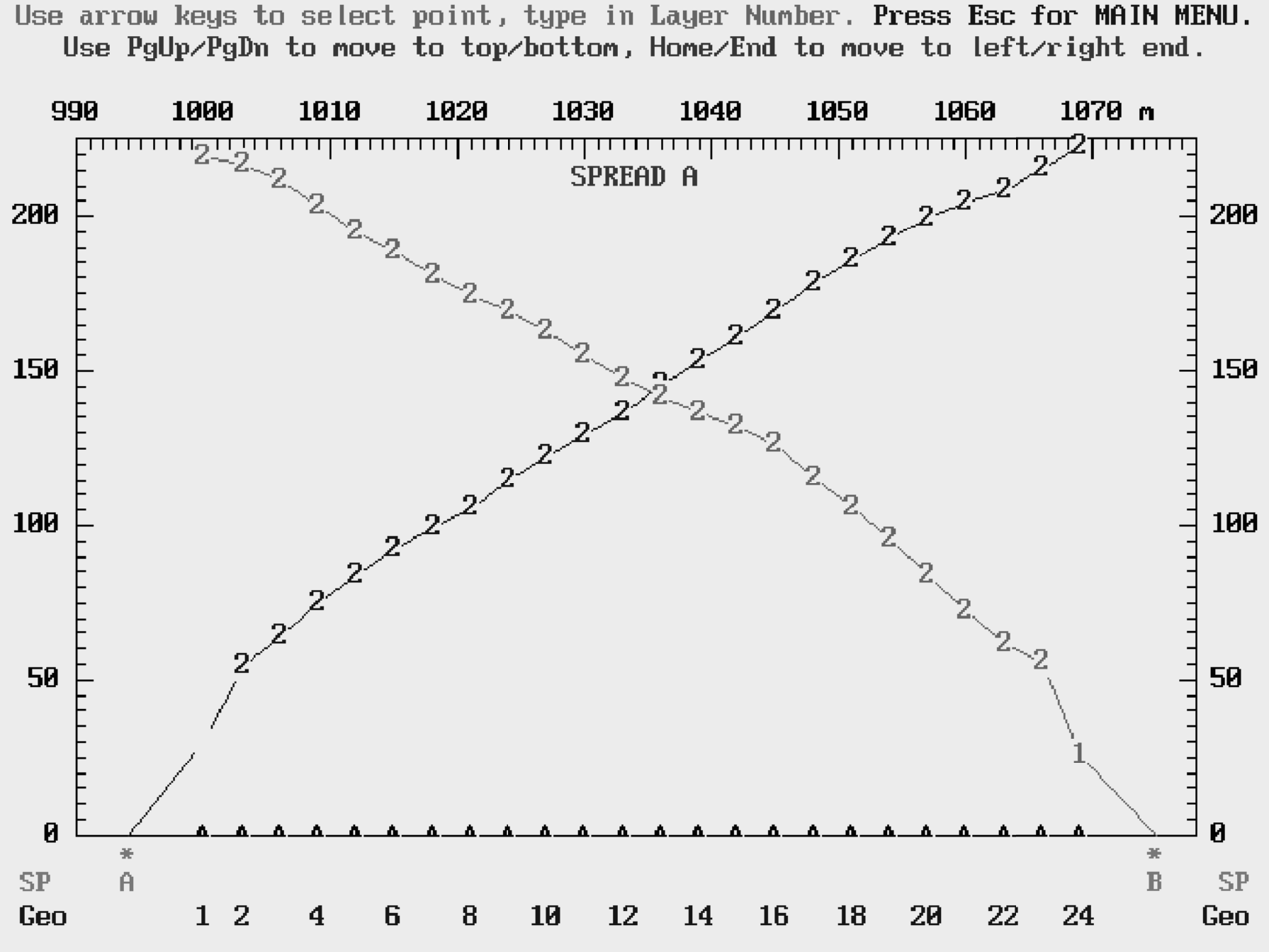

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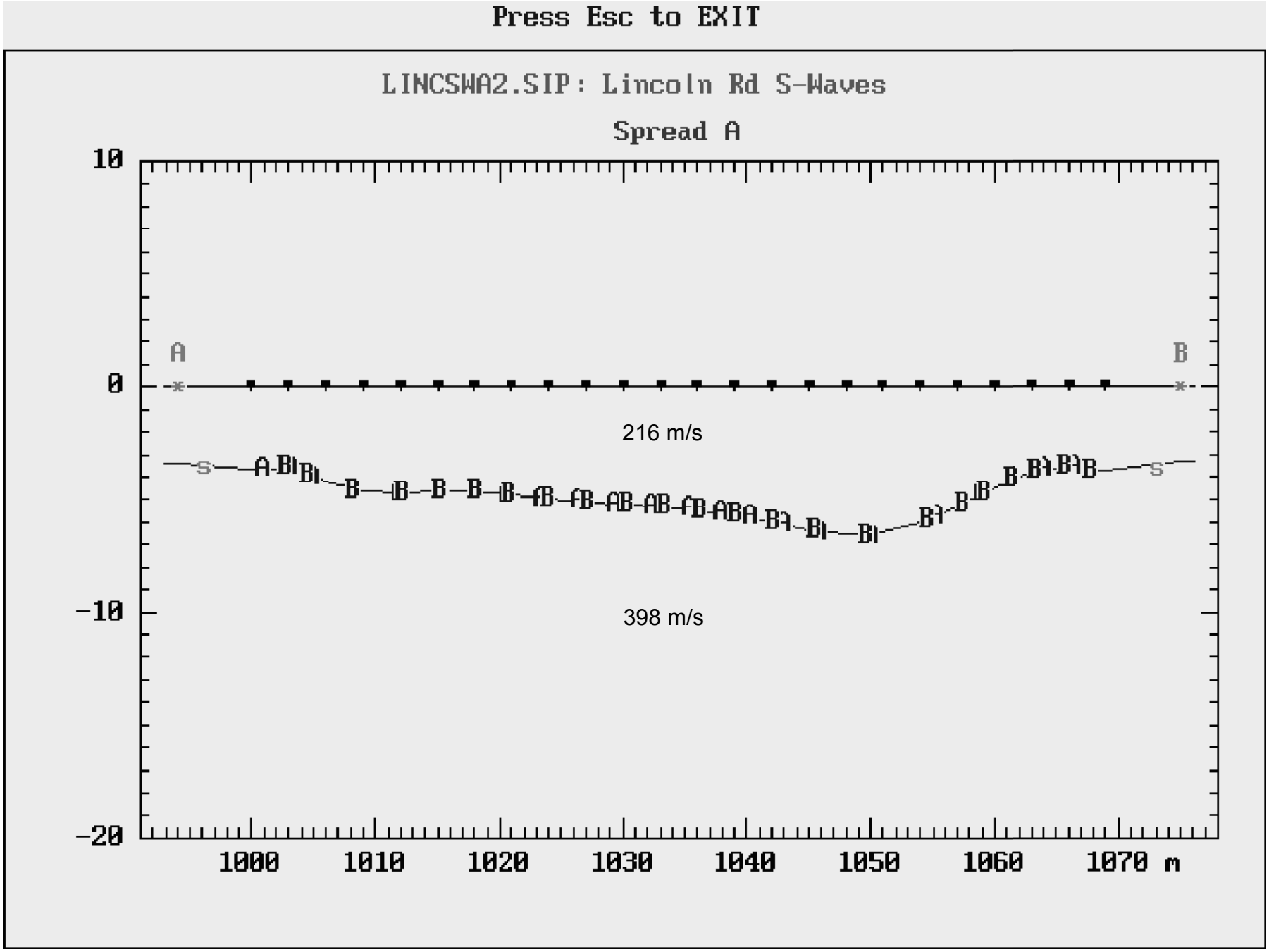

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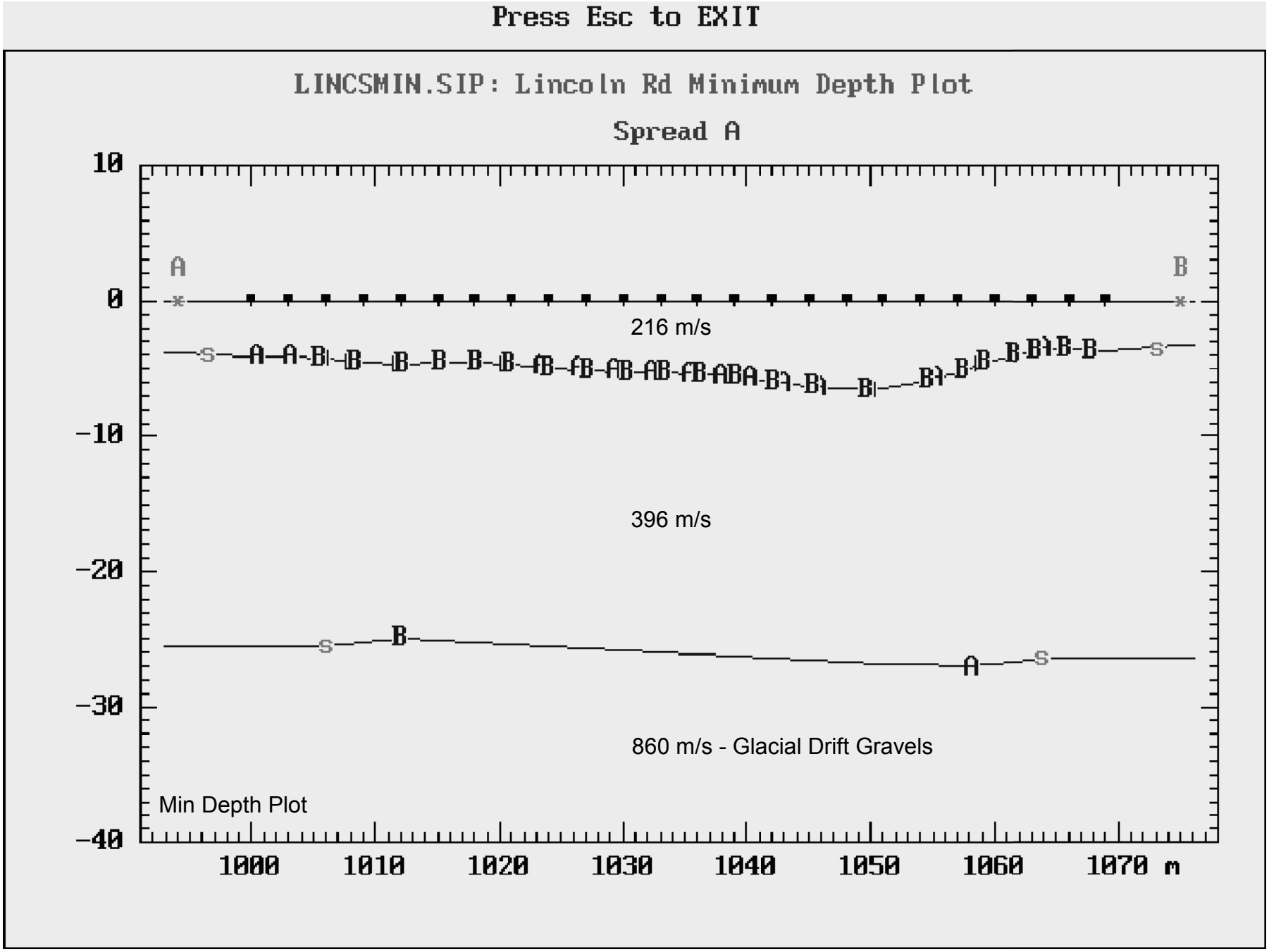
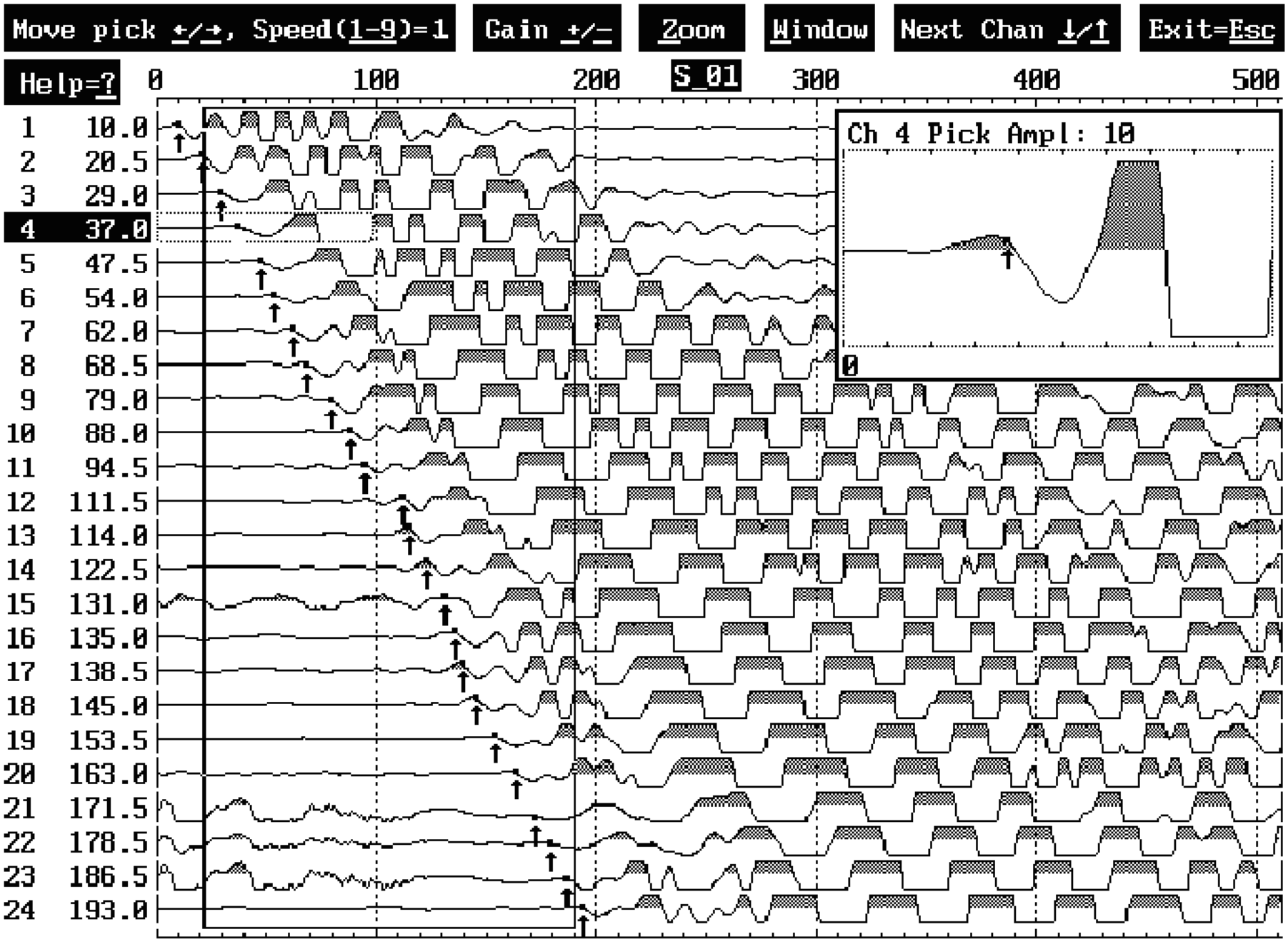


Logan Park S-wave



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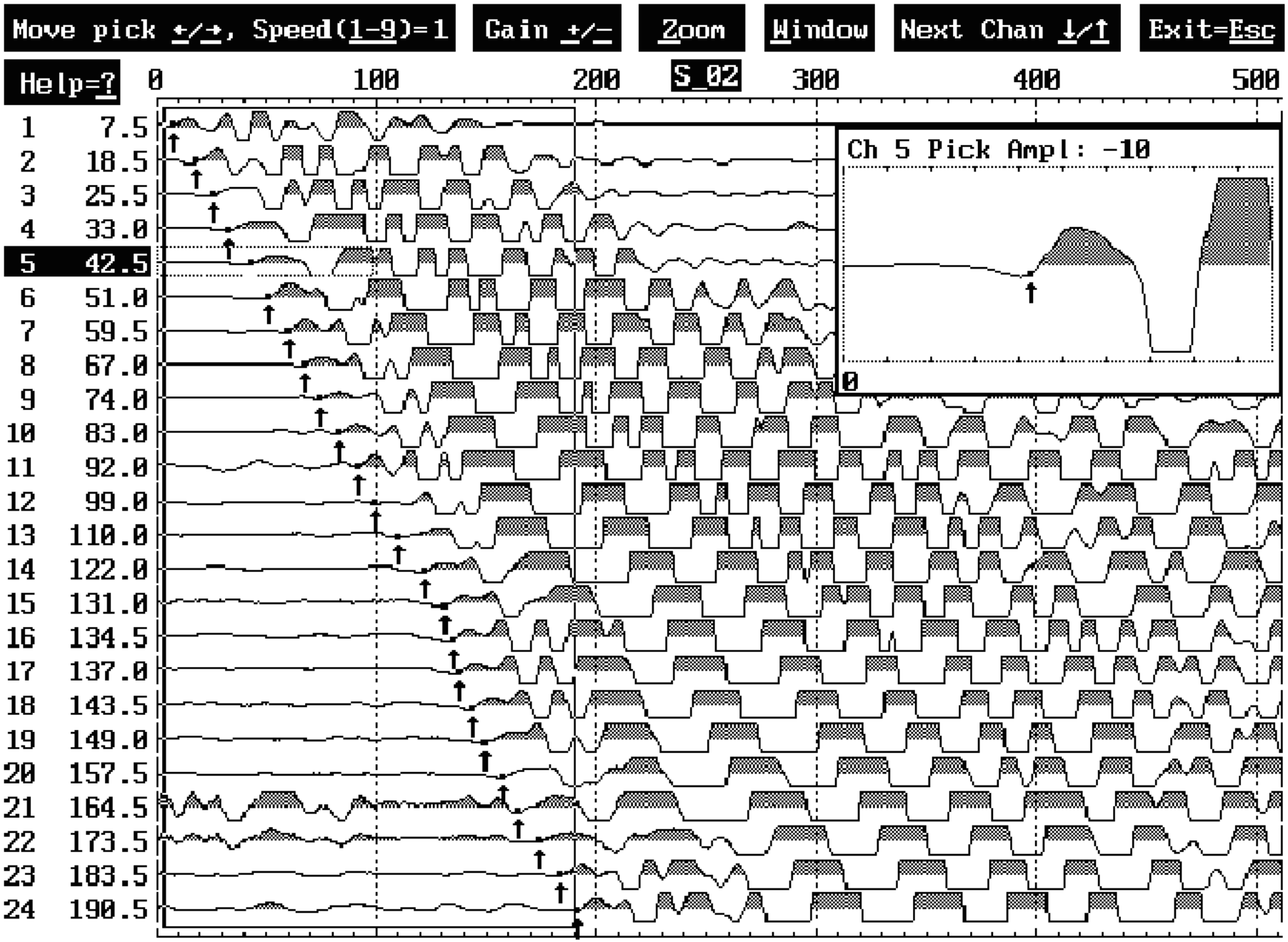

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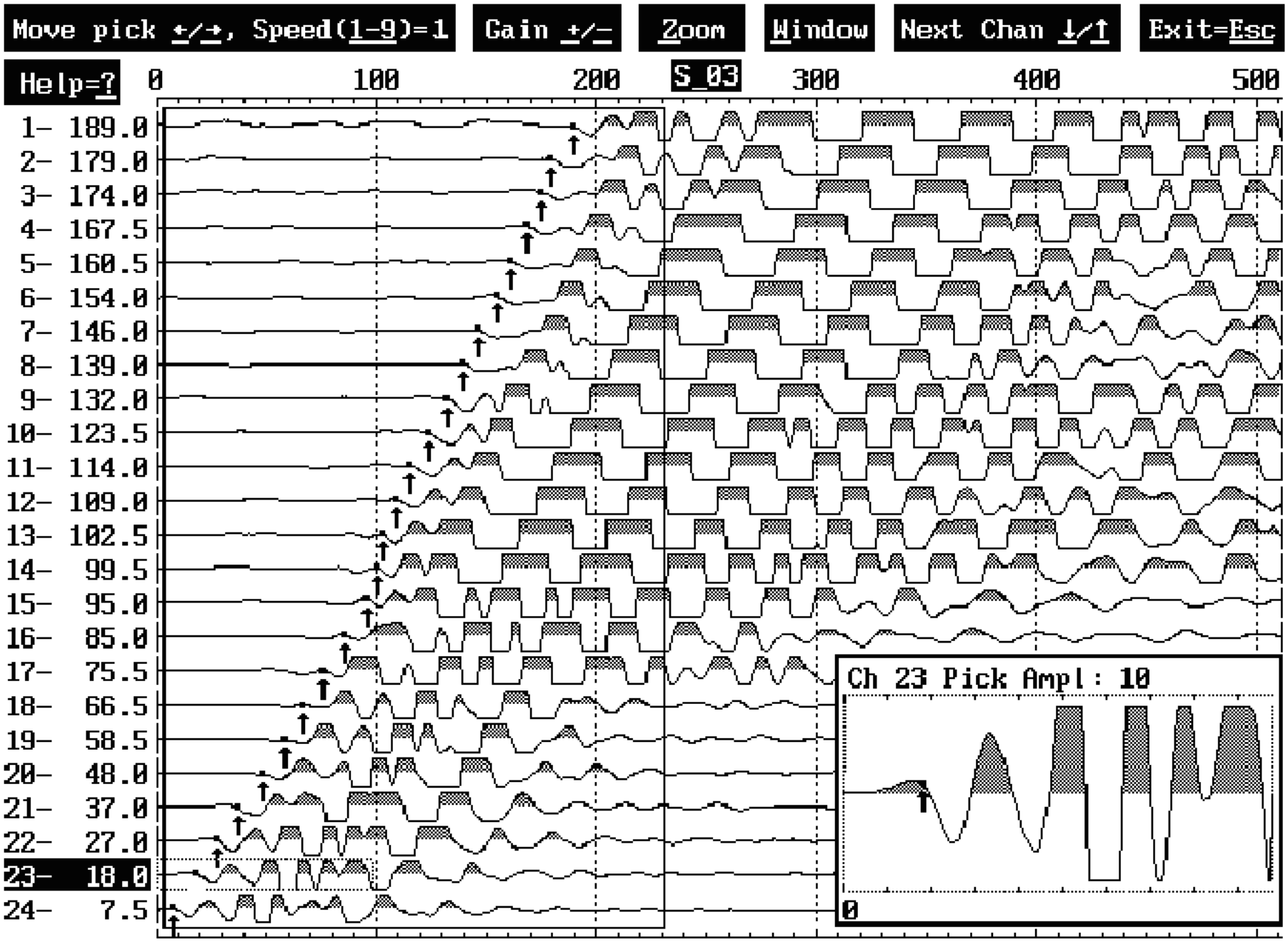

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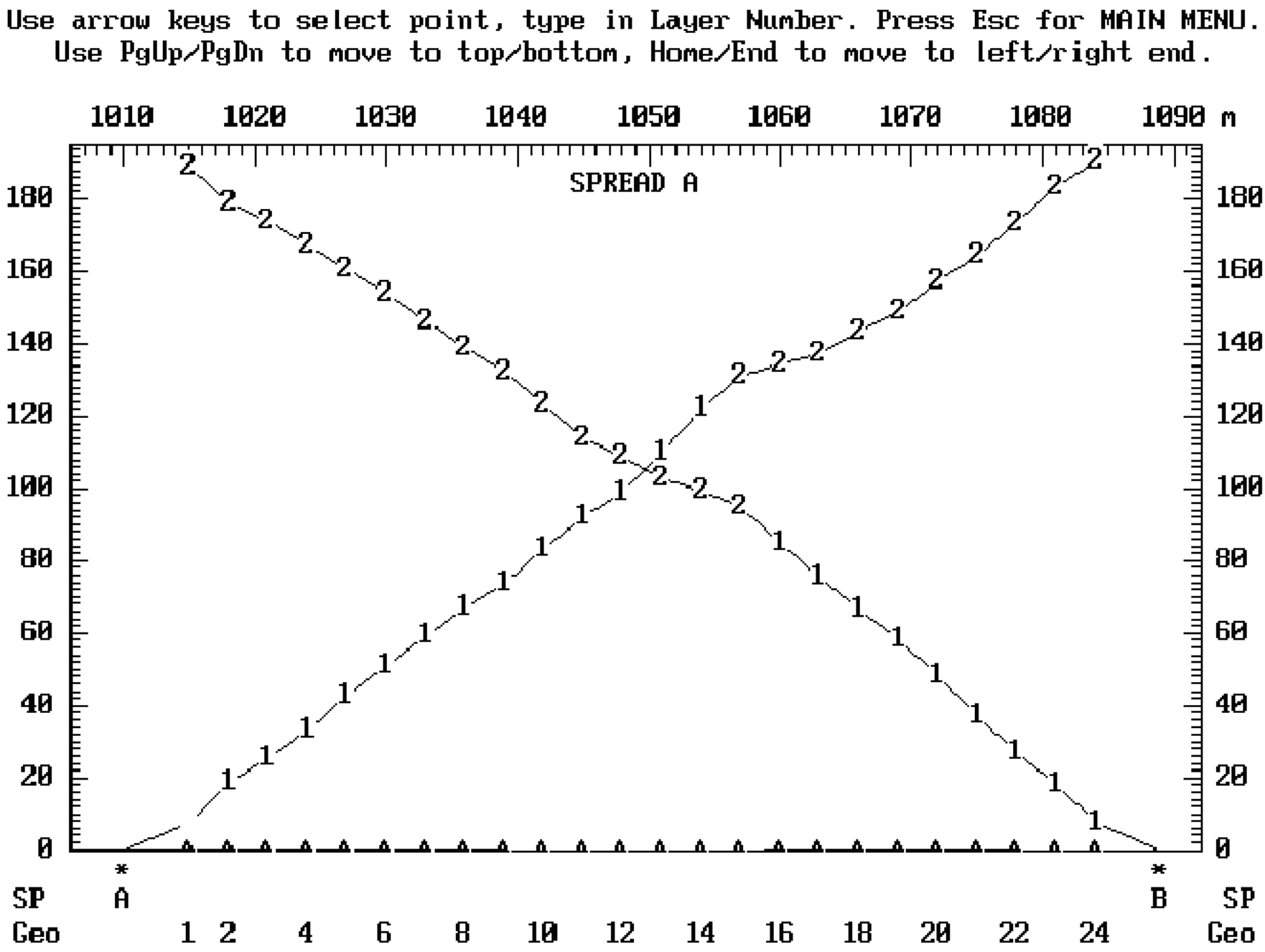
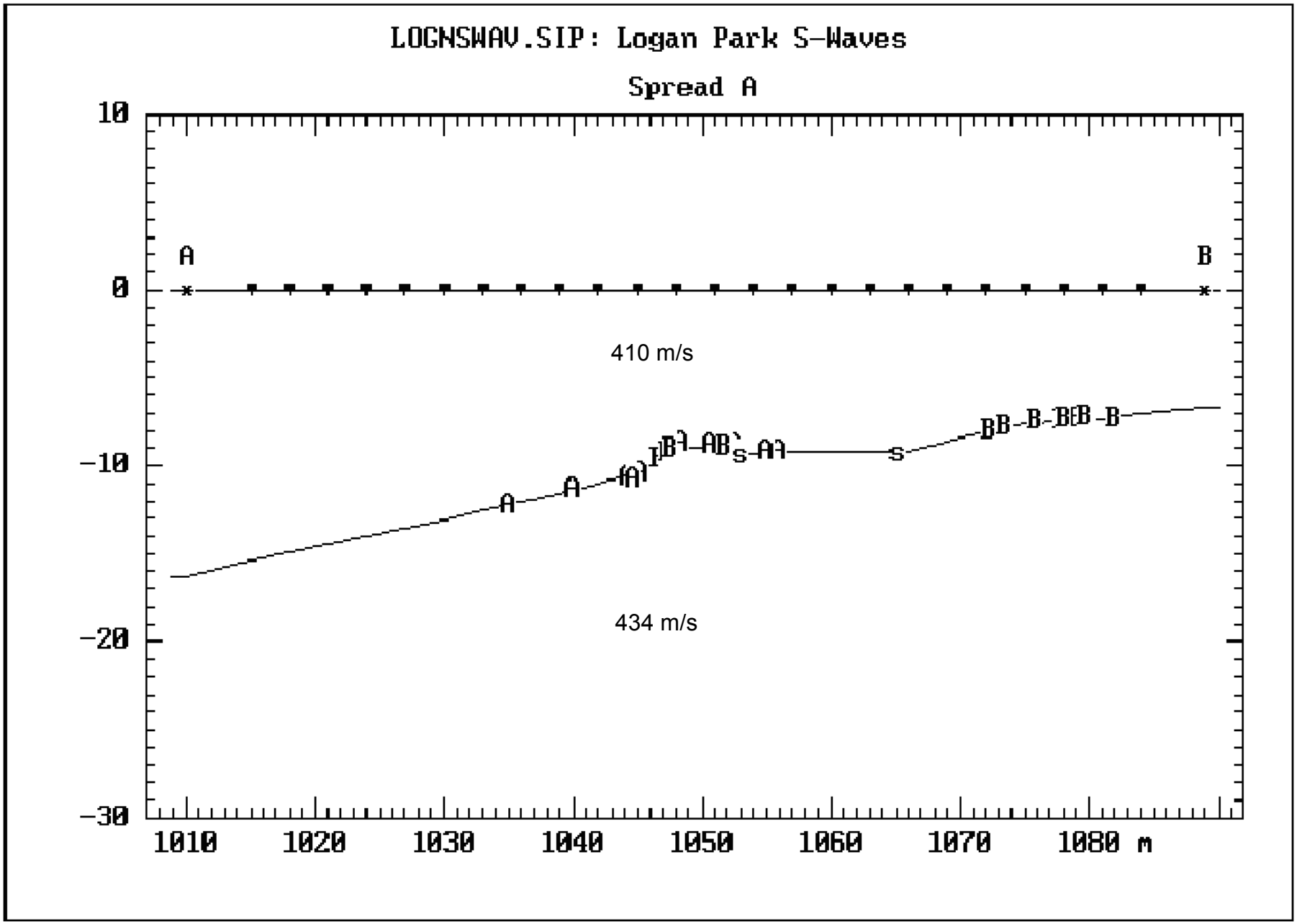


Logan Park S-wave

Press Esc to EXIT



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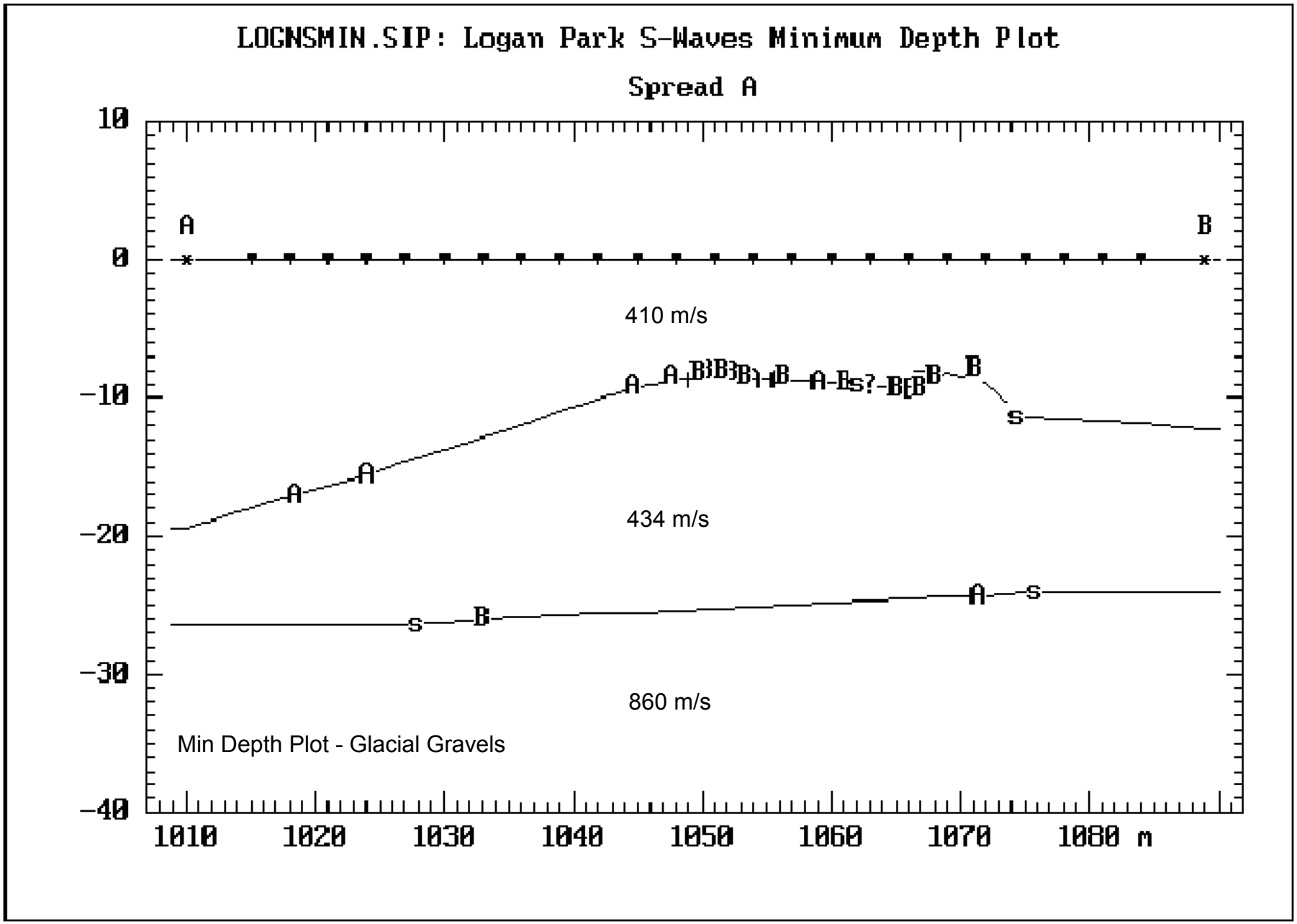
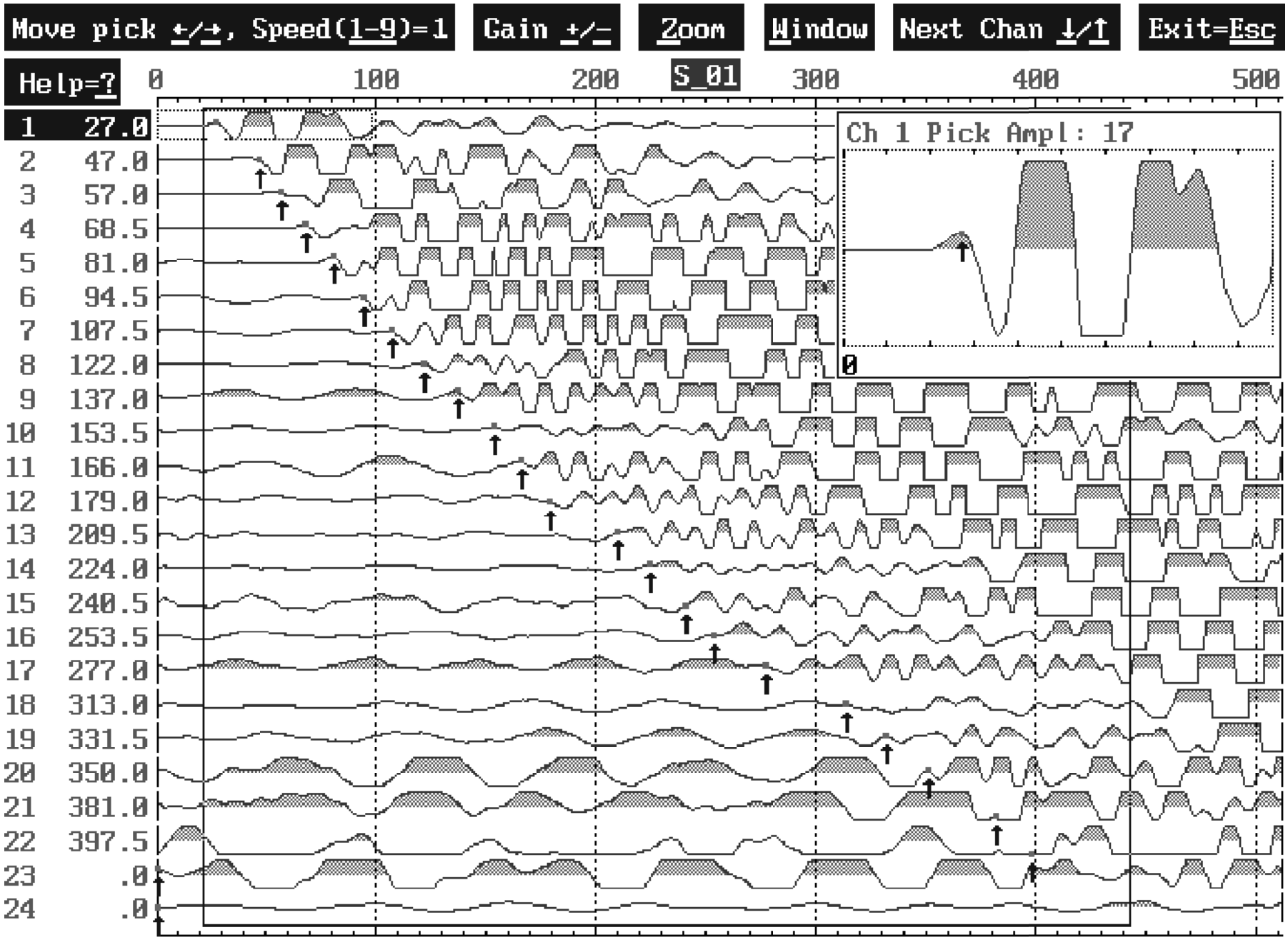
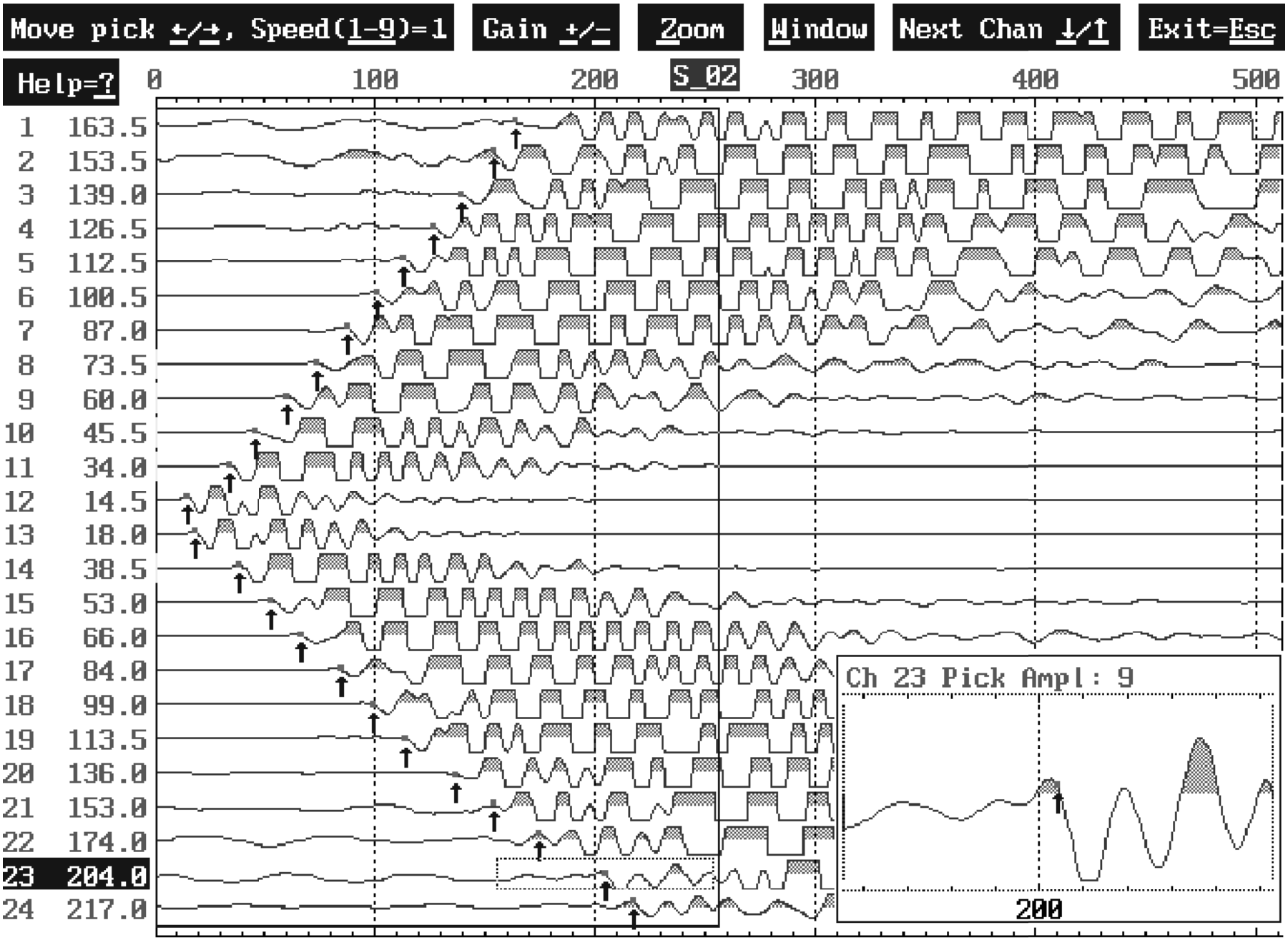


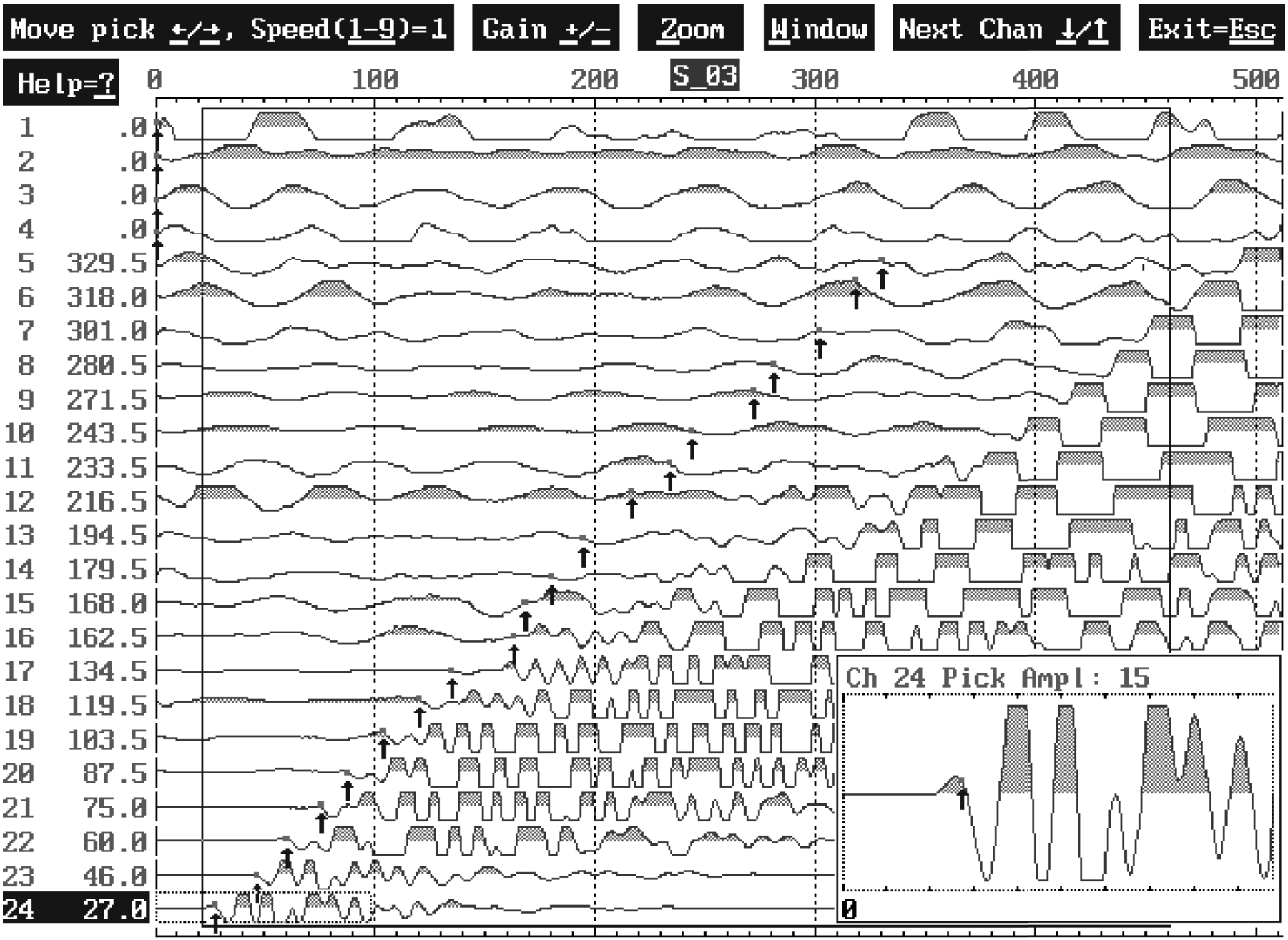
Mark Morris High school S-wave



Mark Morris High school S-wave



Mark Morris High school S-wave



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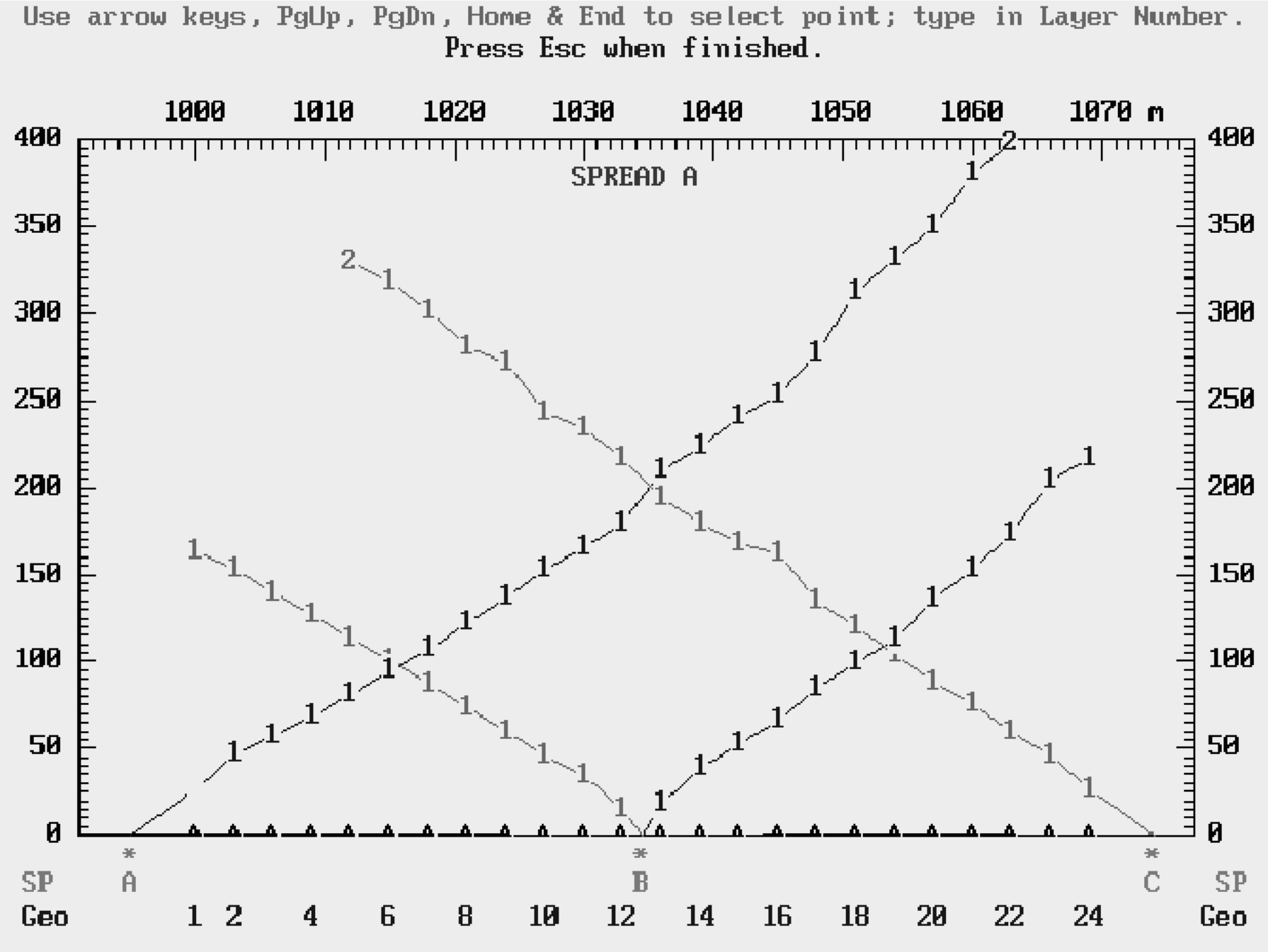

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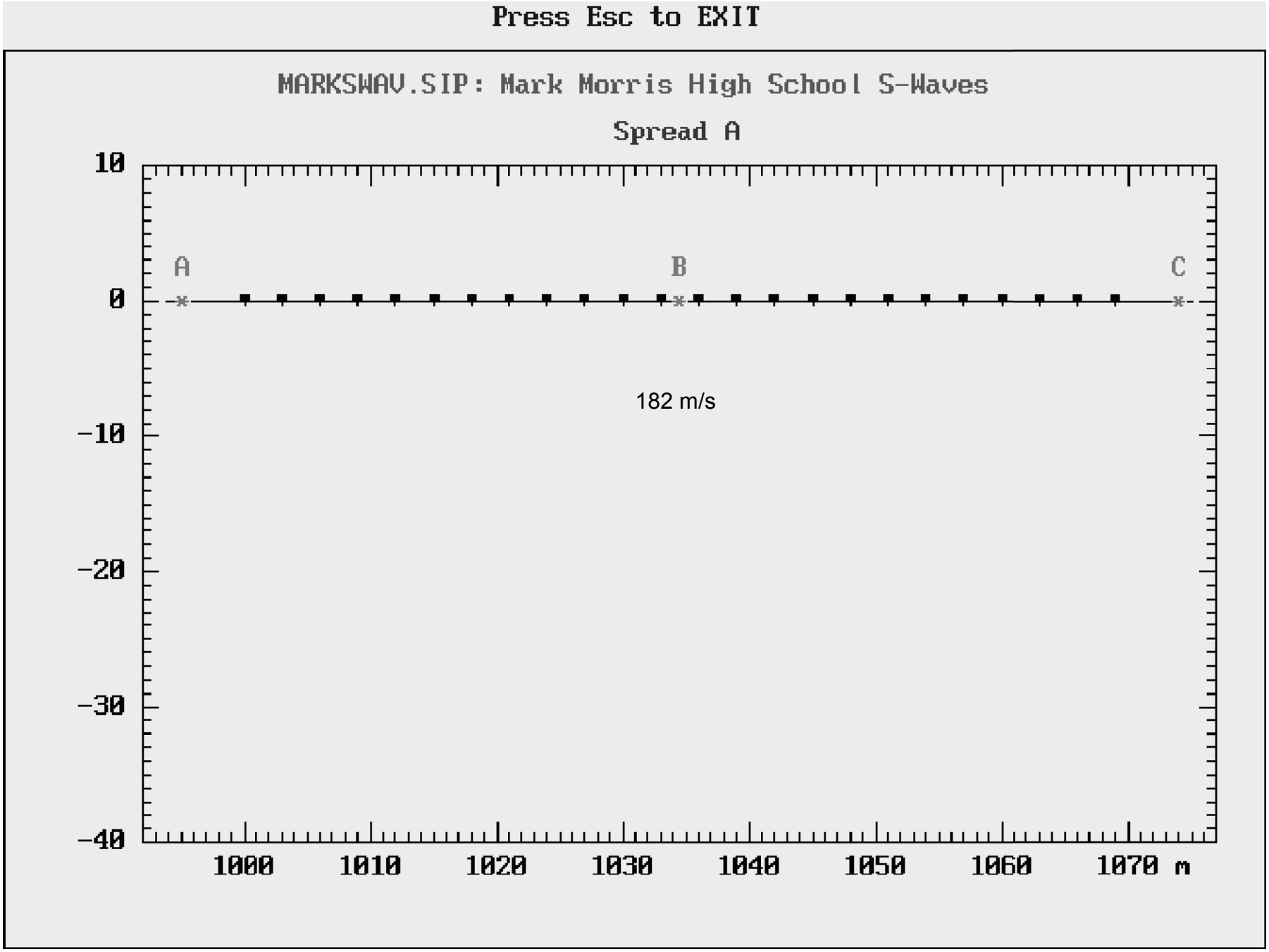

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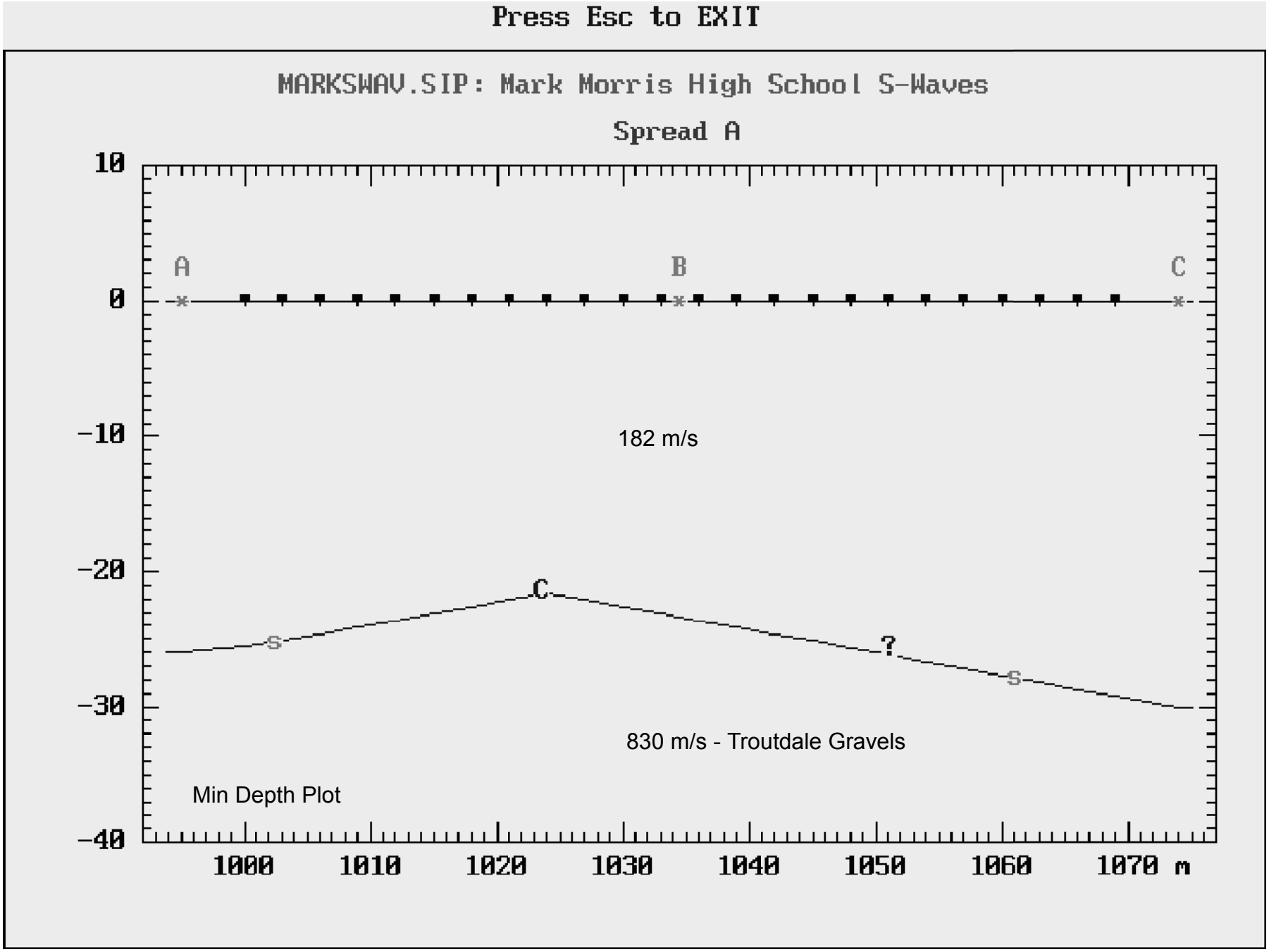
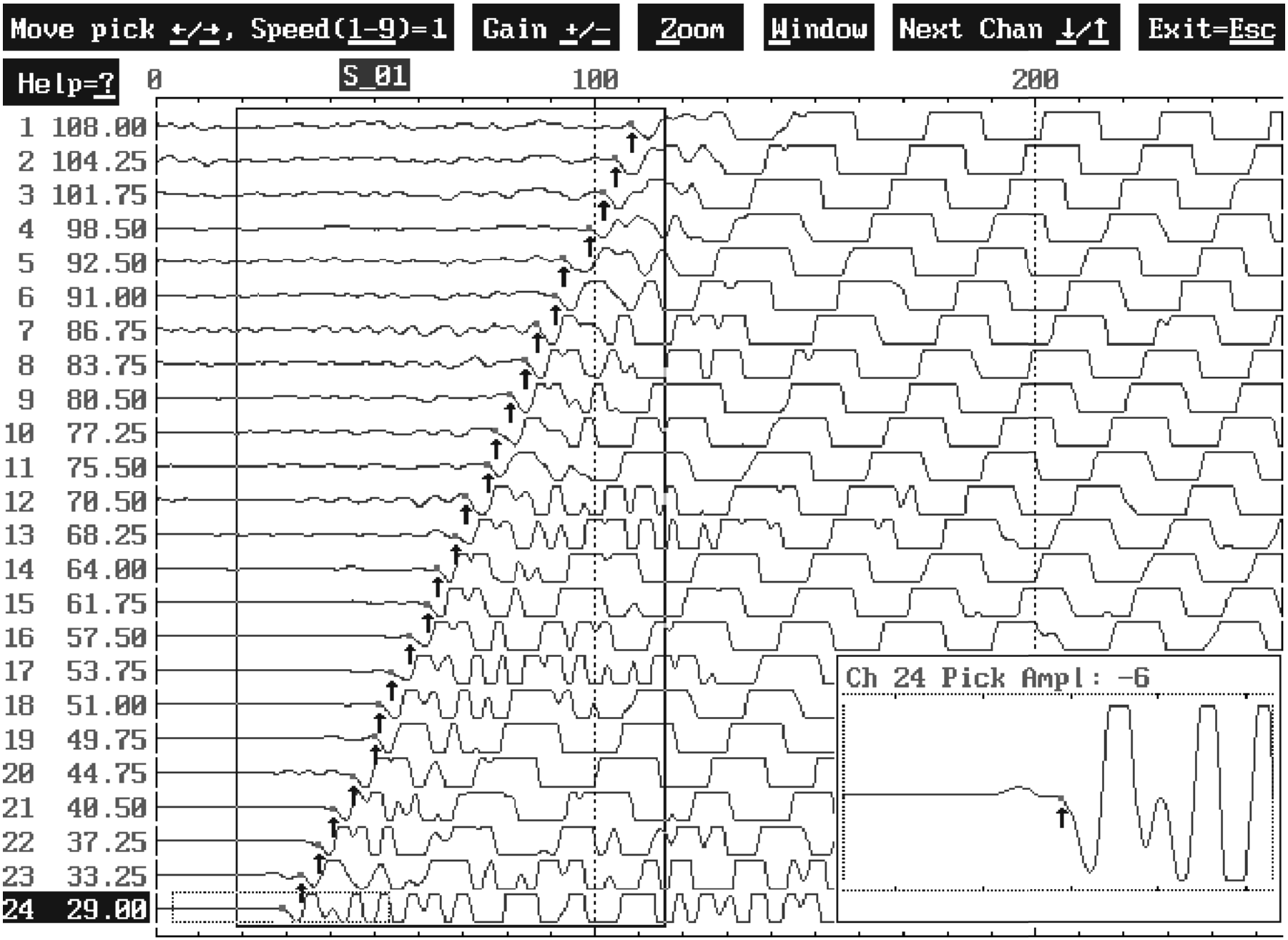
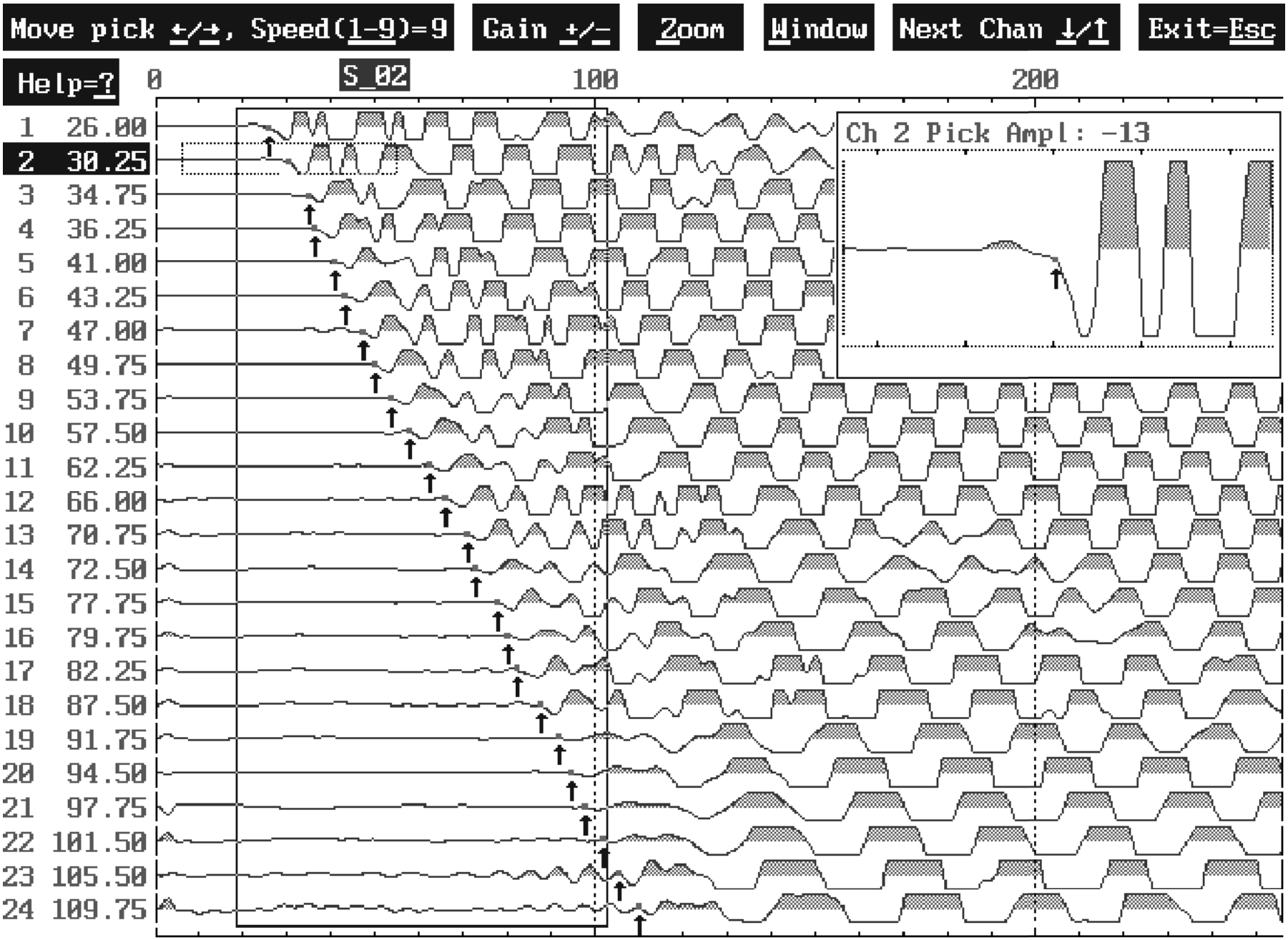


Martha Lake Elementary S-wave



Martha Lake Elementary S-wave



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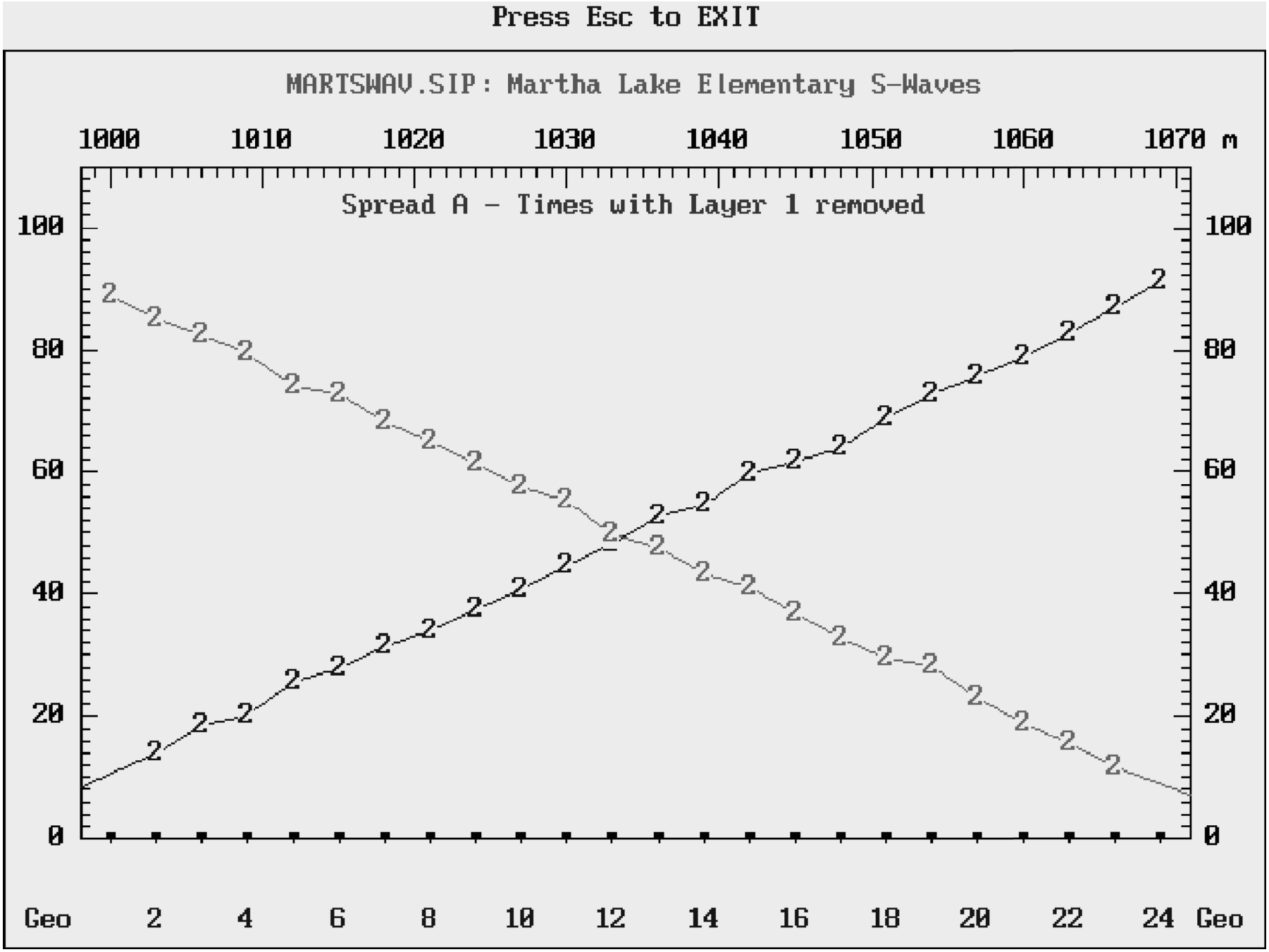

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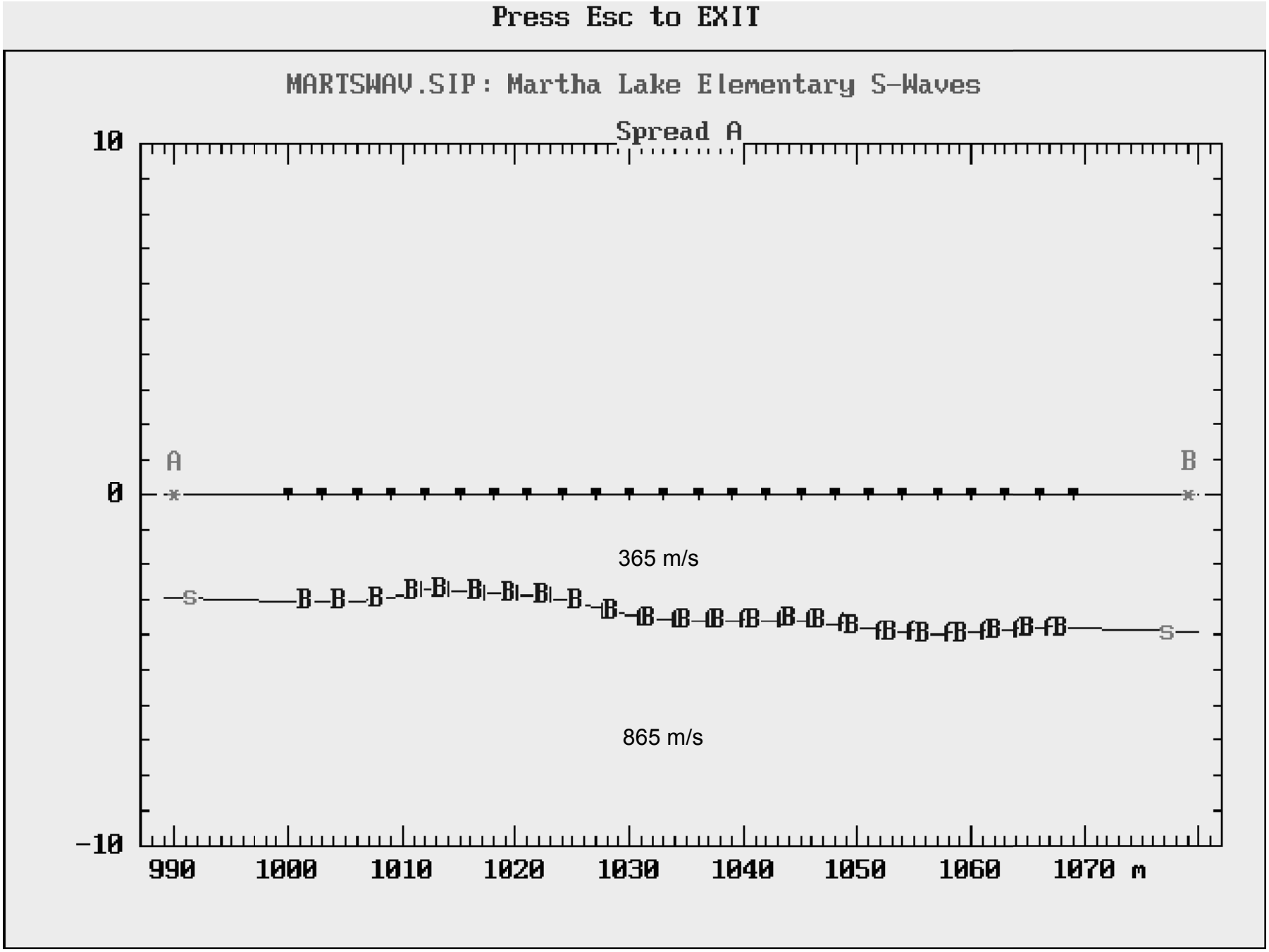

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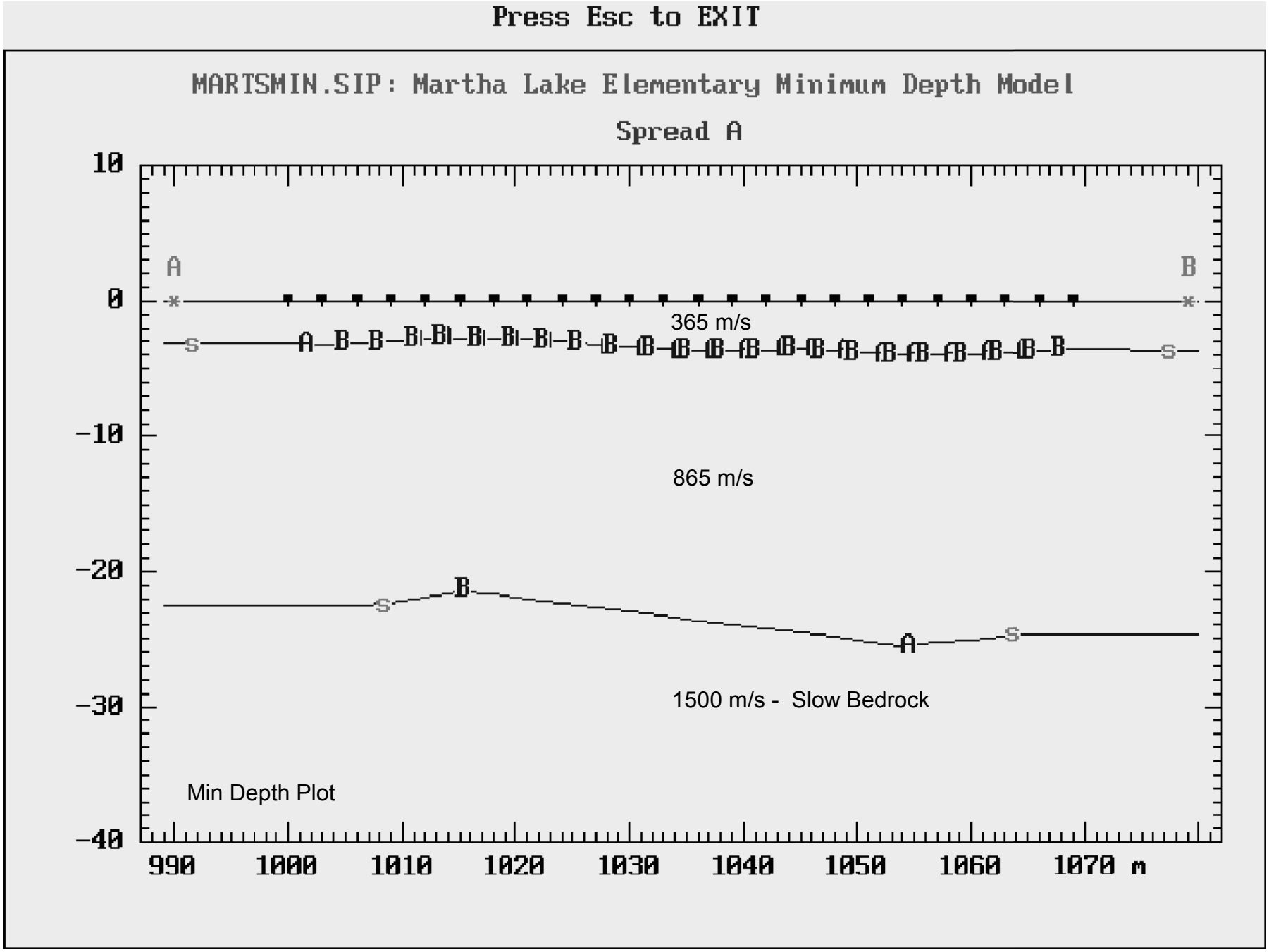
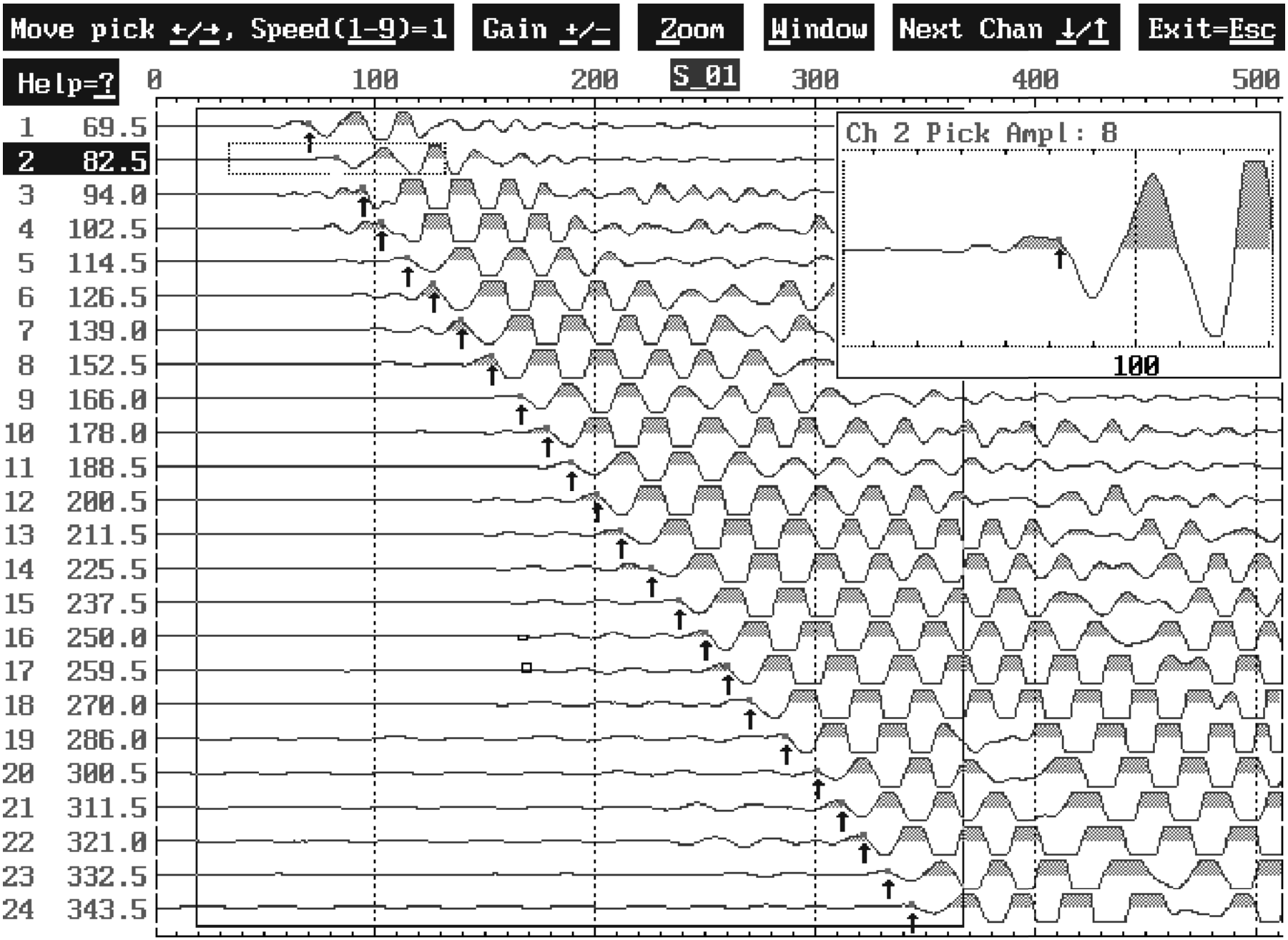
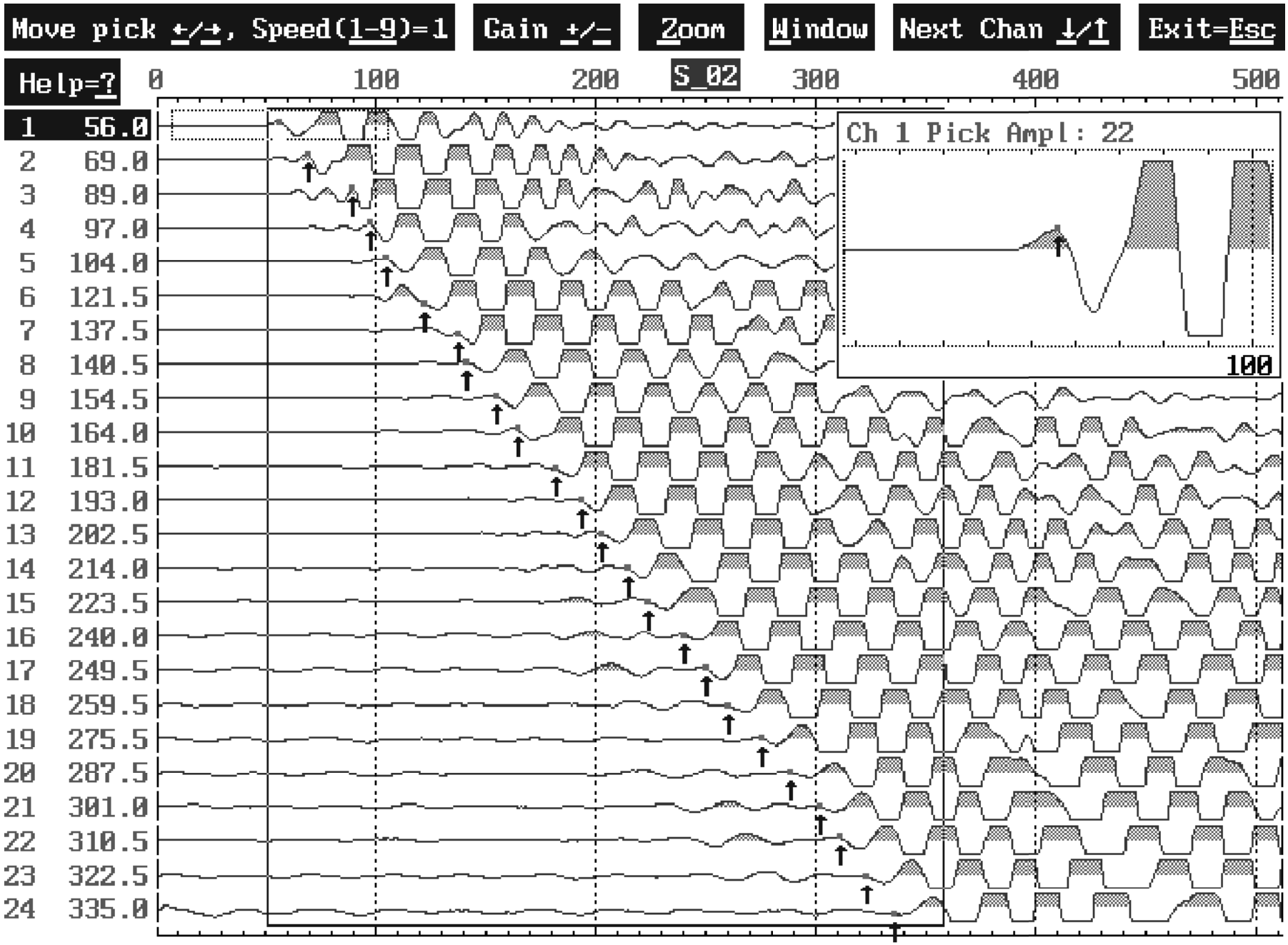


Marymoor Park S-wave



Marymoor Park S-wave



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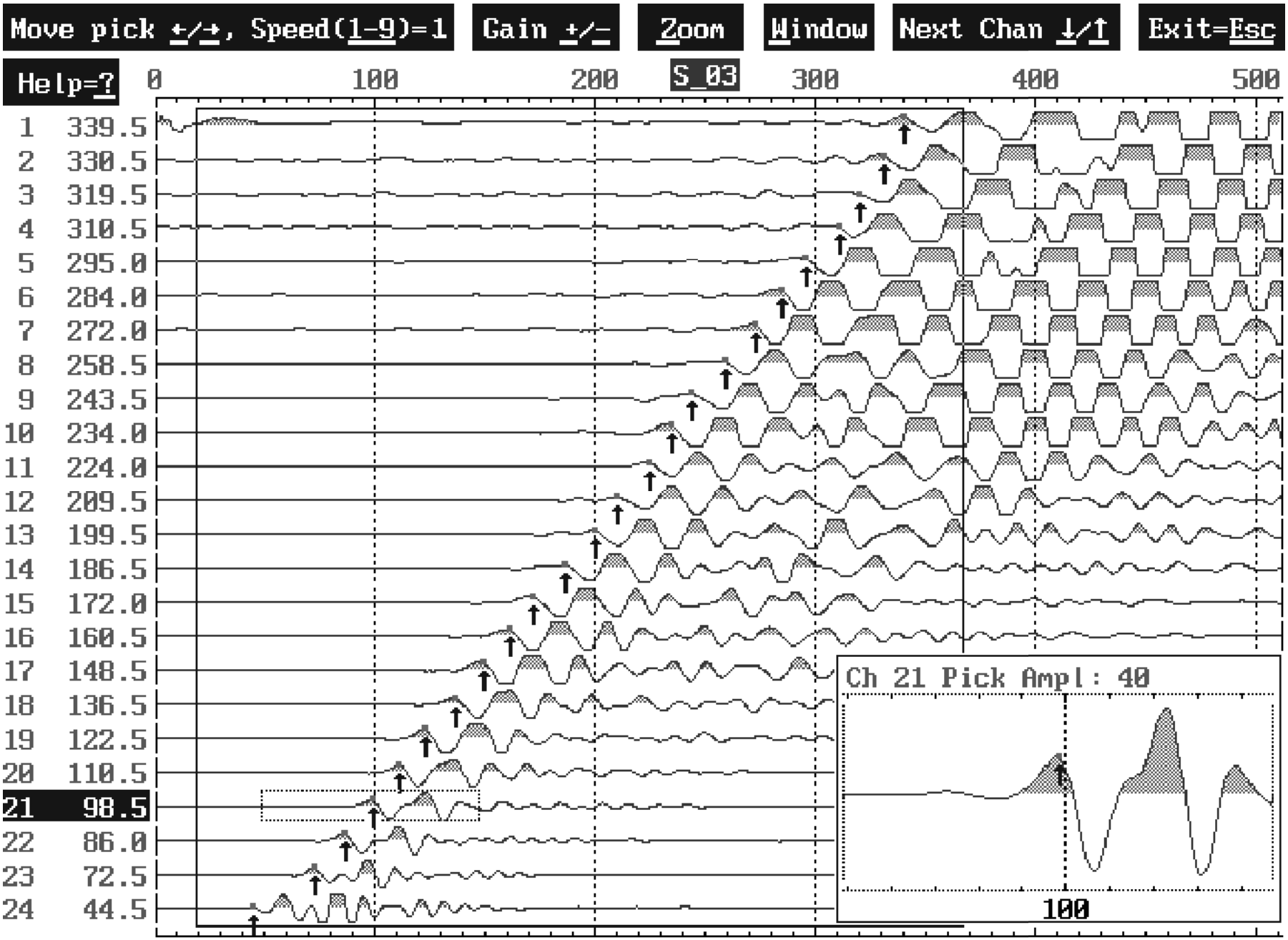

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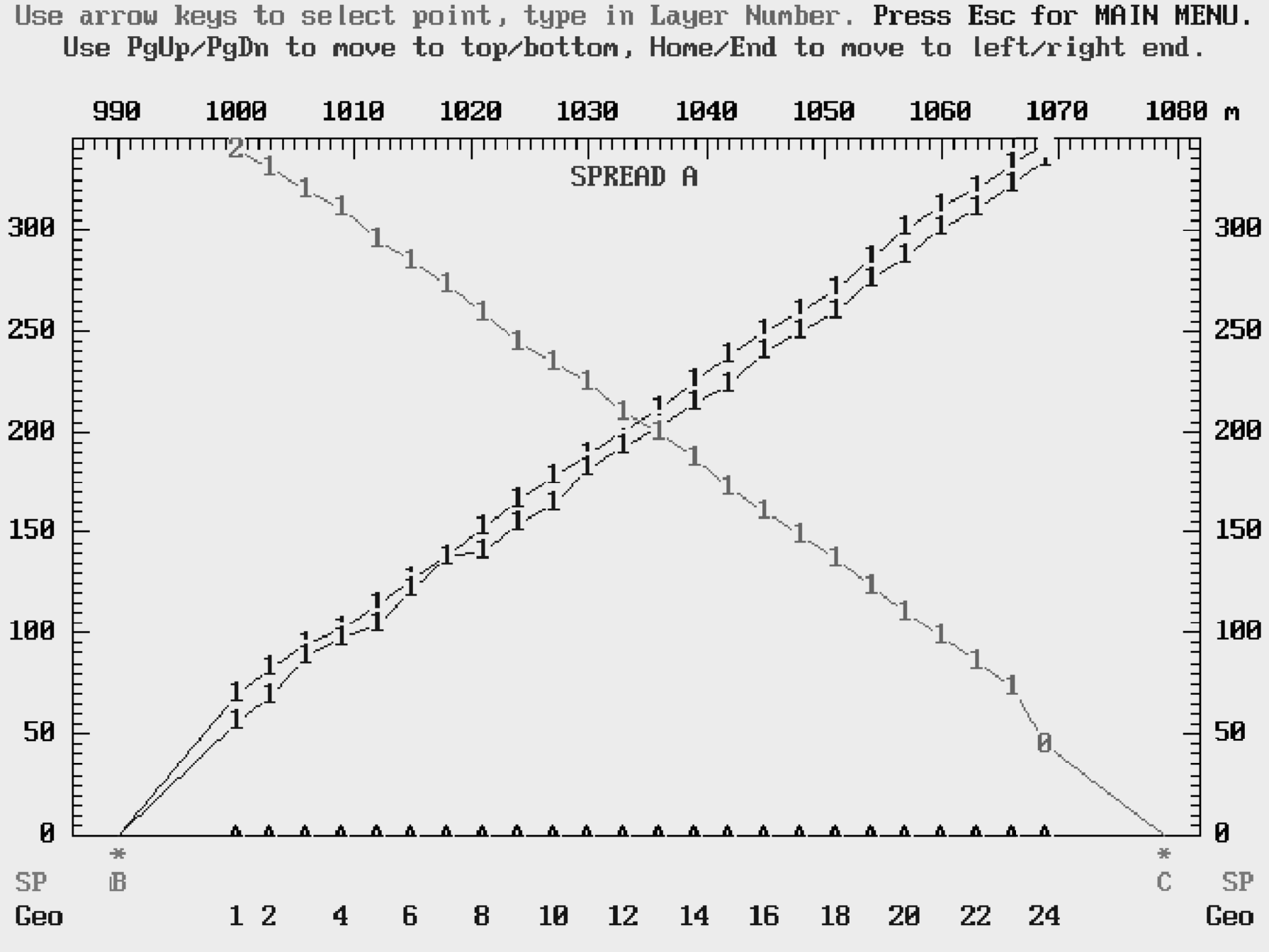

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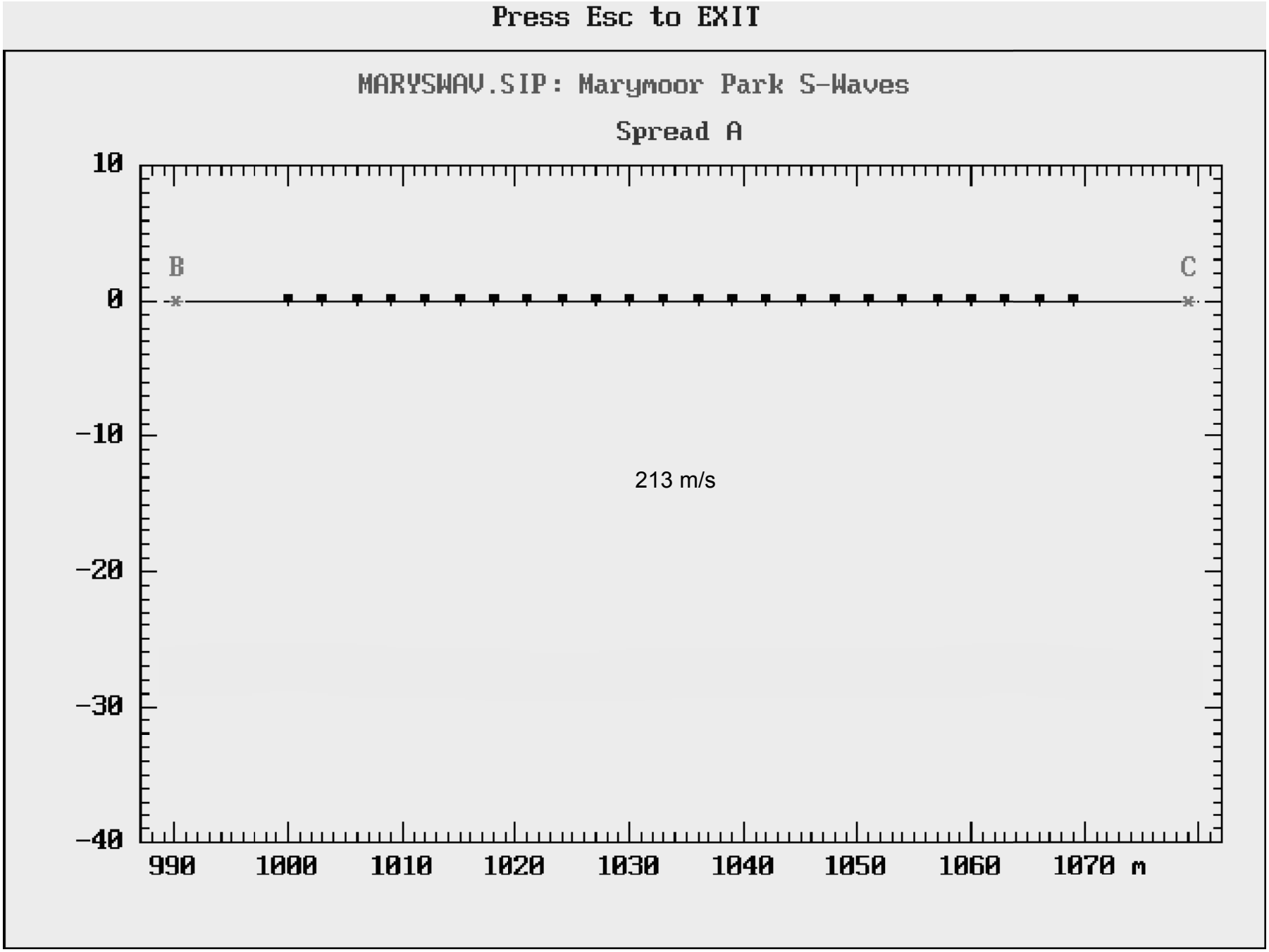

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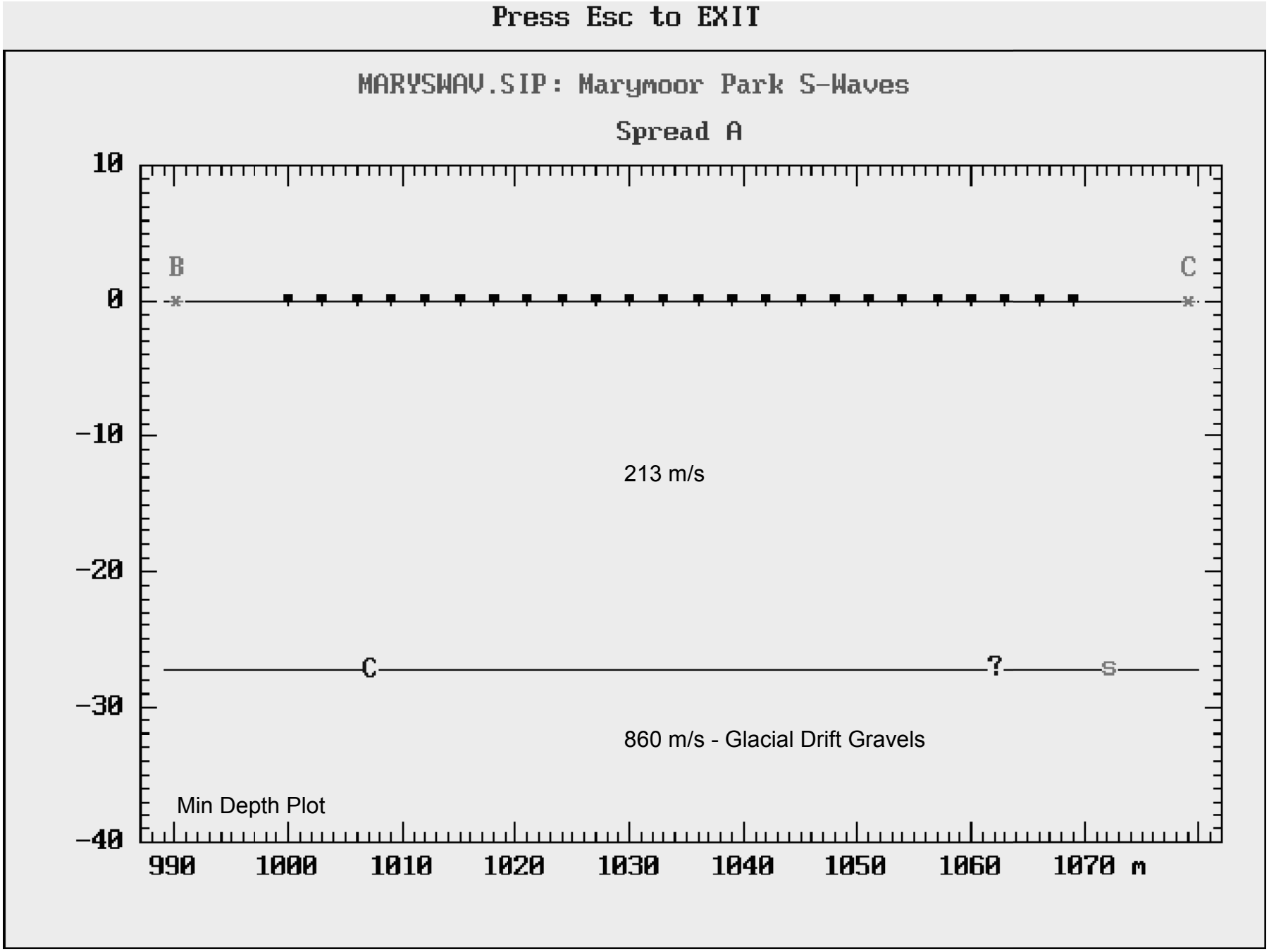
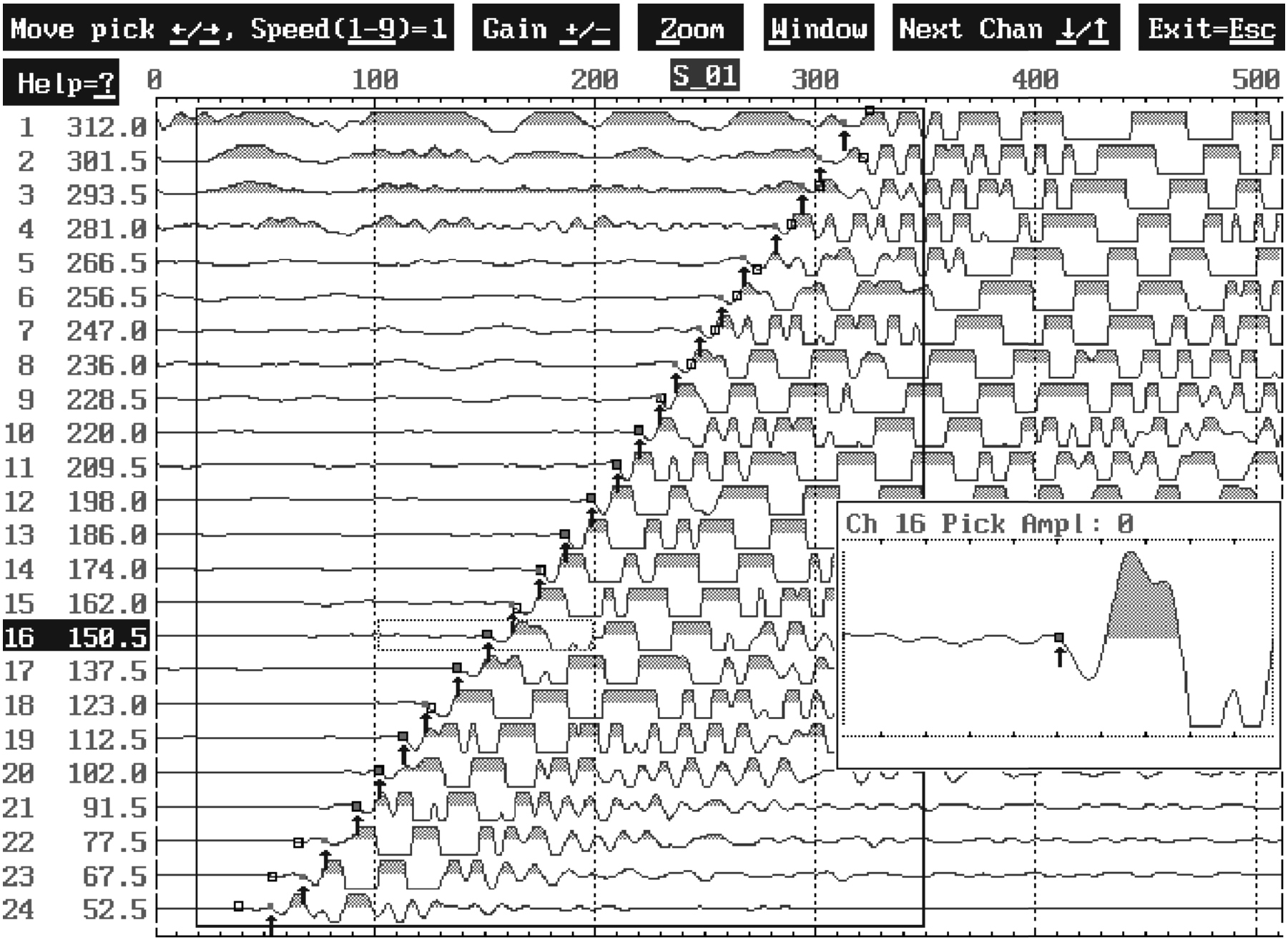
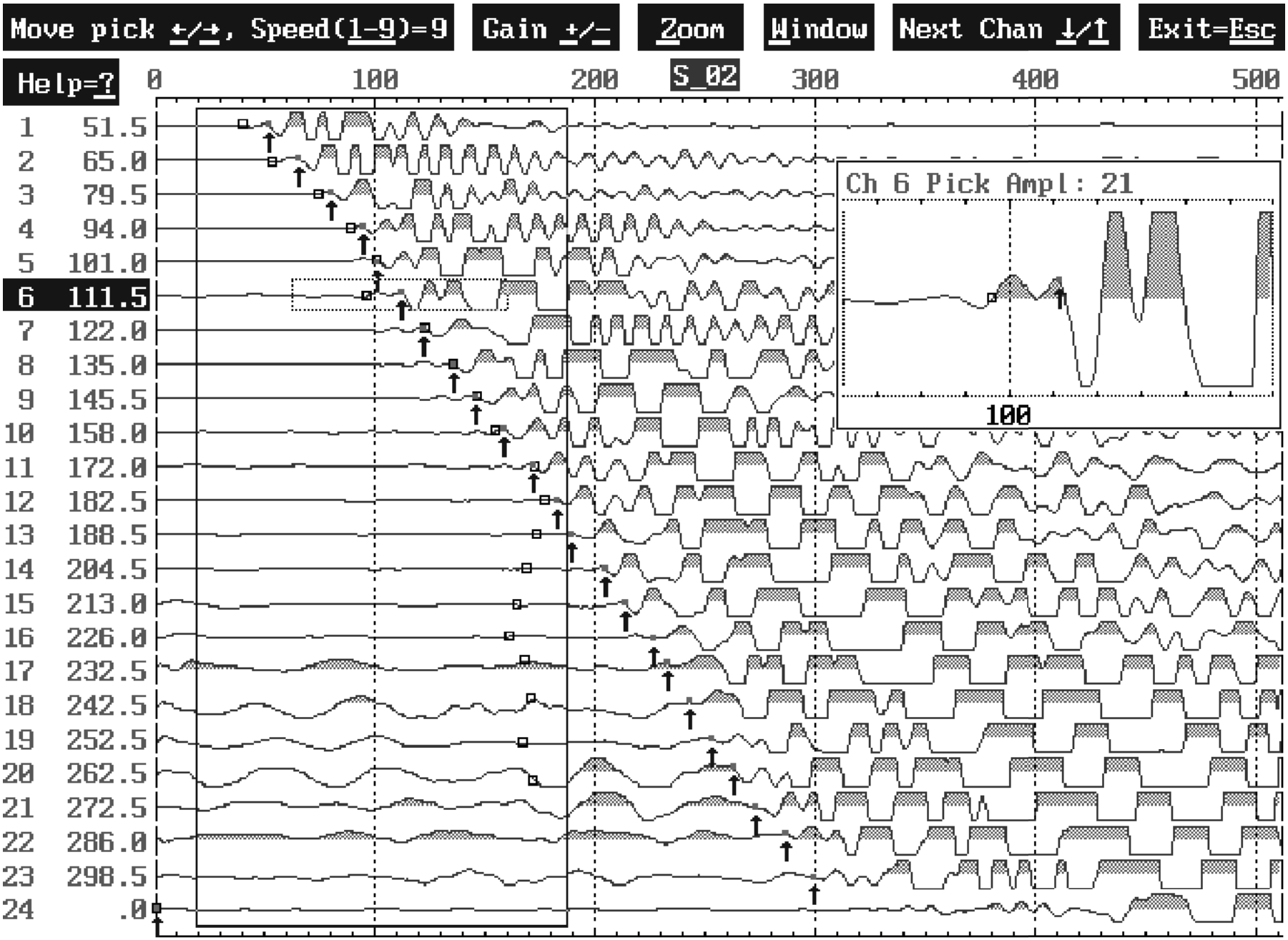


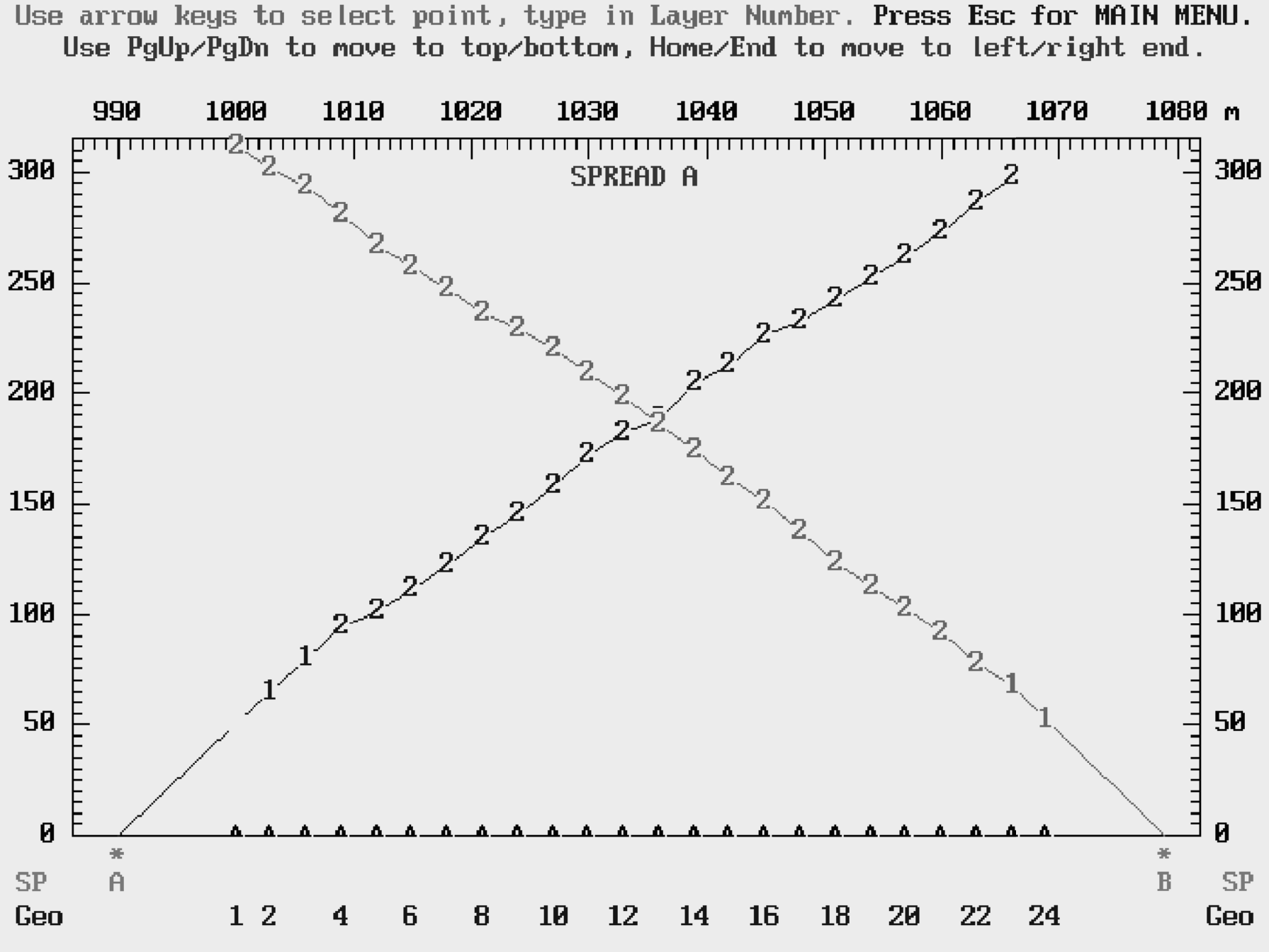
Marysville Middle School S-wave



Marysville Middle School S-wave



Marysville Middle School S-wave



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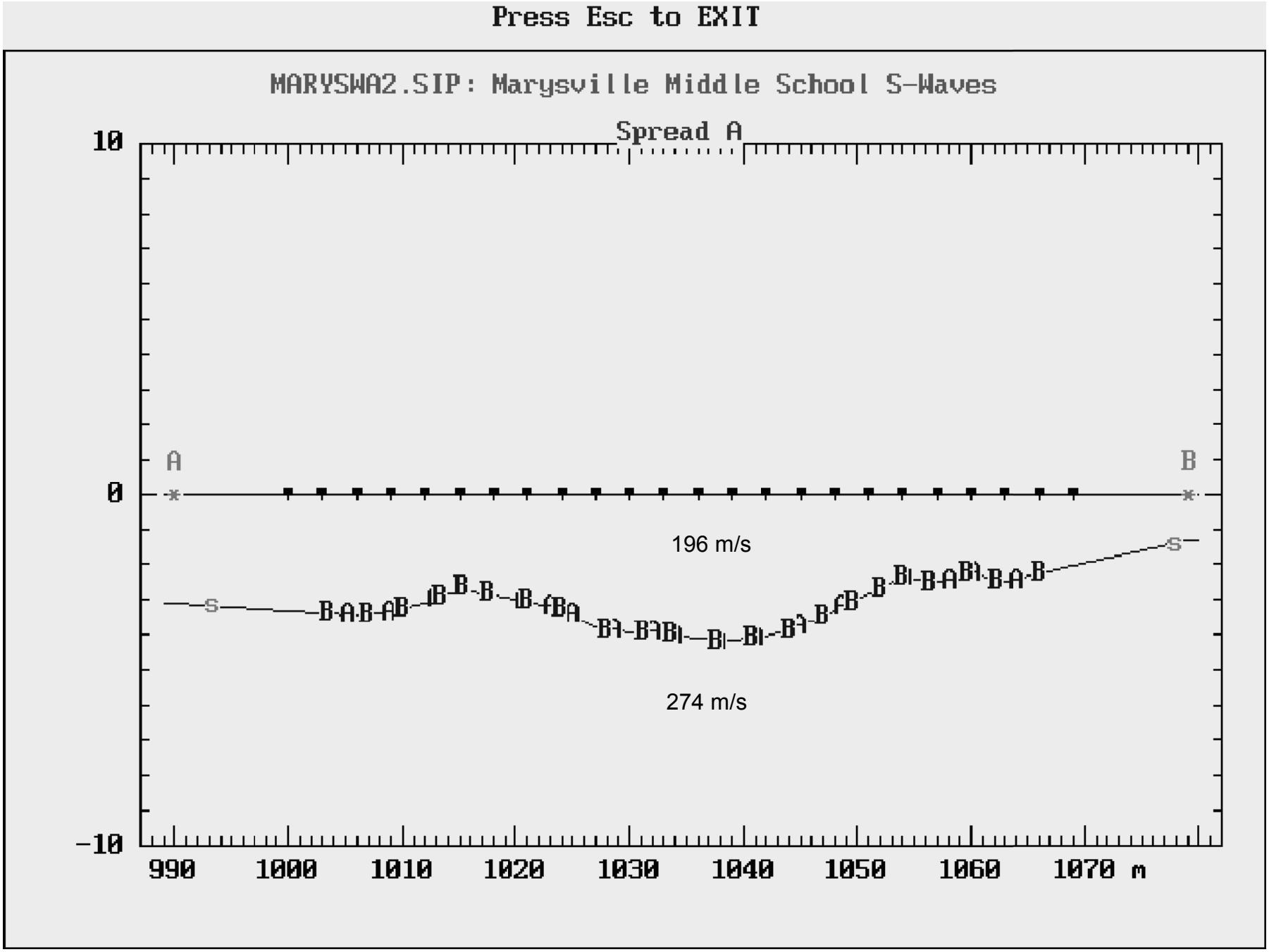

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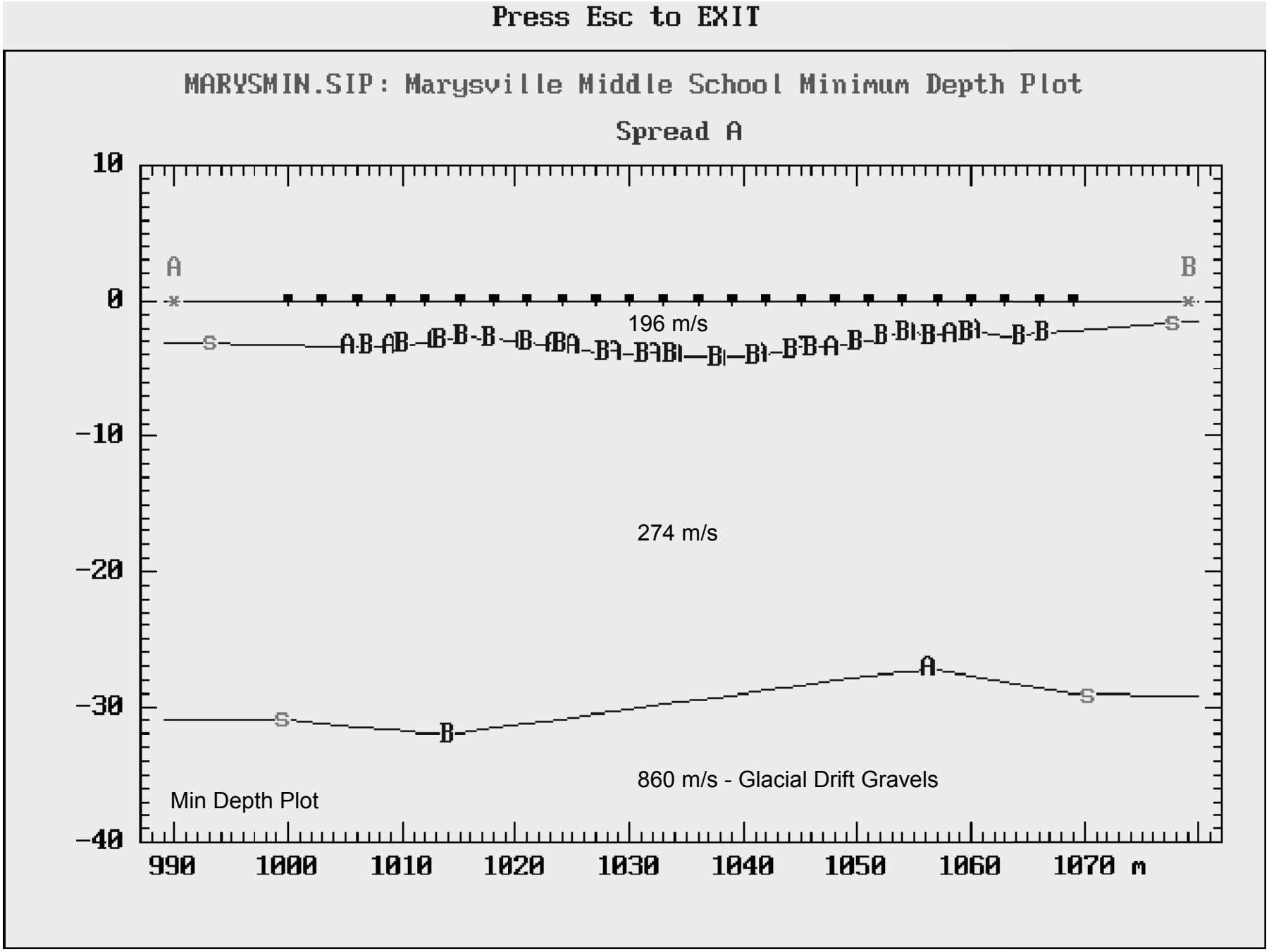
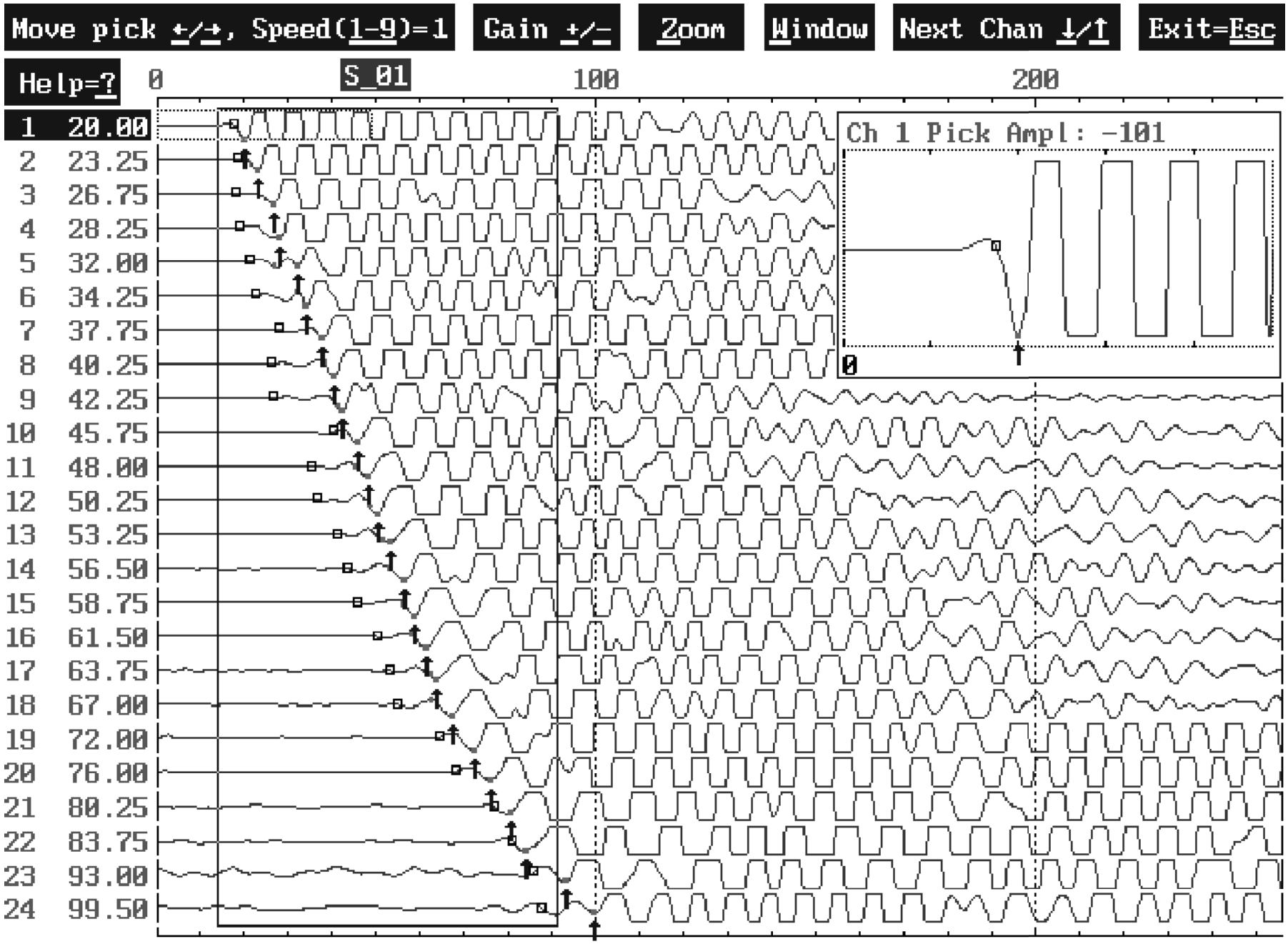


Meadow Middle School S-wave



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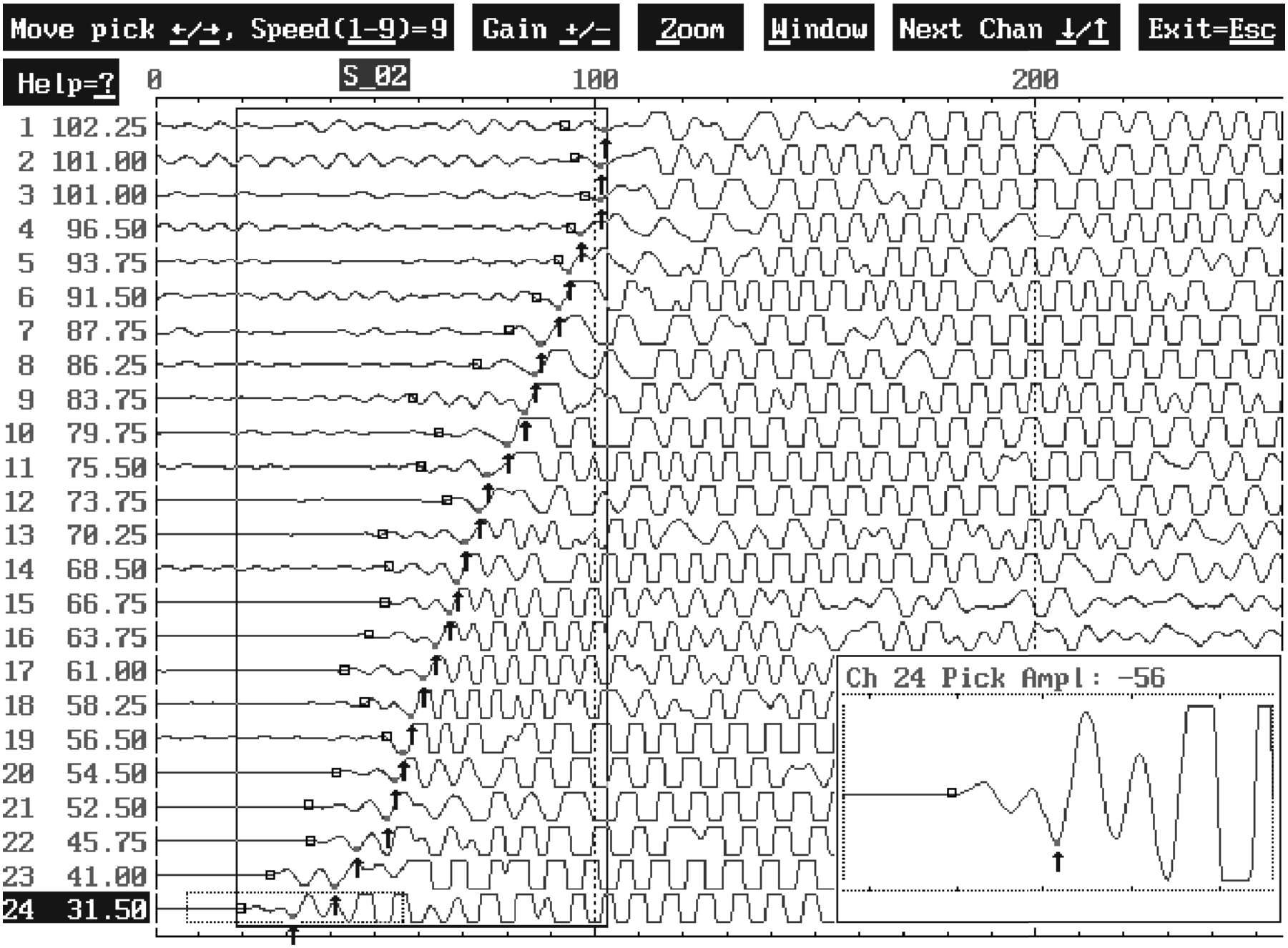

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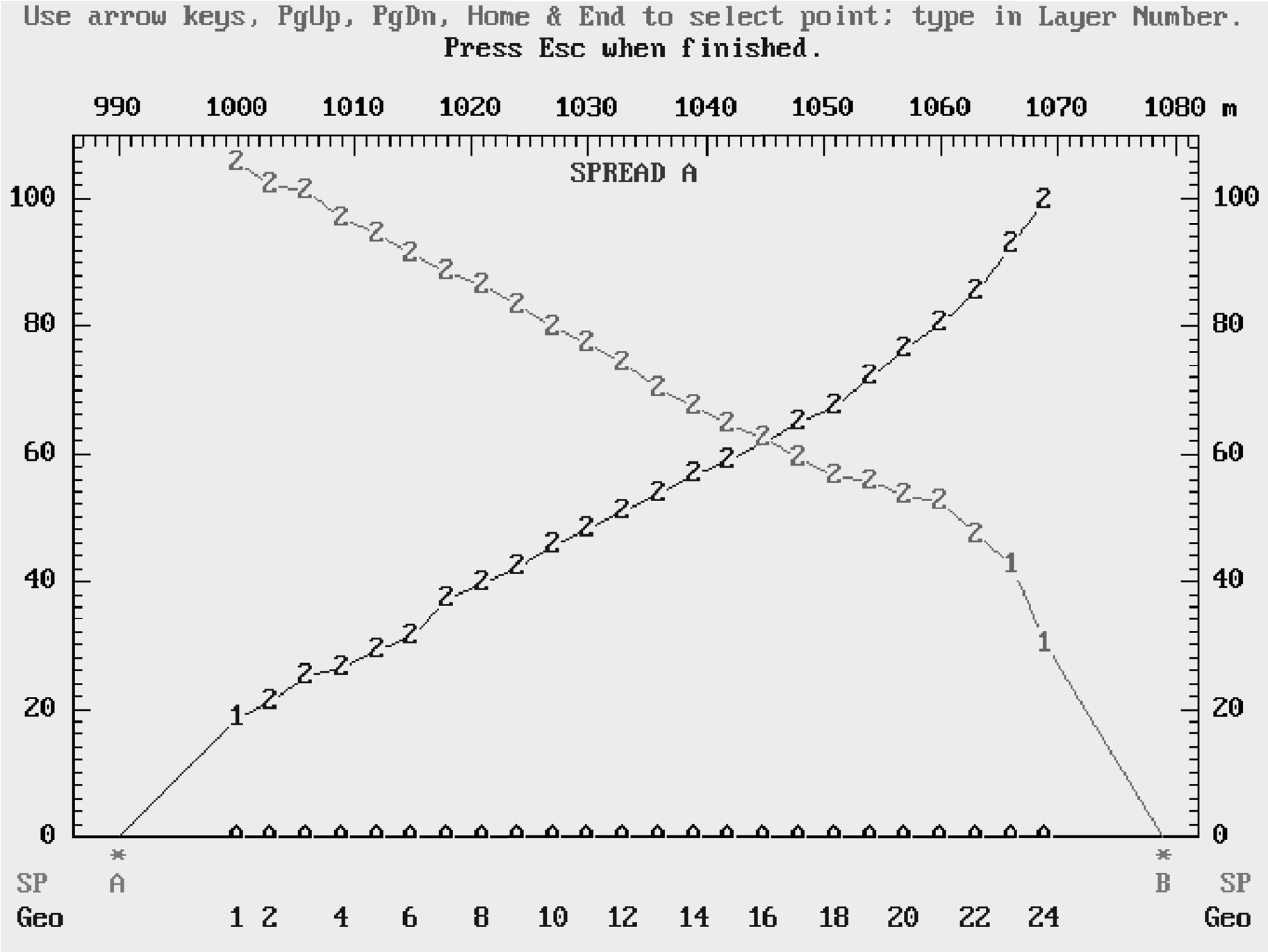

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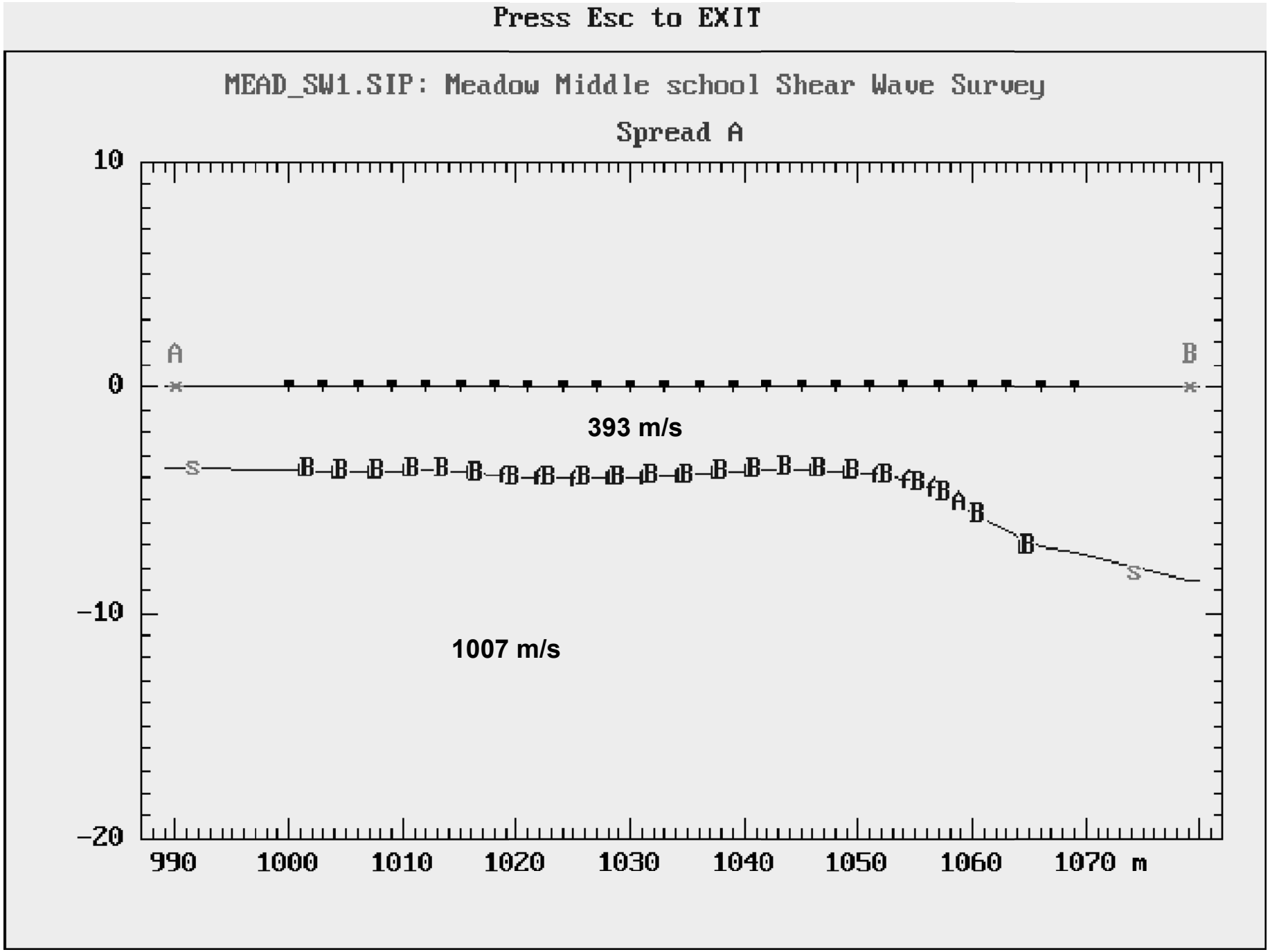

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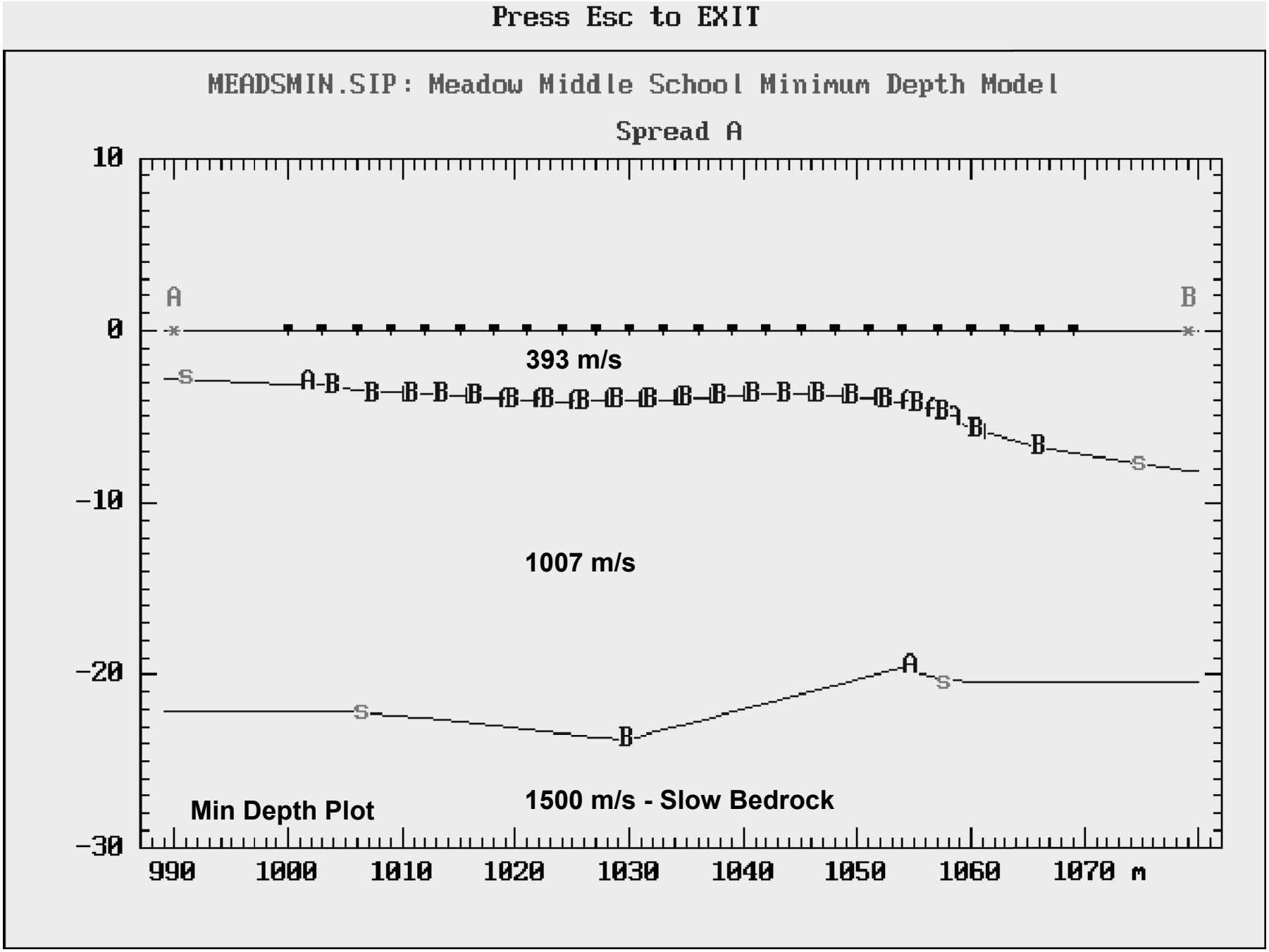
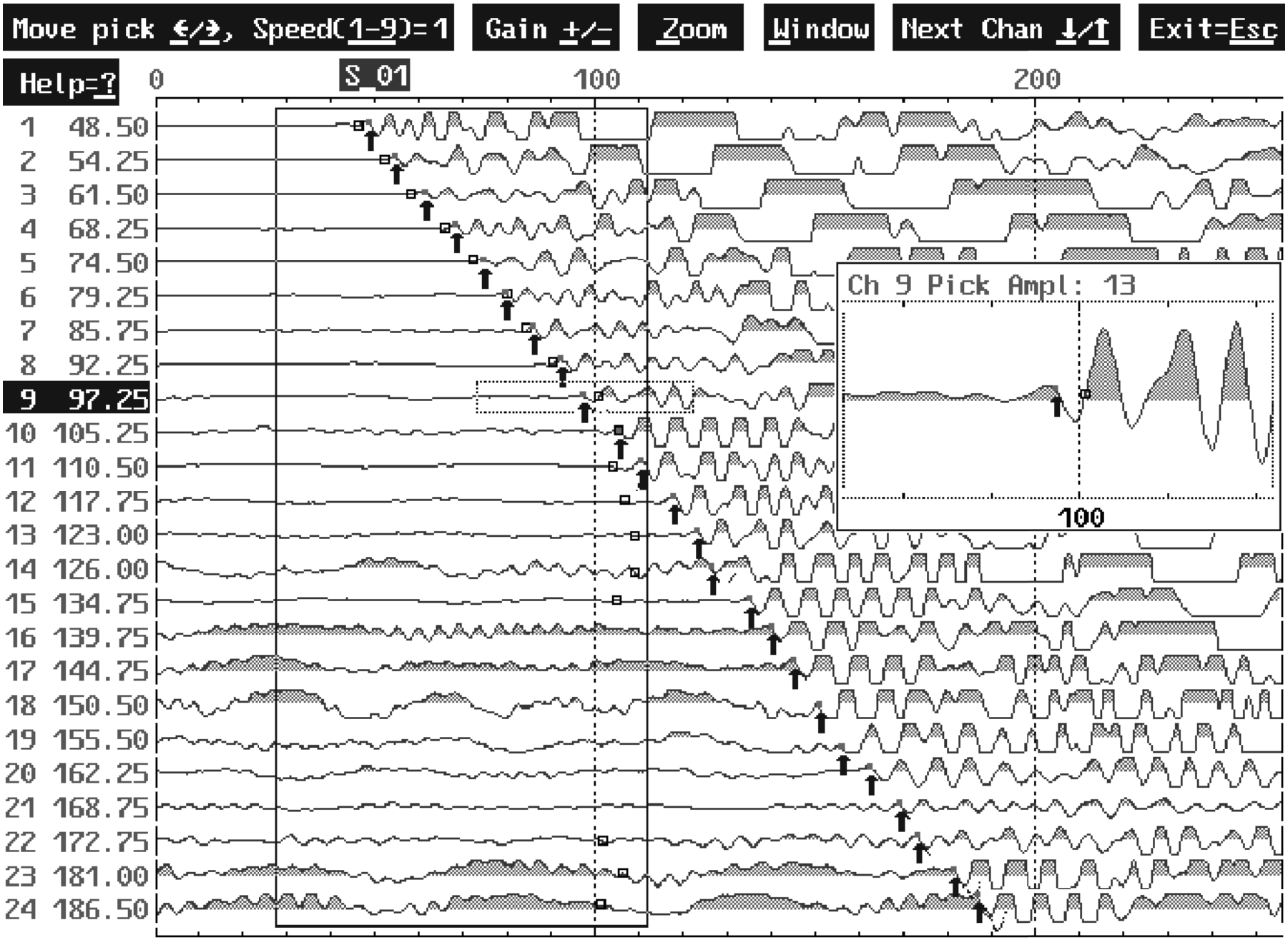


Meridian Middle School S-wave



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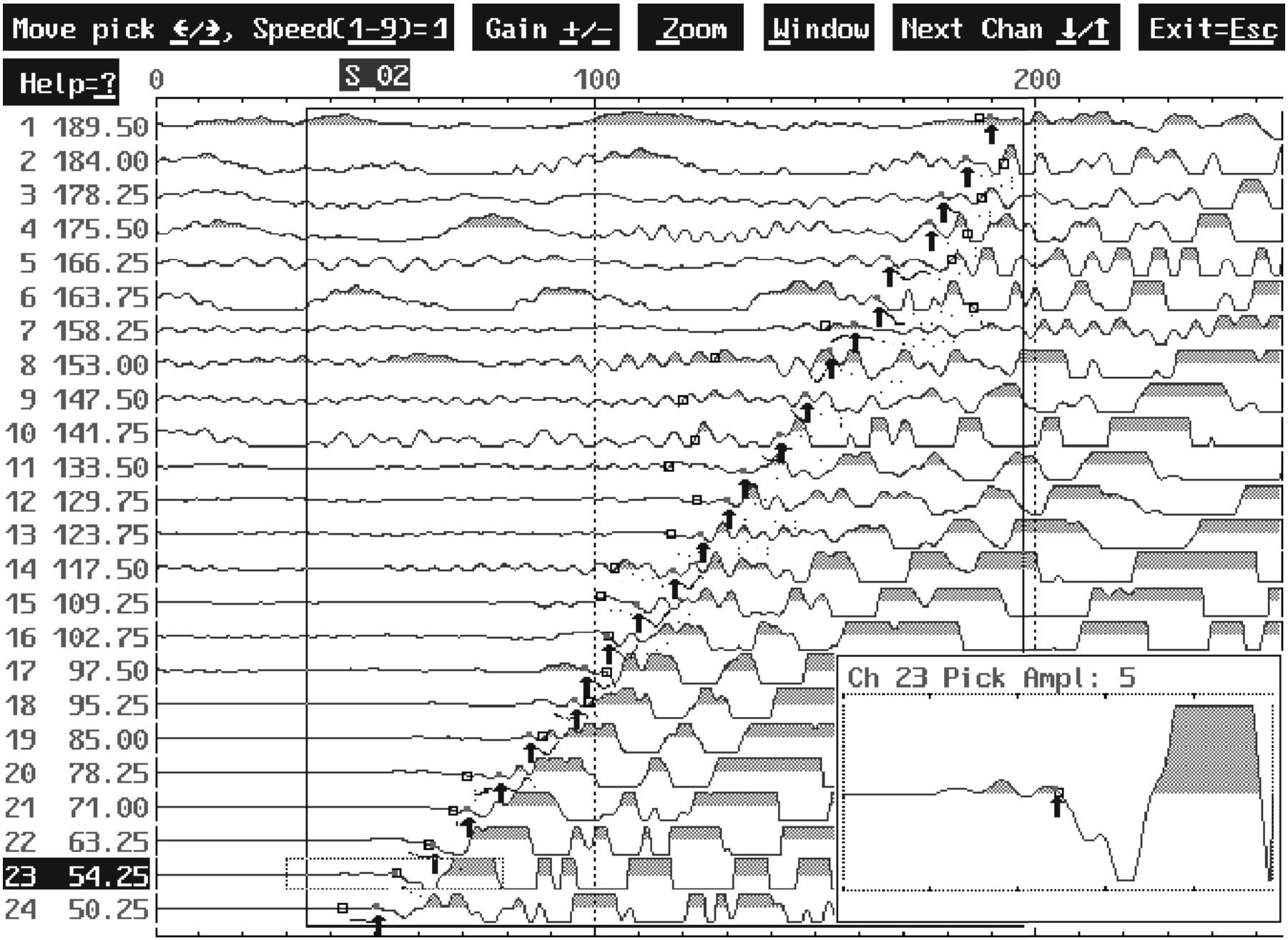

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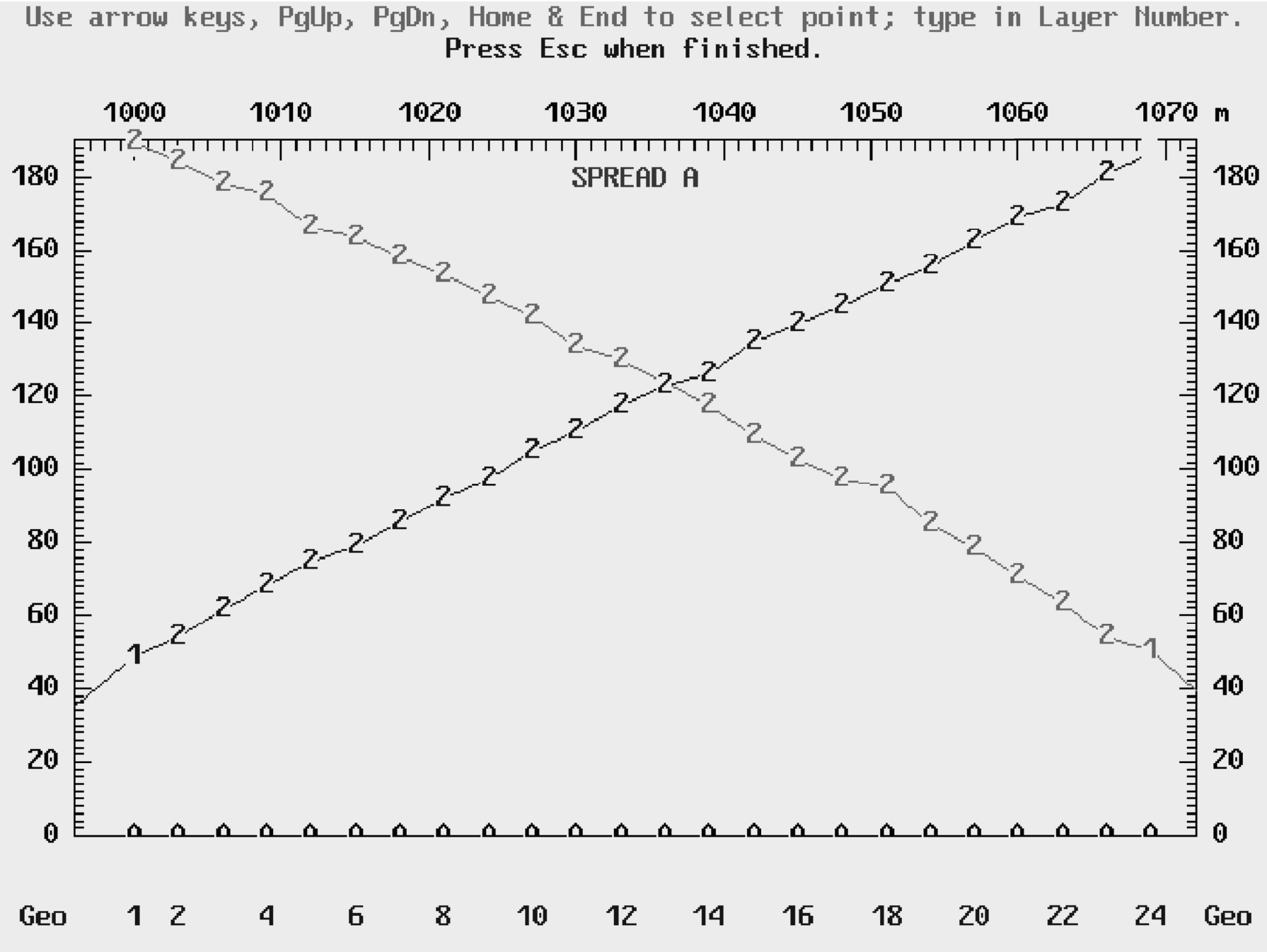

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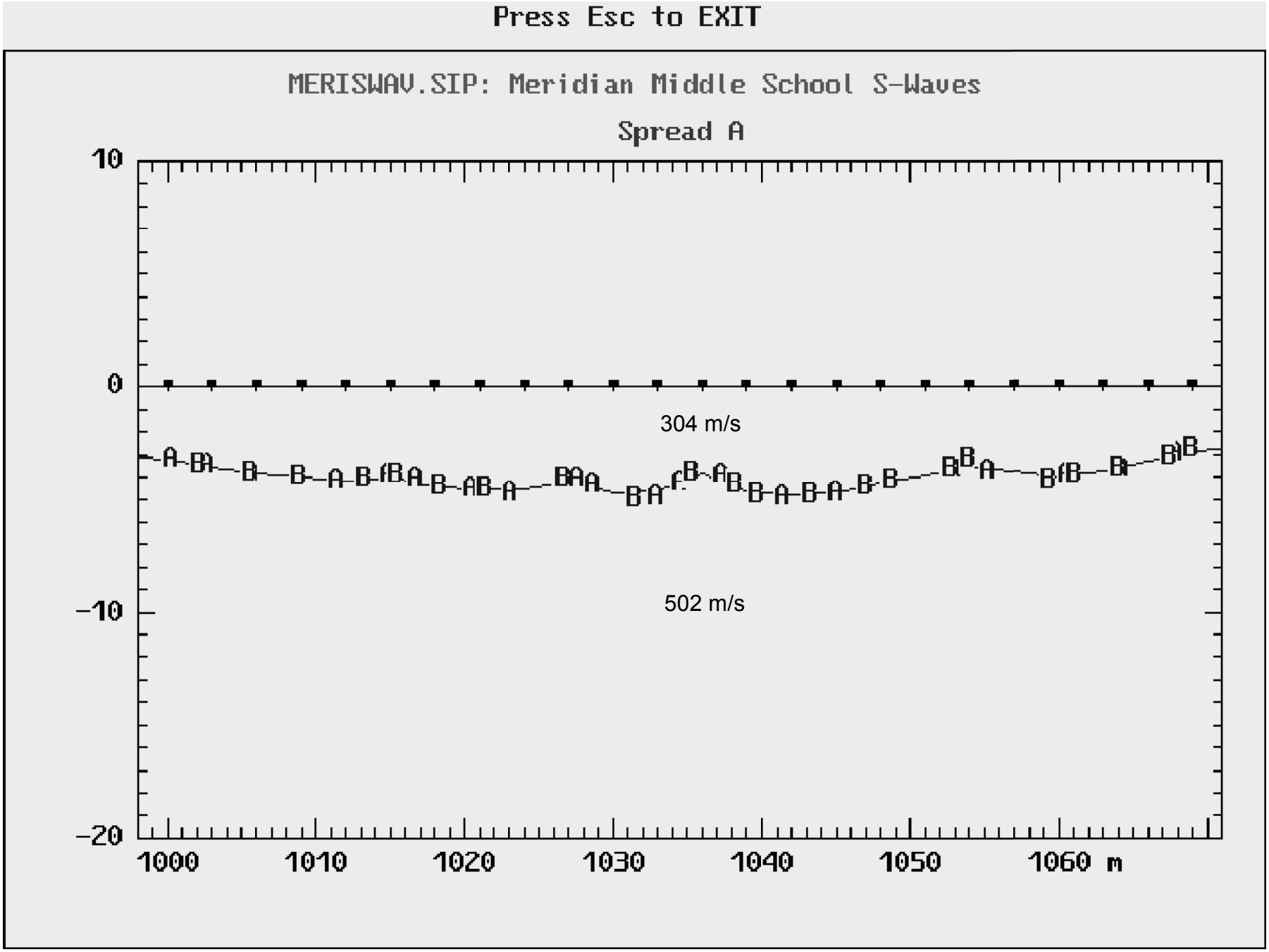

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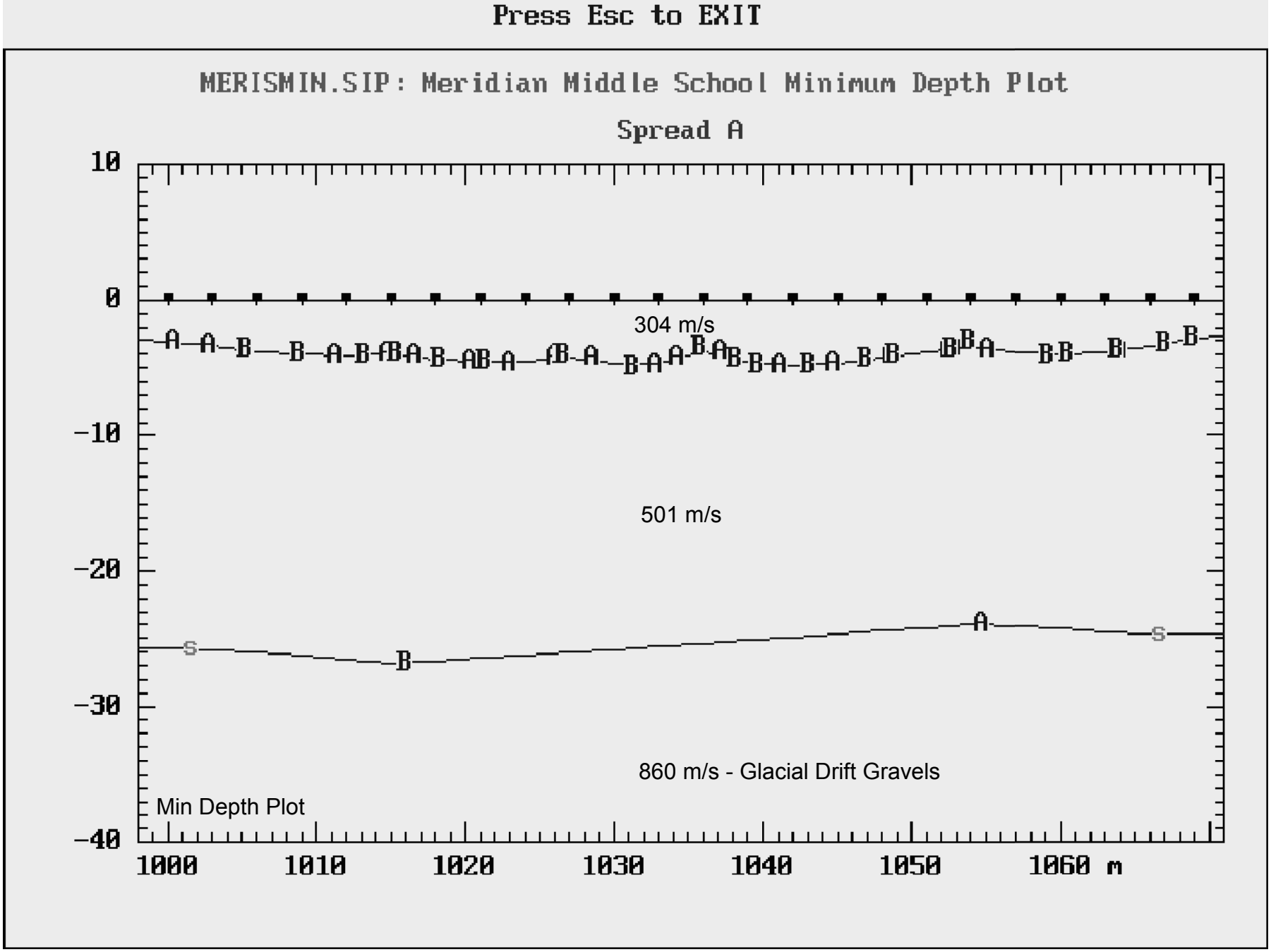
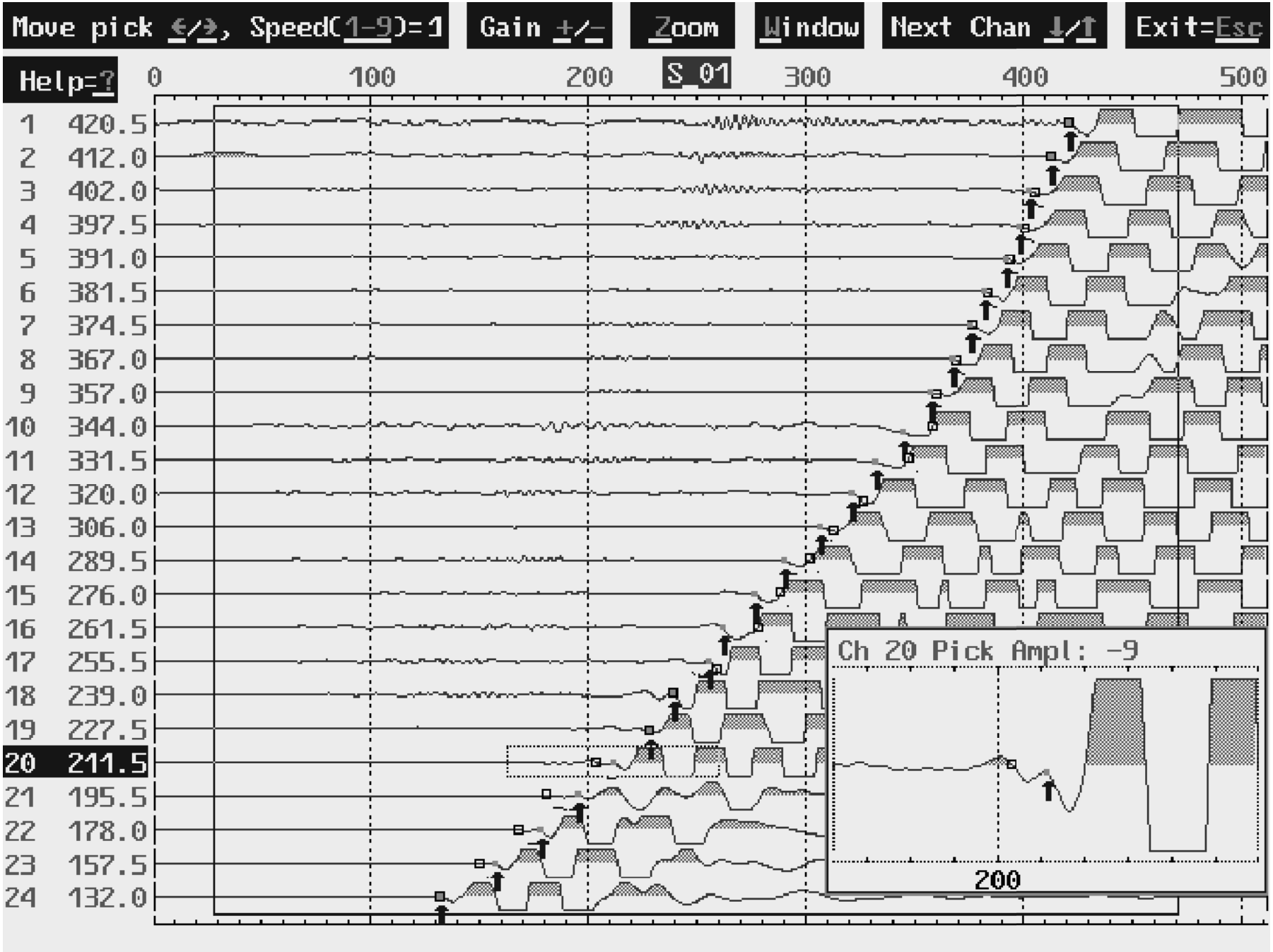


Miller Road - Snohomish S-wave



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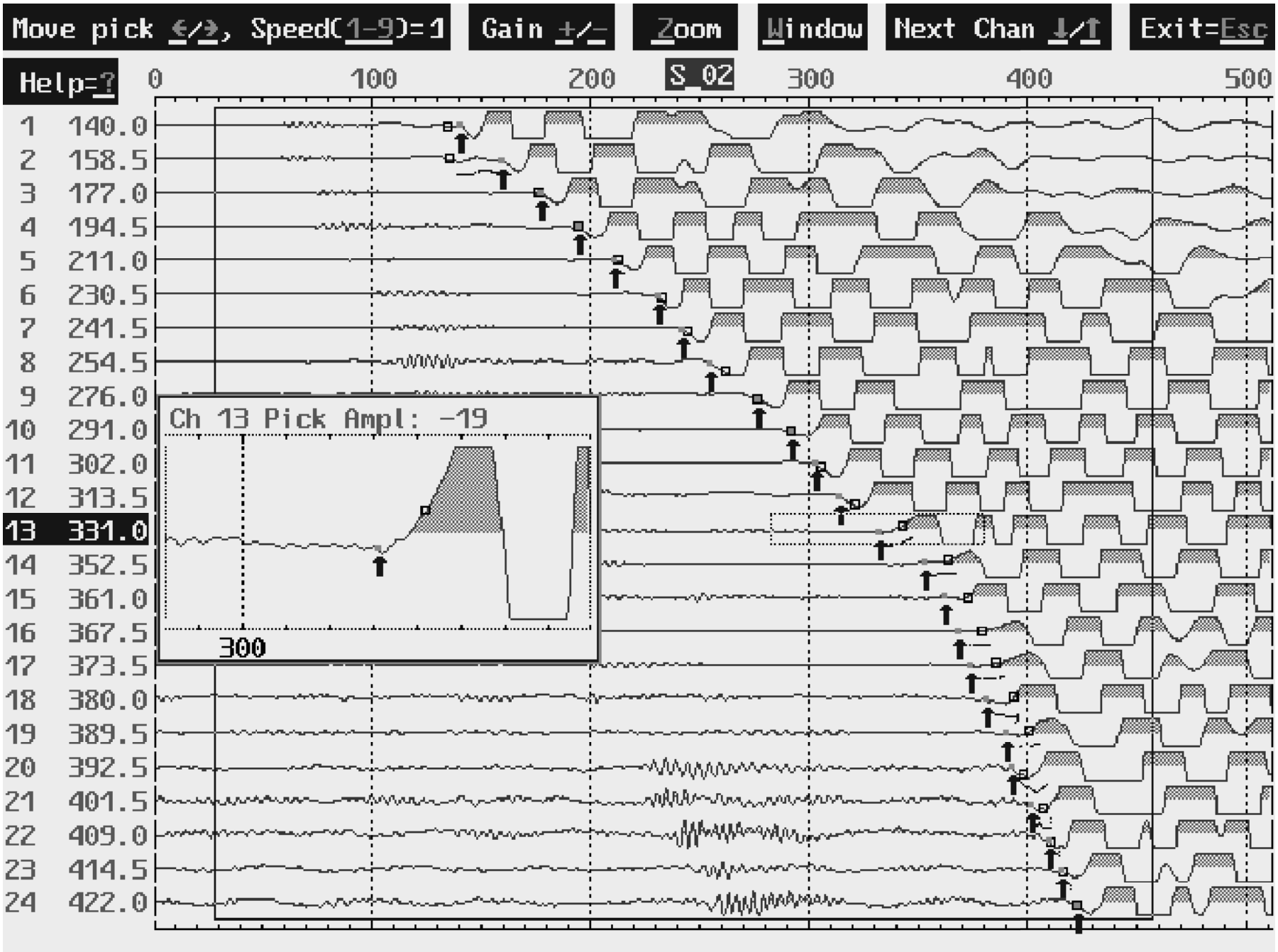

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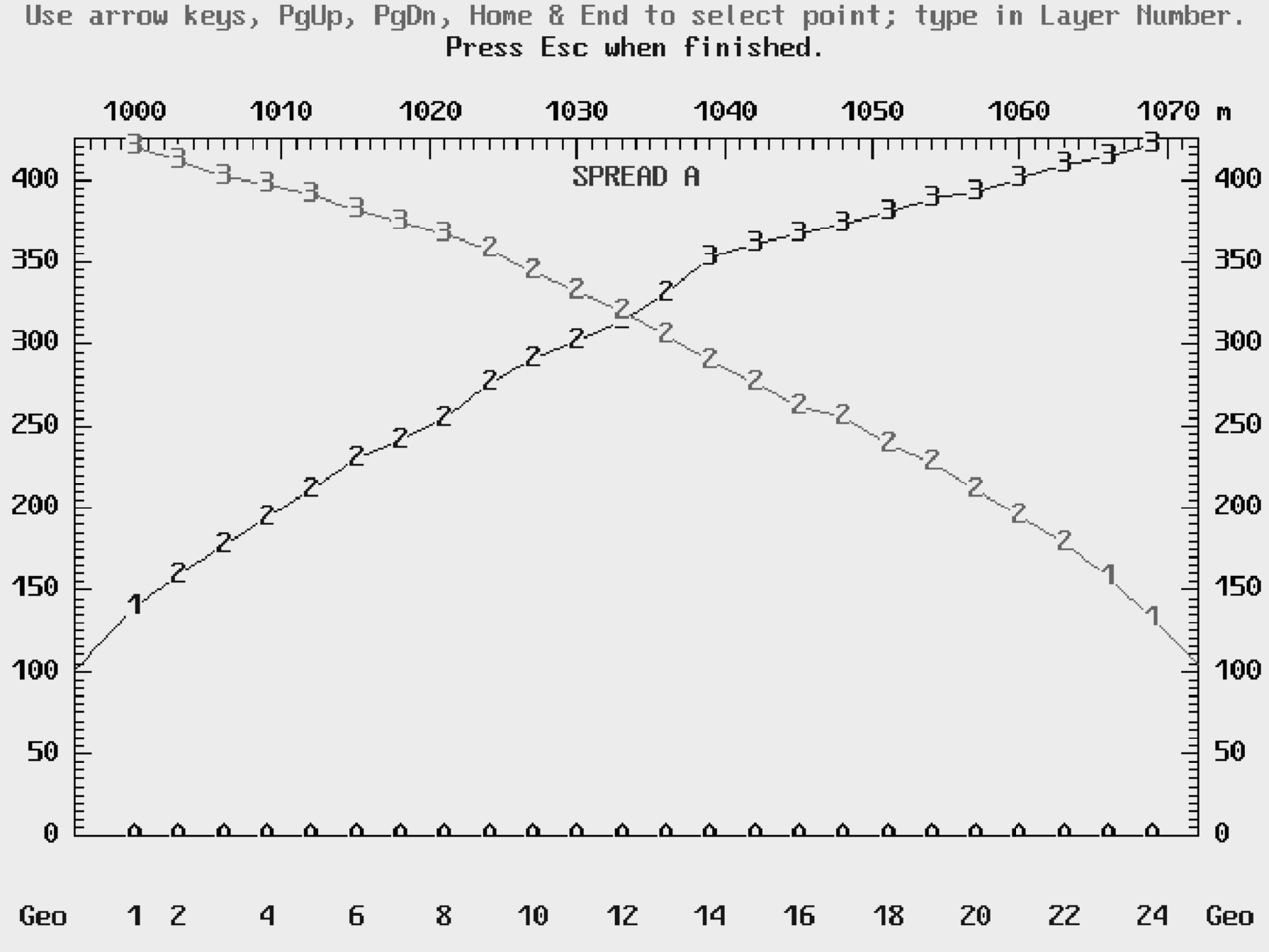

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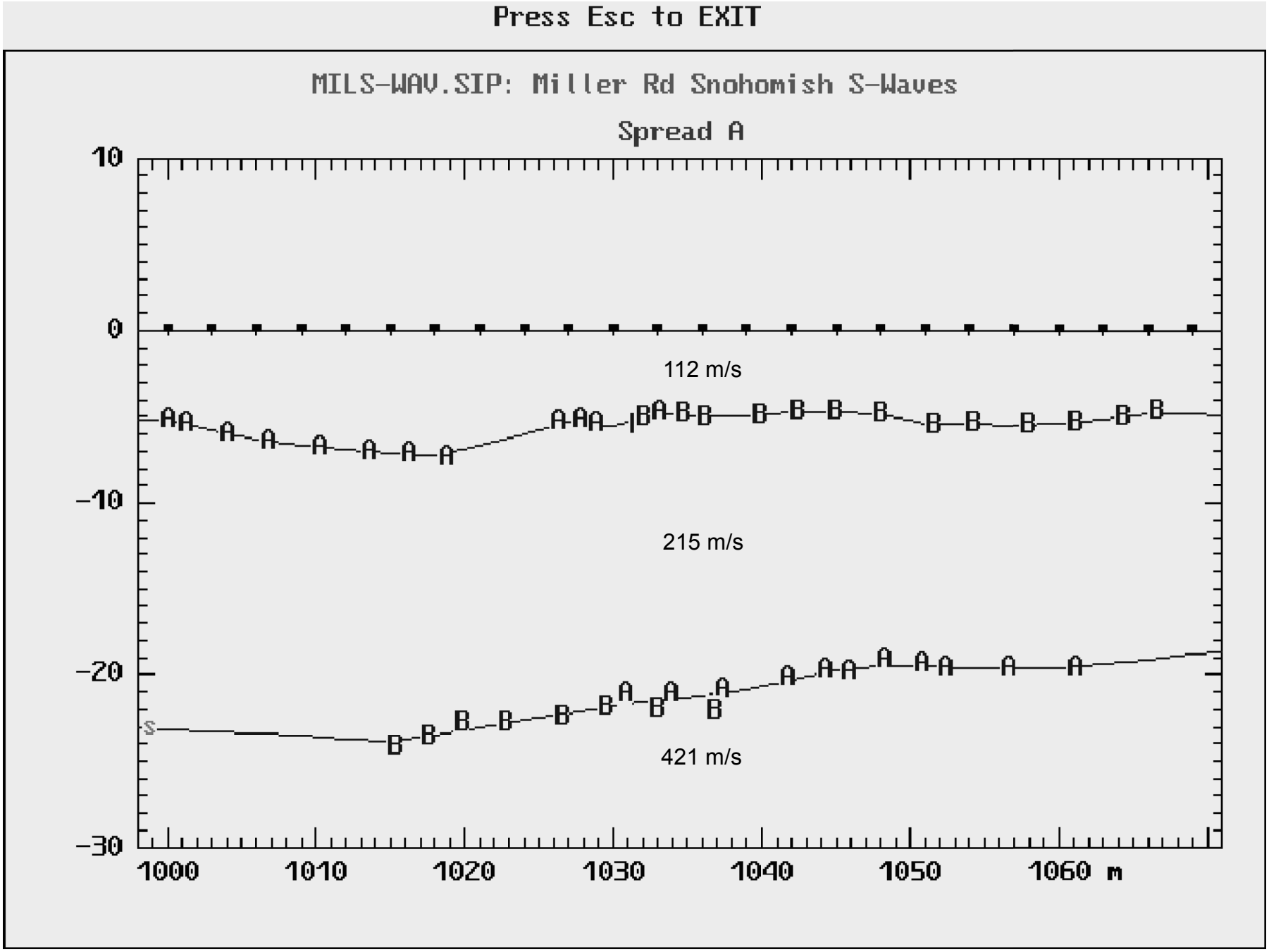

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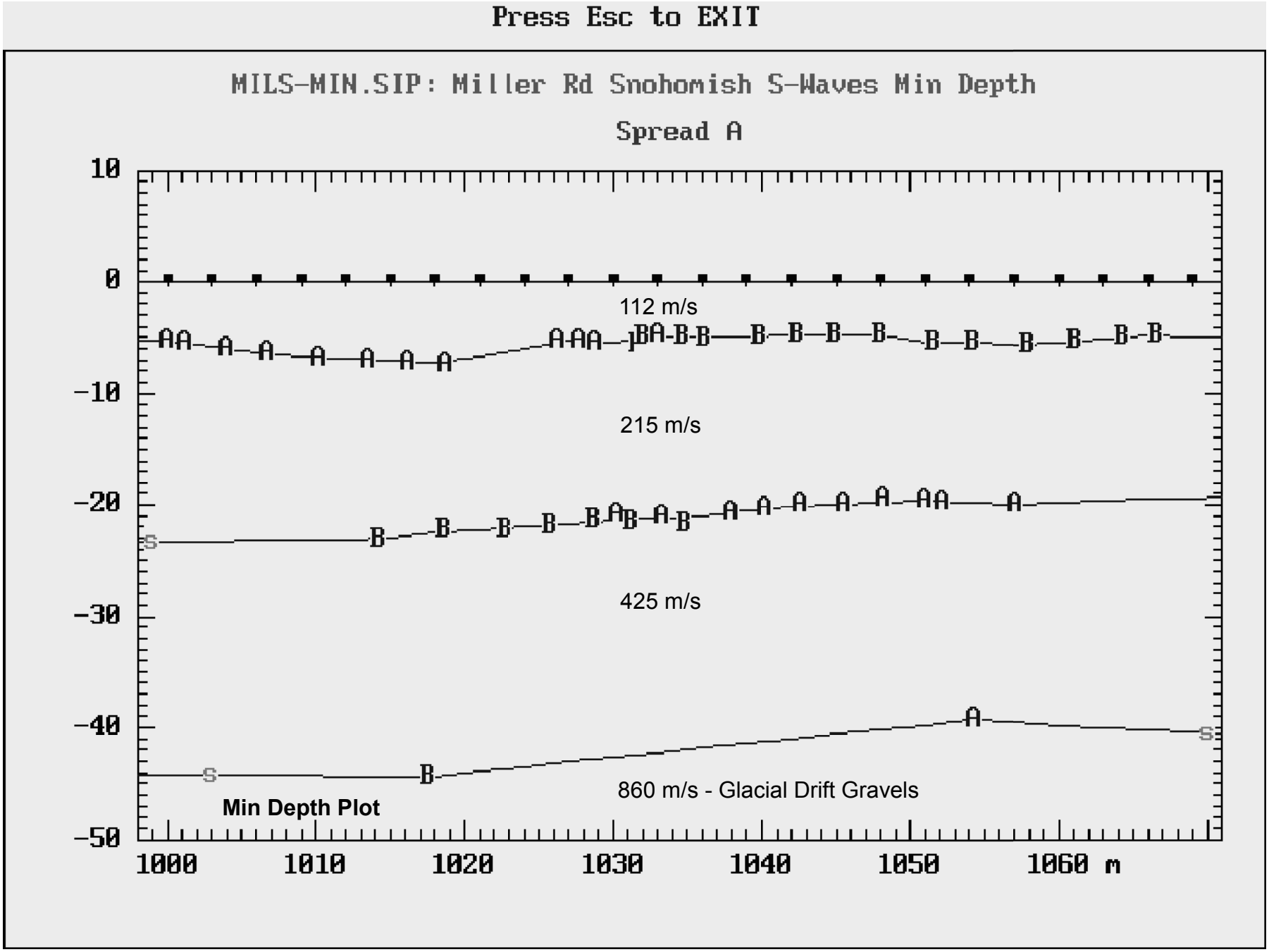

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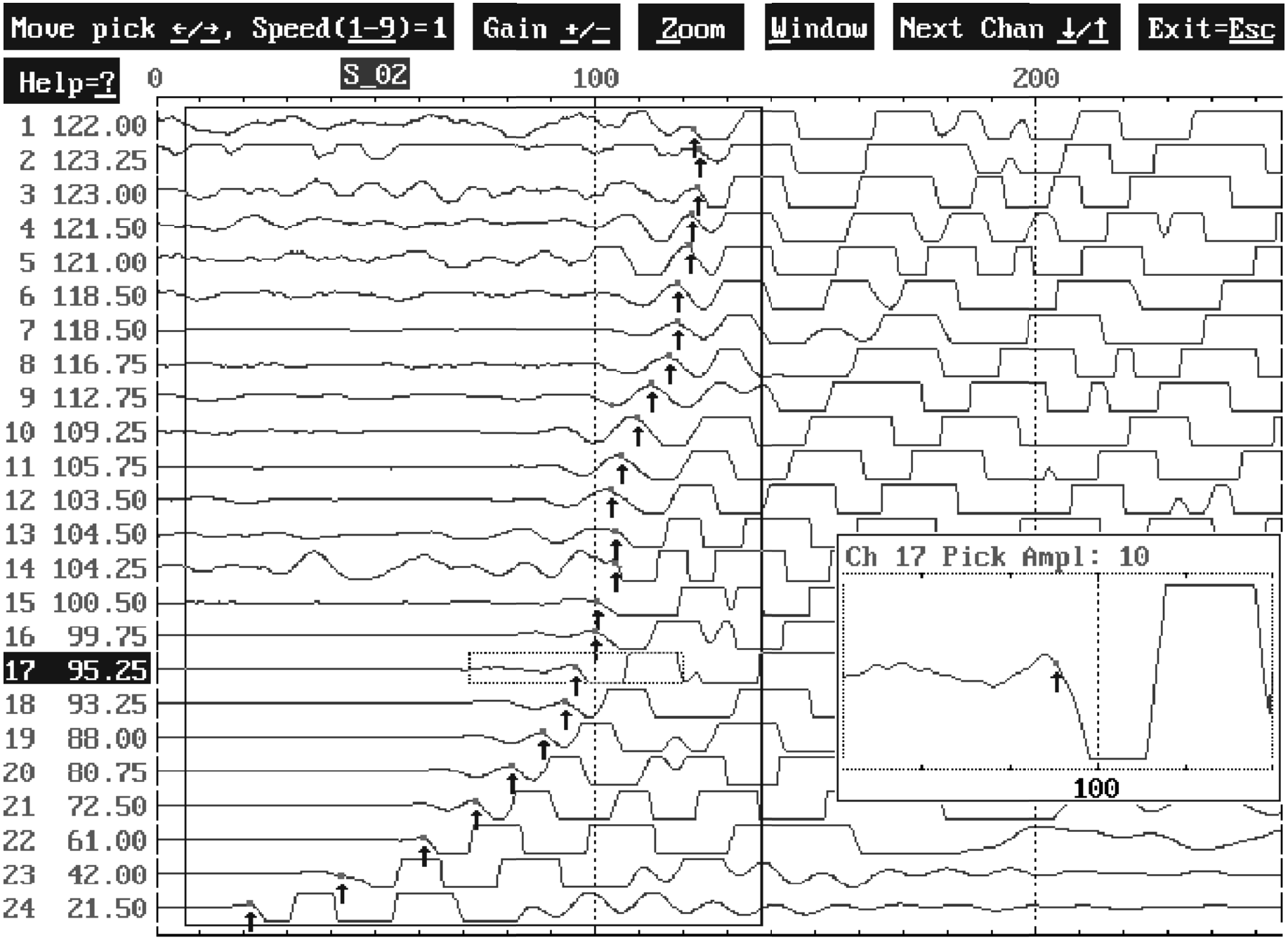

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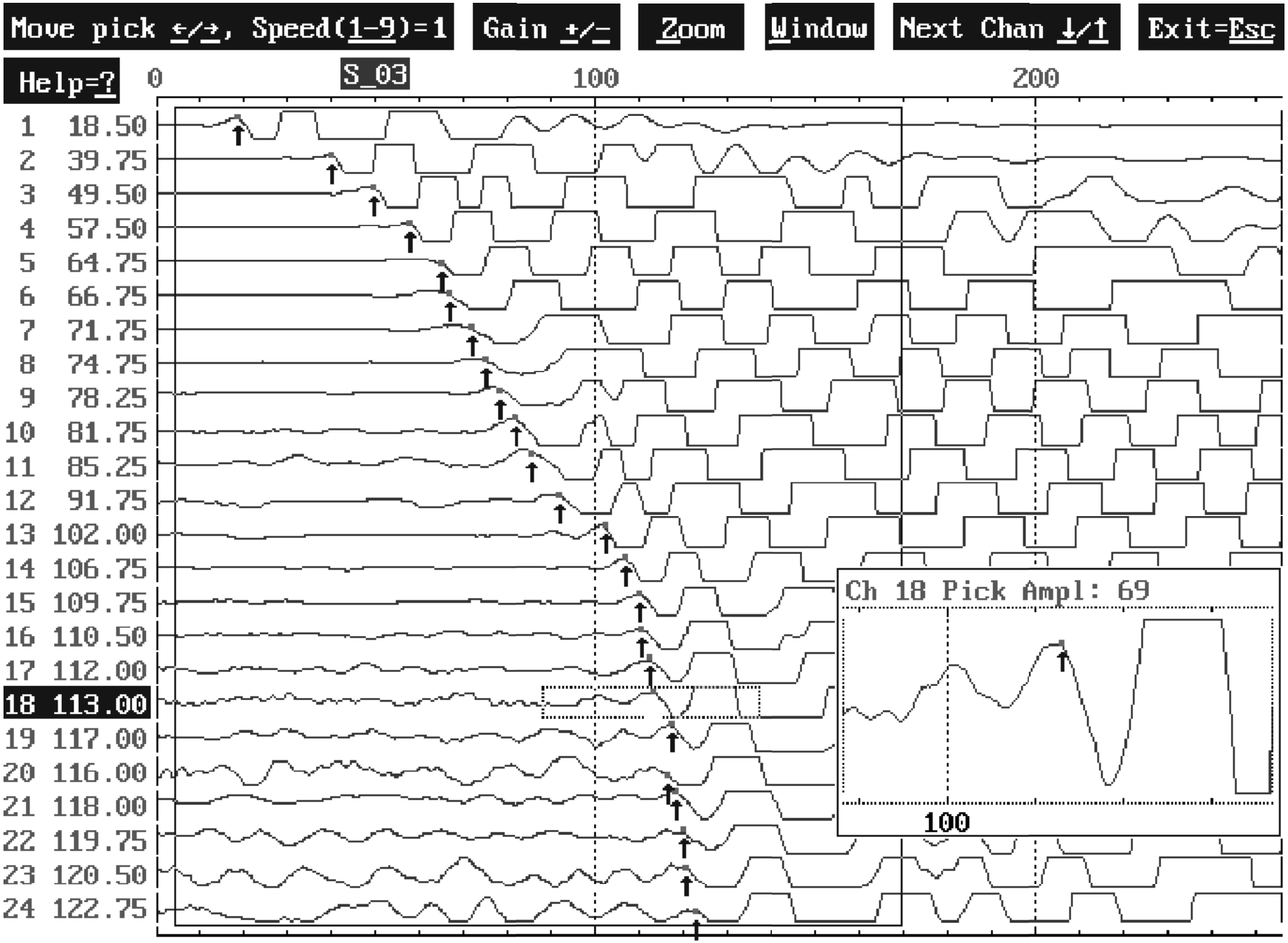

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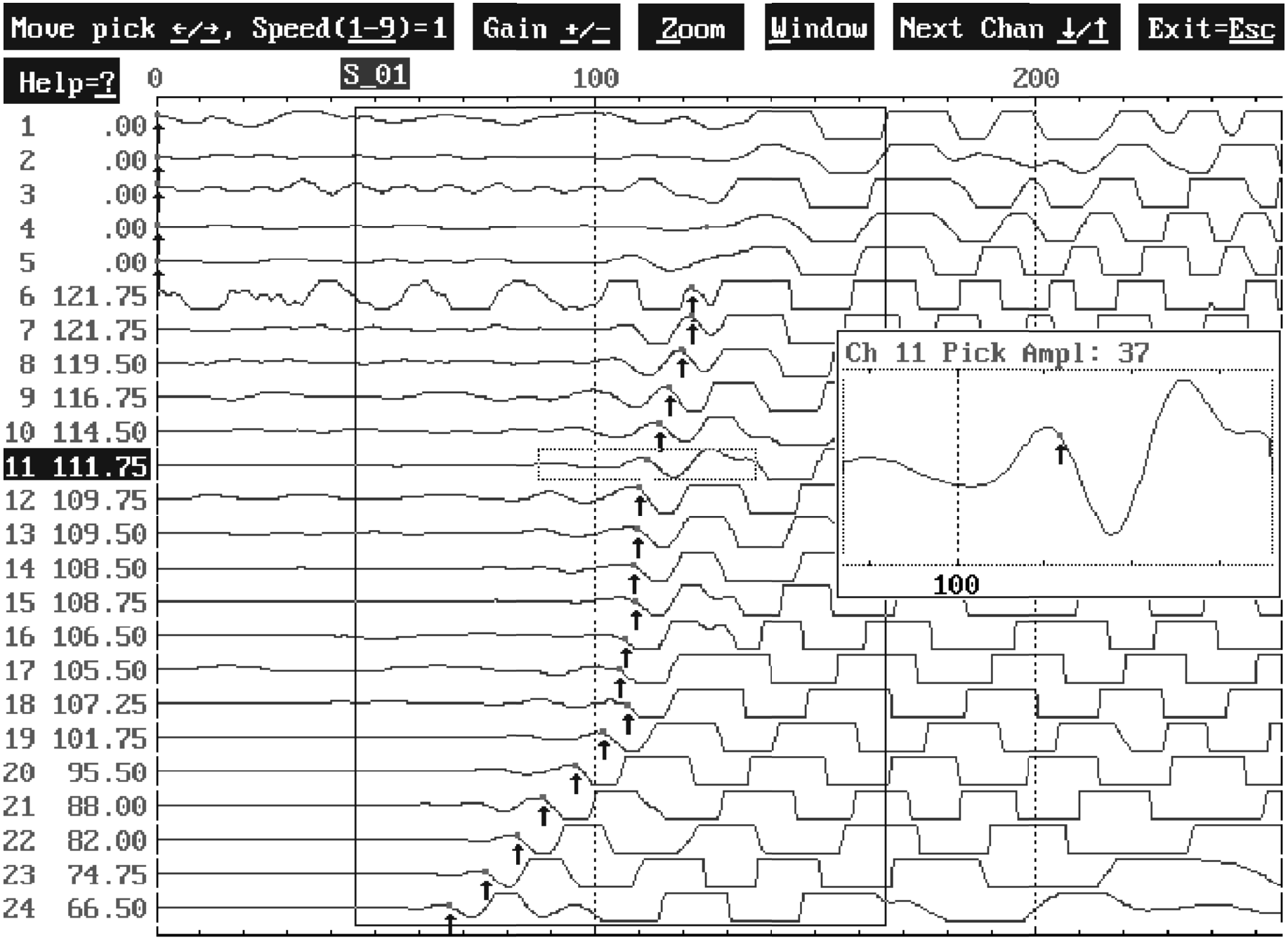

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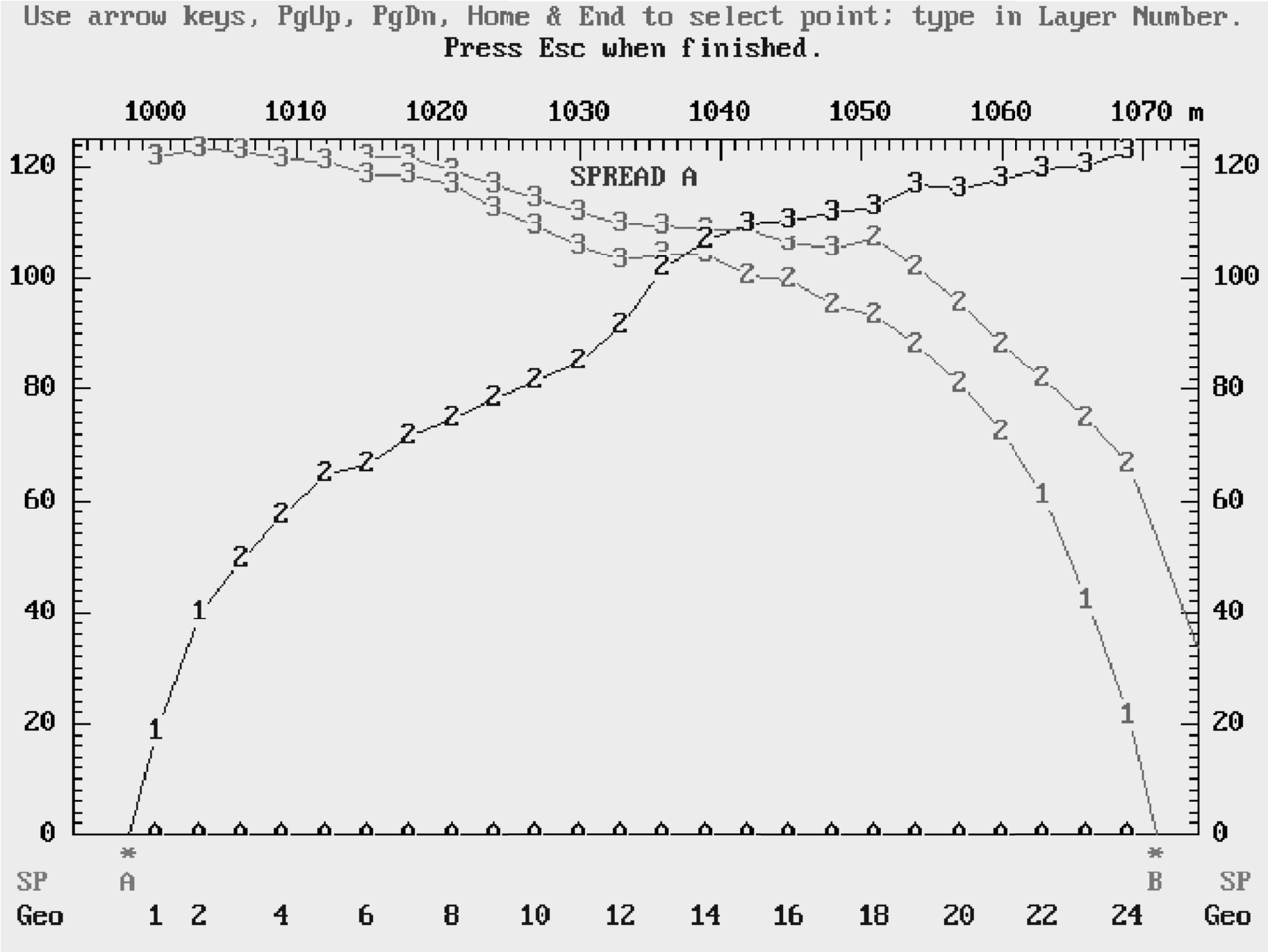

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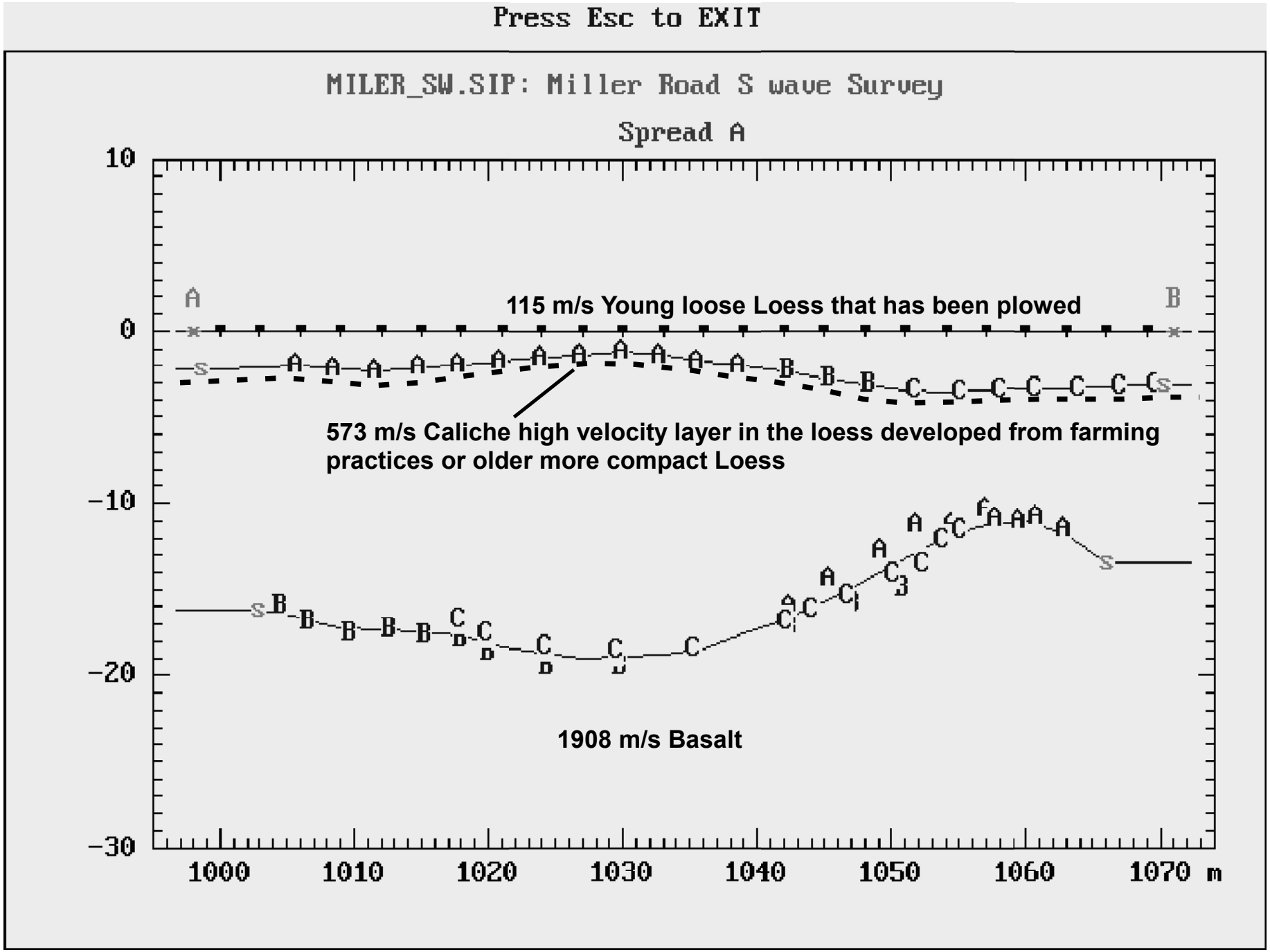
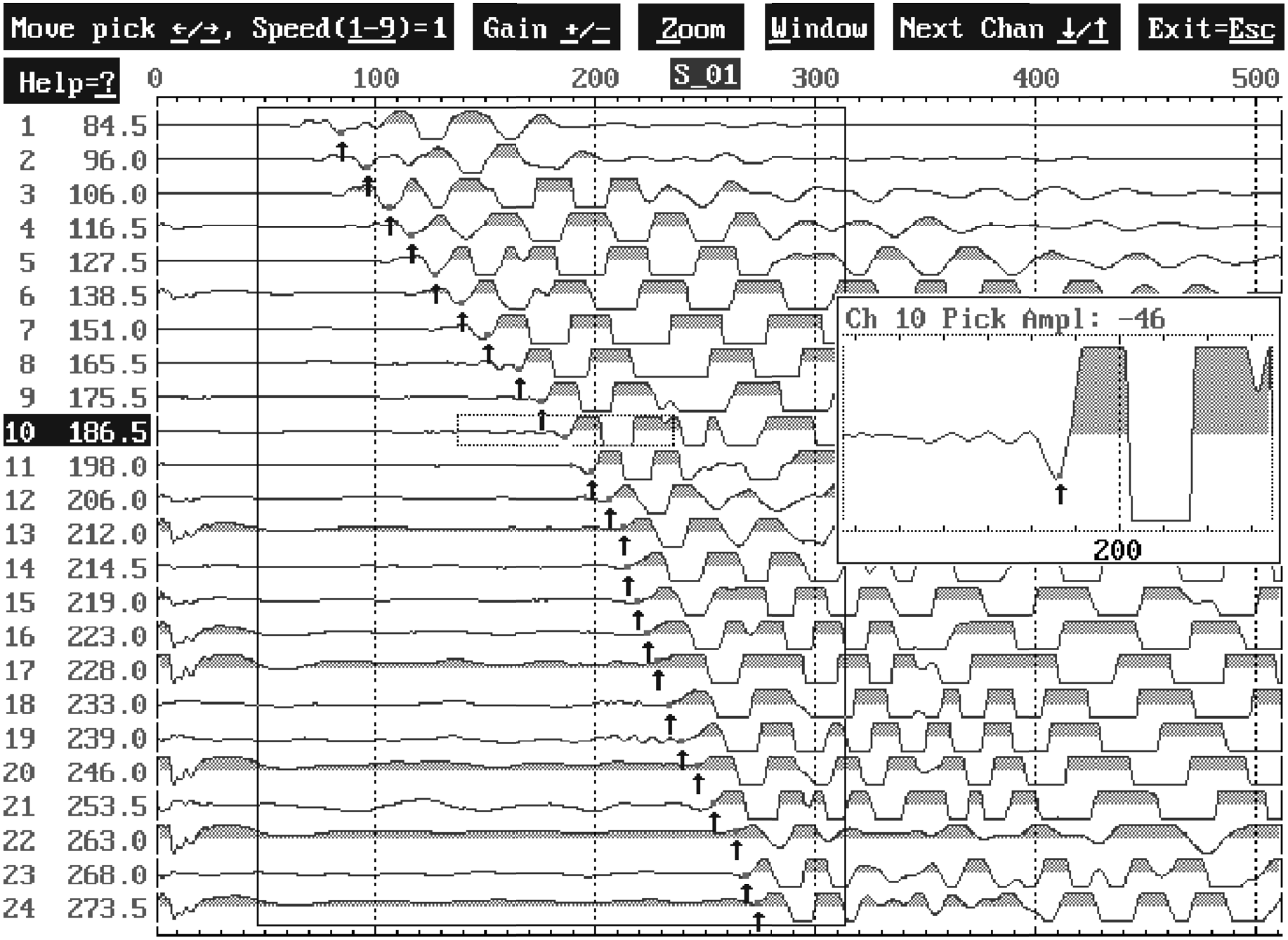


Monroe Correctional Complex S-wave



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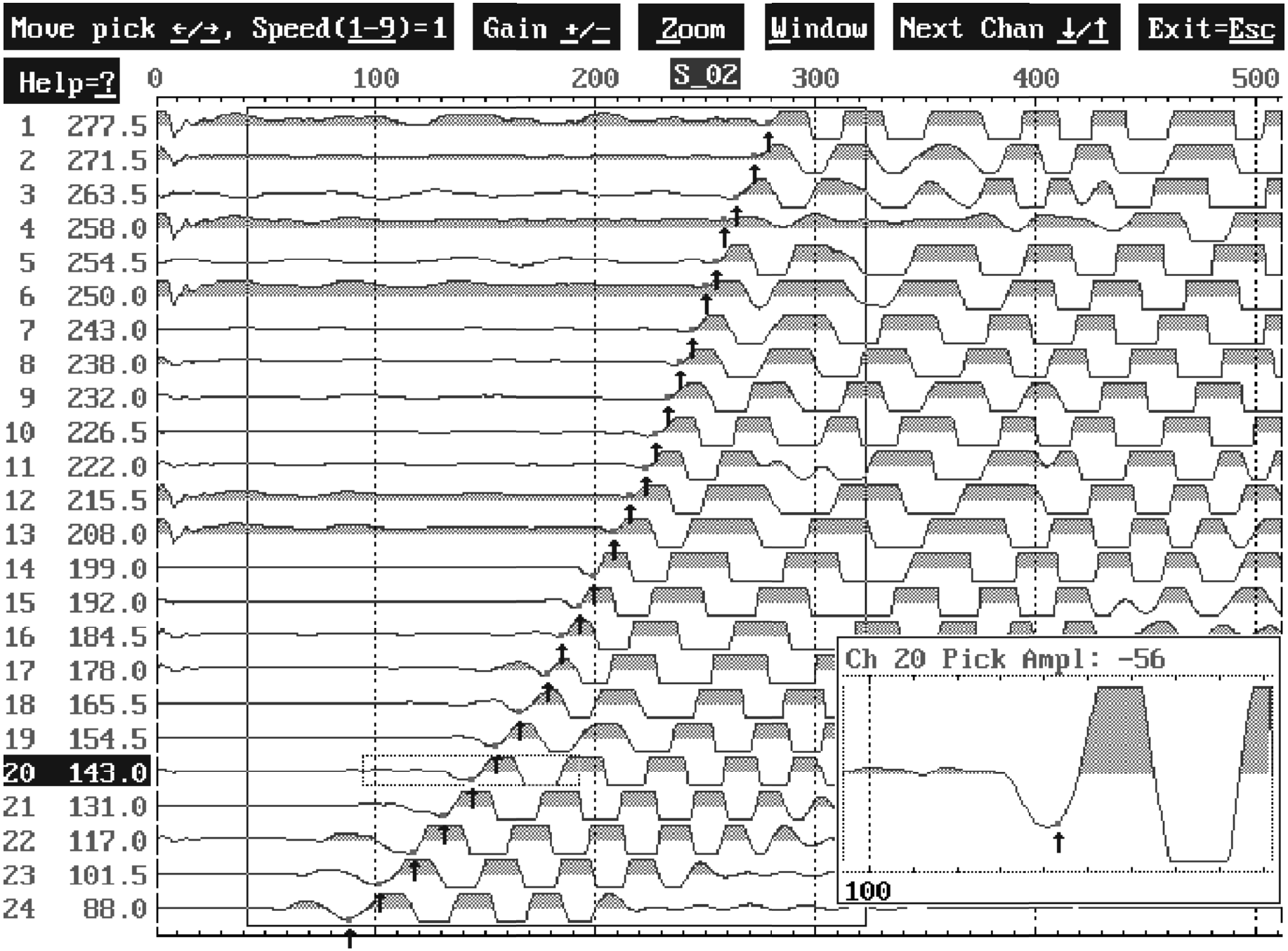

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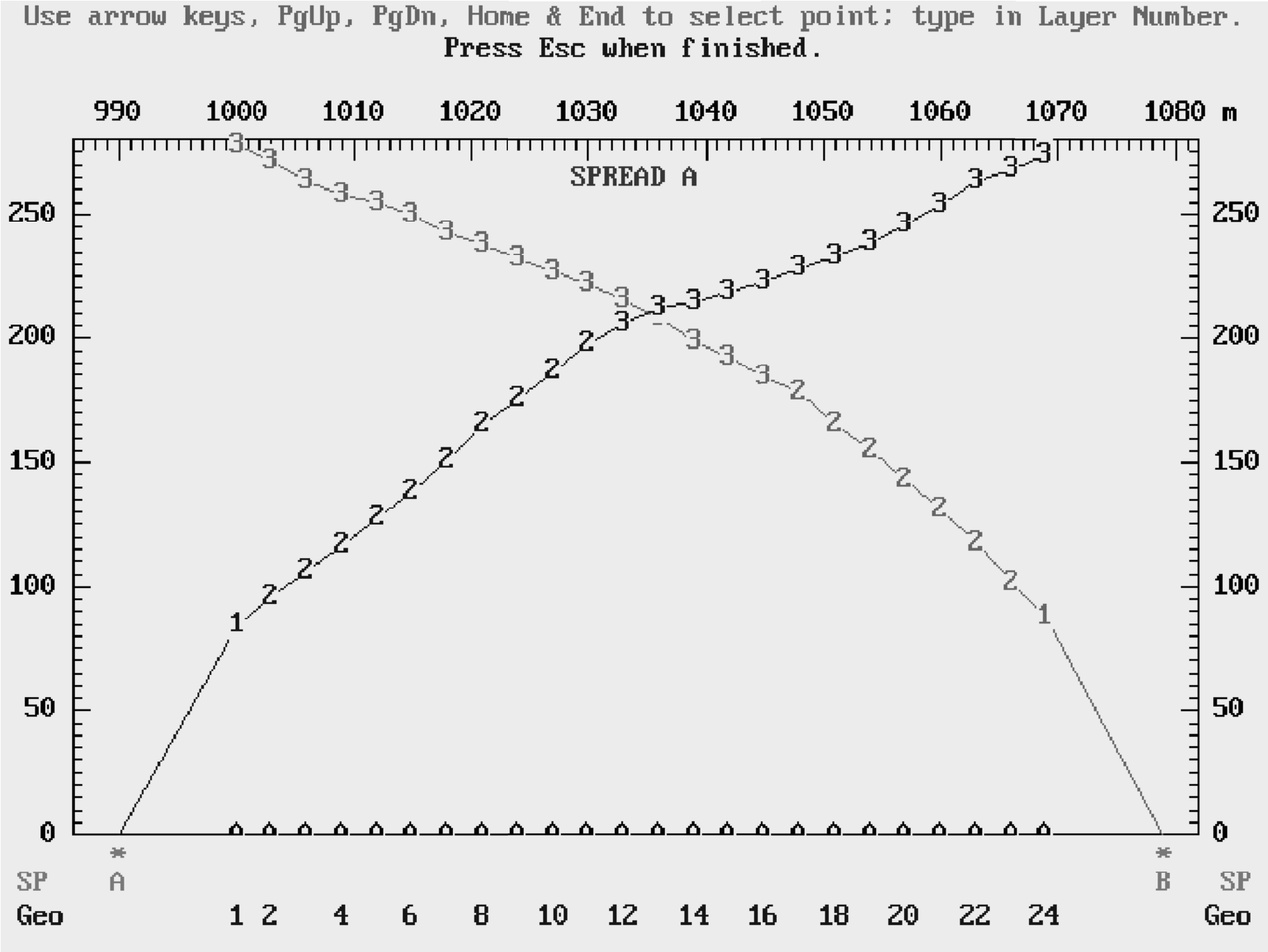

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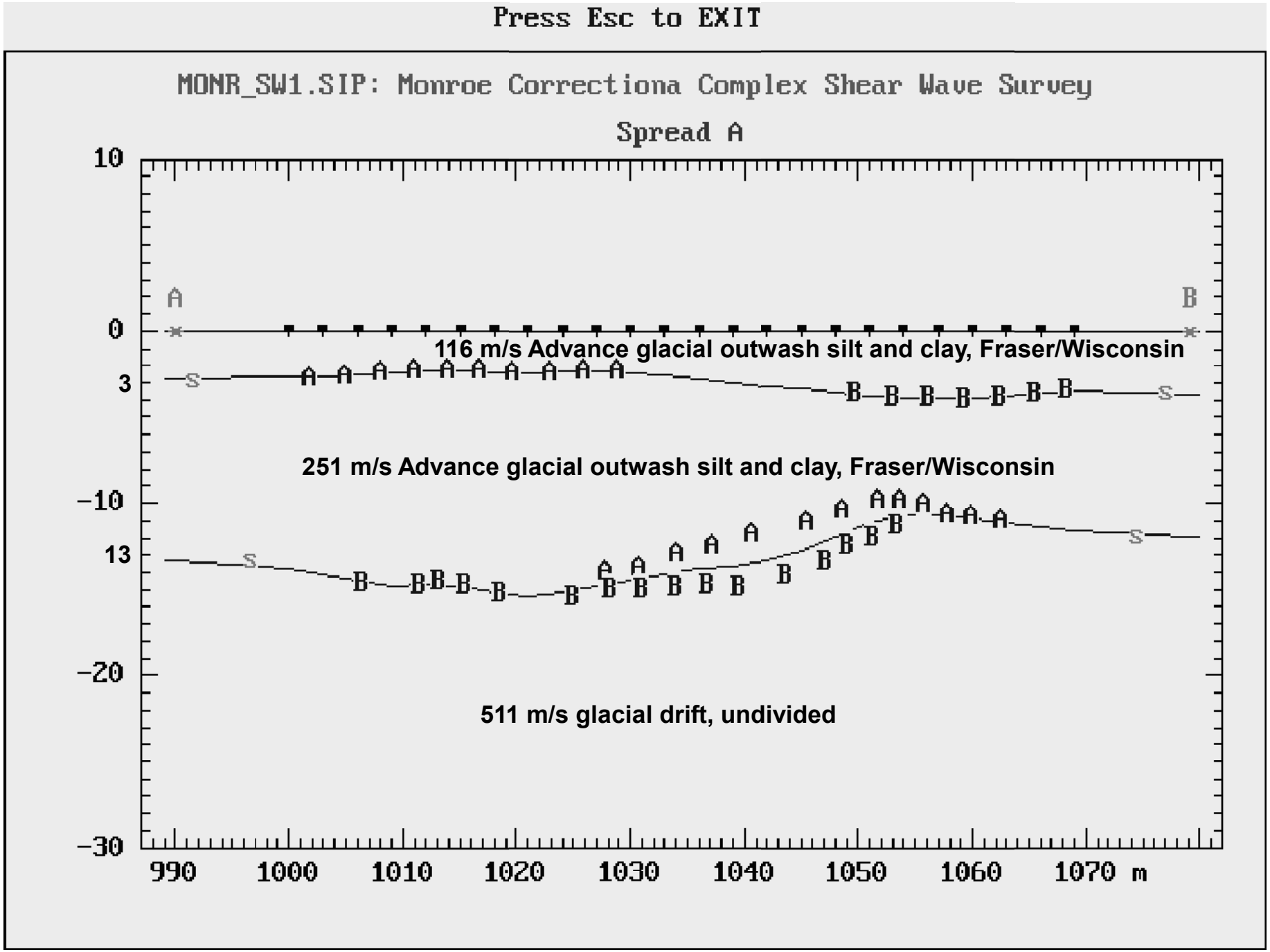

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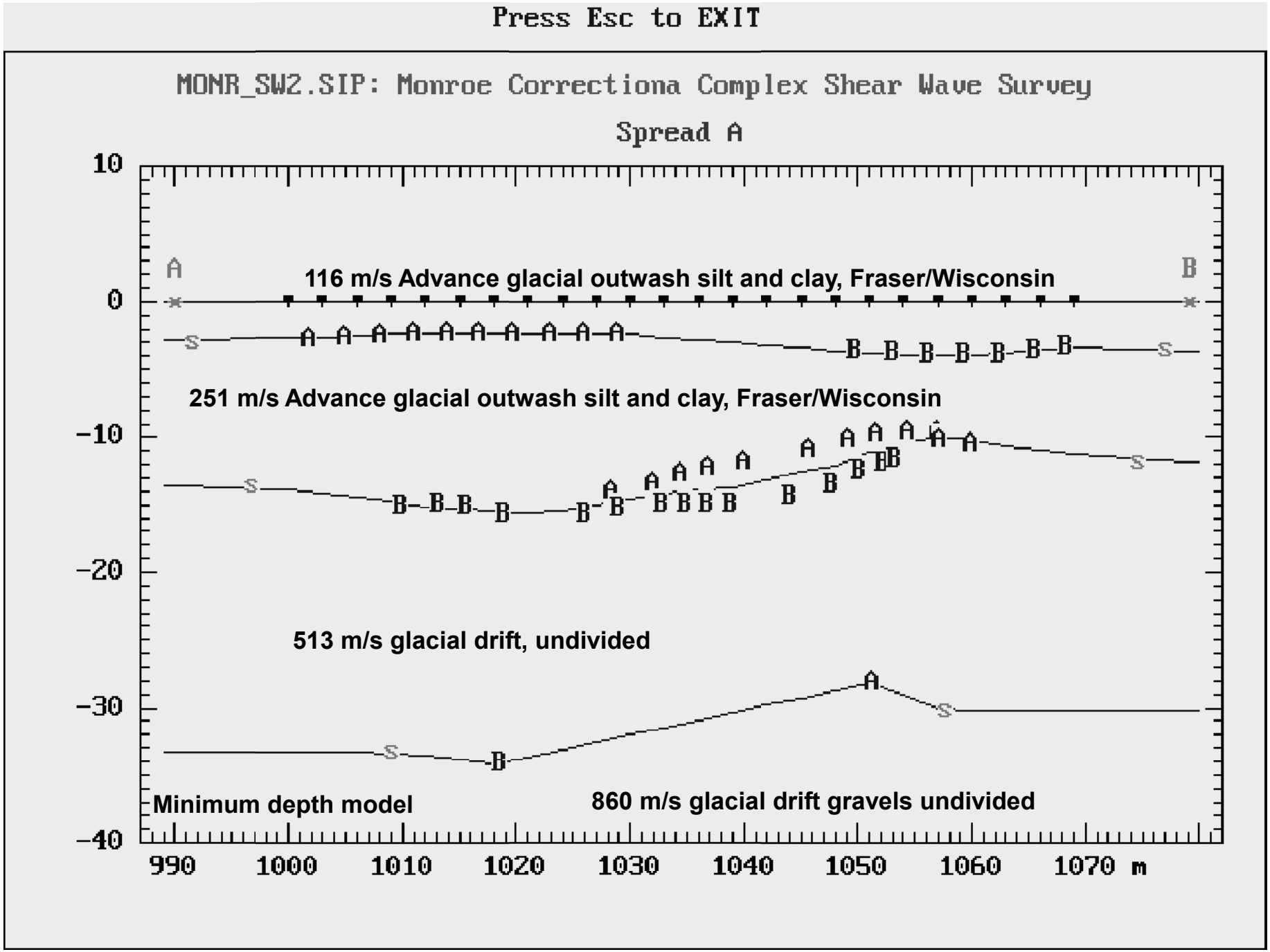
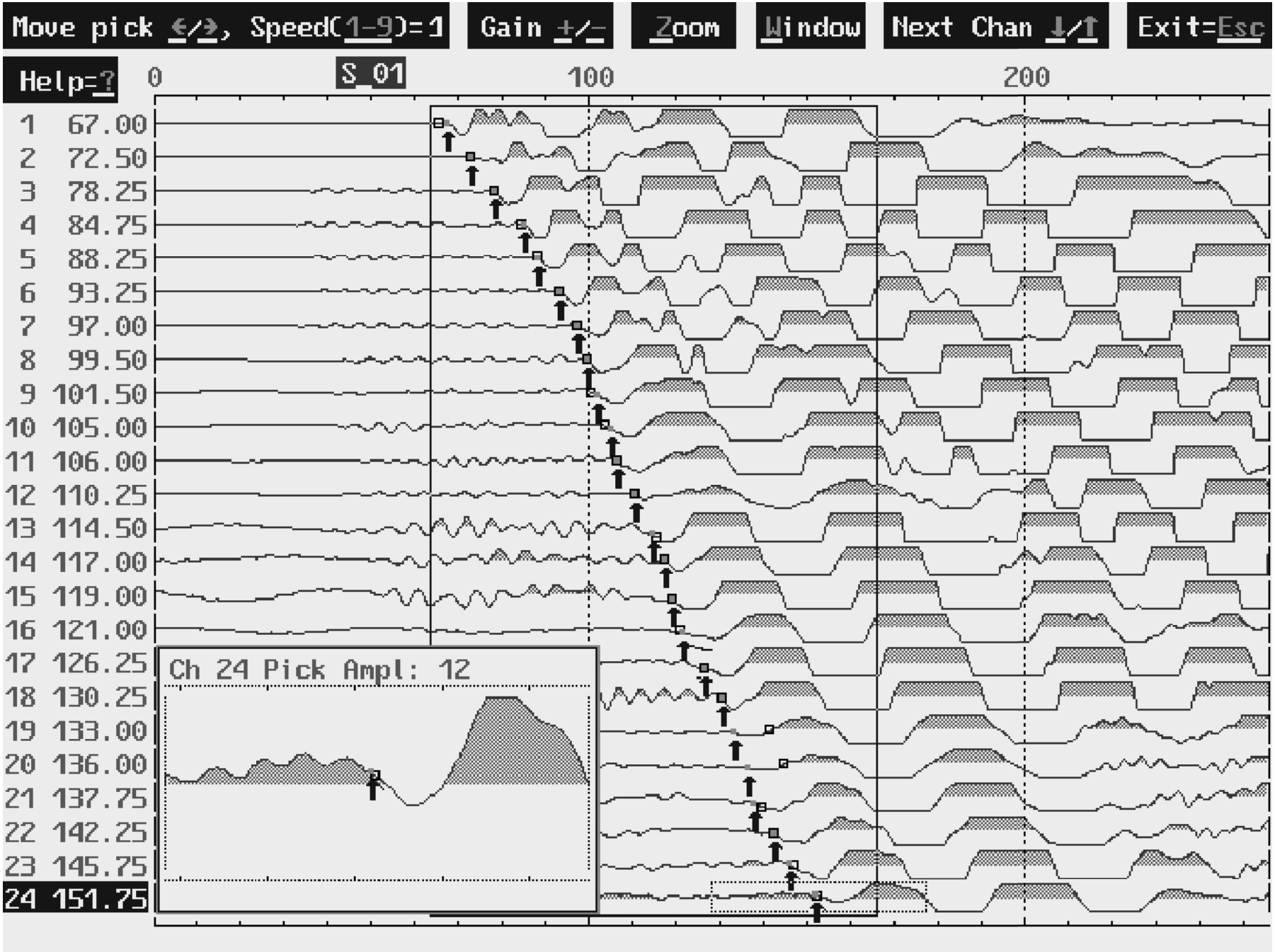


Mount Baker Middle School S-wave



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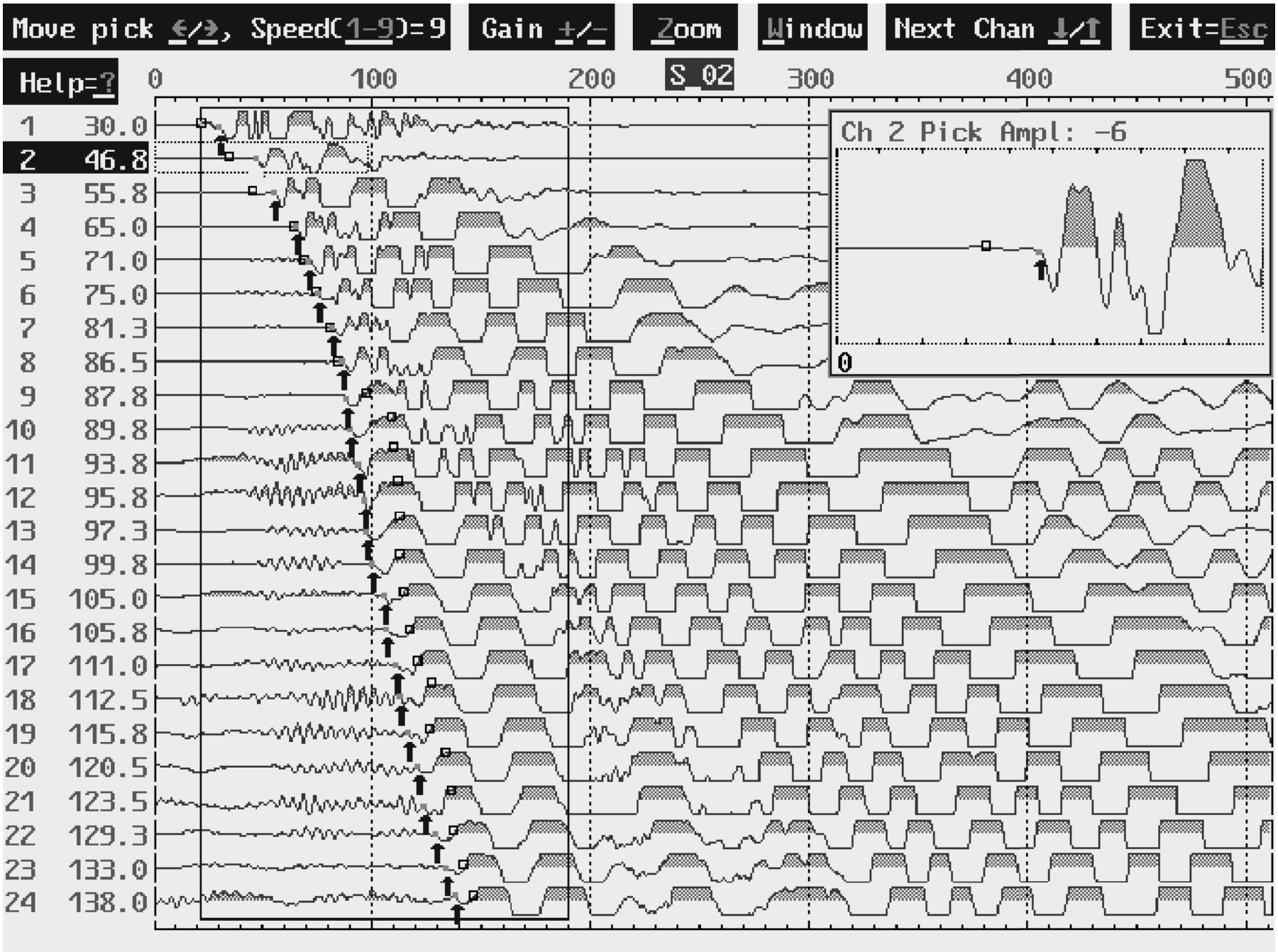

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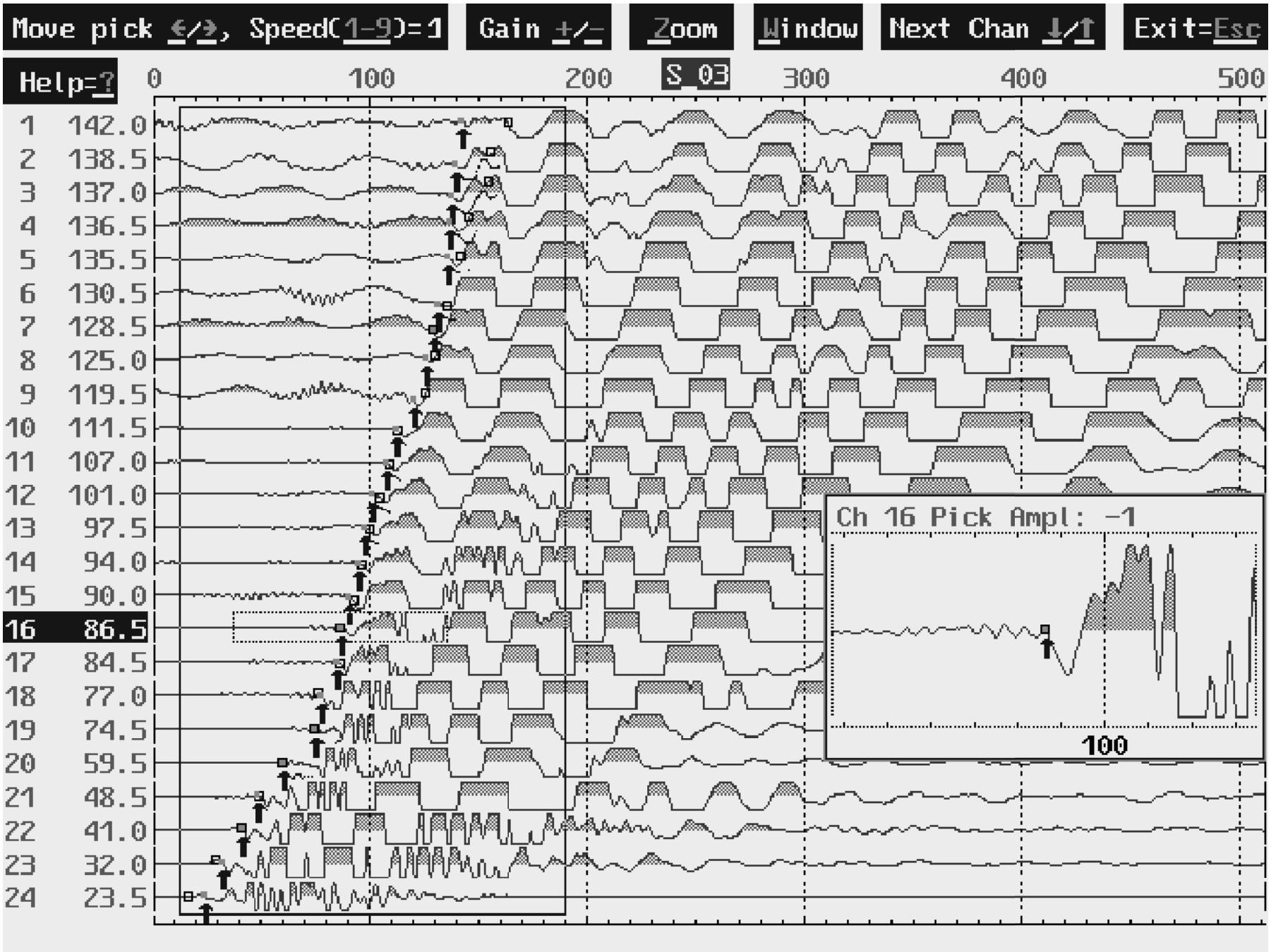

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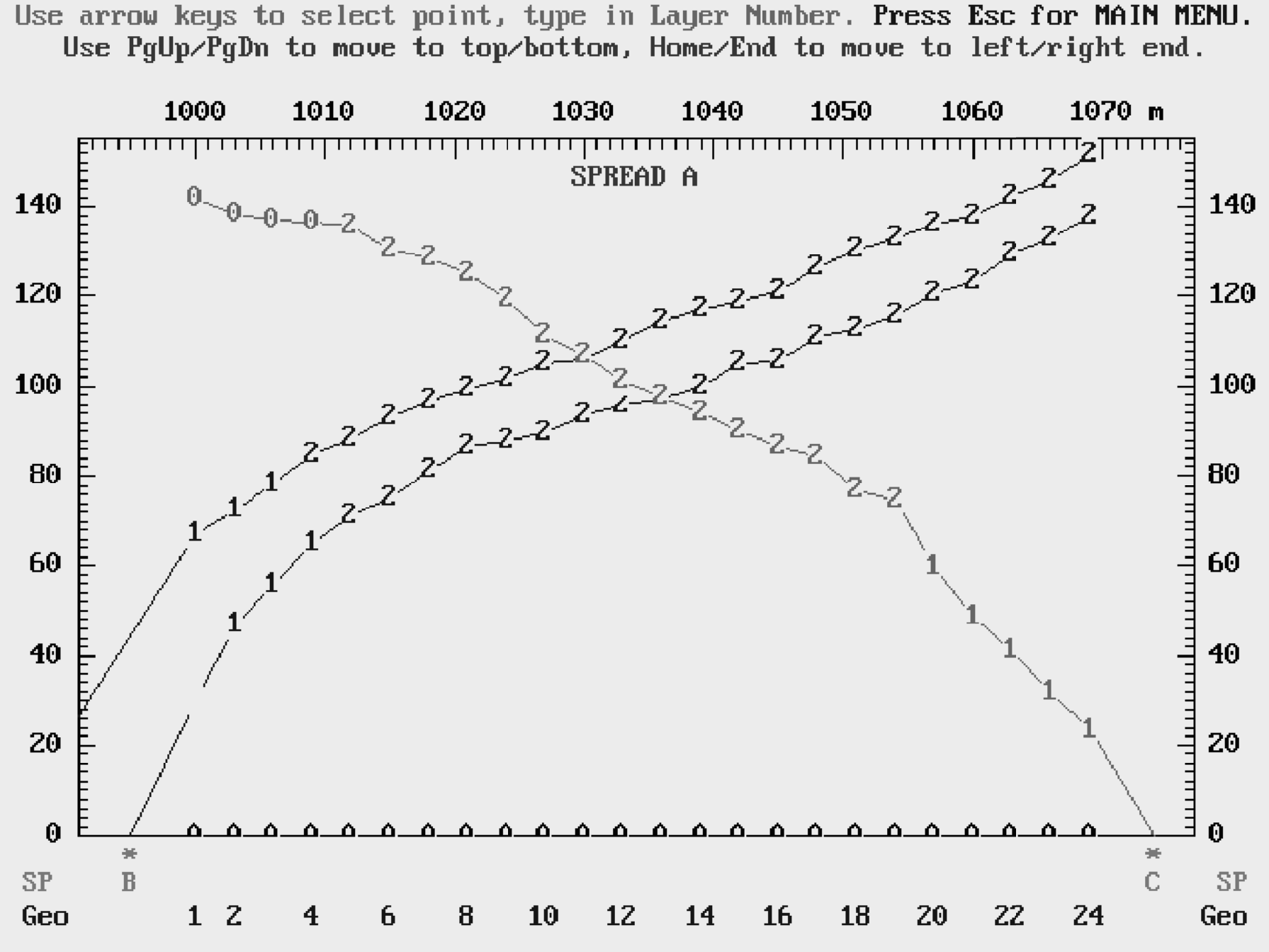

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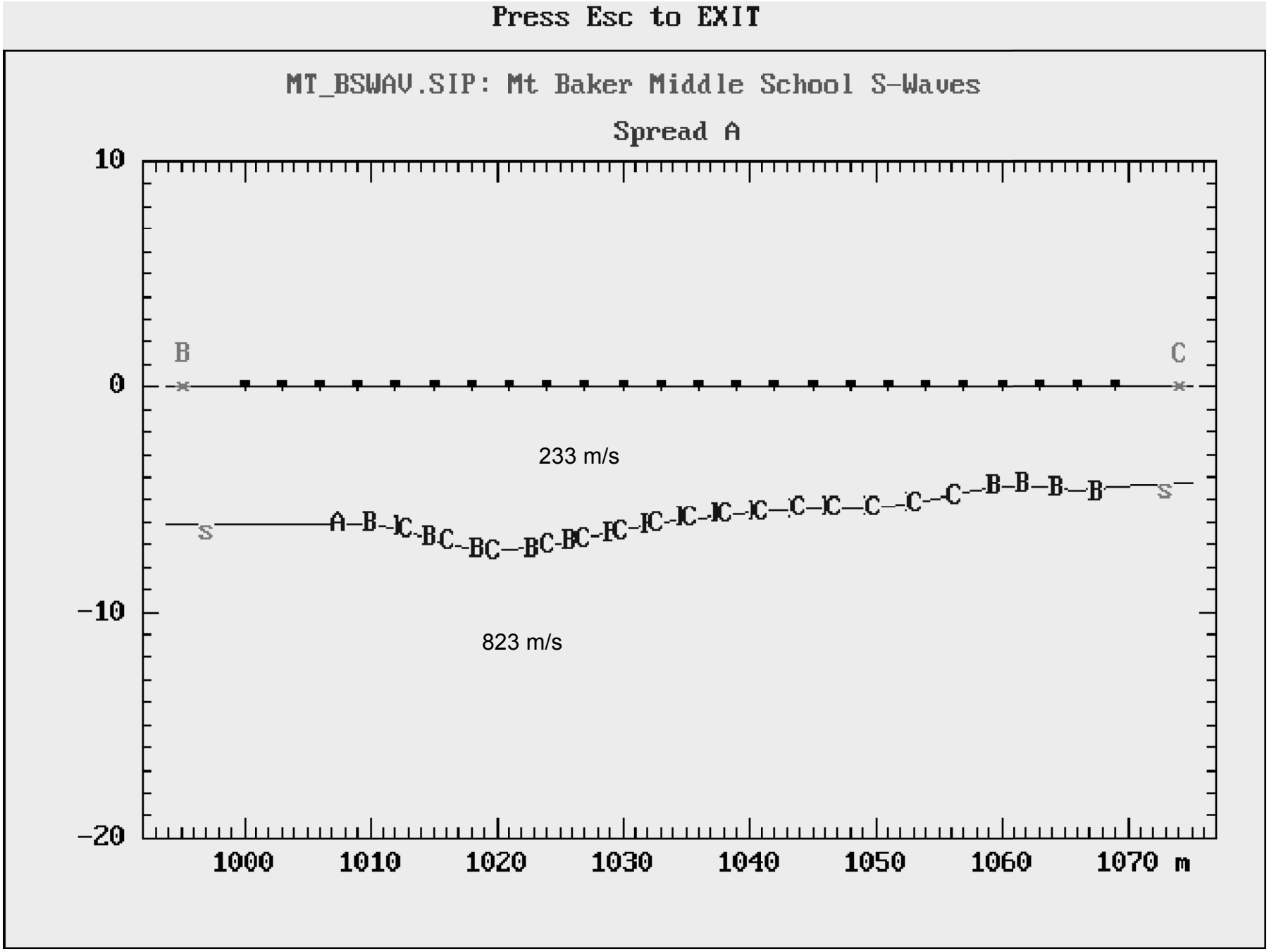

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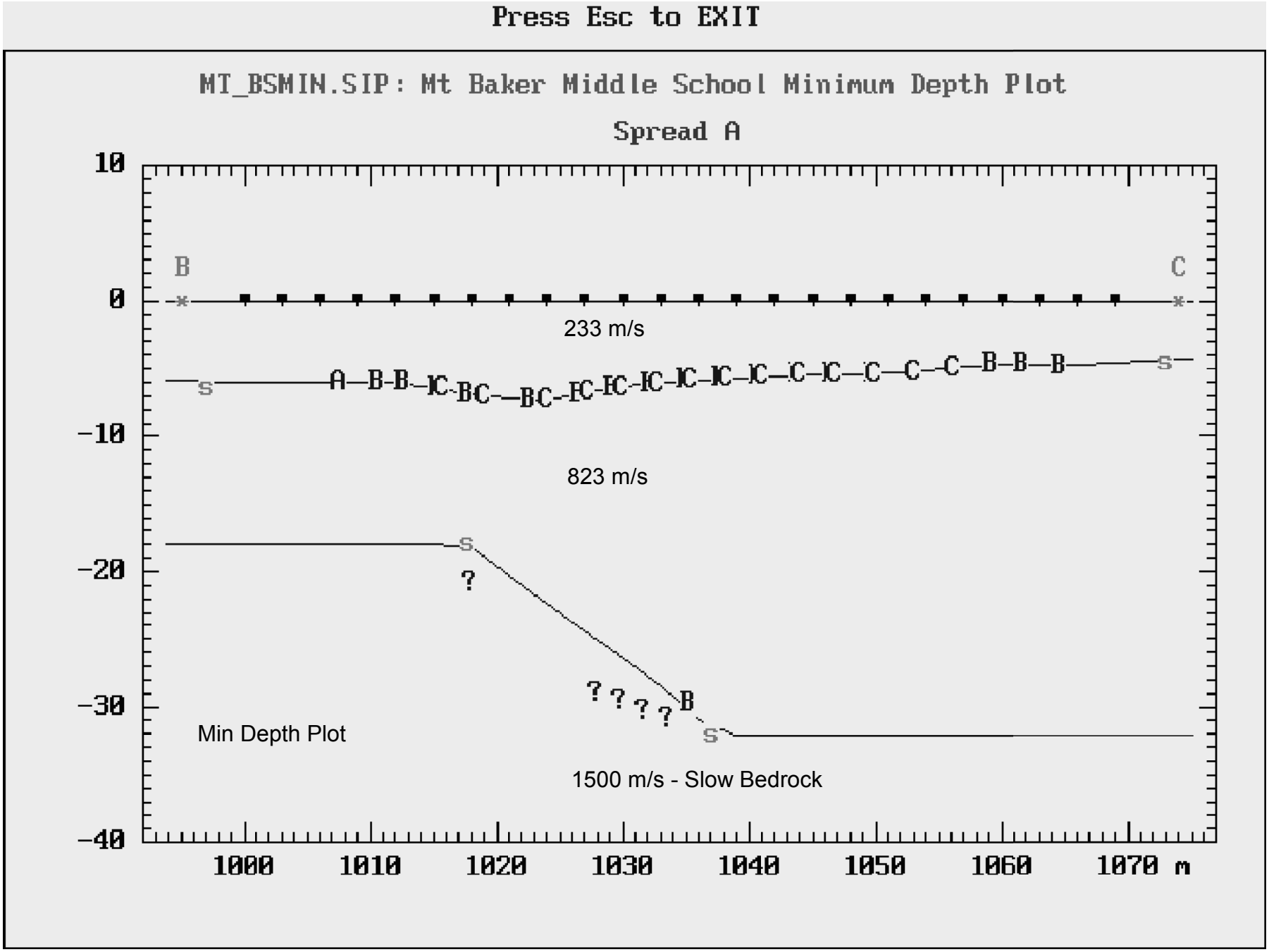
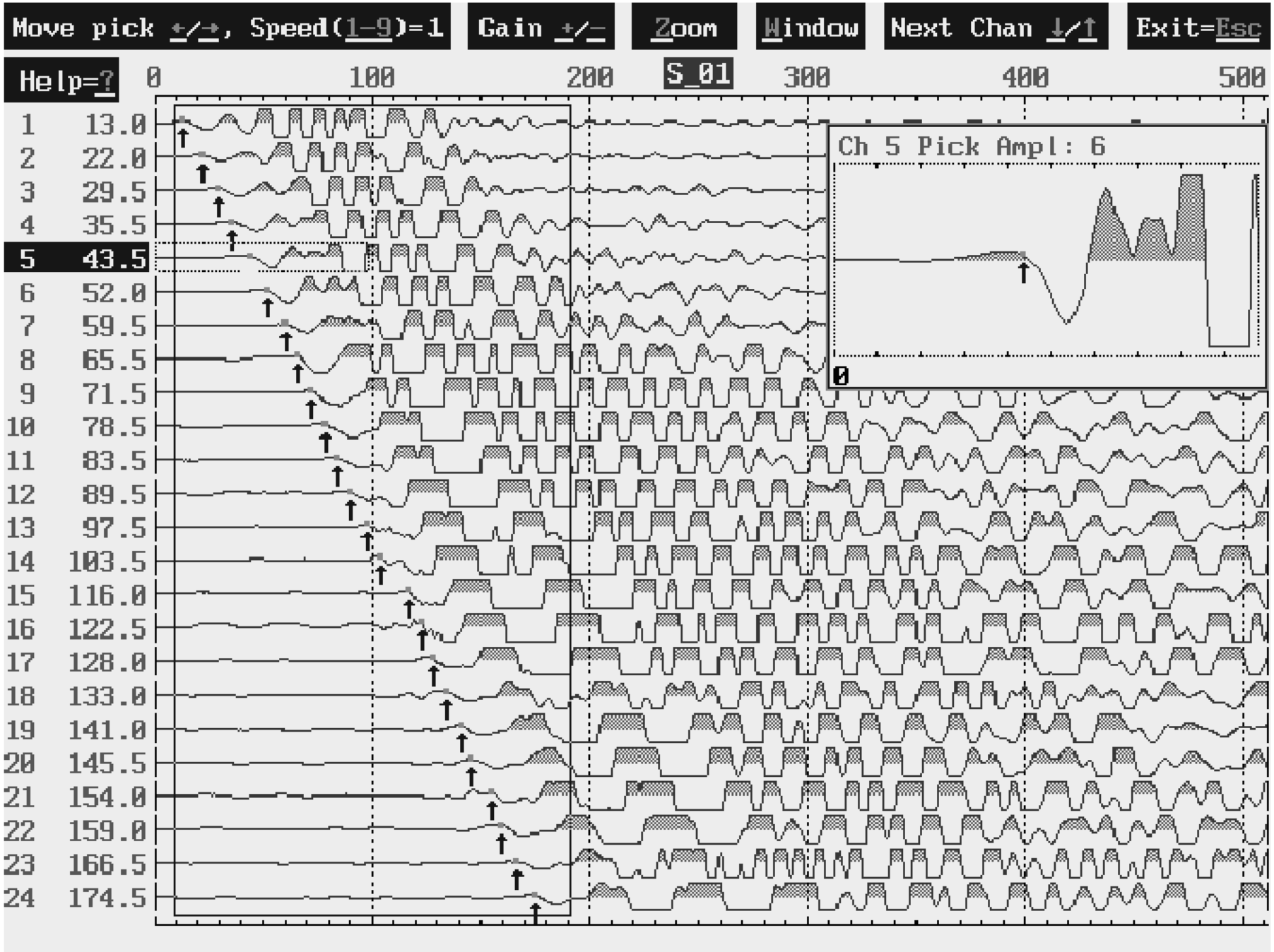
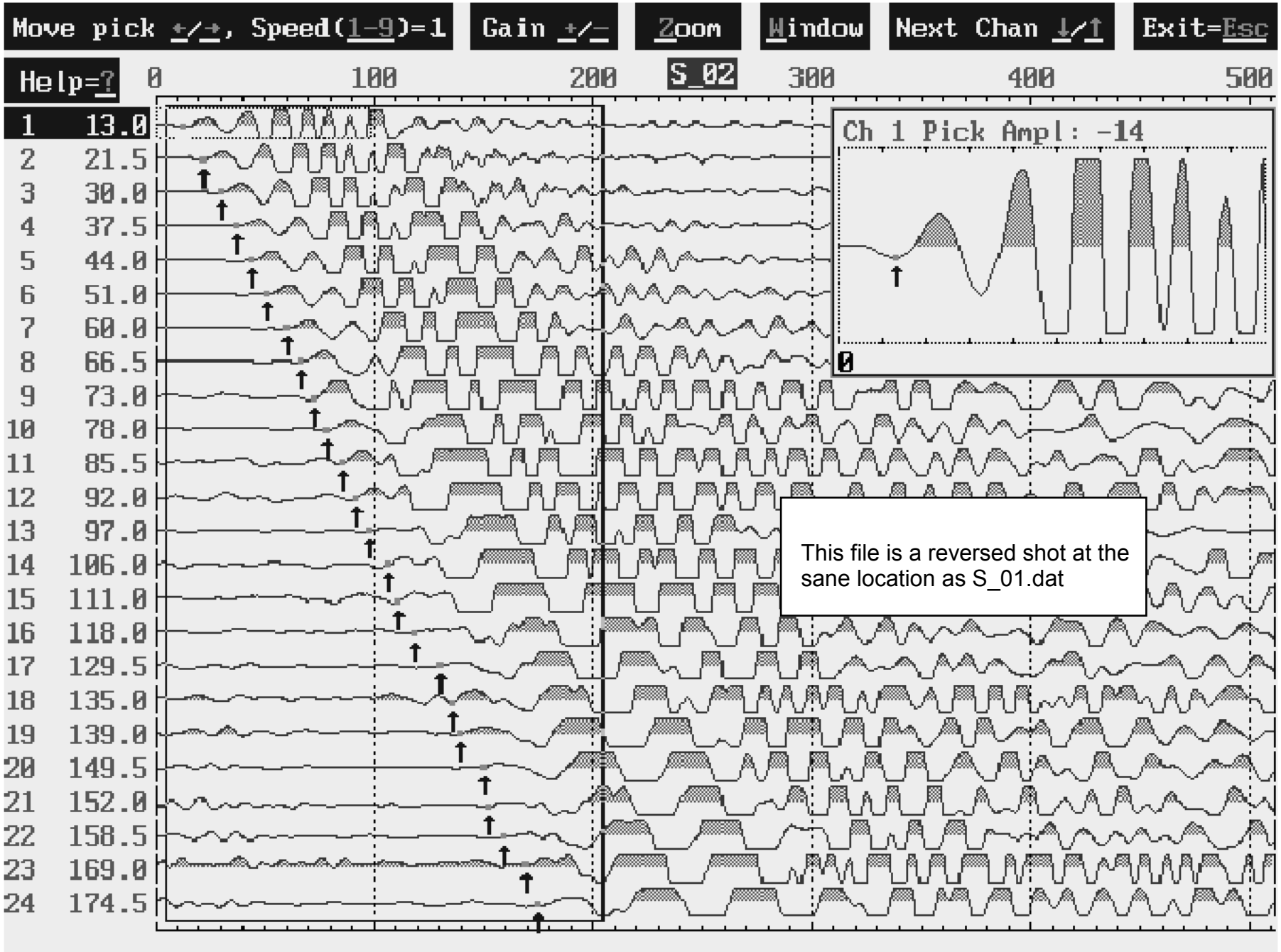


Old Woodway Elementary School S-wave



Old Woodway Elementary School S-wave



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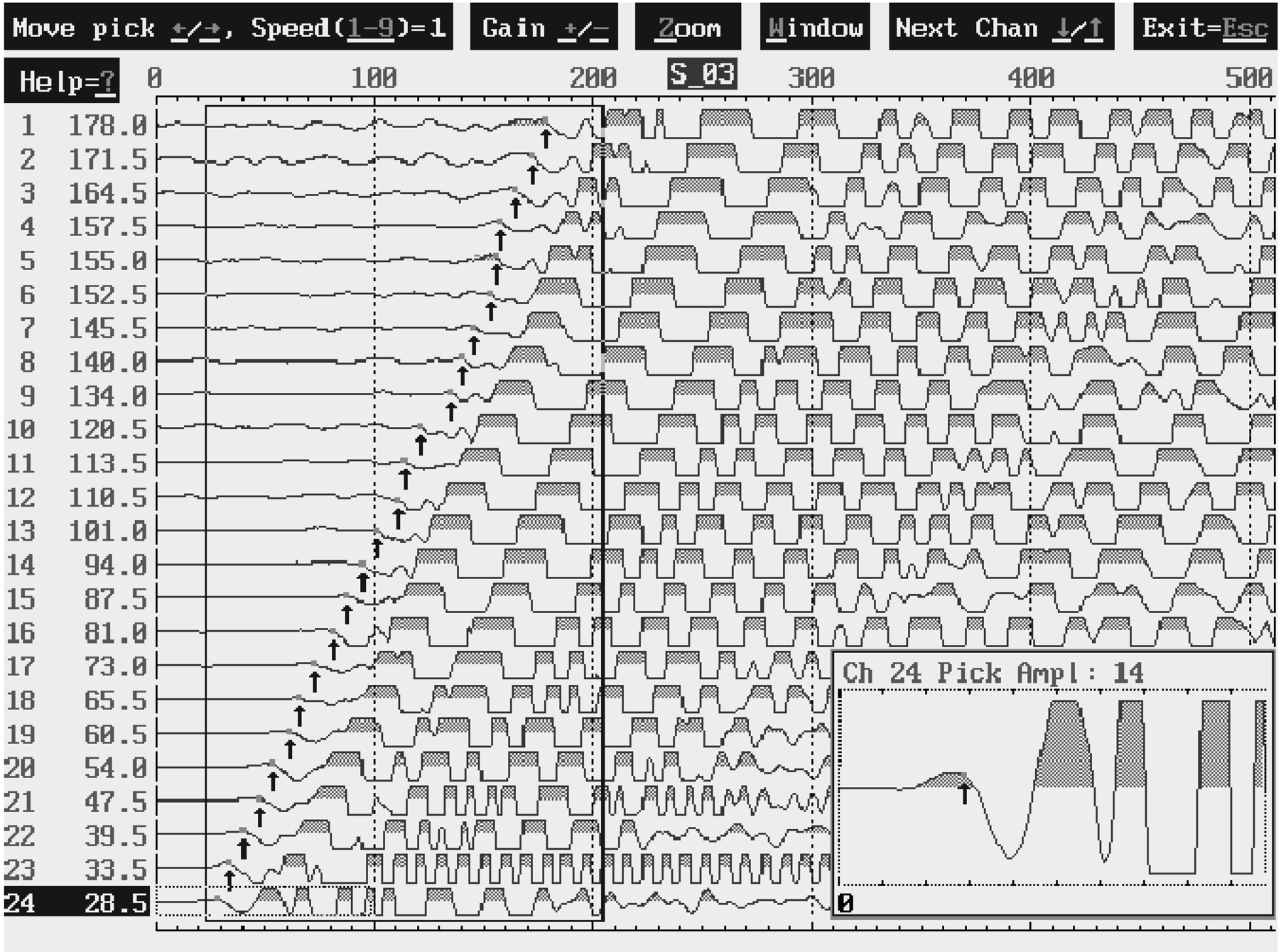

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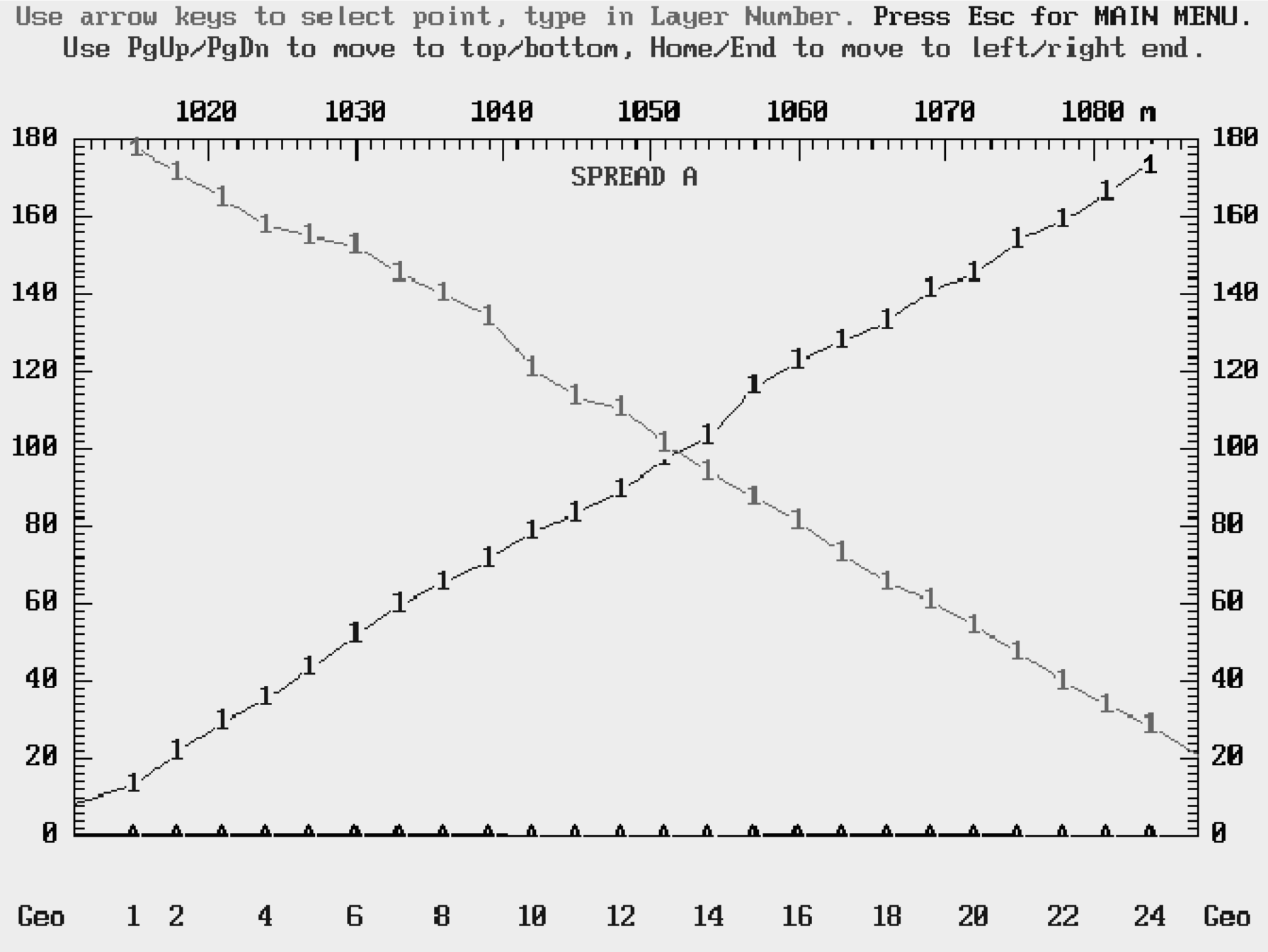

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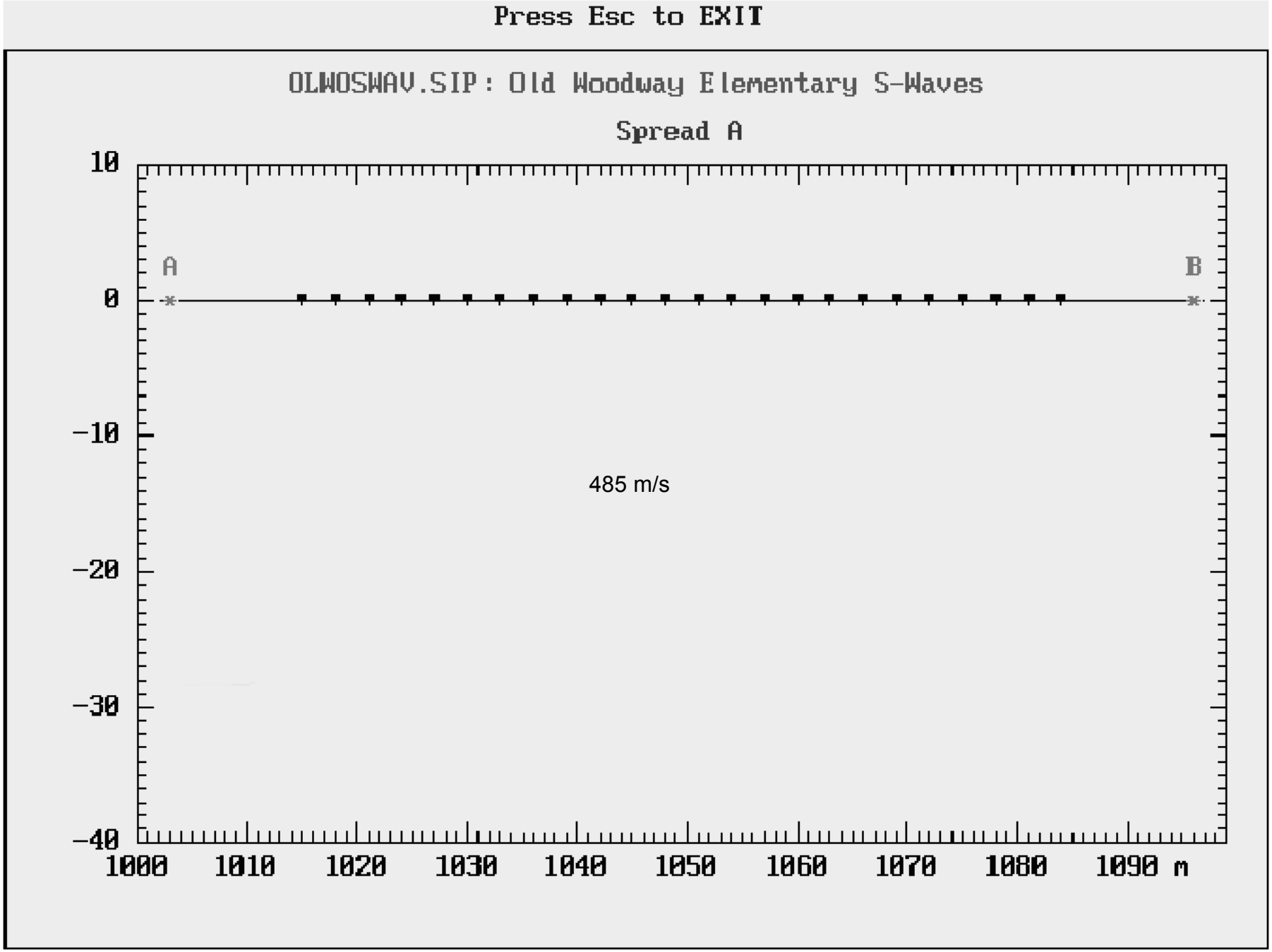

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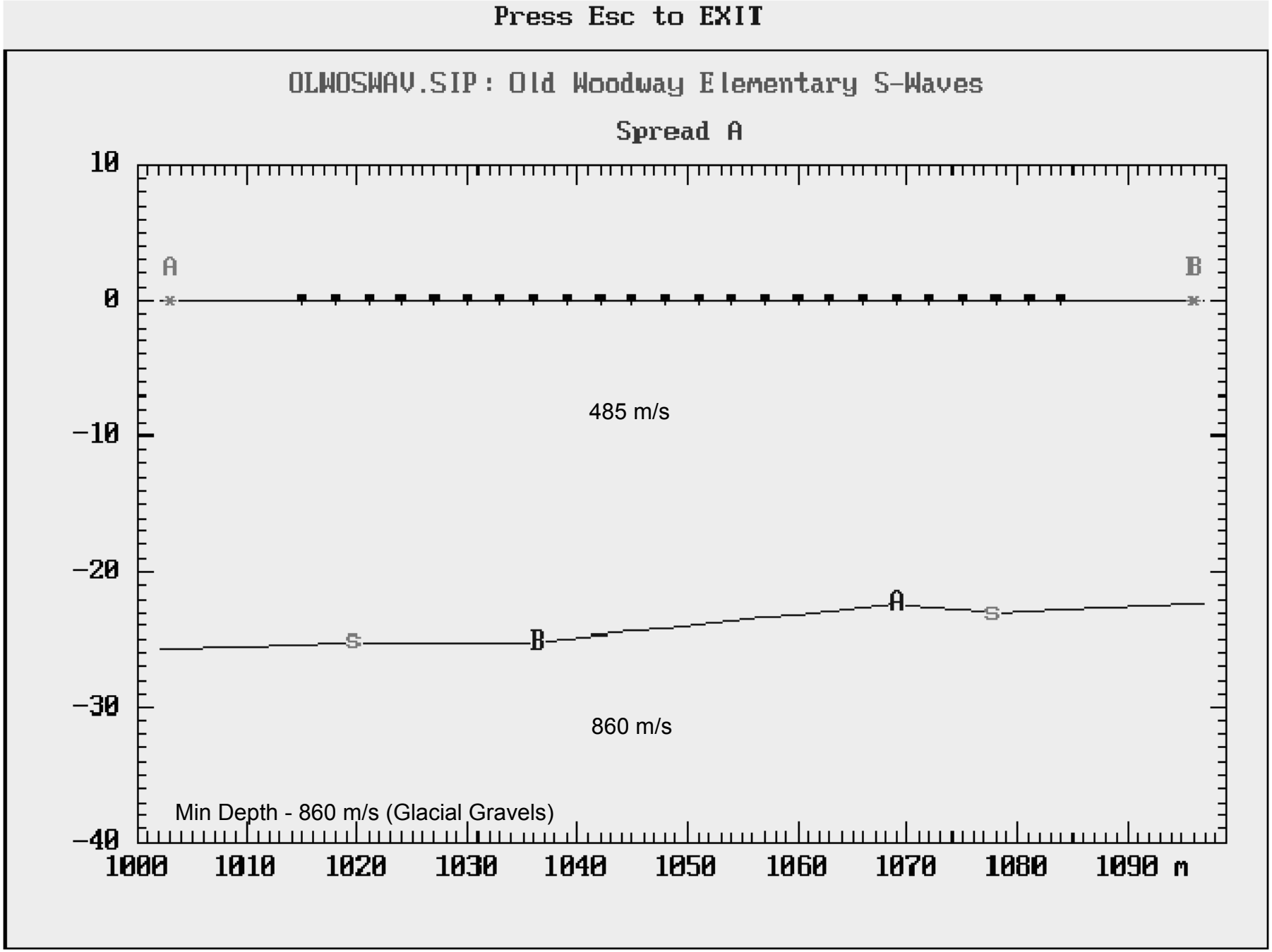
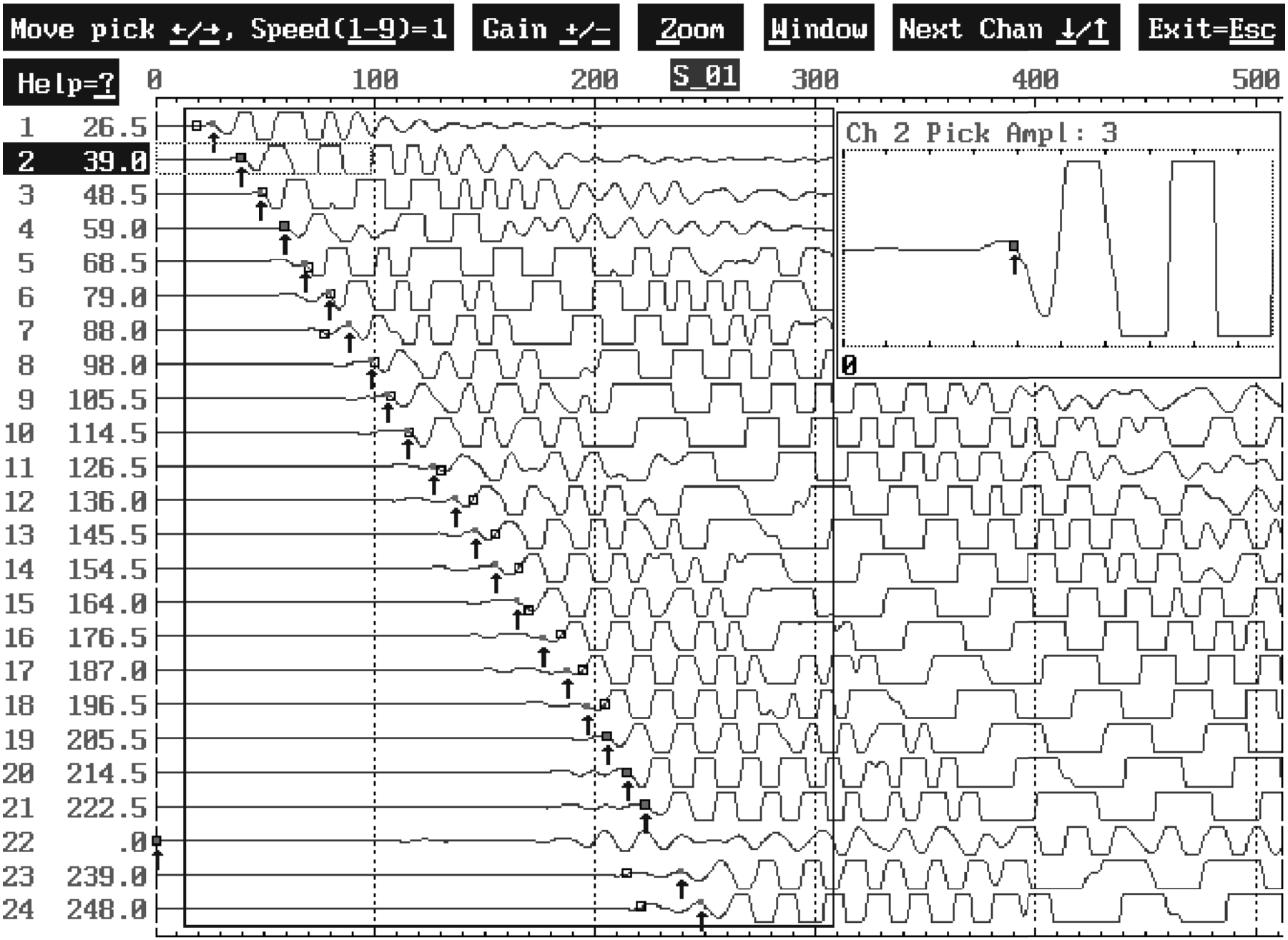


Peone Prairie S-wave



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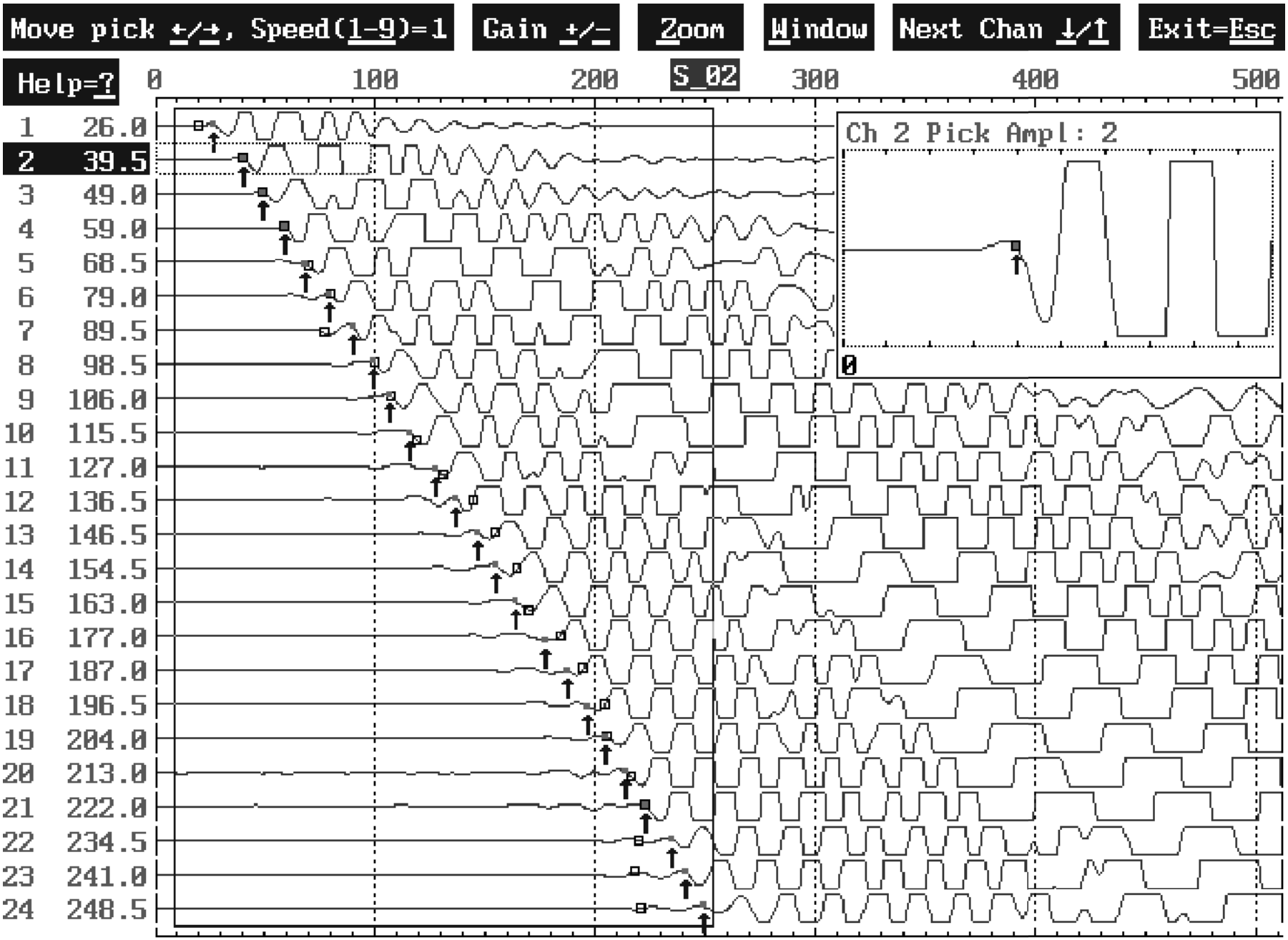

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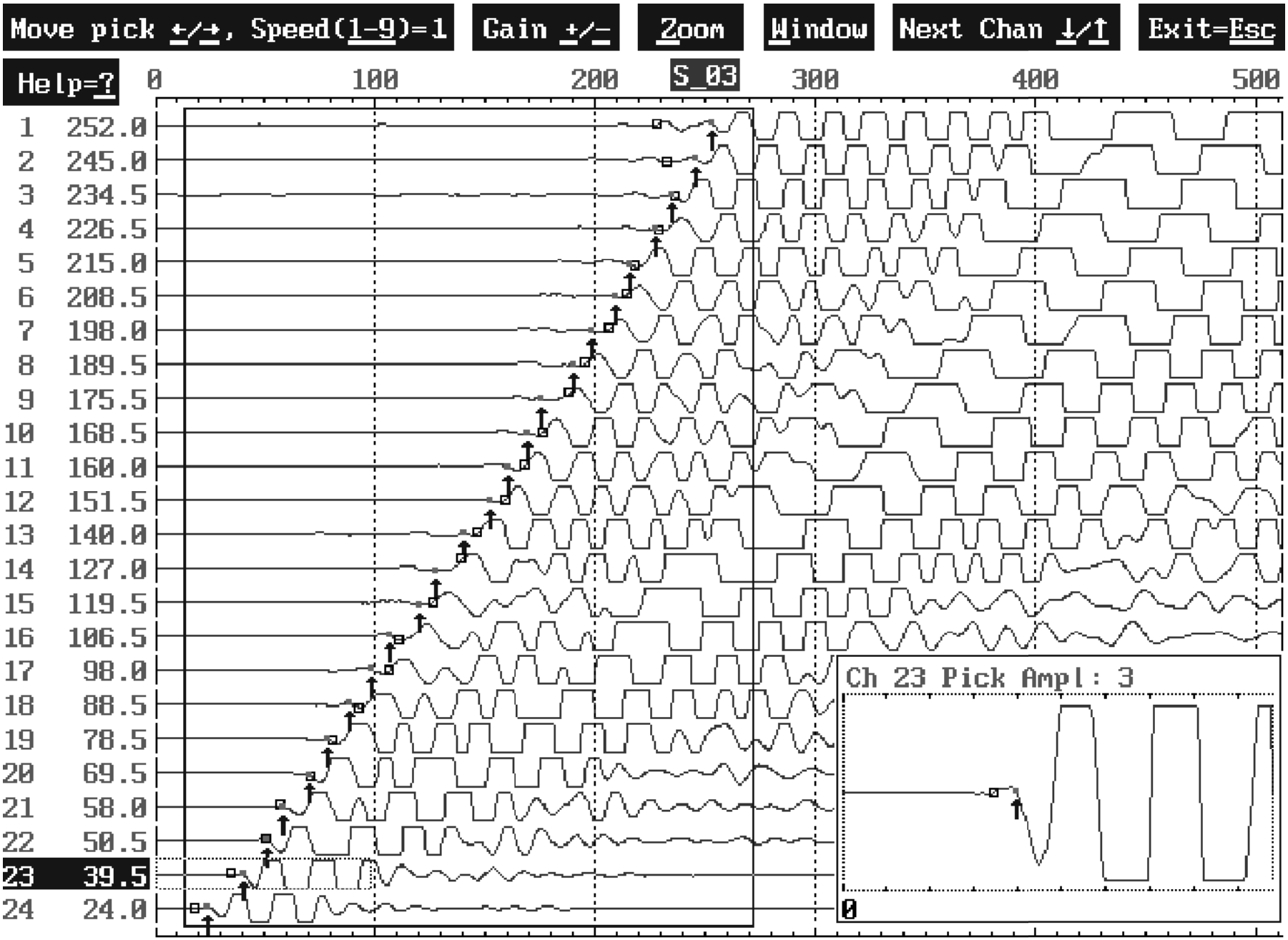

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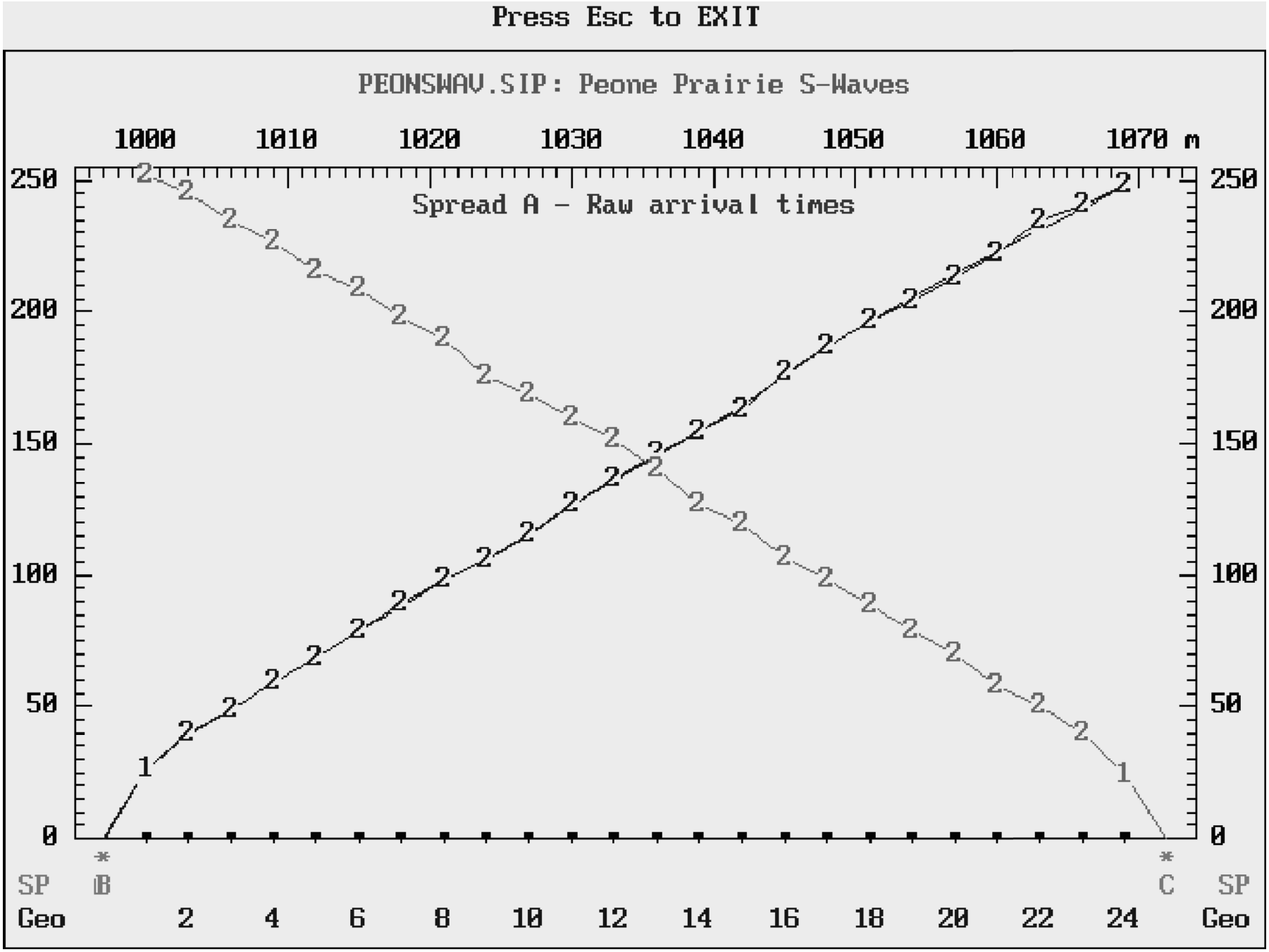

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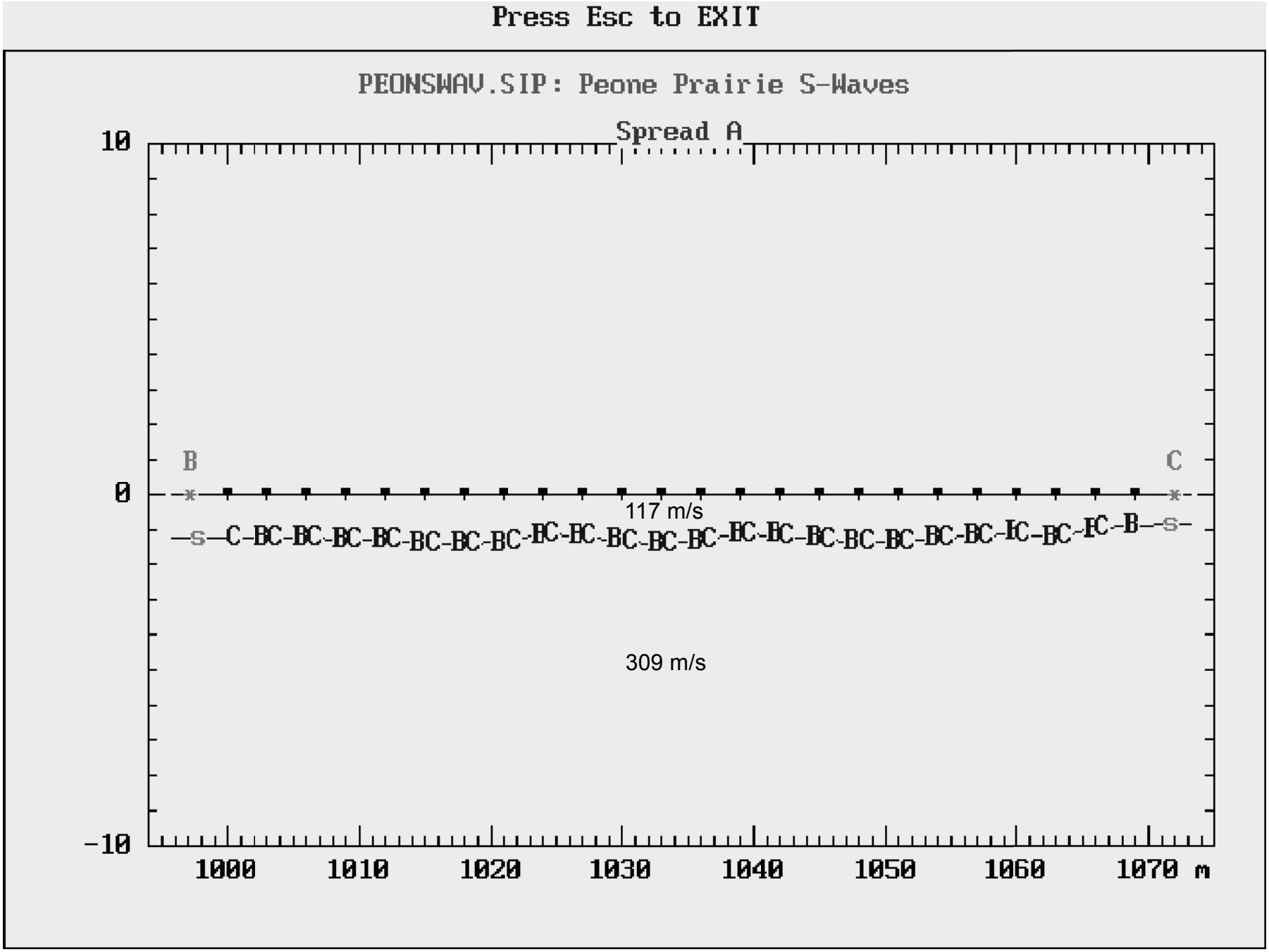

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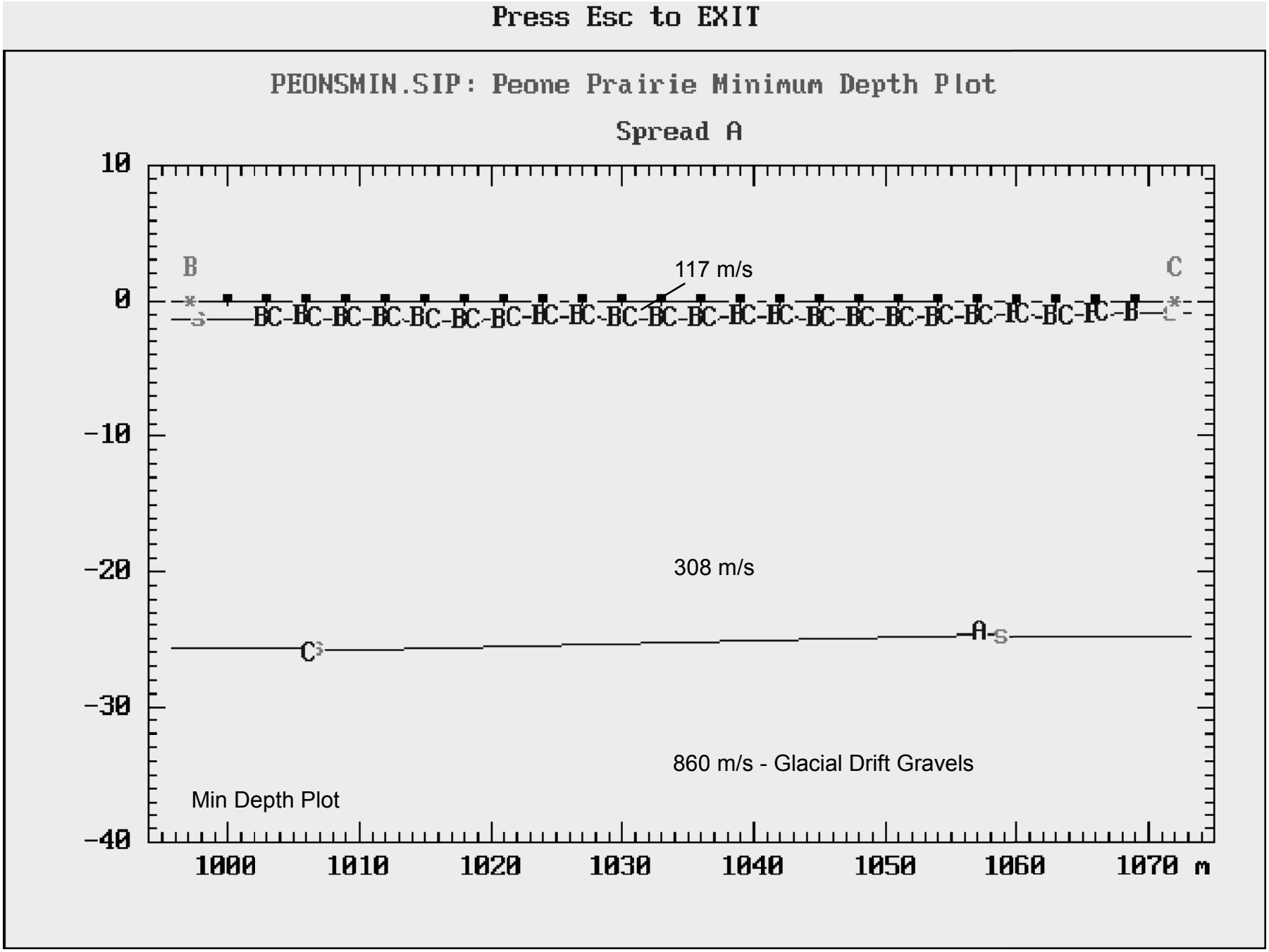
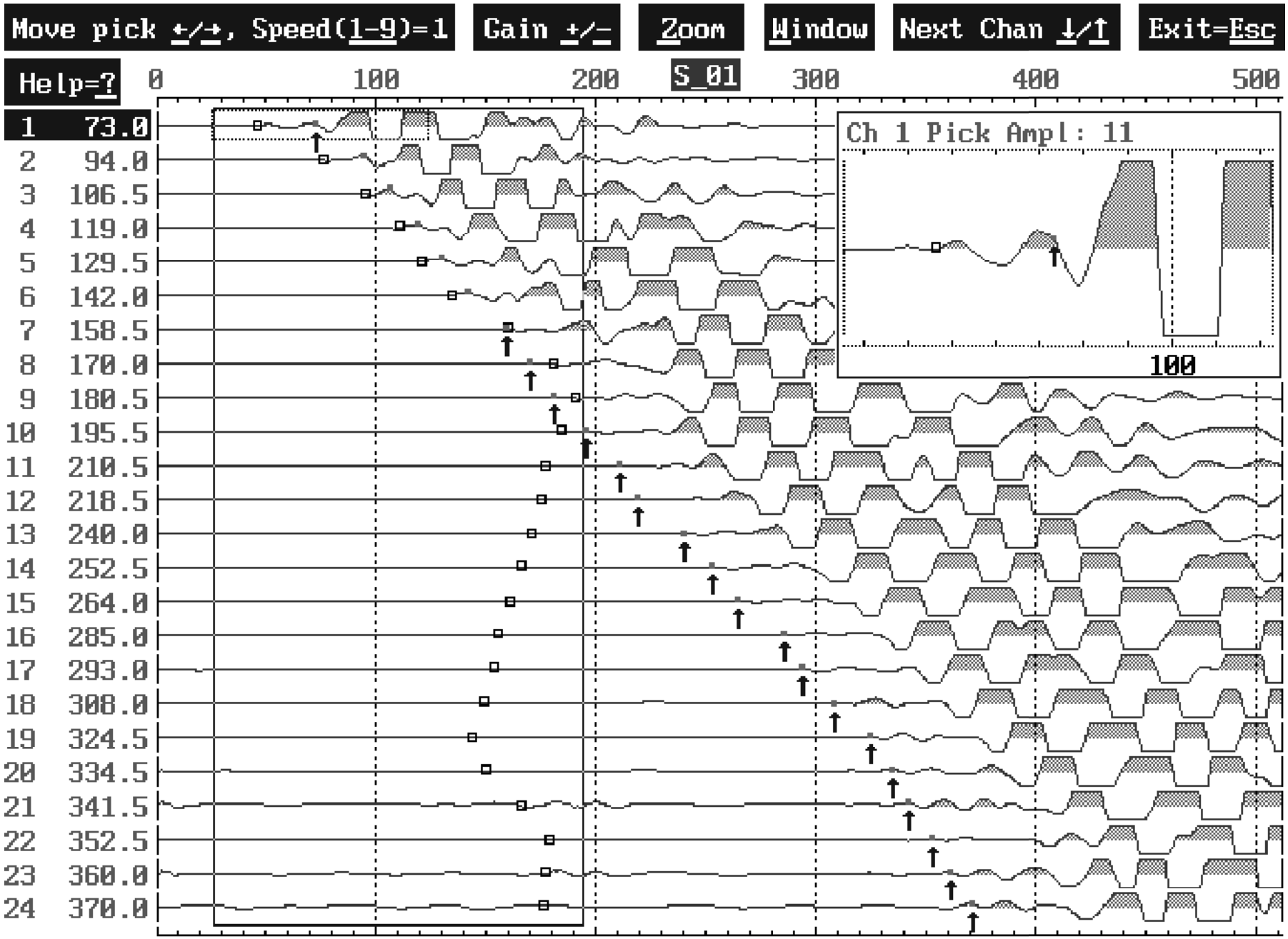


Pigman Farm S-wave



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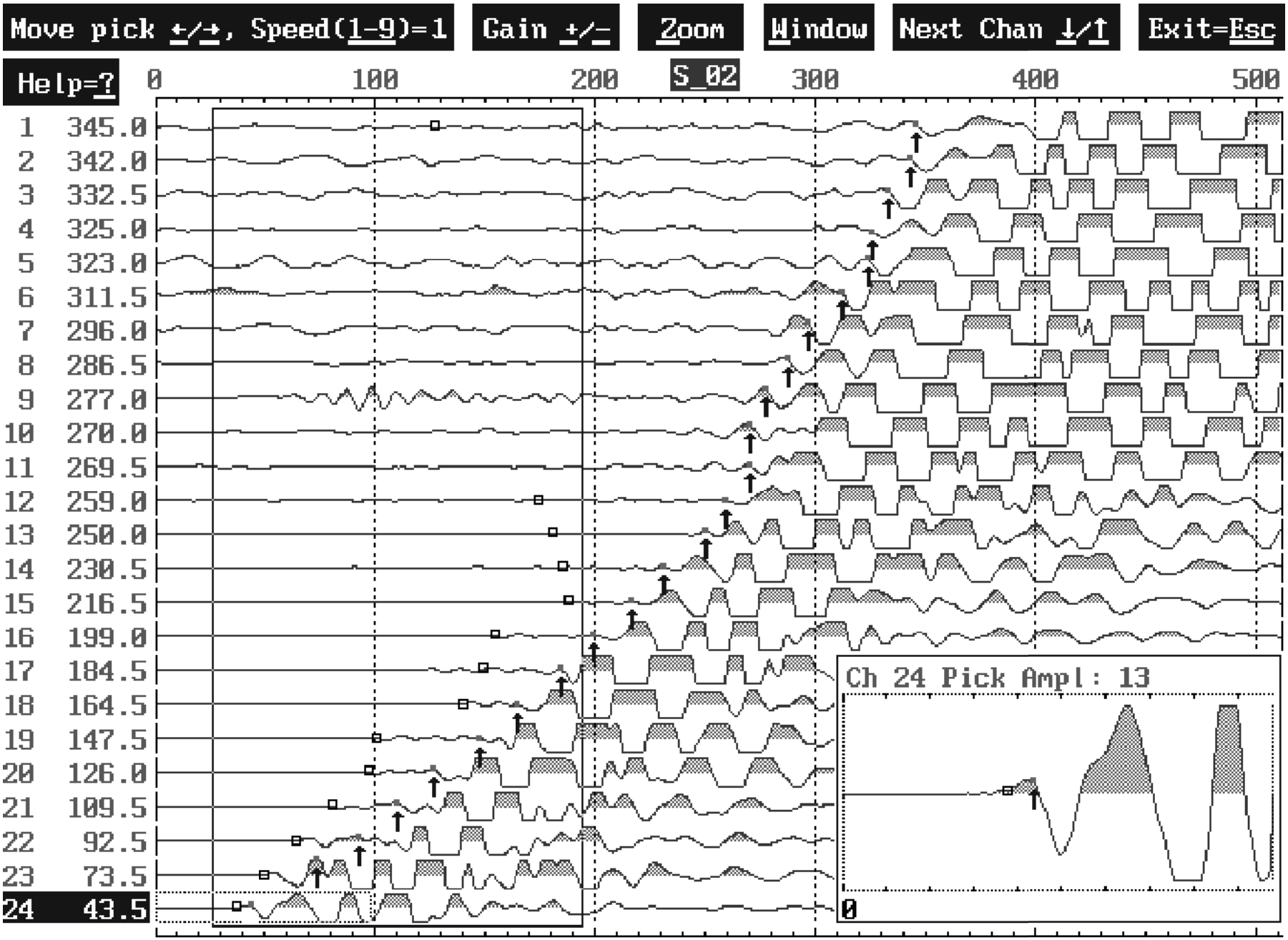

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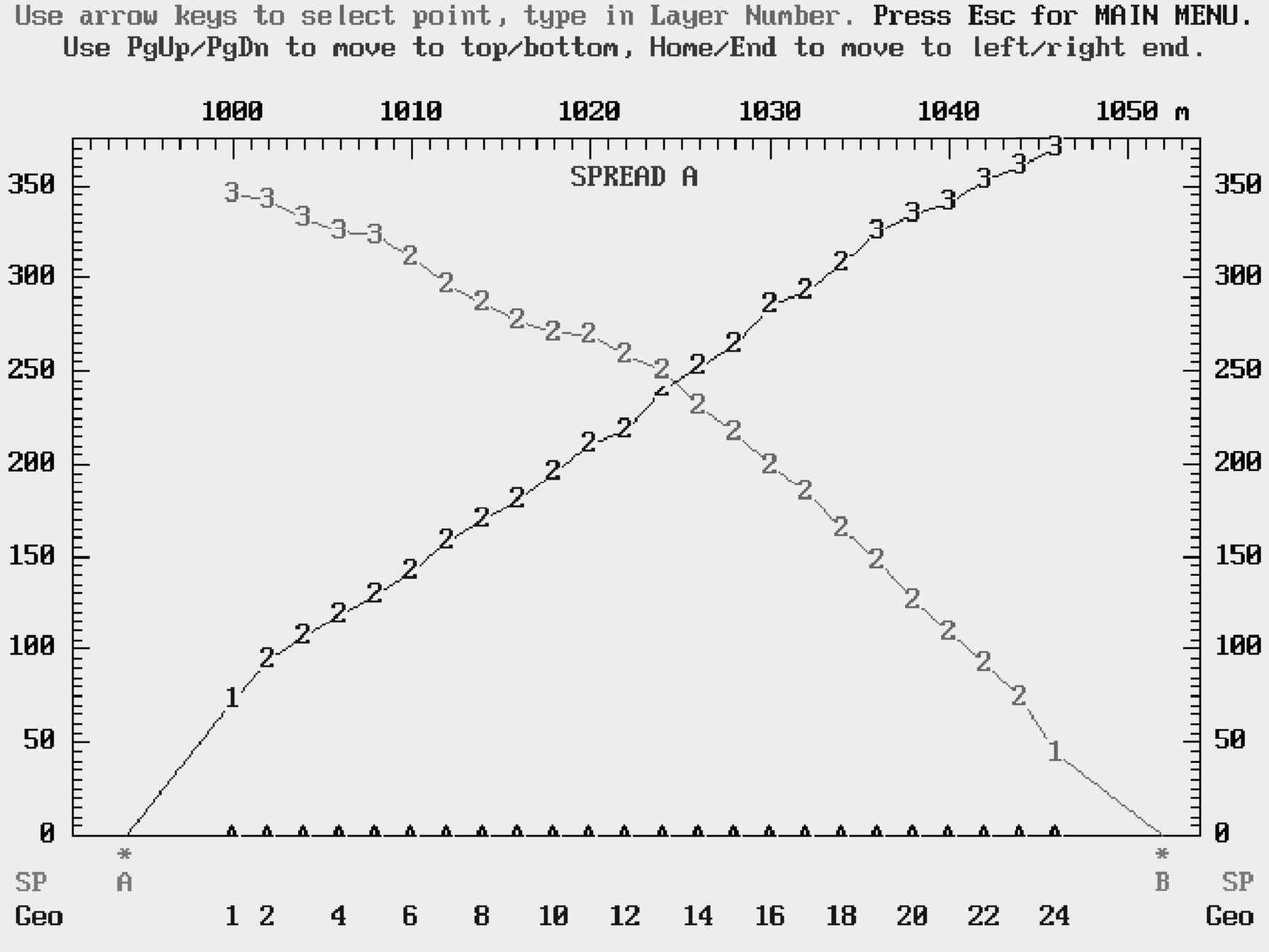

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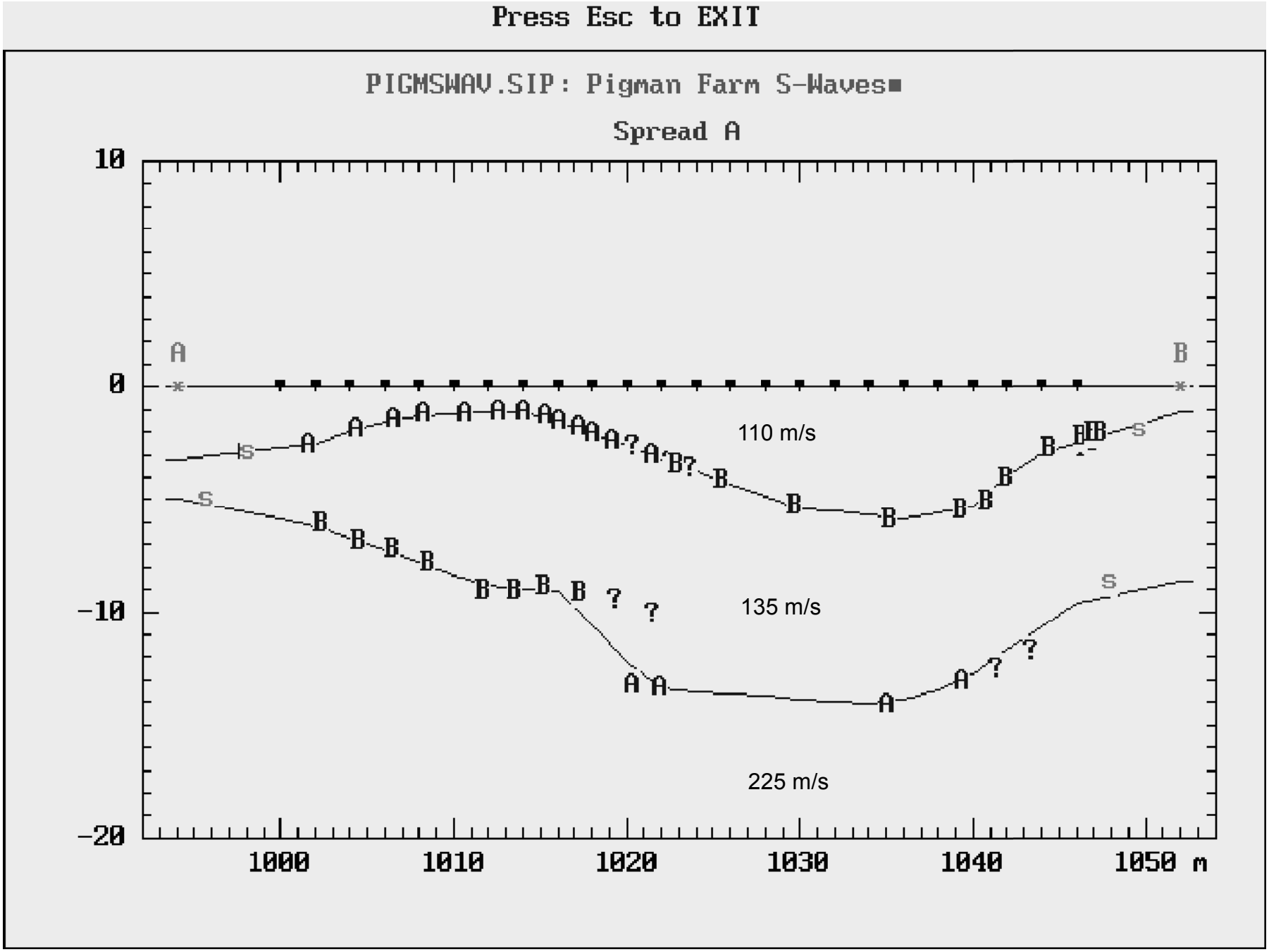

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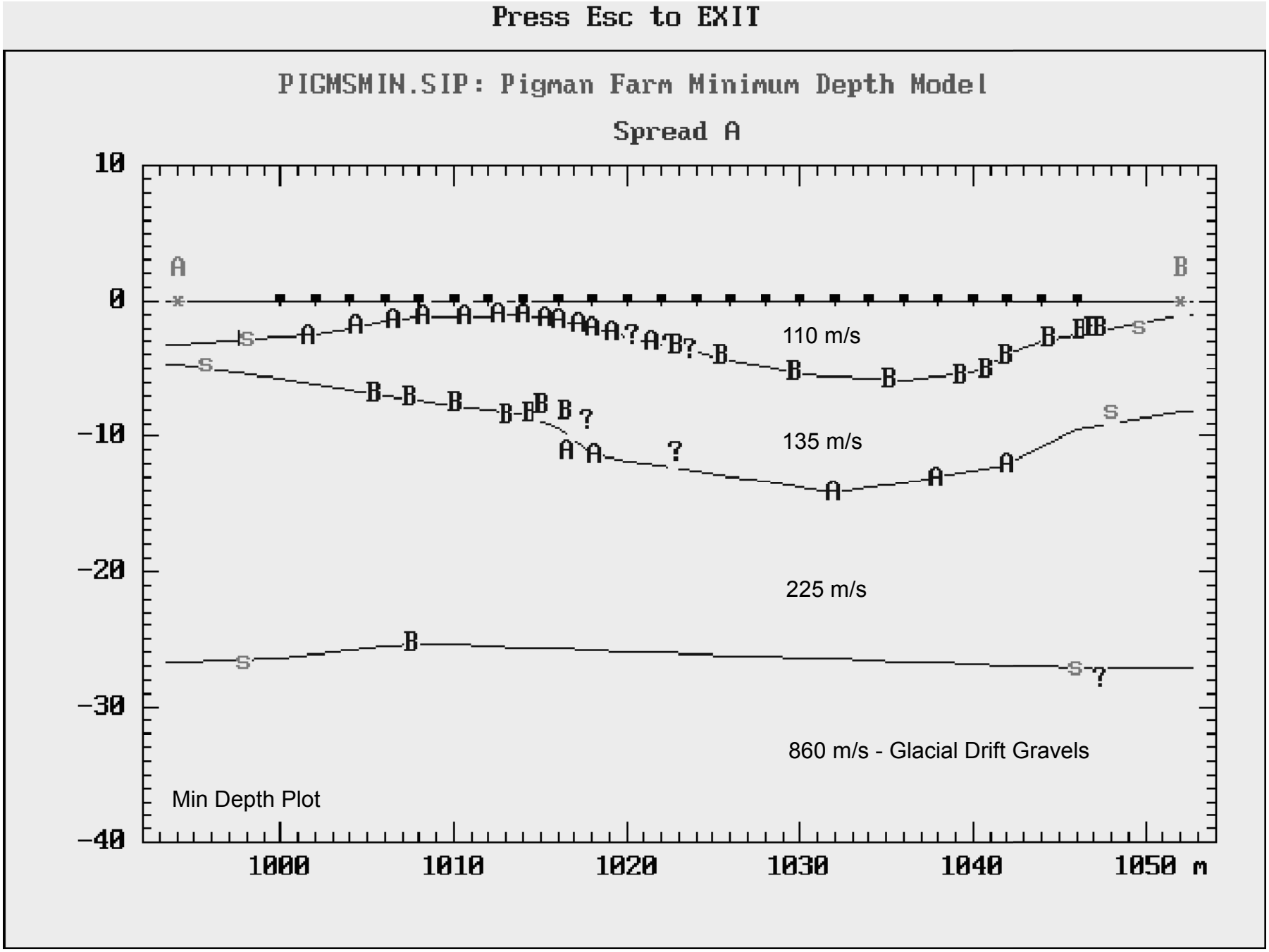
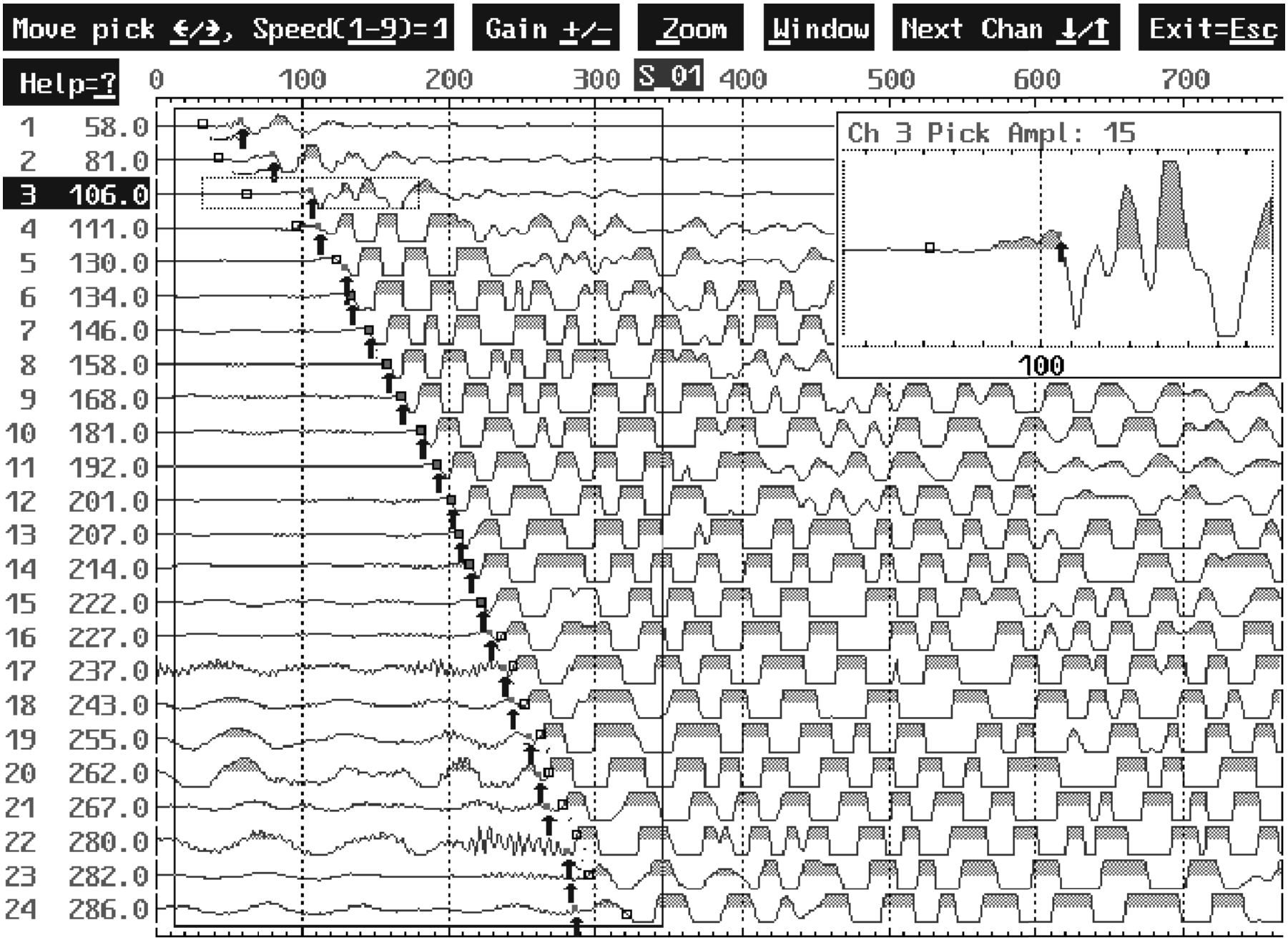
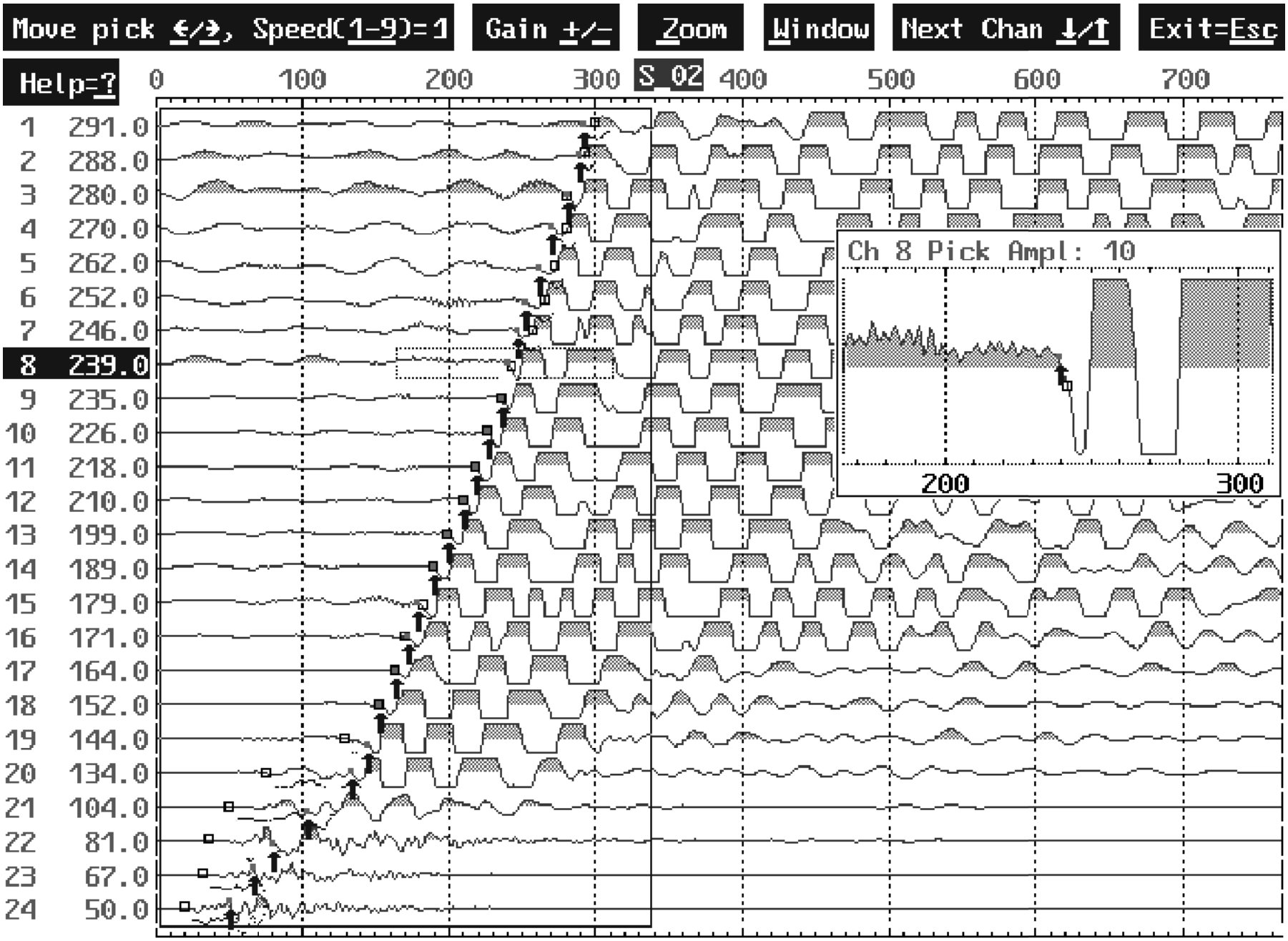


Pilchuck Park S-wave



Pilchuck Park S-wave



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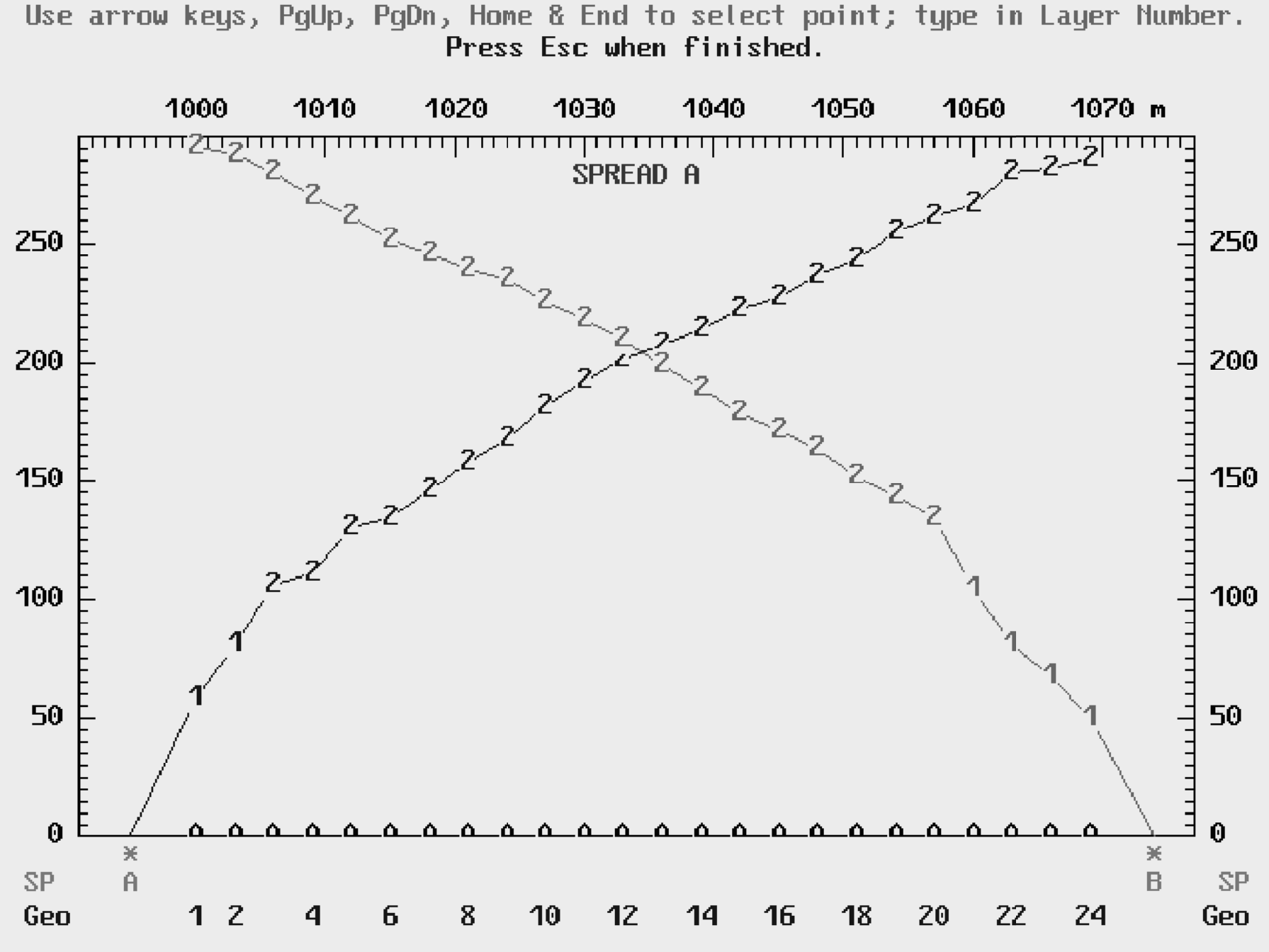

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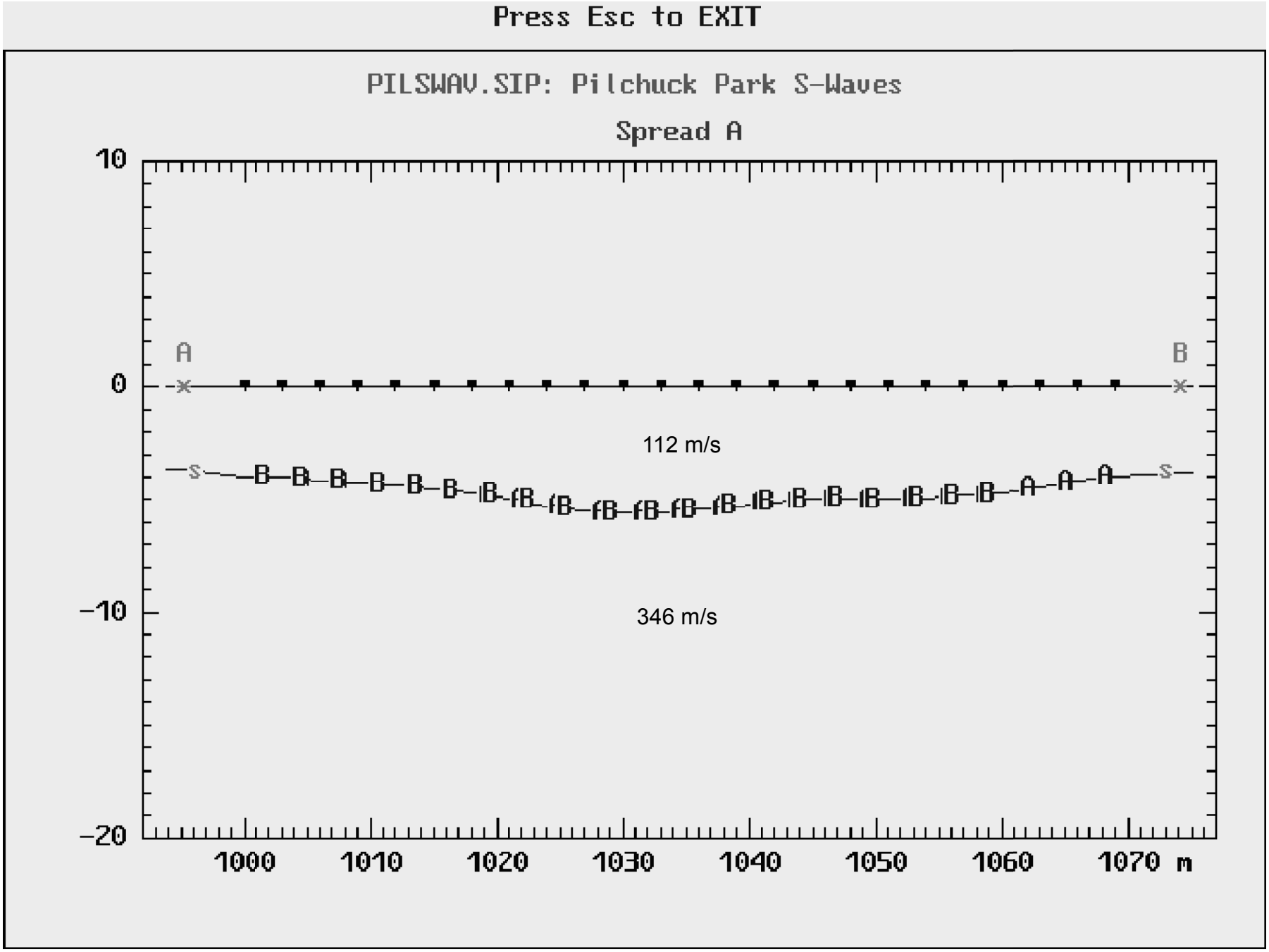

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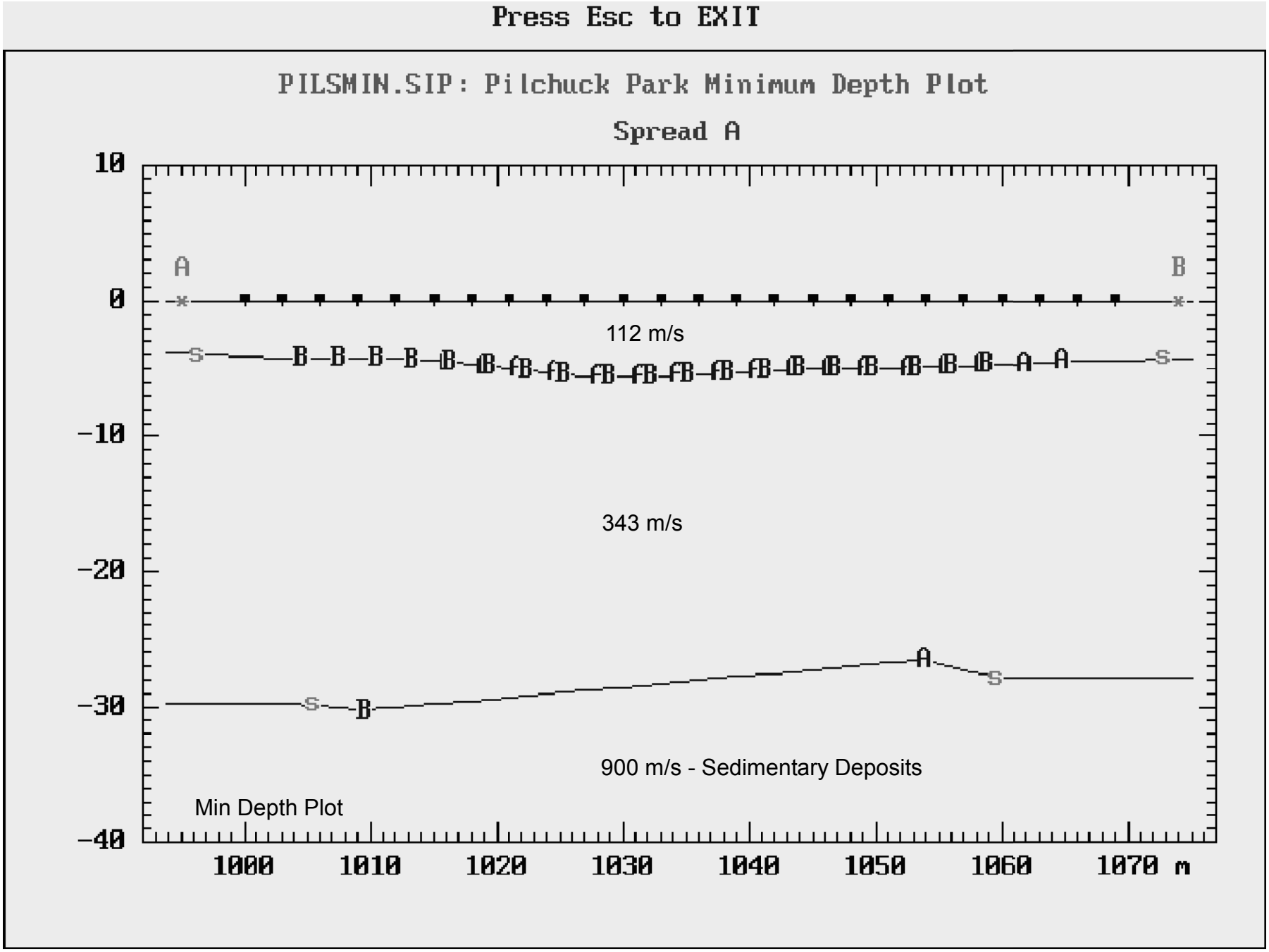
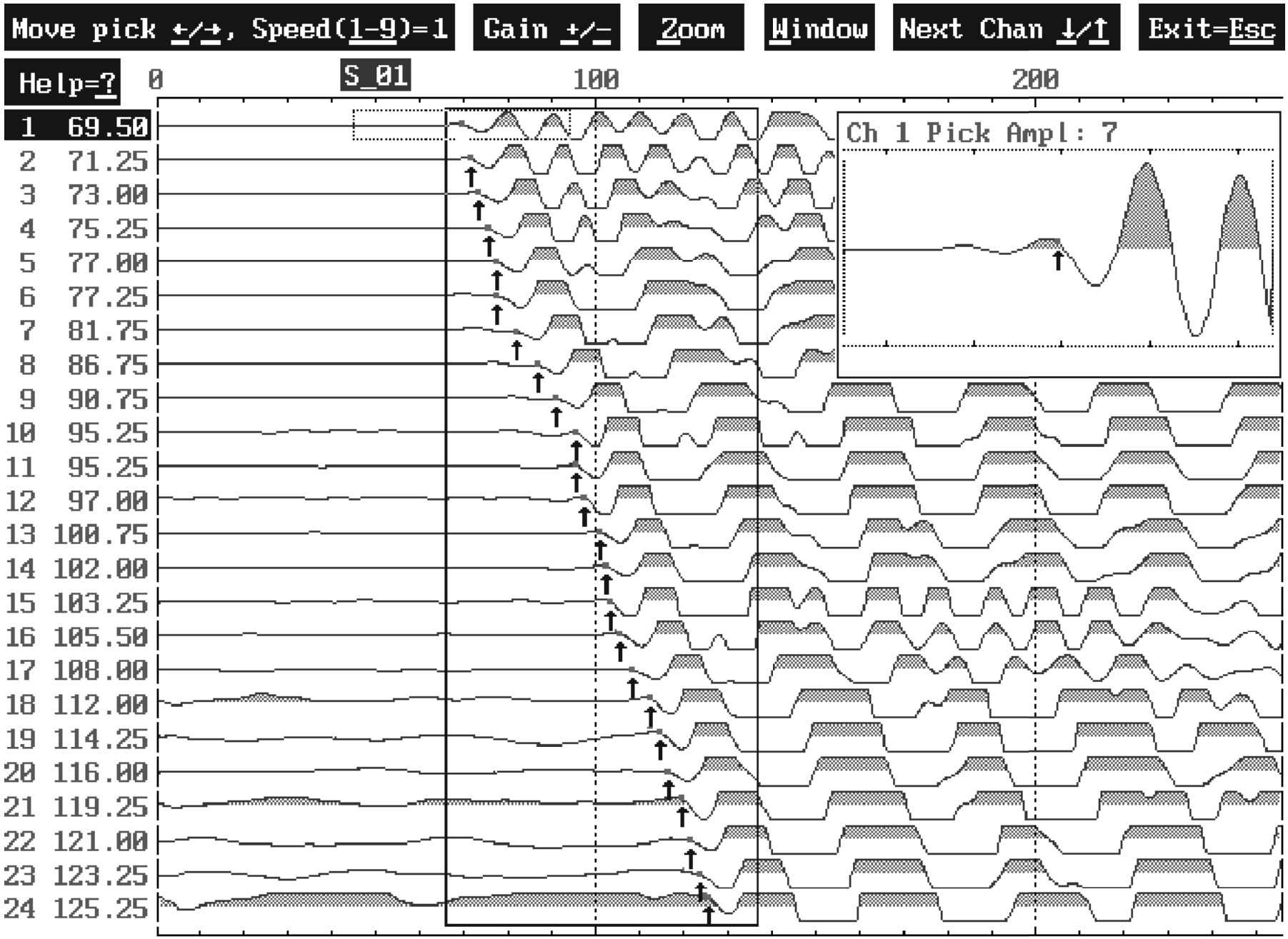
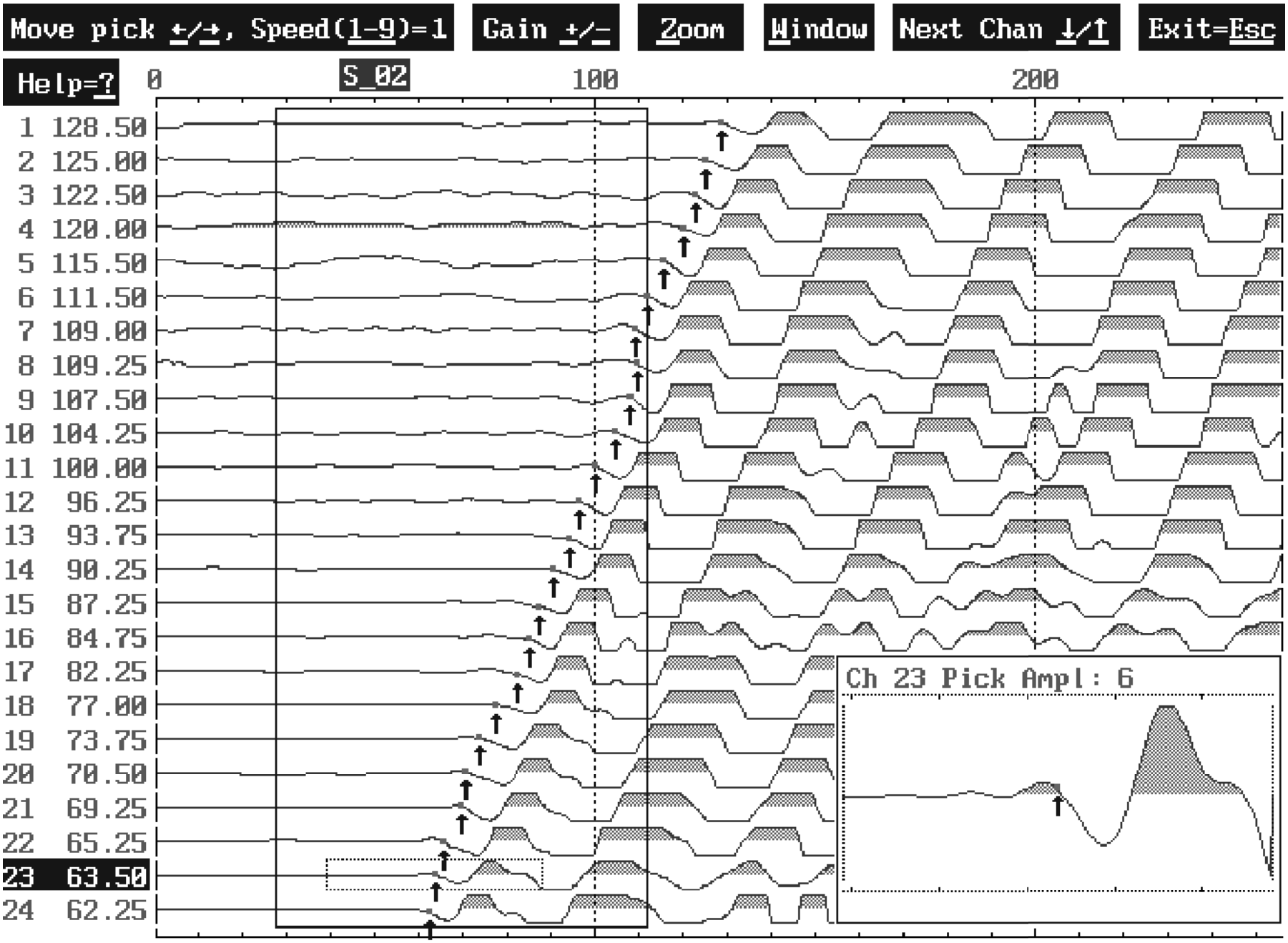


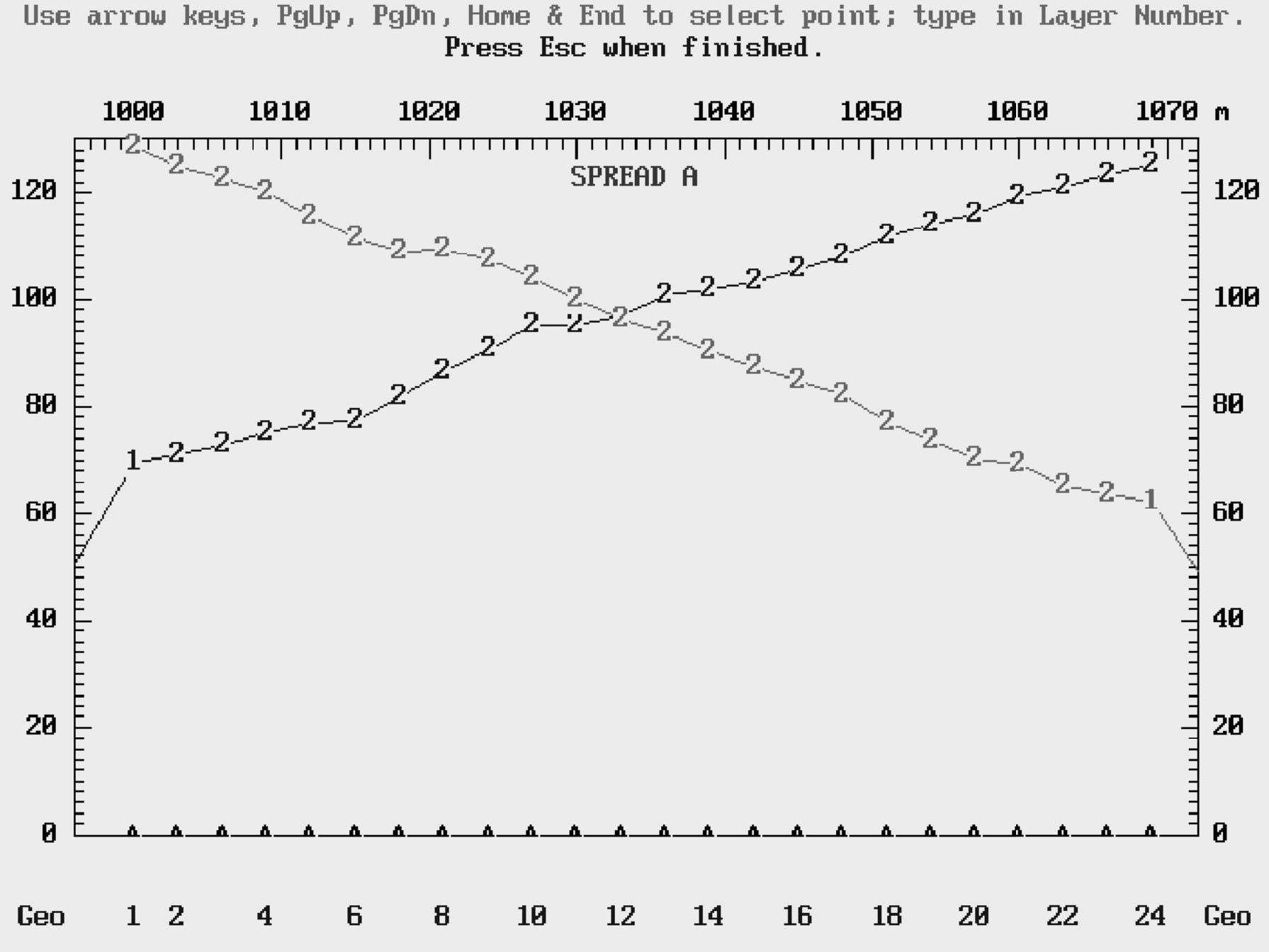
Pioneer Middle School S-wave



Pioneer Middle School S-wave



Pioneer Middle School S-wave



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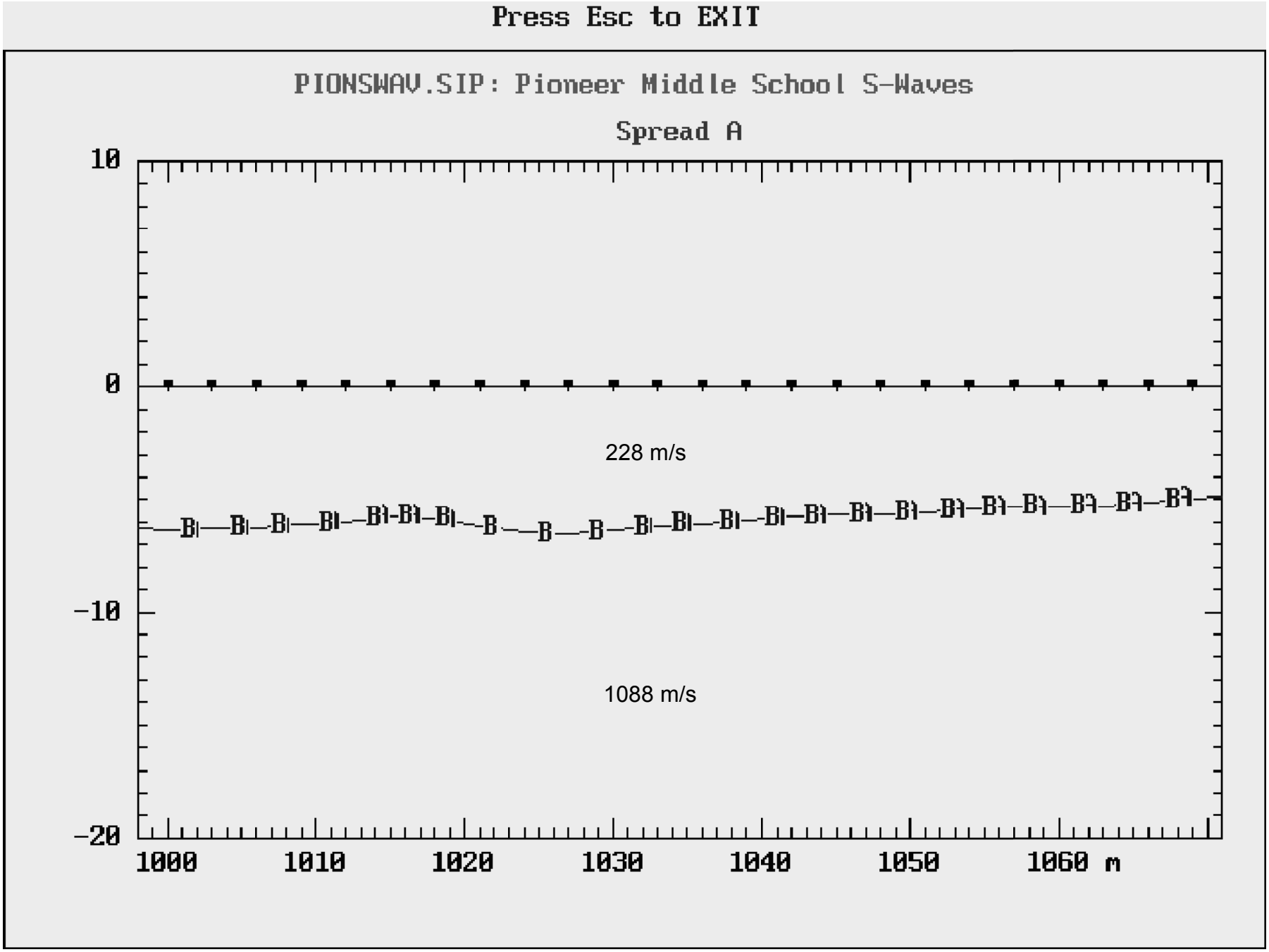

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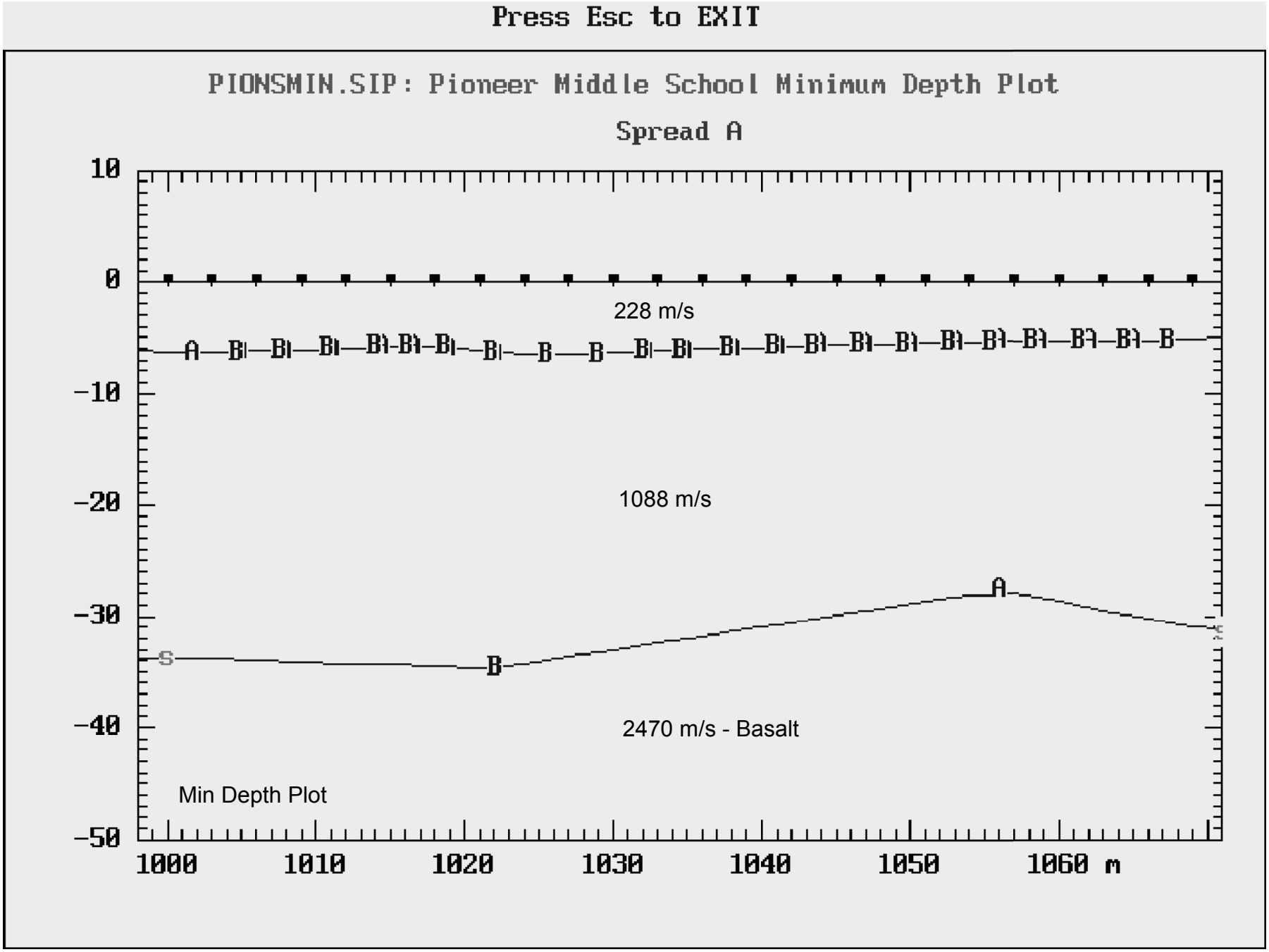

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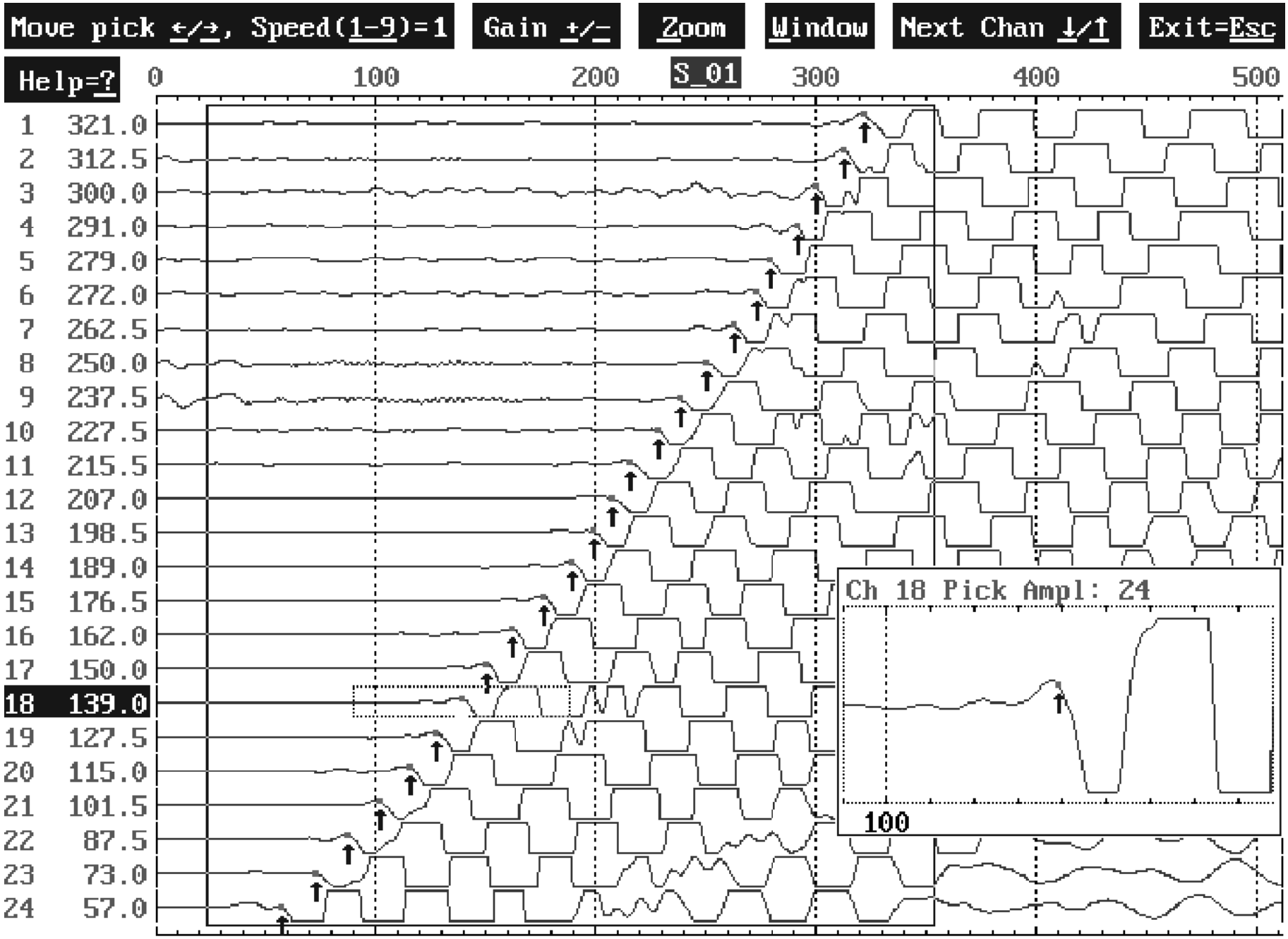

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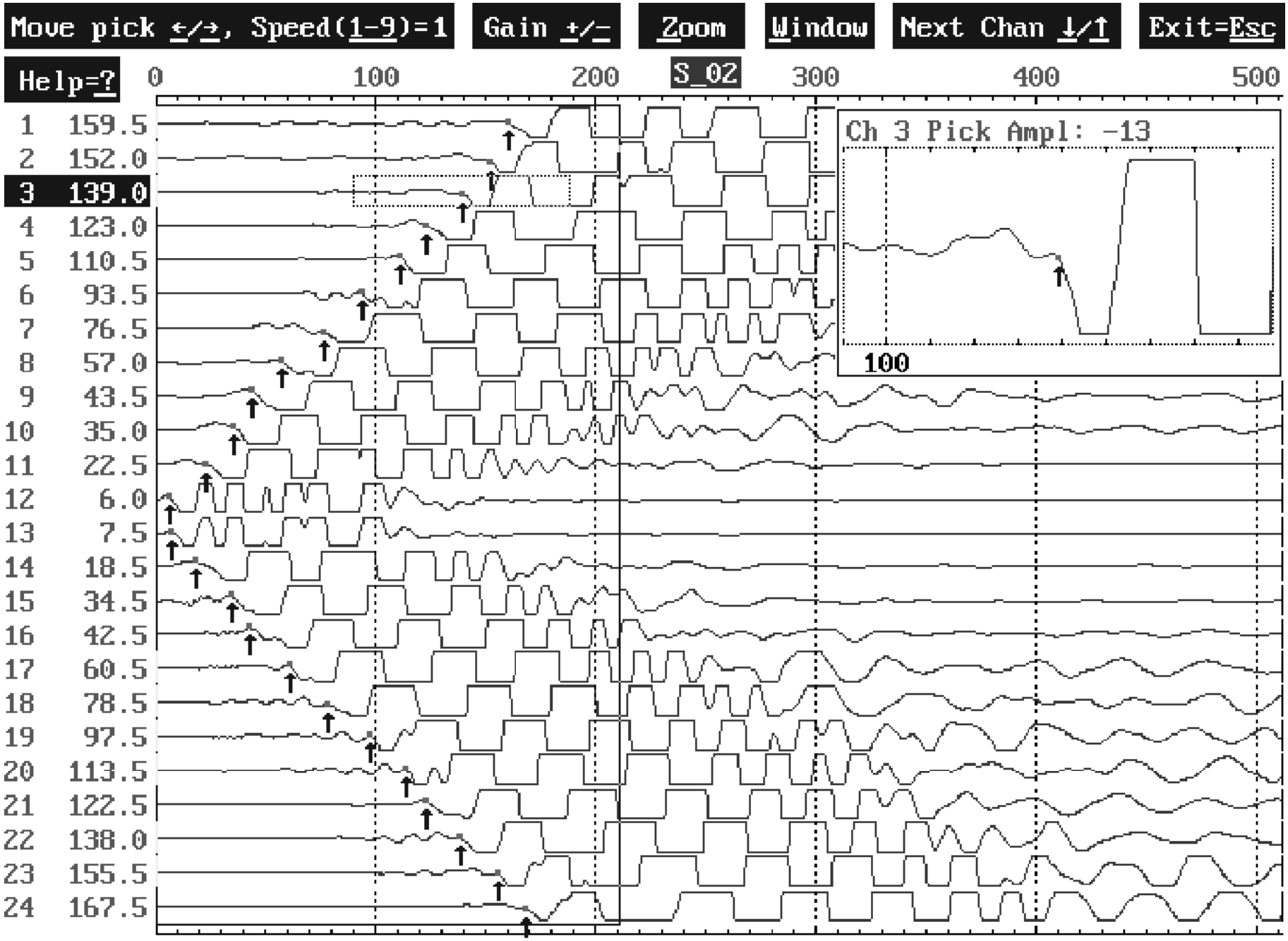

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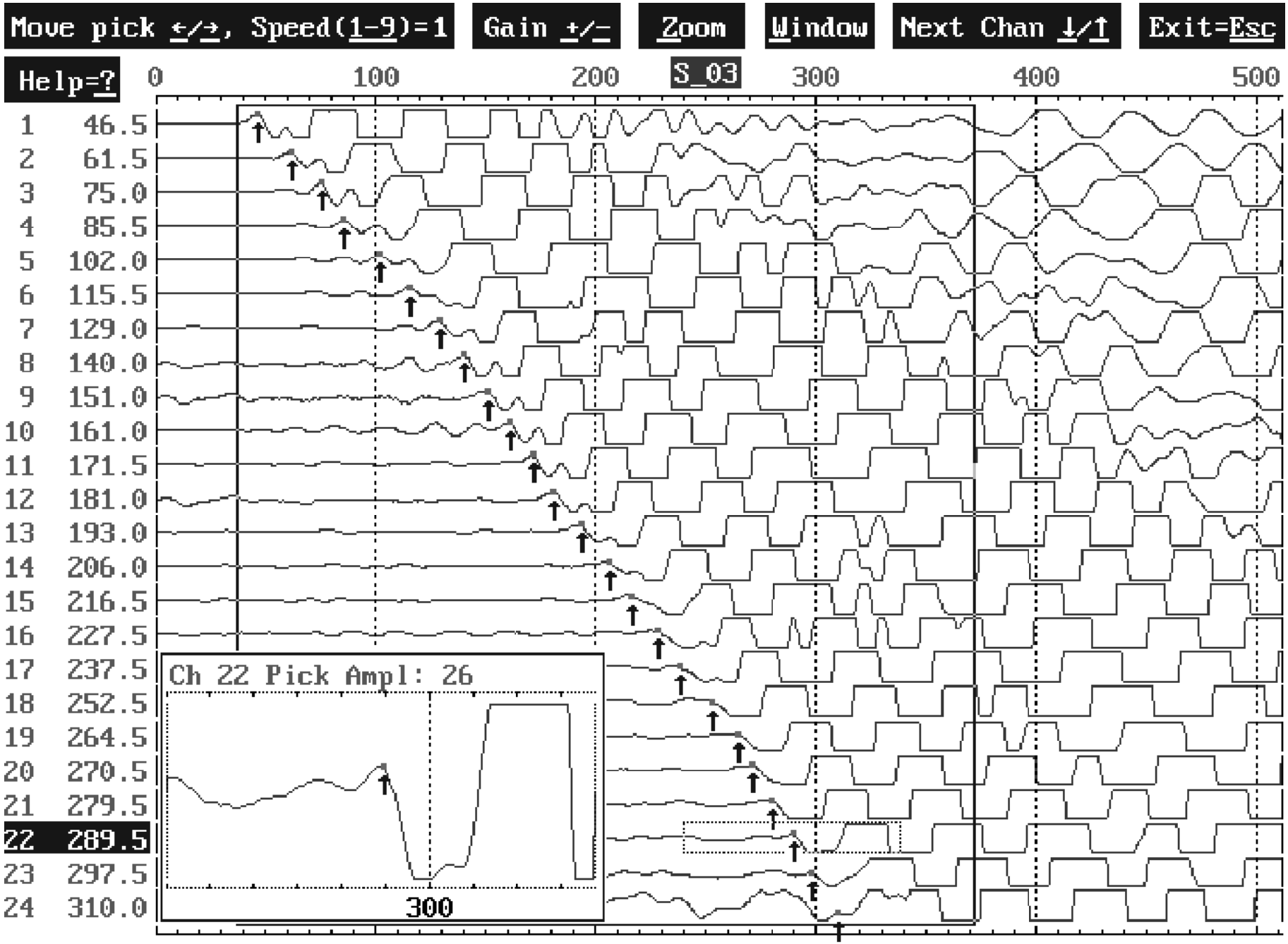

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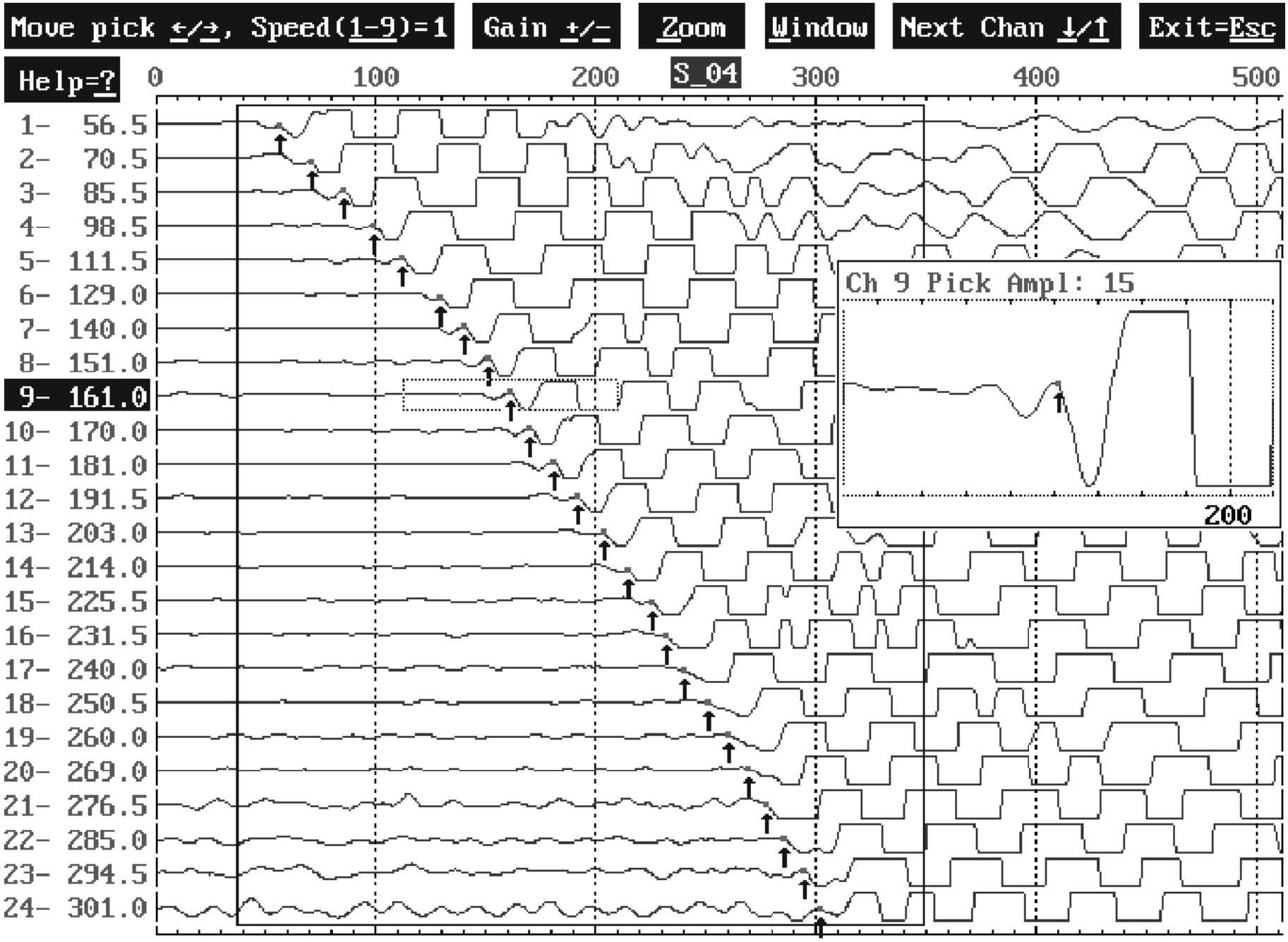

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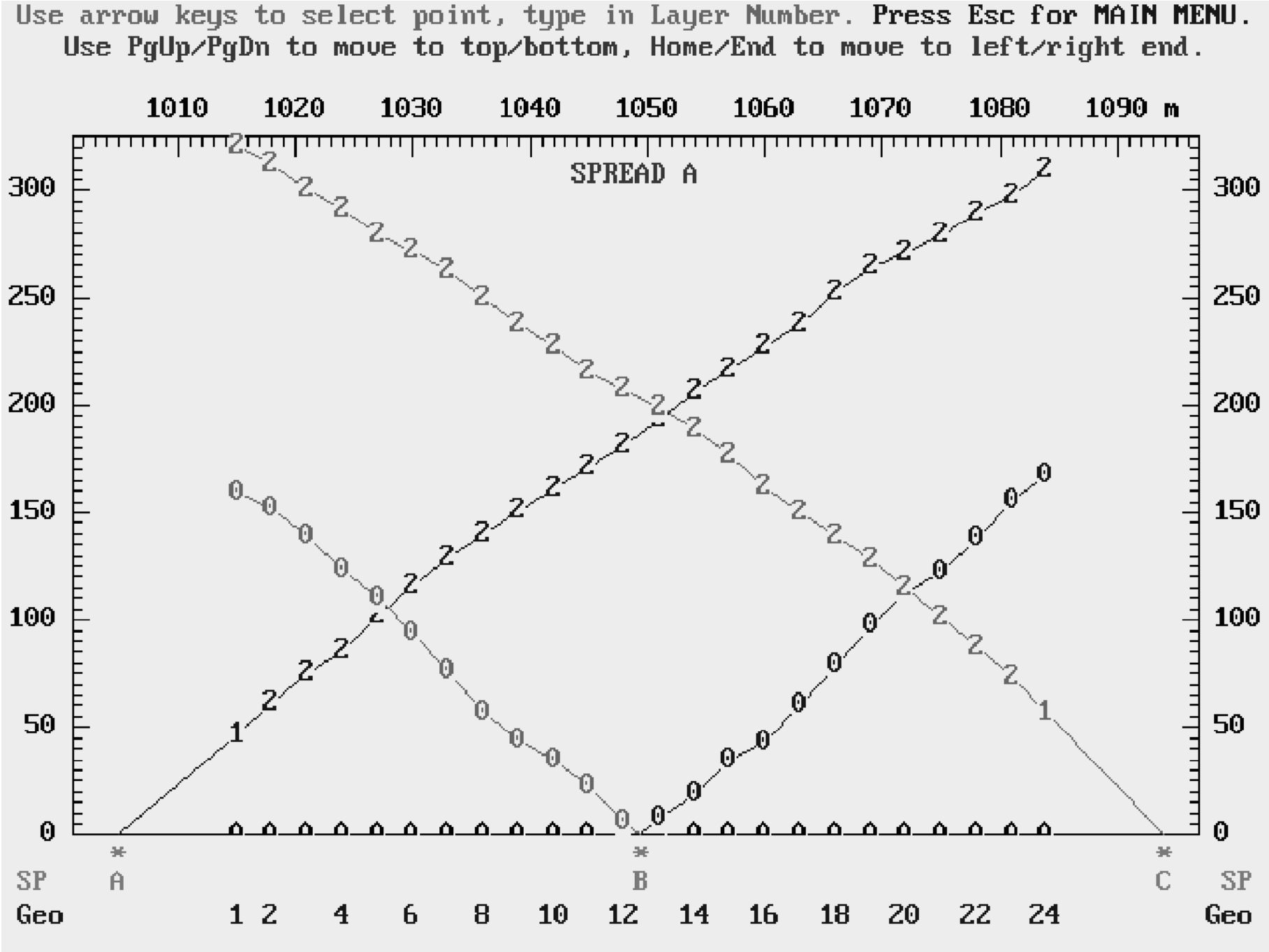

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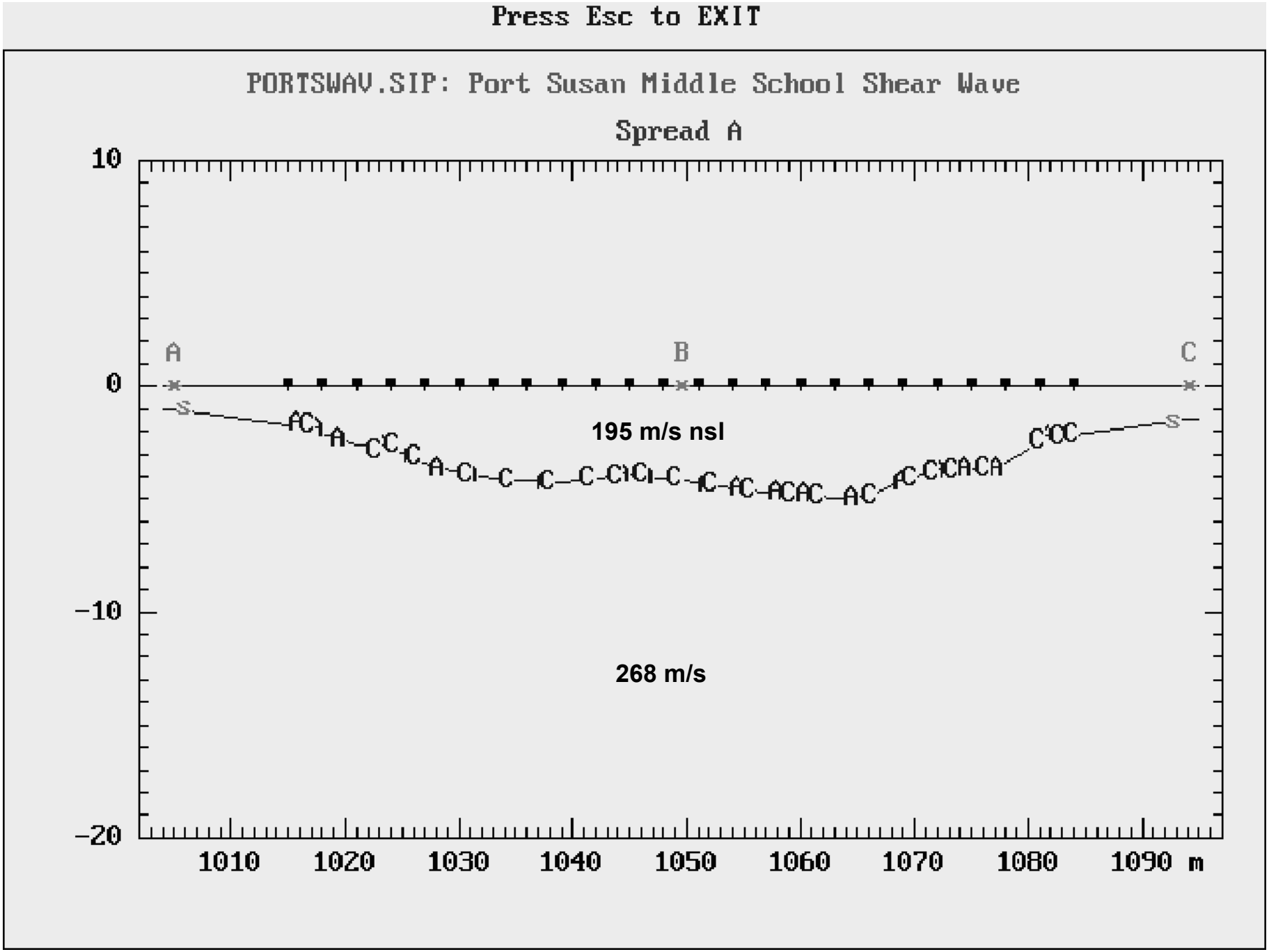

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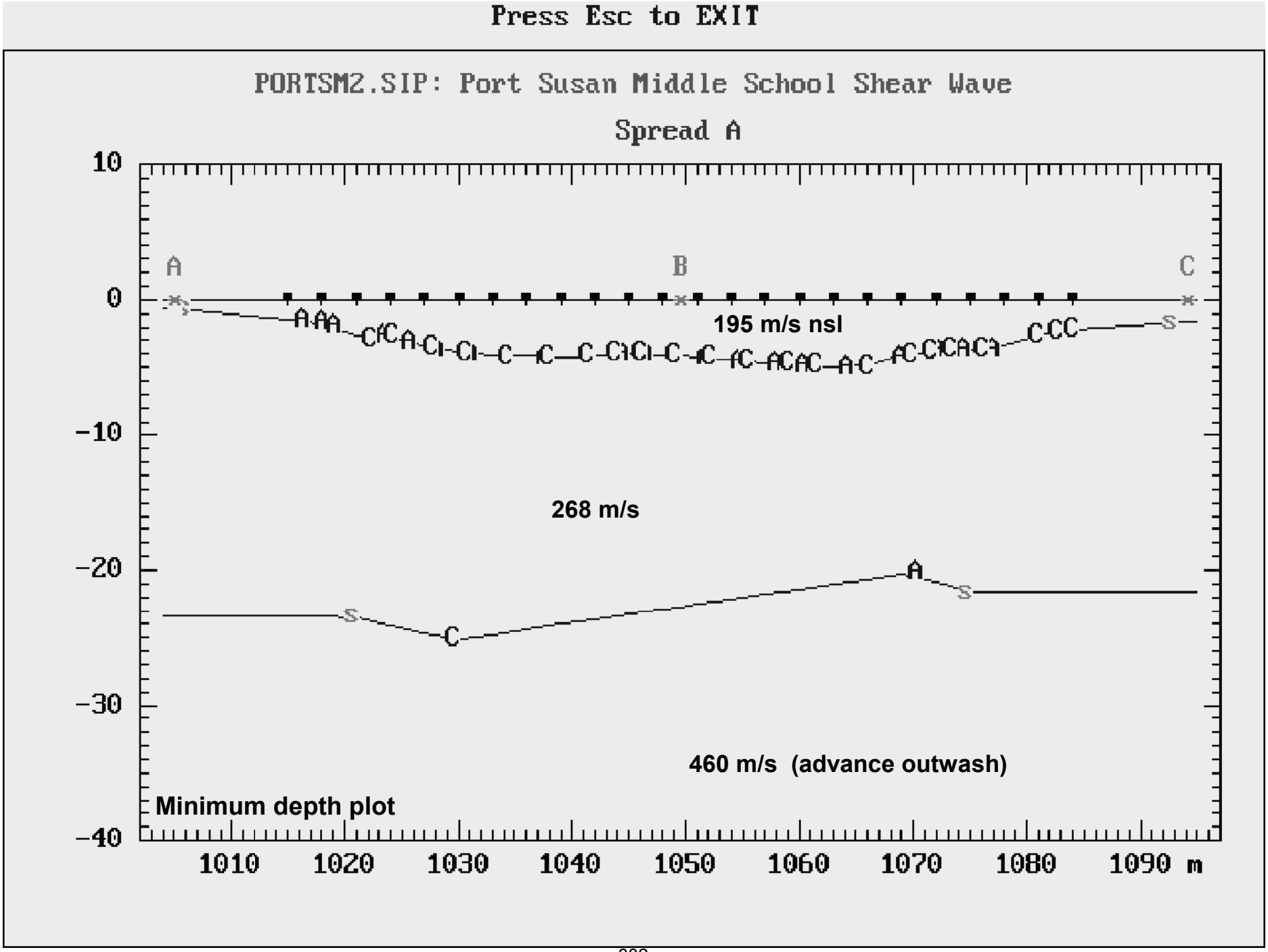
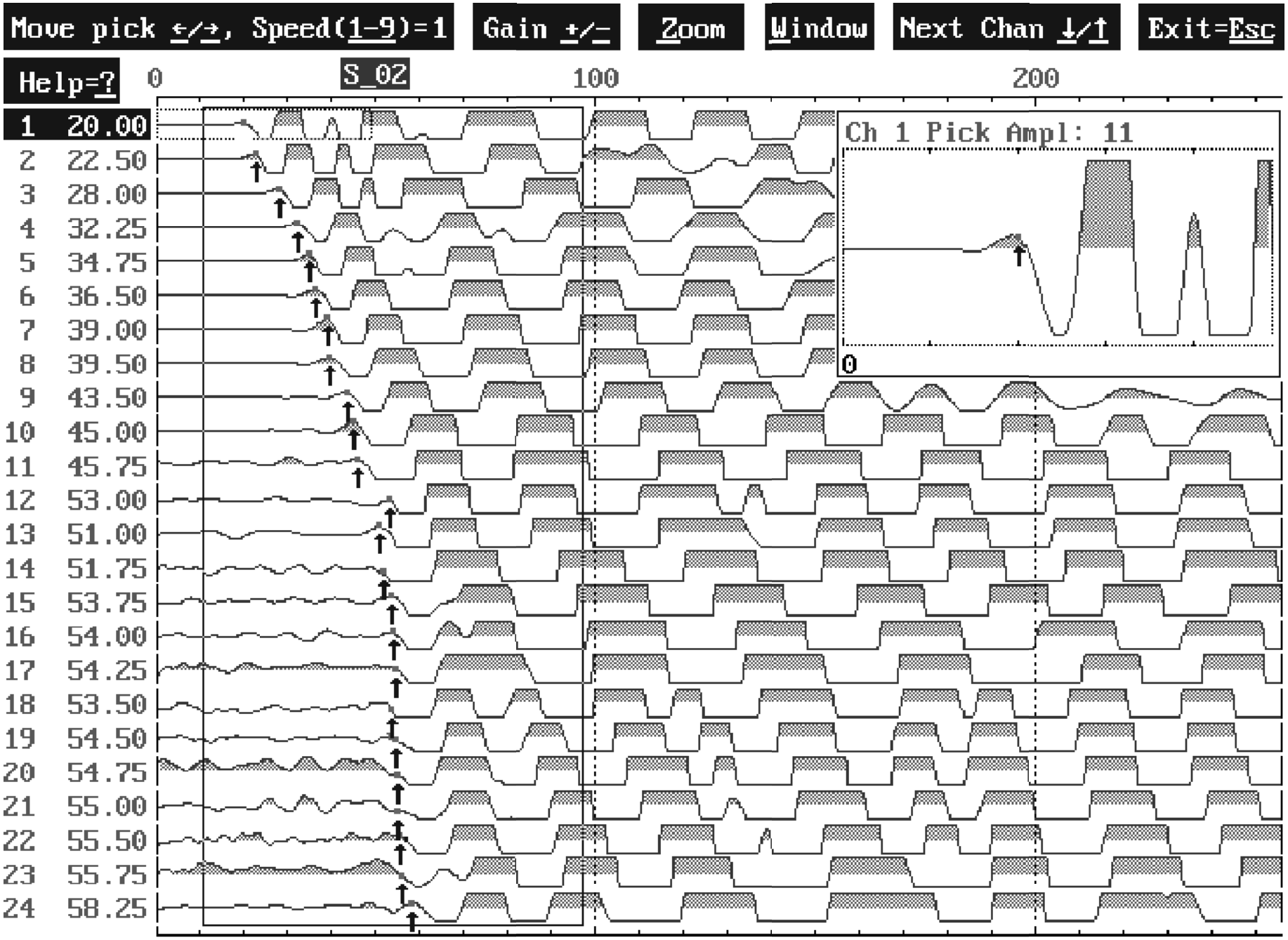


Rambo Road S-wave



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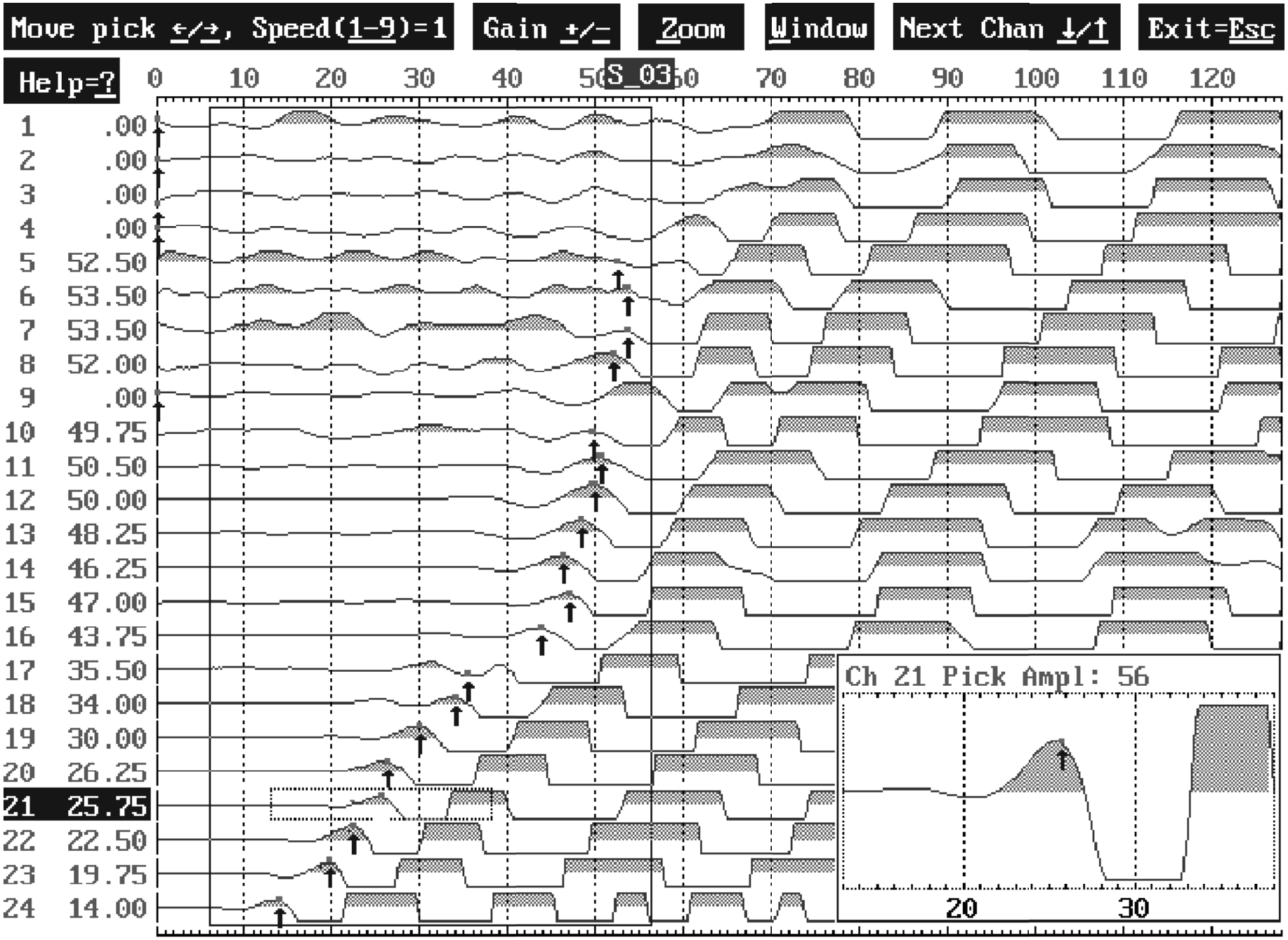

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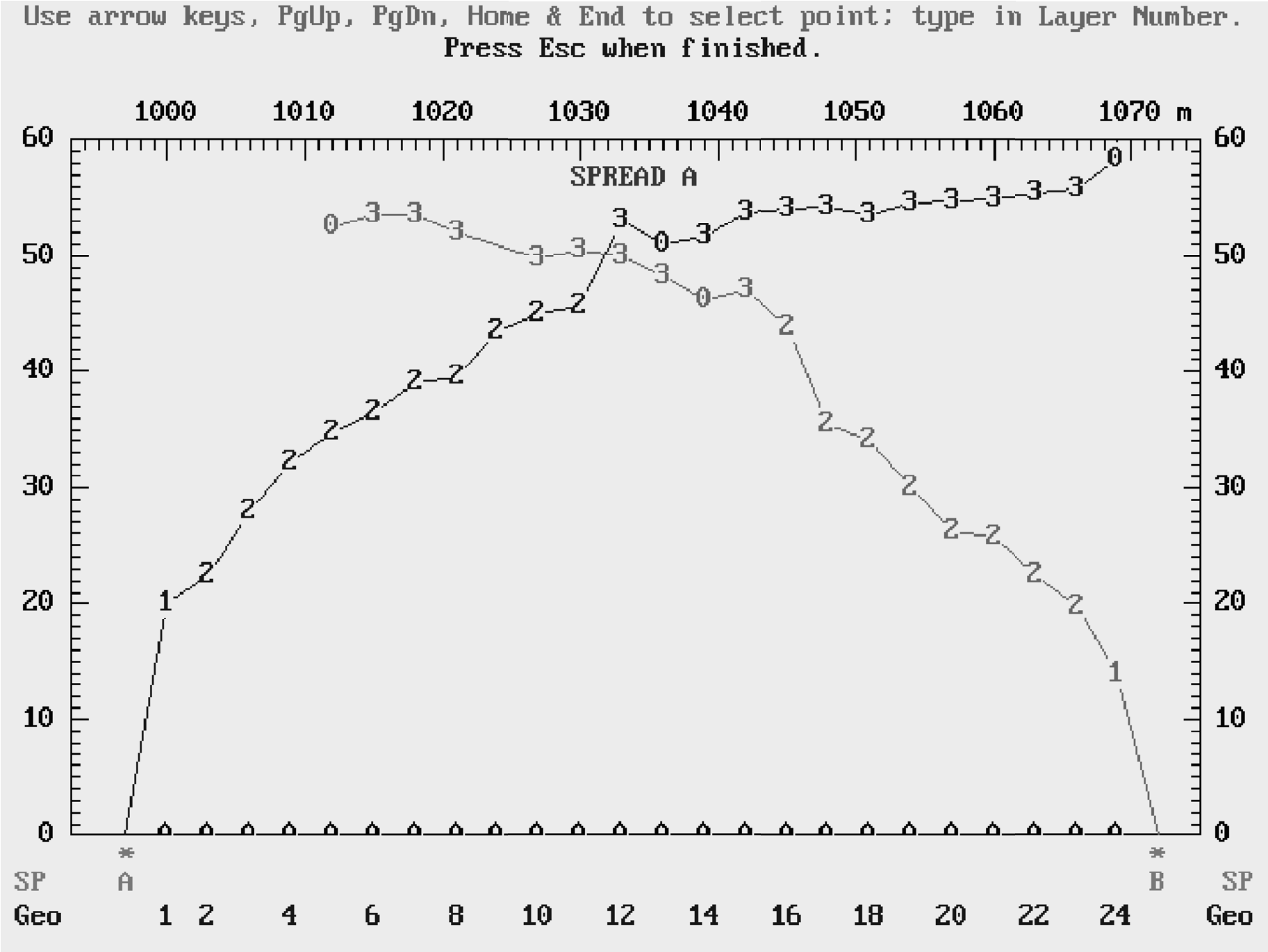

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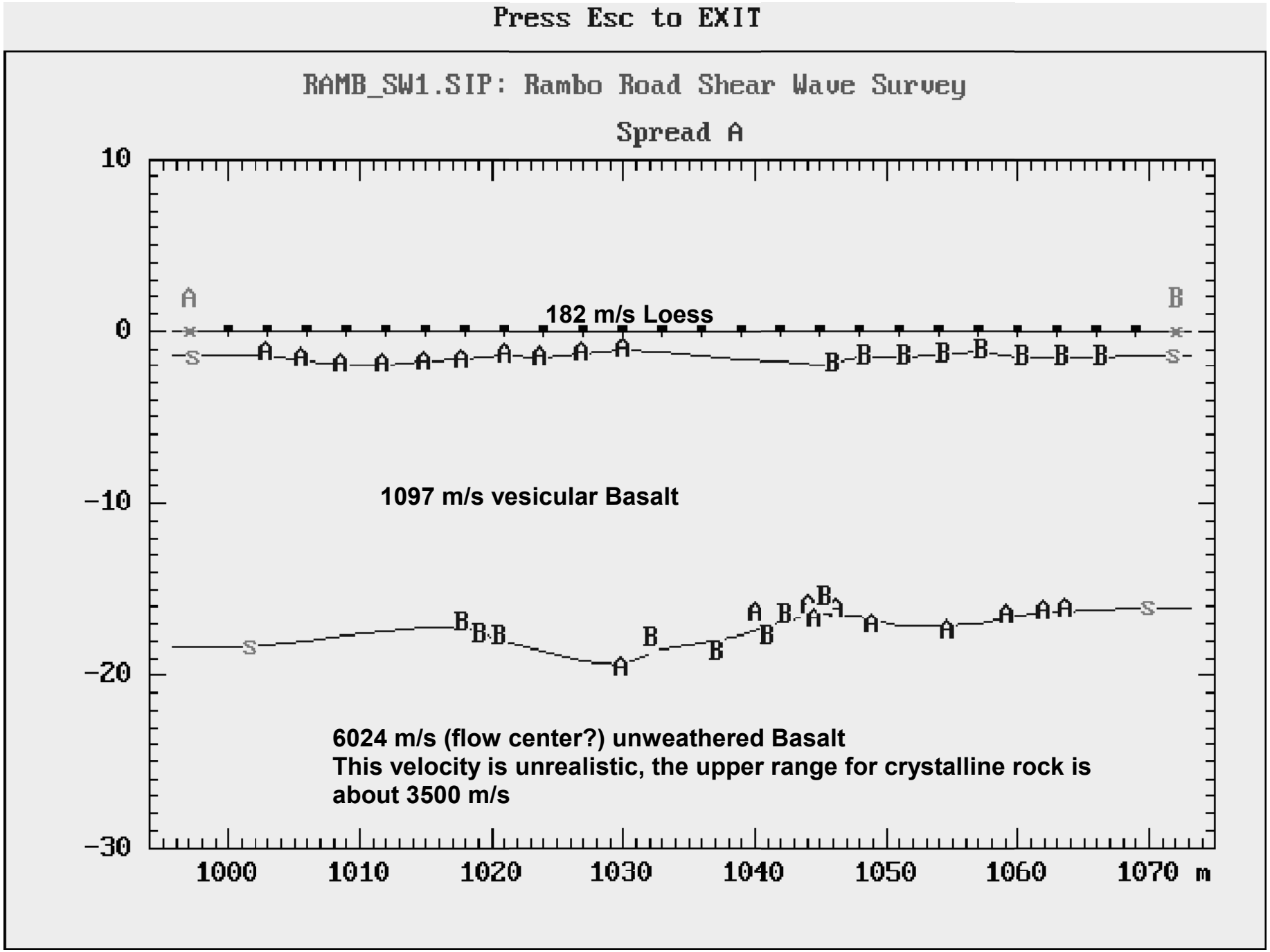

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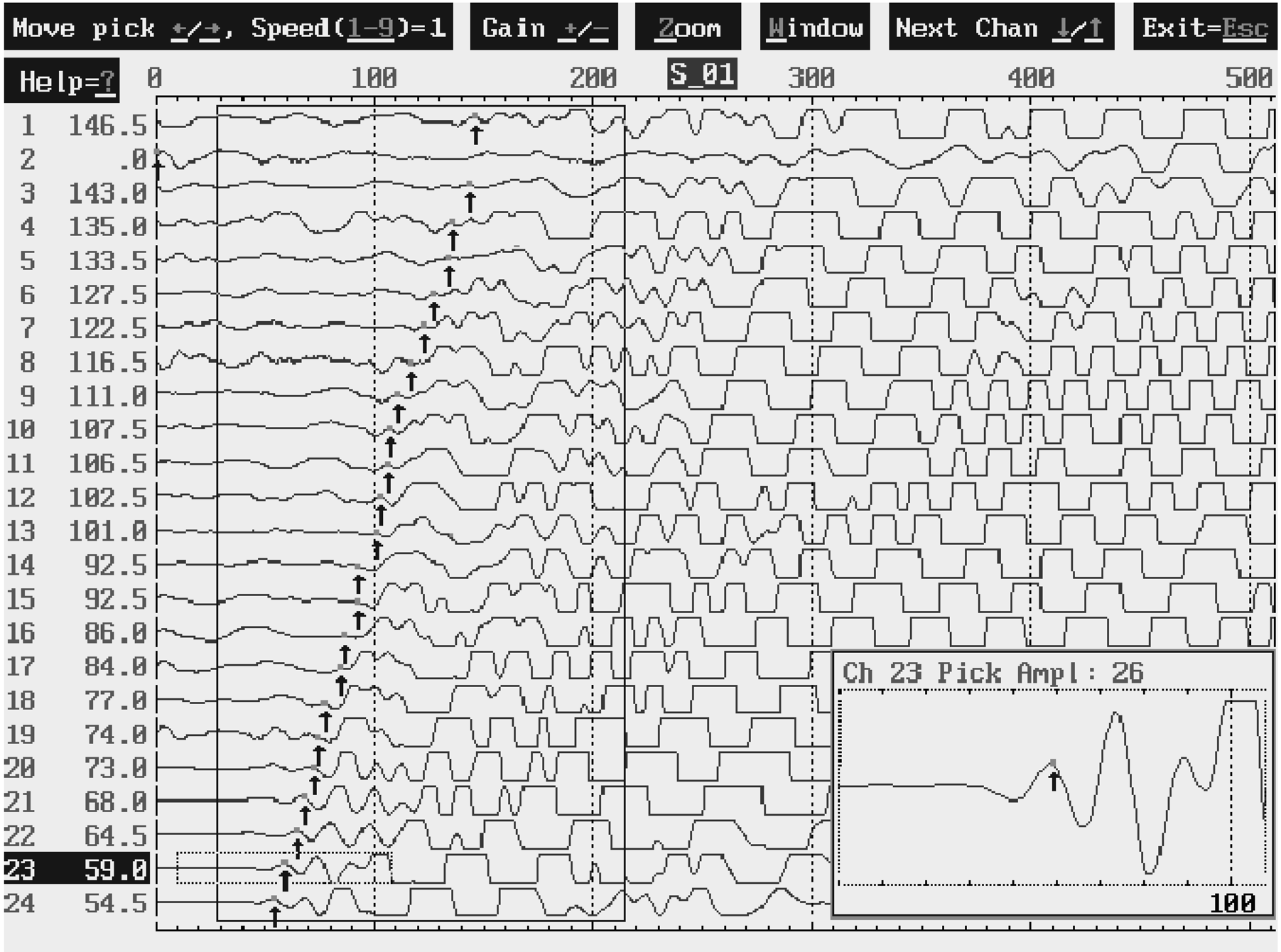

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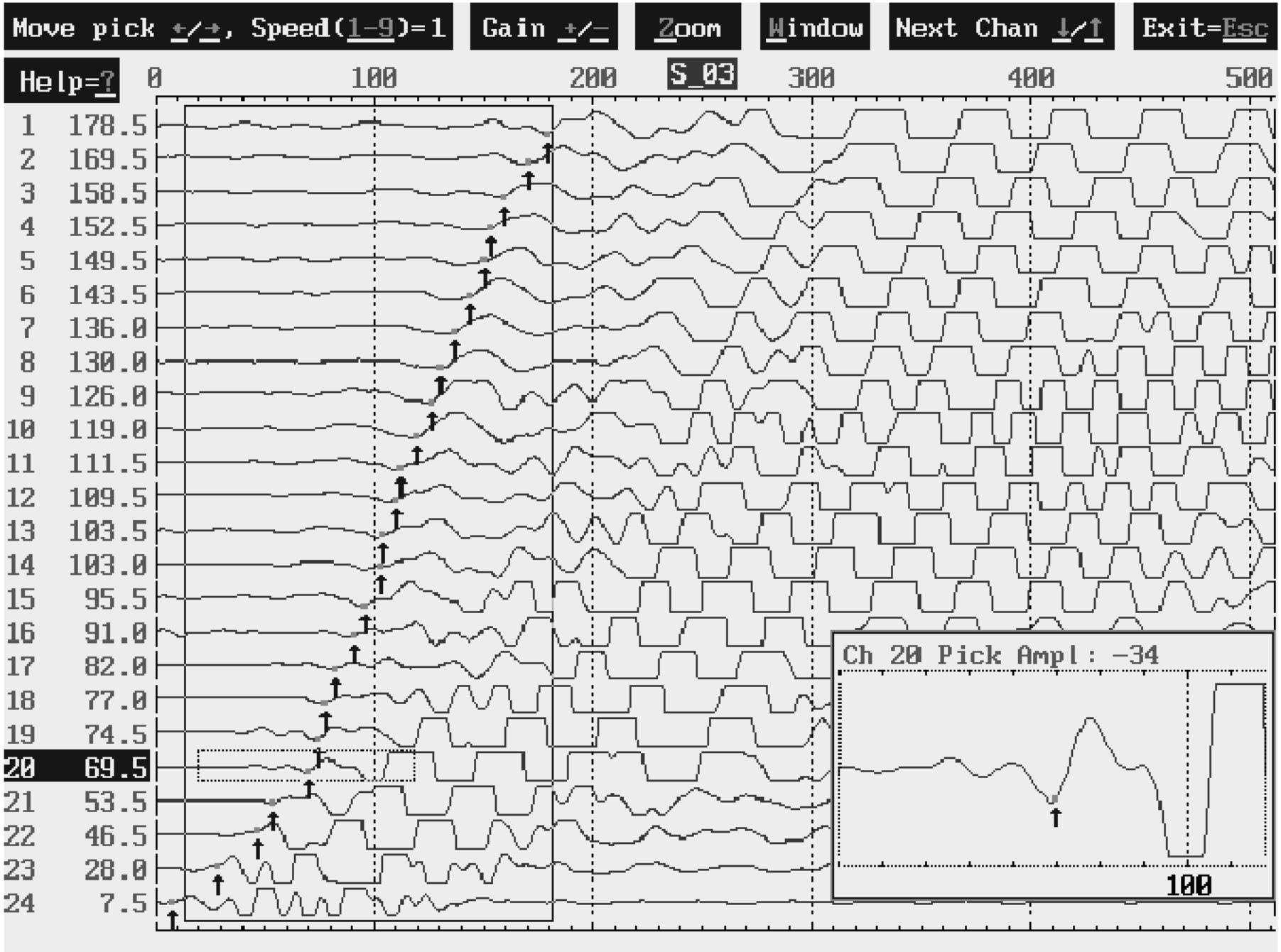

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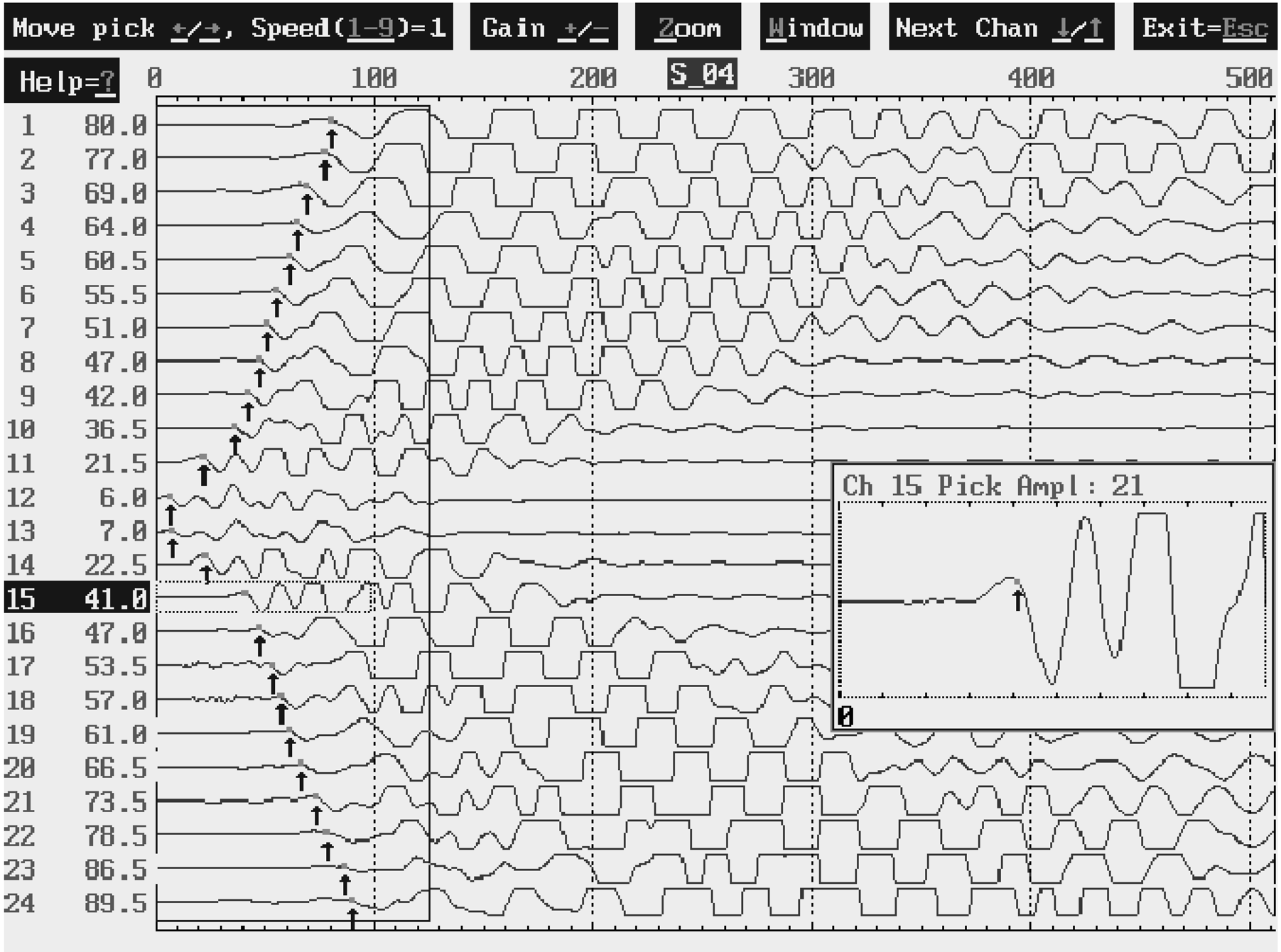

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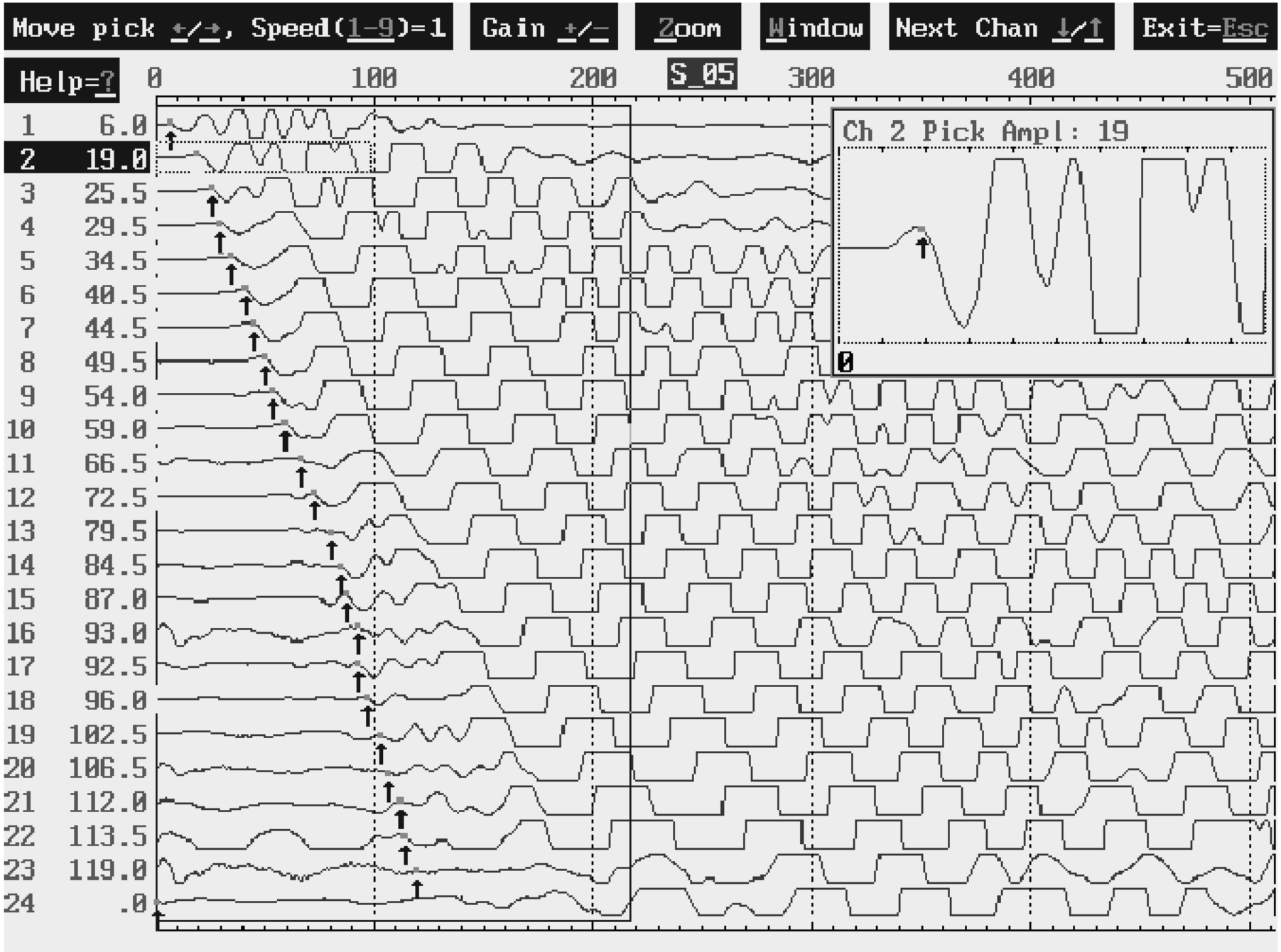

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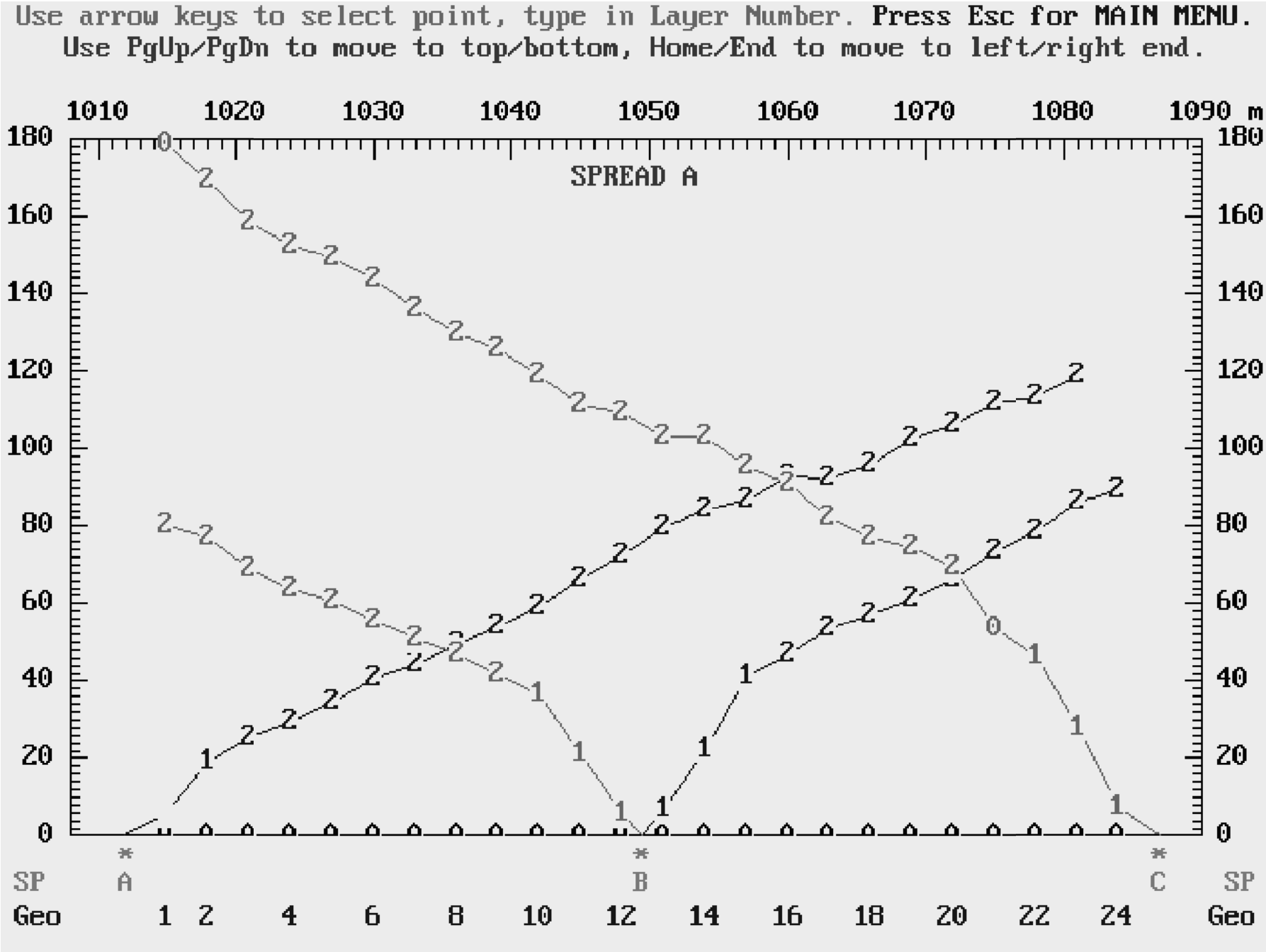

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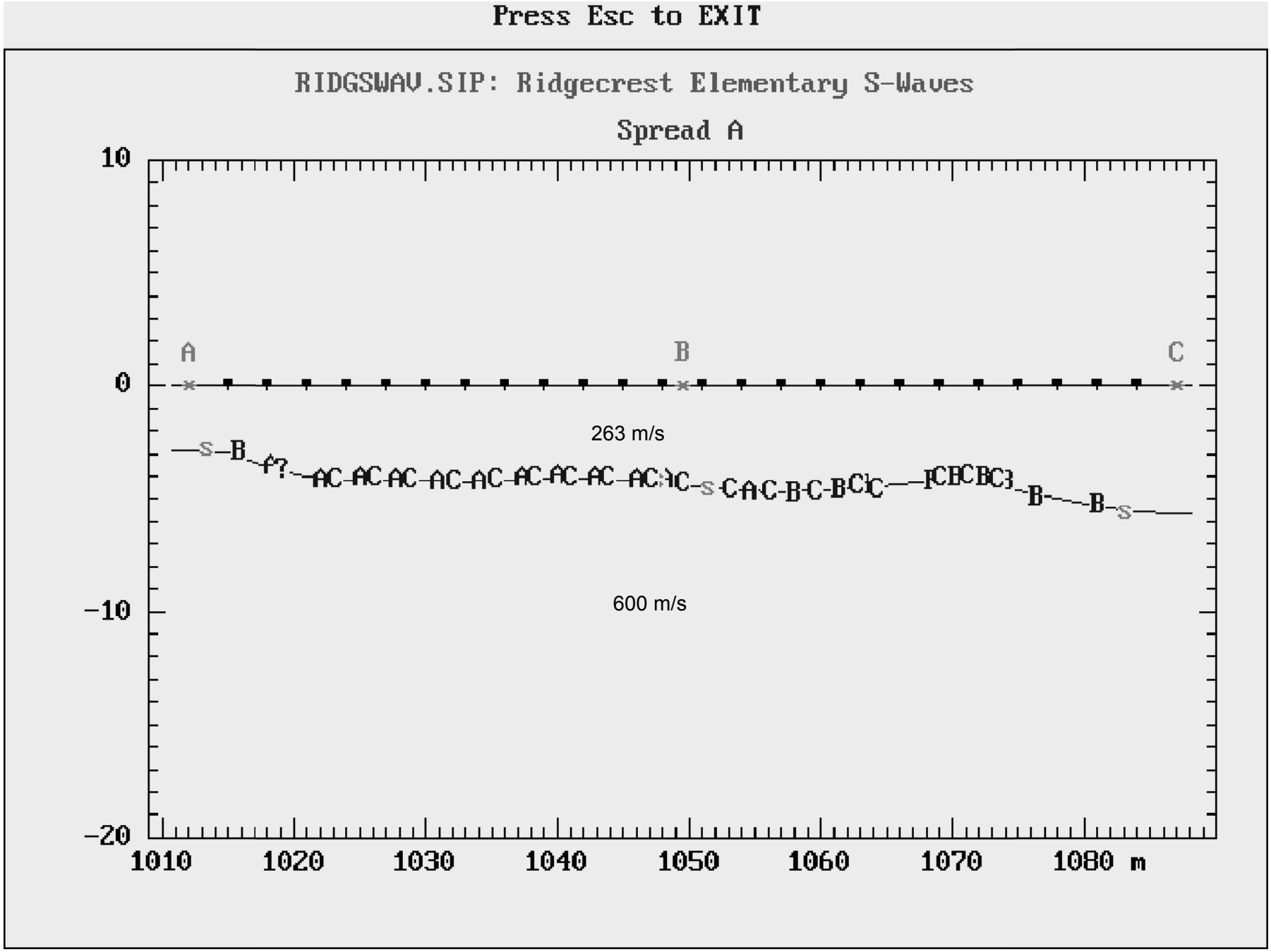

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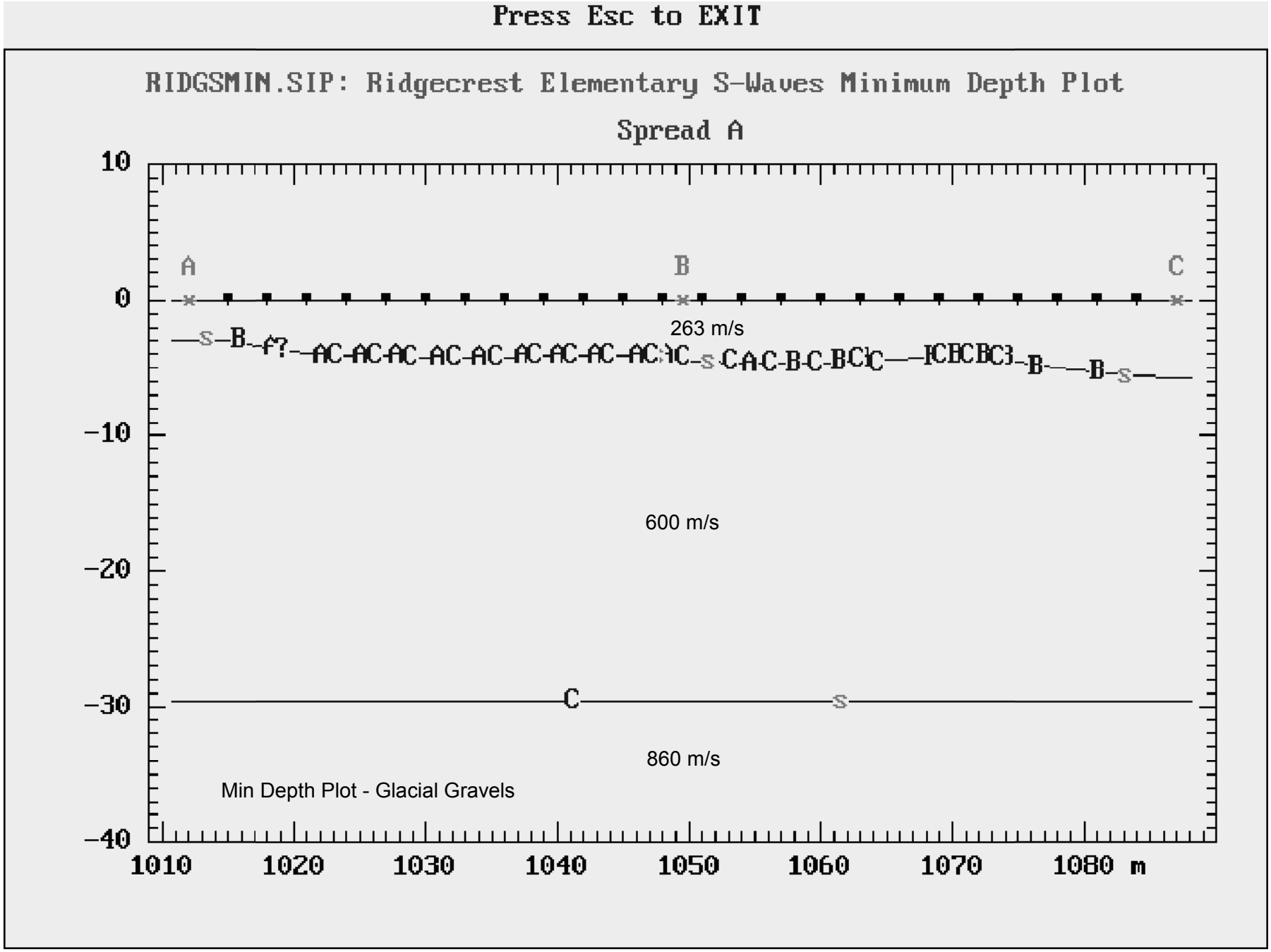

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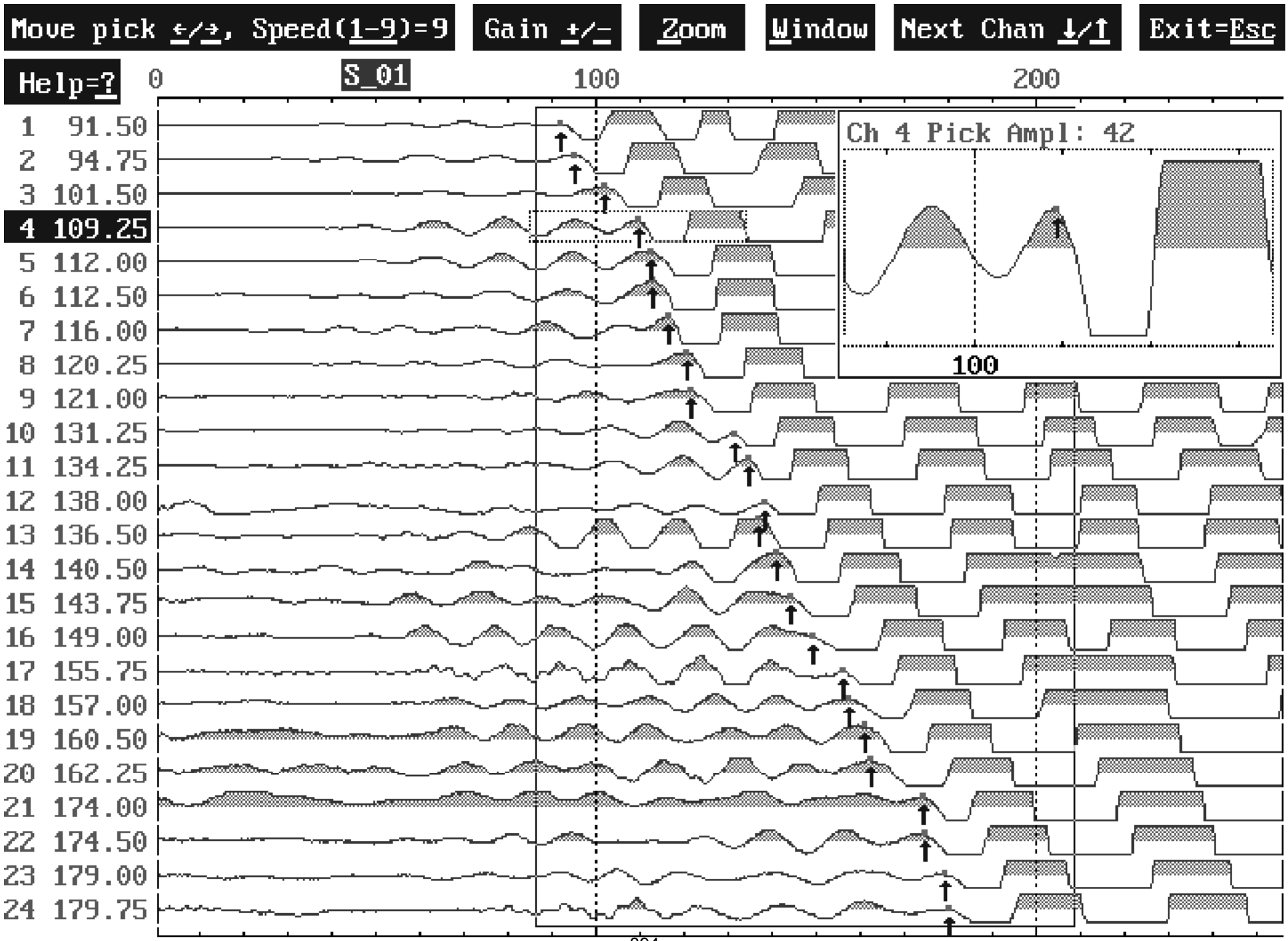

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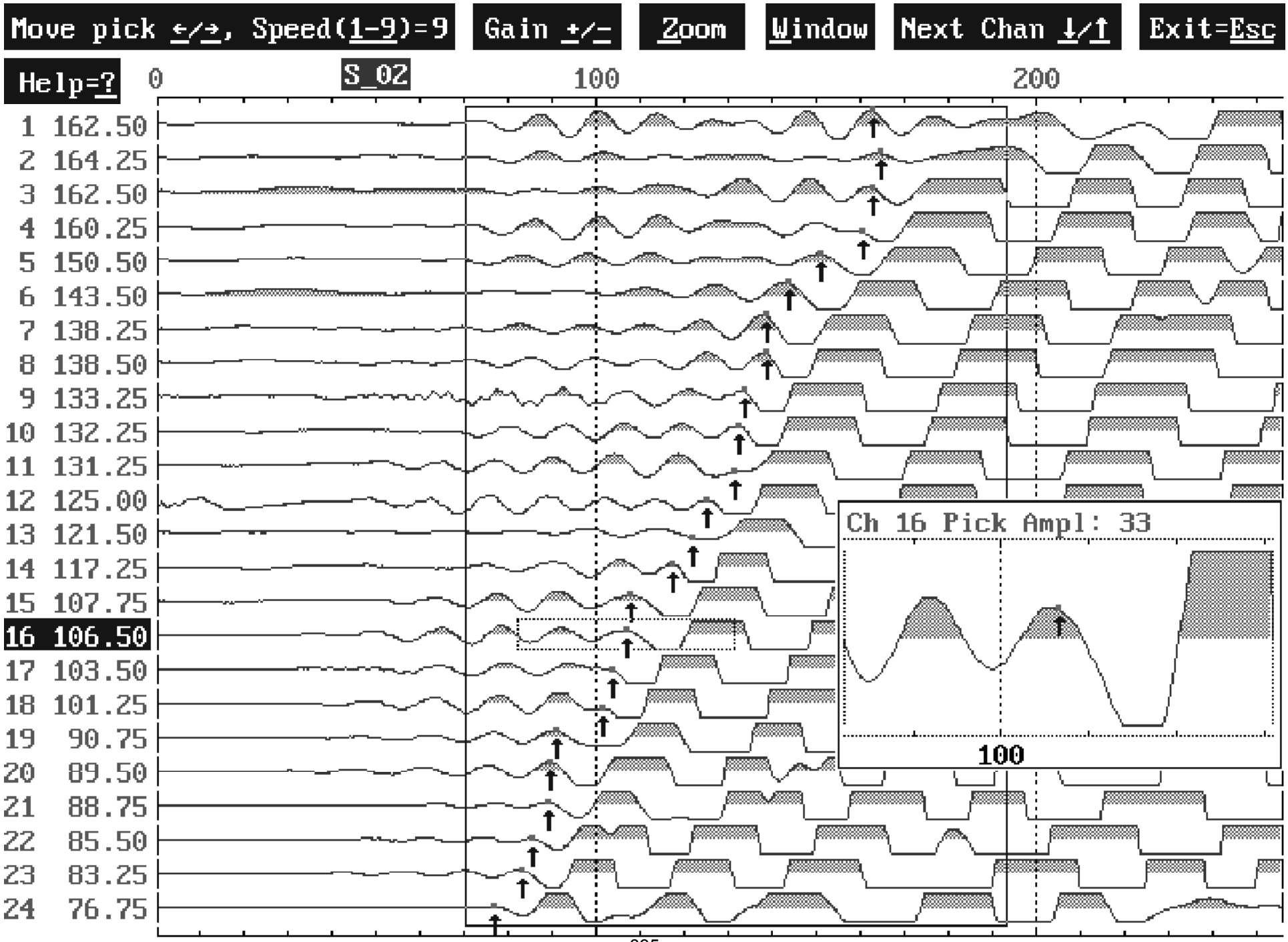

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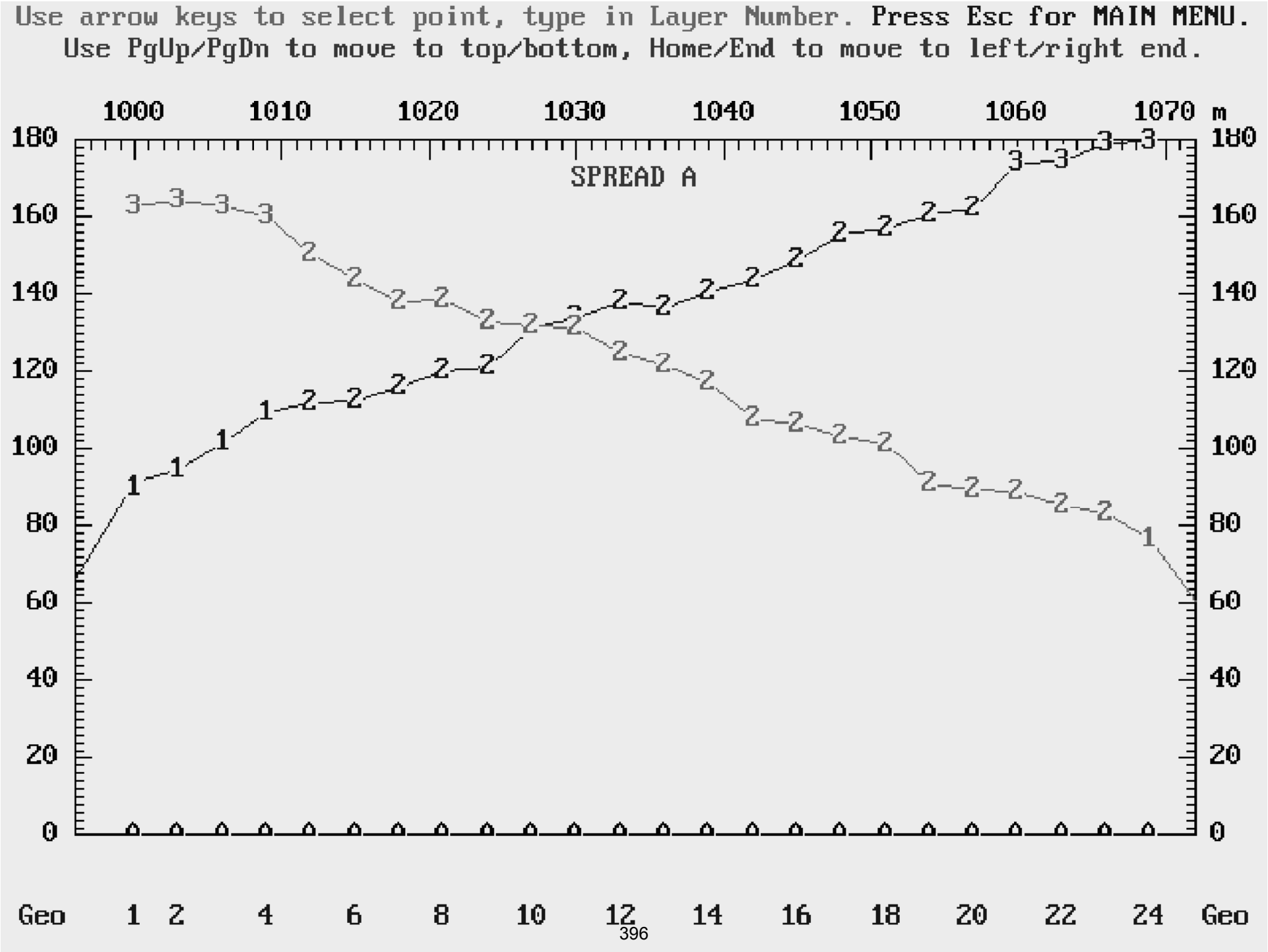

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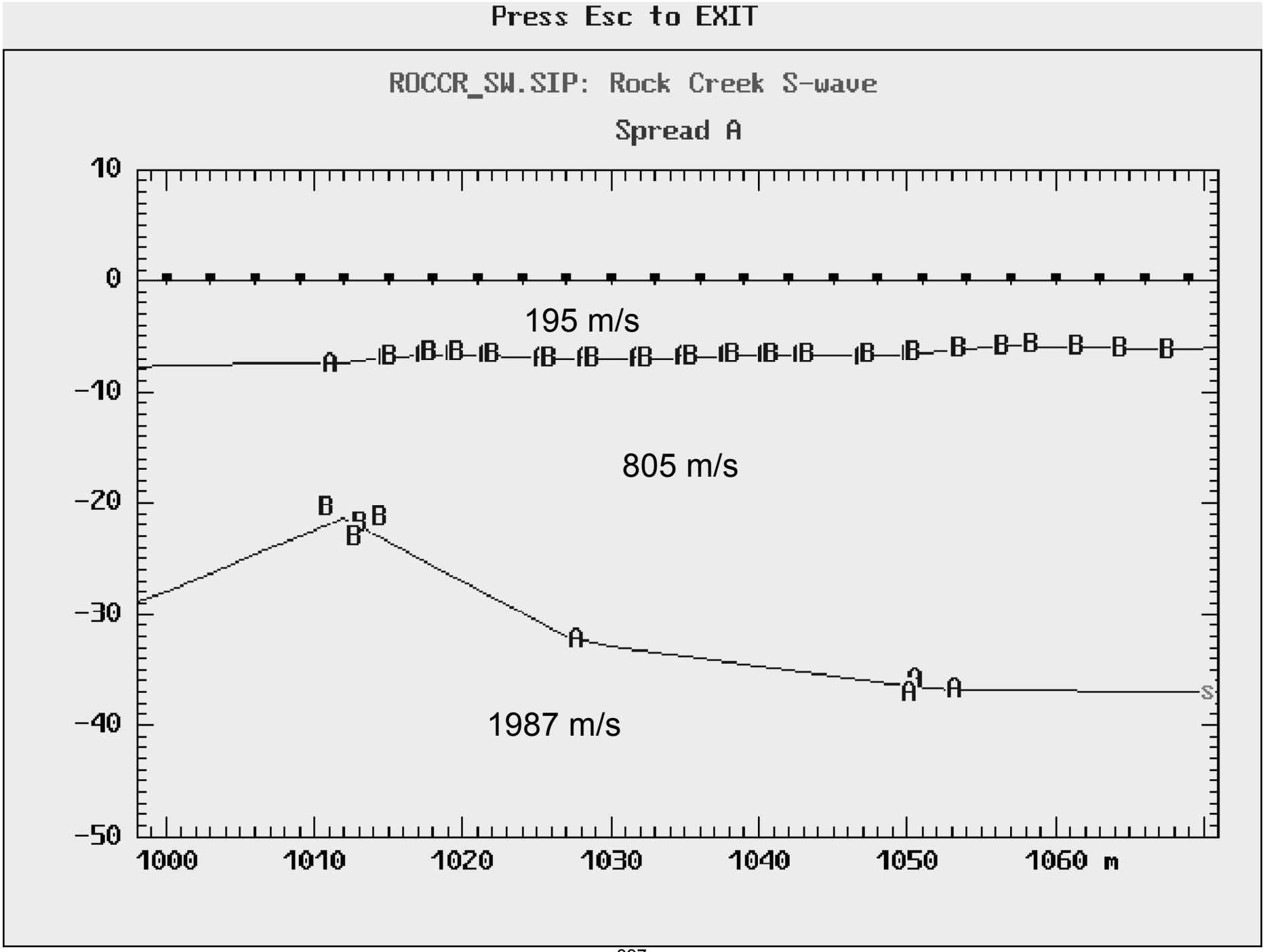

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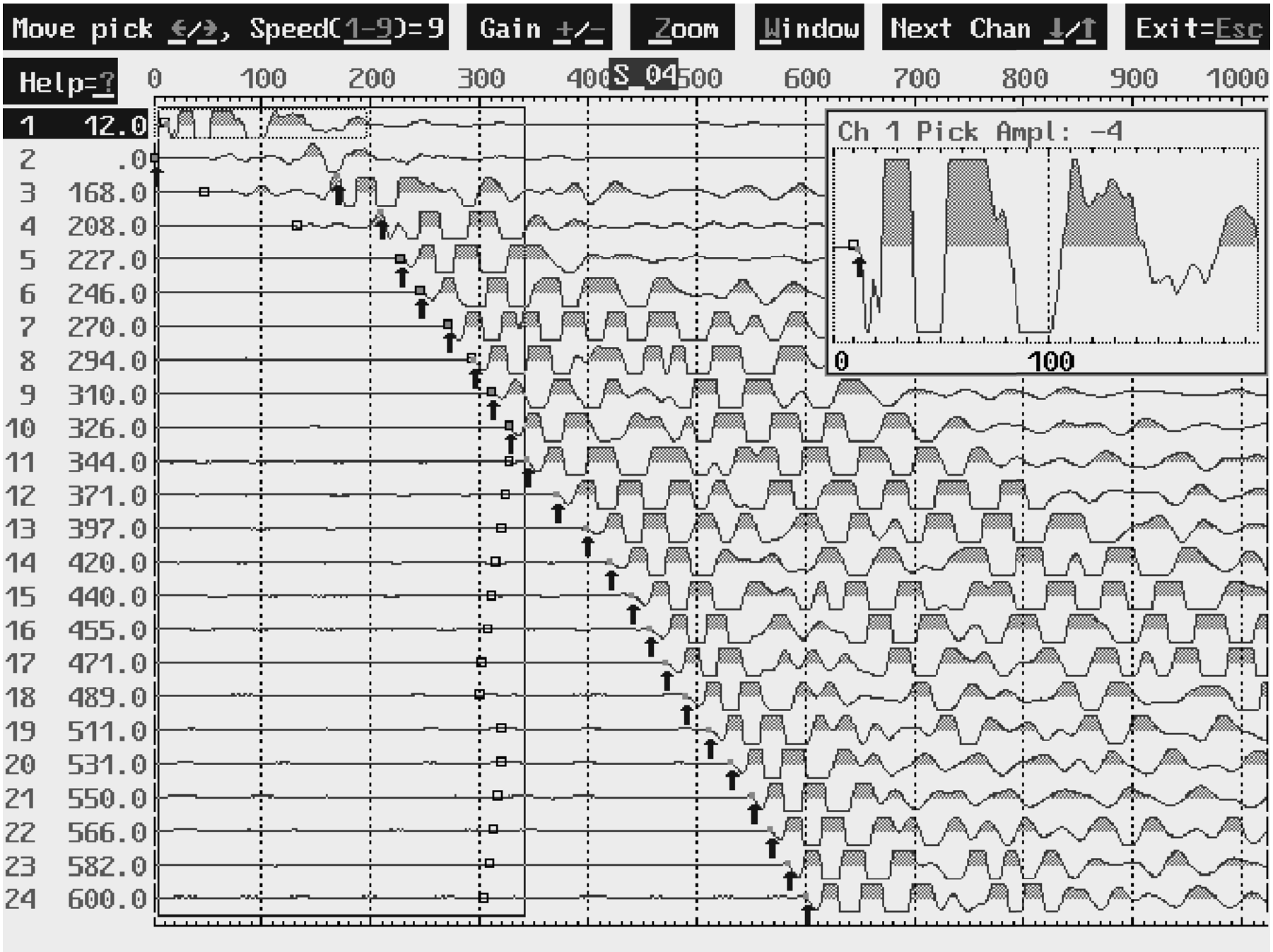

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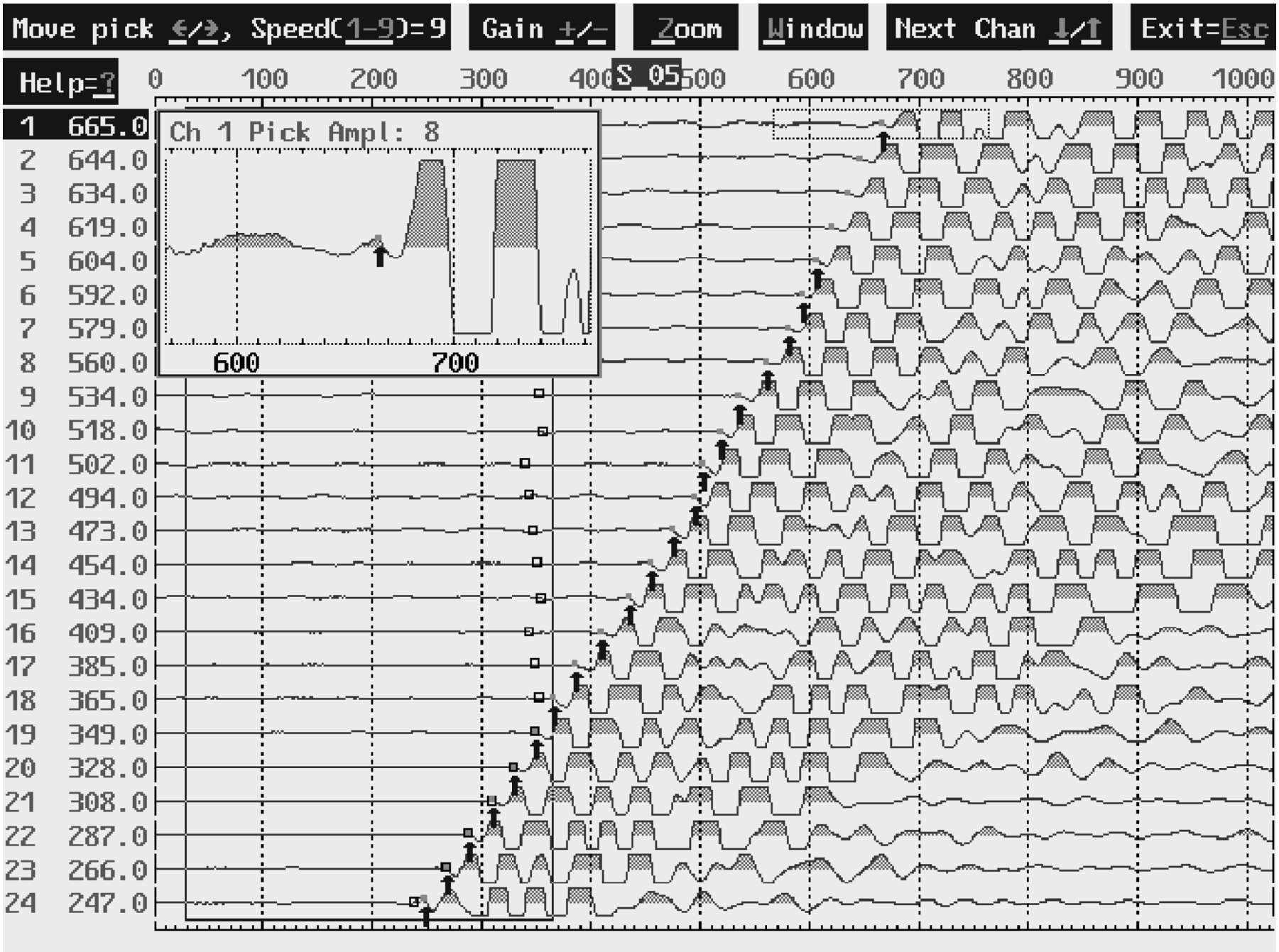

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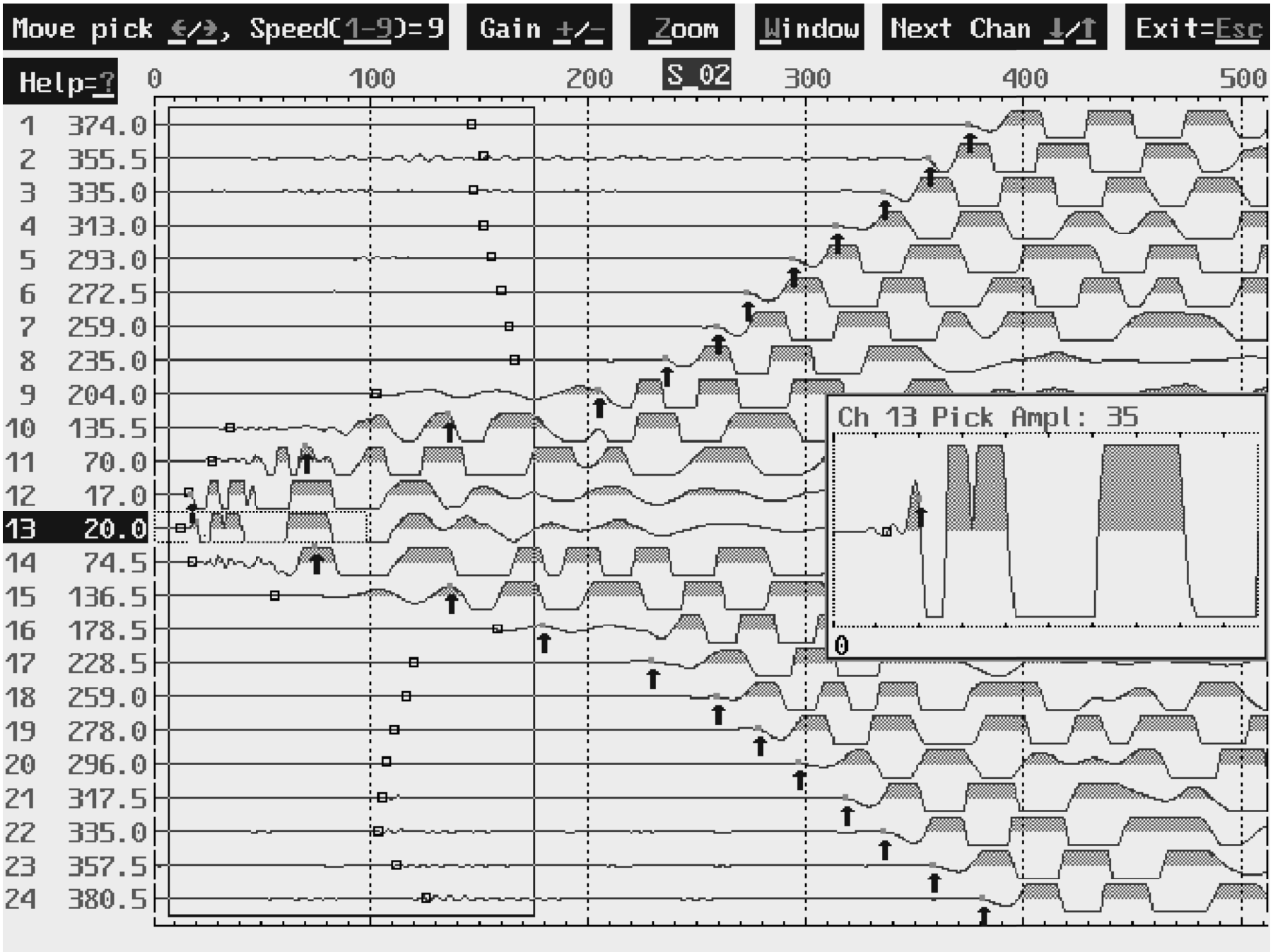

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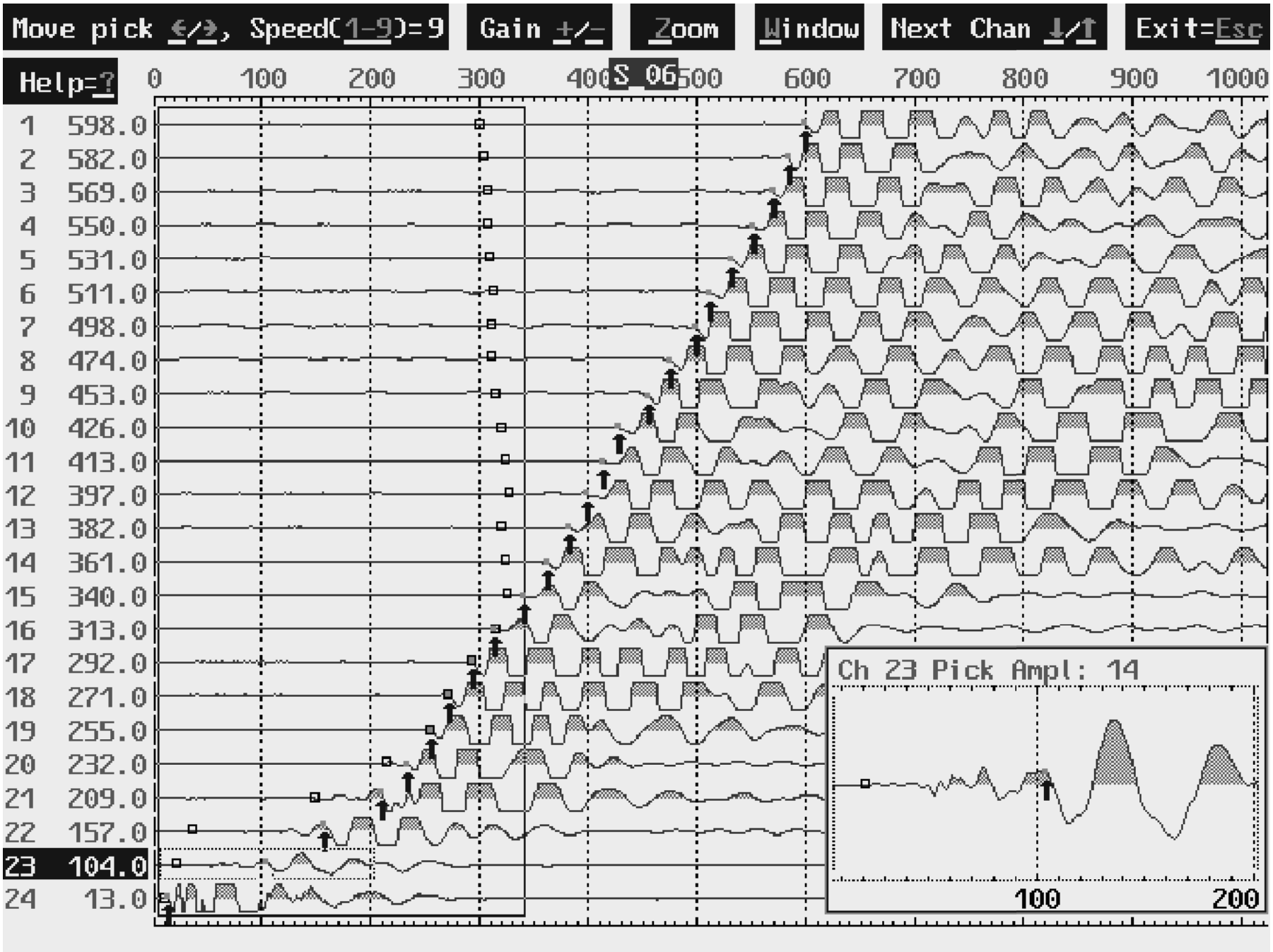

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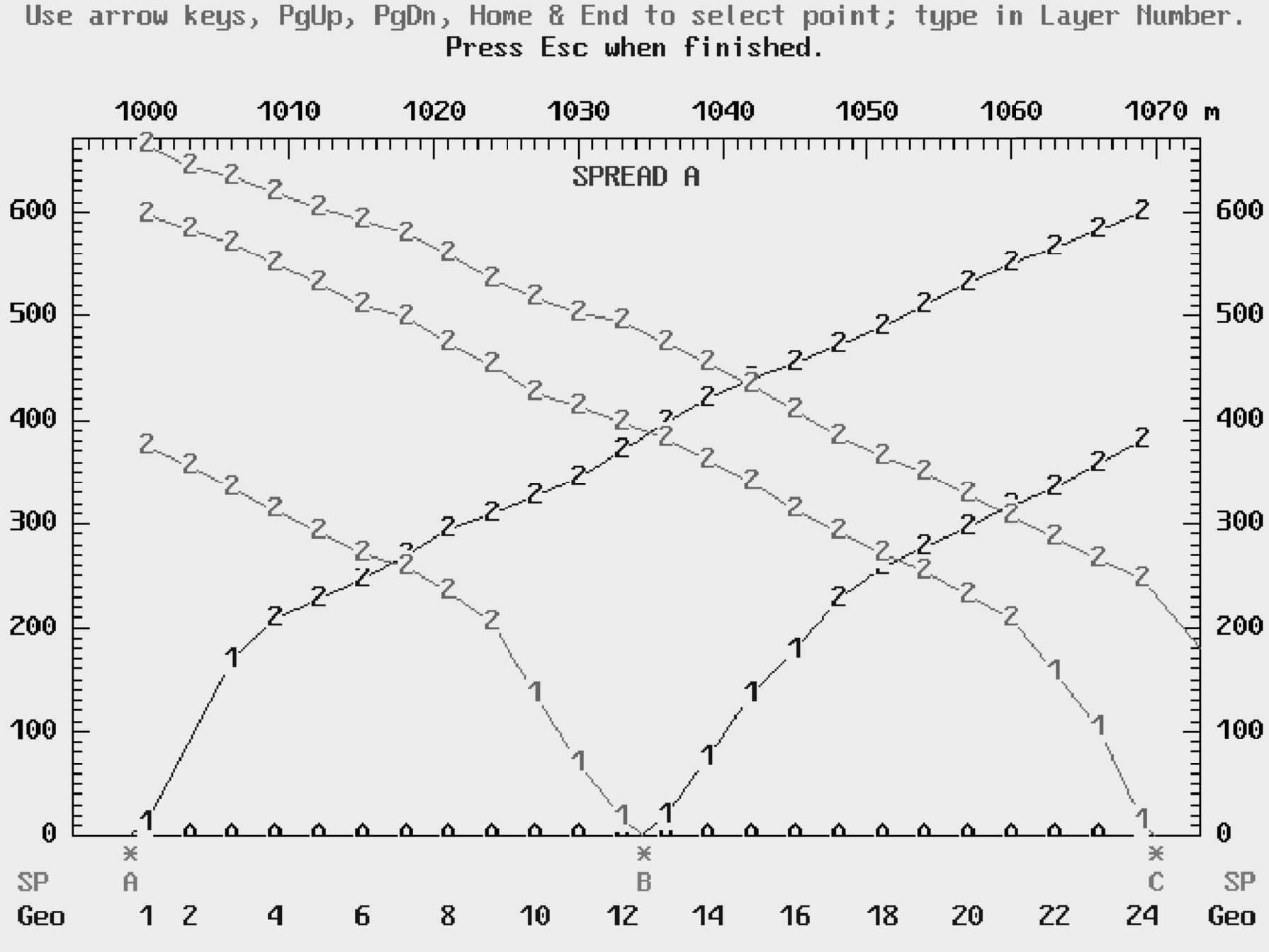

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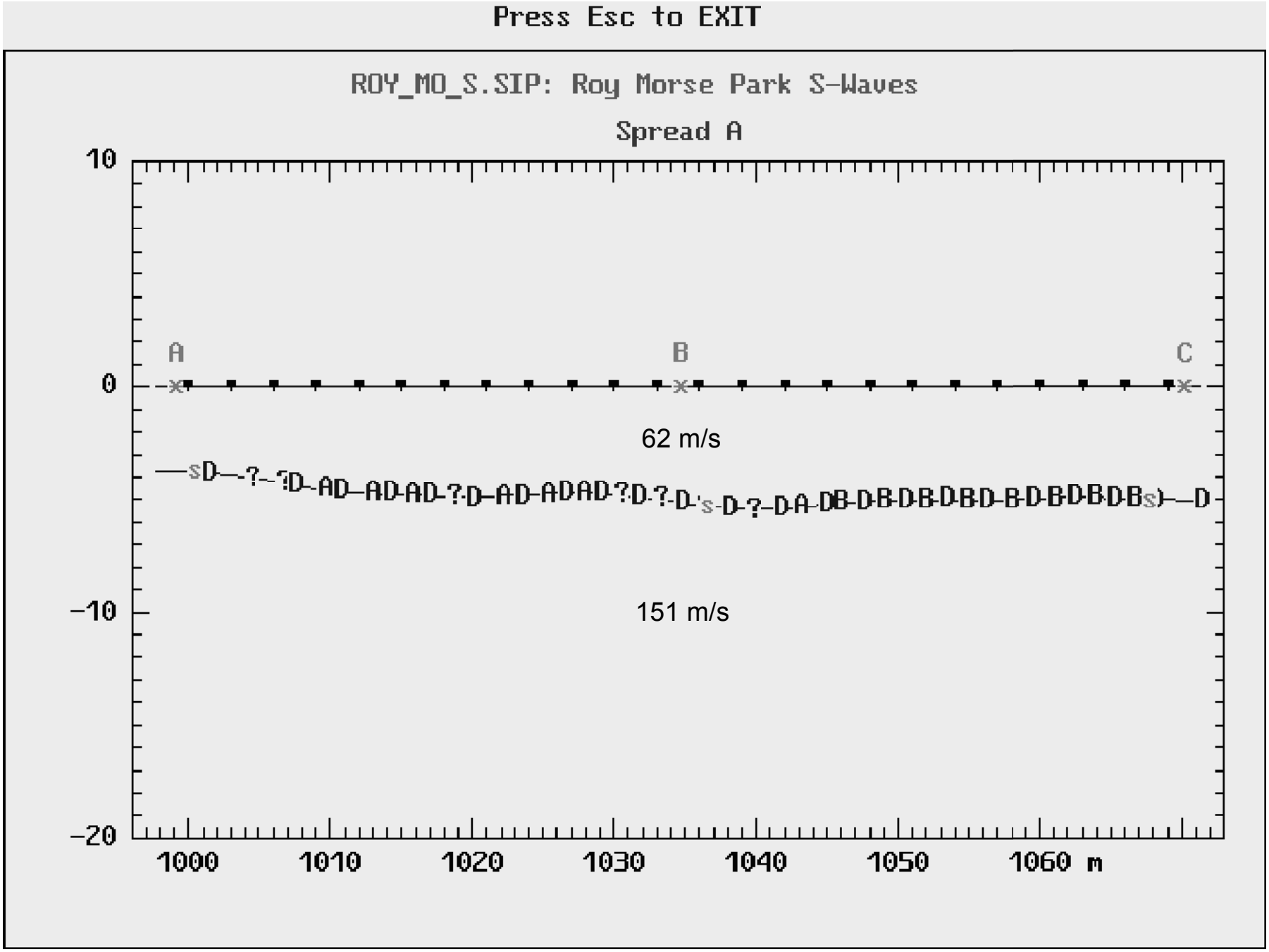

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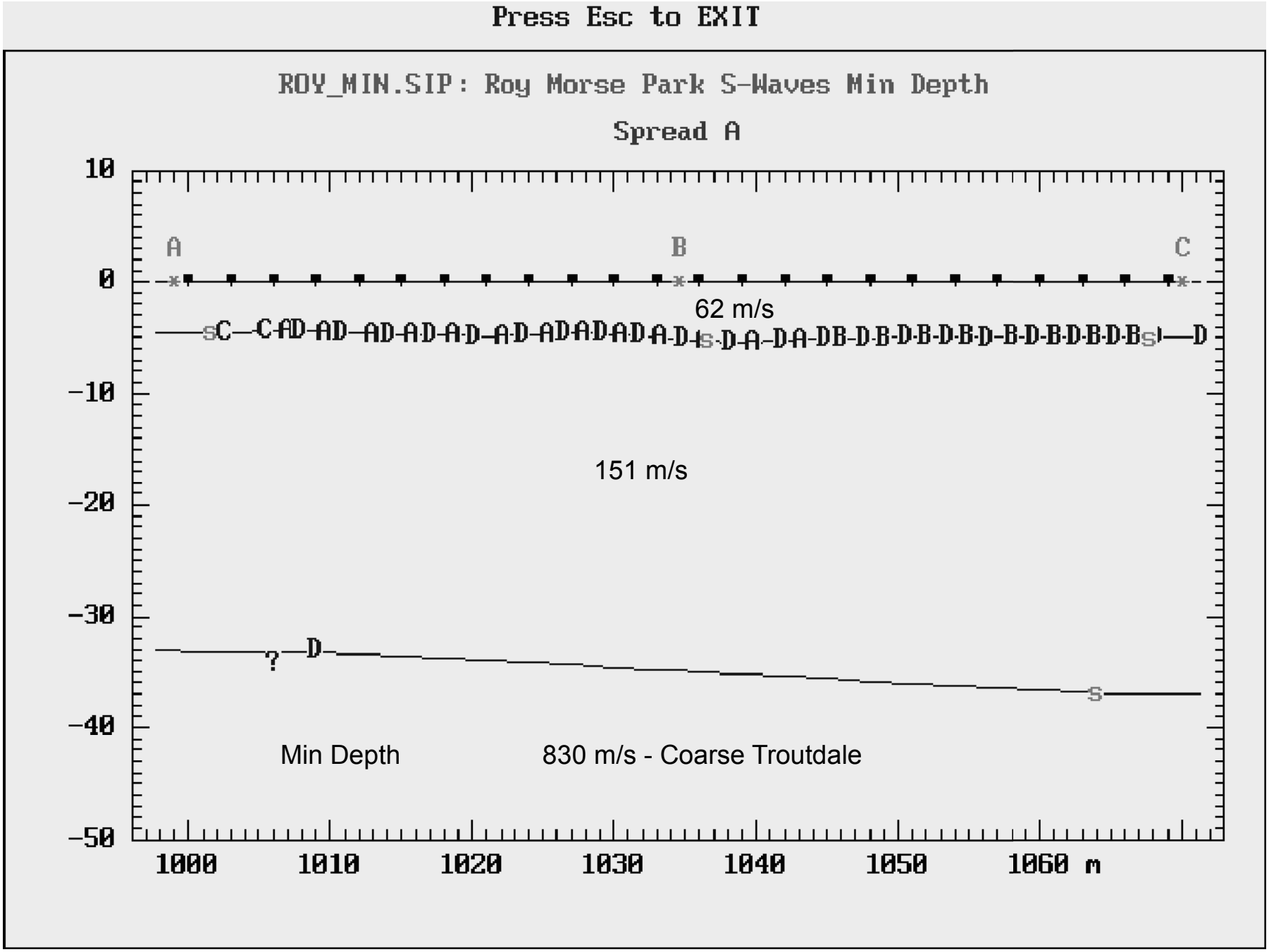

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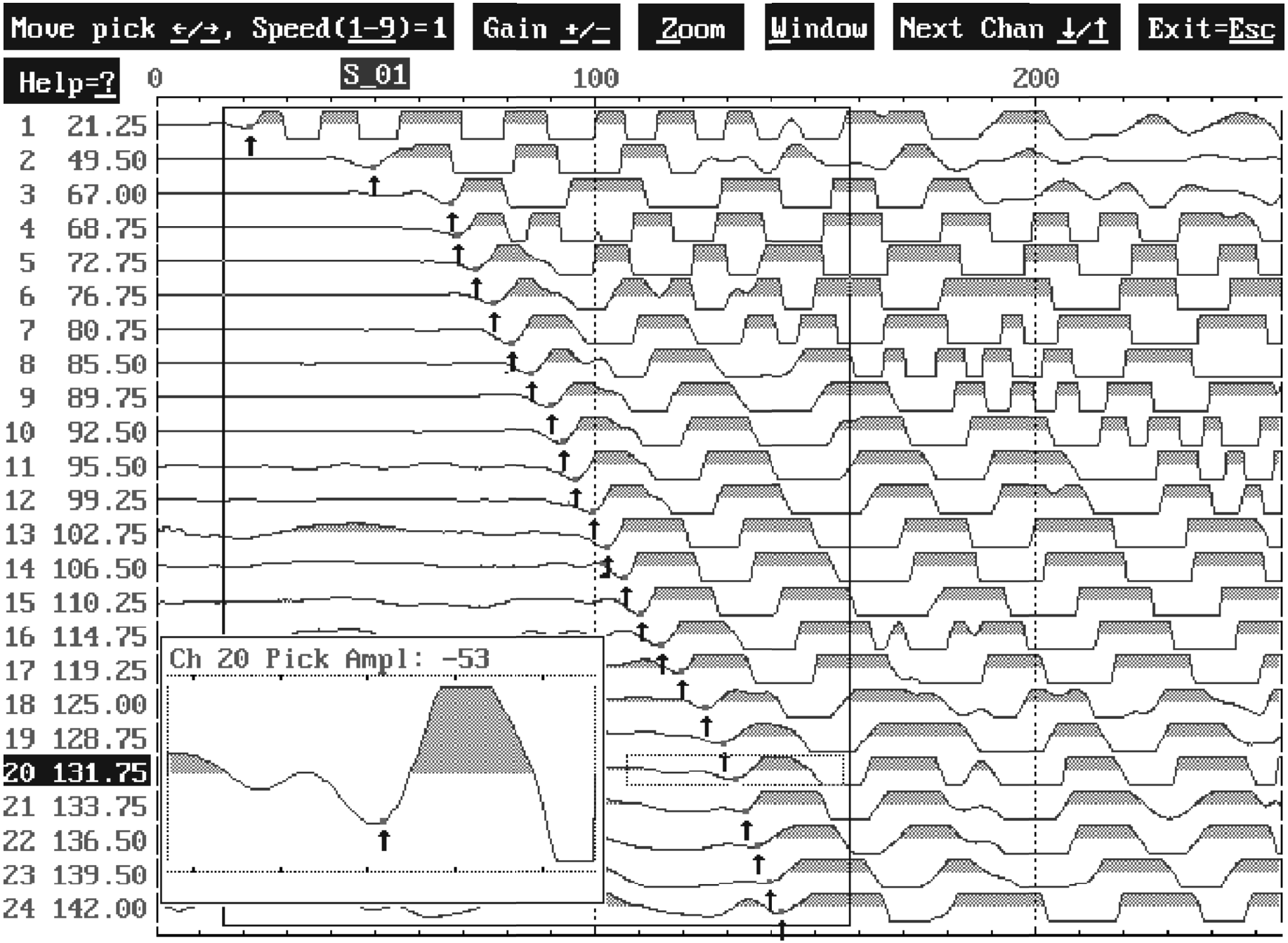

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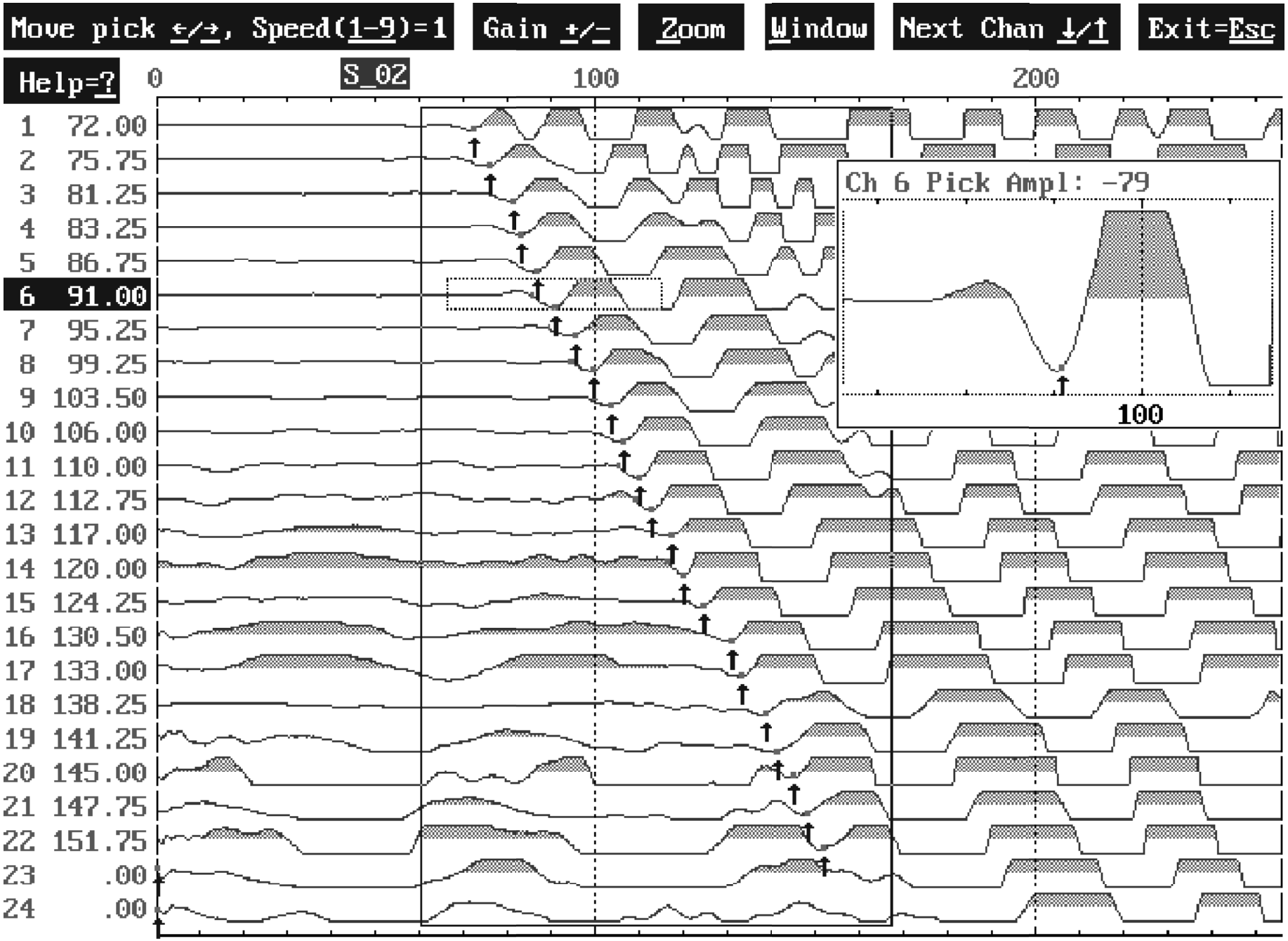

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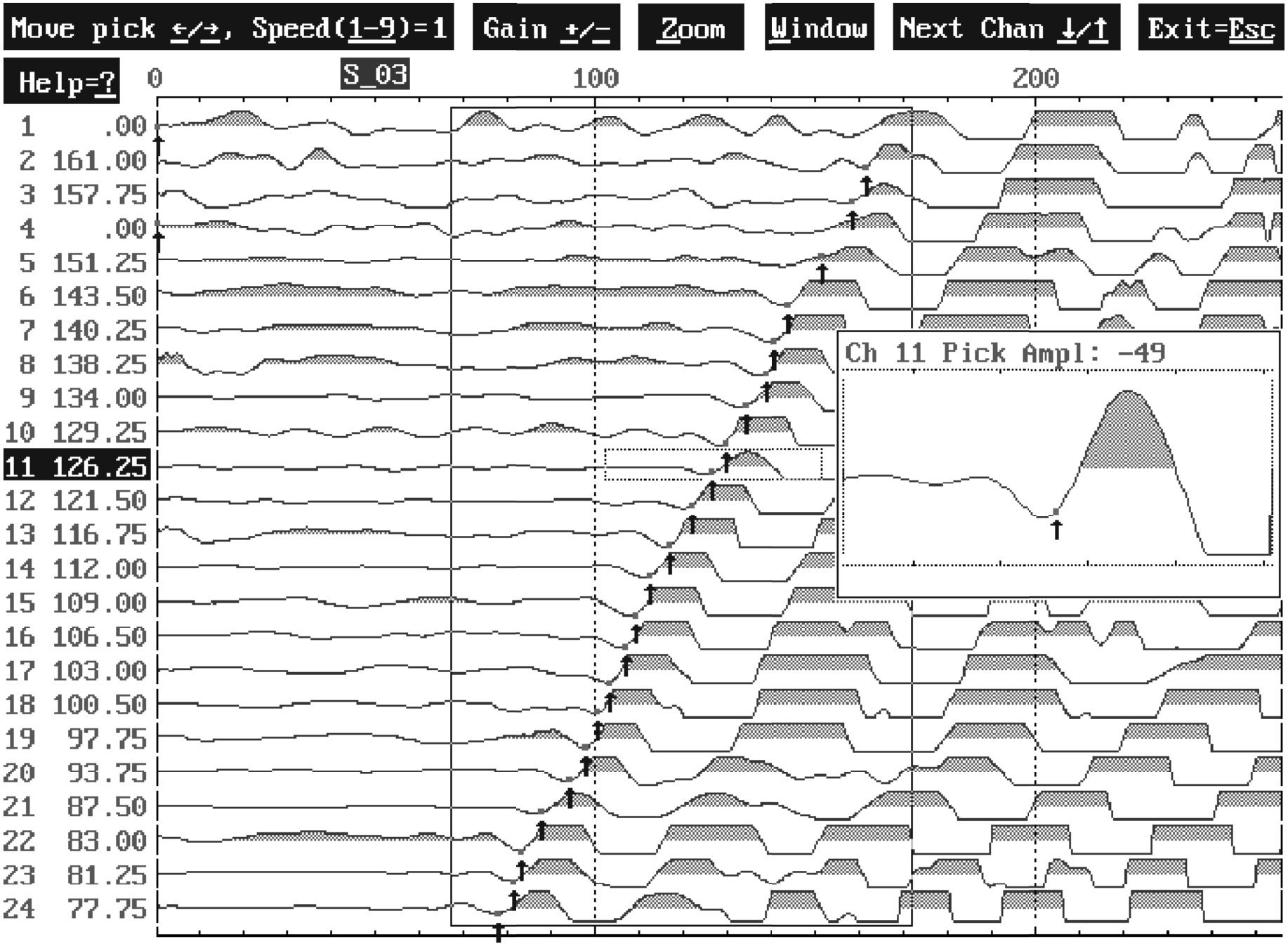

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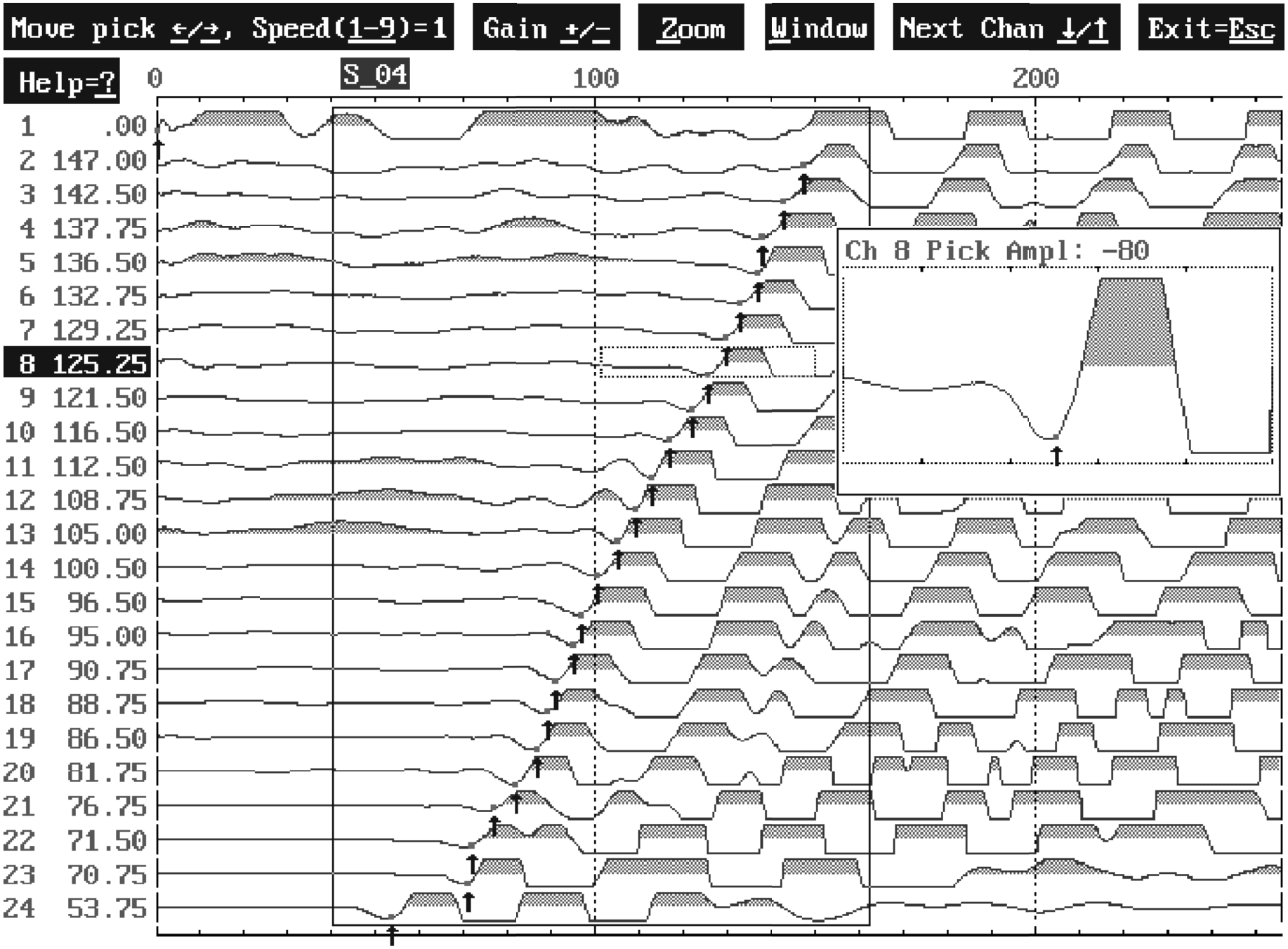

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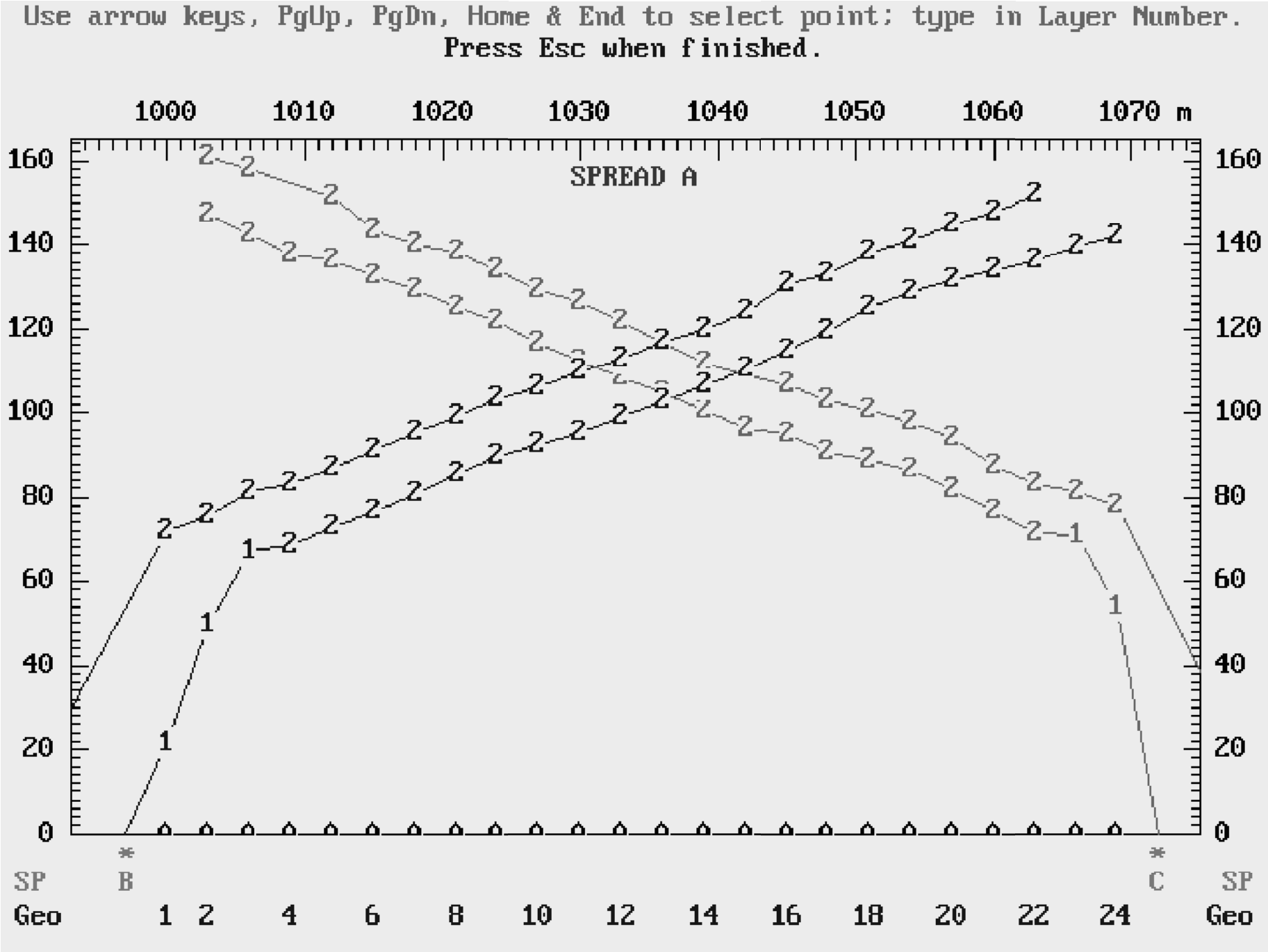

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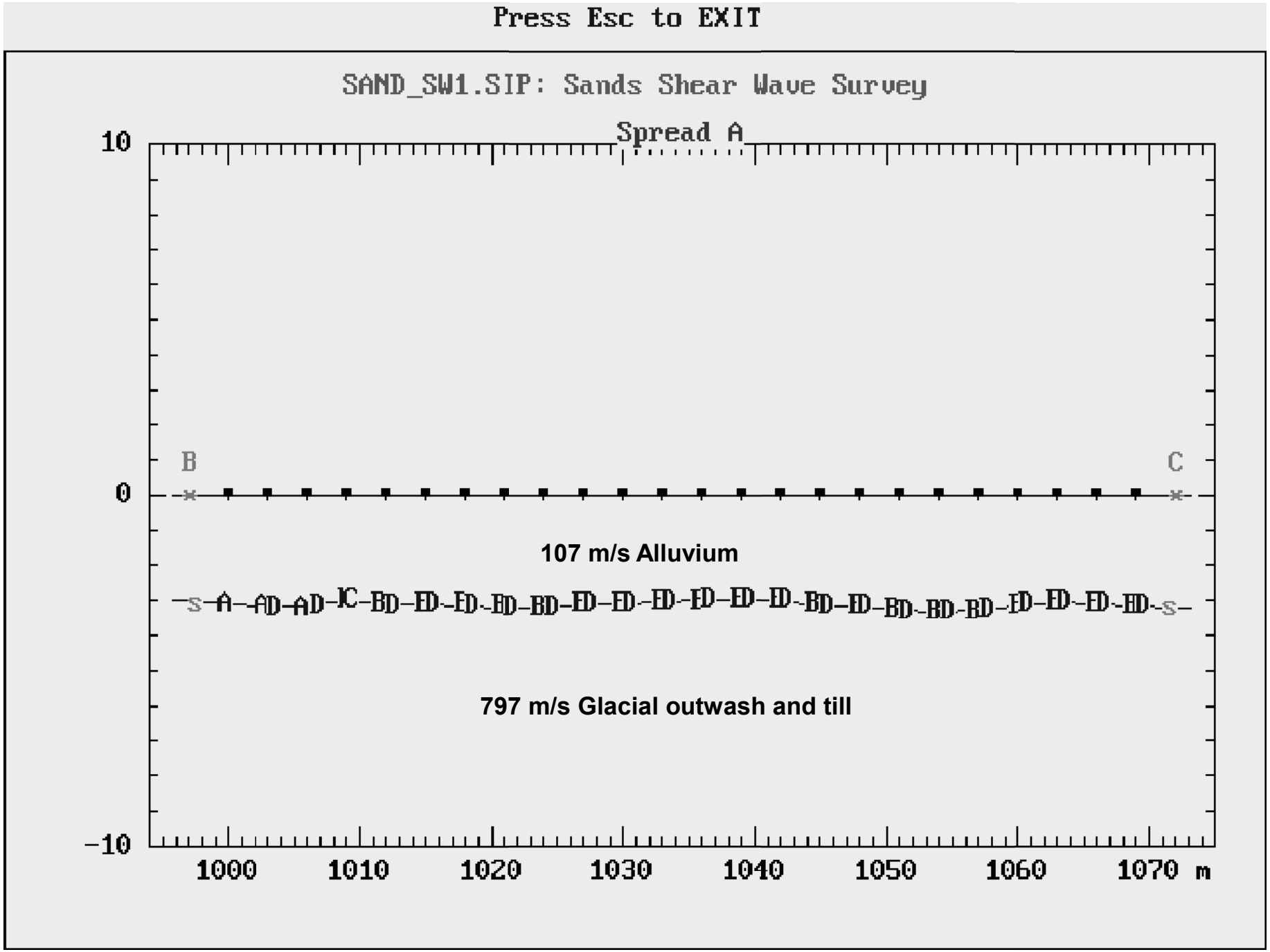

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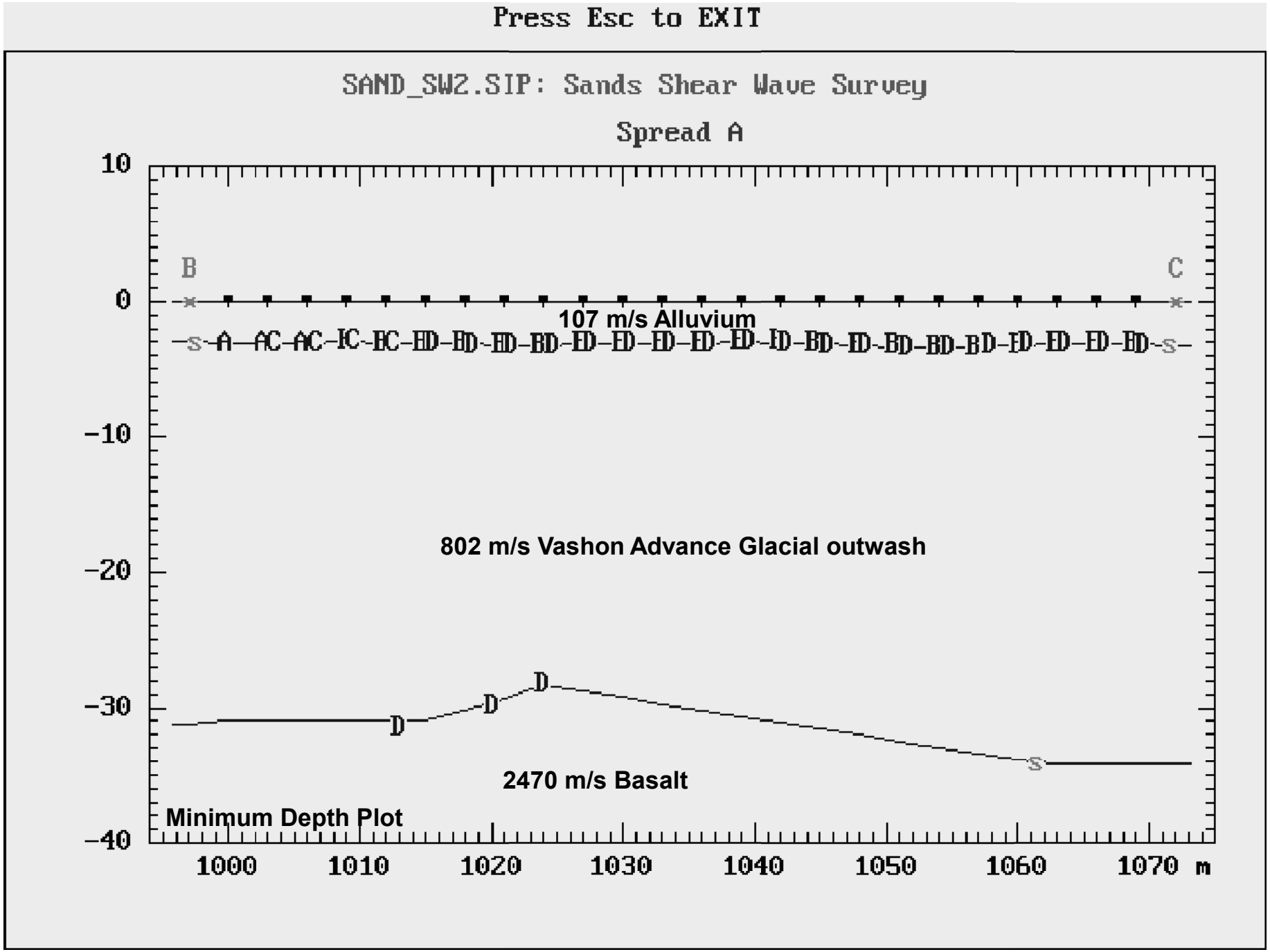

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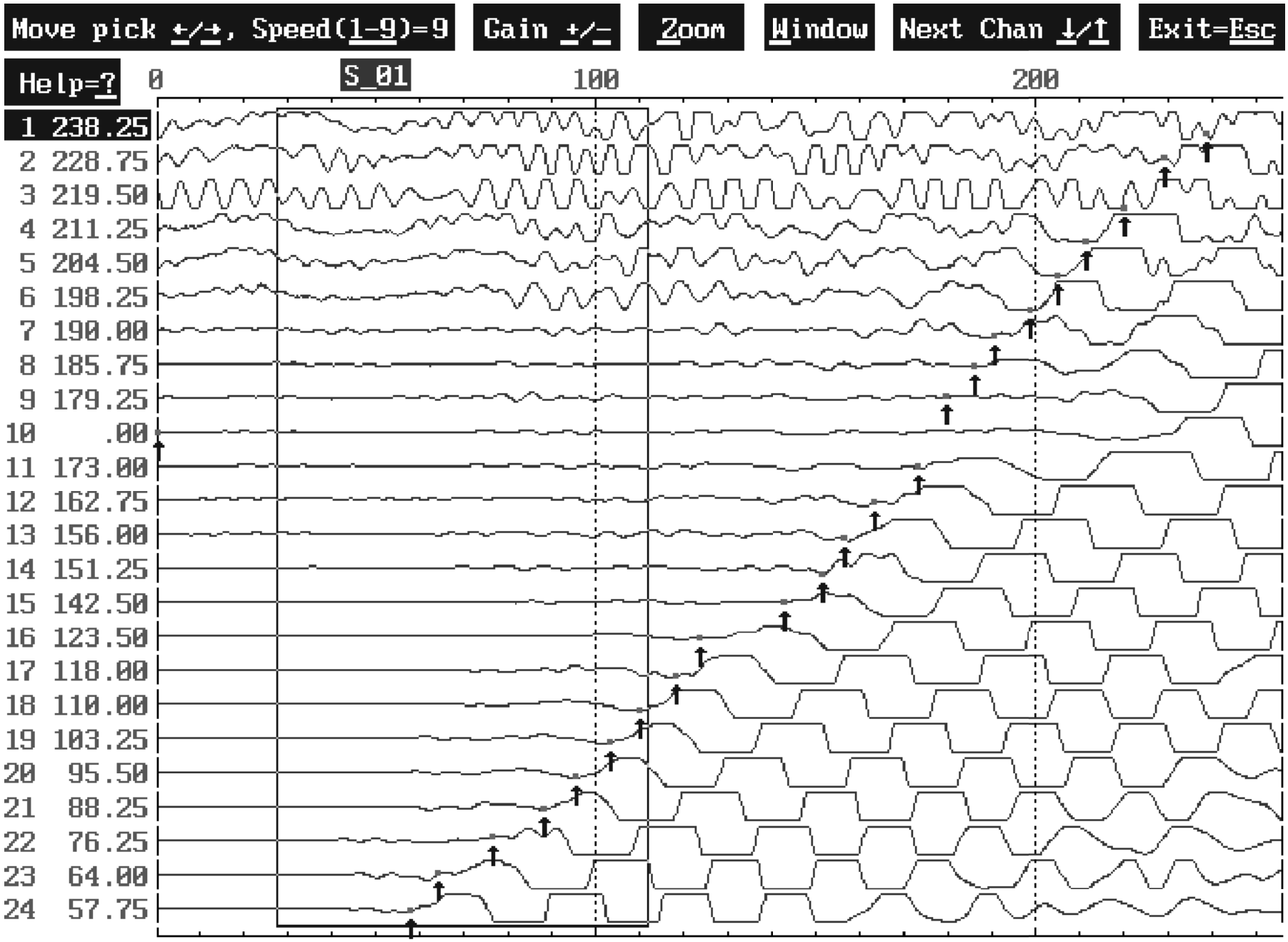

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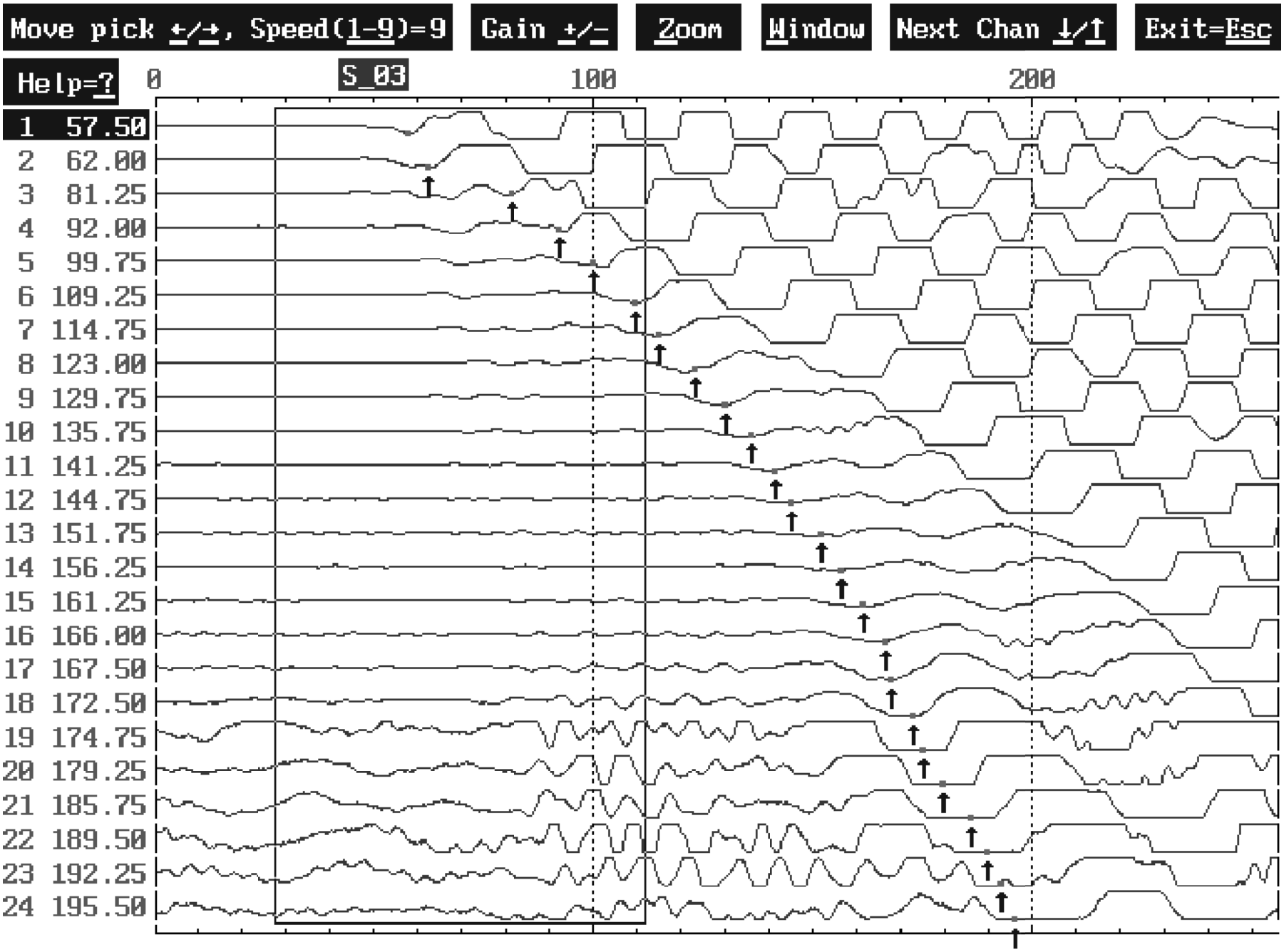

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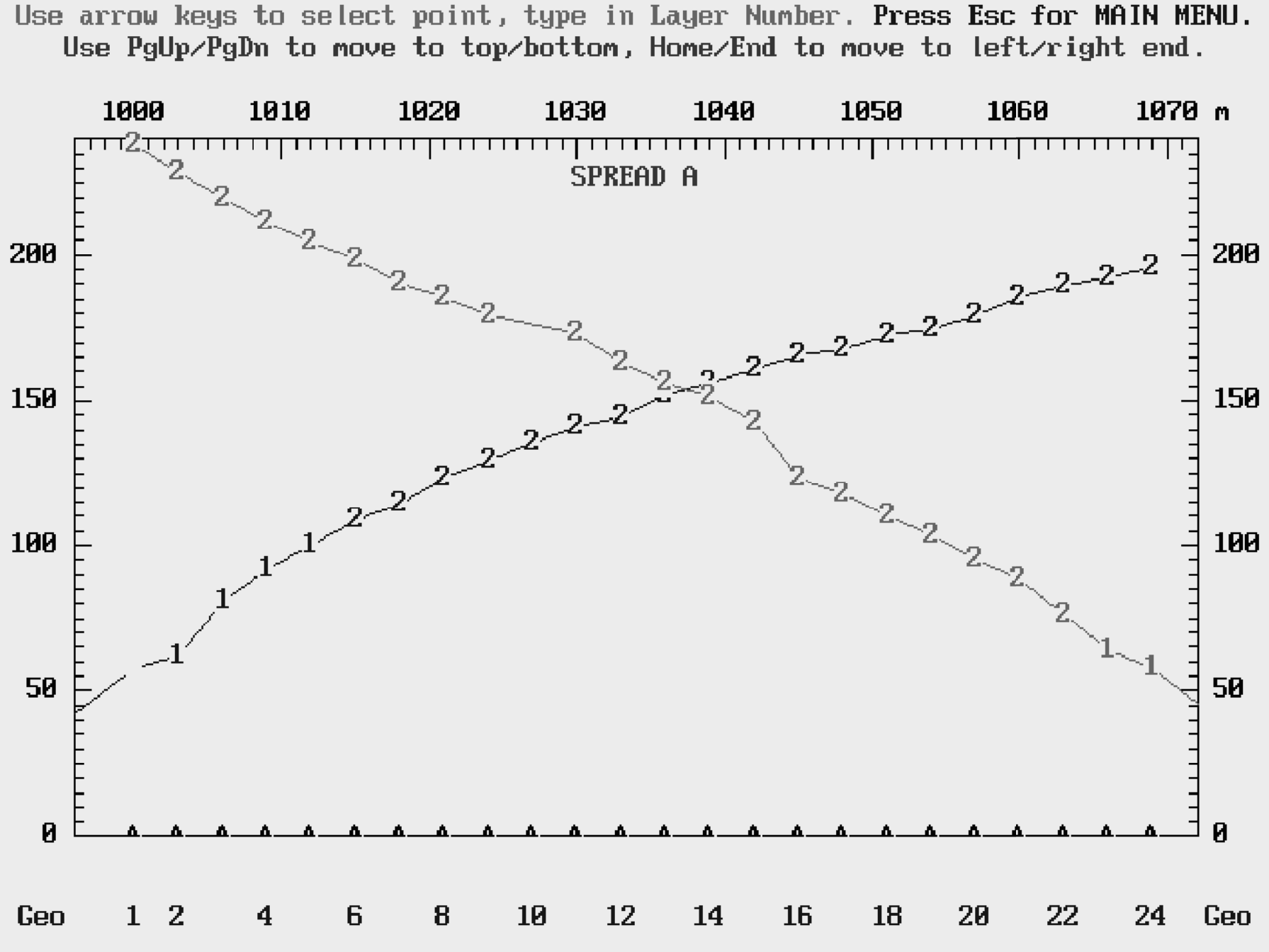

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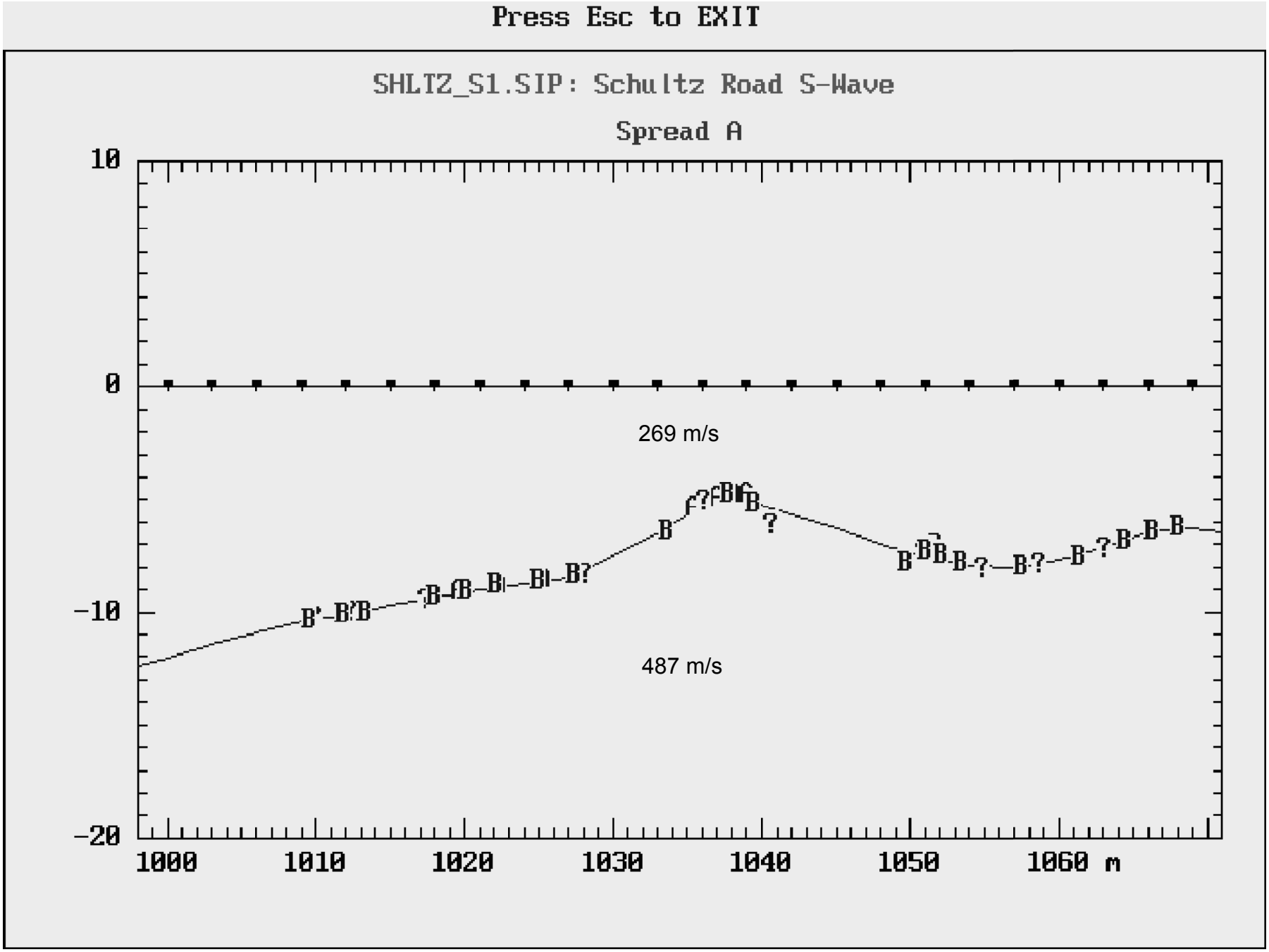

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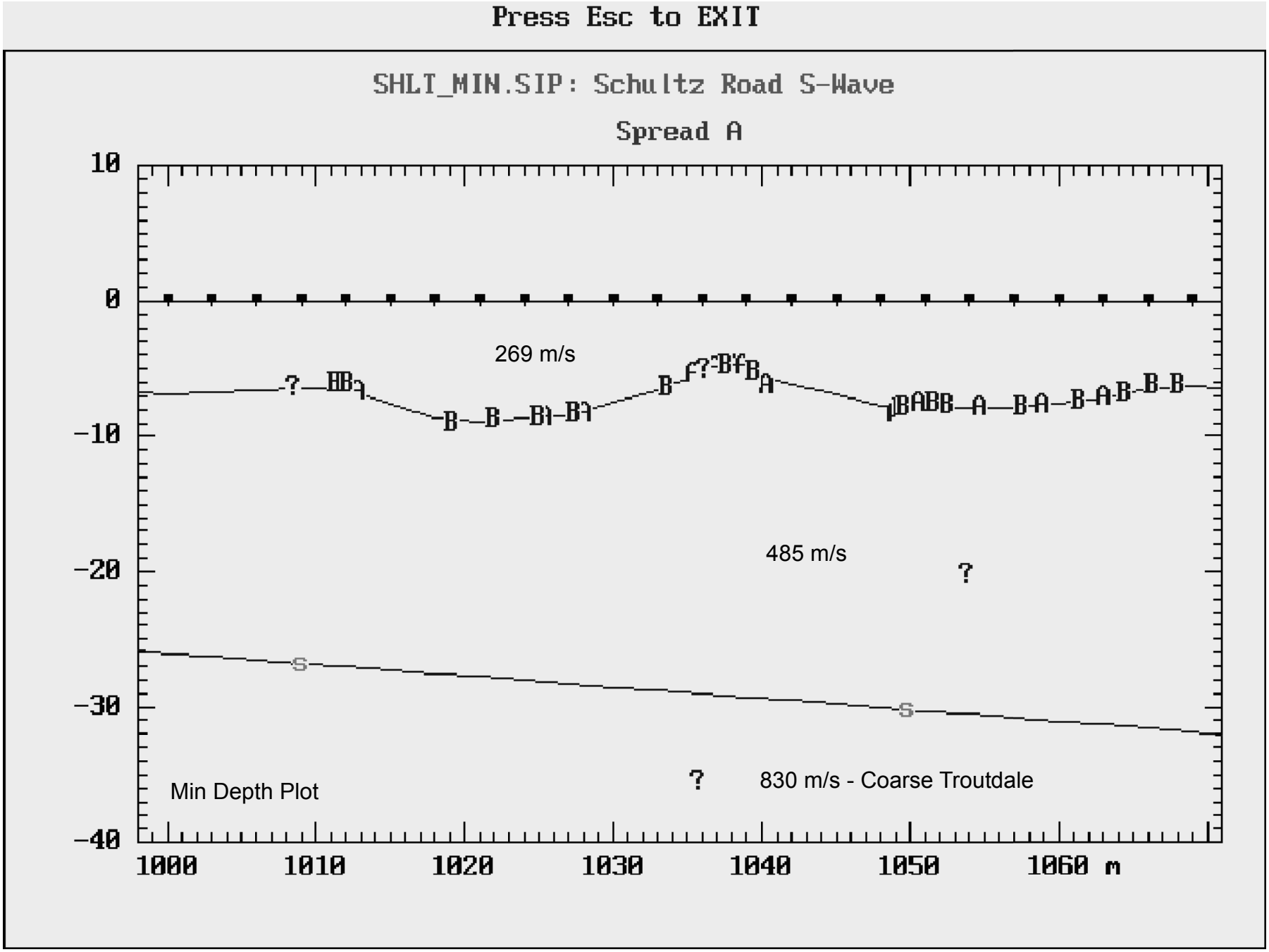

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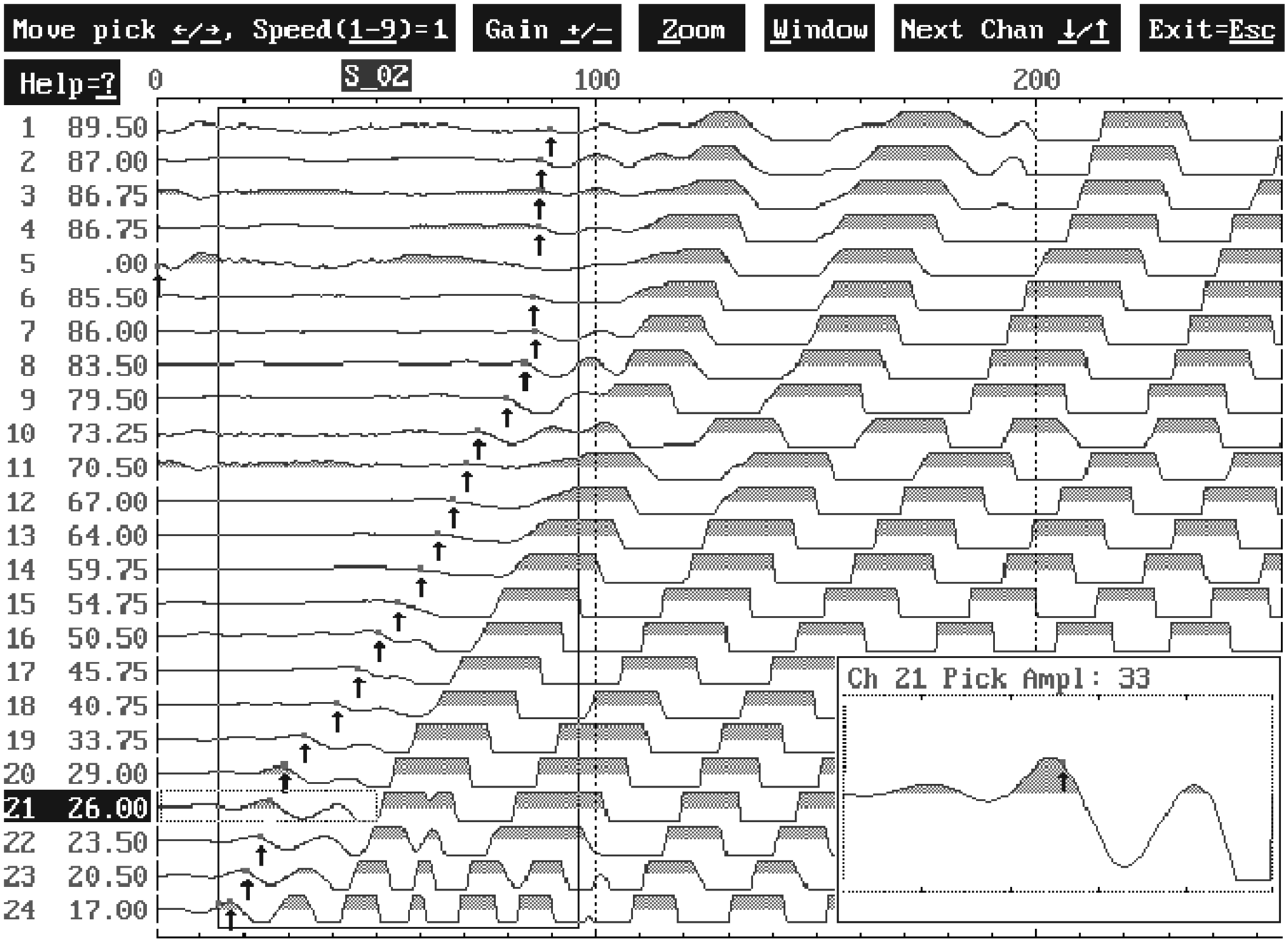

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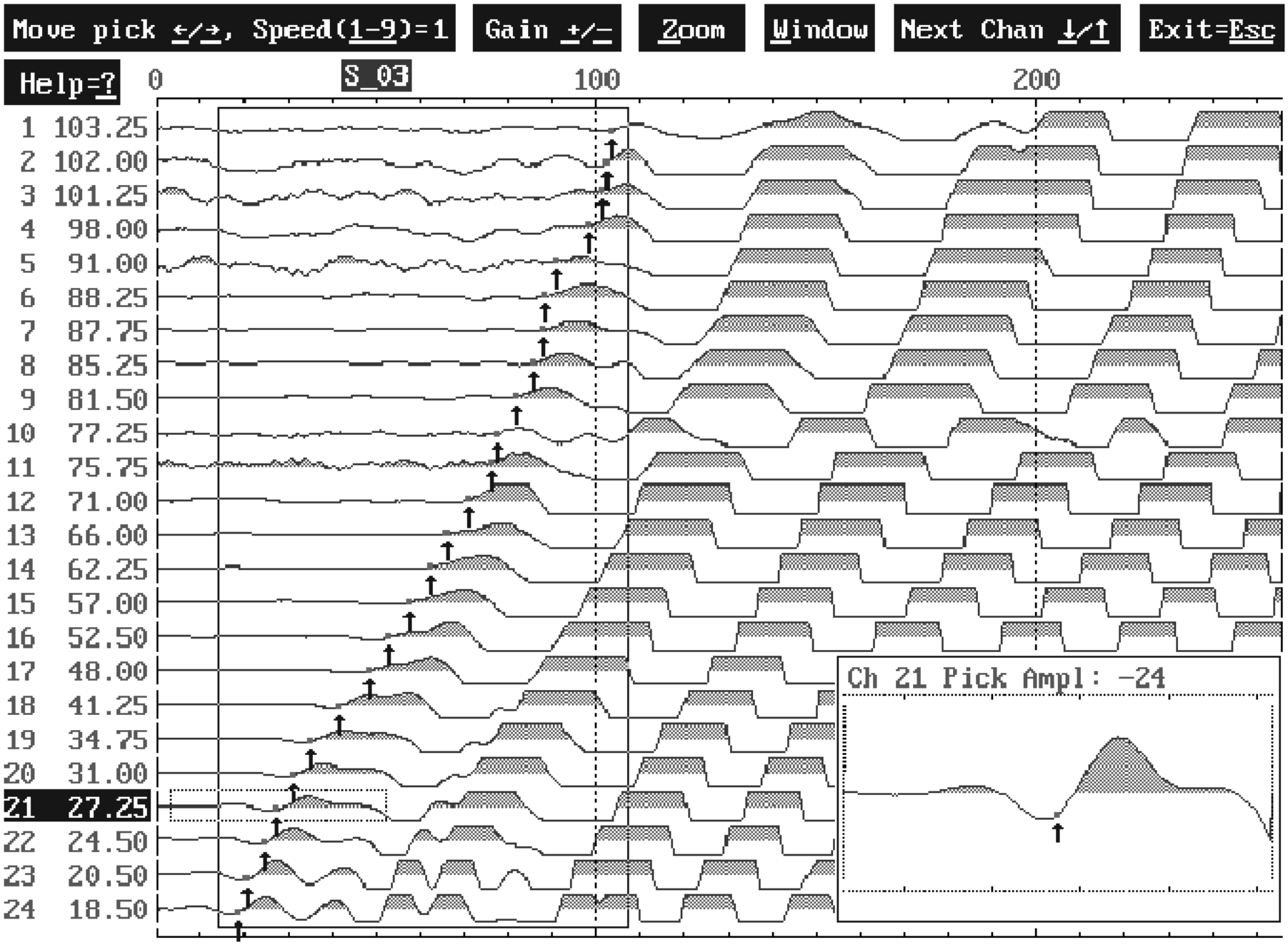

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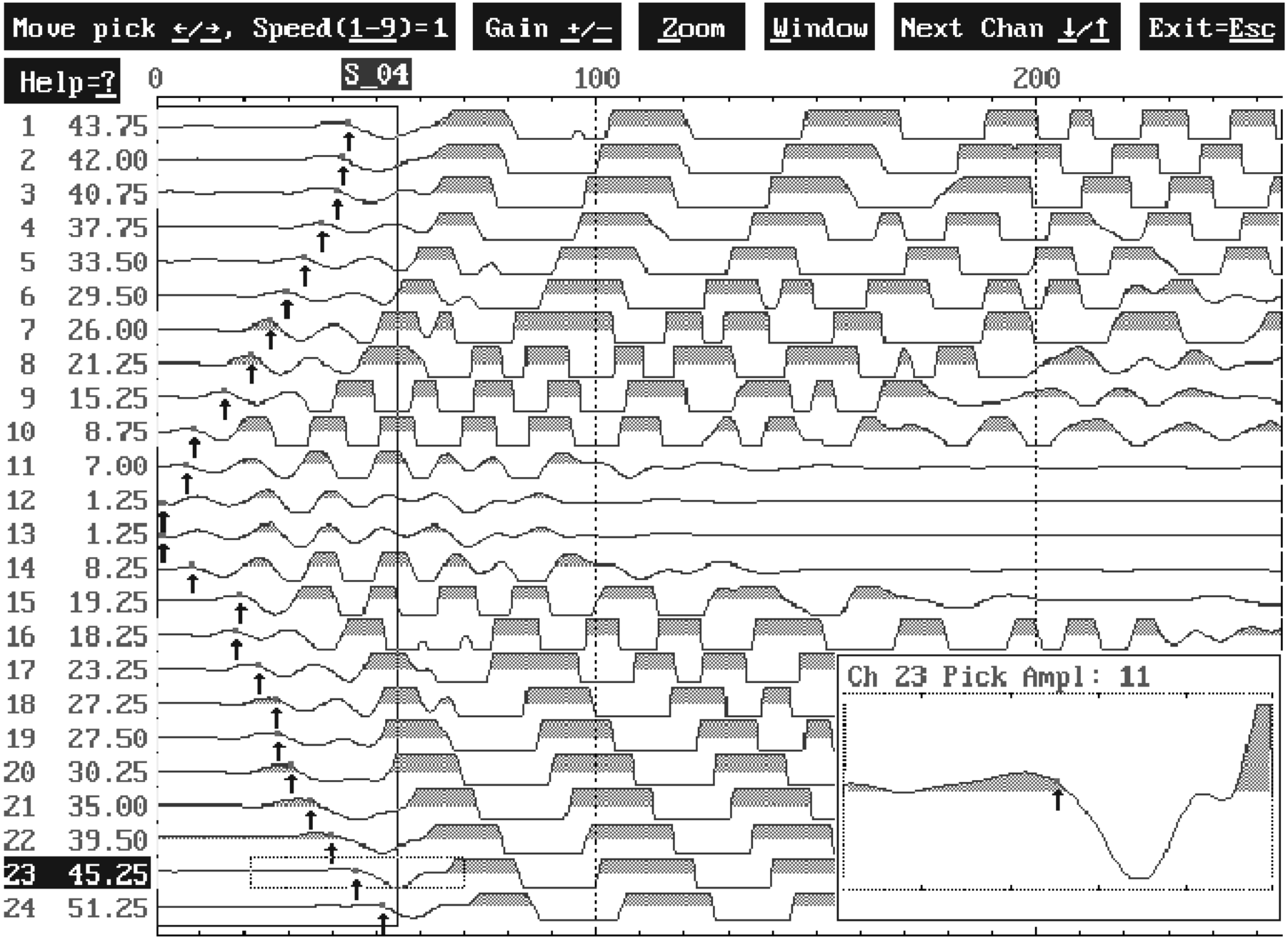

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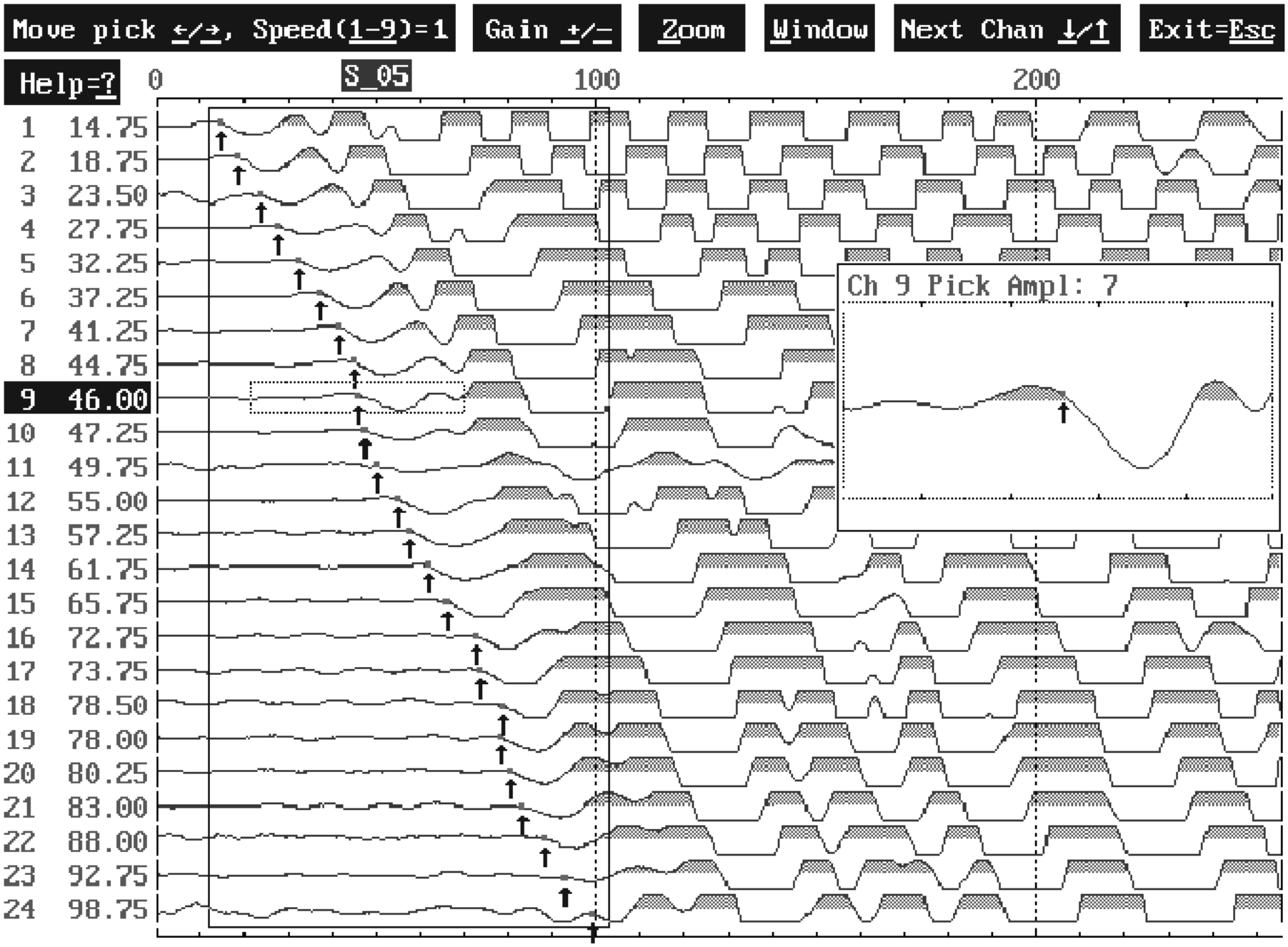

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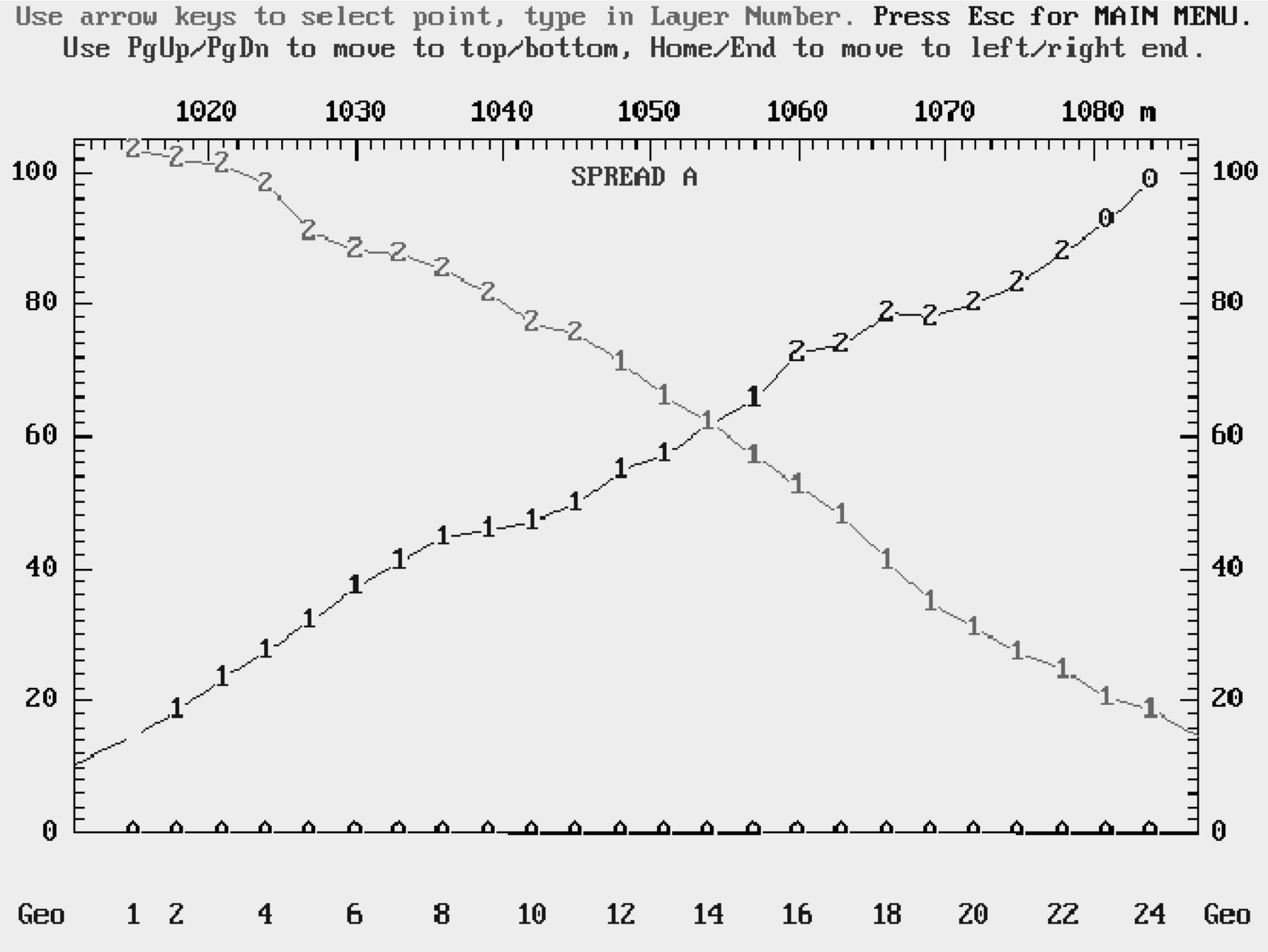

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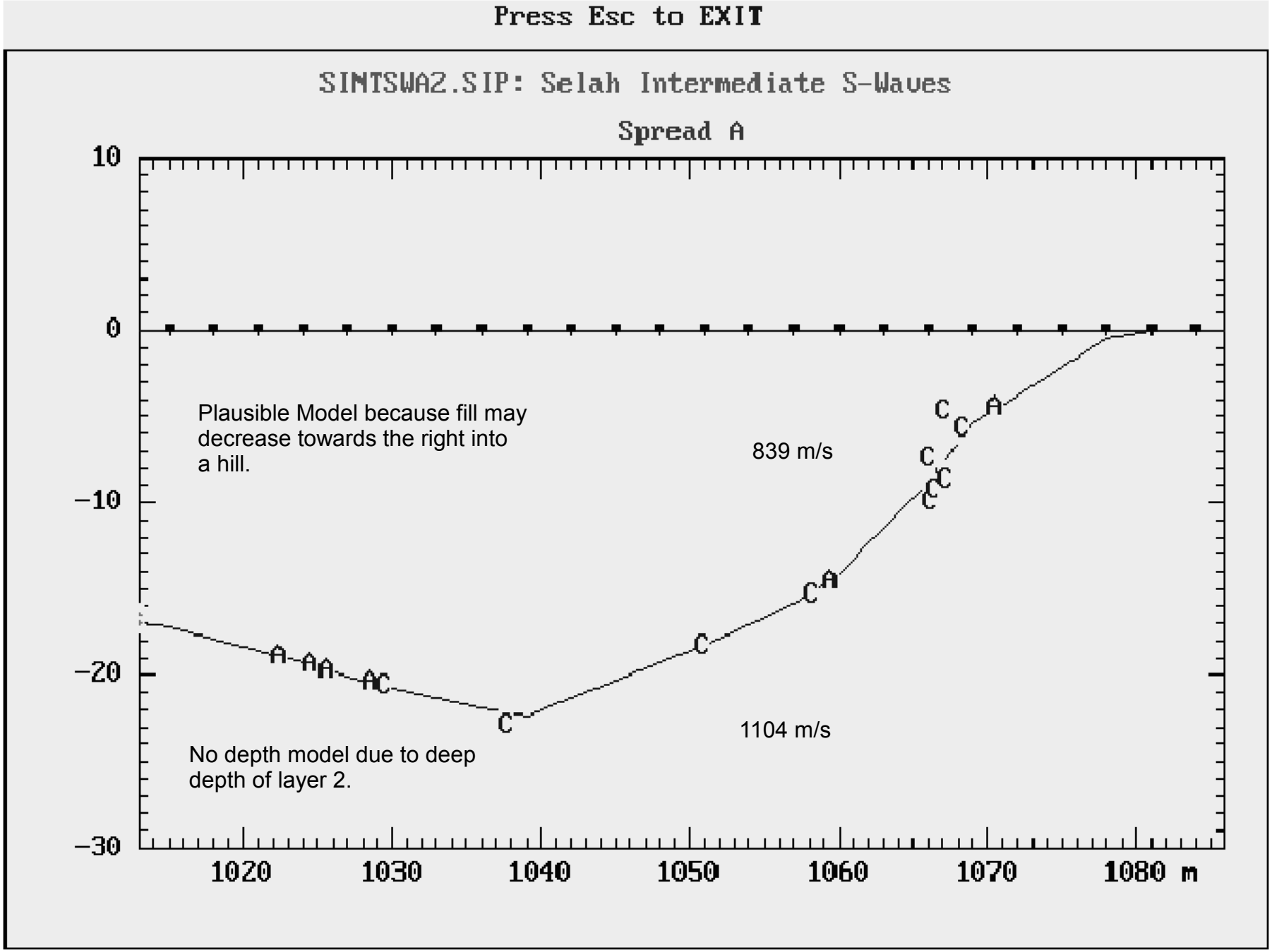

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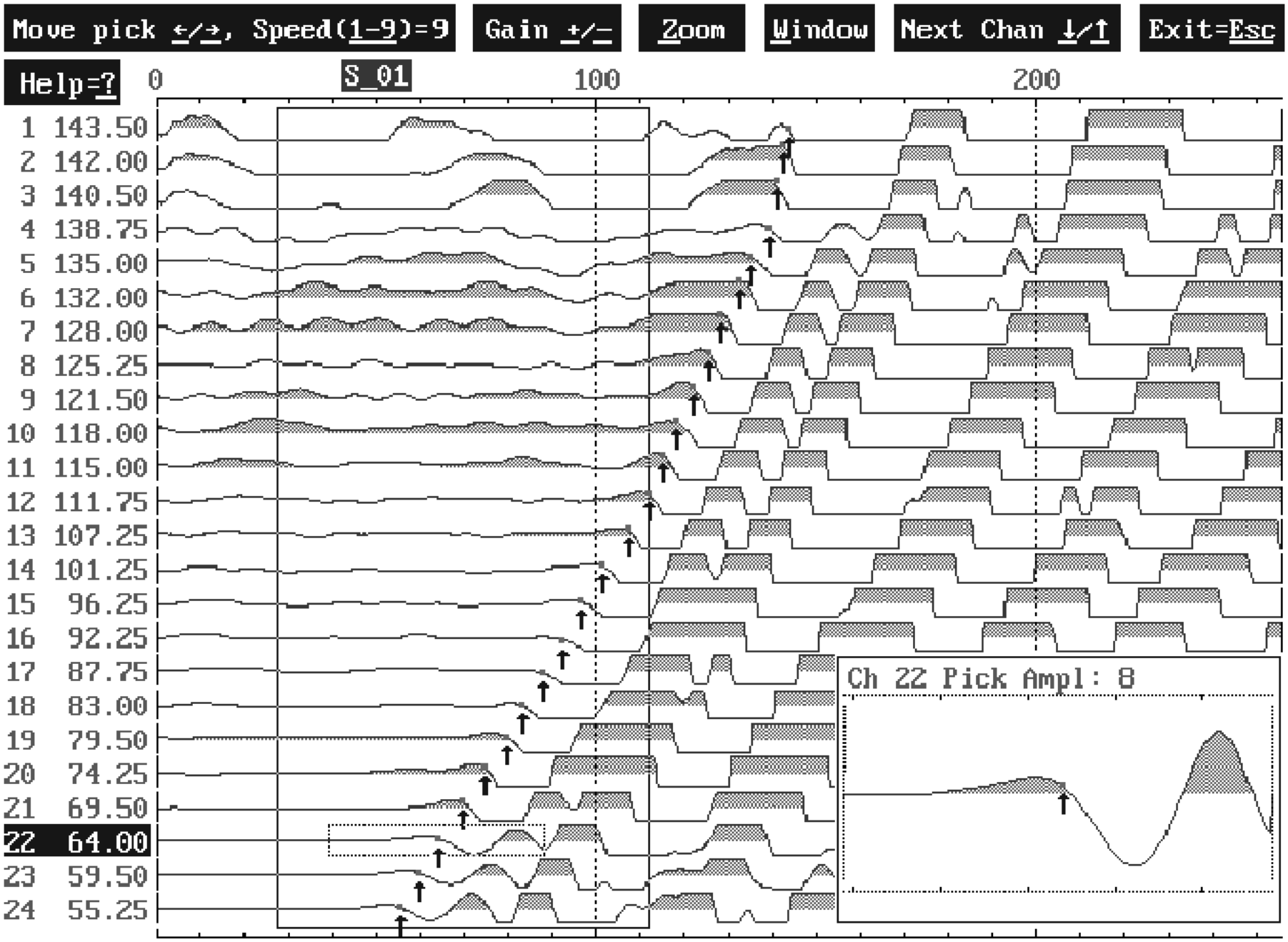

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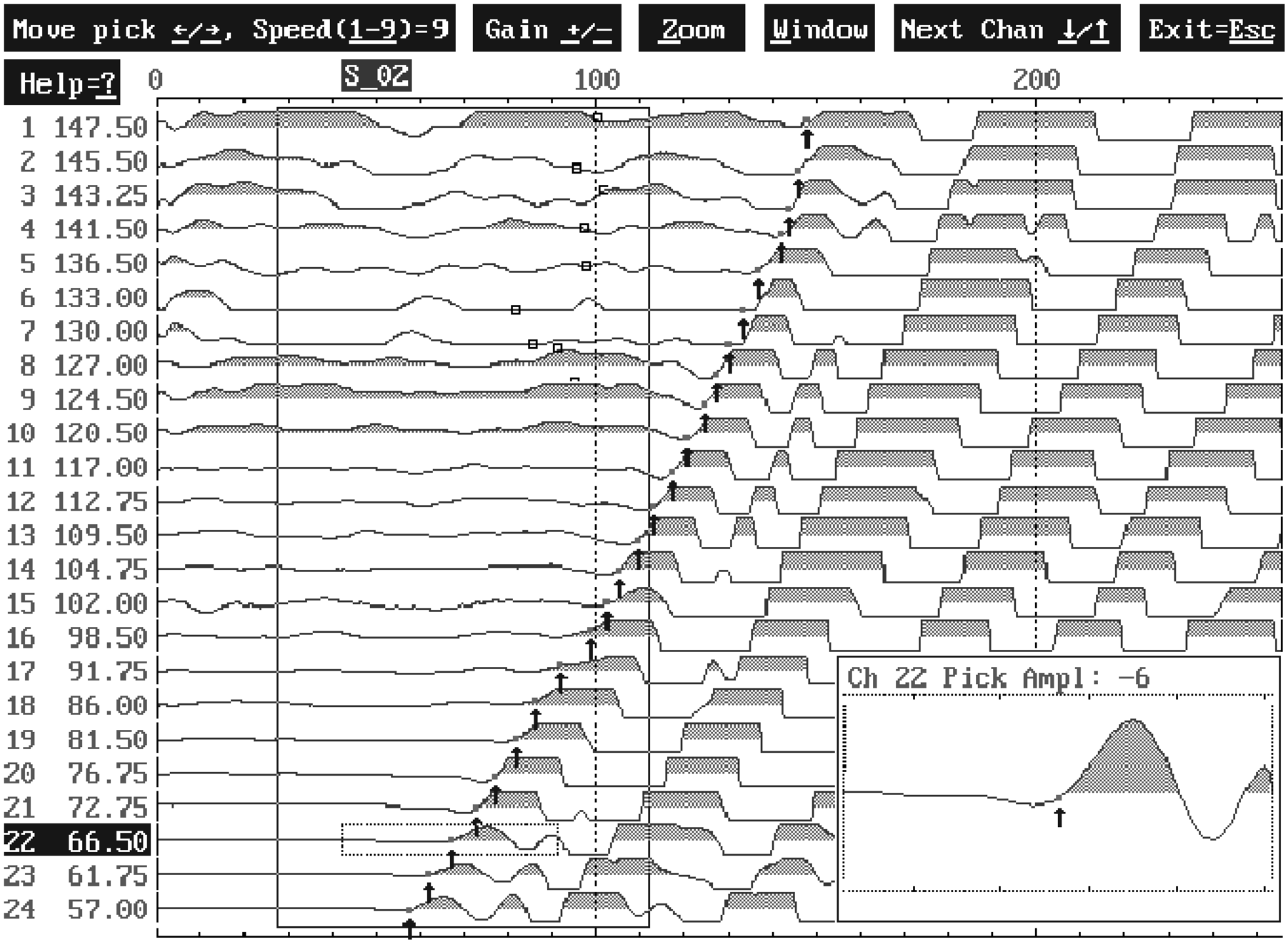

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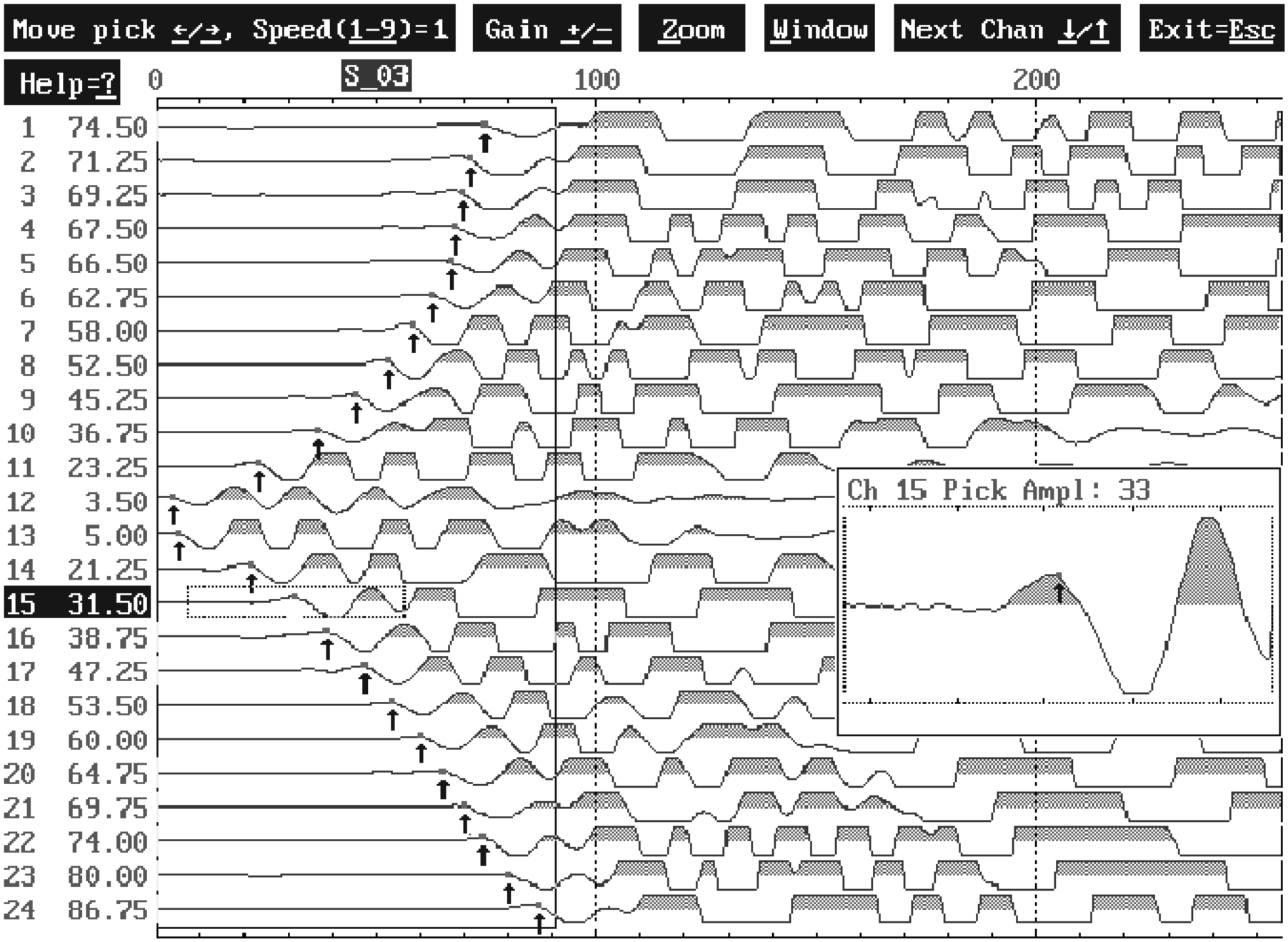

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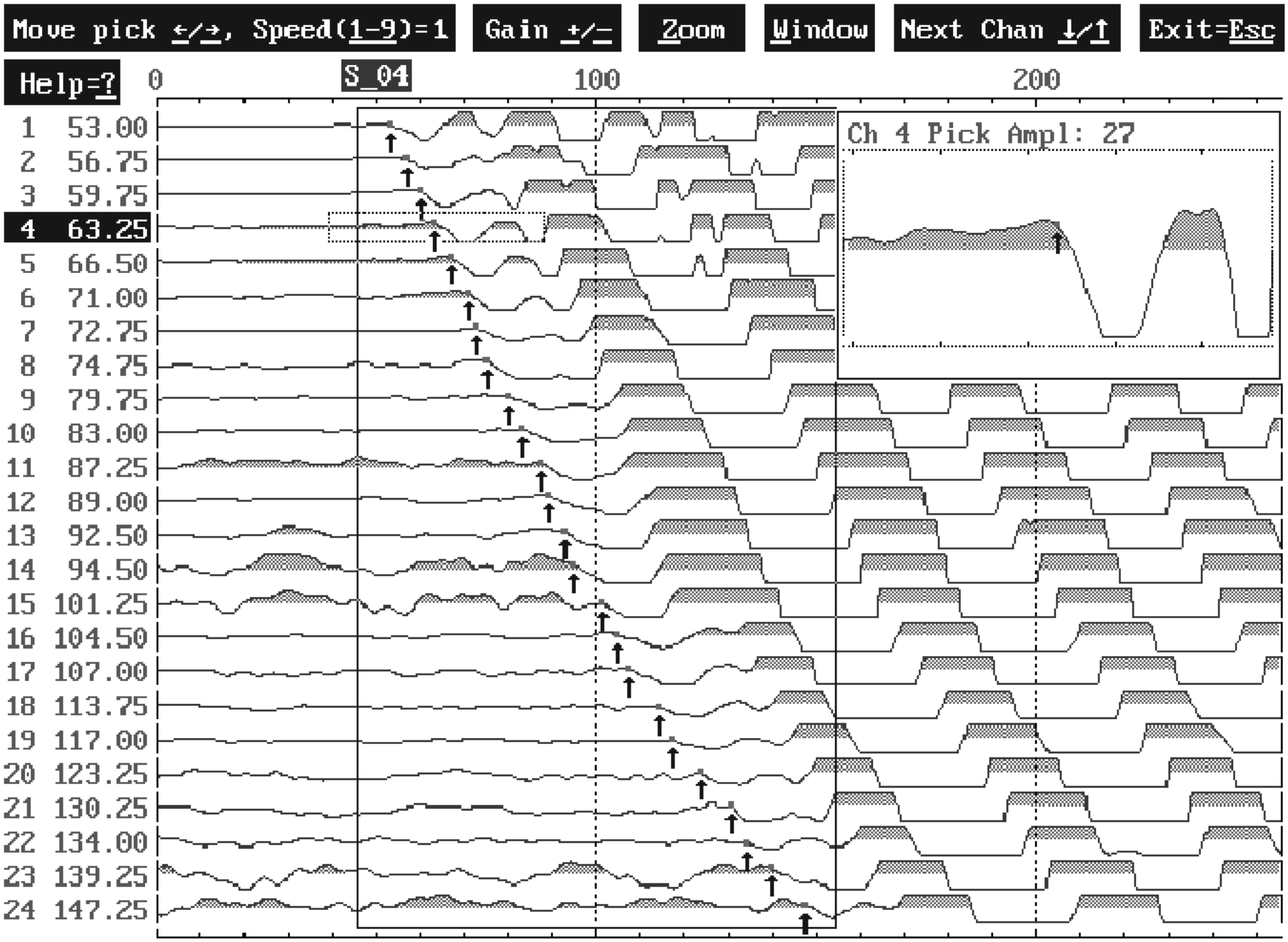

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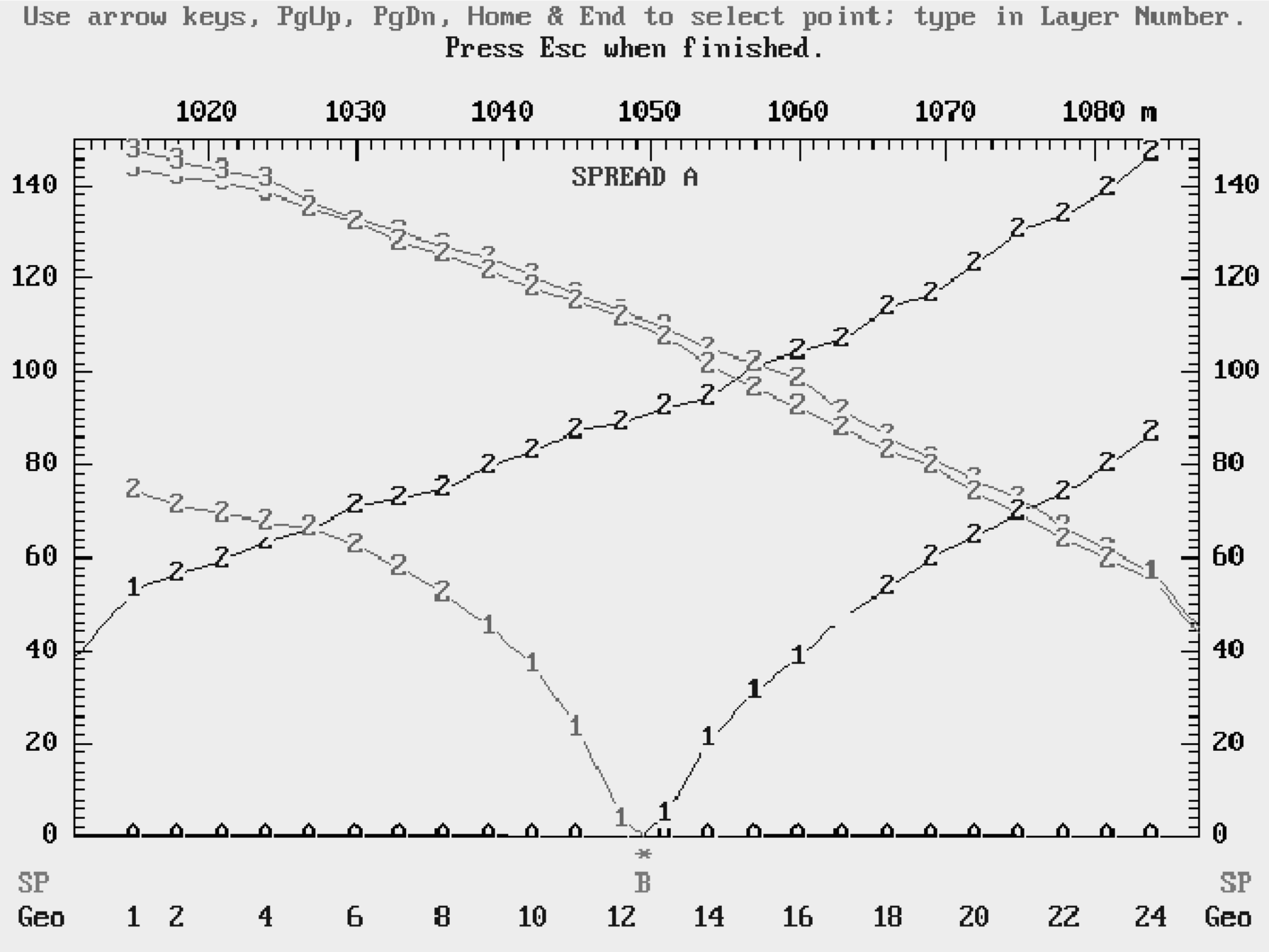

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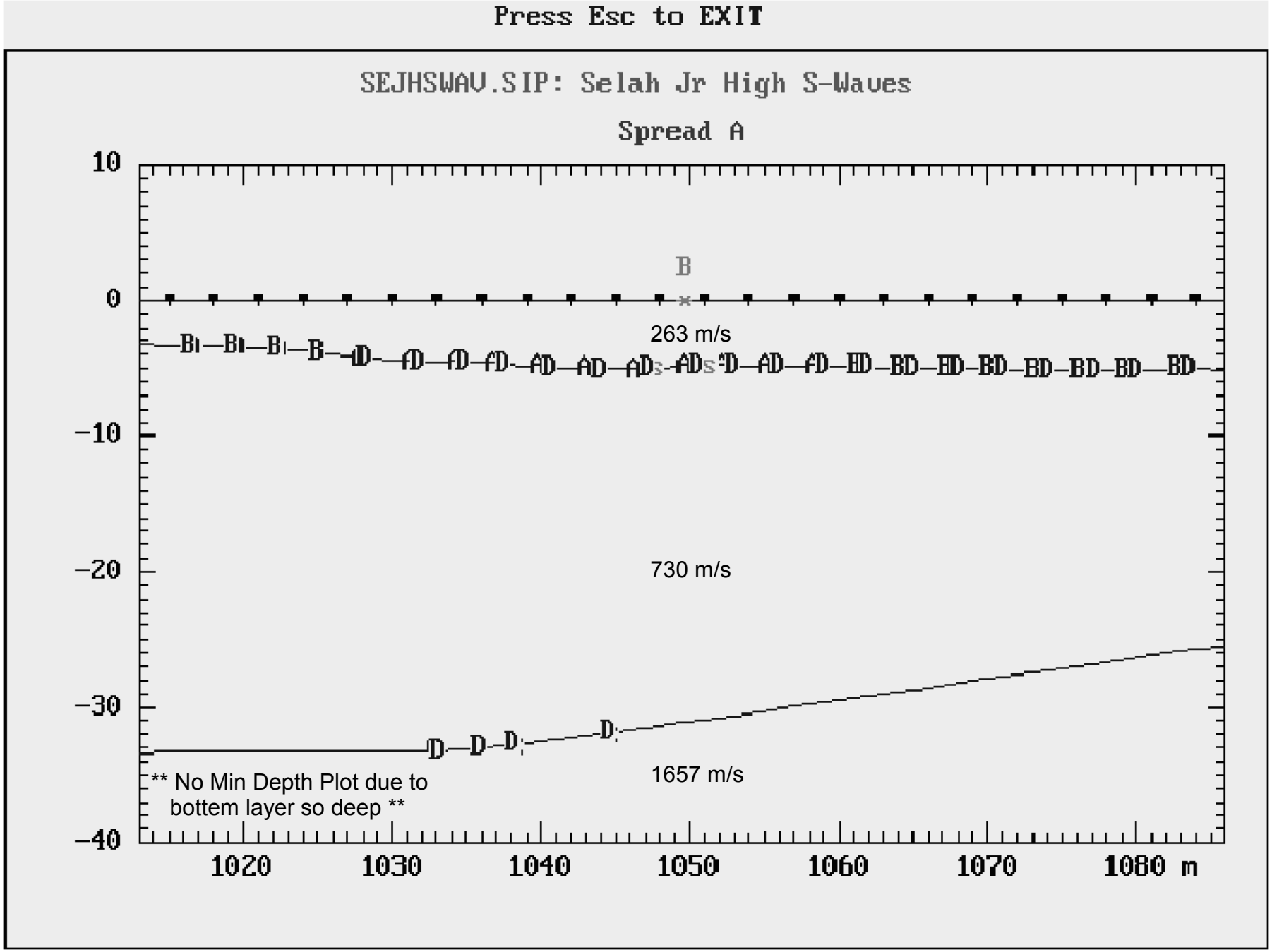
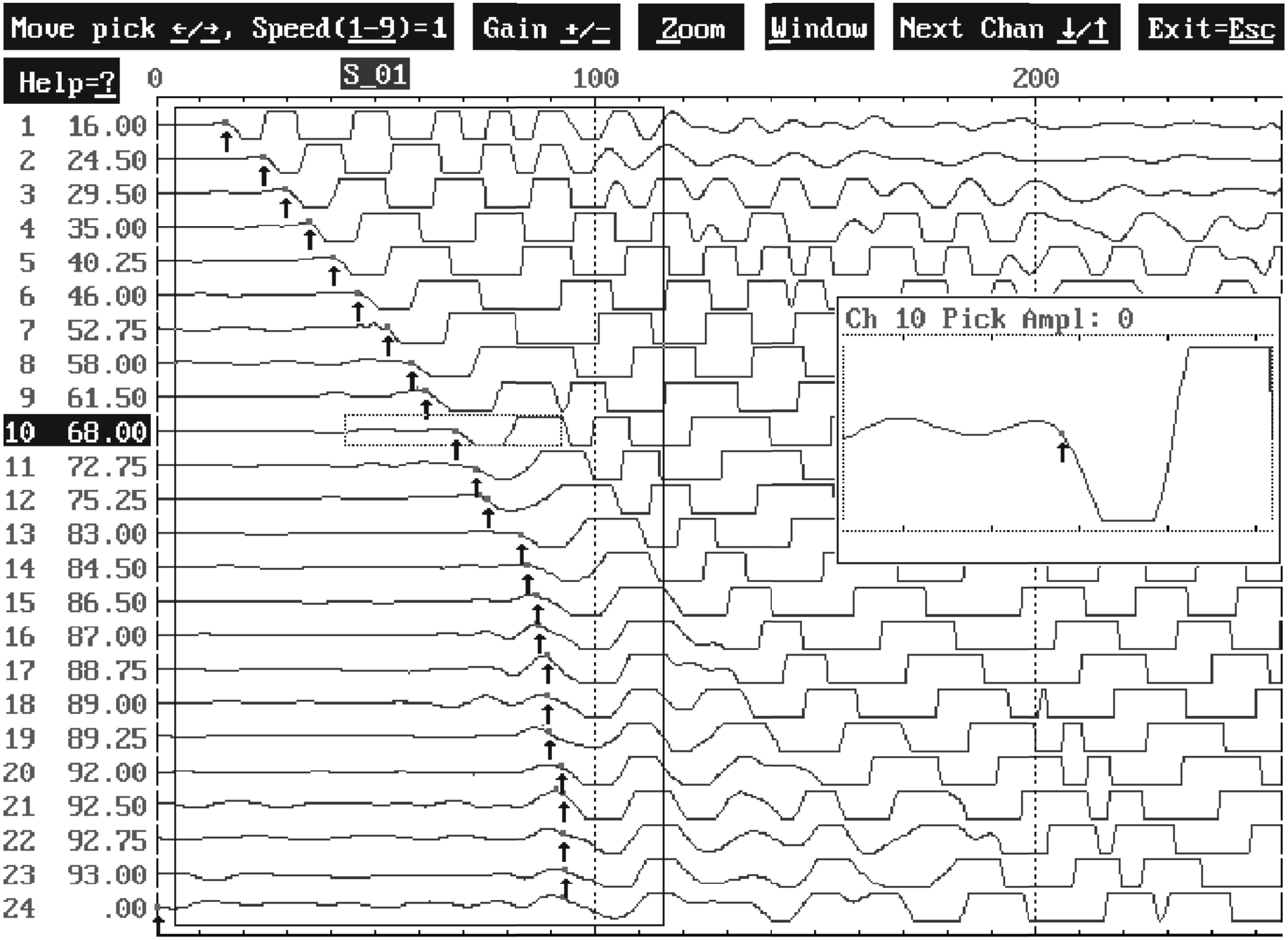
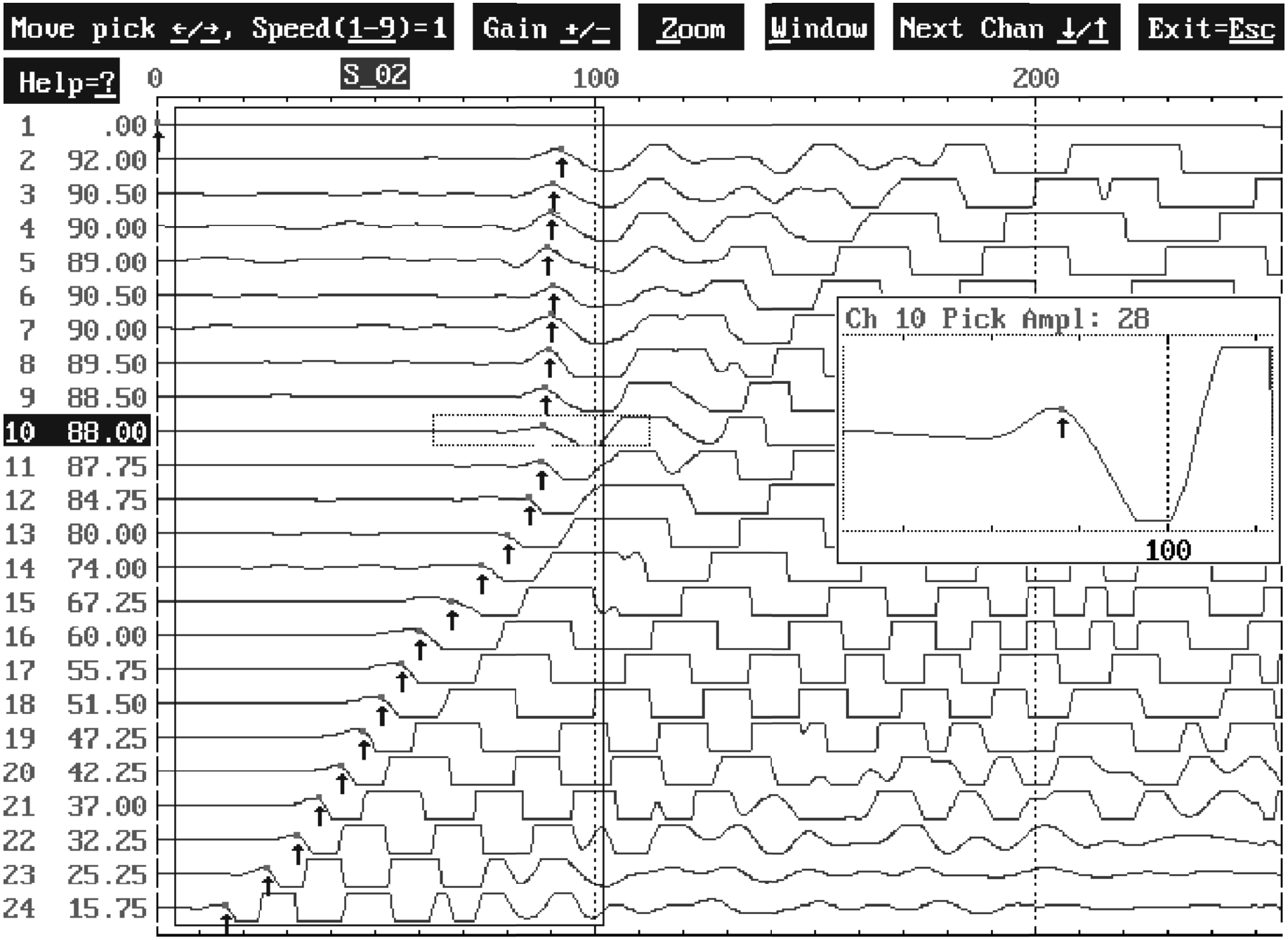


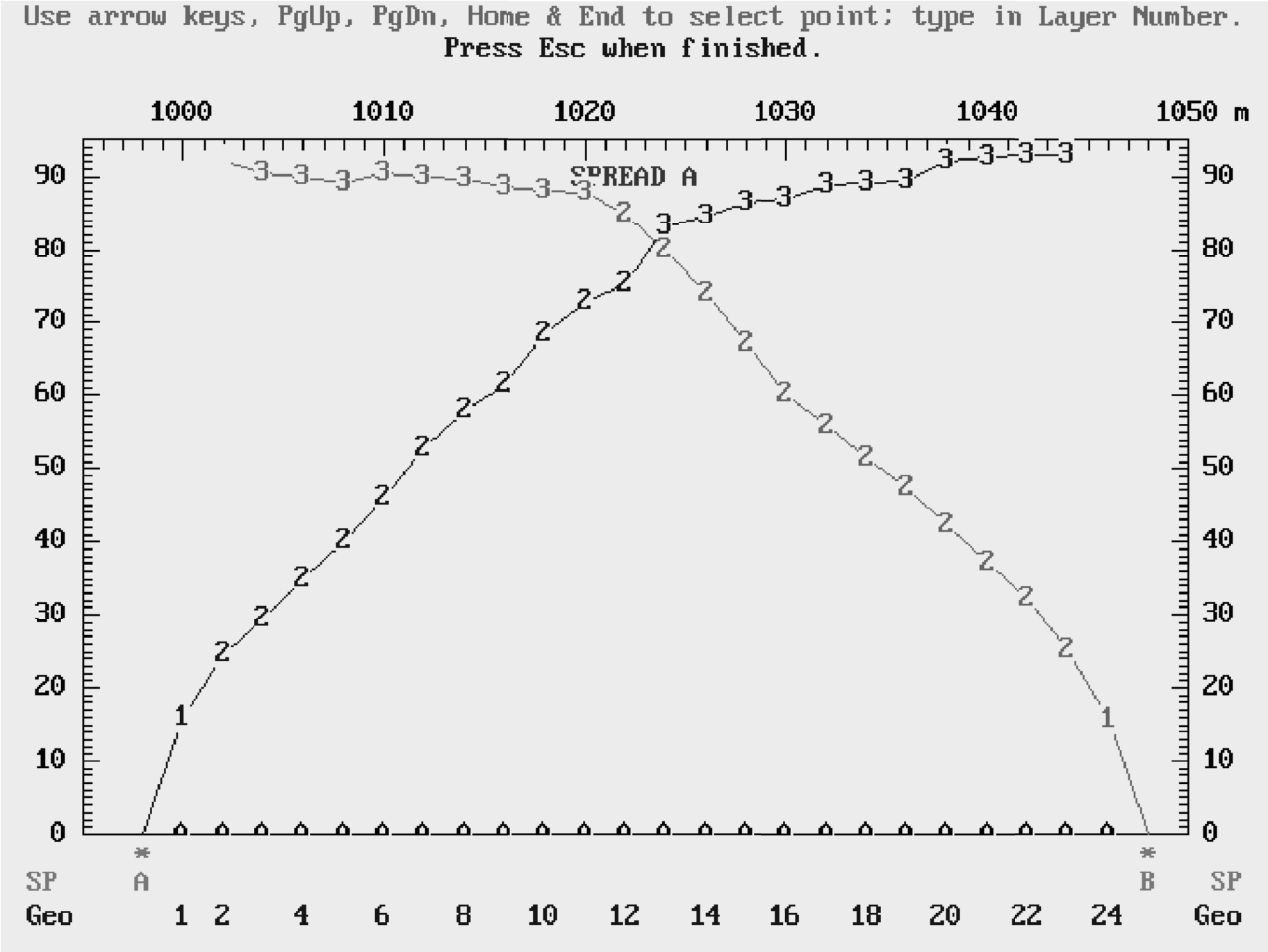
Sheffler Road S-wave



Sheffler Road S-wave



Sheffler Road S-wave



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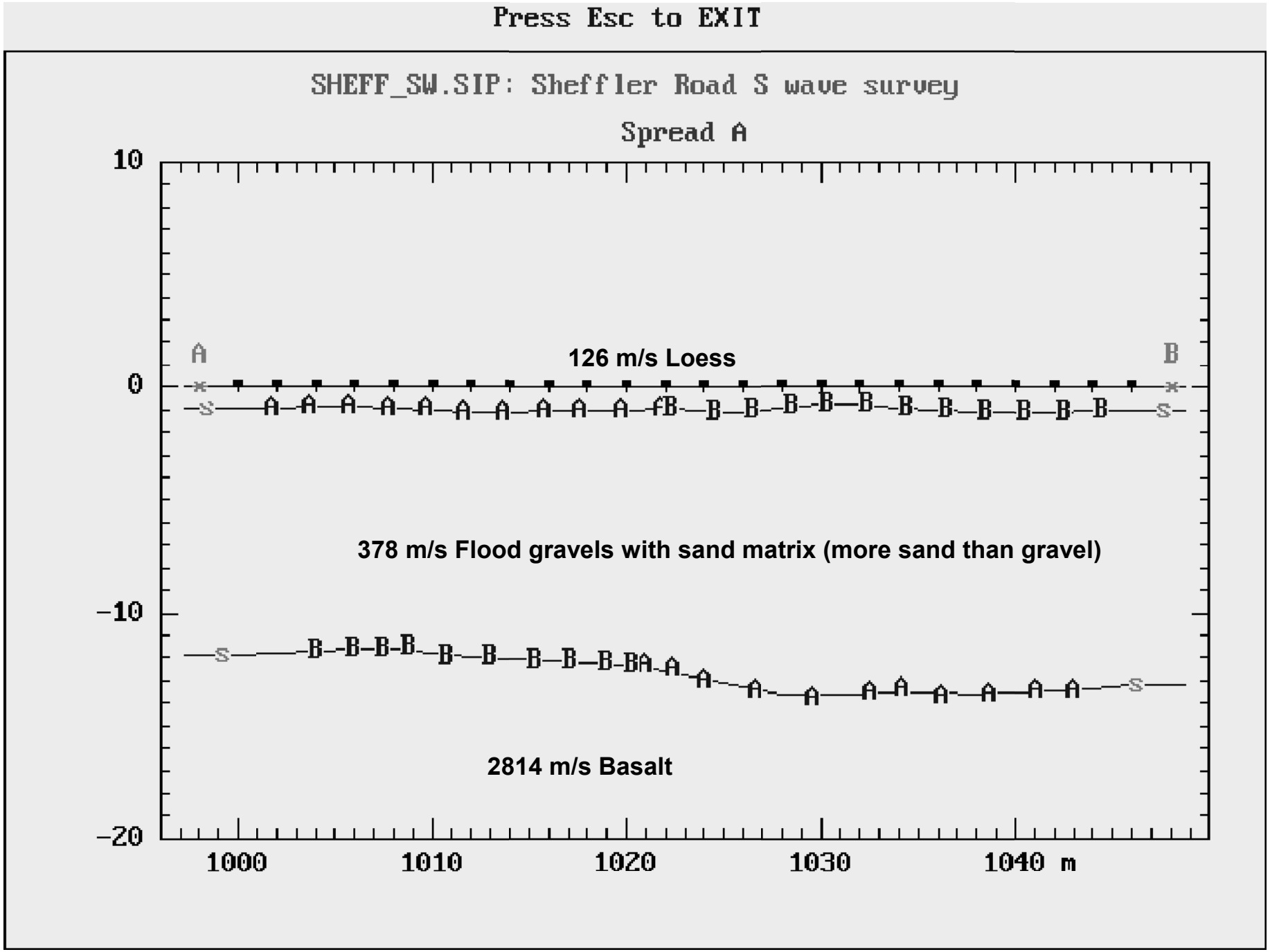

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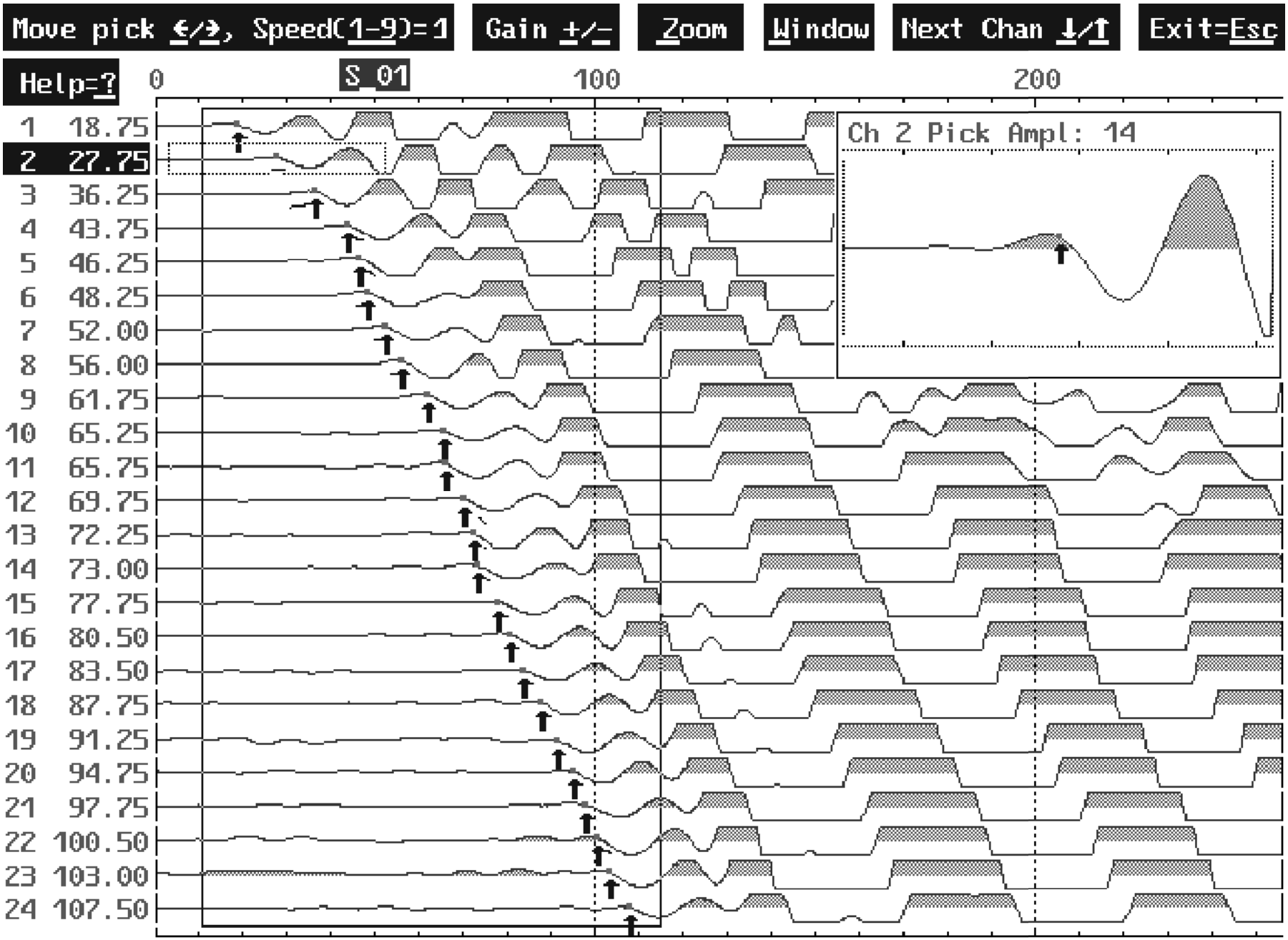

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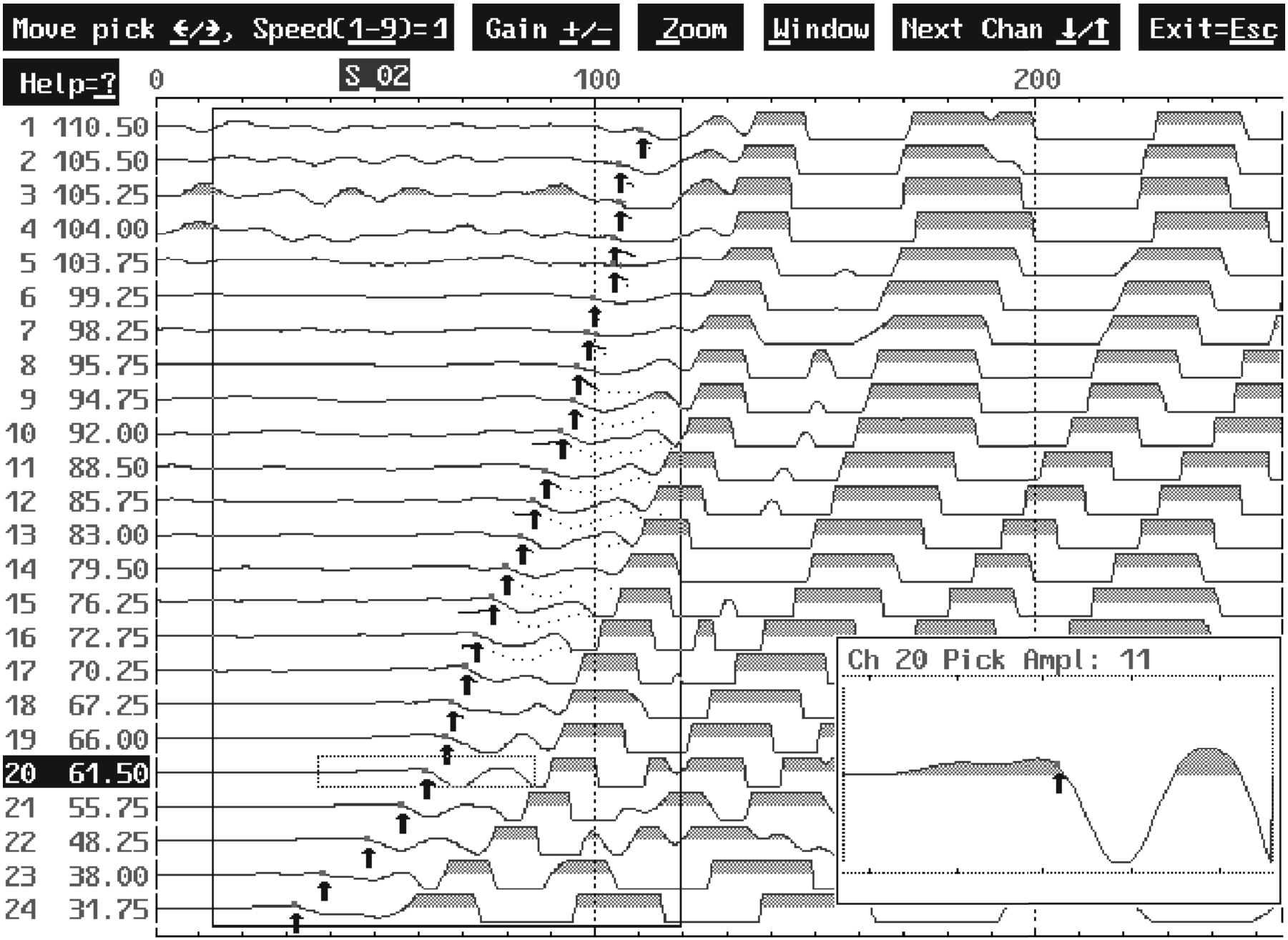

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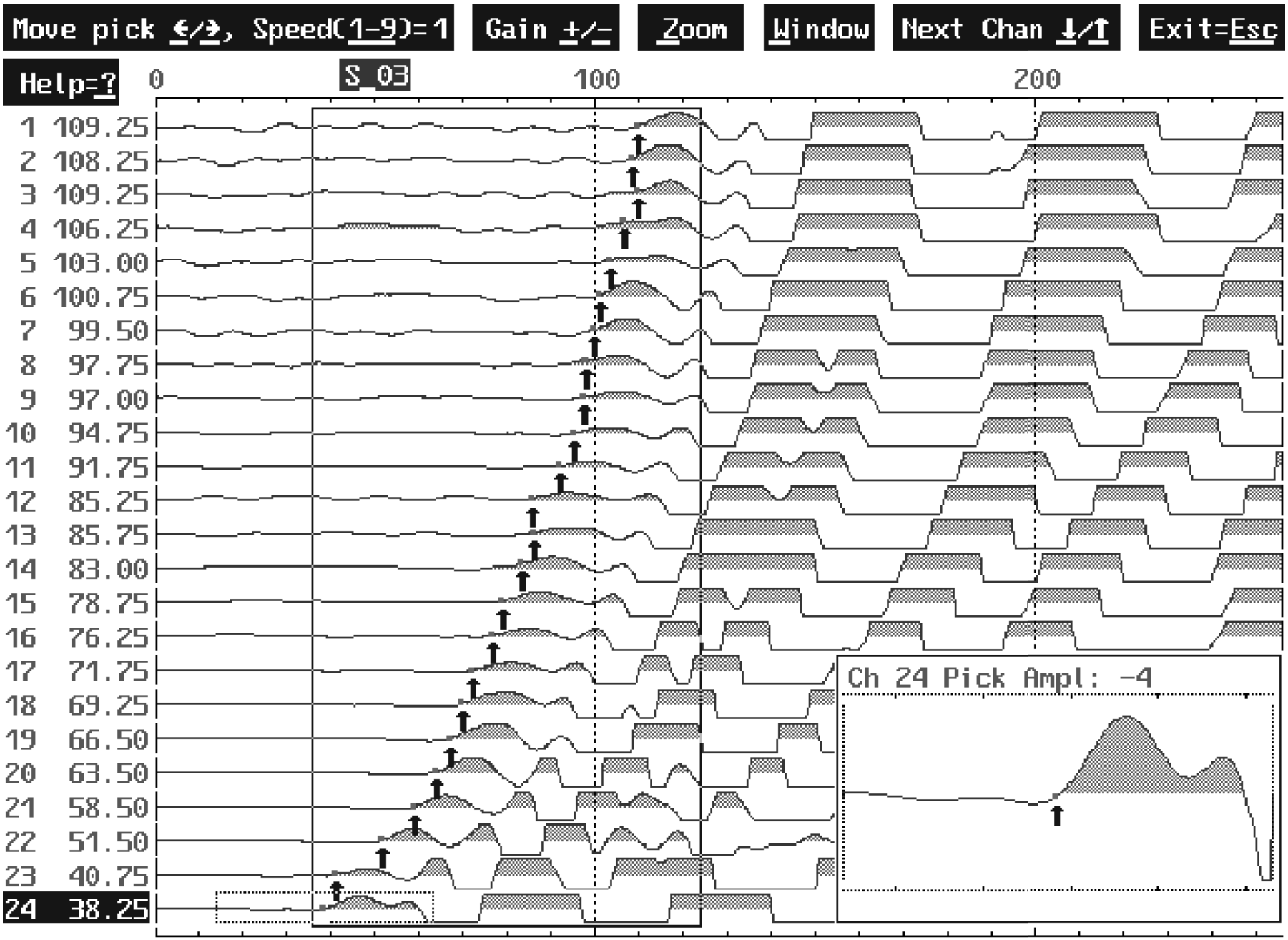

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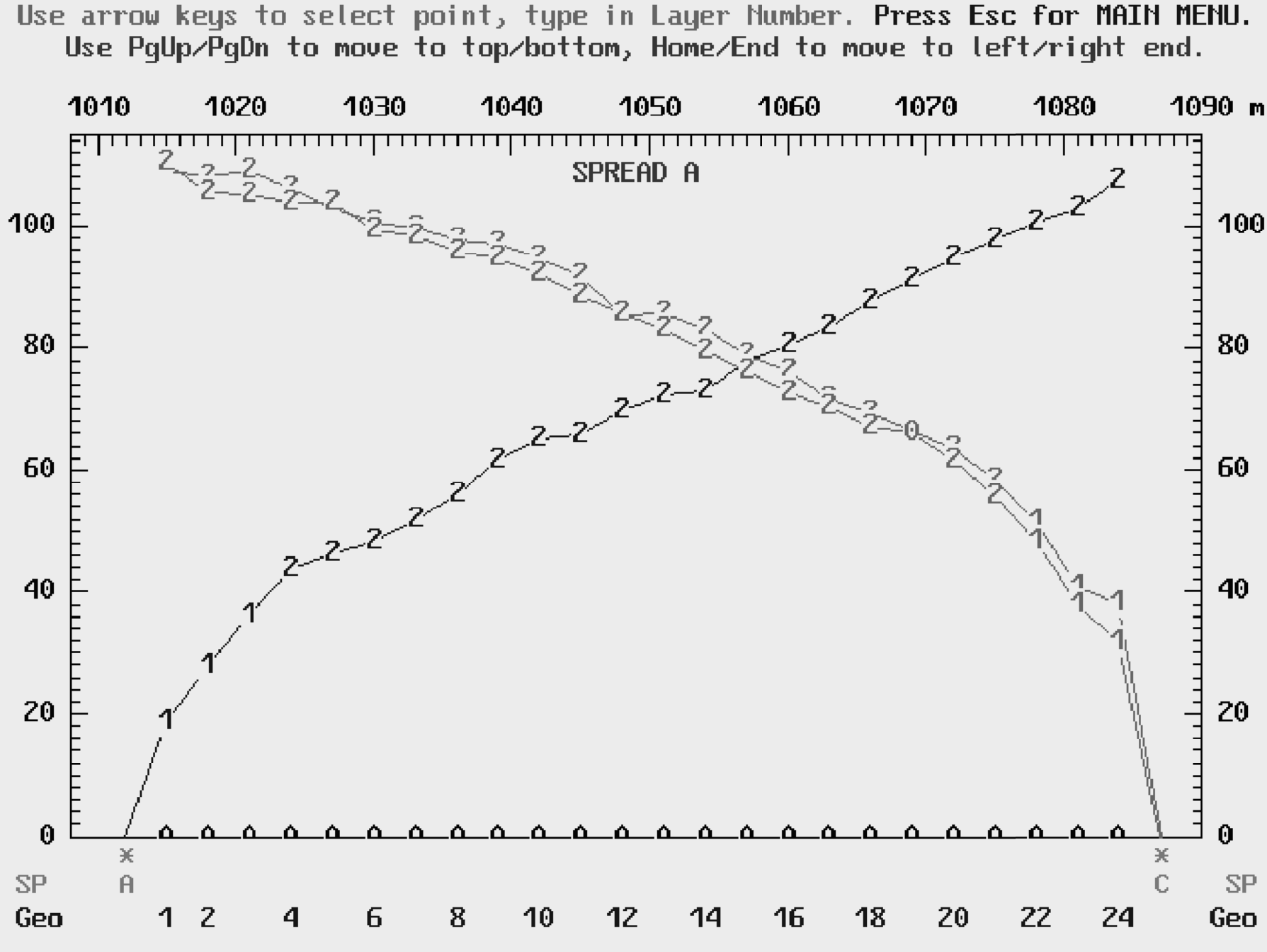

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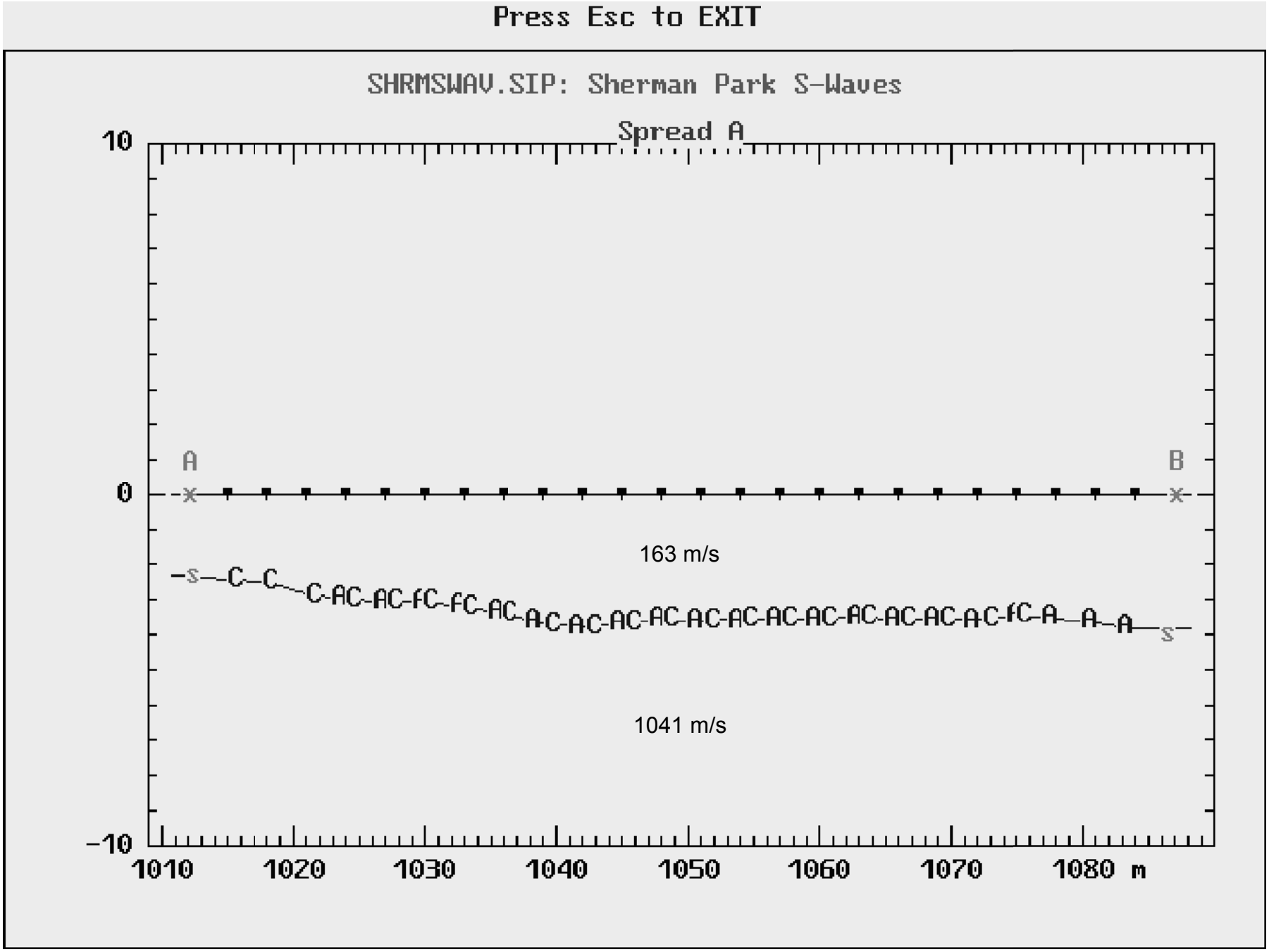

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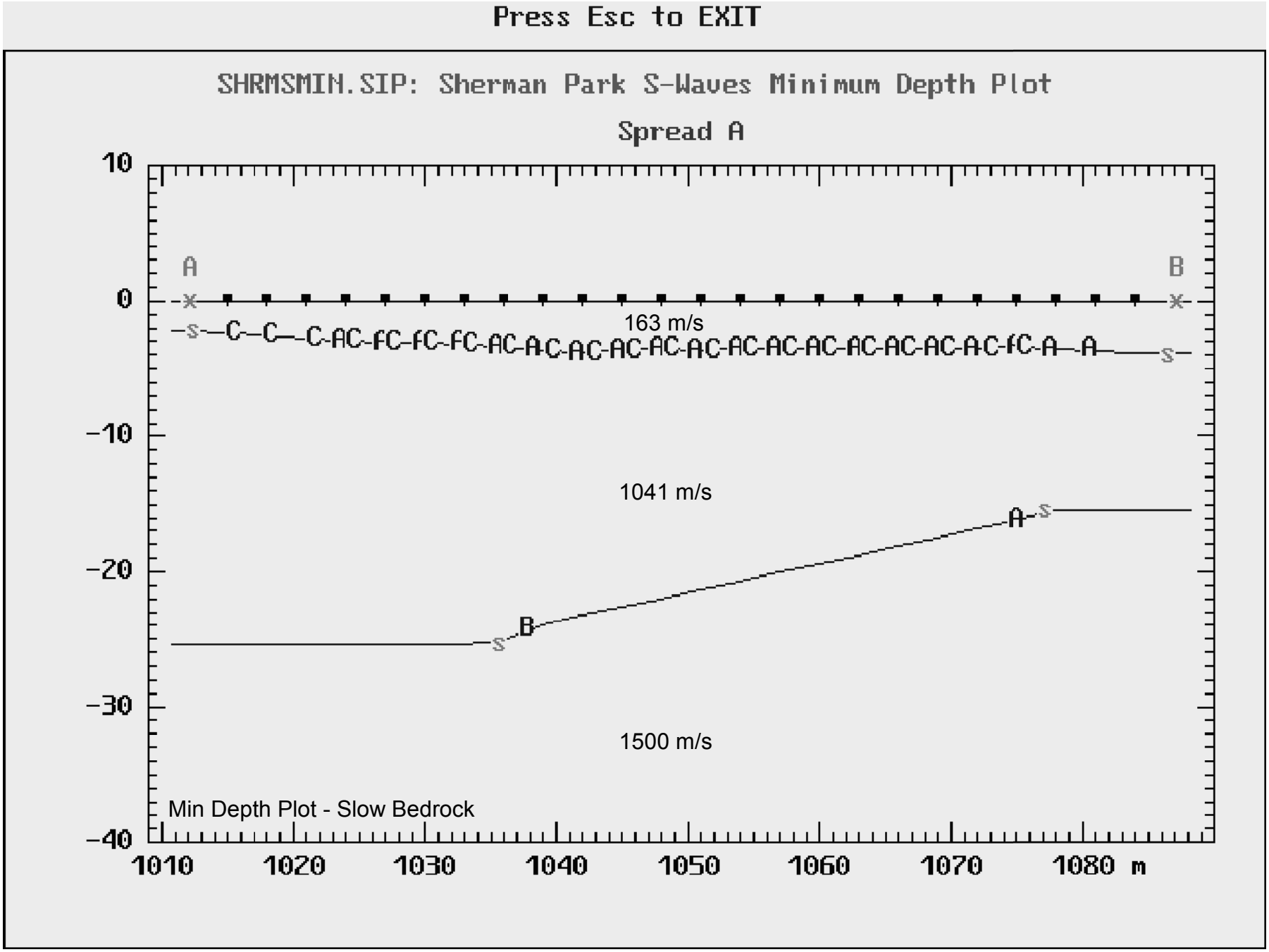

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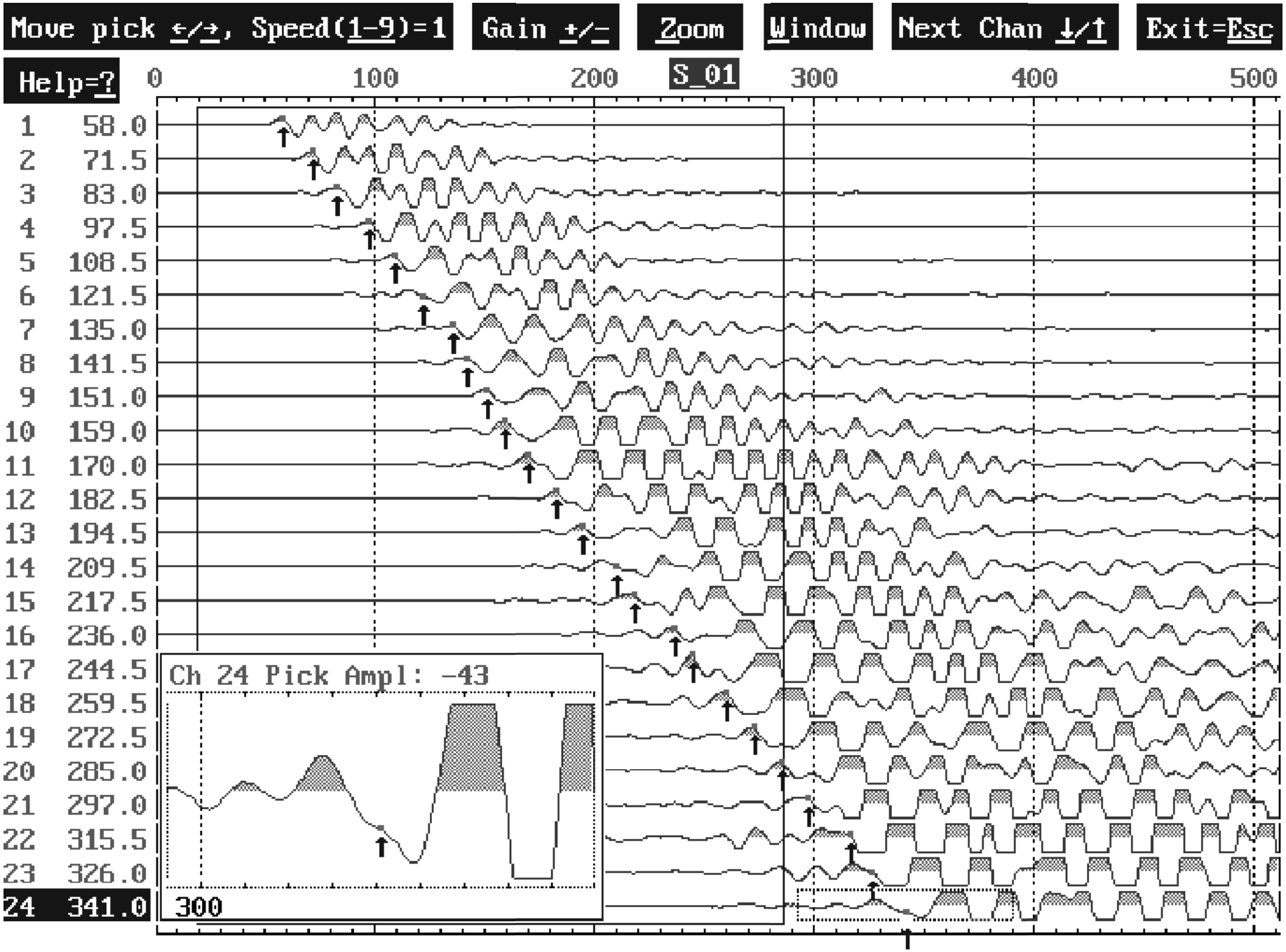

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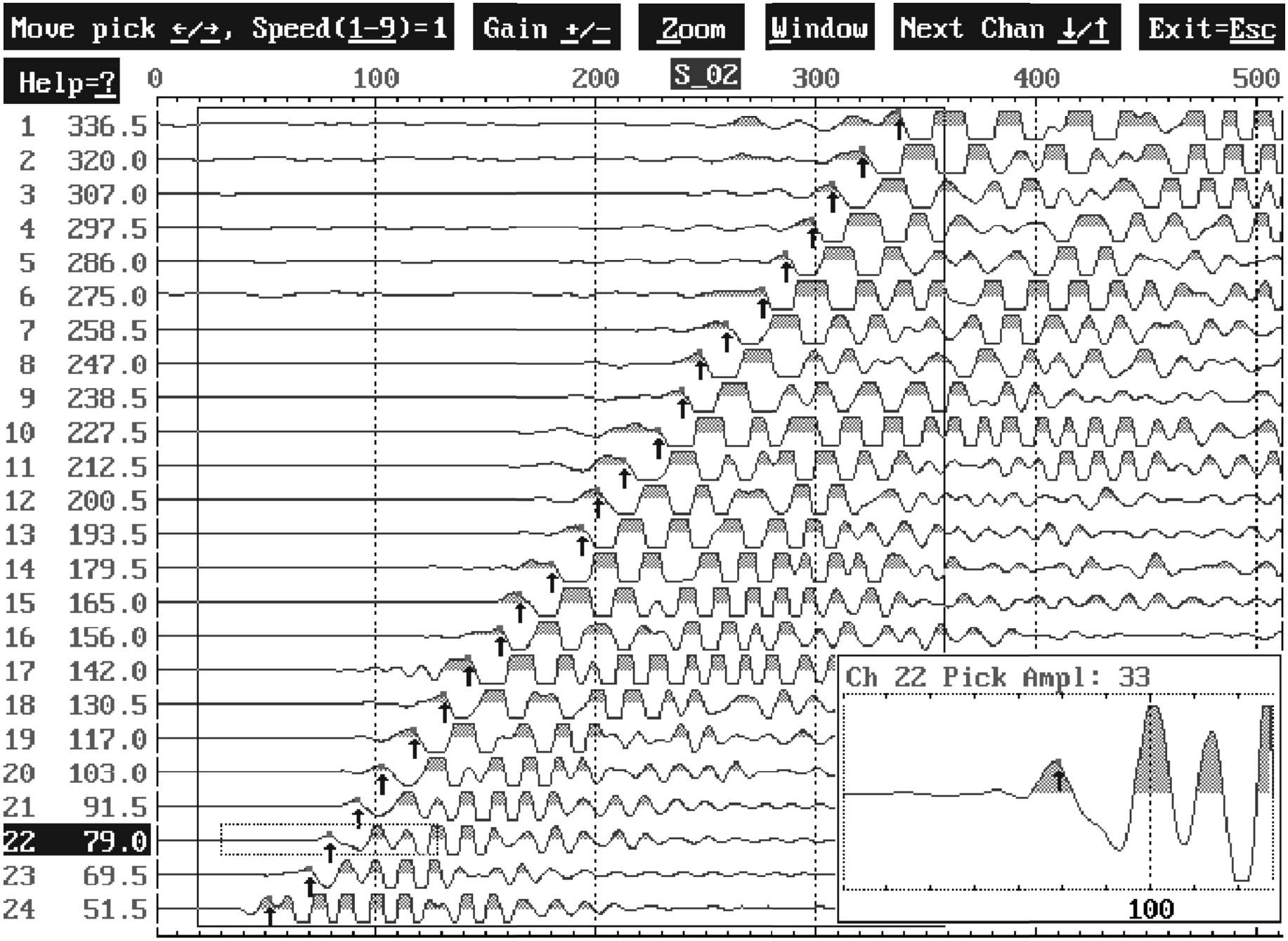

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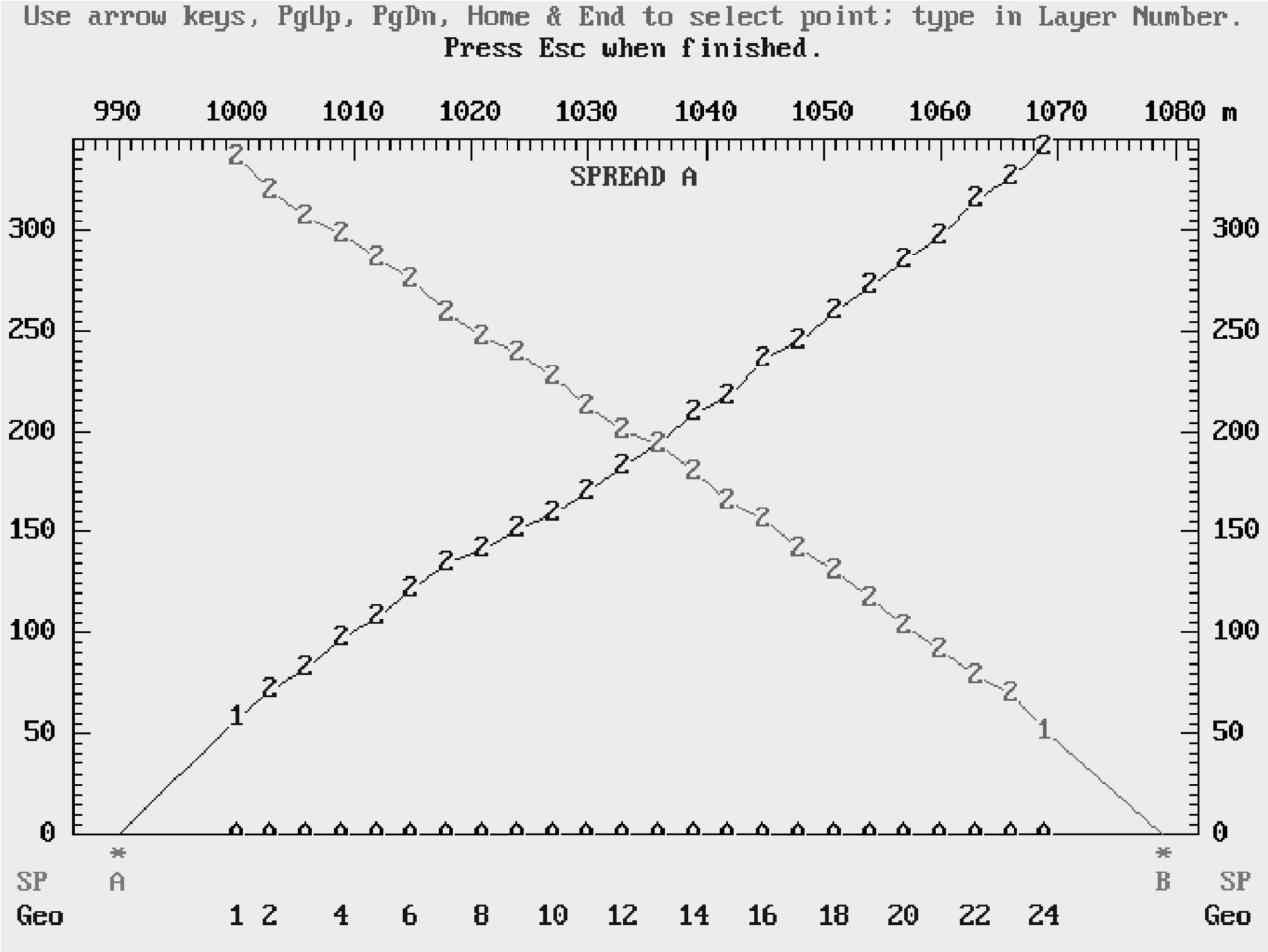

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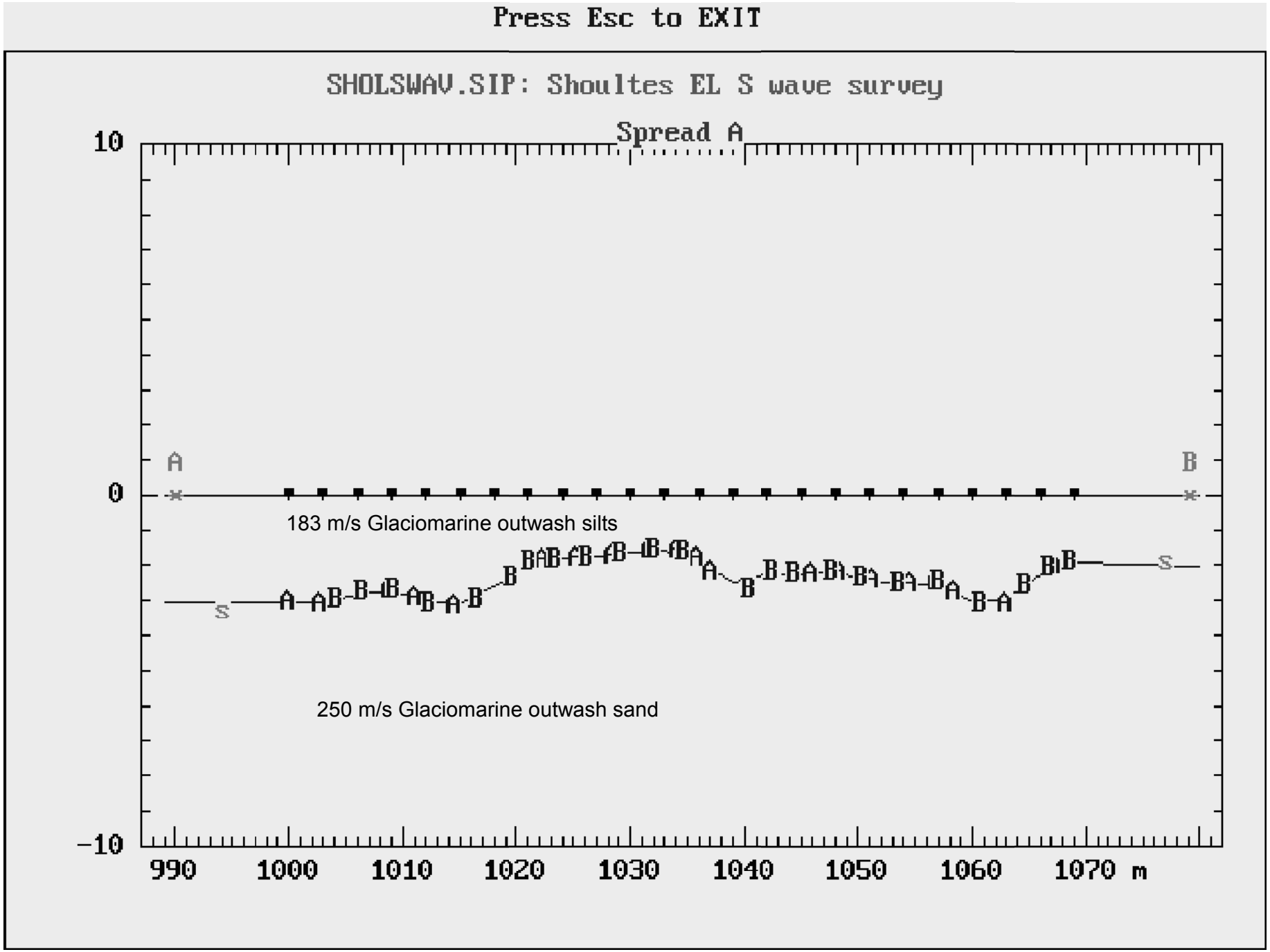

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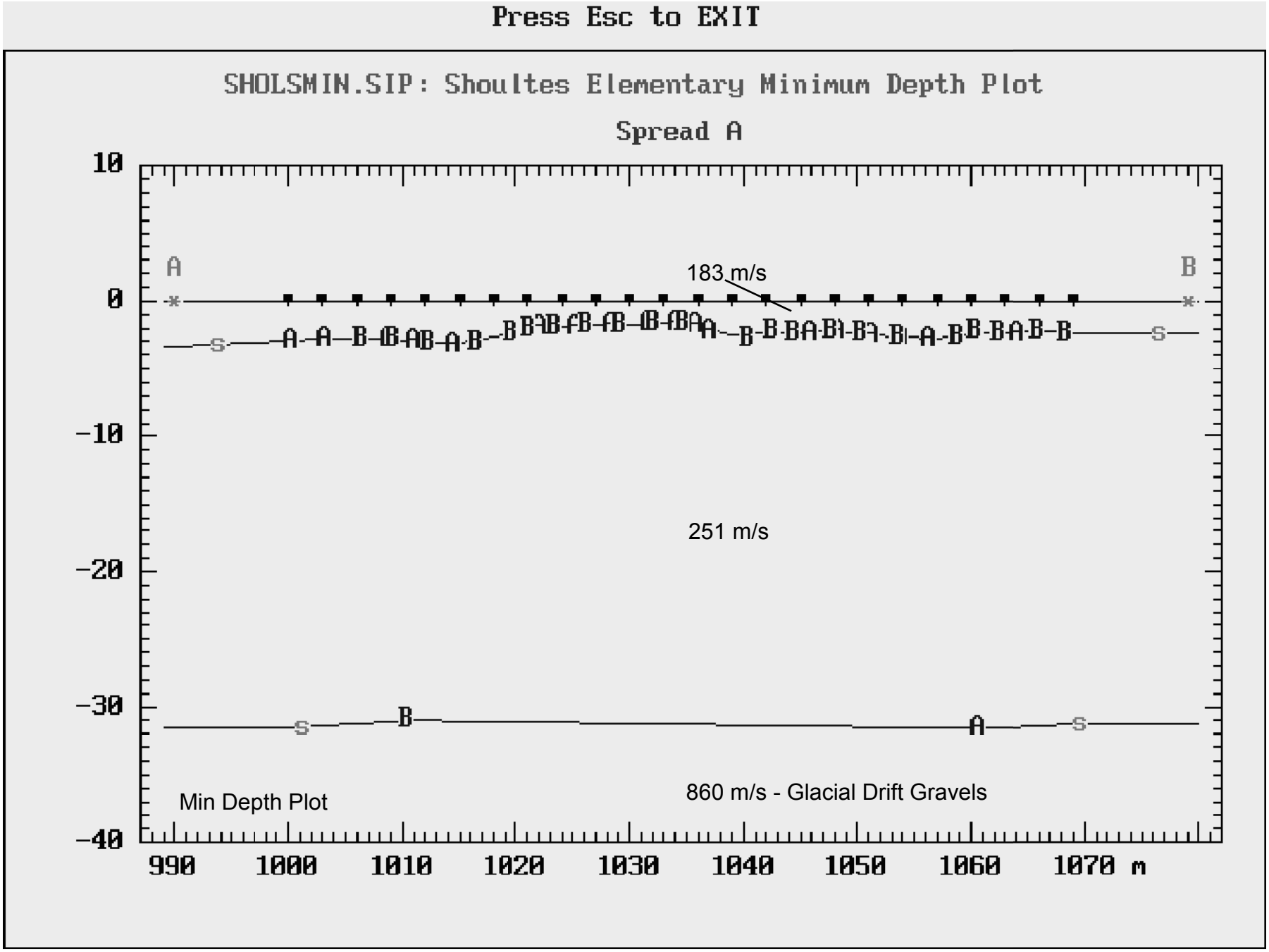

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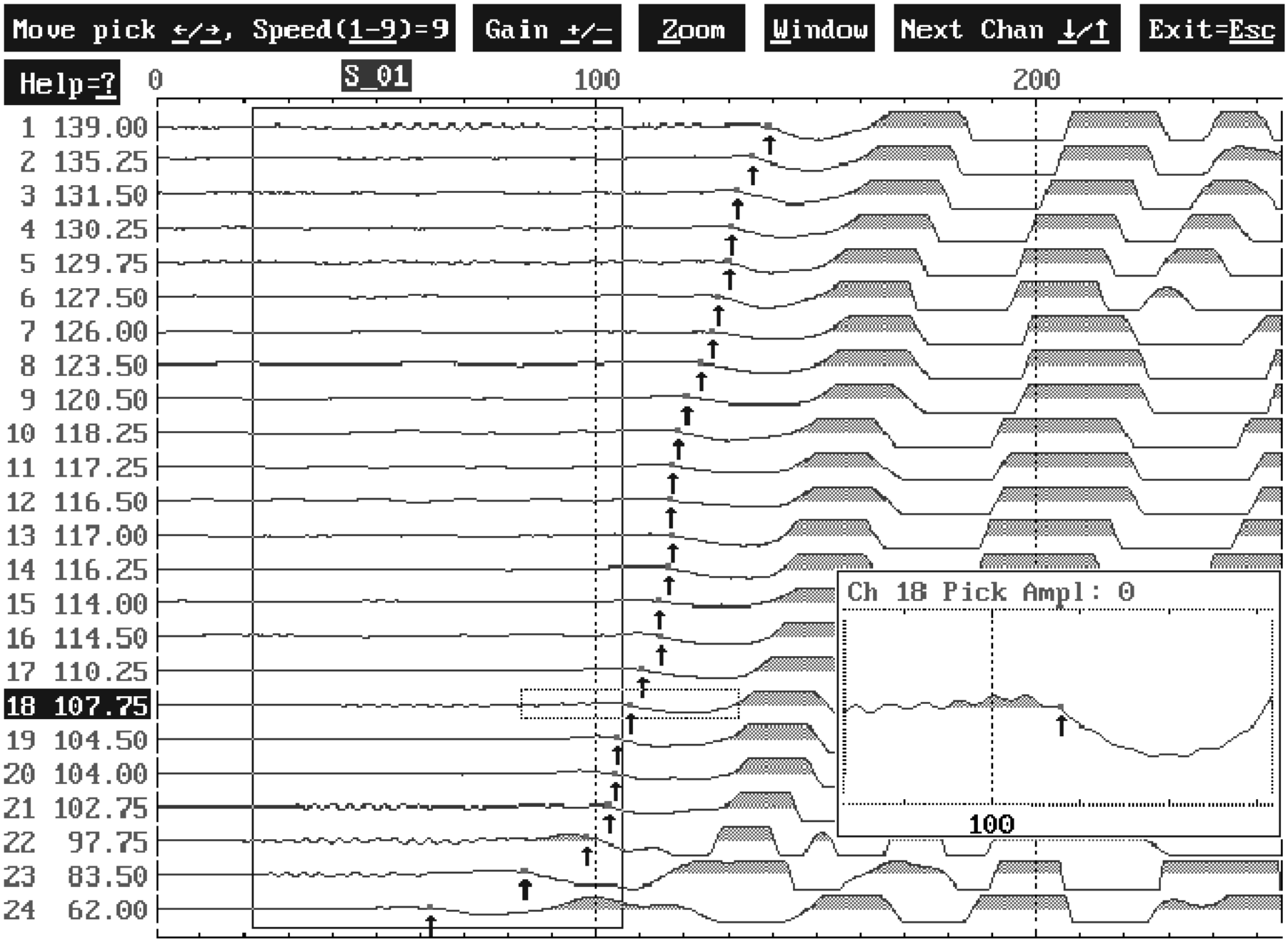

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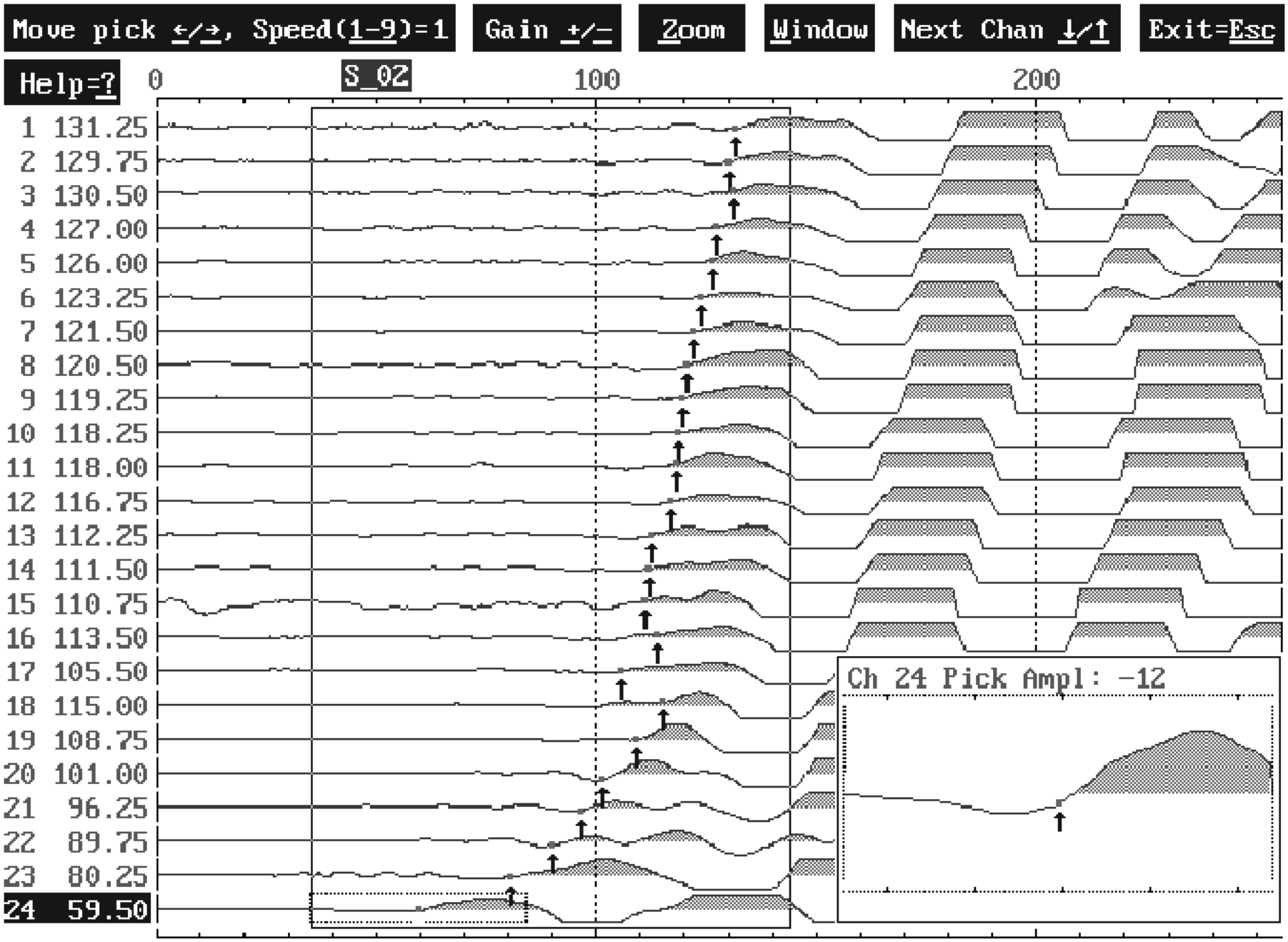

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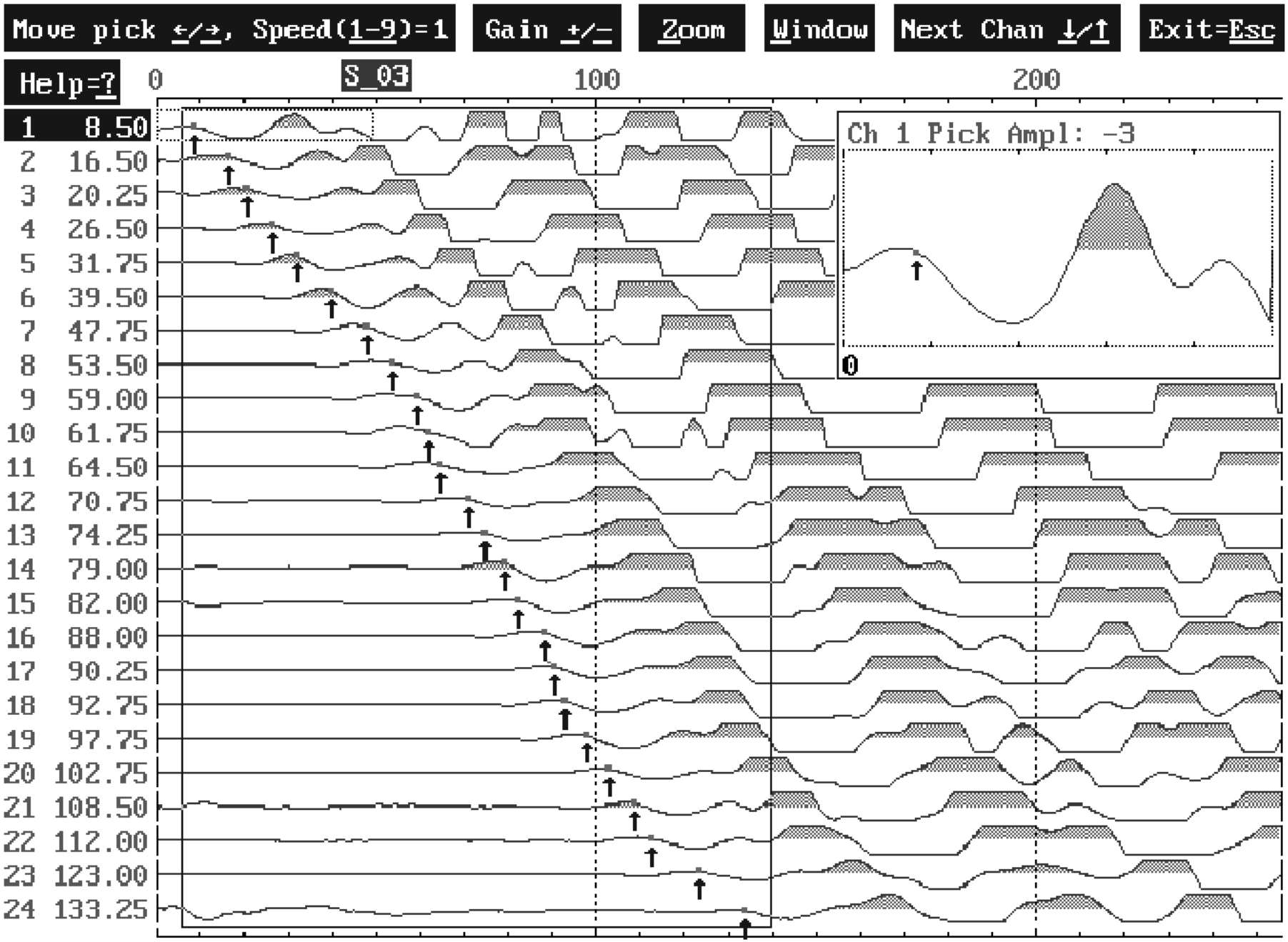

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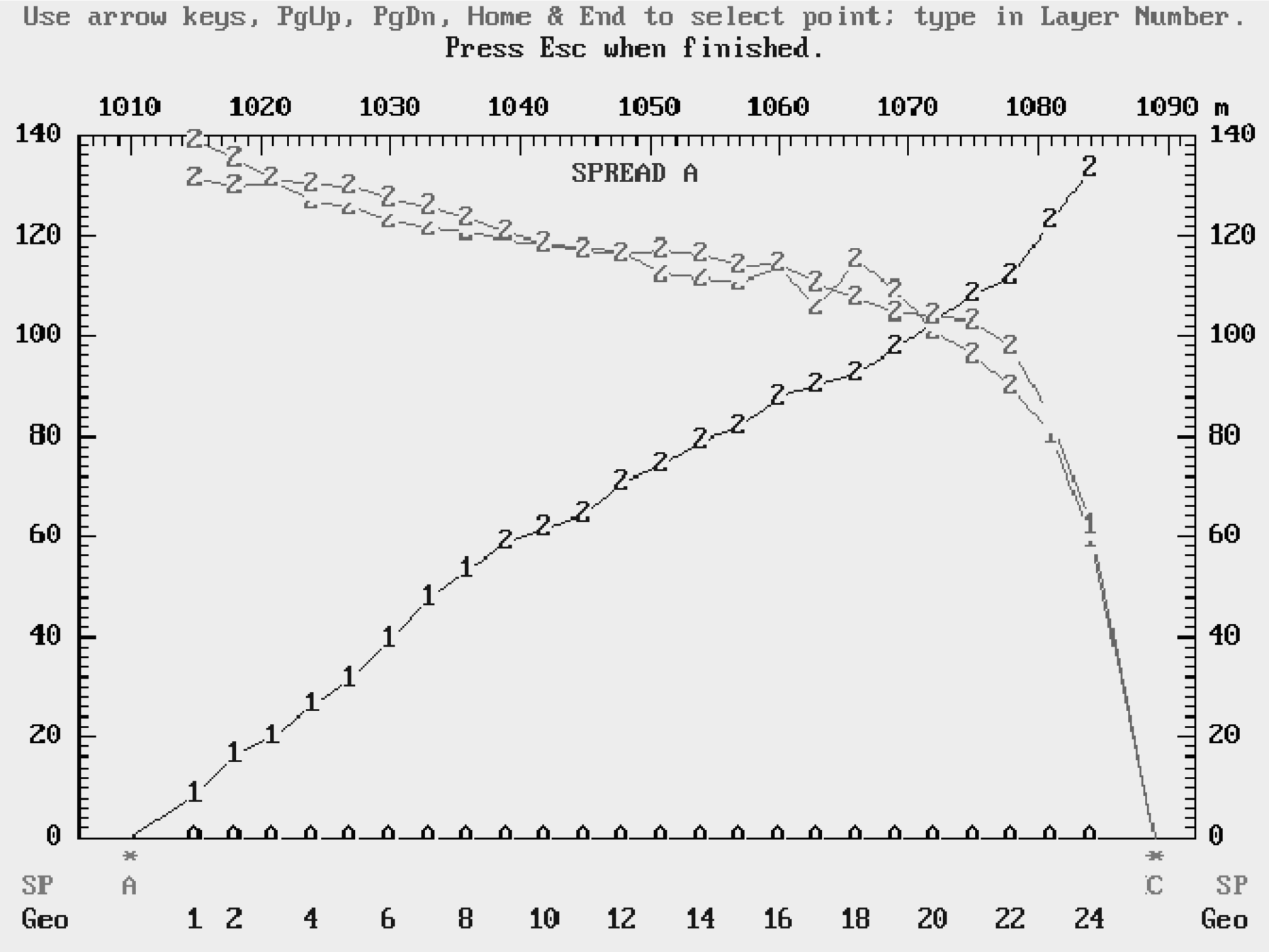

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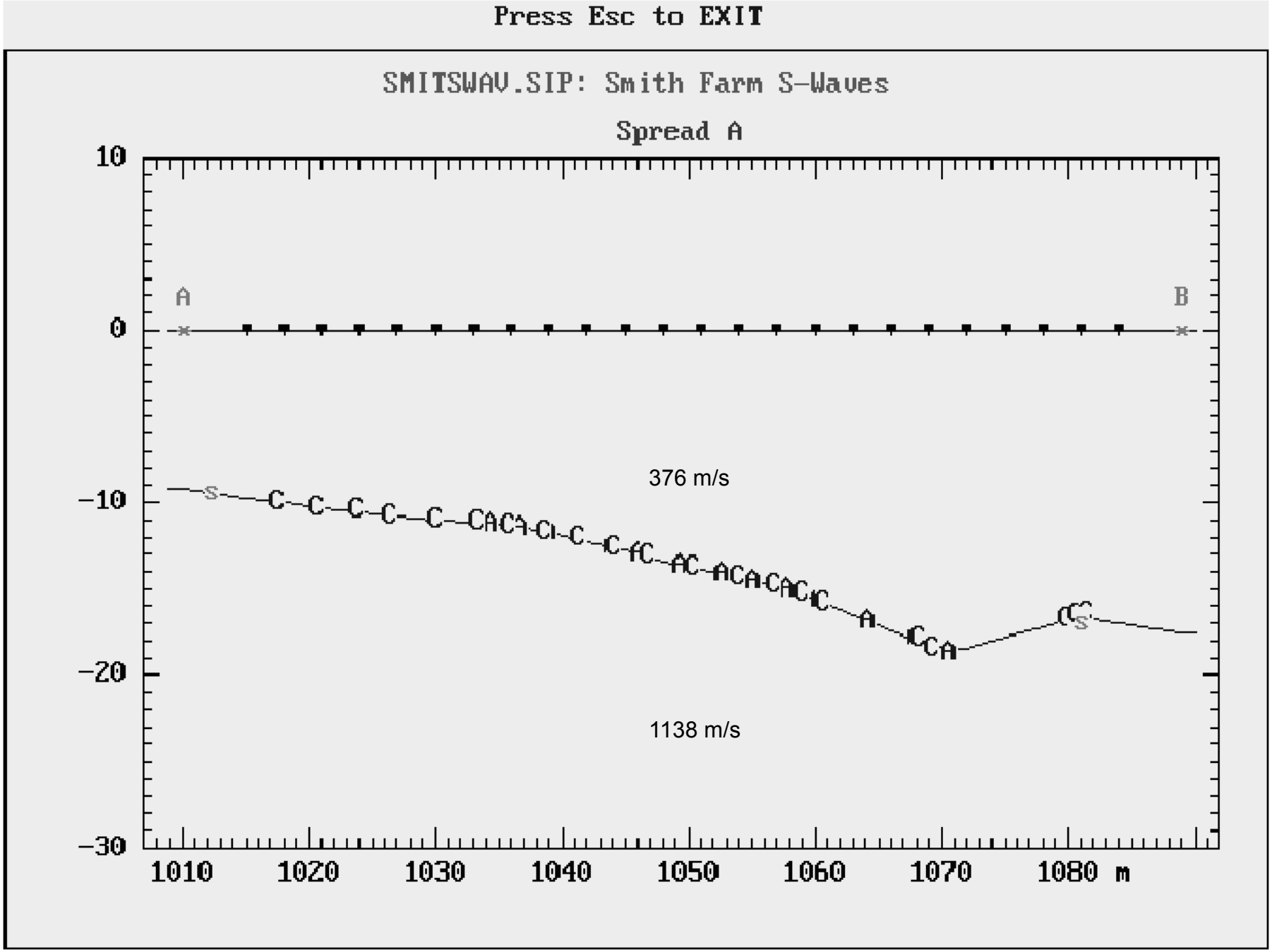

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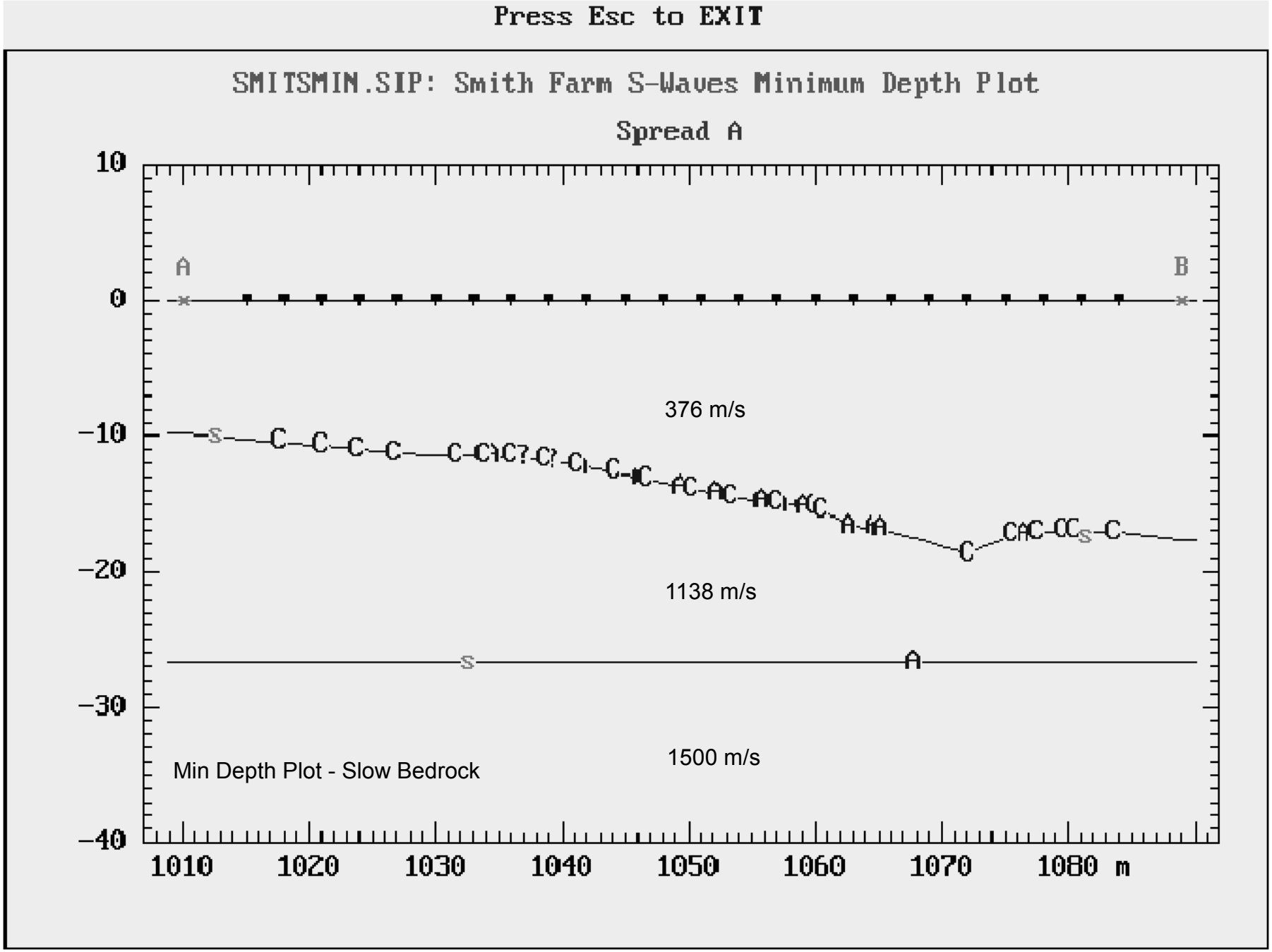
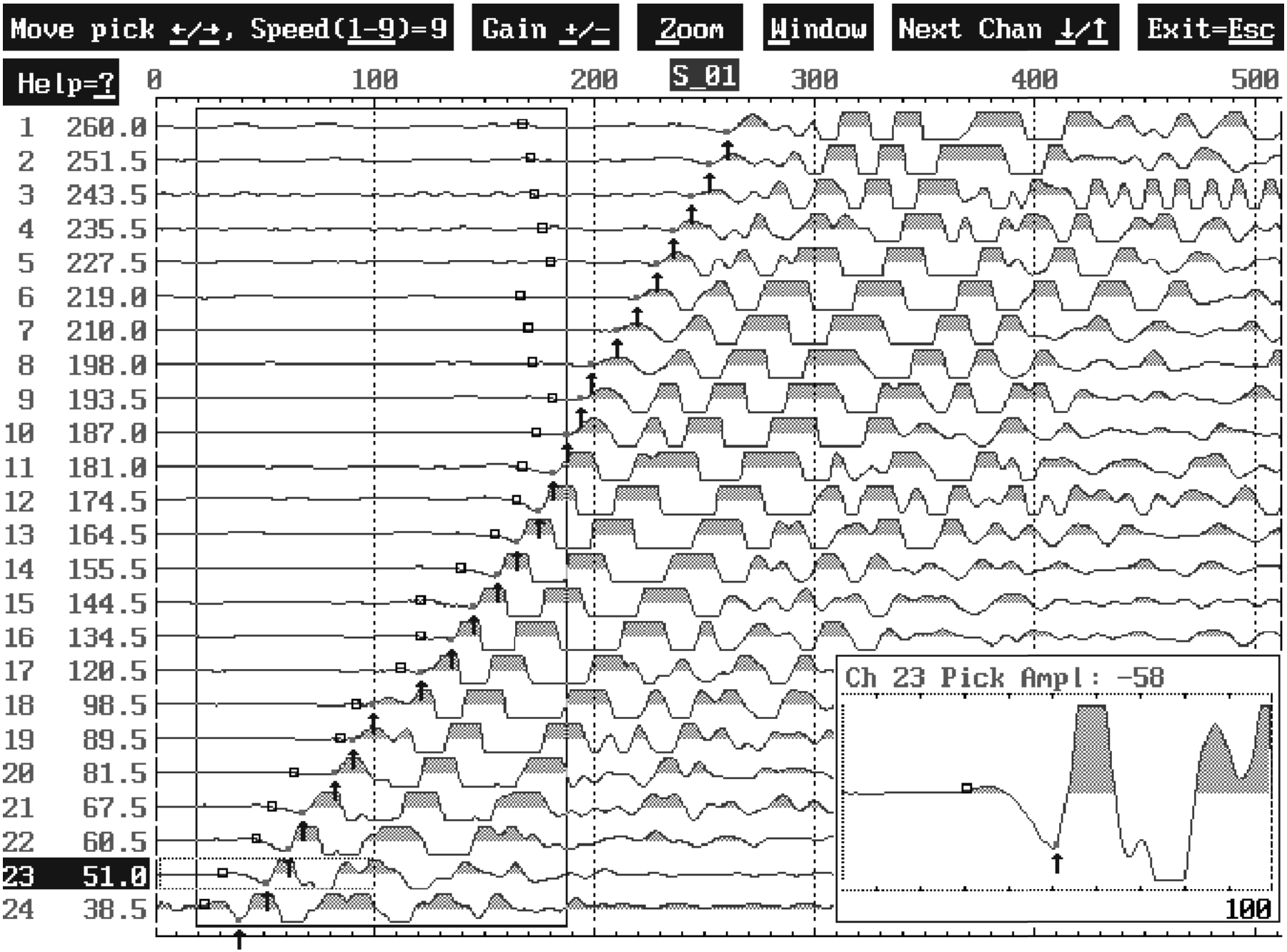


St. Elizabeth Ann Seton Church S-wave



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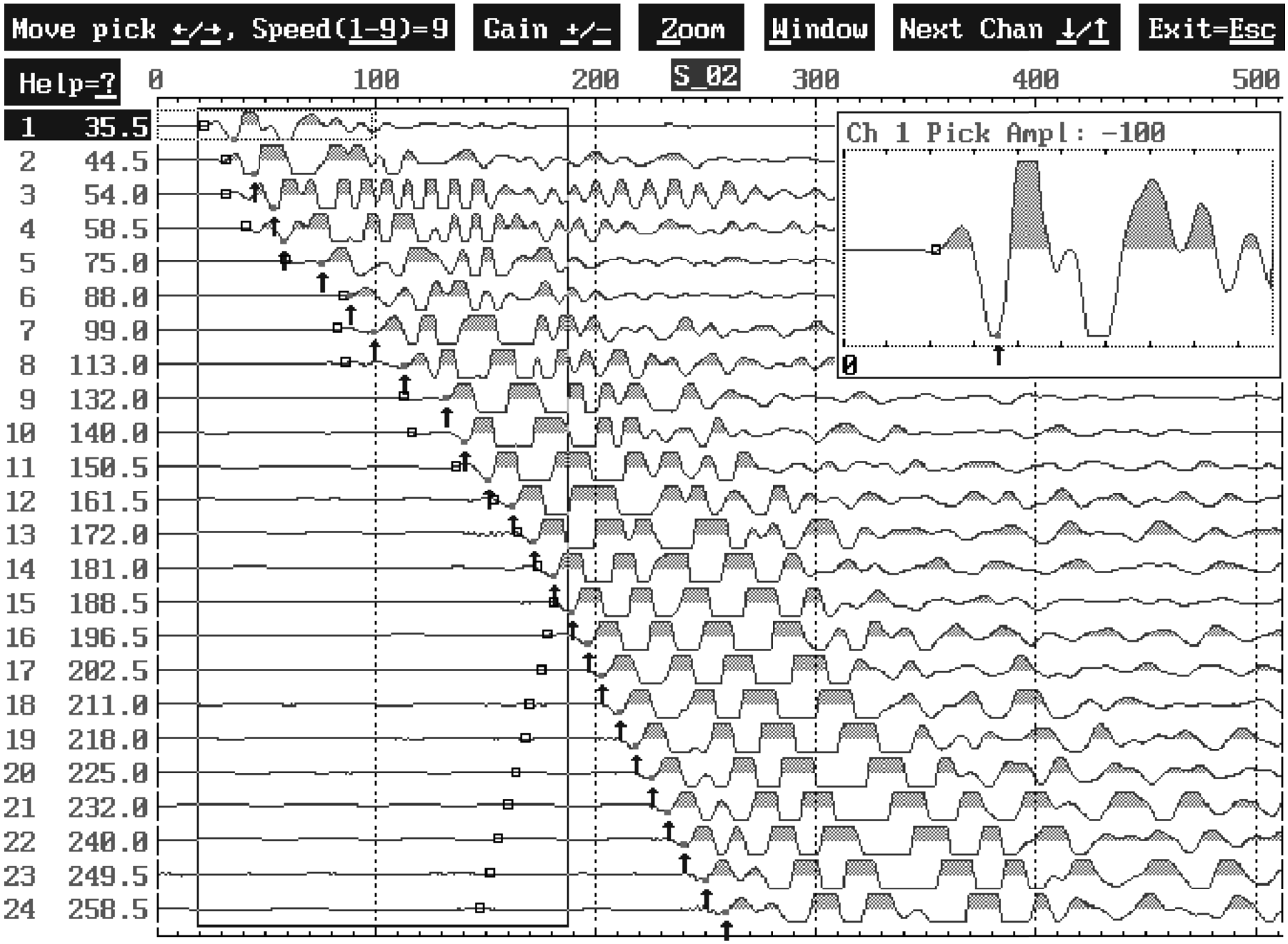

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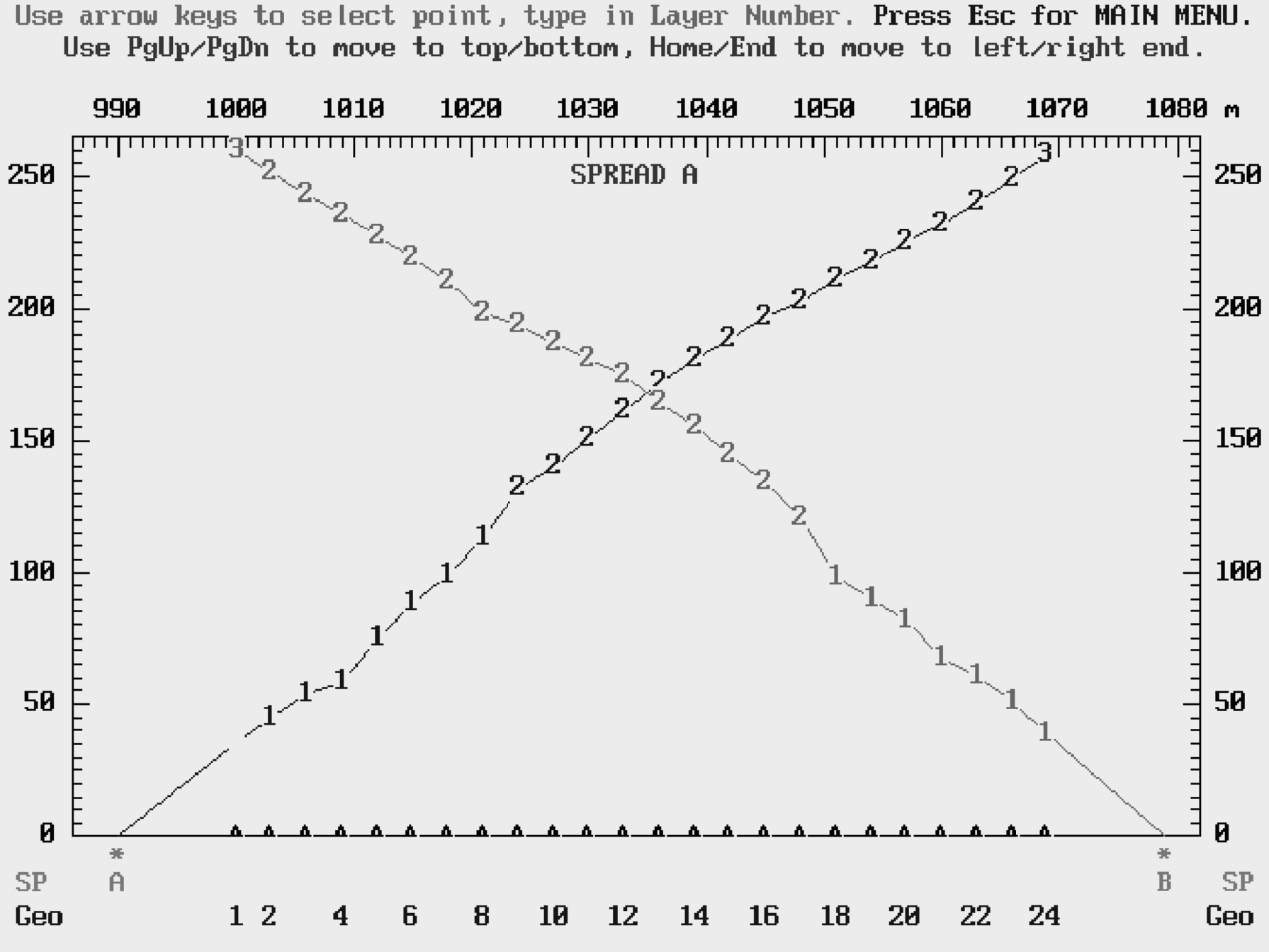

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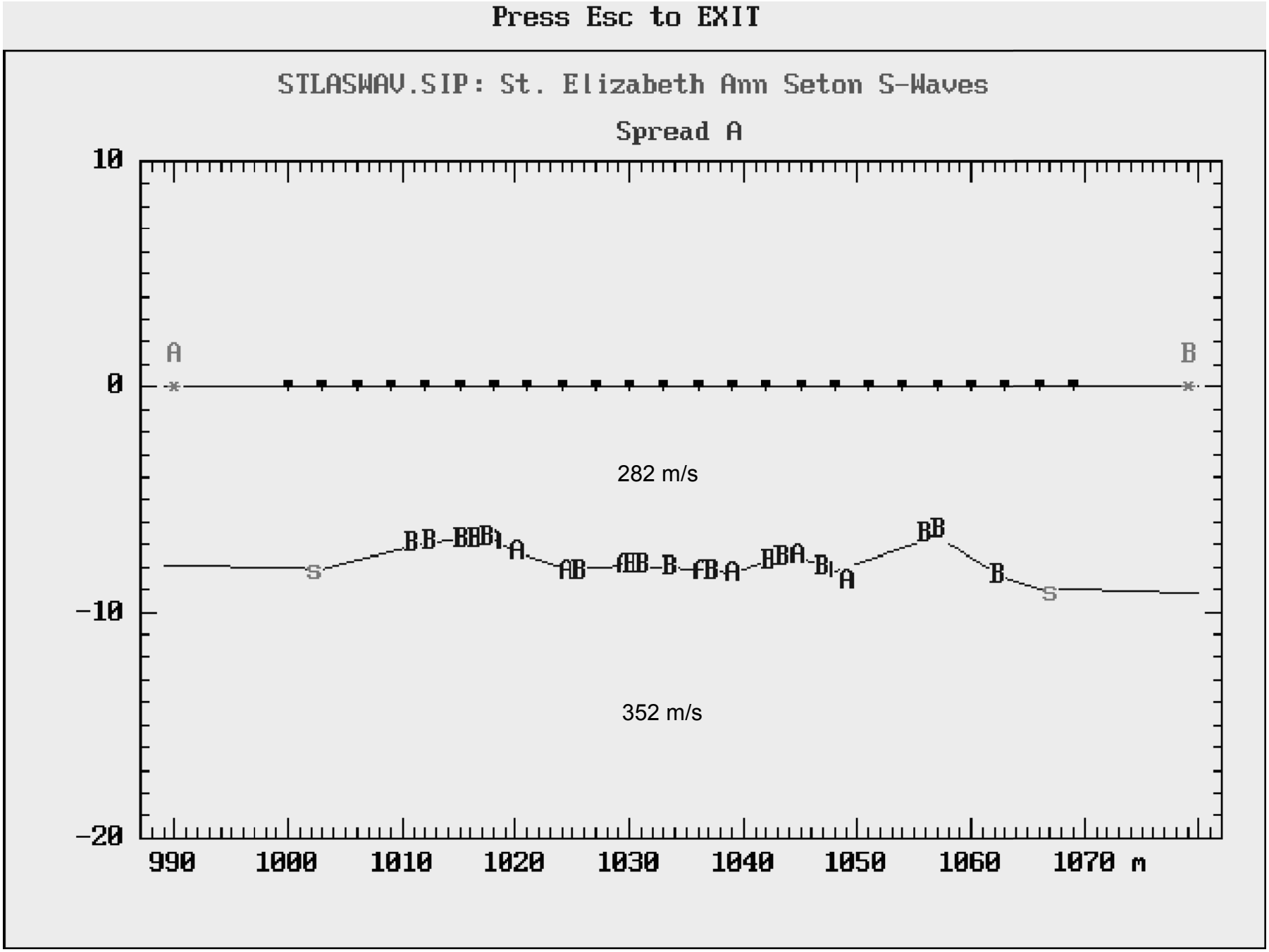

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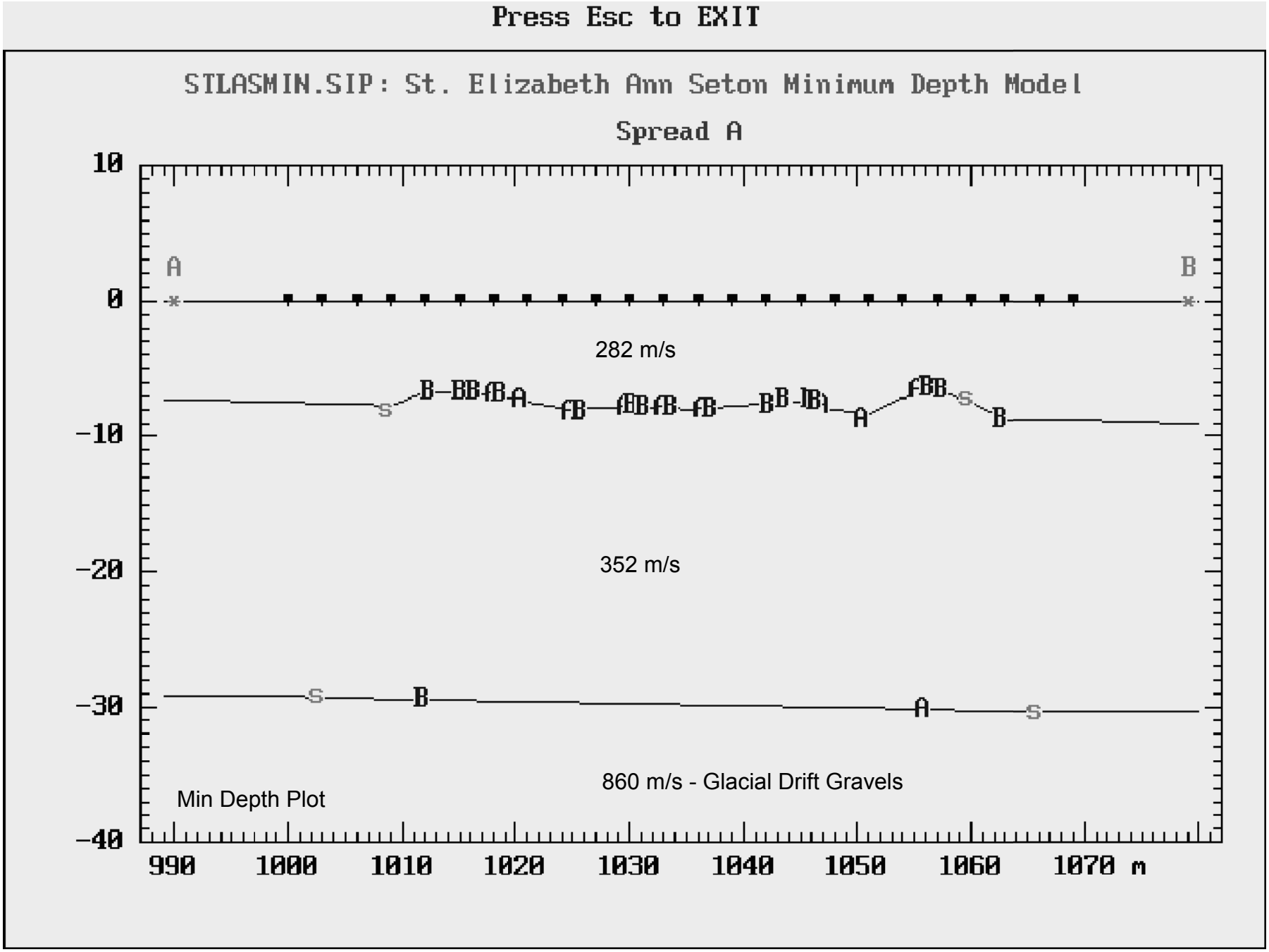

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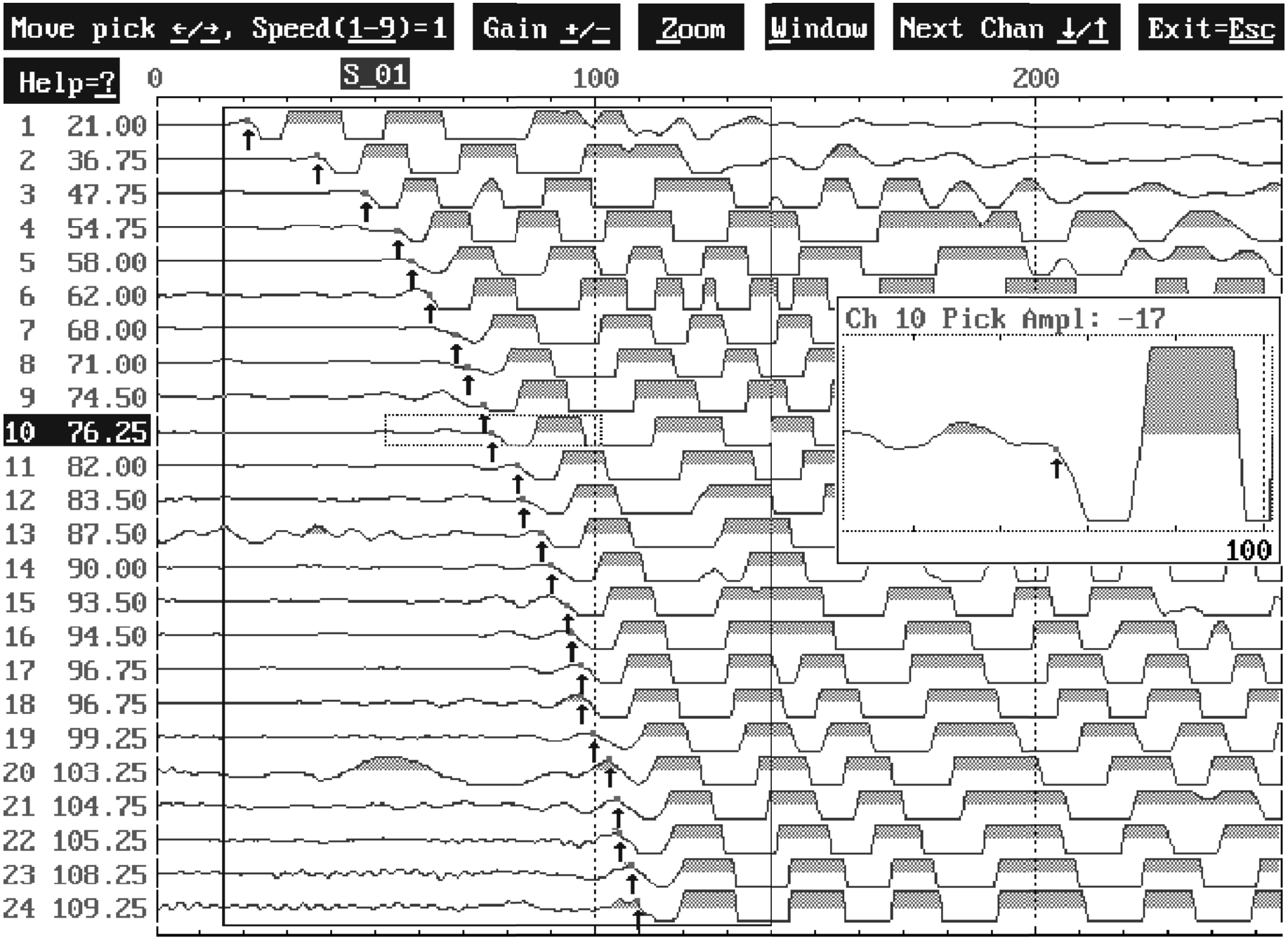

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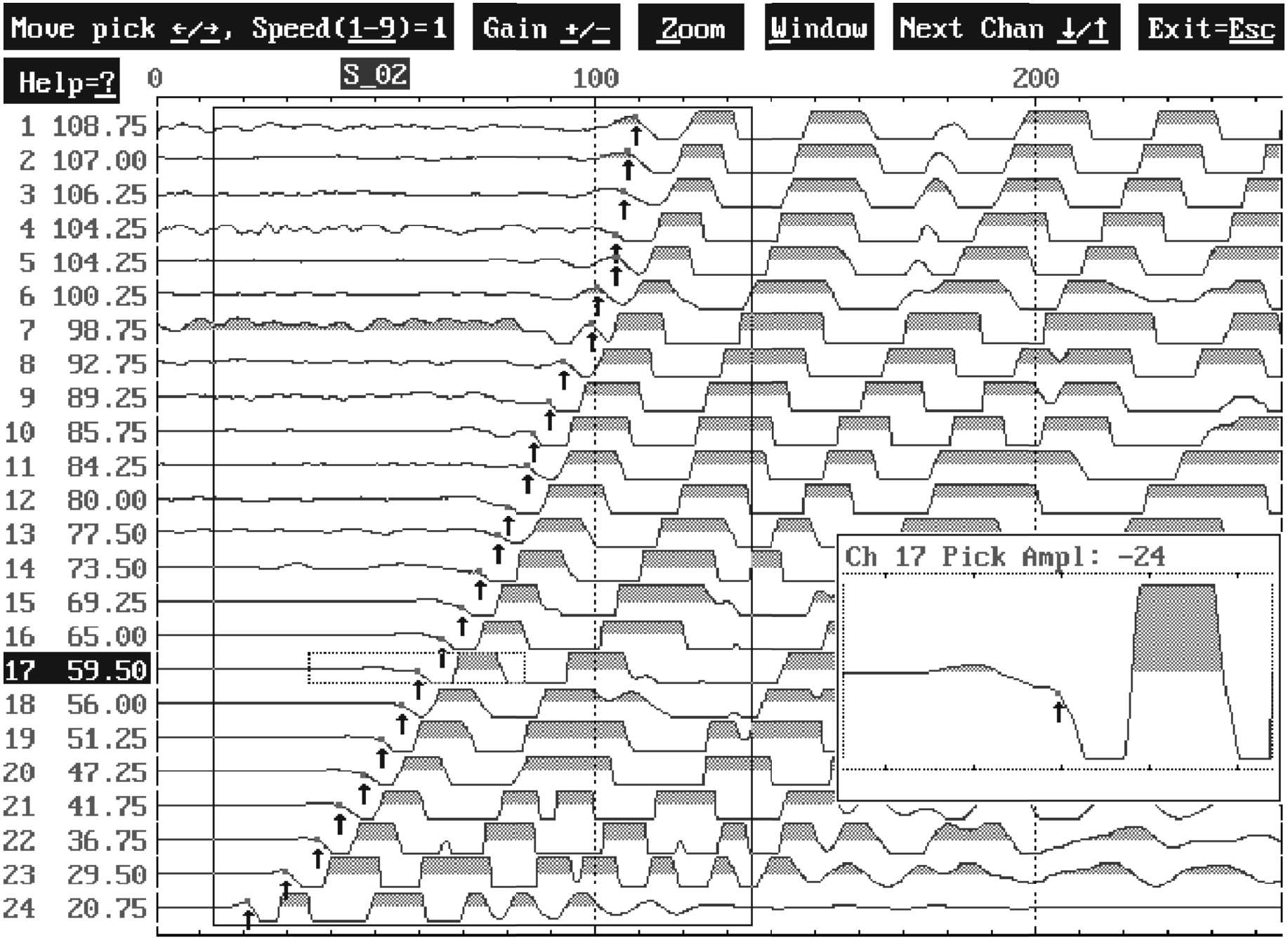

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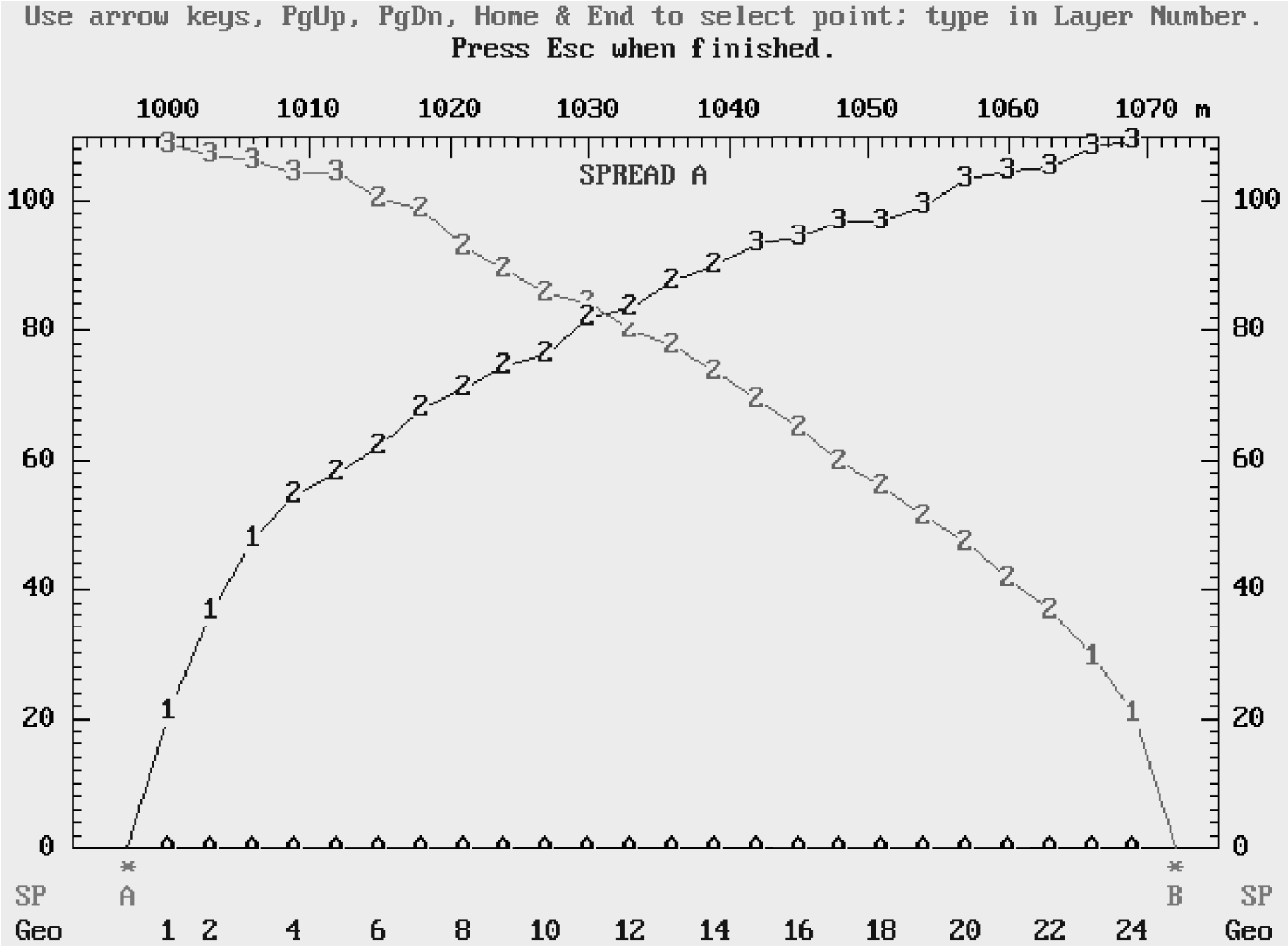
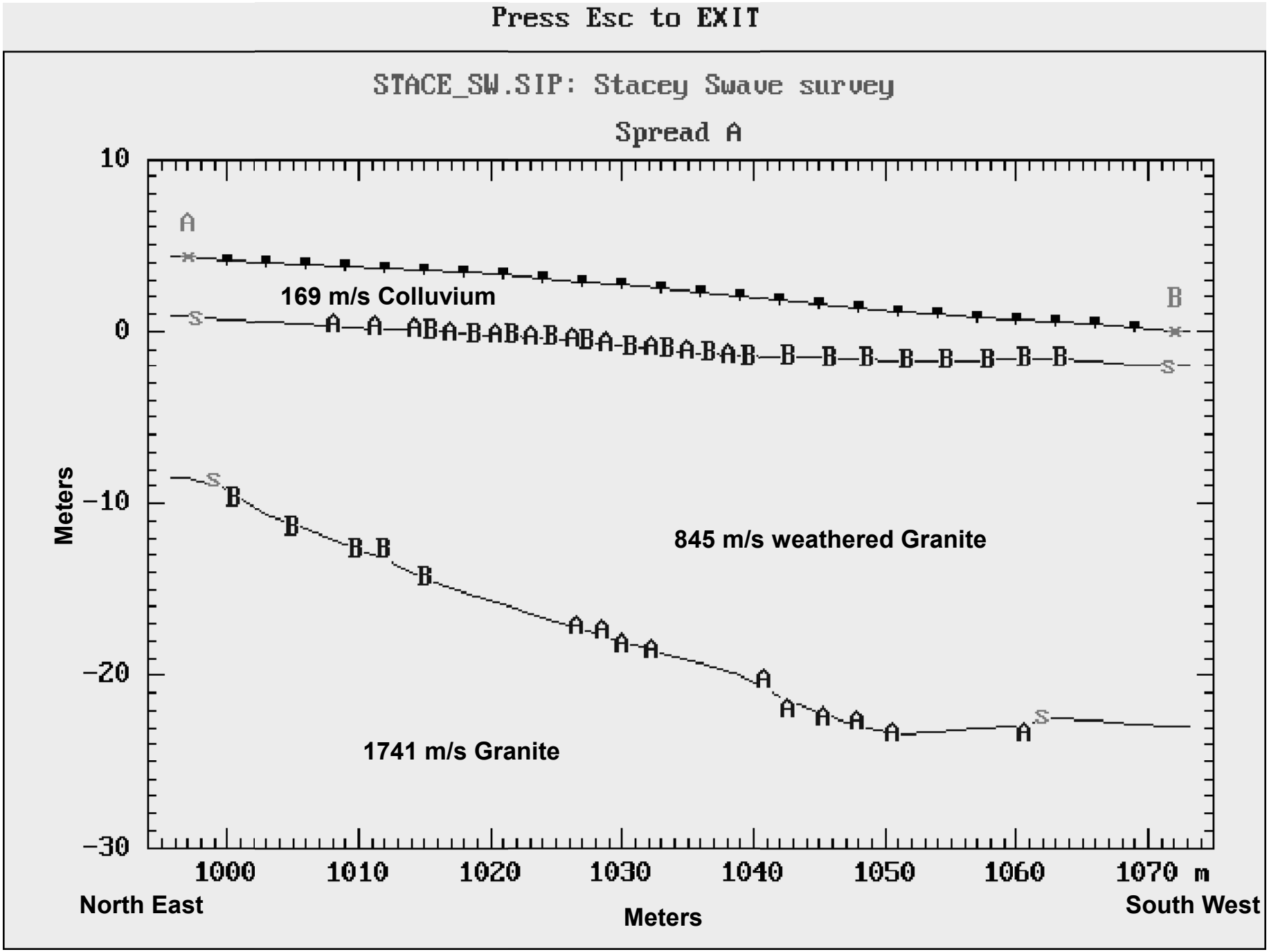


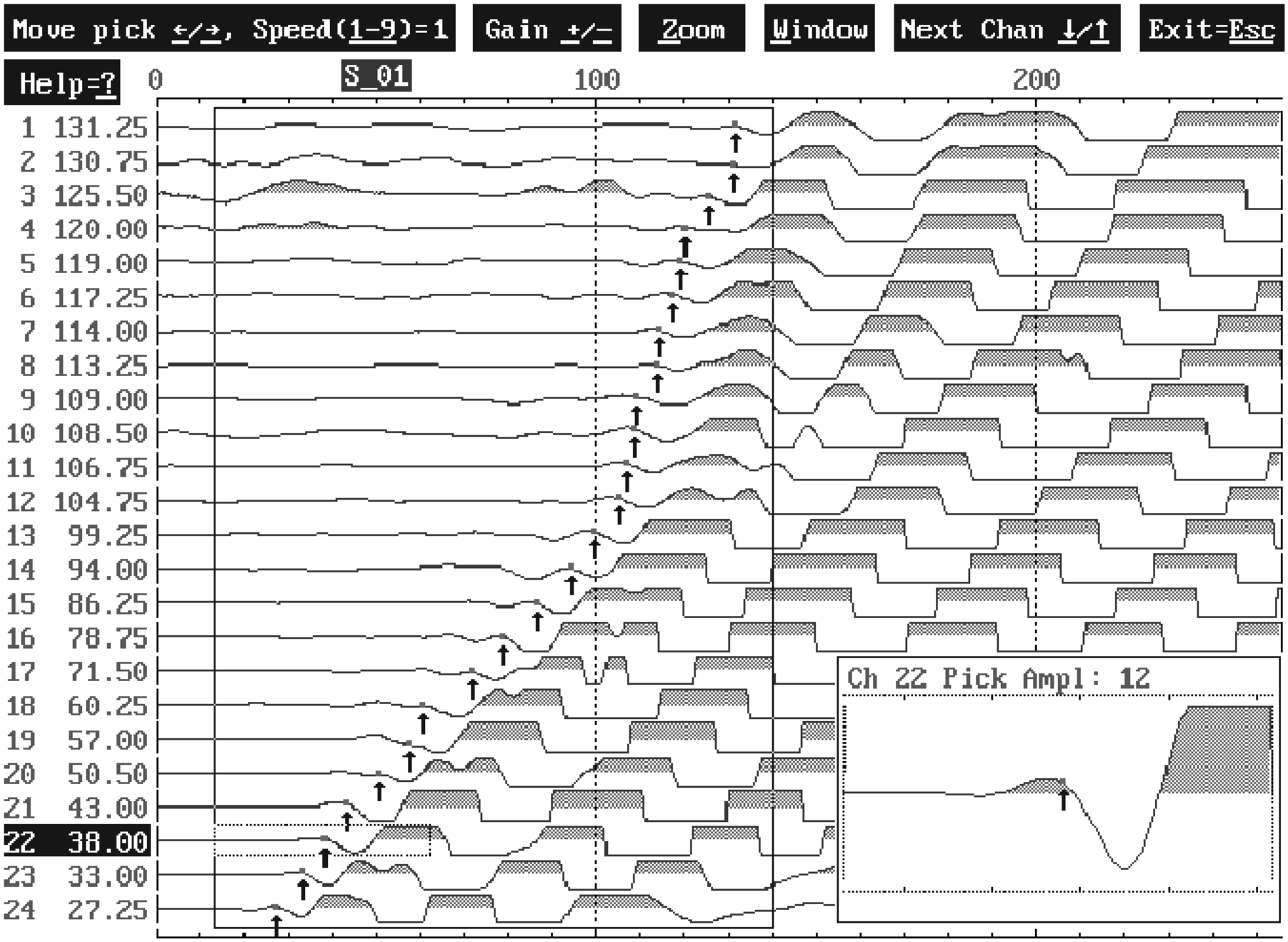
North East

South West

Stacey S-wave



Summitview Baptist Church S-wave



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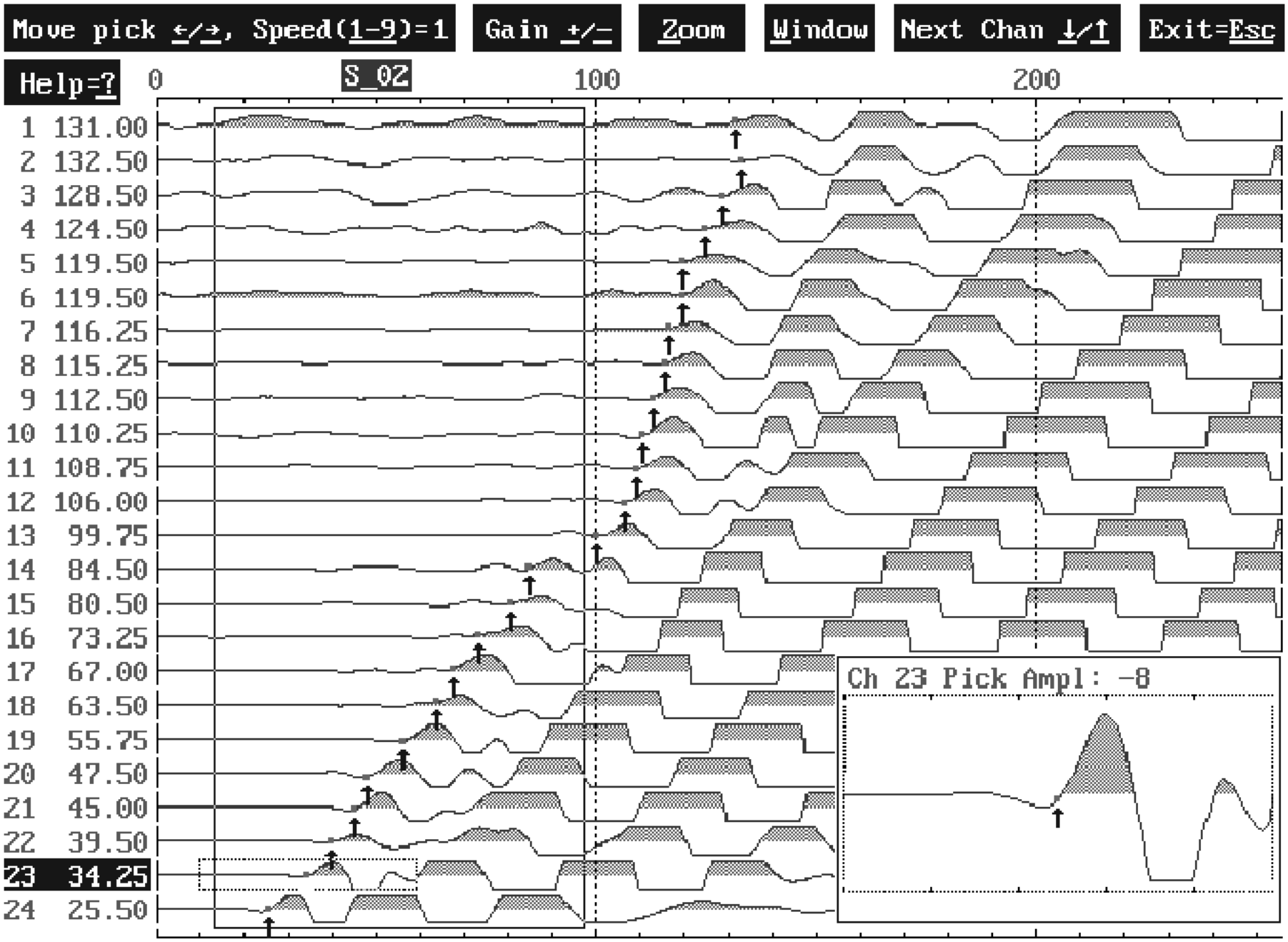

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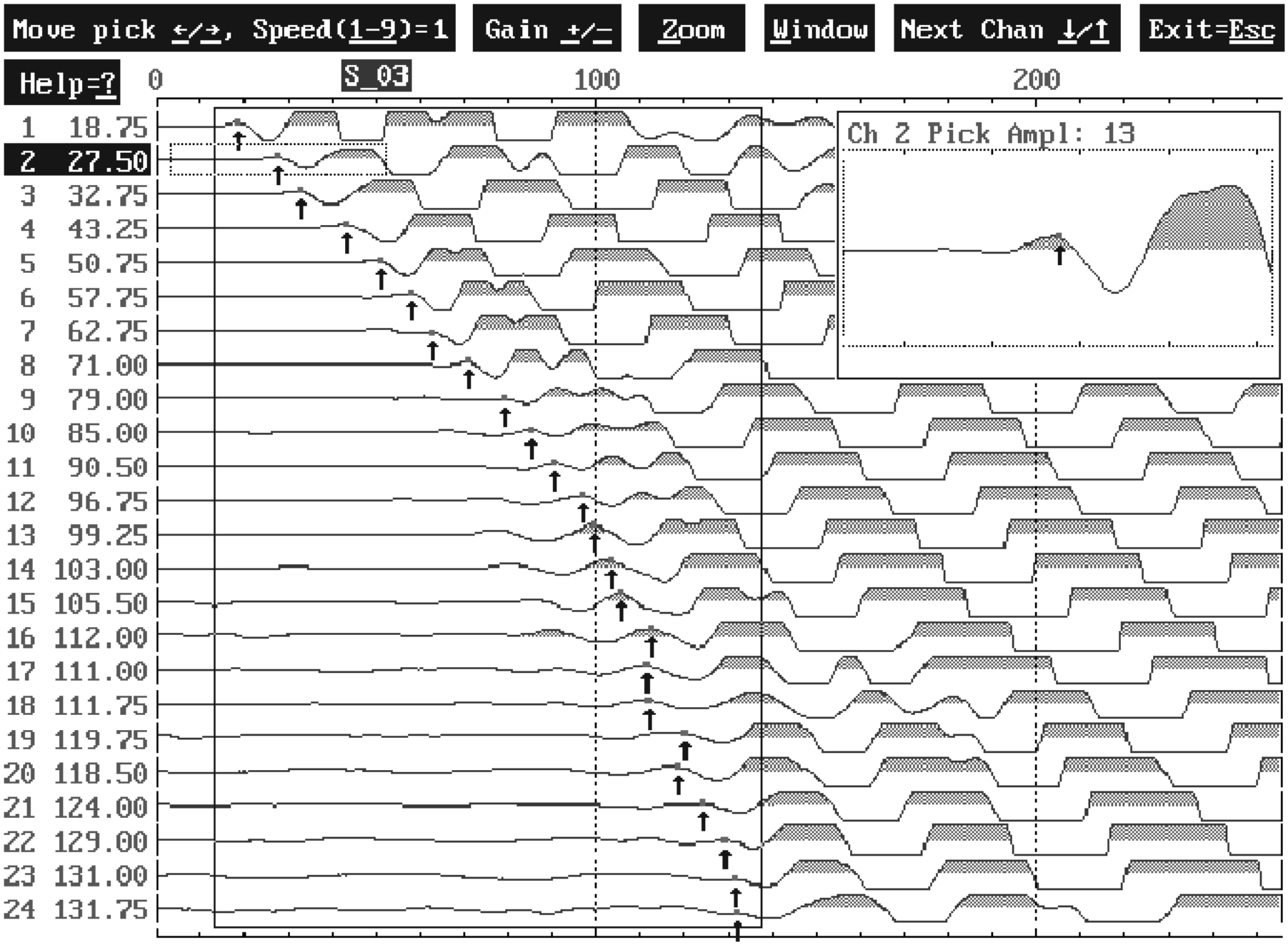

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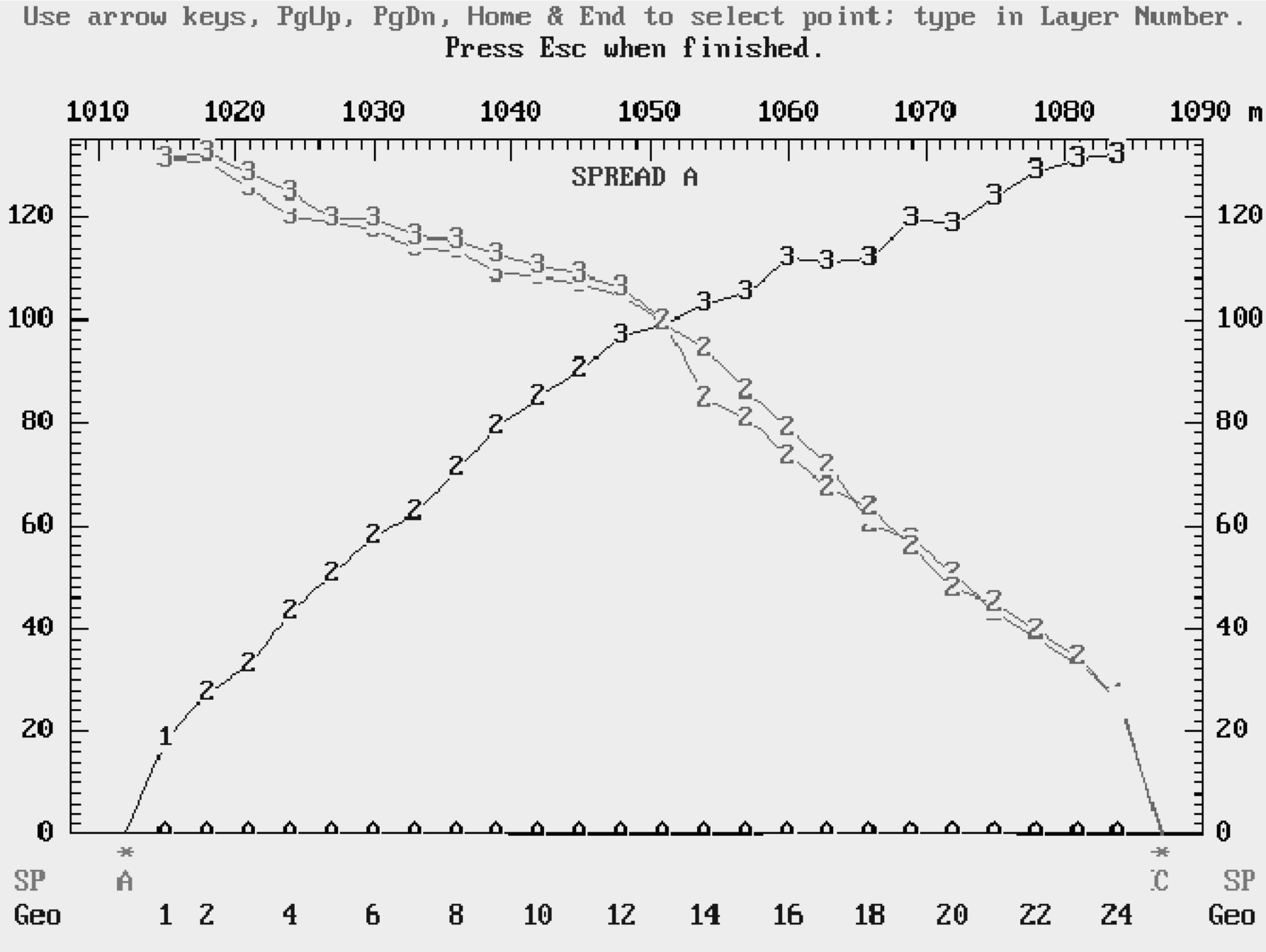

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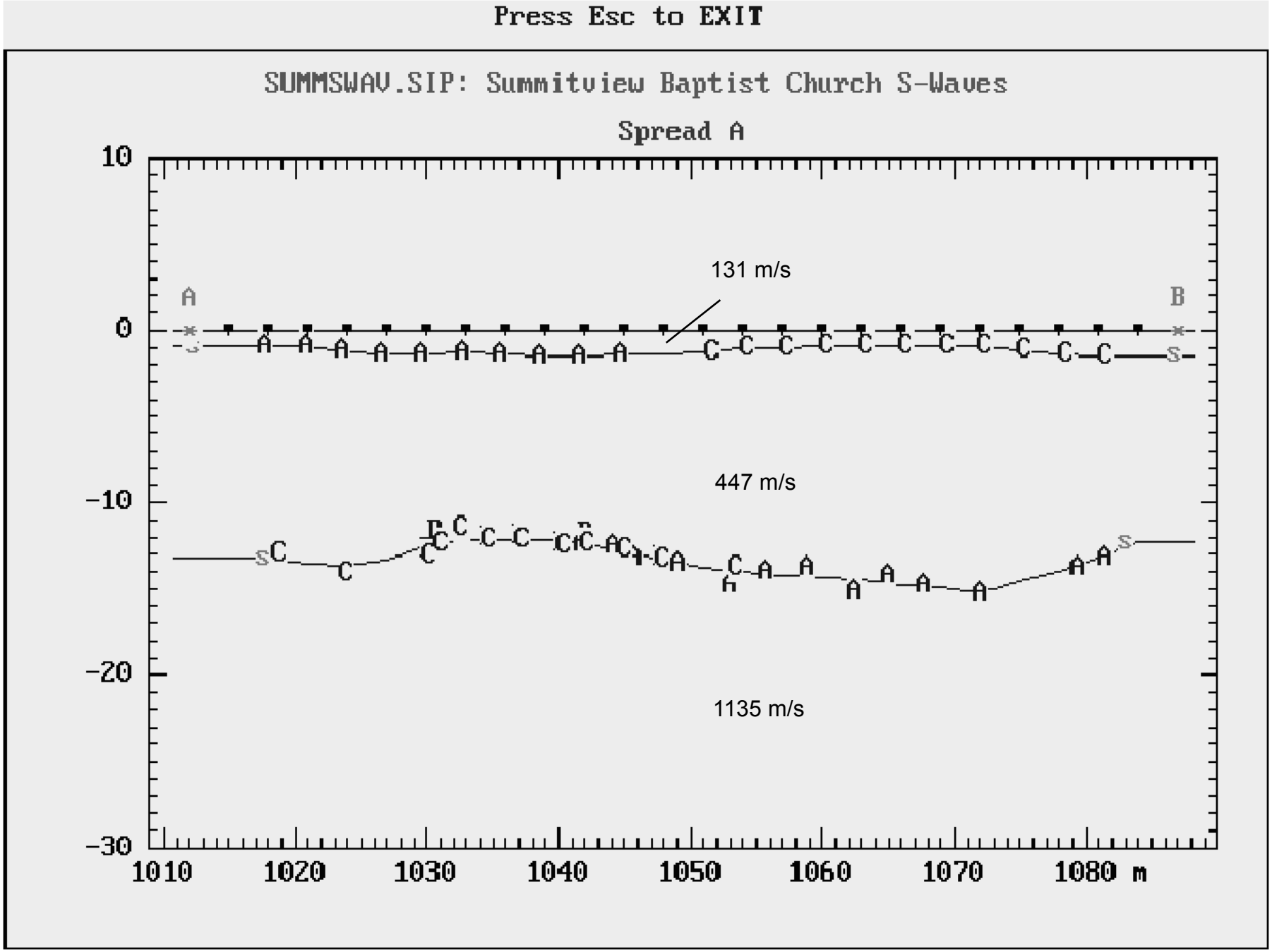

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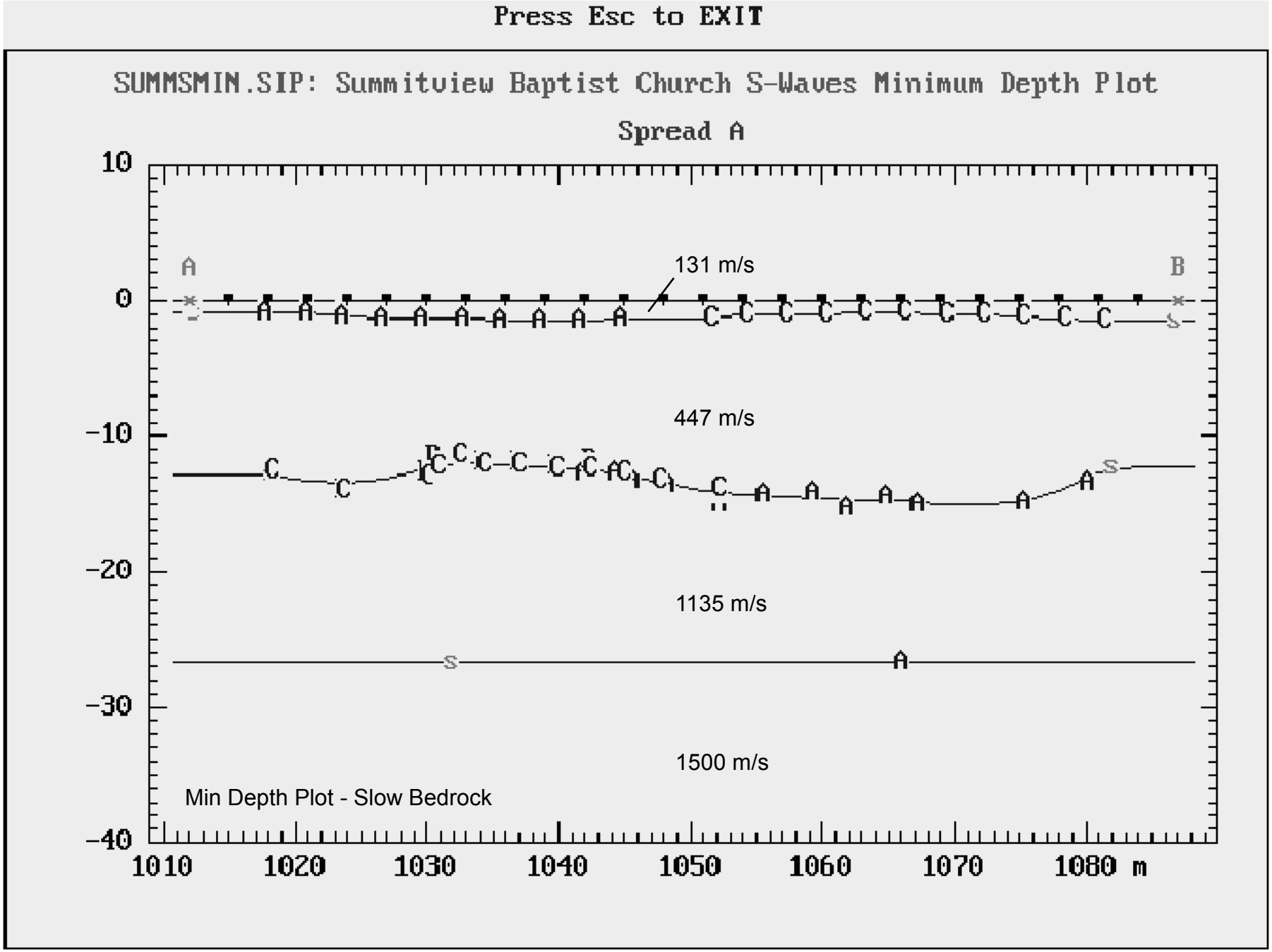
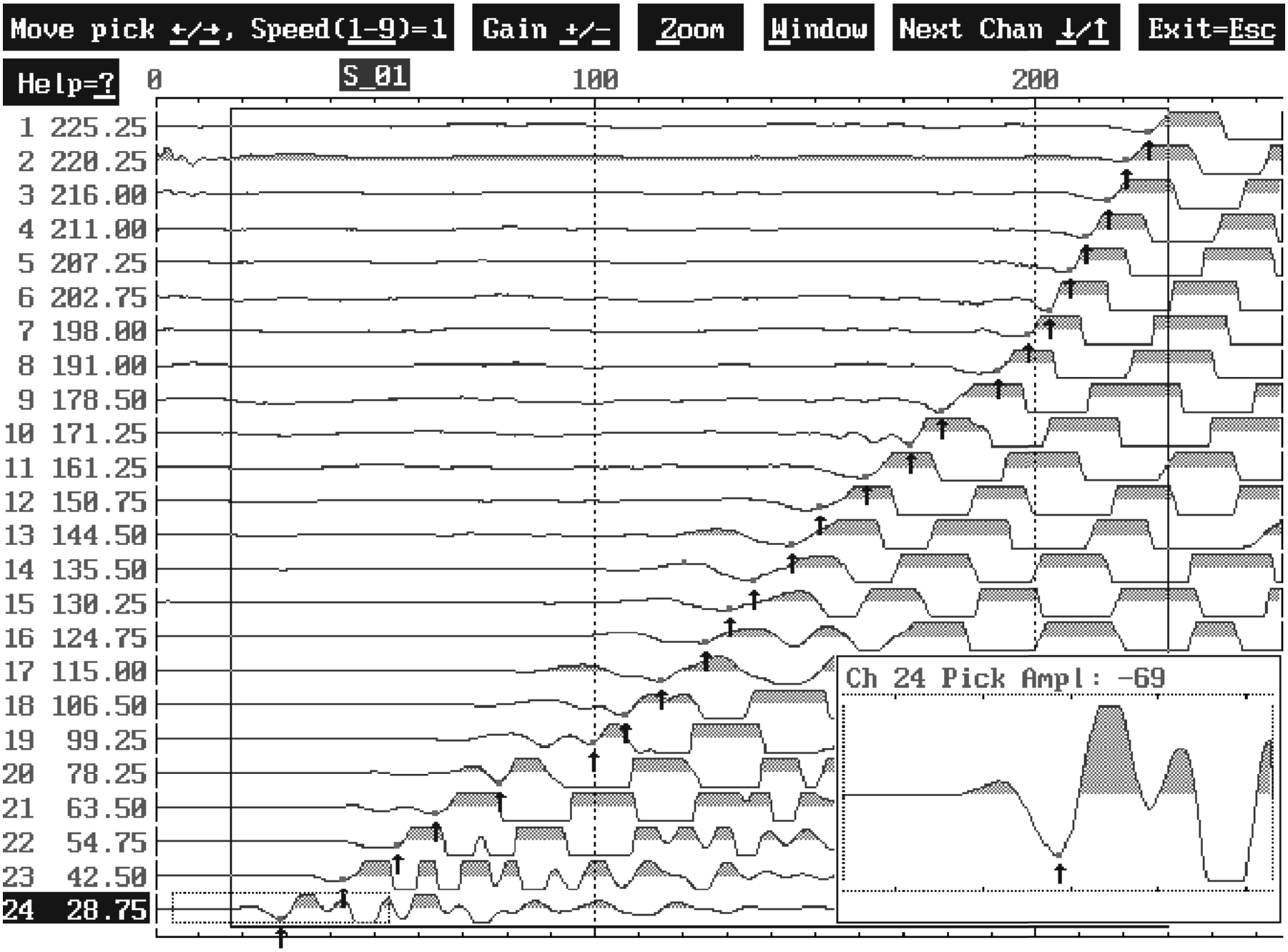
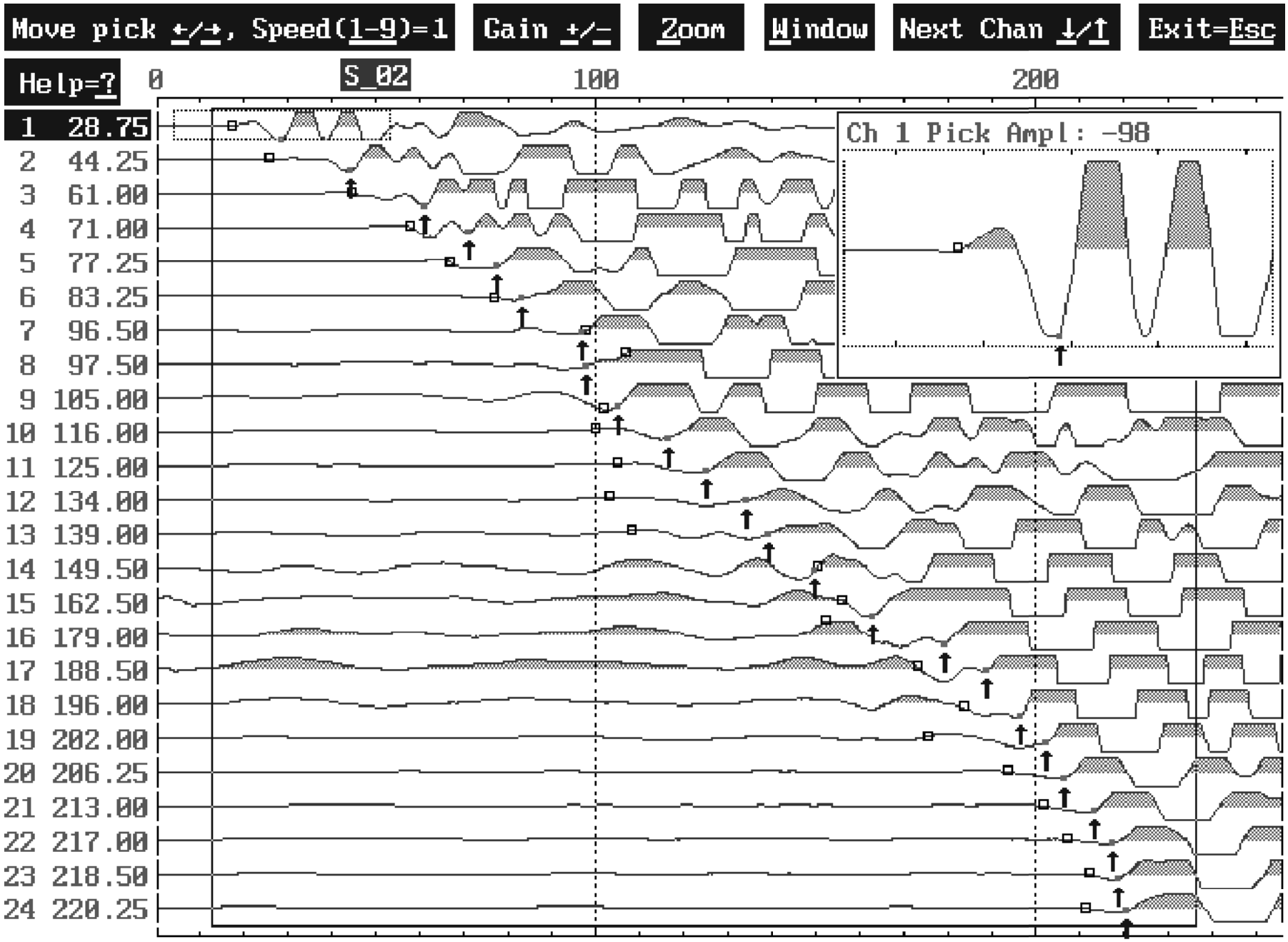


Sunnyside Elementary School S-wave



Sunnyside Elementary School S-wave



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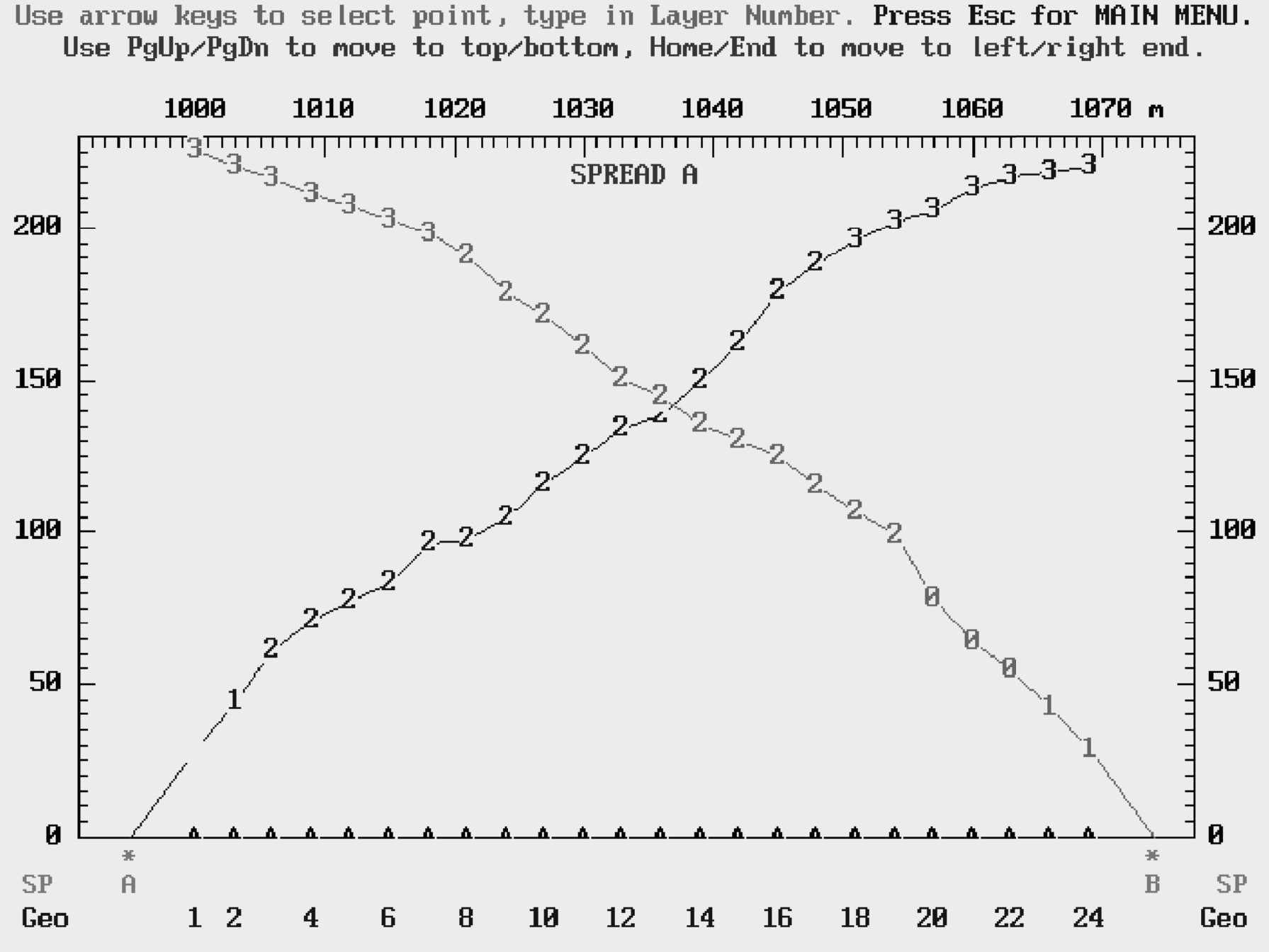

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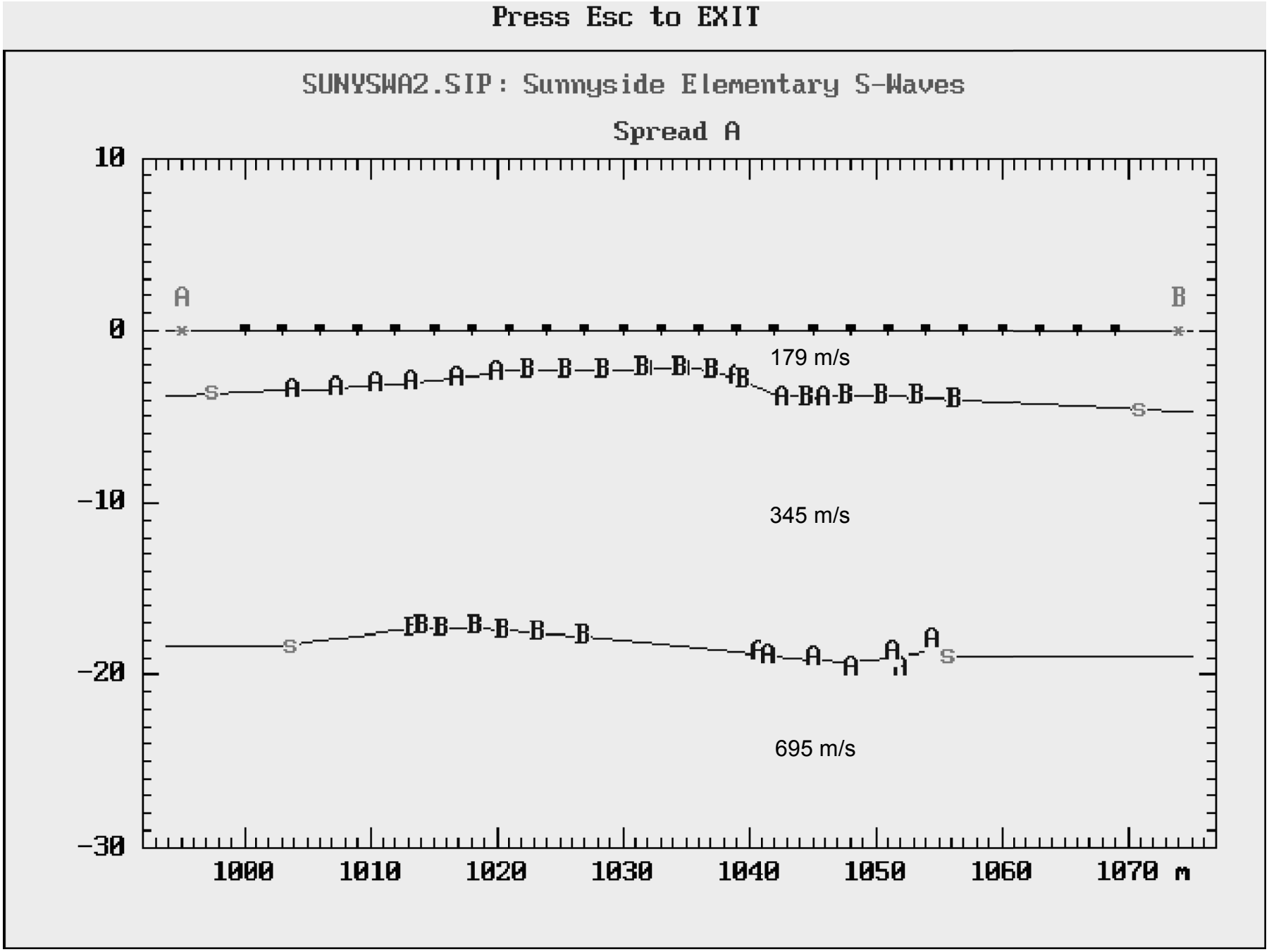

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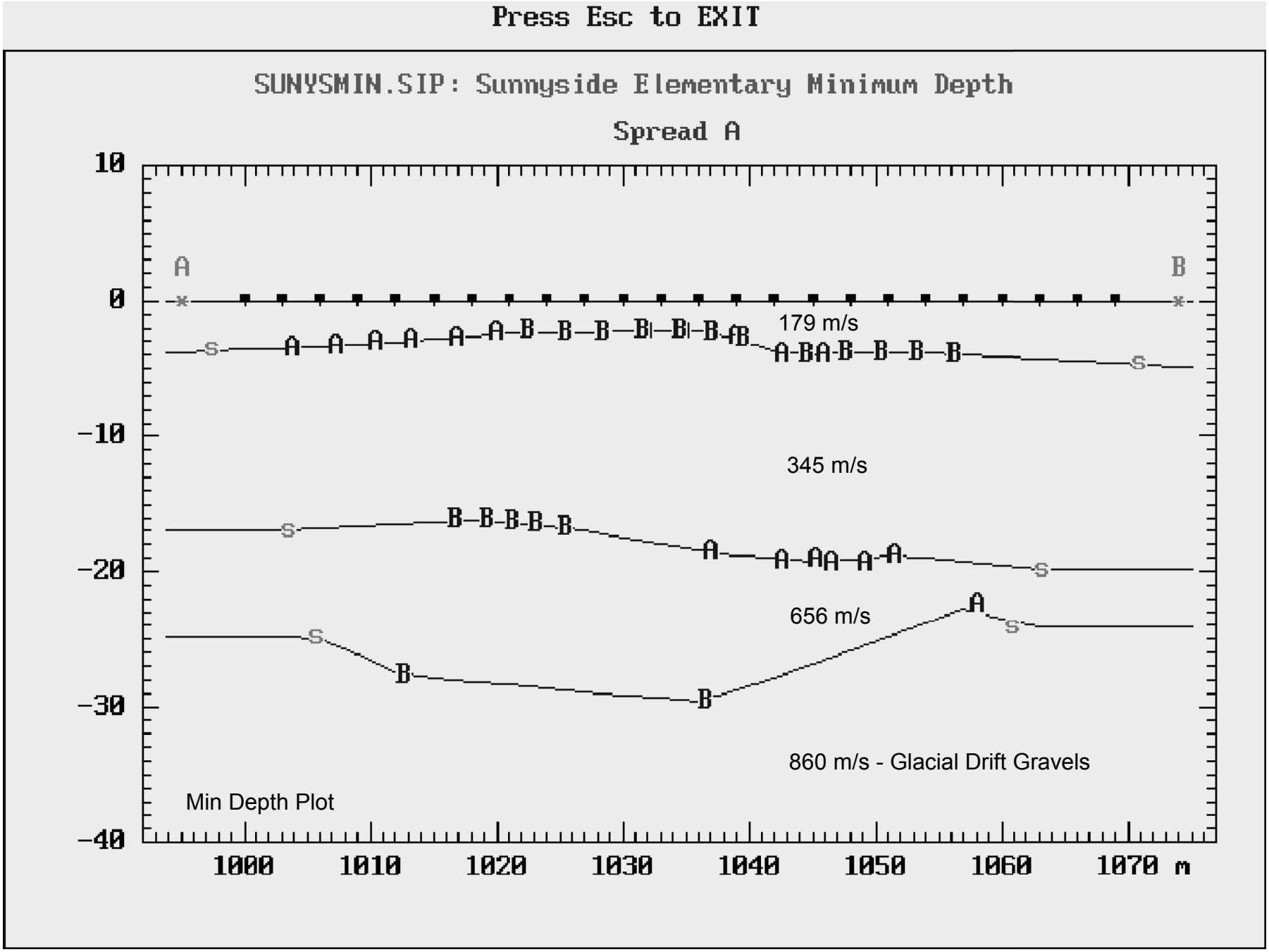
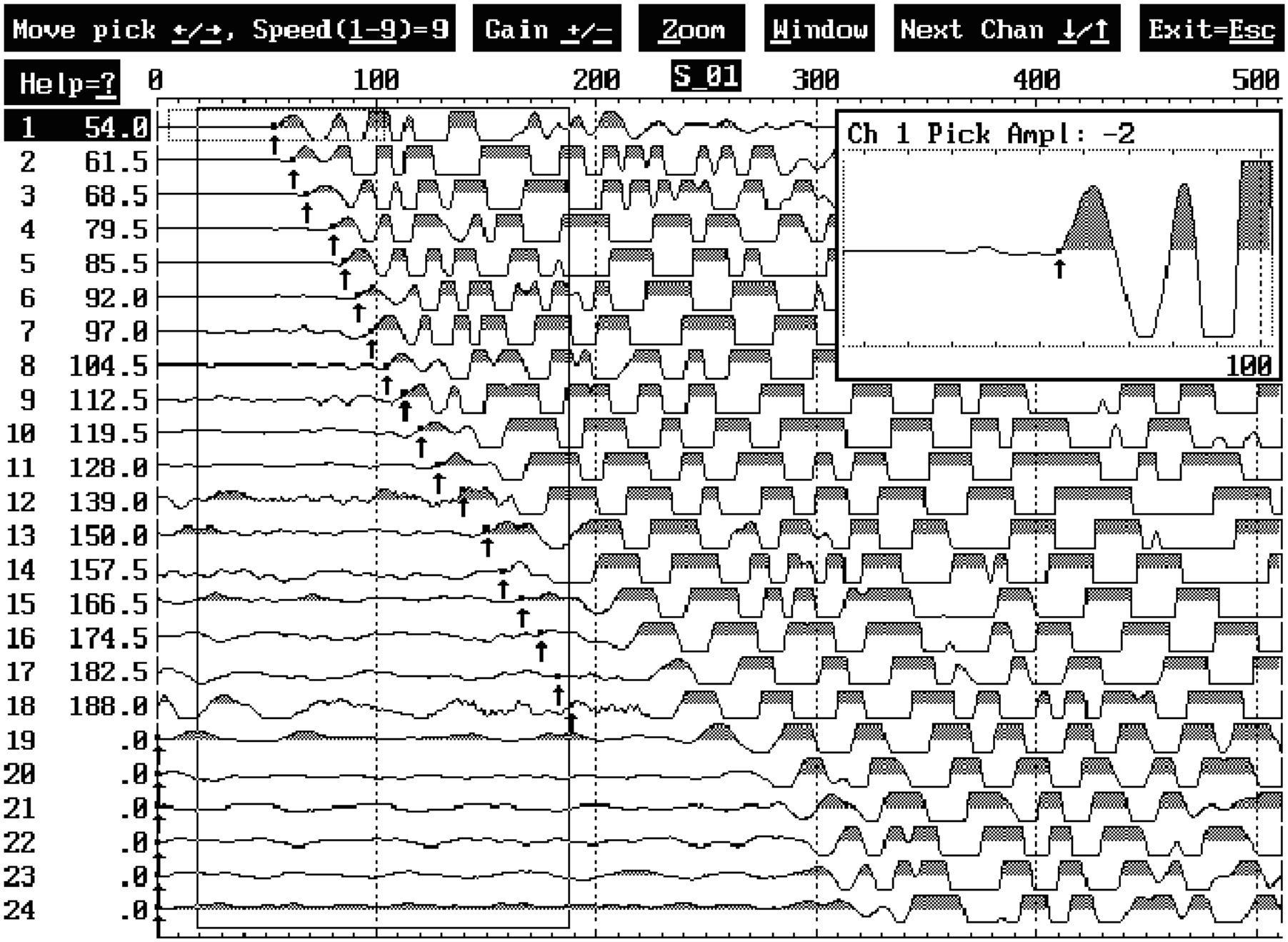


Syre Elementary S-wave



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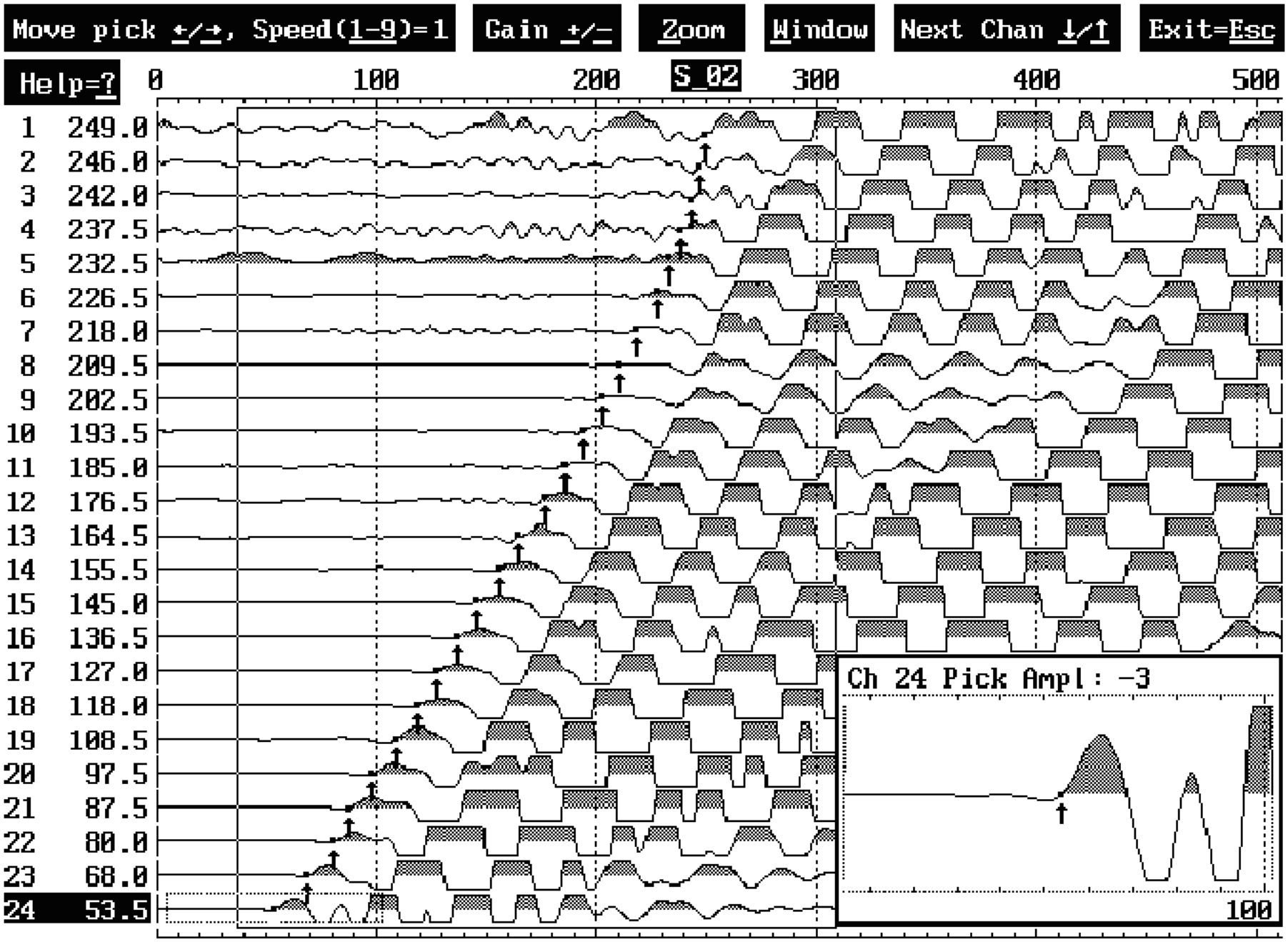

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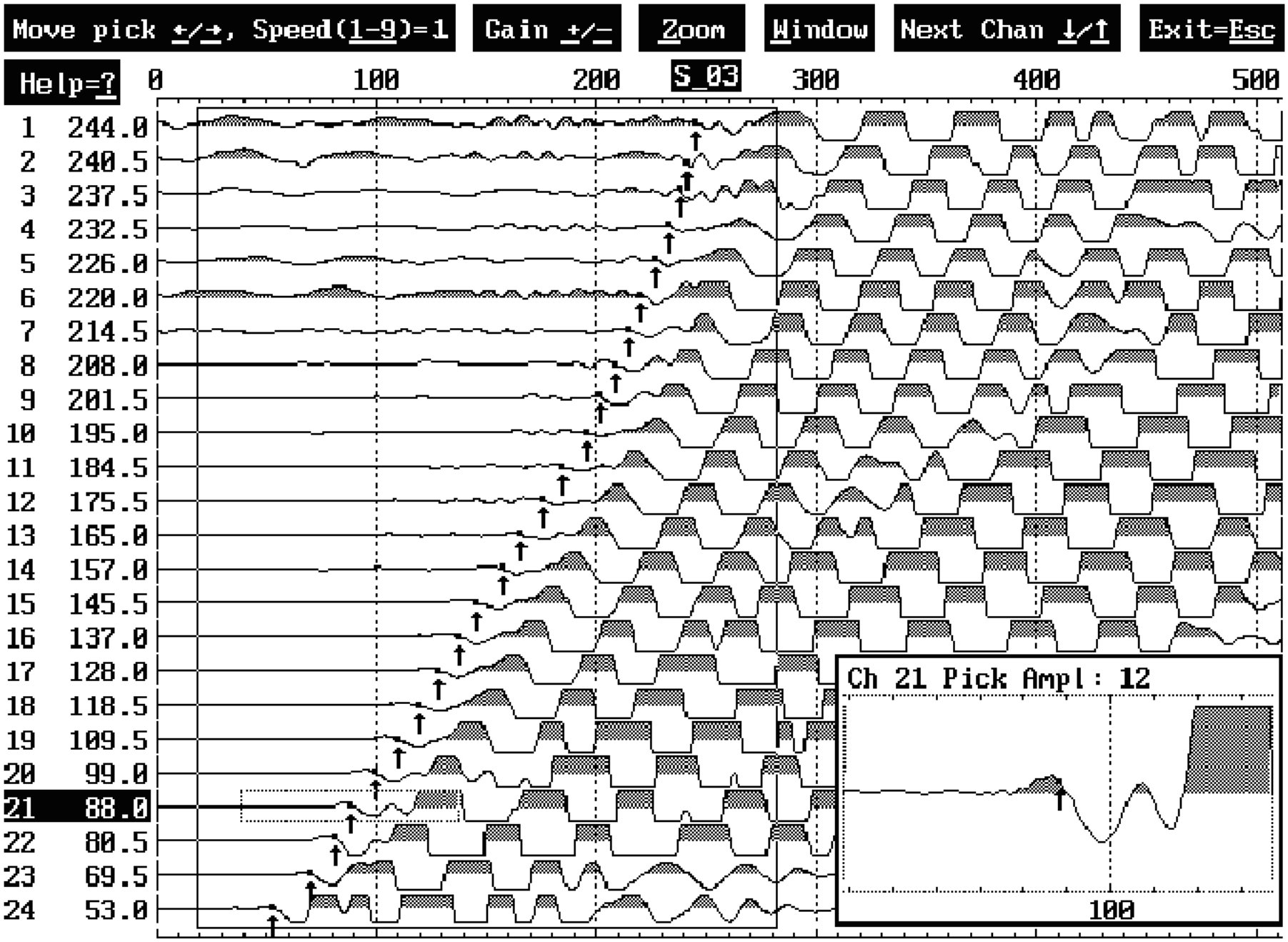

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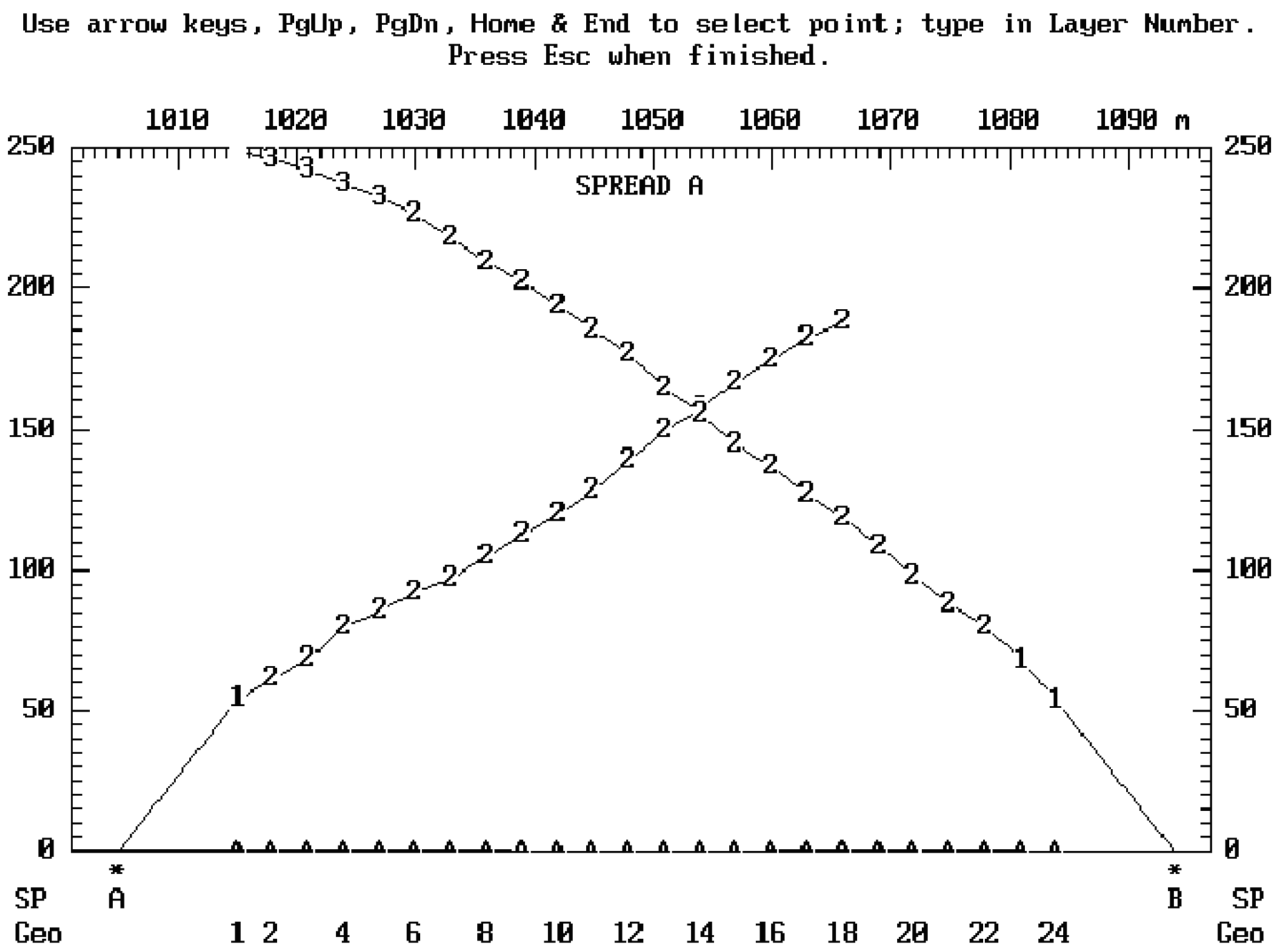
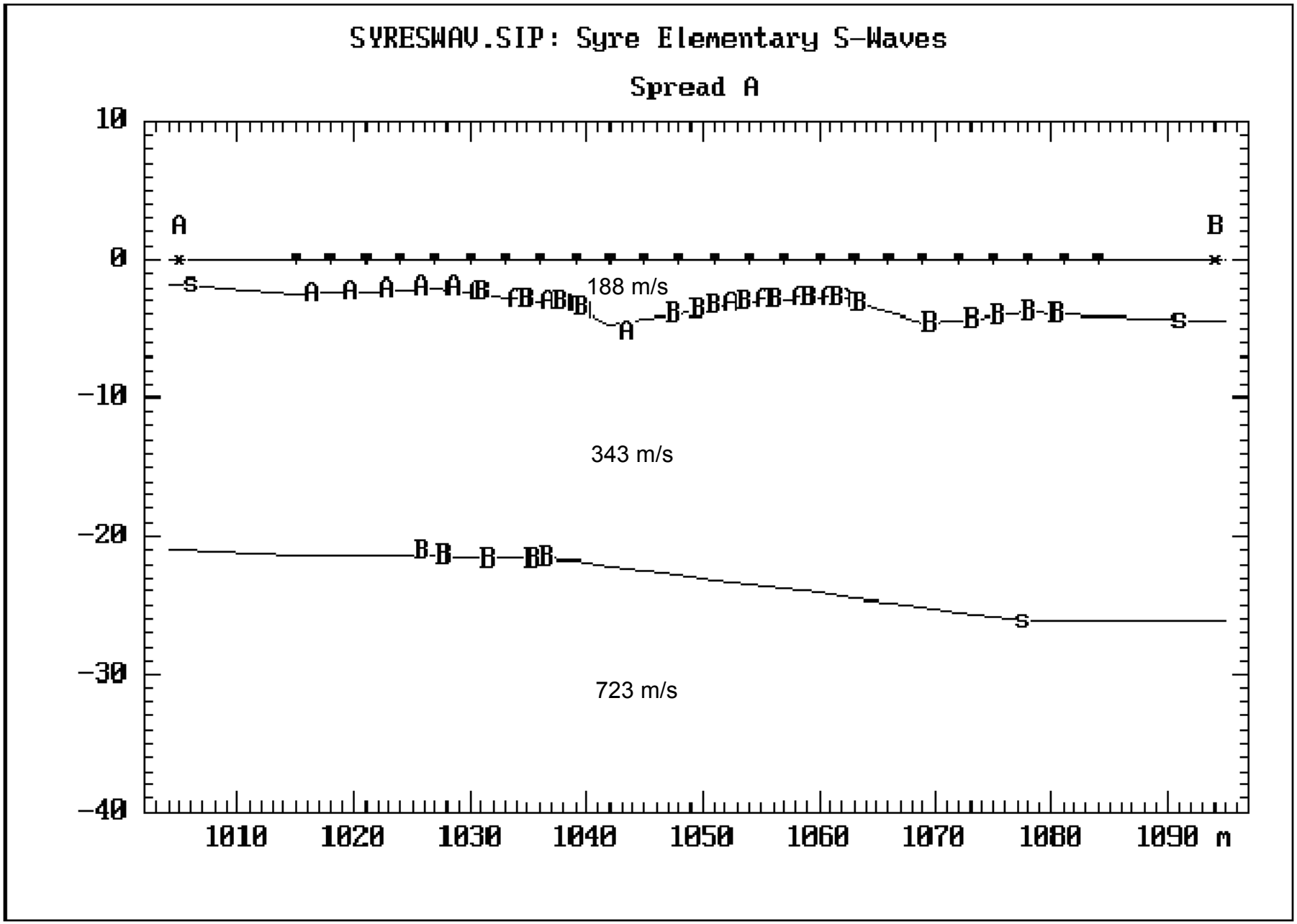


Syre Elementary S-wave

Press Esc to EXIT



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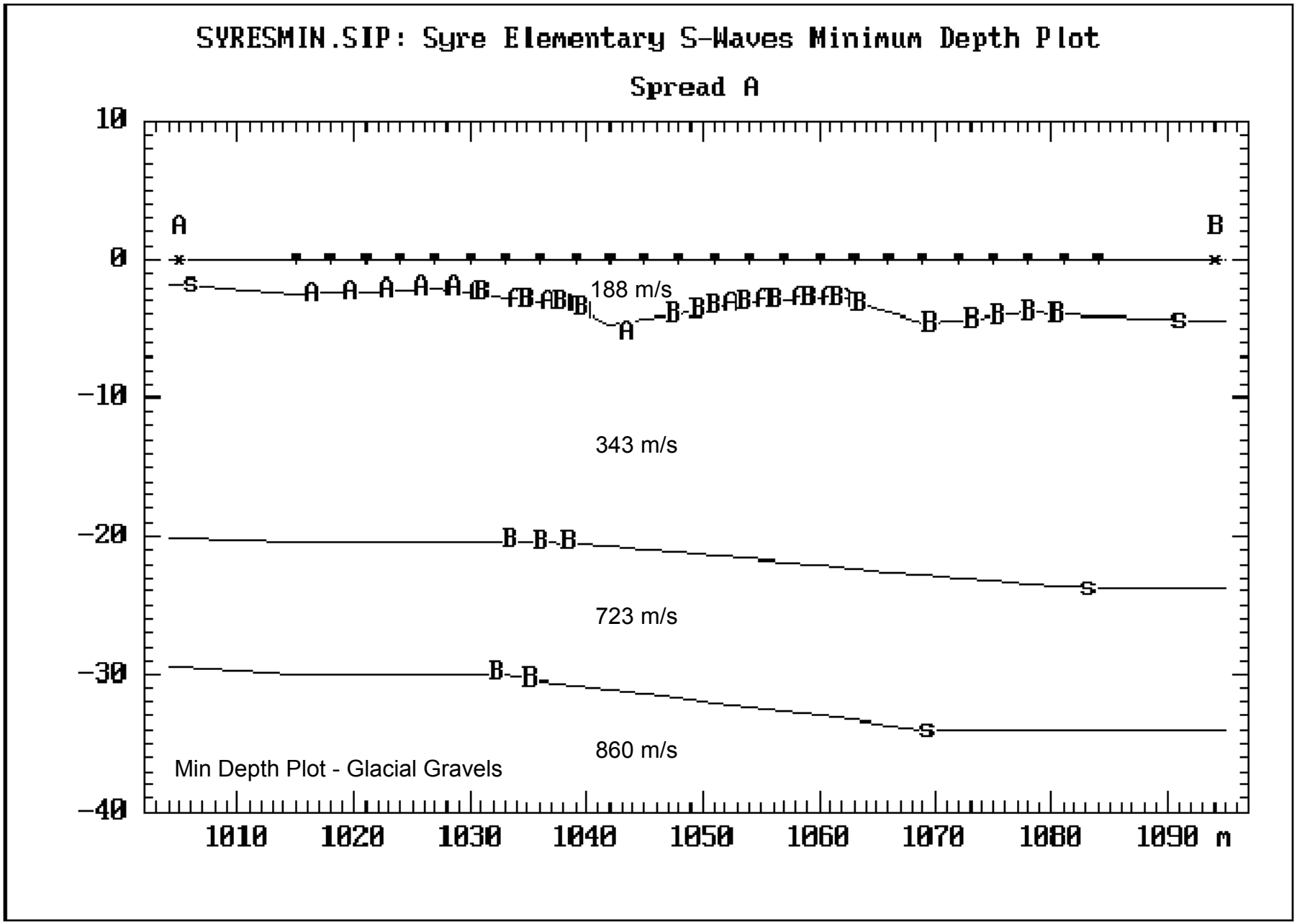
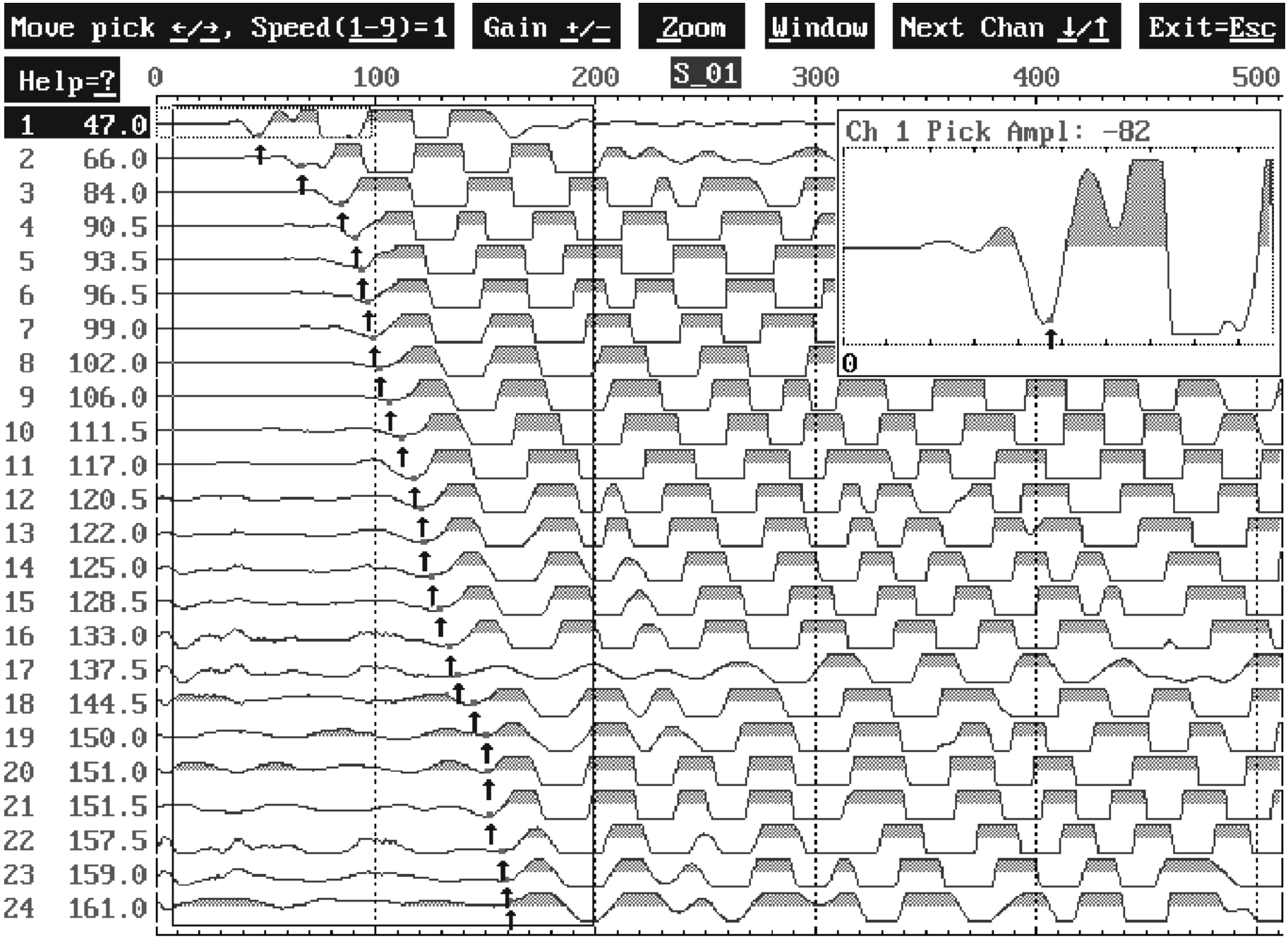


Twin Rivers Park S-wave



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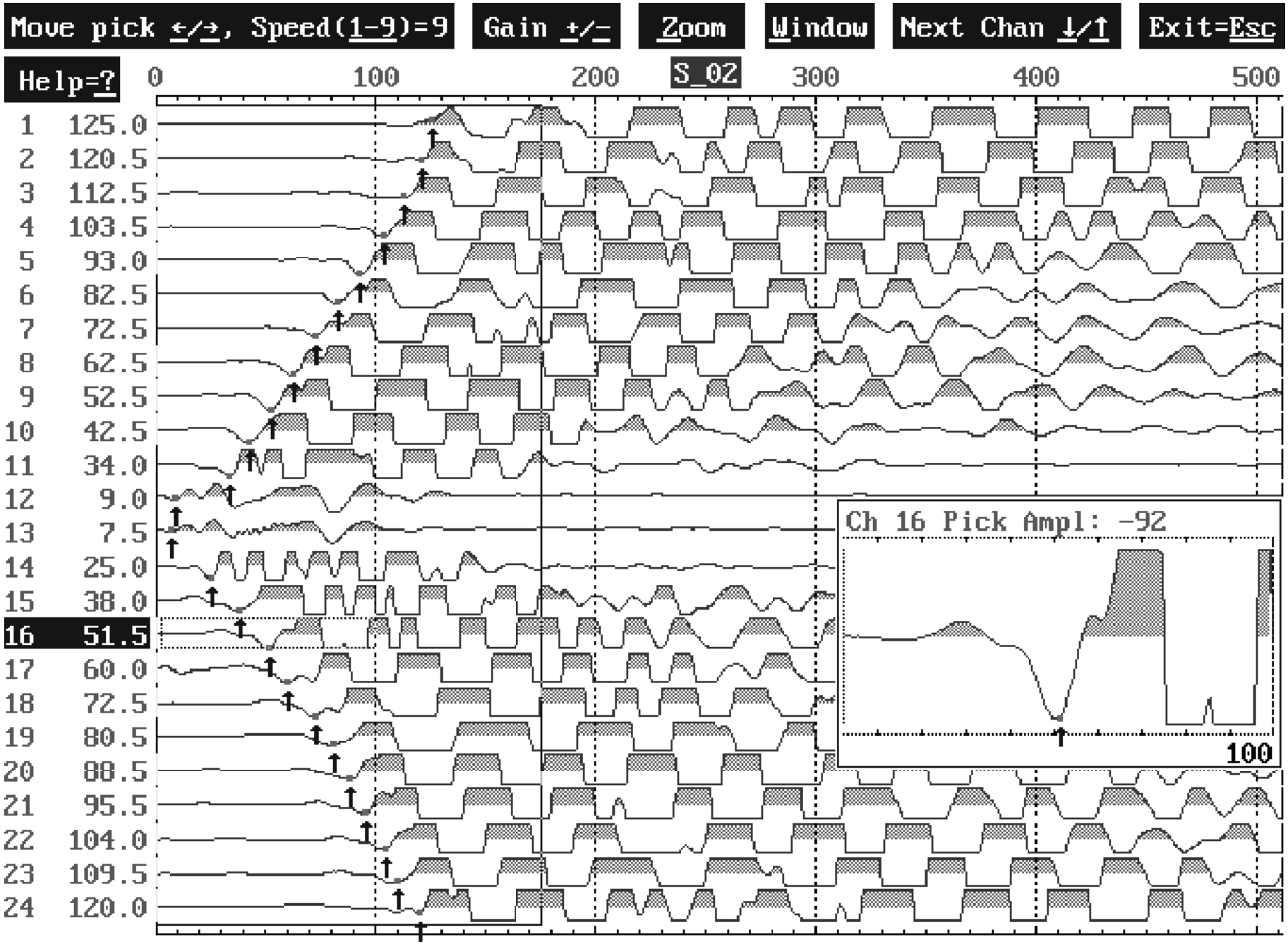

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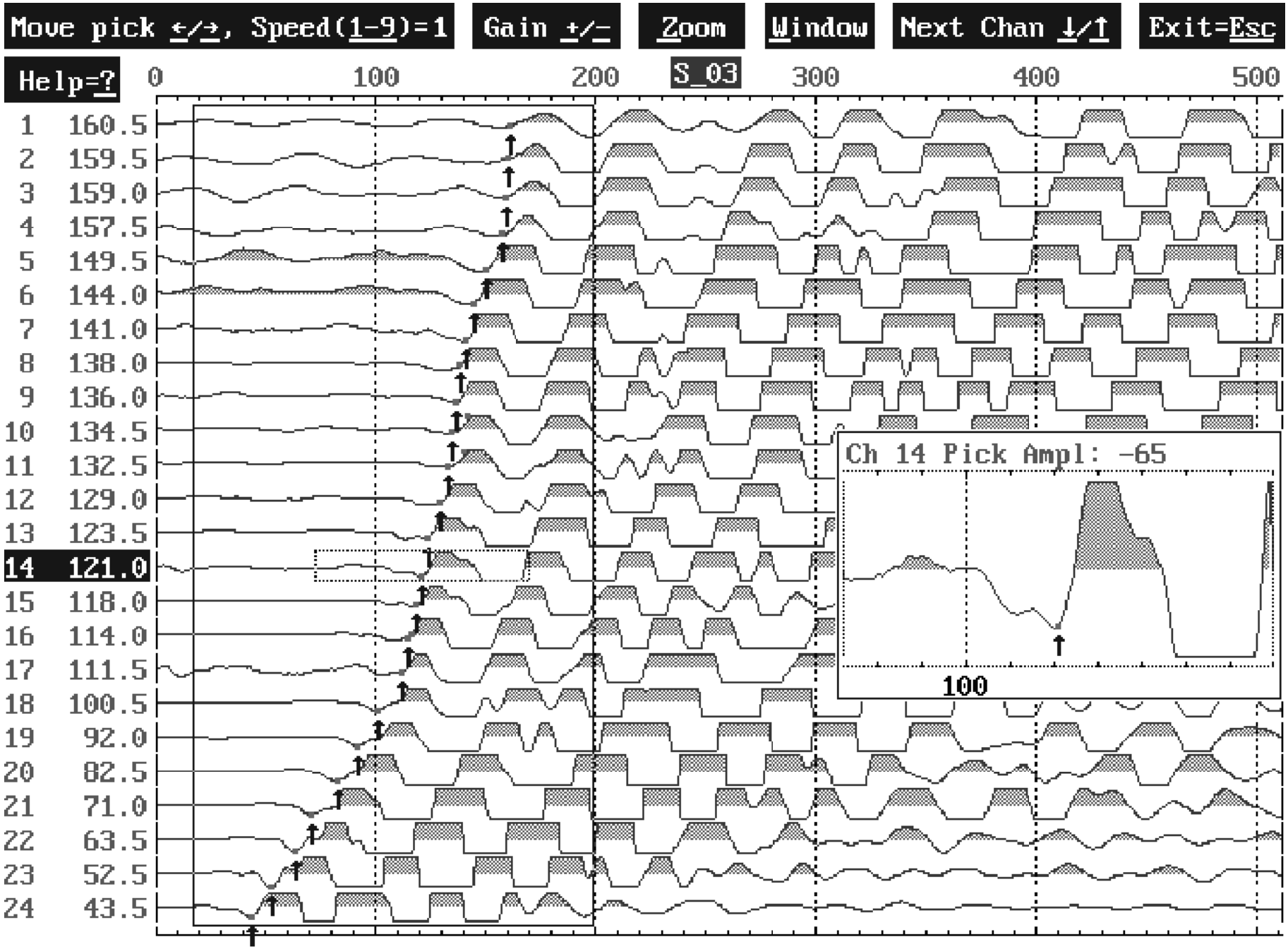

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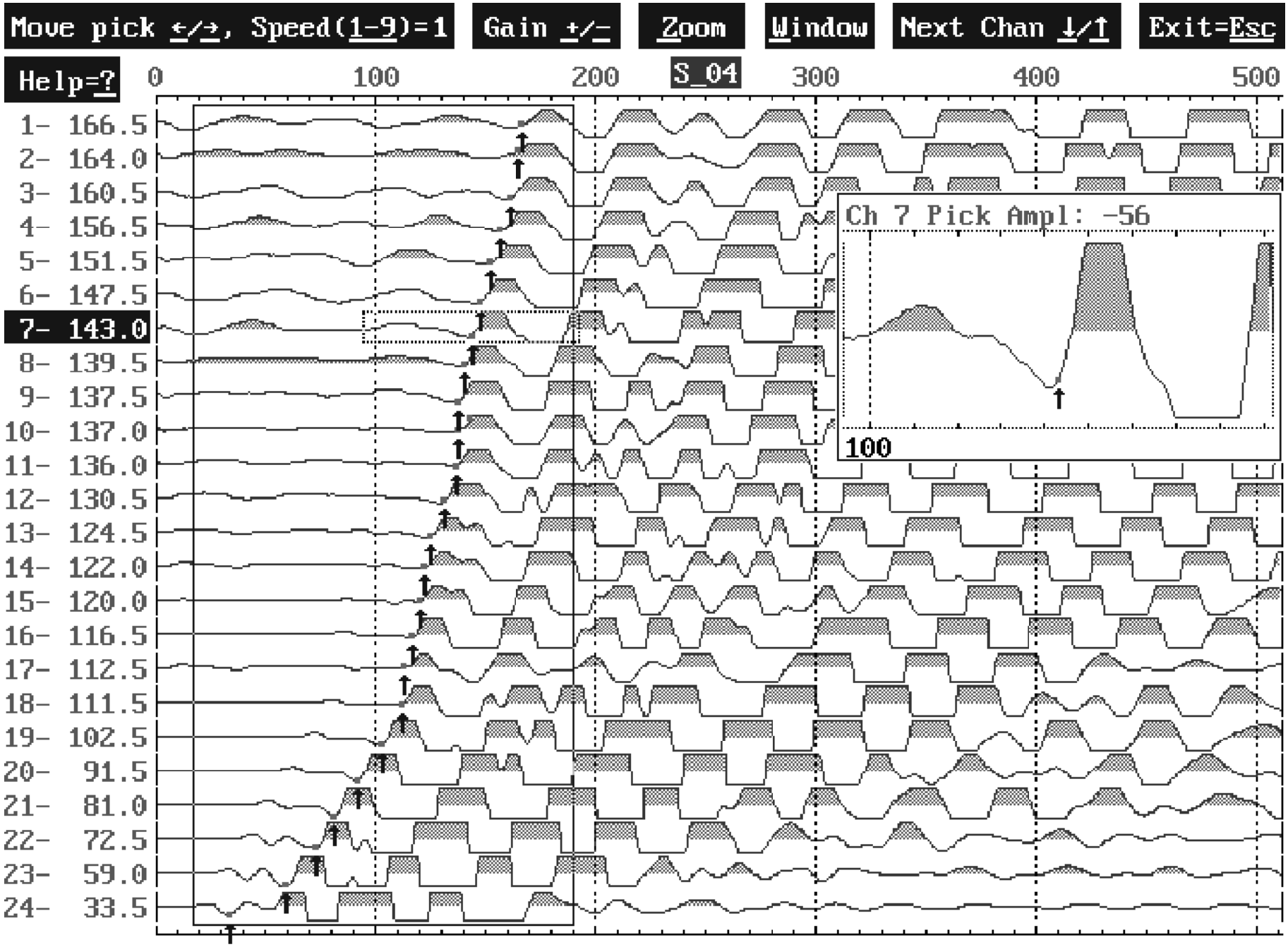

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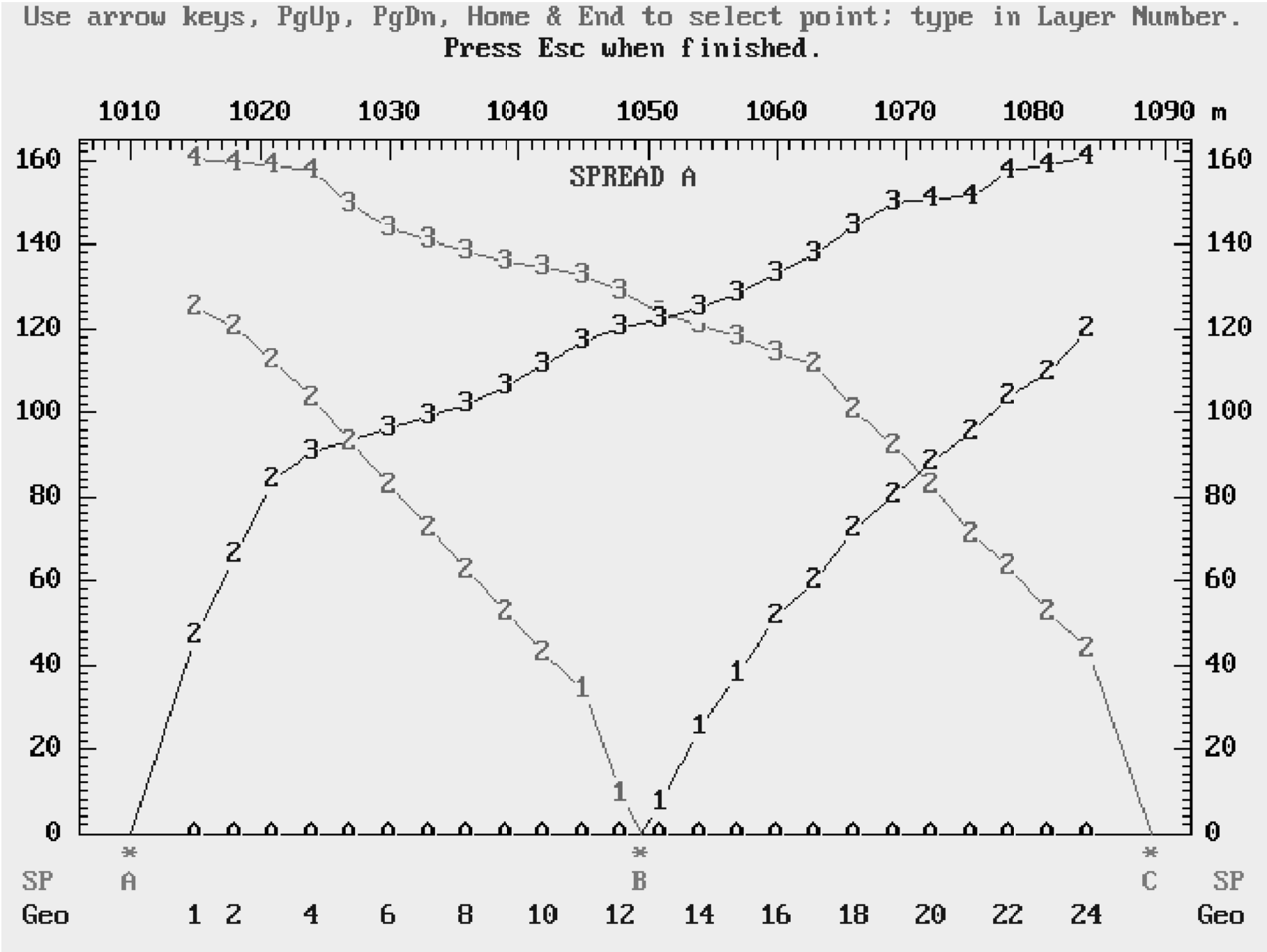

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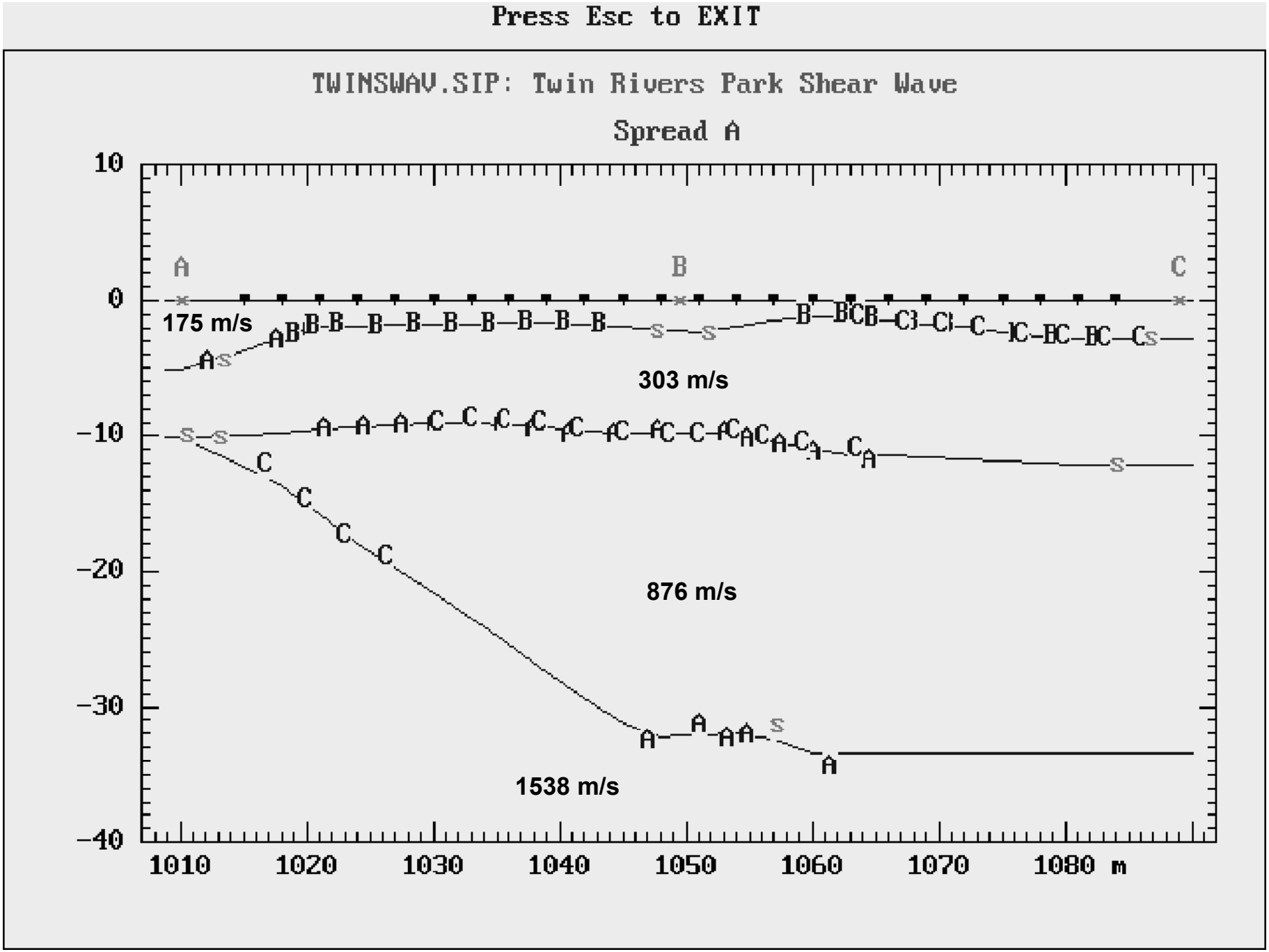
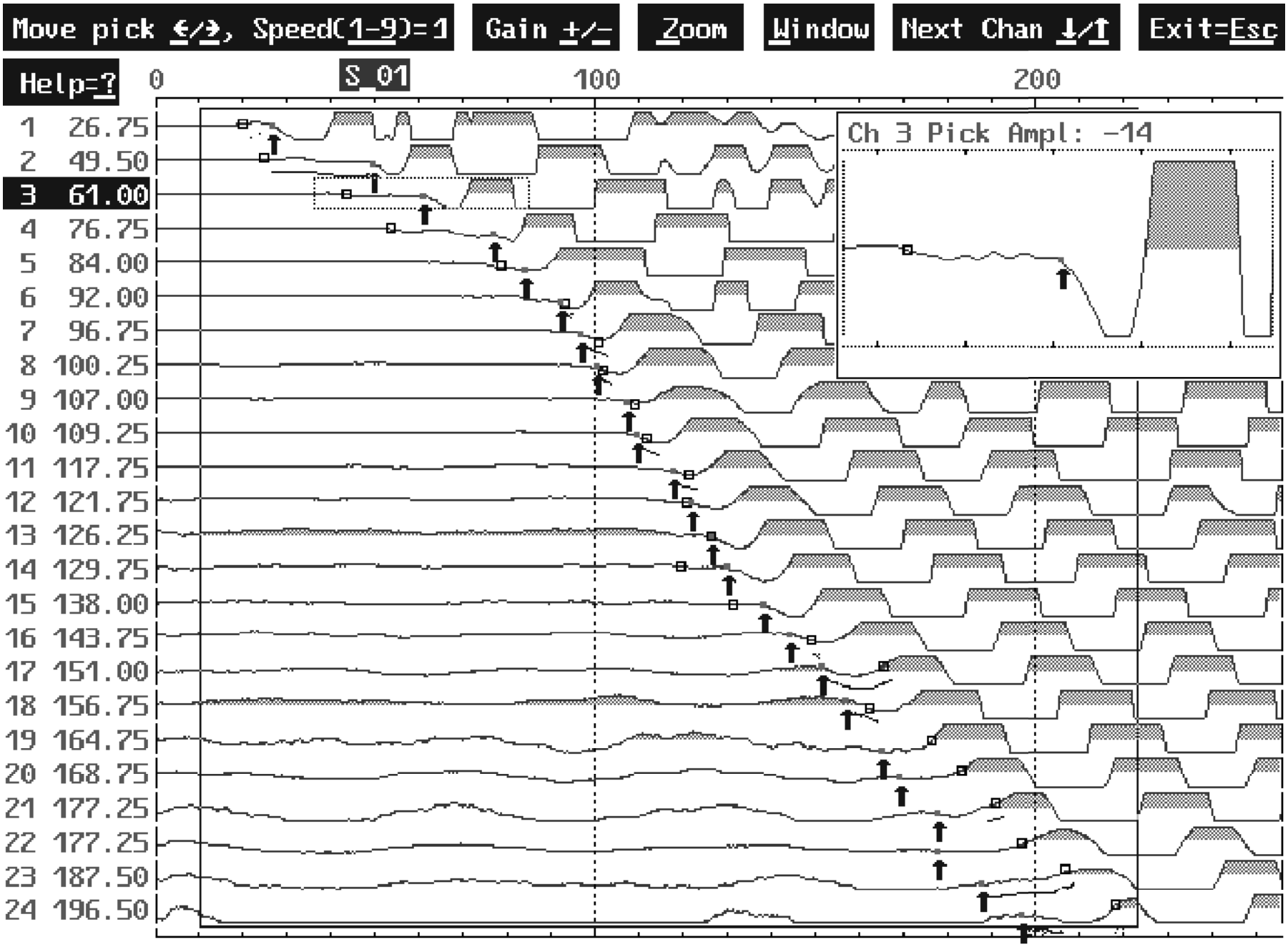


Van Wyck RD S-wave



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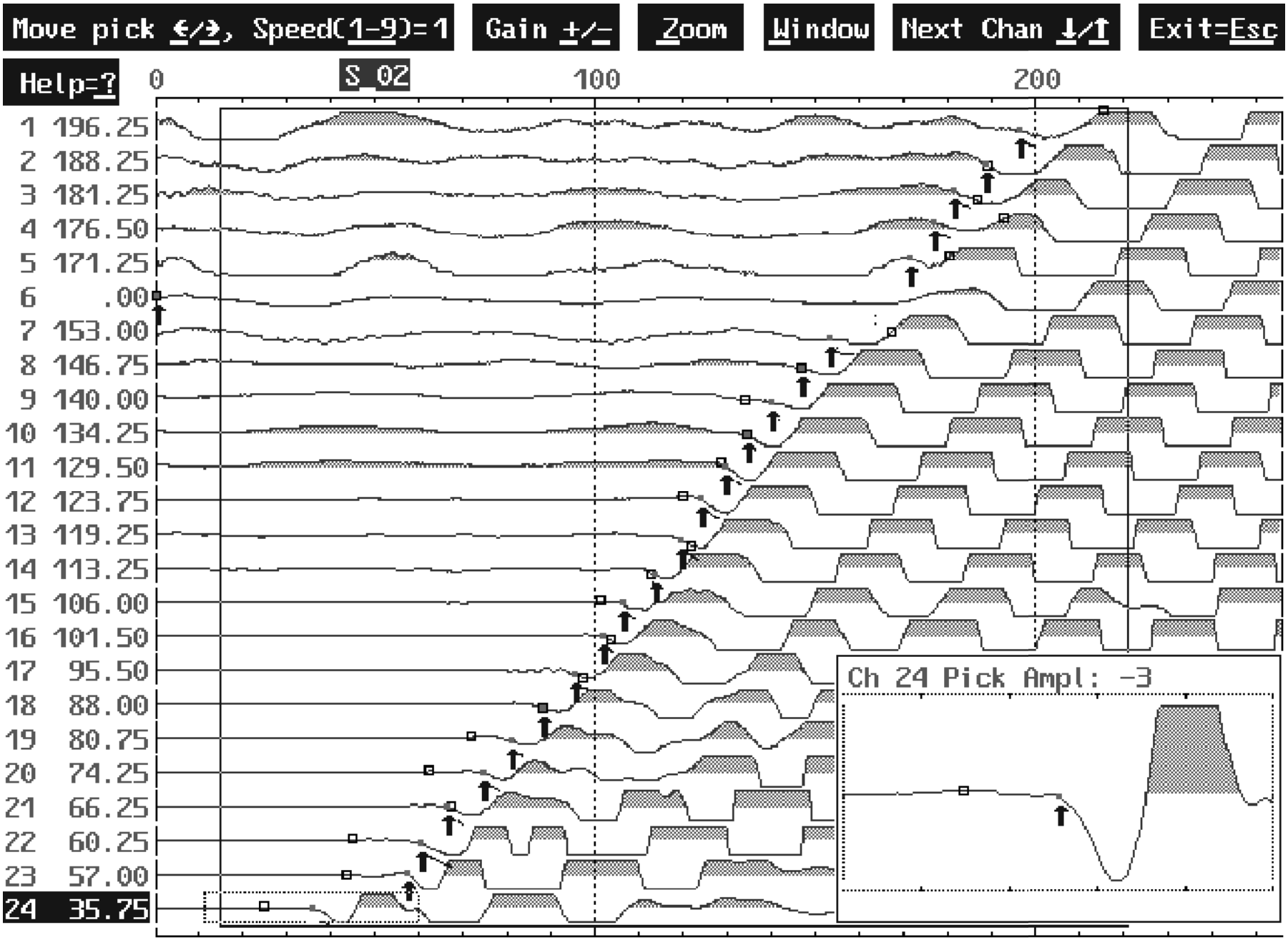

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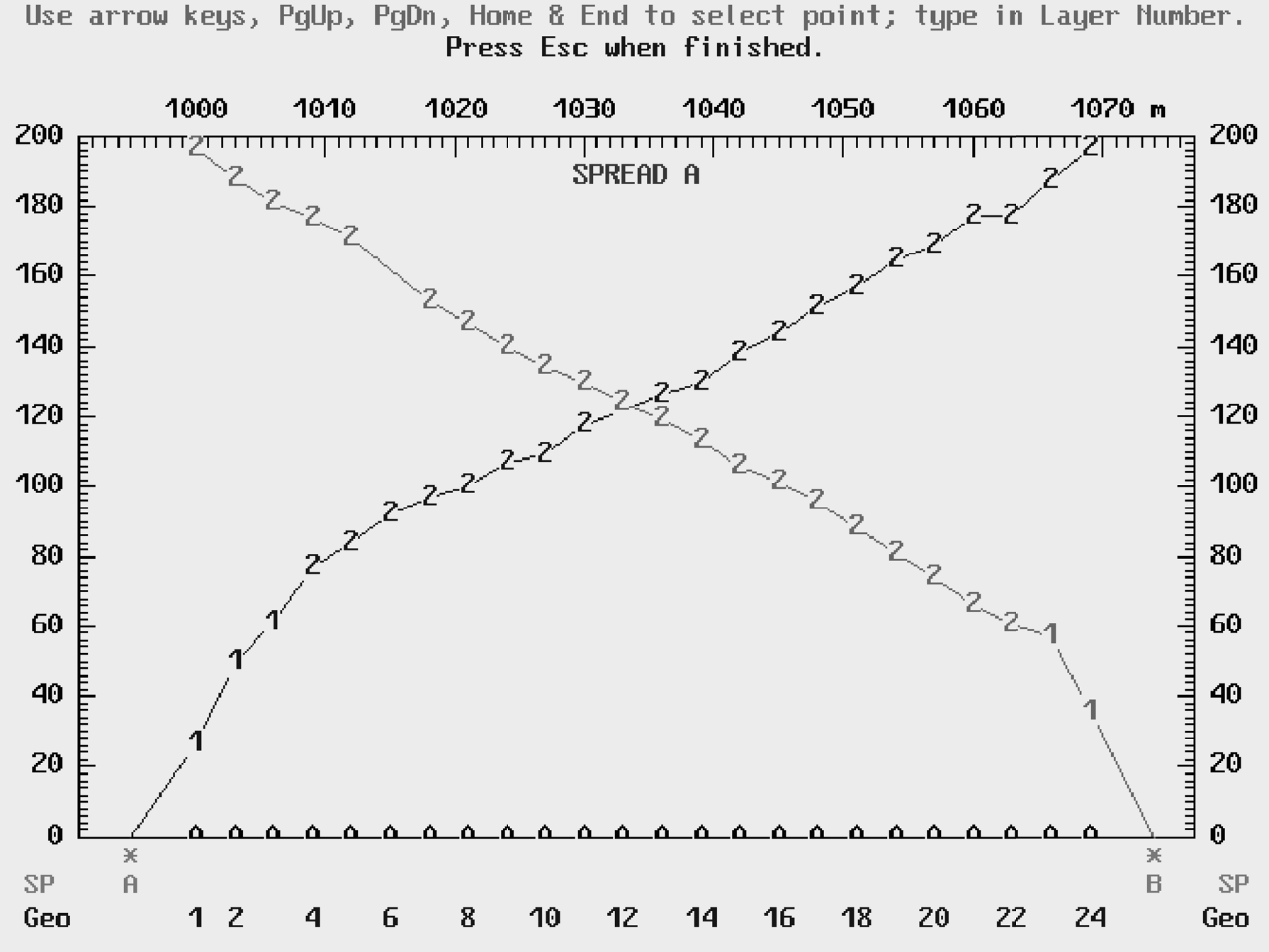

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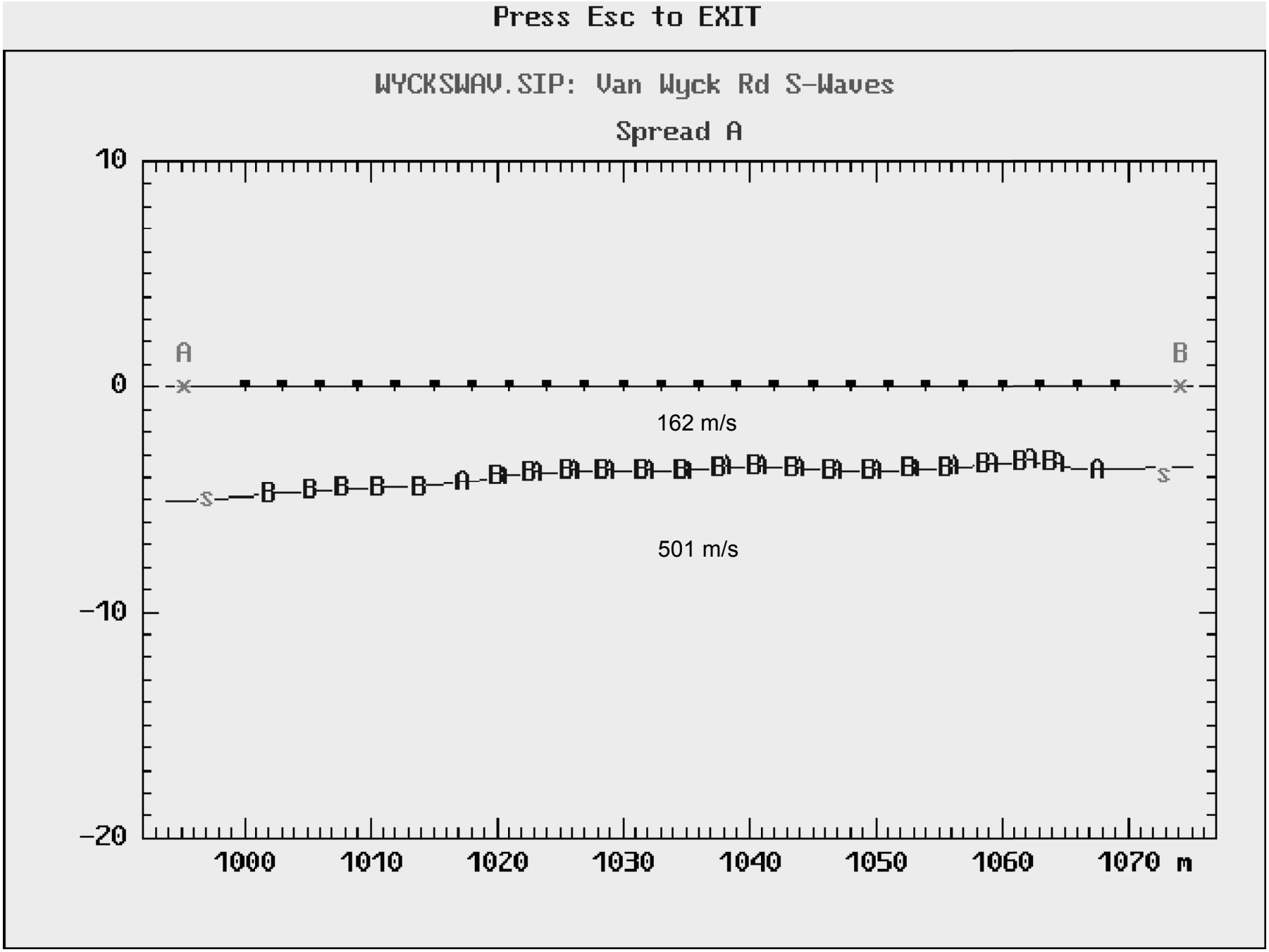

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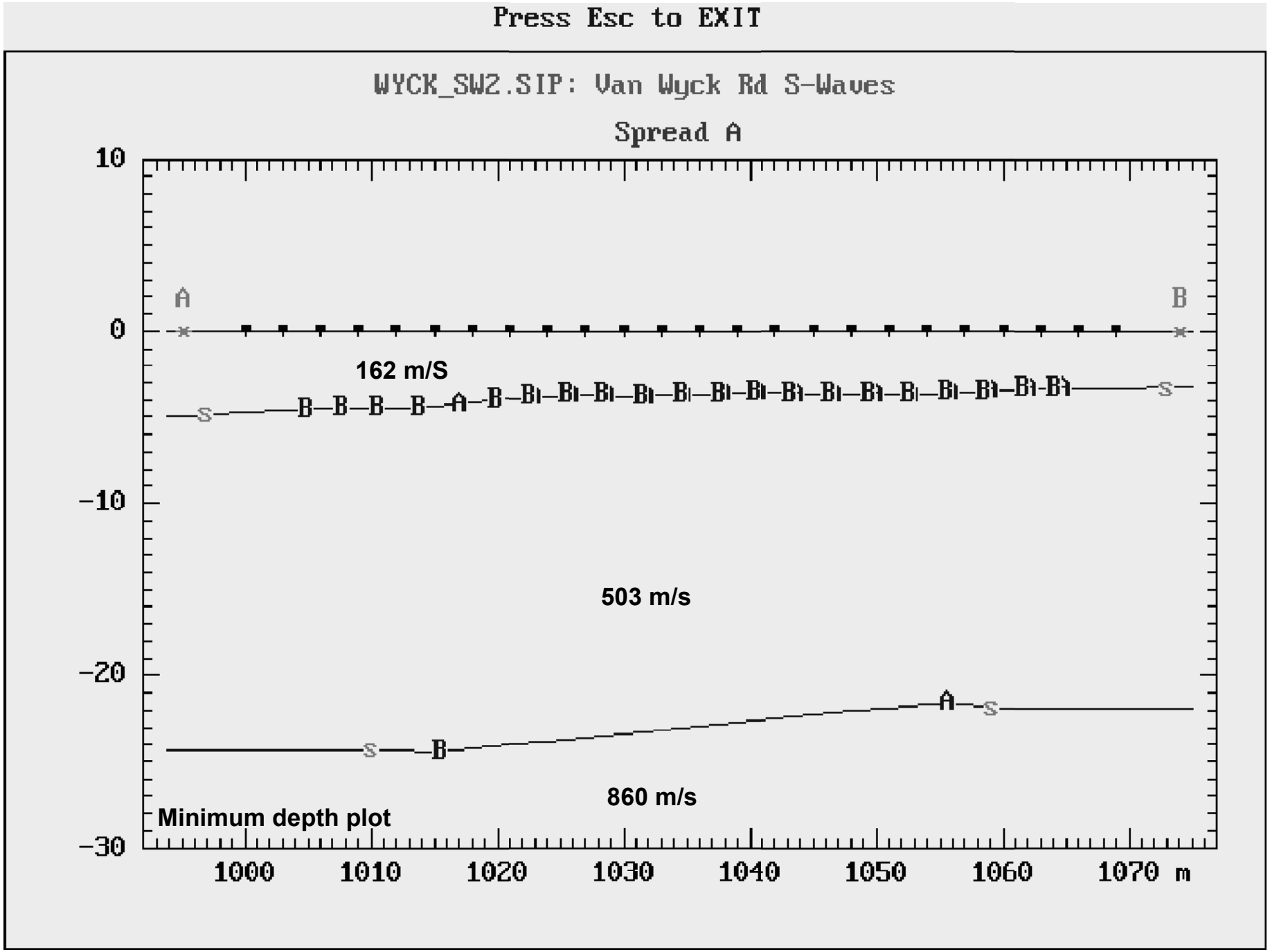
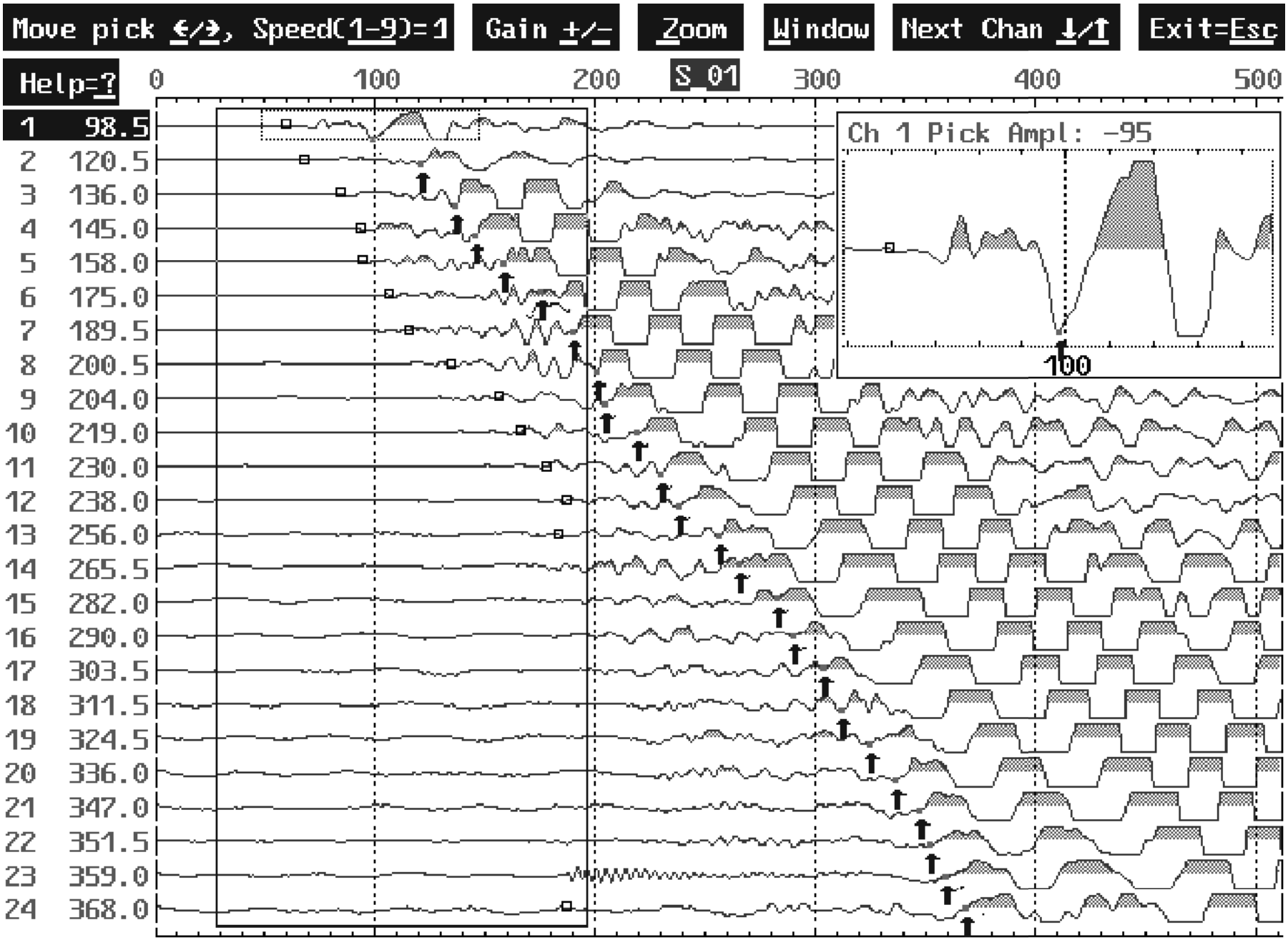


Vossbeck Elementary S-wave



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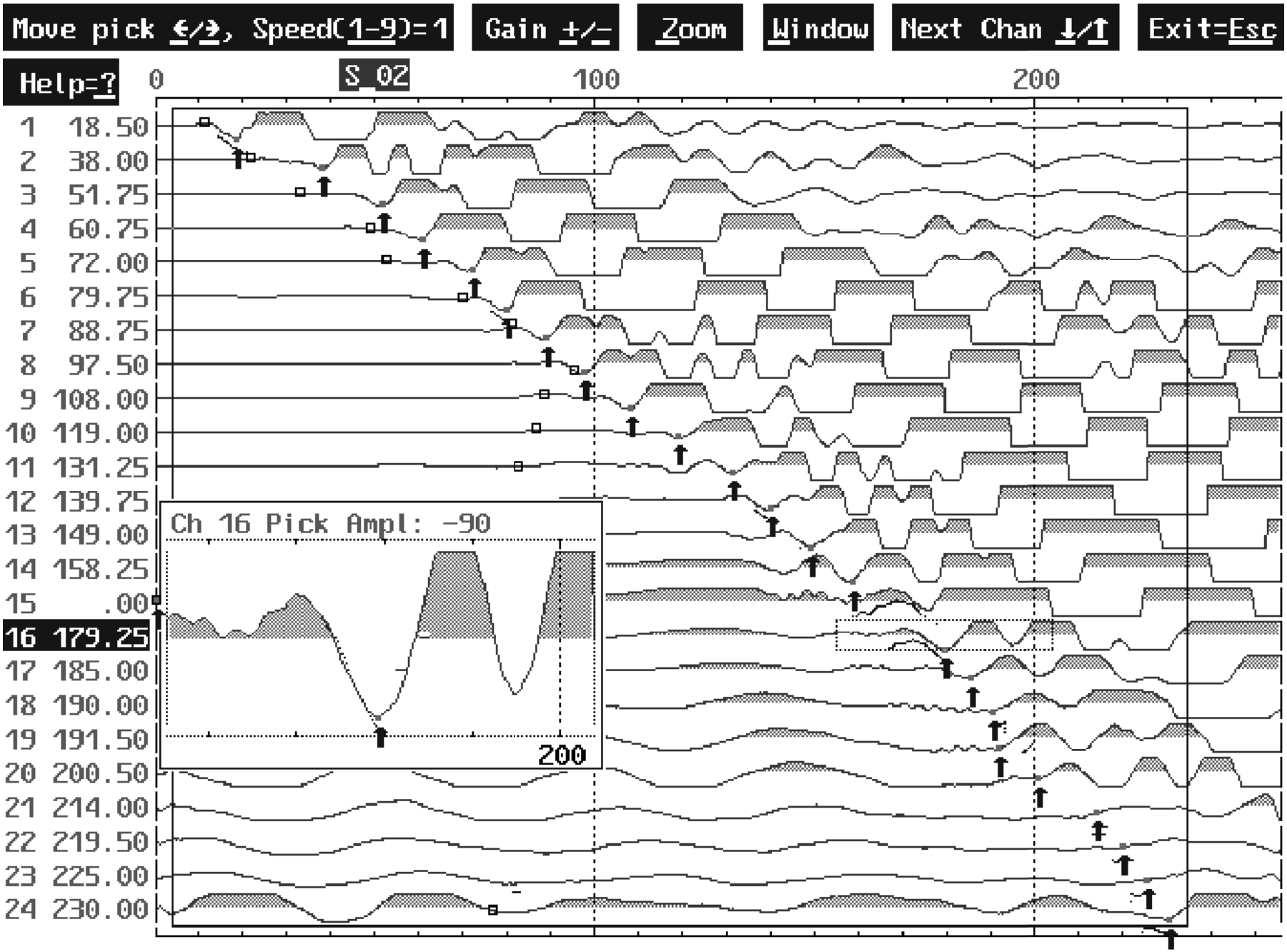
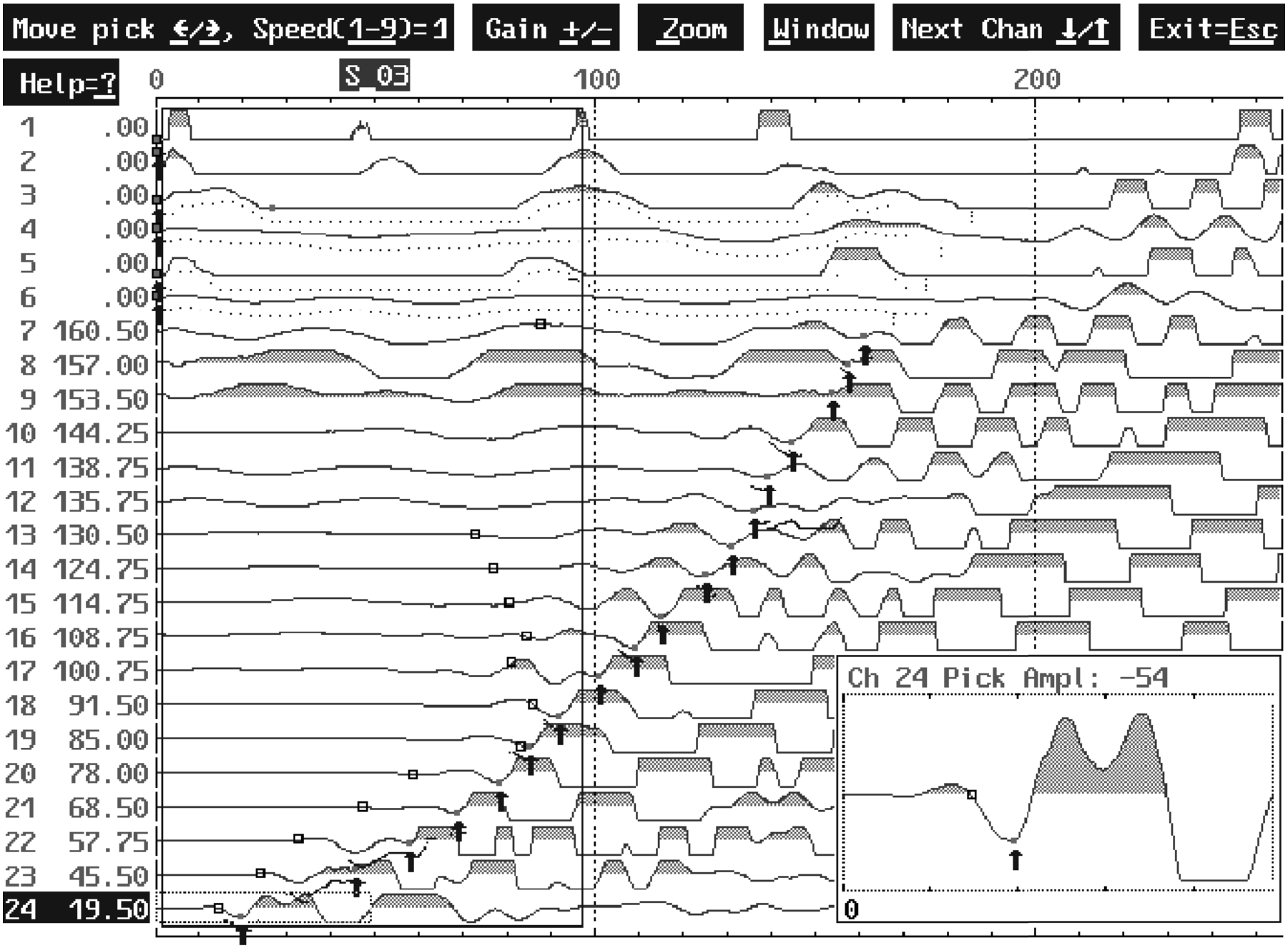


Vossbeck Elementary S-wave



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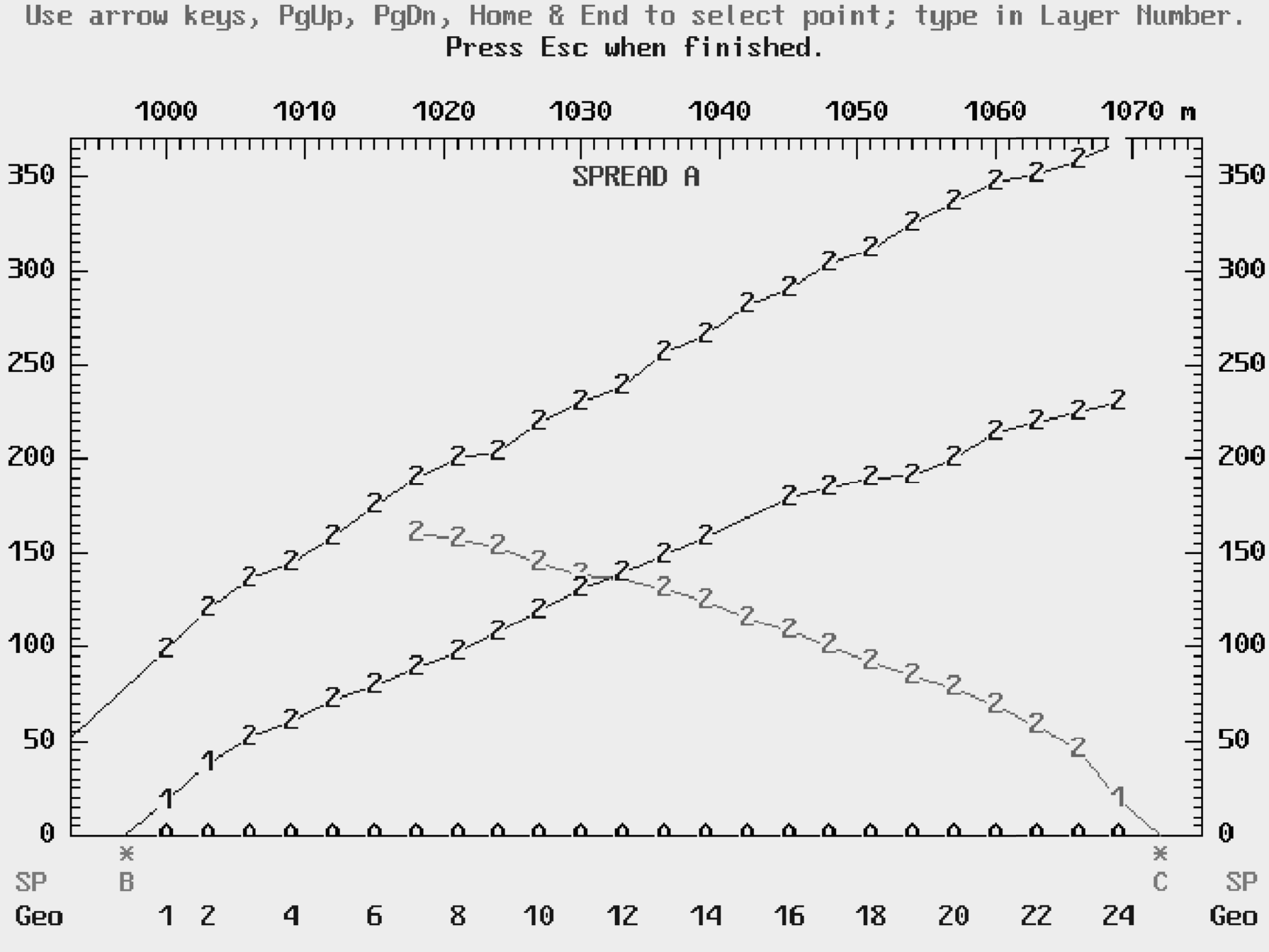

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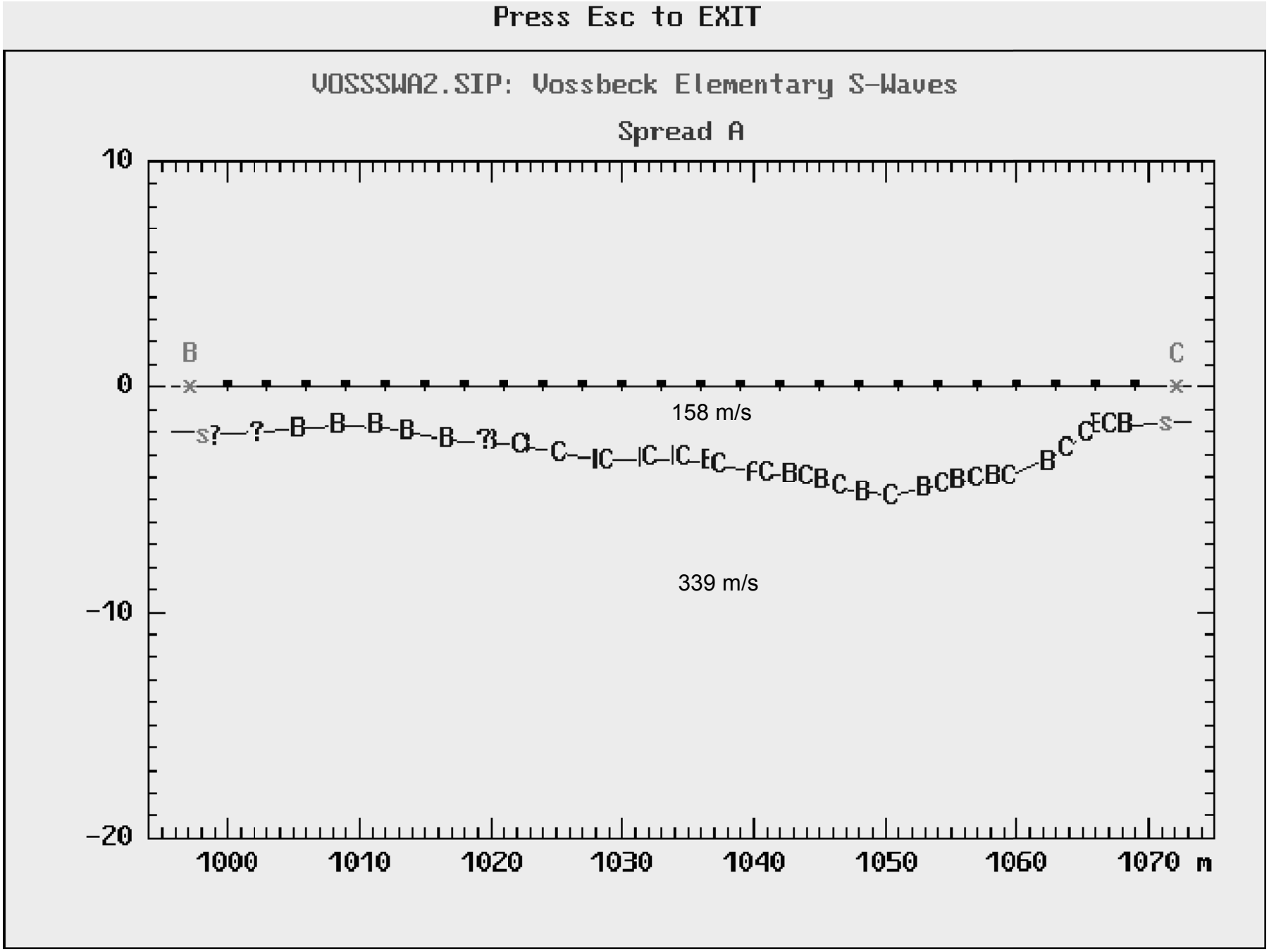

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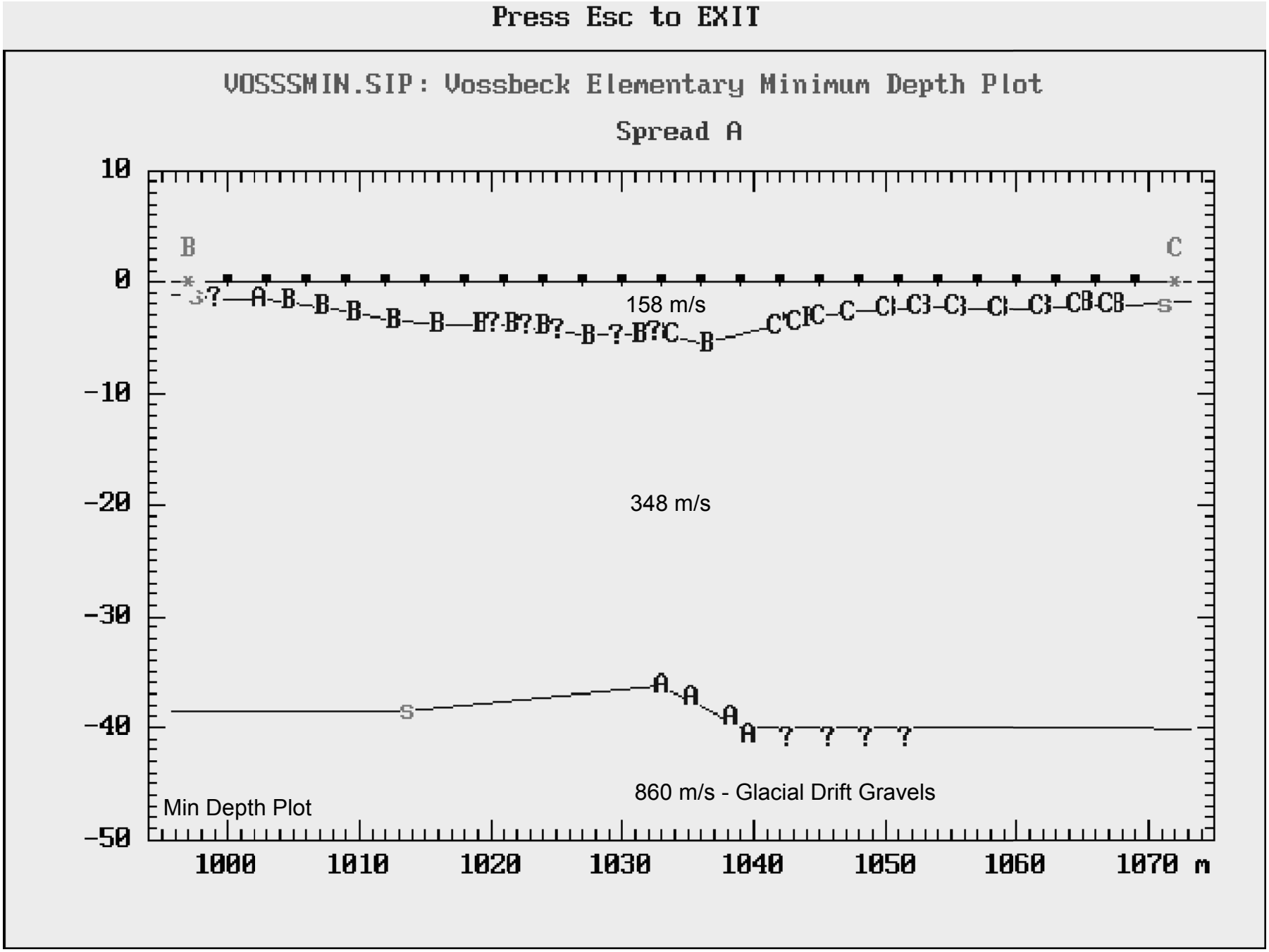

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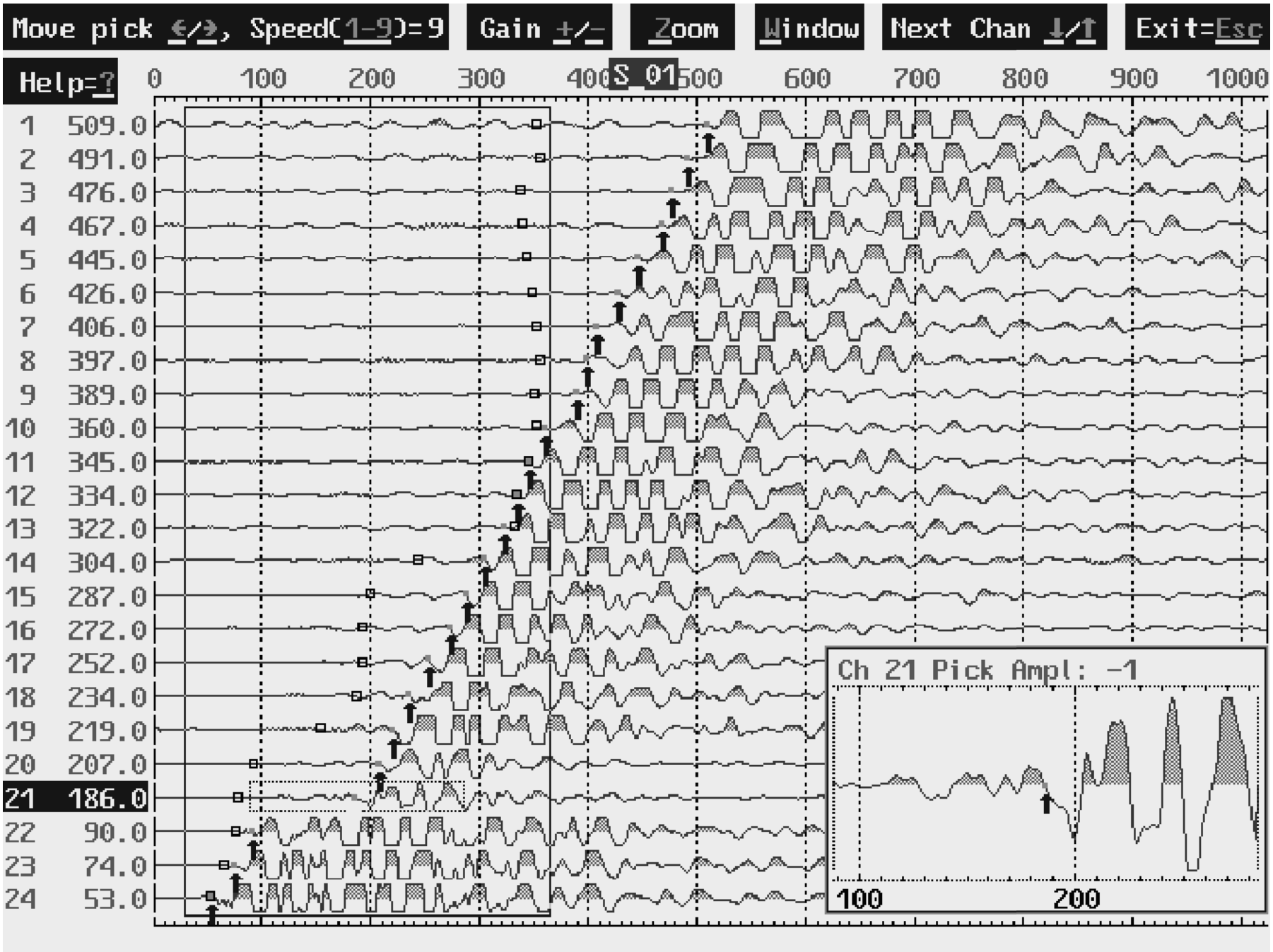

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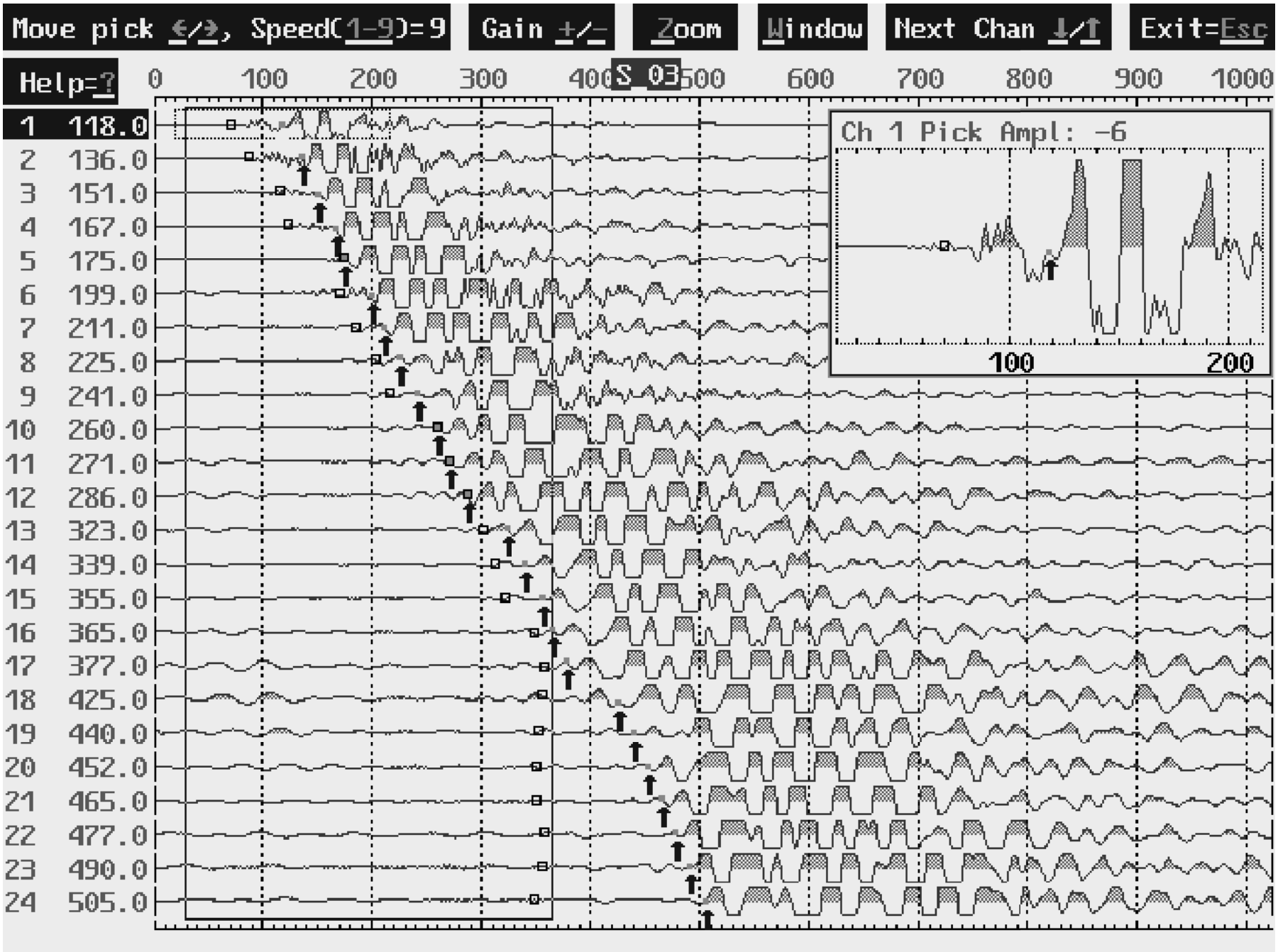

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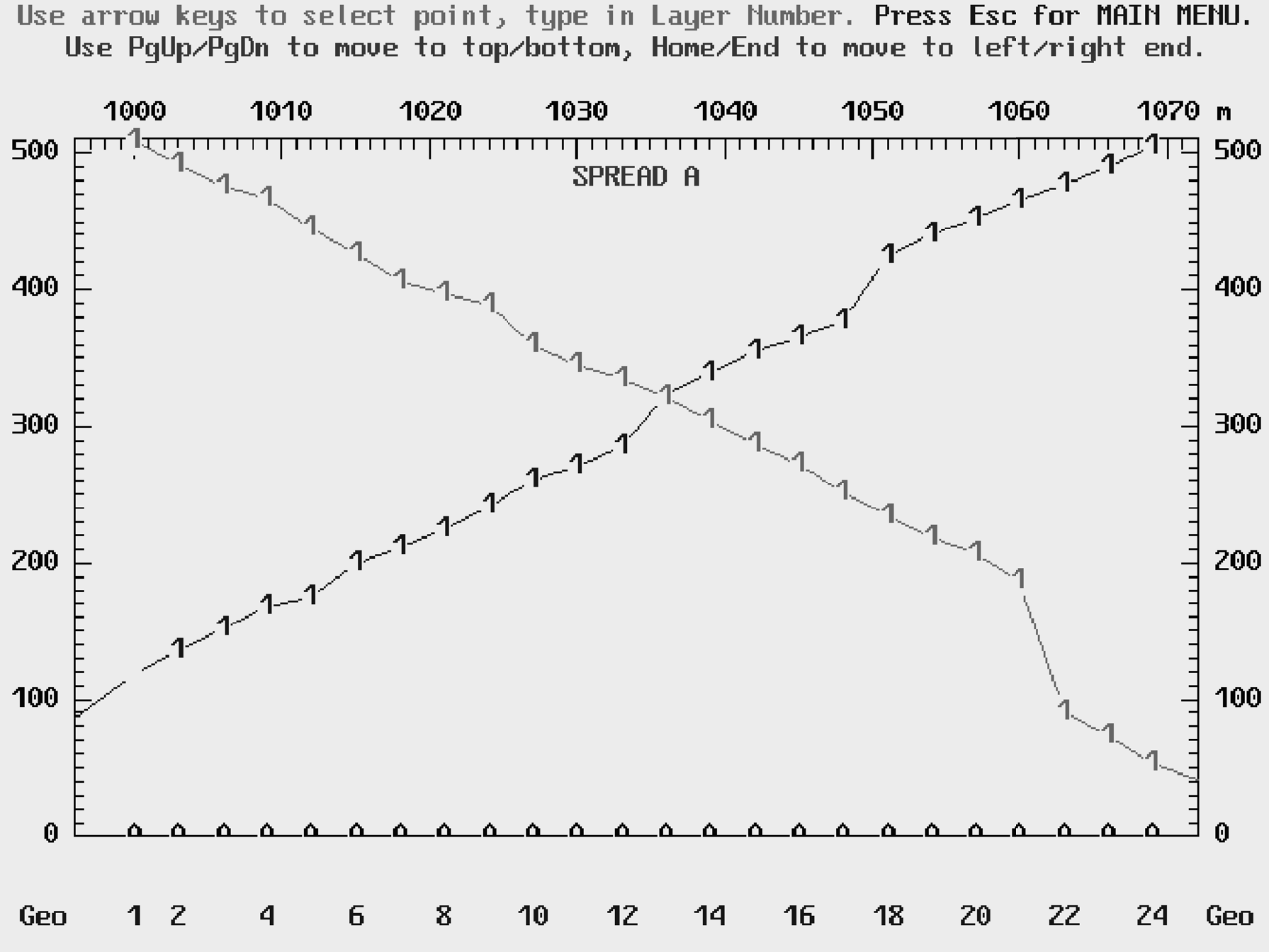

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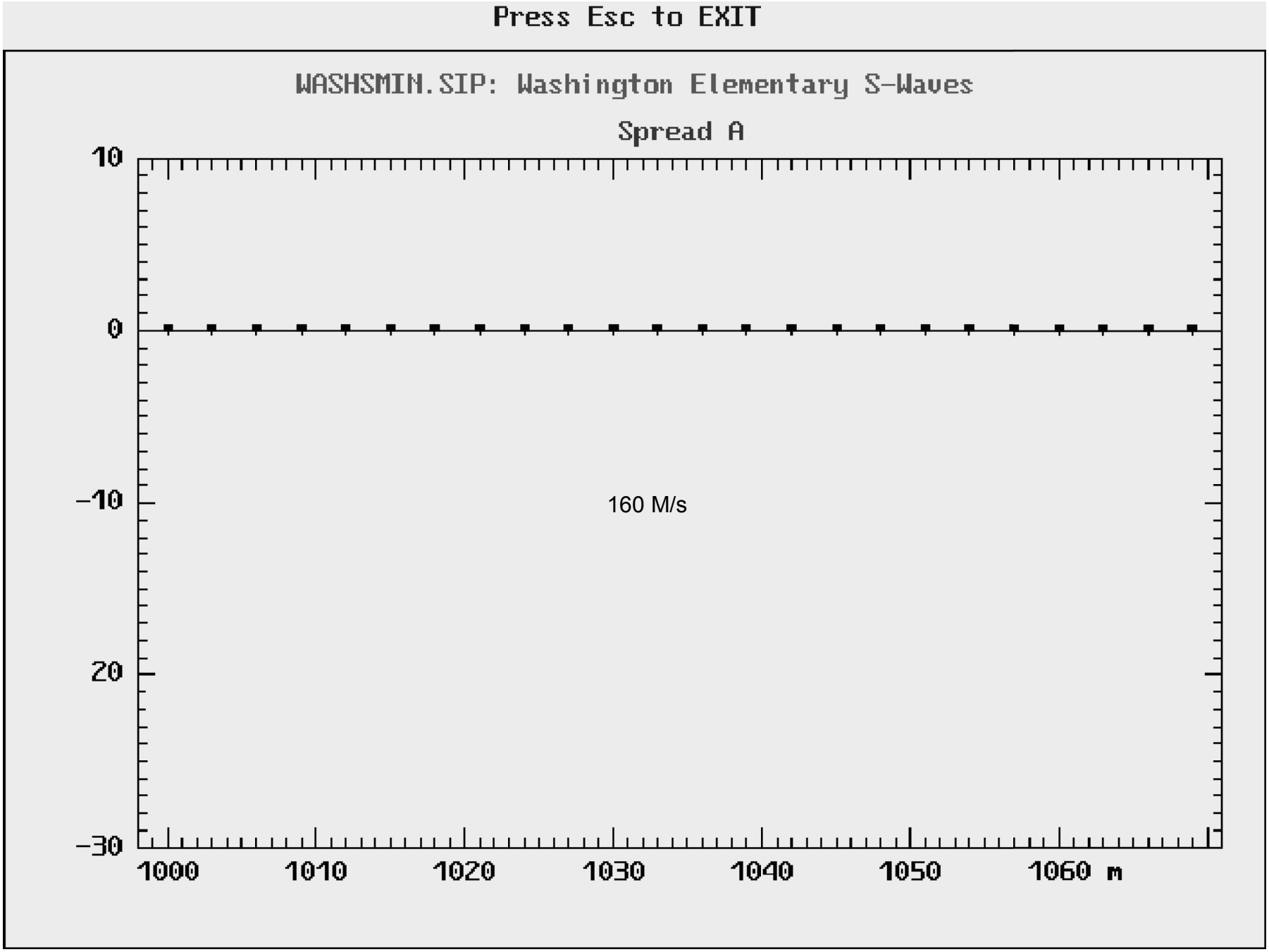

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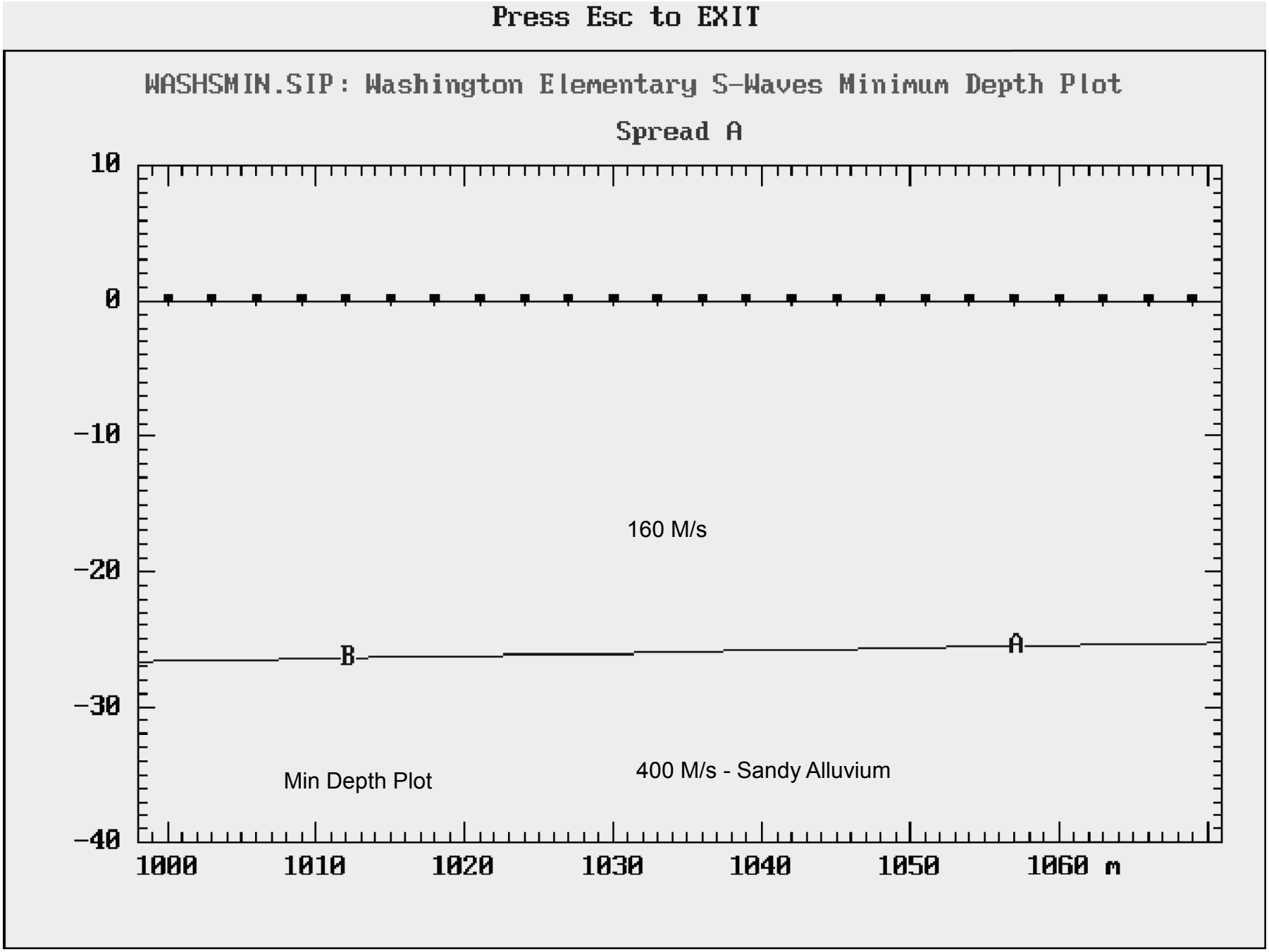

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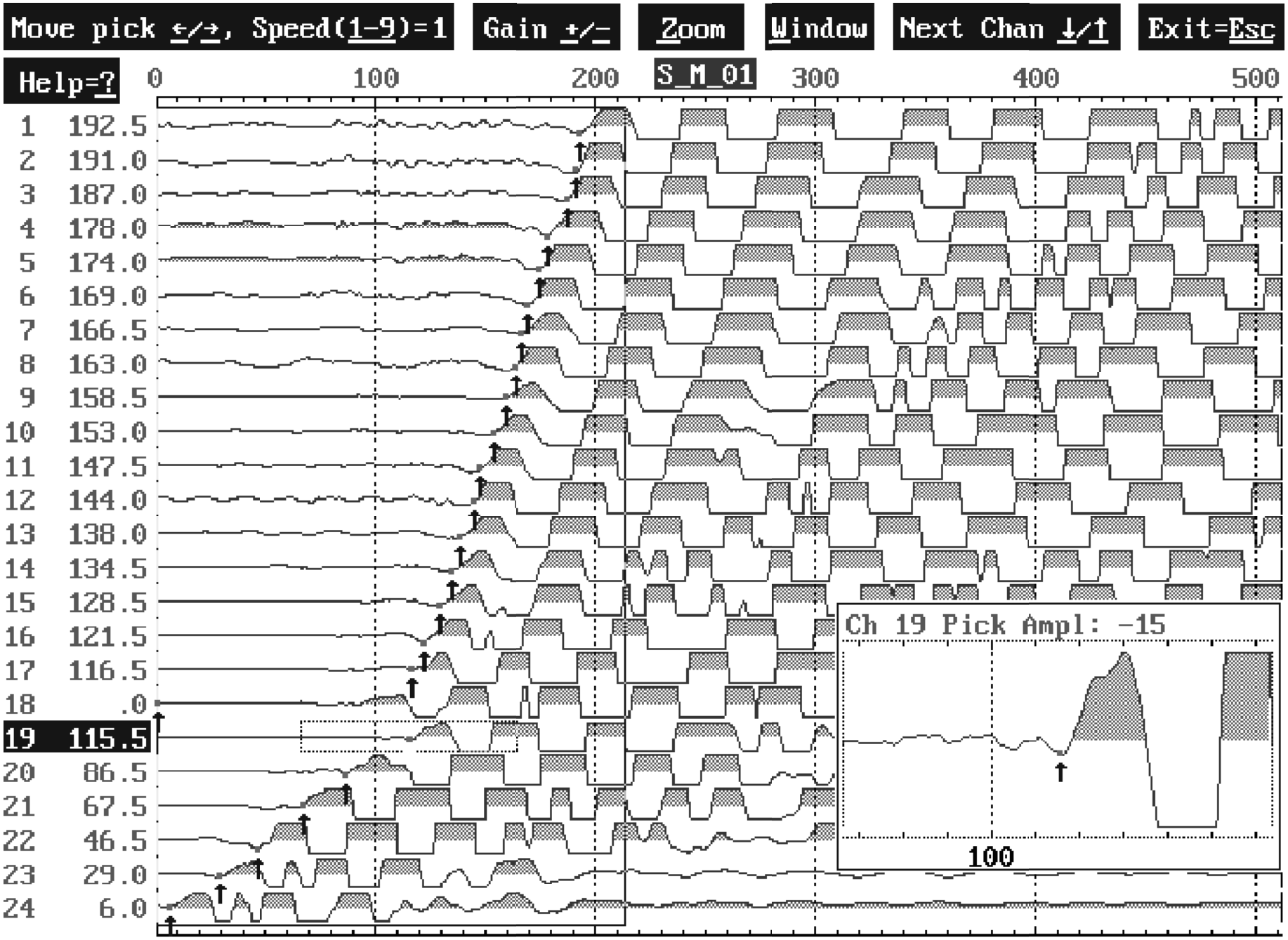

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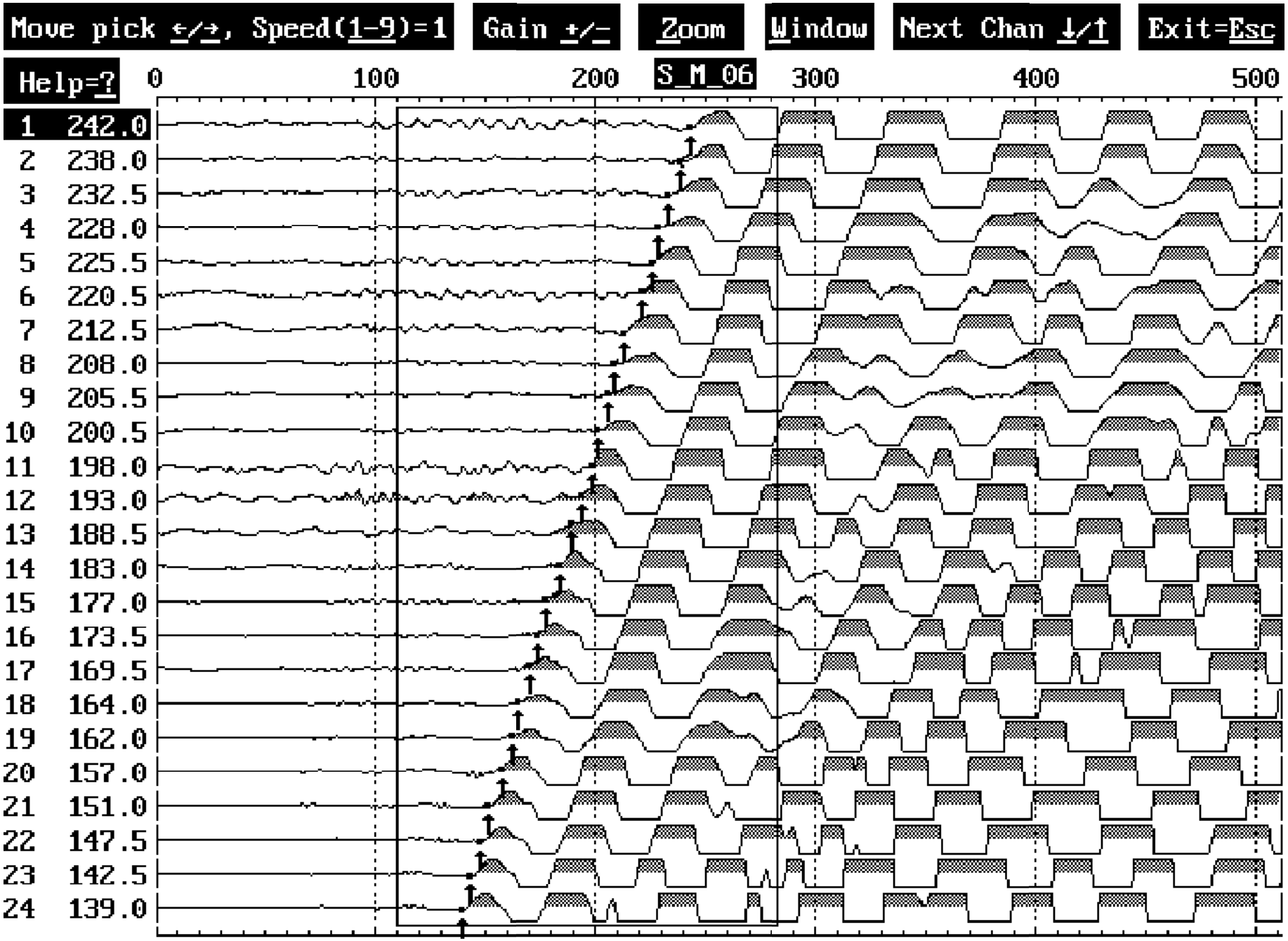

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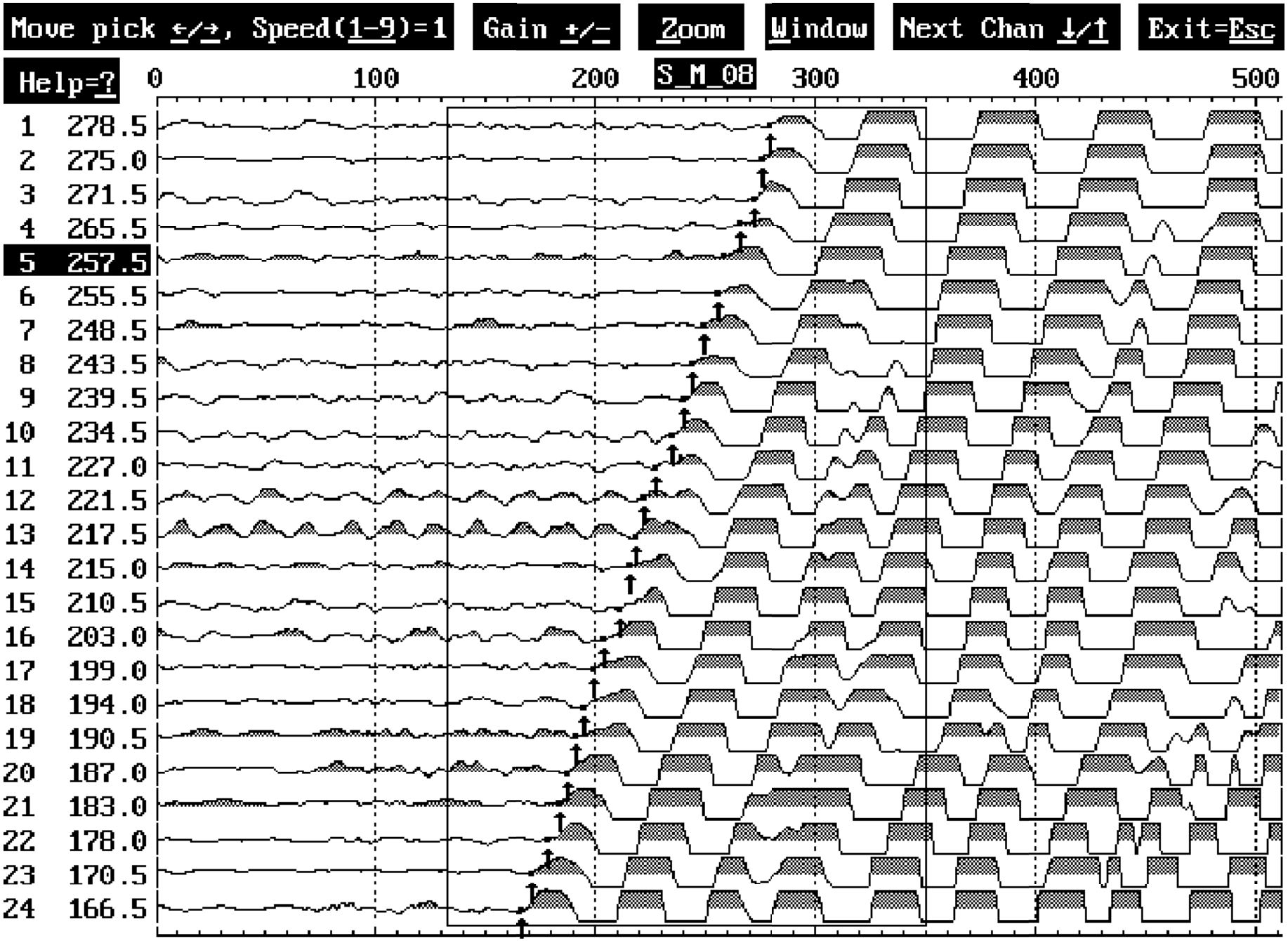

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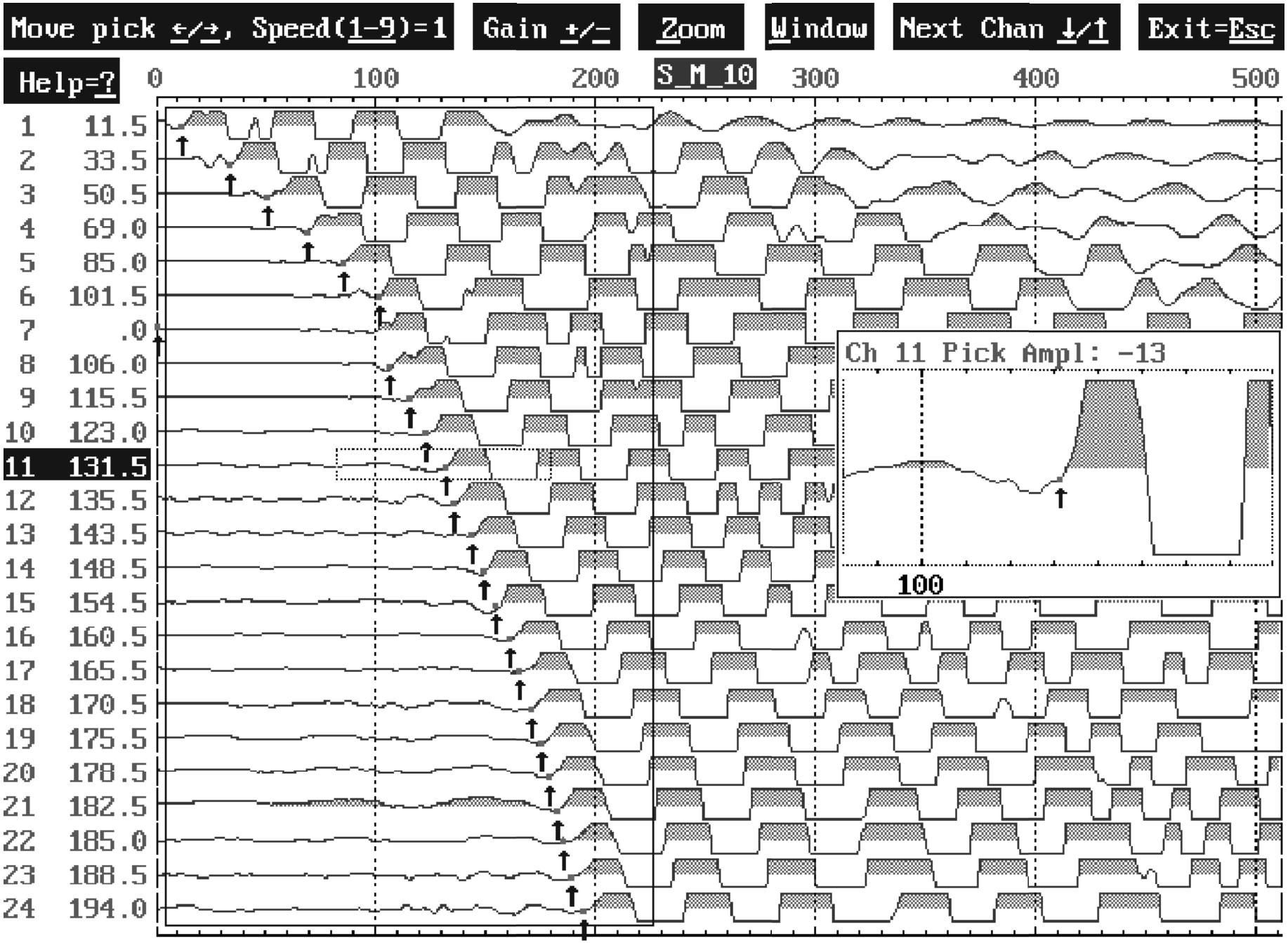

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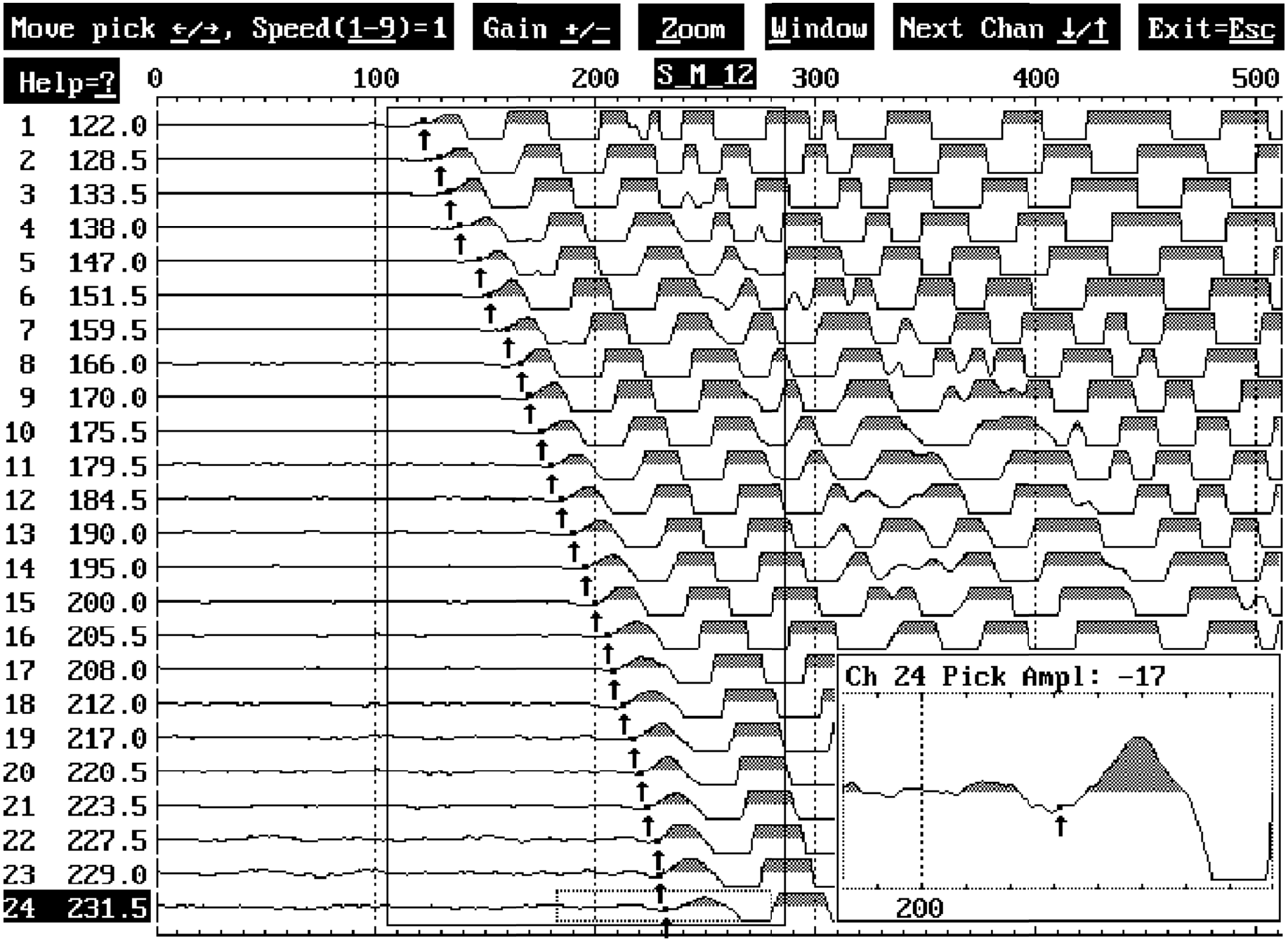

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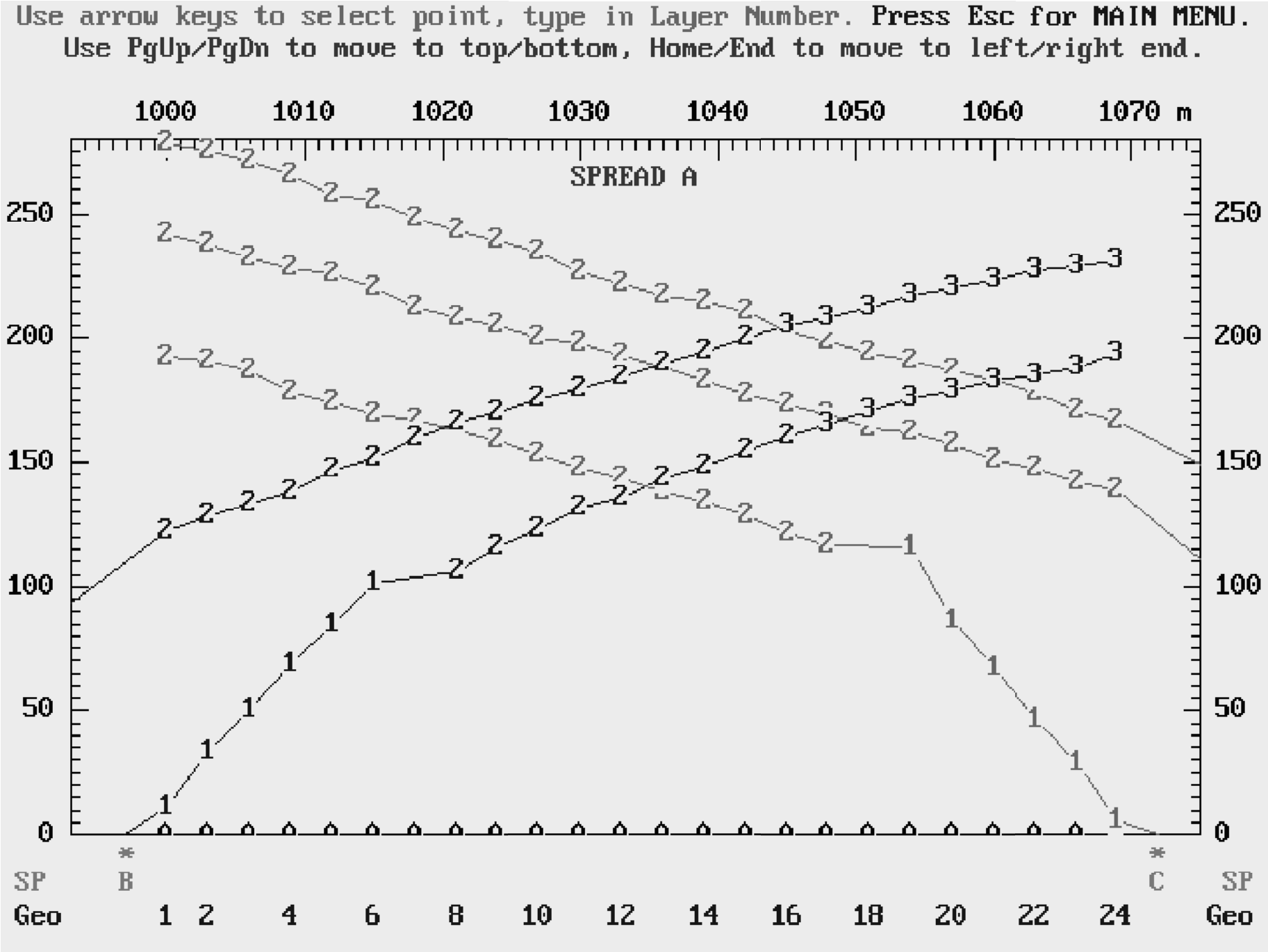

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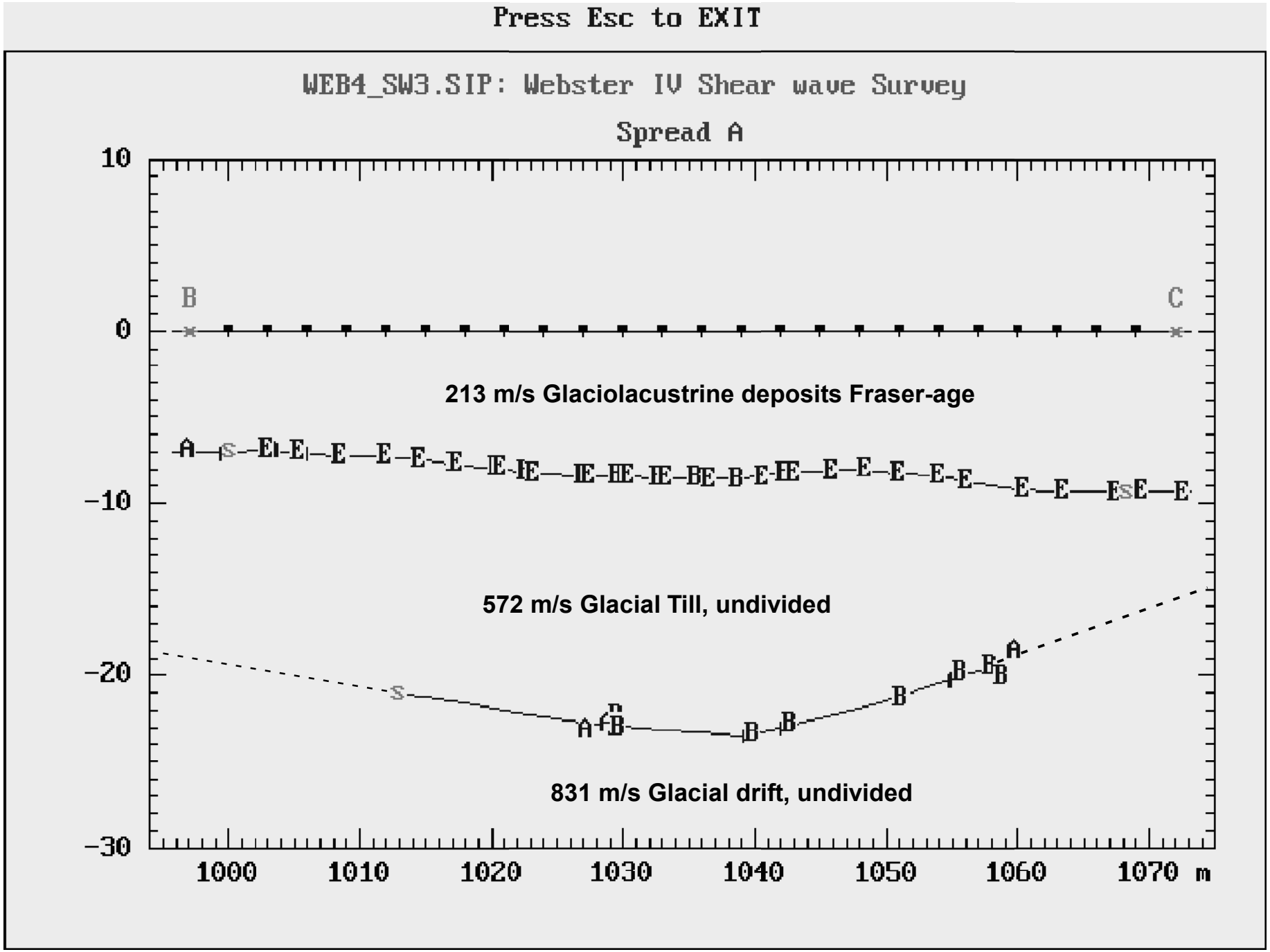

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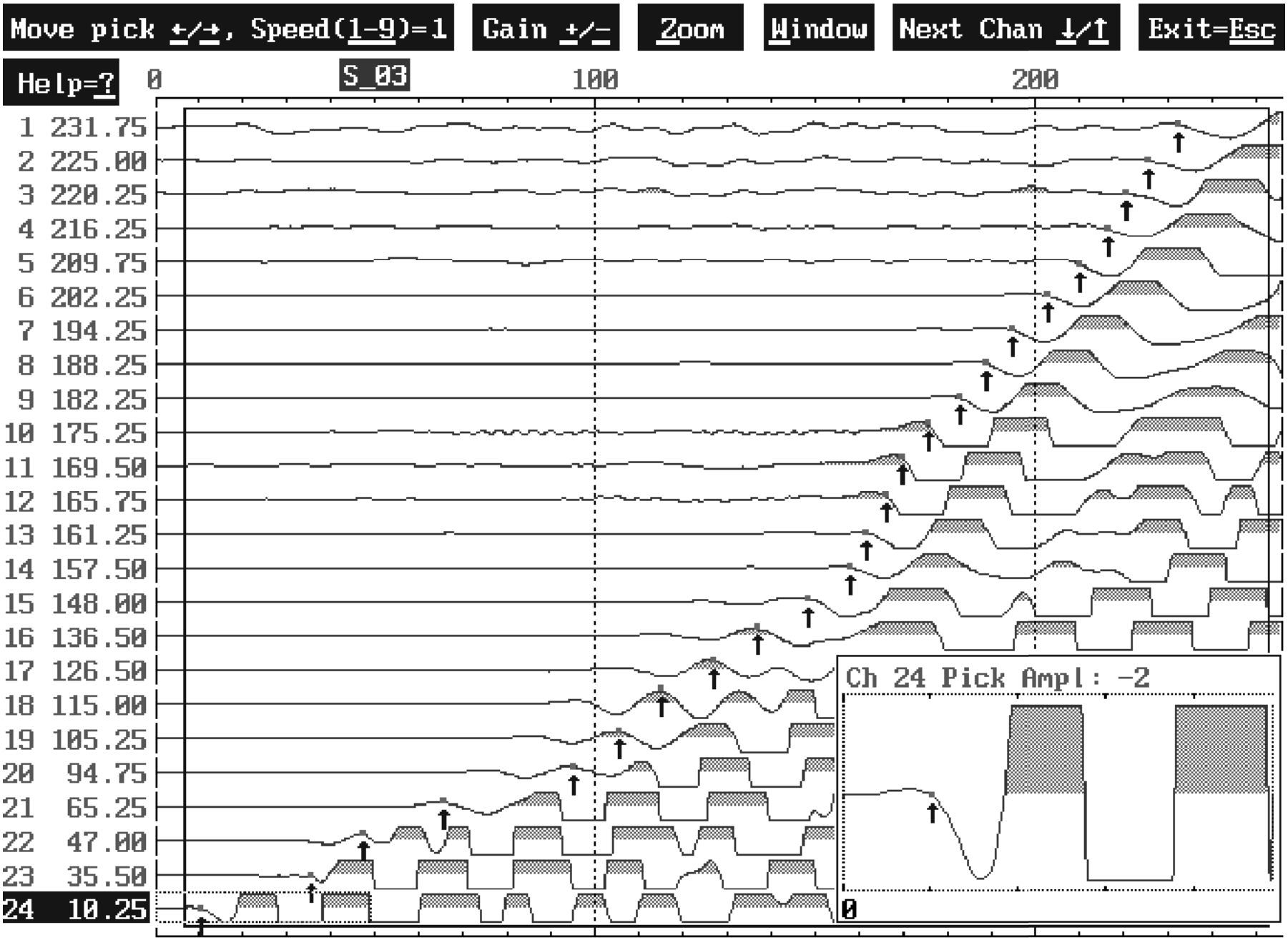

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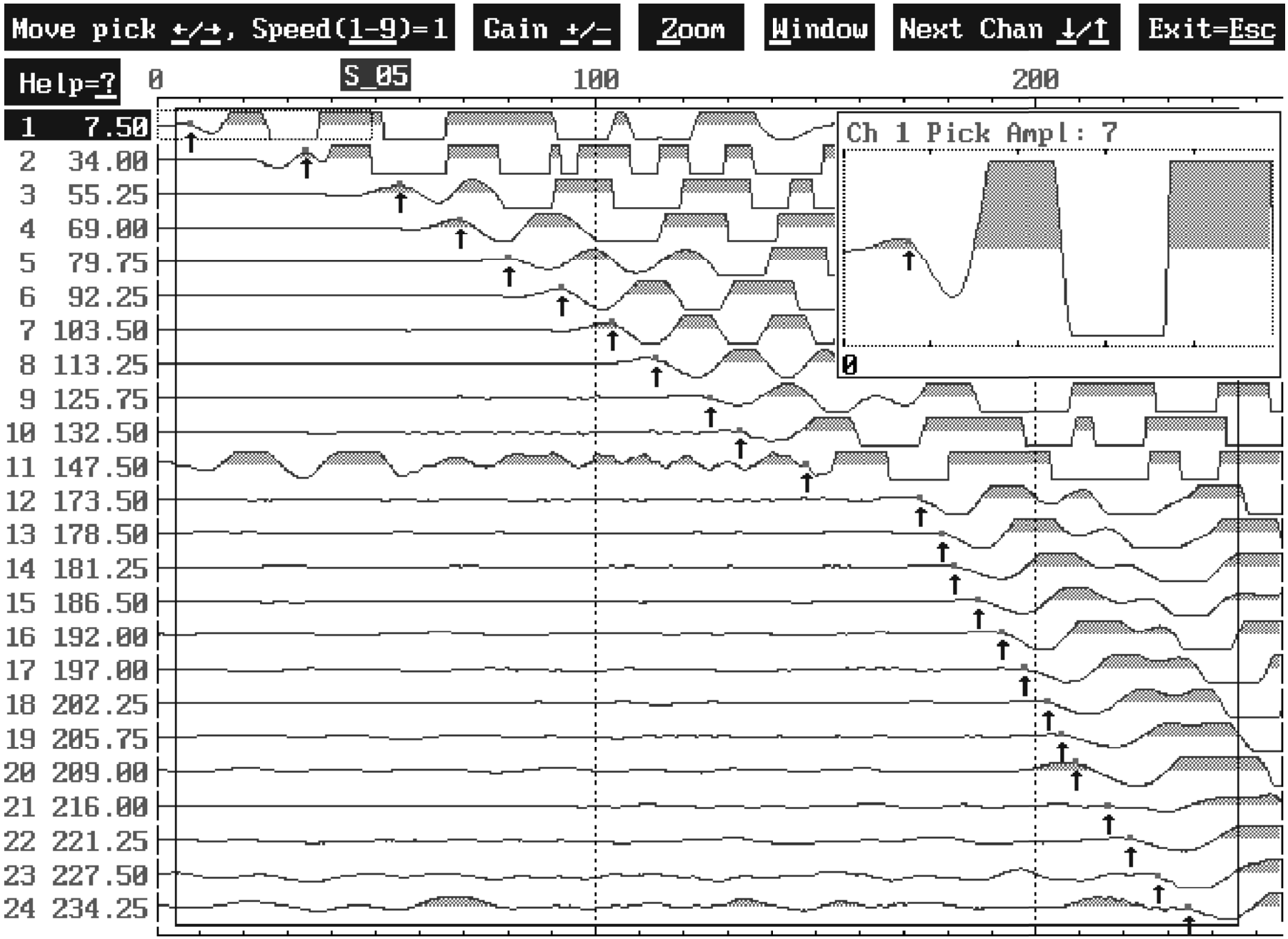

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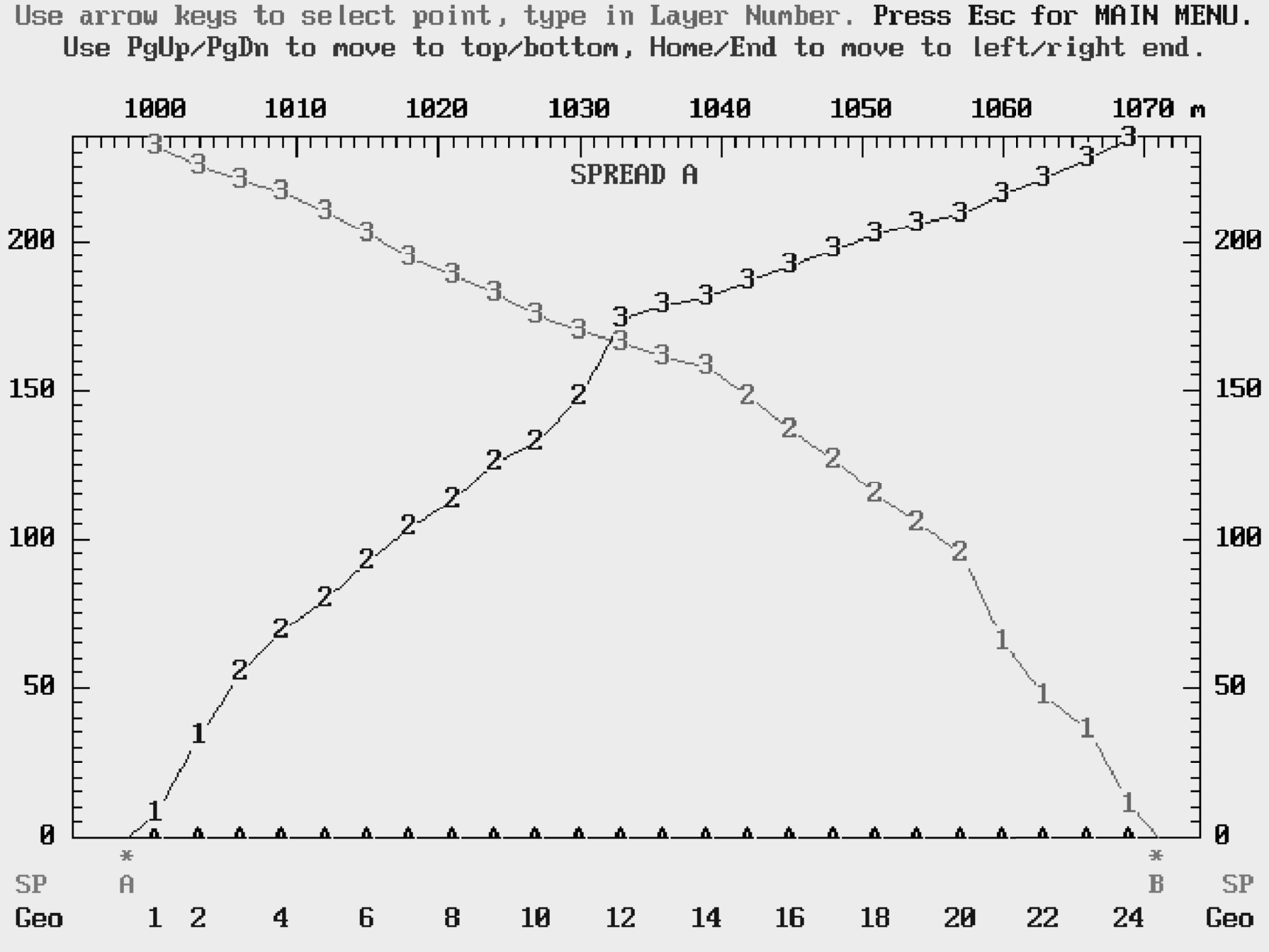

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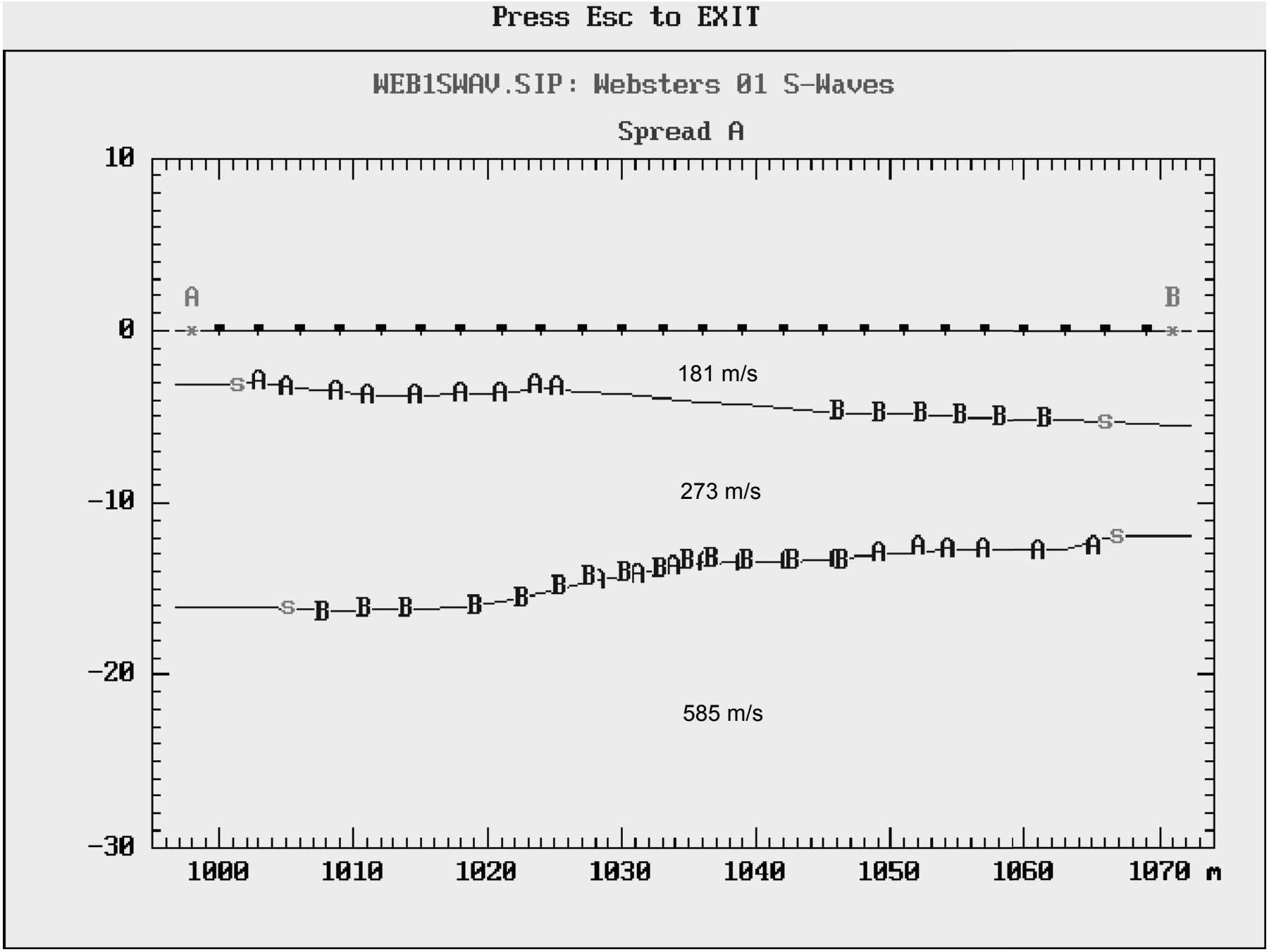

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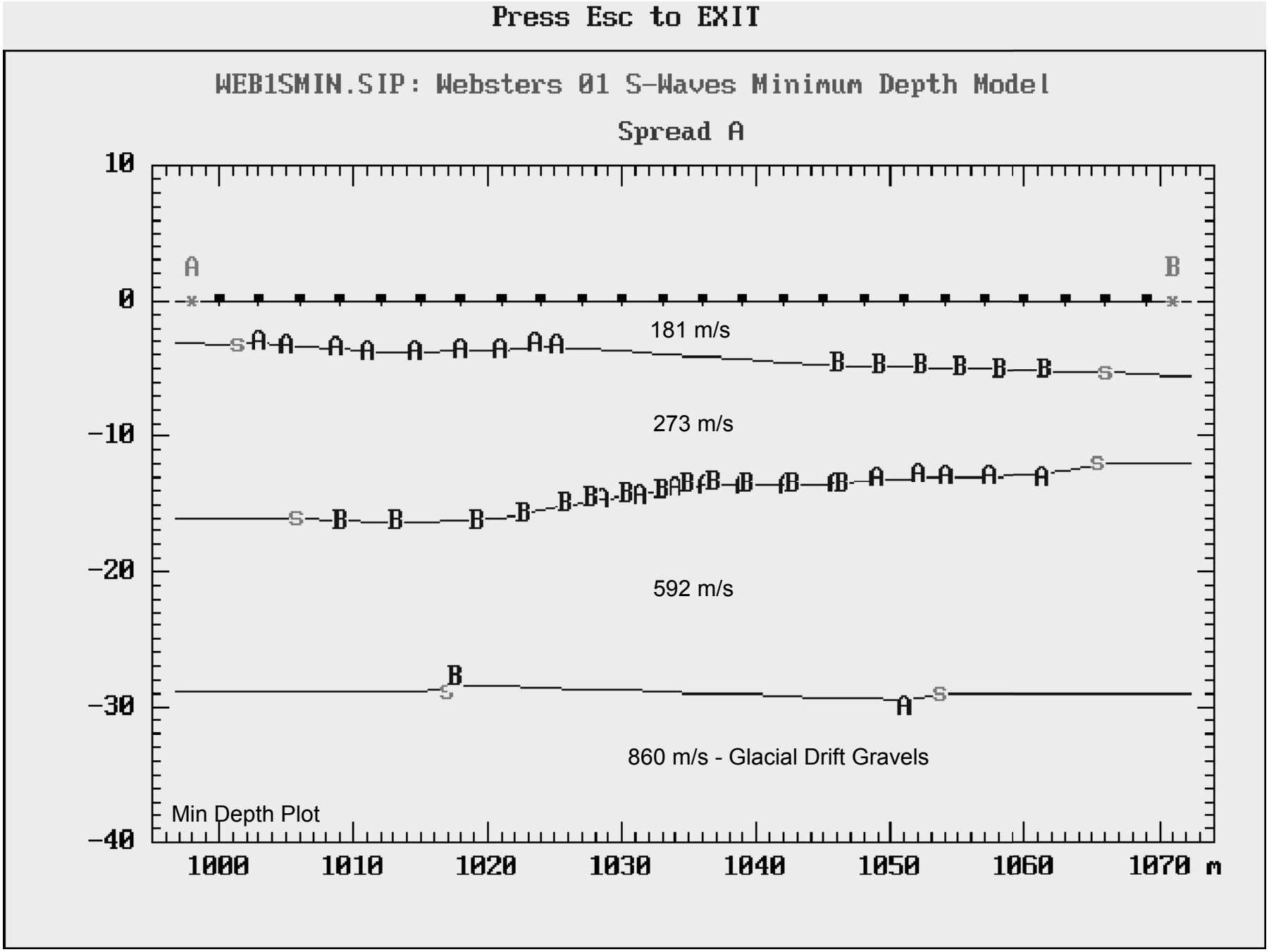

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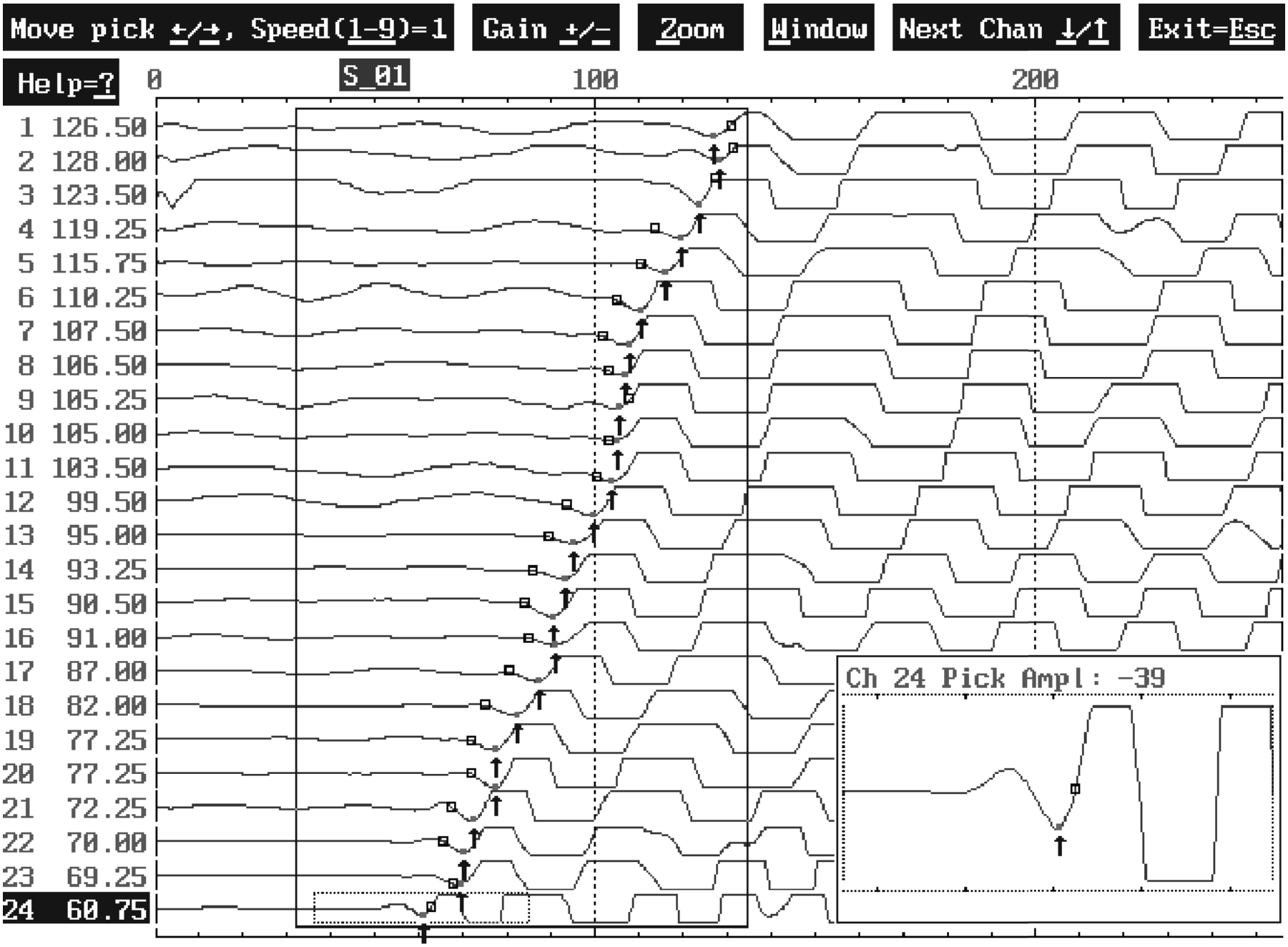

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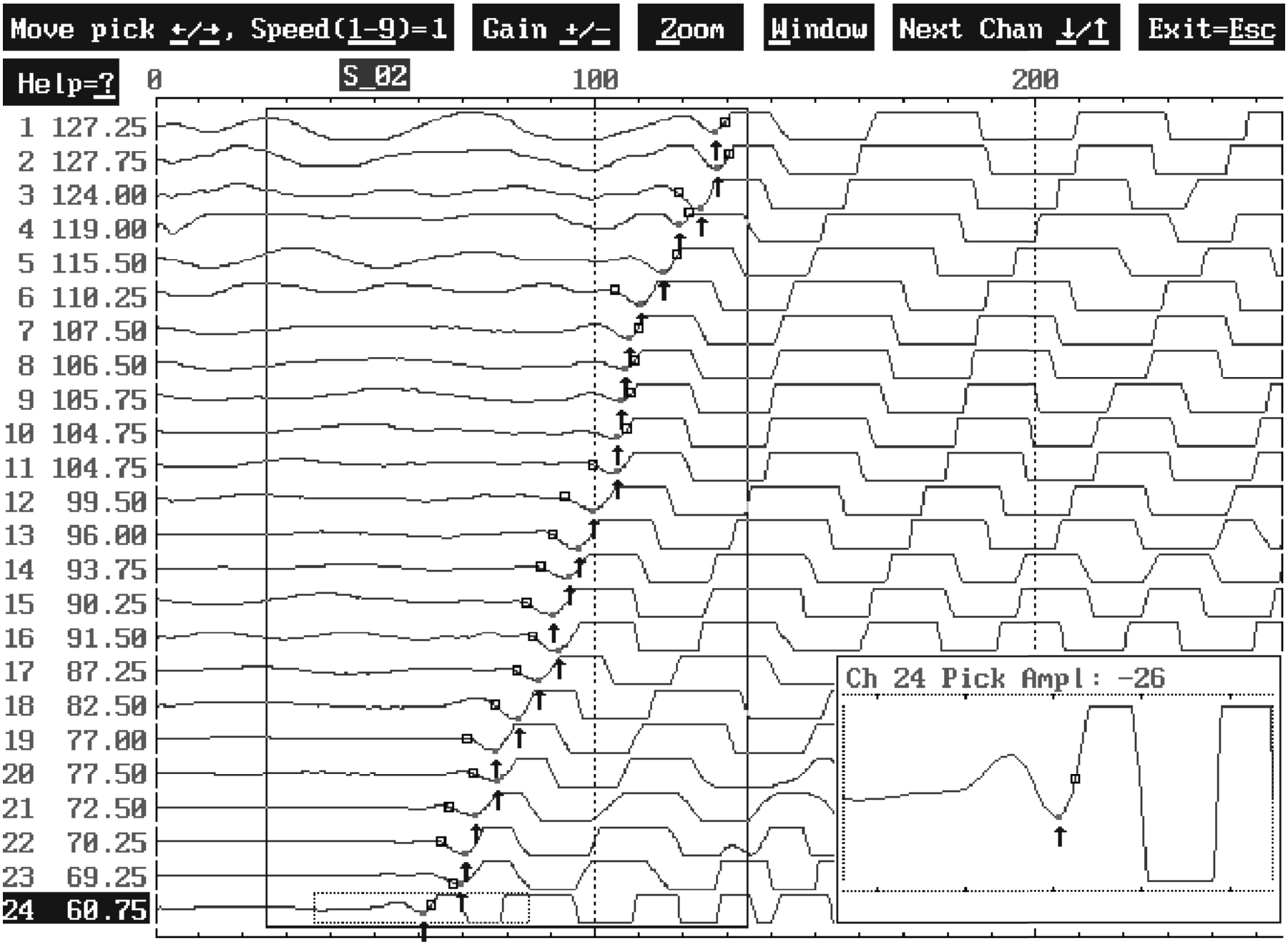

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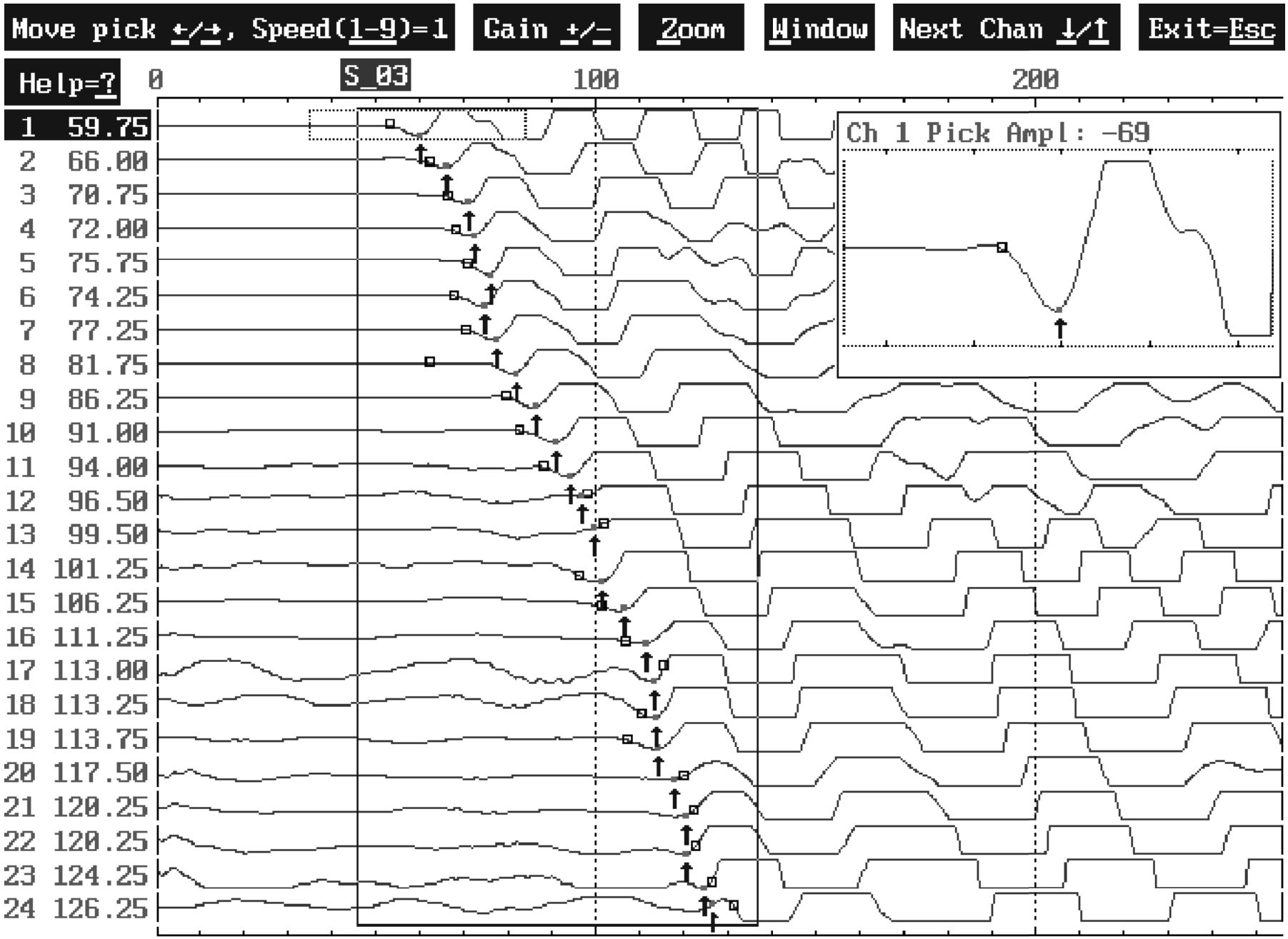

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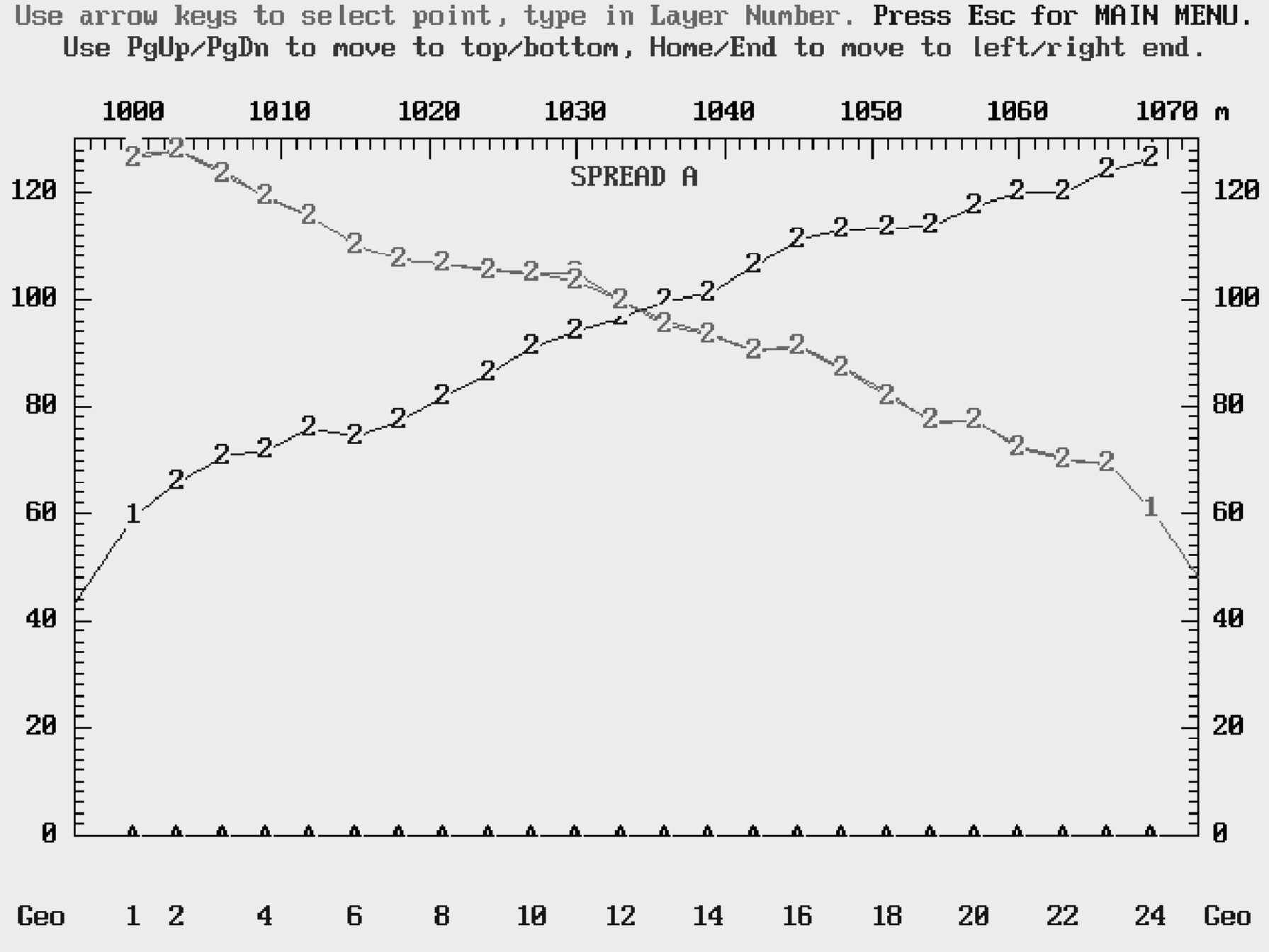

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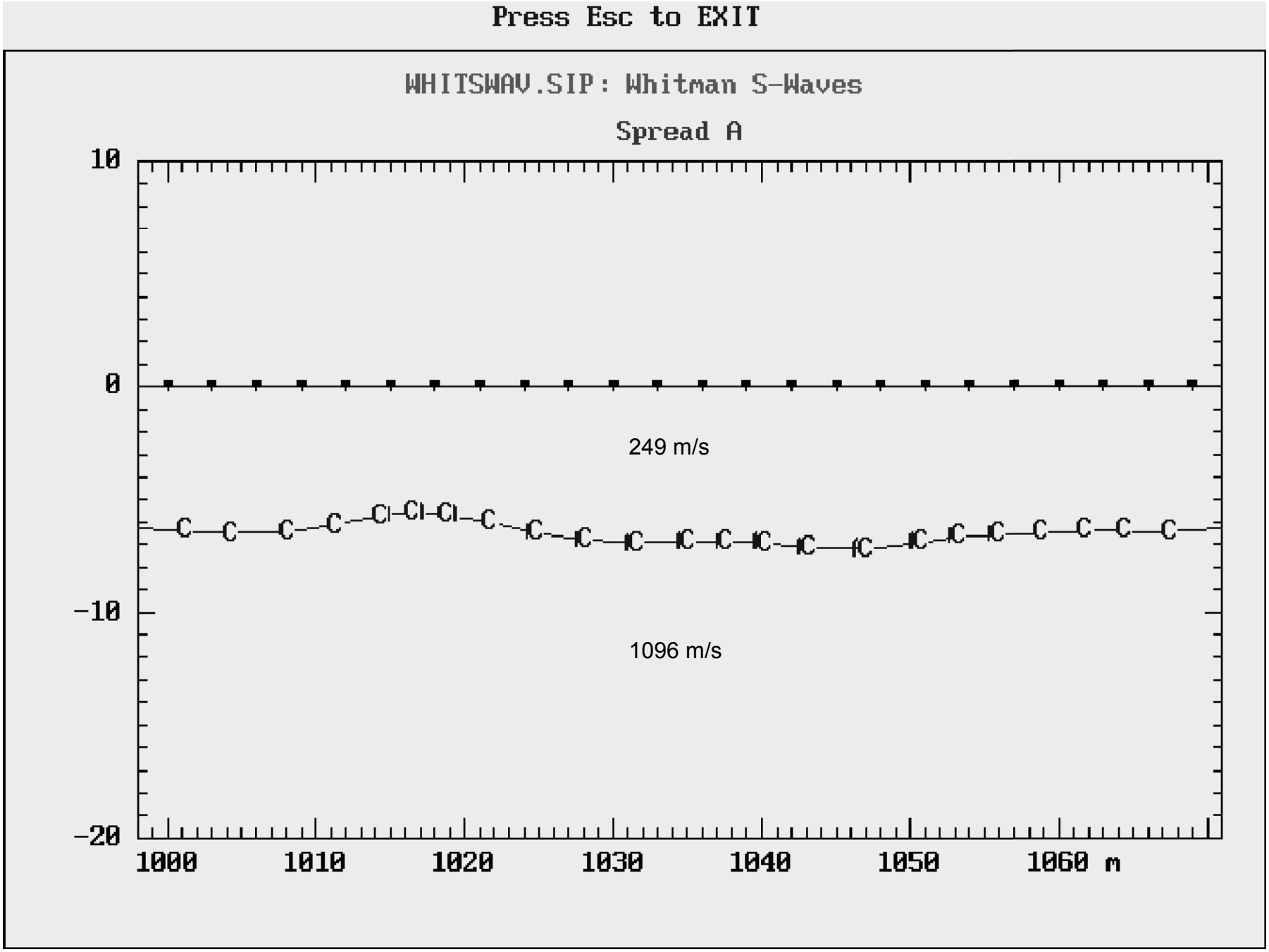

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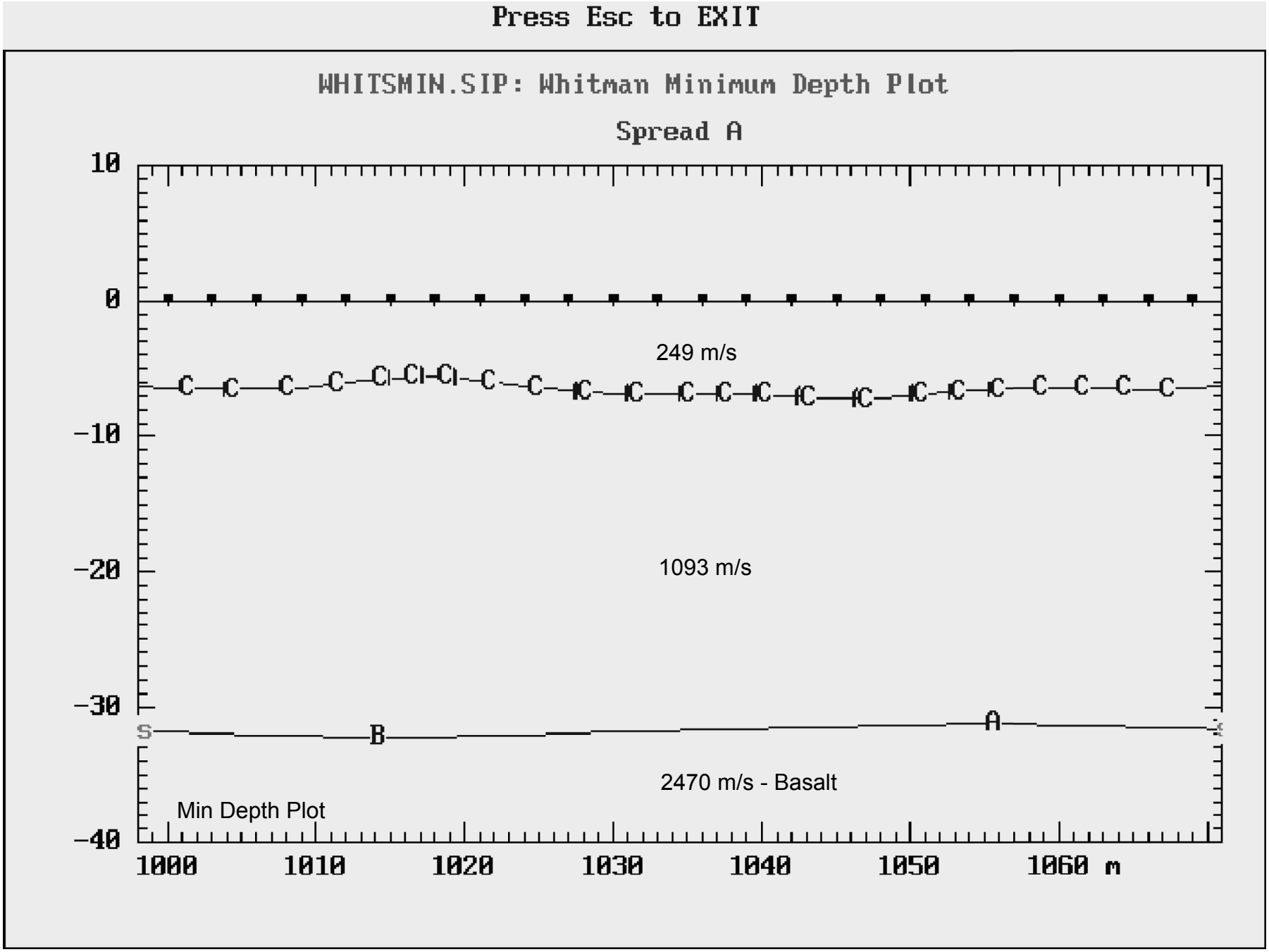

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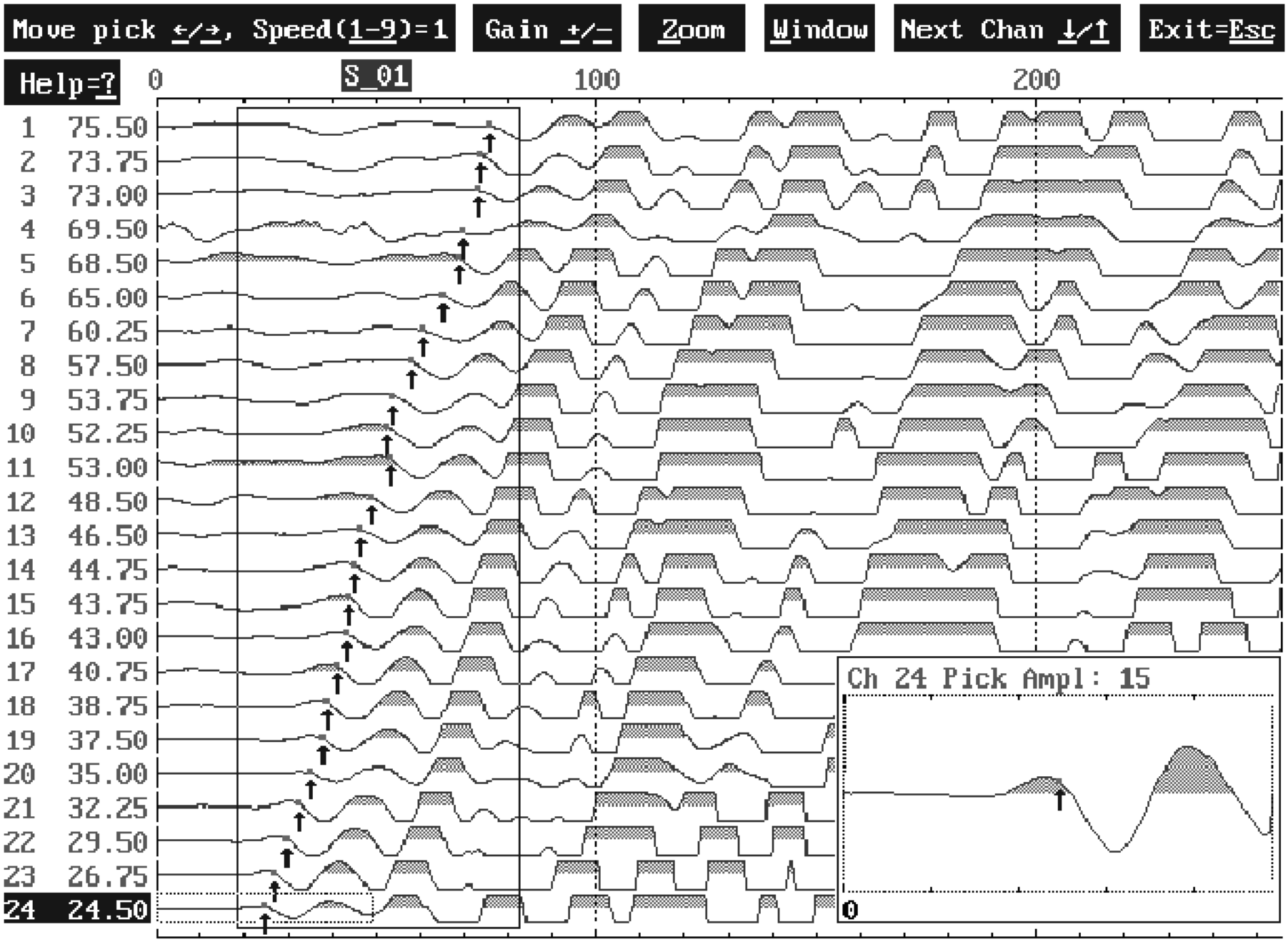

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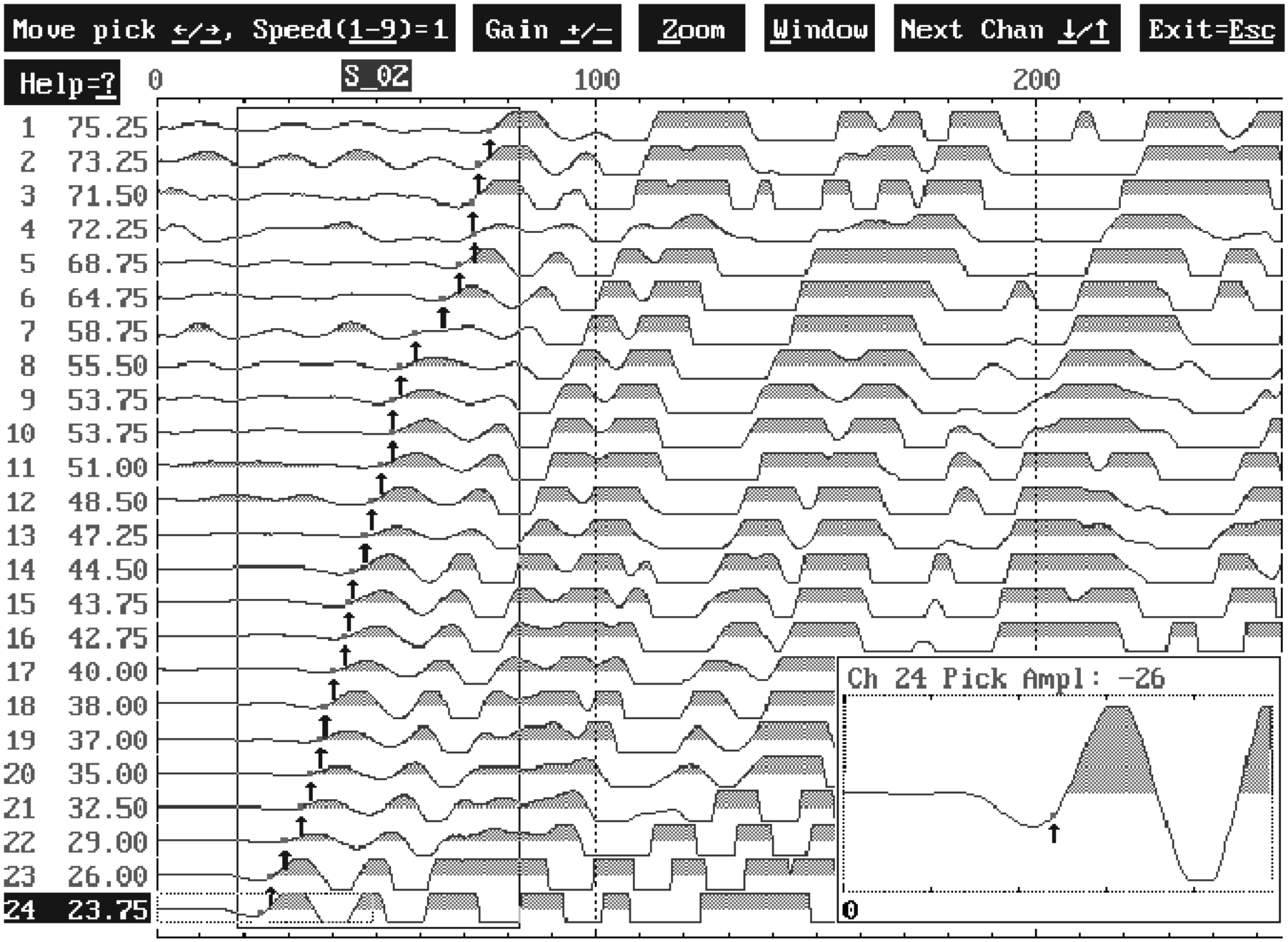

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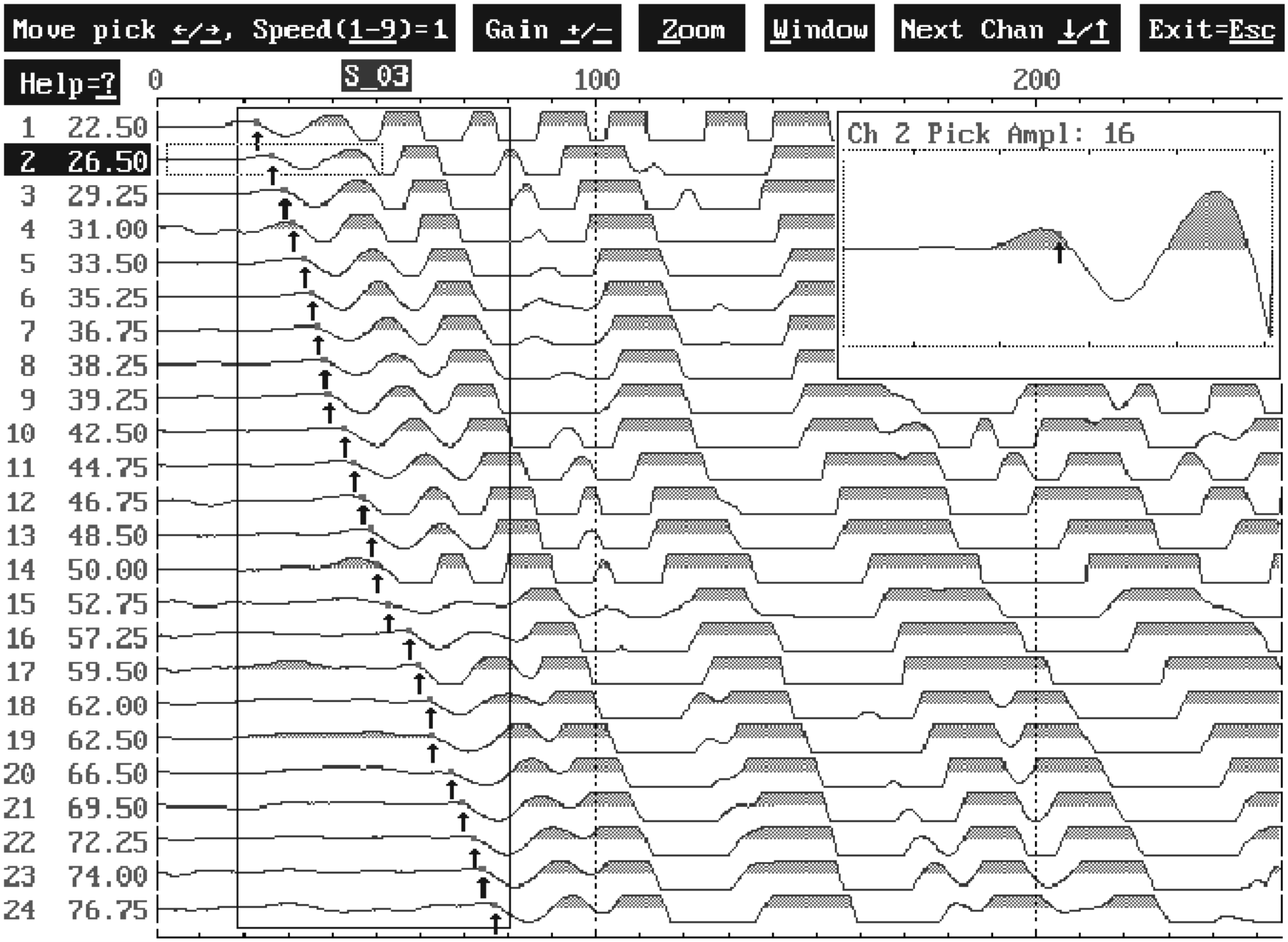

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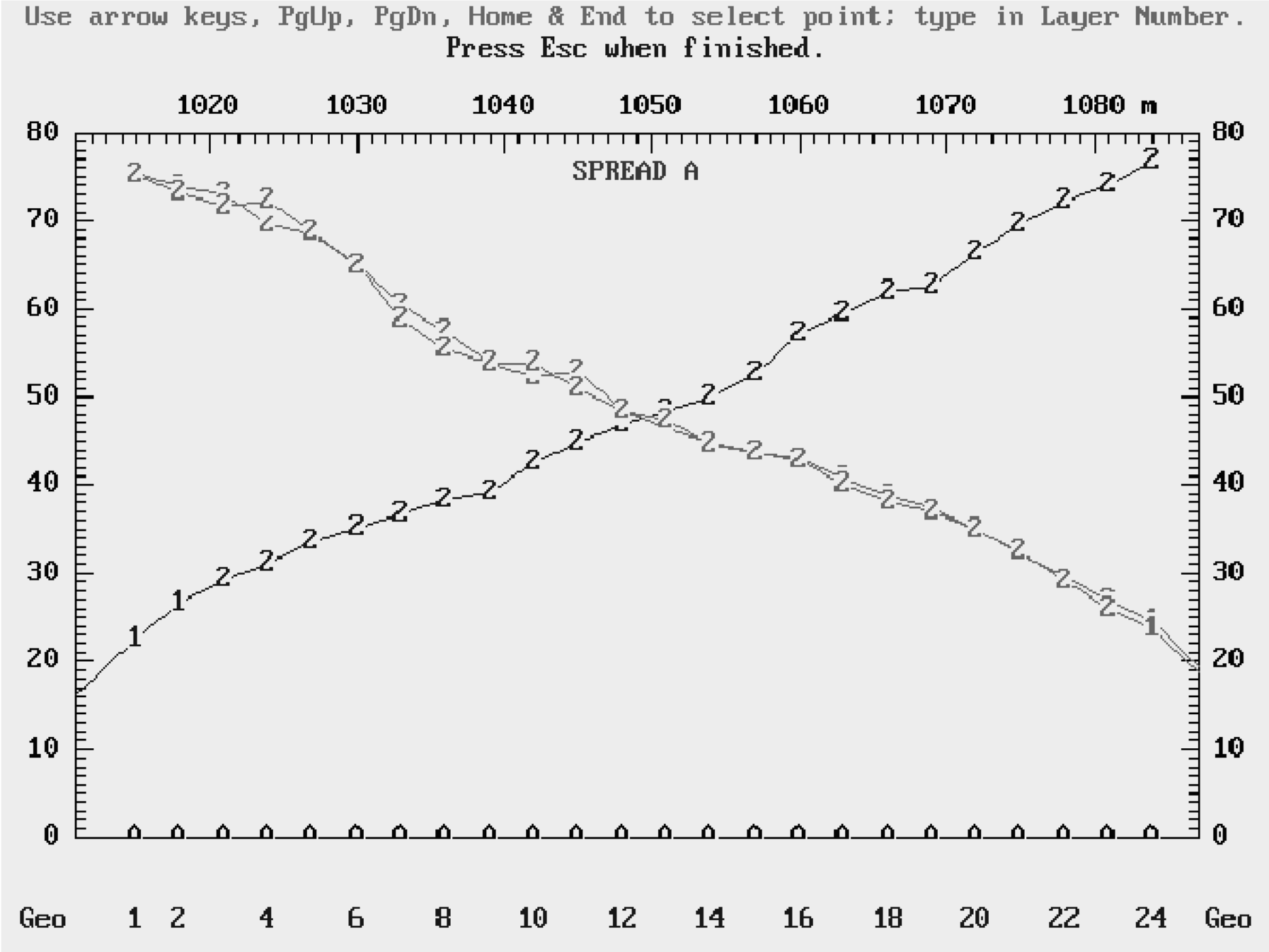

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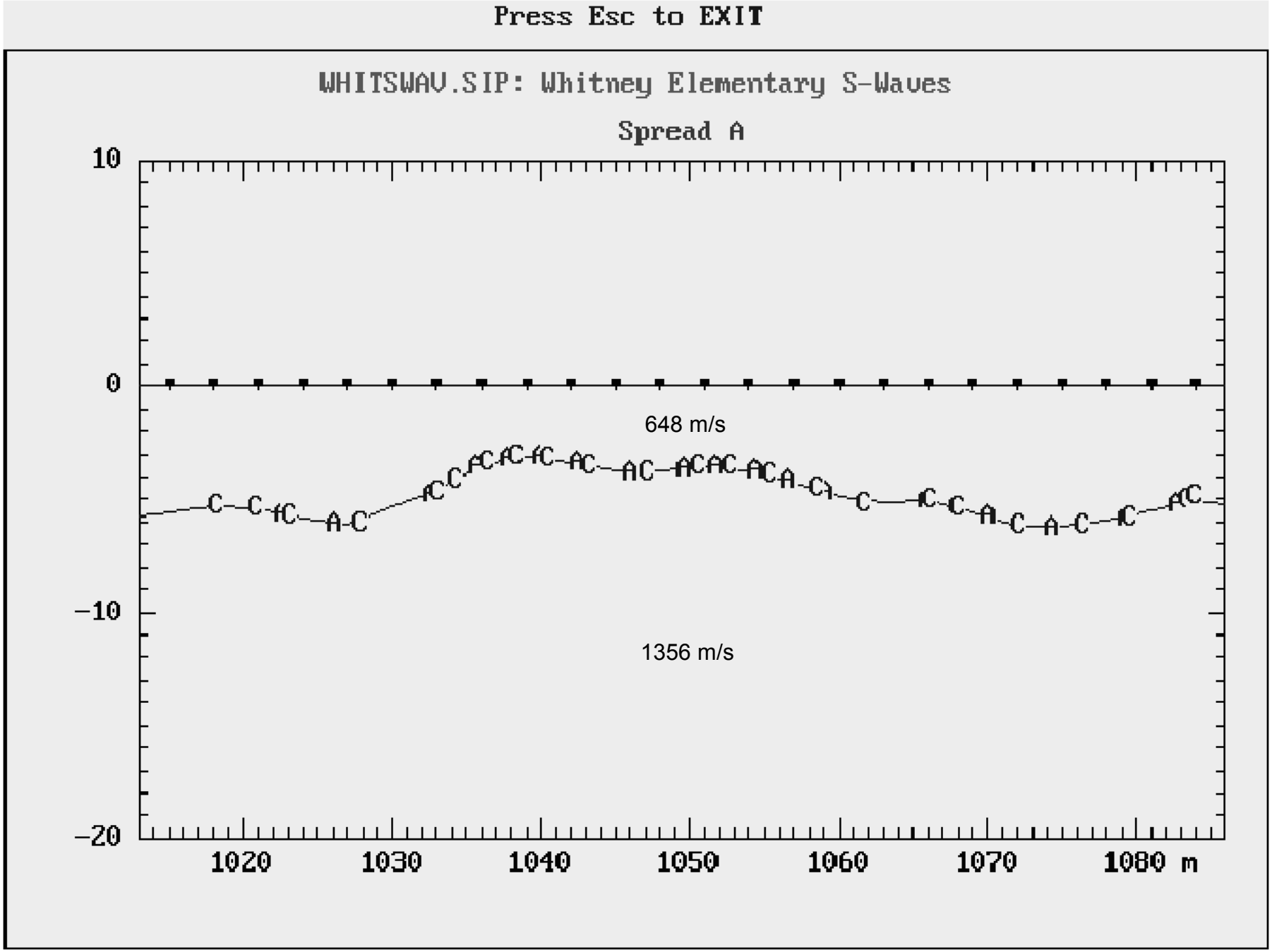

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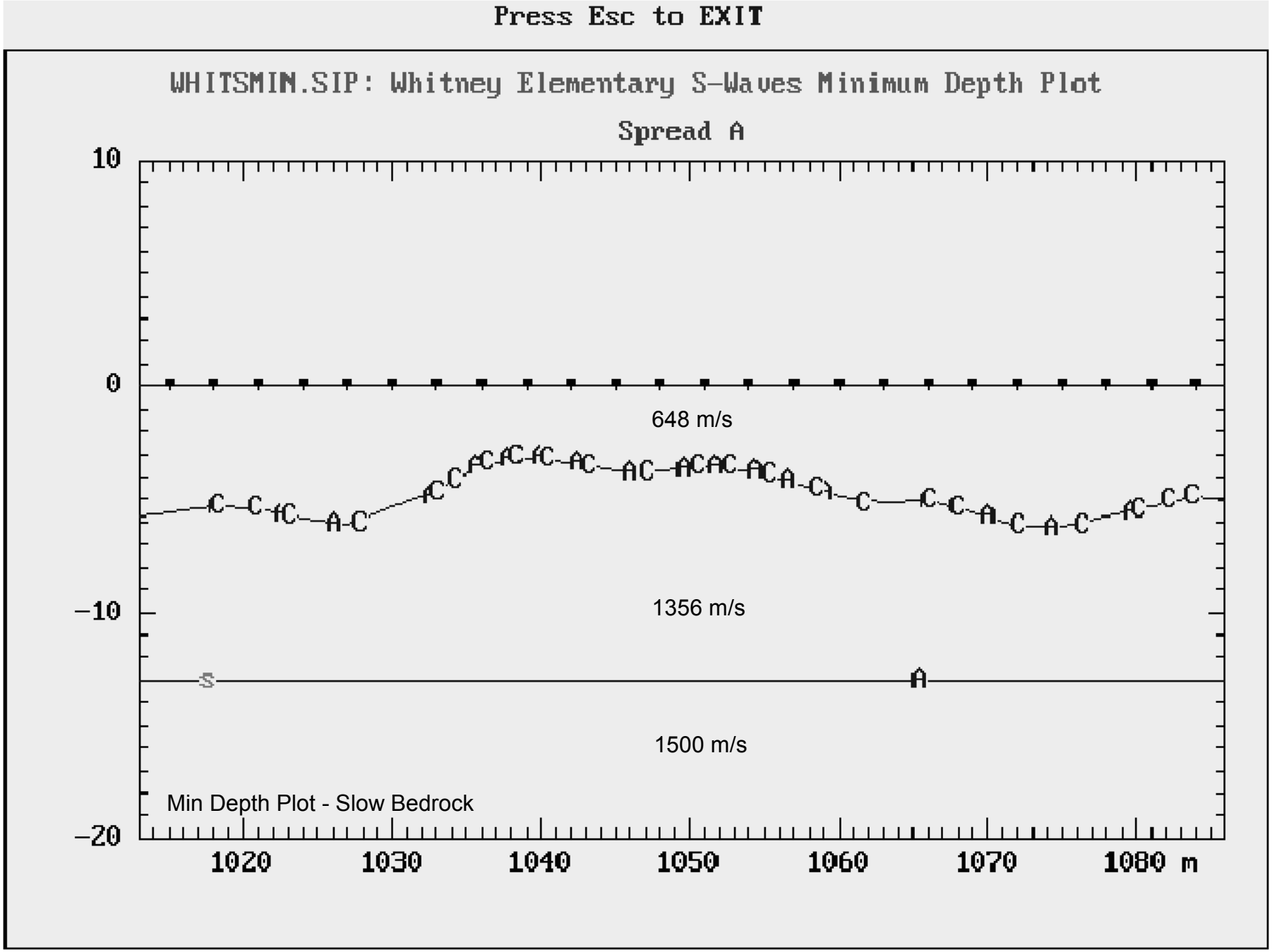

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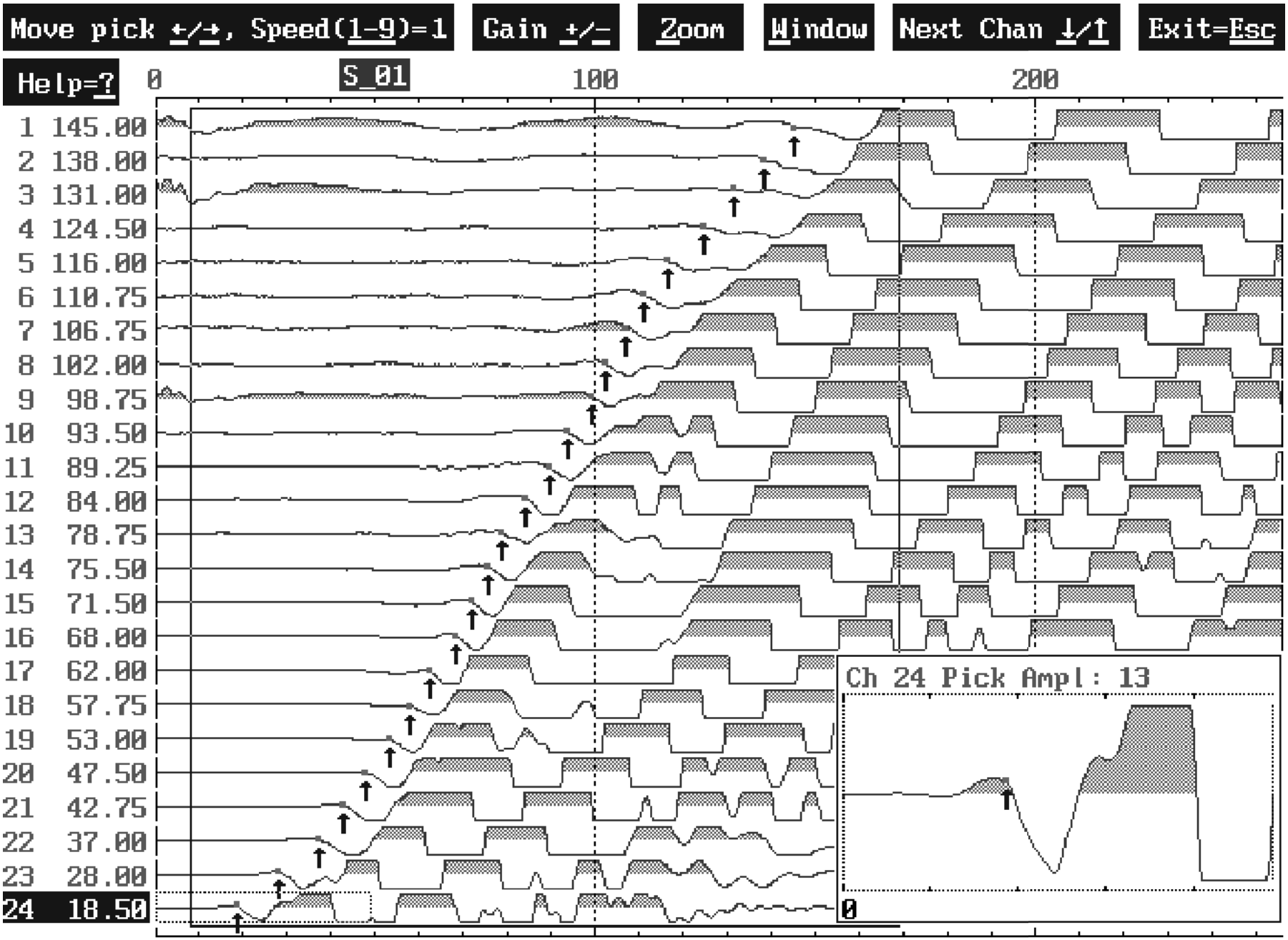

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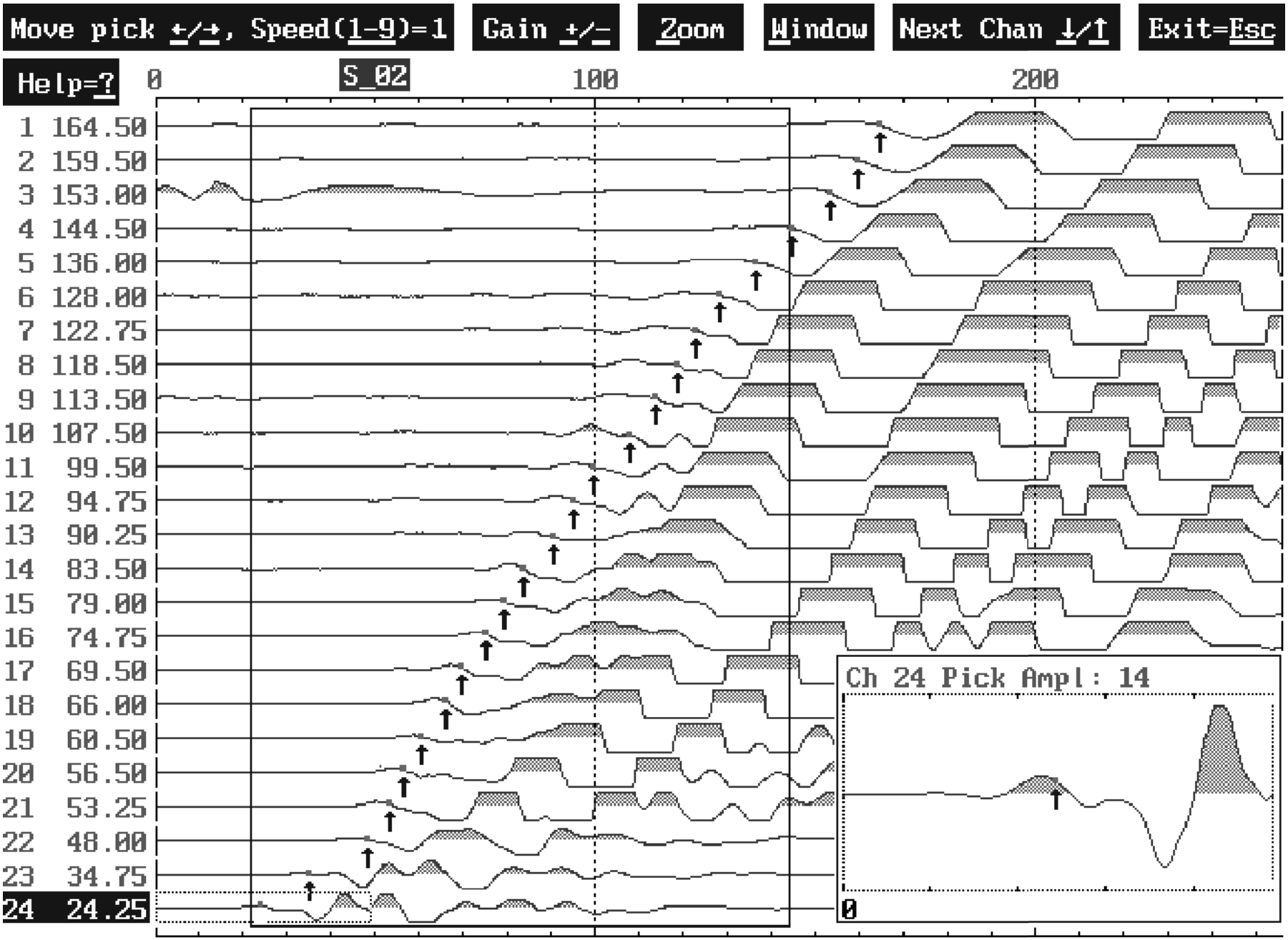

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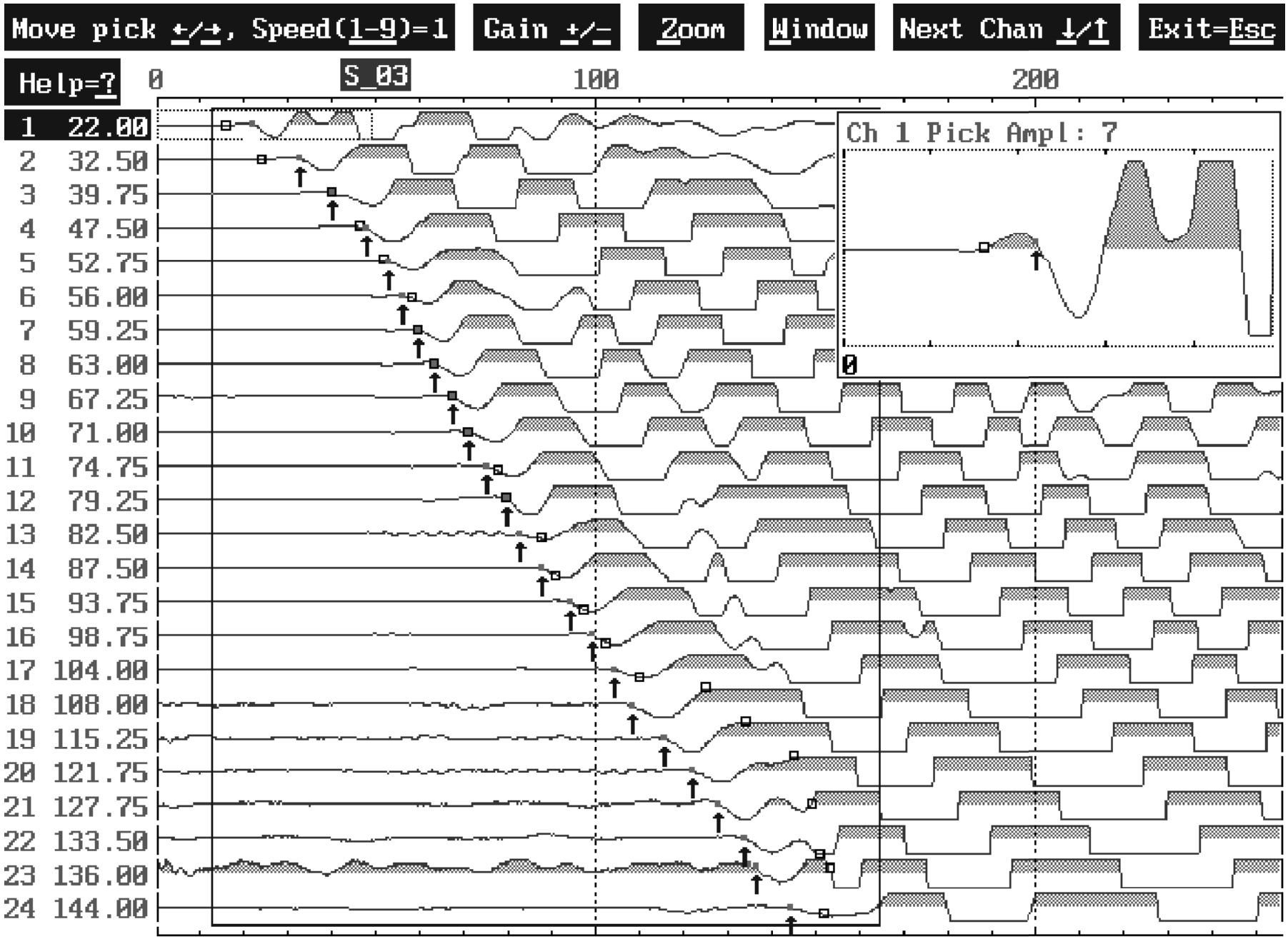

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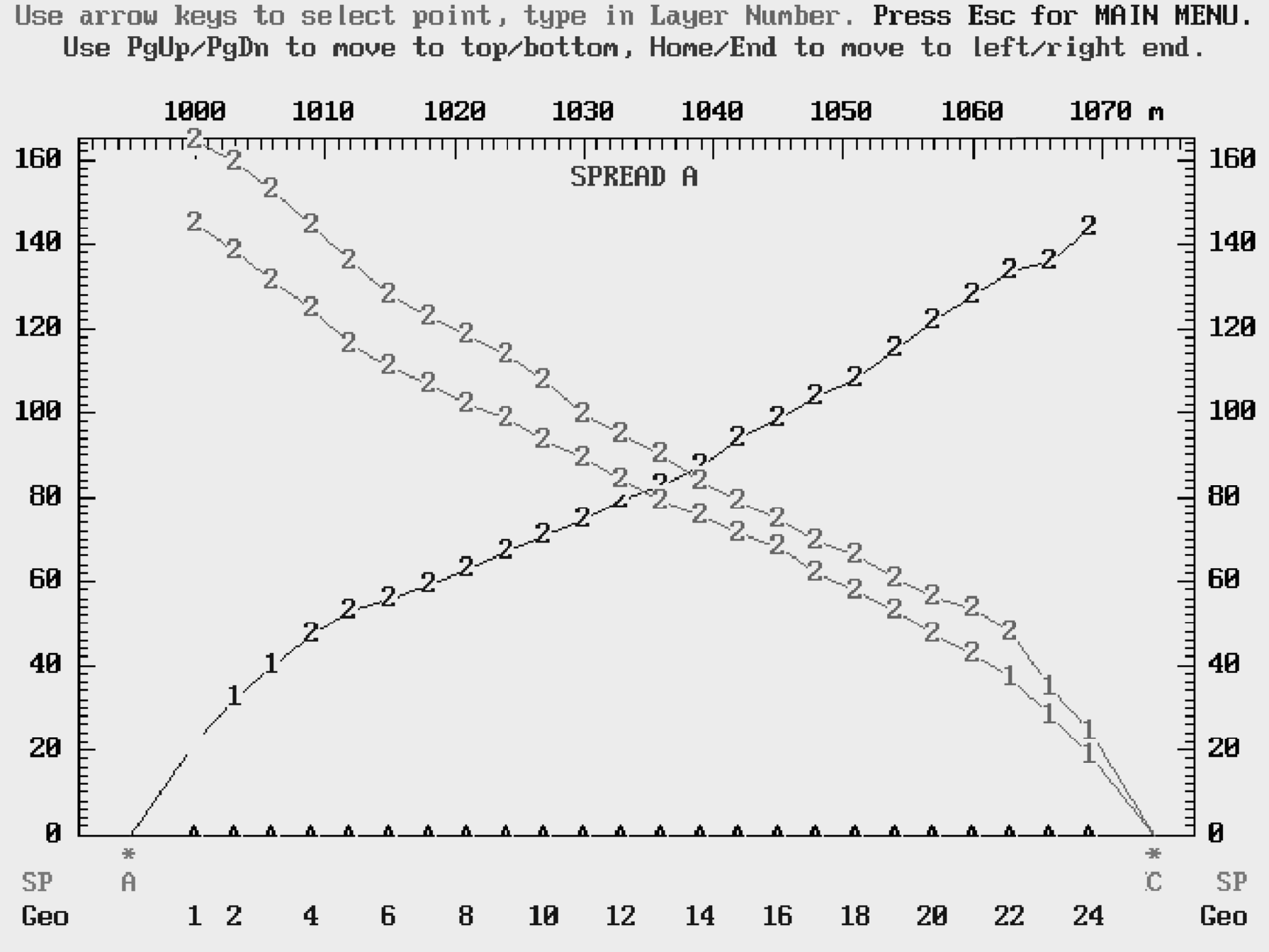

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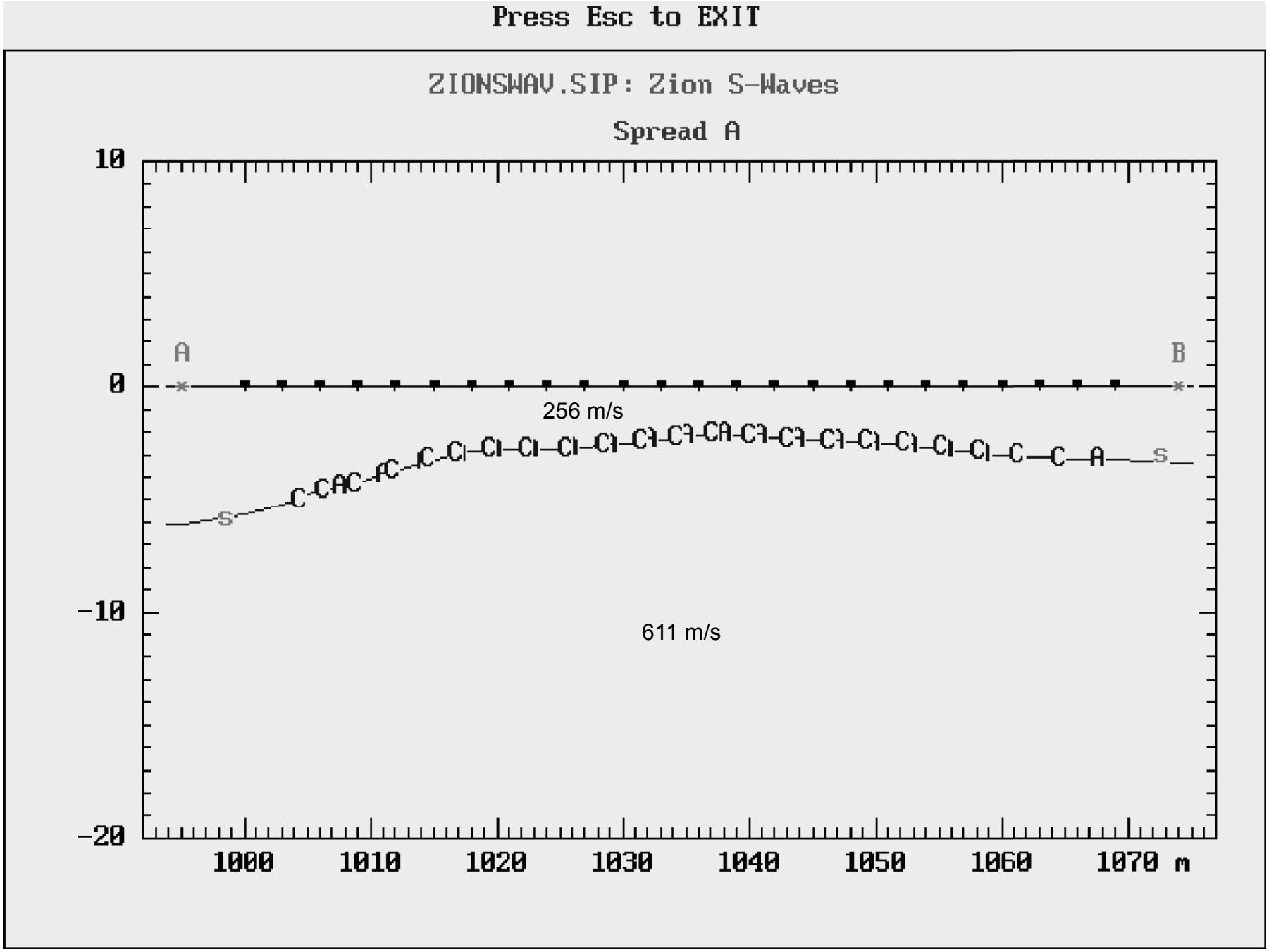

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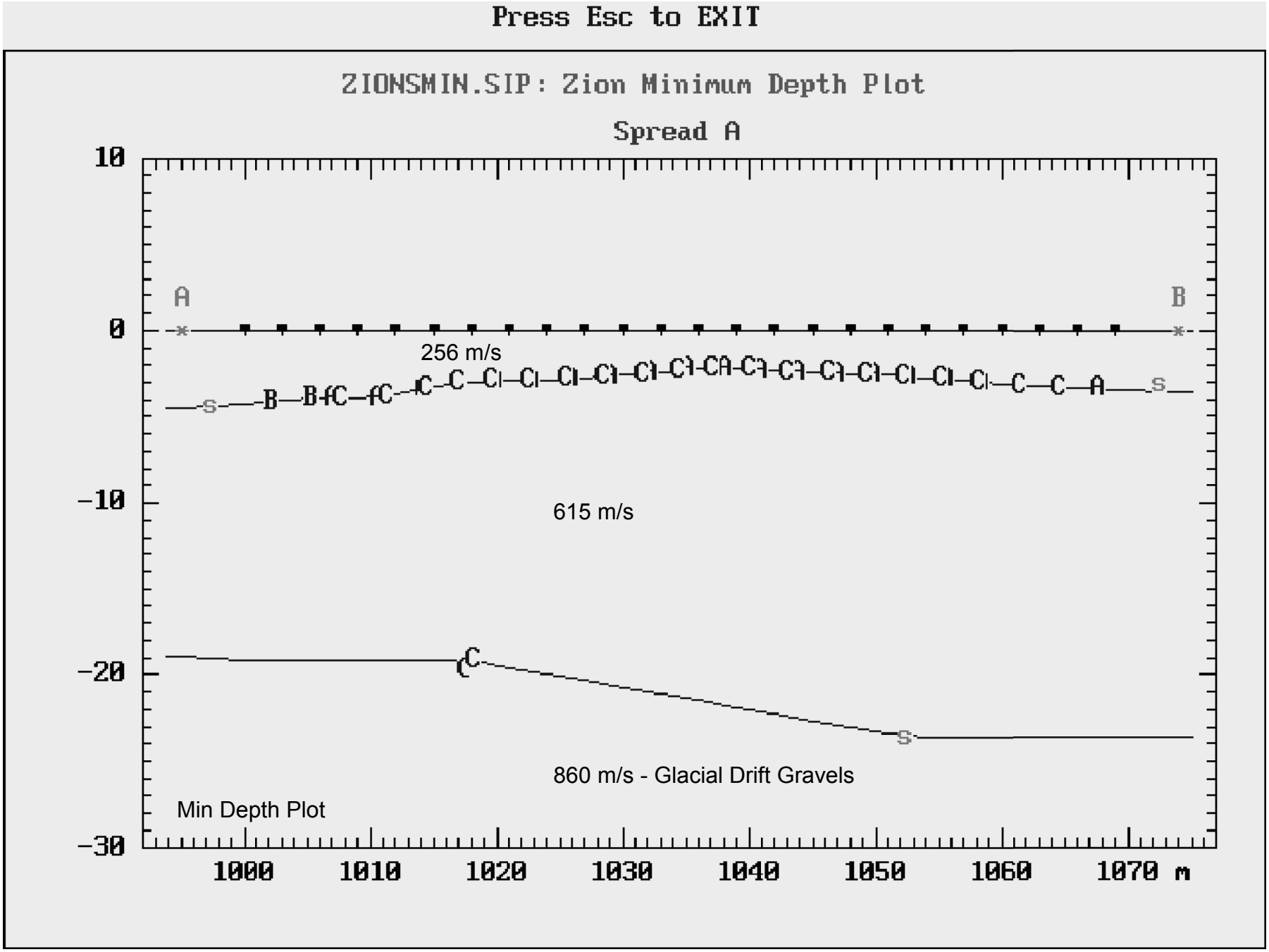

Appendix D

Table: UnitDescription

Record Count: **48**

Field Name	Type	Description
GeoUnit	Text	Geologic Unit Code
Description	Text	Description of Geologic Unit
Count	Number	Number of measurements per unit

Table: Locations

Record Count: **243**

Field Name	Type	Description
Site_ID	Number	Unique site number used to link the Location and Velocity tables together
Source	Text	Original Source for Data
Site_Name	Text	Site Name (as reported in original data source if possible)
Survey_Date	Date/Time	Date of the survey, if reported
Depth_of_Survey_m	Number	Depth of survey (m) if reported
Depth_of_Survey_ft	Number	Depth of survey (ft) if reported
Number_of_Measurements	Number	Number of velocity measurements associated with this site
x	Number	Easting - NAD 1983 HARN StatePlane Washington South FIPS 4602 (Feet)
y	Number	Northing - NAD 1983 HARN StatePlane Washington South FIPS 4602 (Feet)

Table: Velocity

Record Count: **712**

Field Name	Type	Description
Site_ID	Number	Unique site number used to link the Location and Velocity tables together
DepthStart_m	Number	Top depth of unit (m)
DepthEnd_m	Number	Bottom depth of unit (m)
UnitThickness_m	Number	Unit Thickness (m)
DepthStart_ft	Number	Top depth of unit (ft)
DepthEnd_ft	Number	Bottom depth of unit (ft)
UnitThickness_ft	Number	Unit Thickness (ft)
Vs-ms	Number	Shear wave velocity (m/s)
Vs-fts	Number	Shear wave velocity (ft/s)
GeoUnit	Text	Geologic Unit Code