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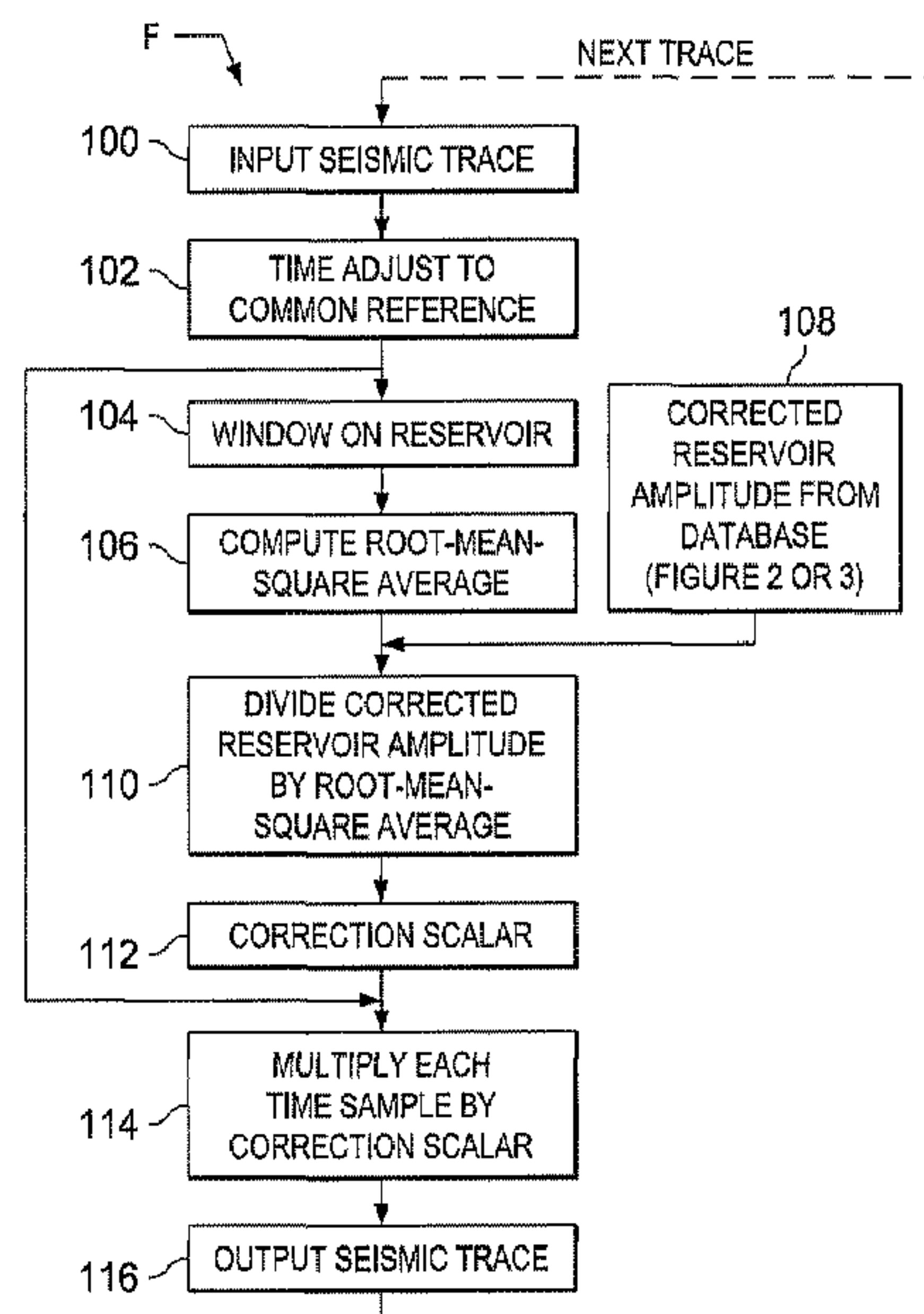


FIG. 1

(57) **Abrégé/Abstract:**

Time lapse or 4D seismic data are corrected for geologic overburden and seismic recording system effects. The data from a survey at one time of interest is processed within a selected frequency band and the reservoir level is normalized by the overburden. The results are used to extract reservoir amplitudes from the data of that same survey. Frequencies where overburden signal-to-noise ratios vary dramatically between time lapse surveys may then be avoided in processing of data from the area of interest.



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(54) Title: CORRECTING TIME LAPSE SEISMIC DATA FOR OVERBURDEN AND RECORDING EFFECTS

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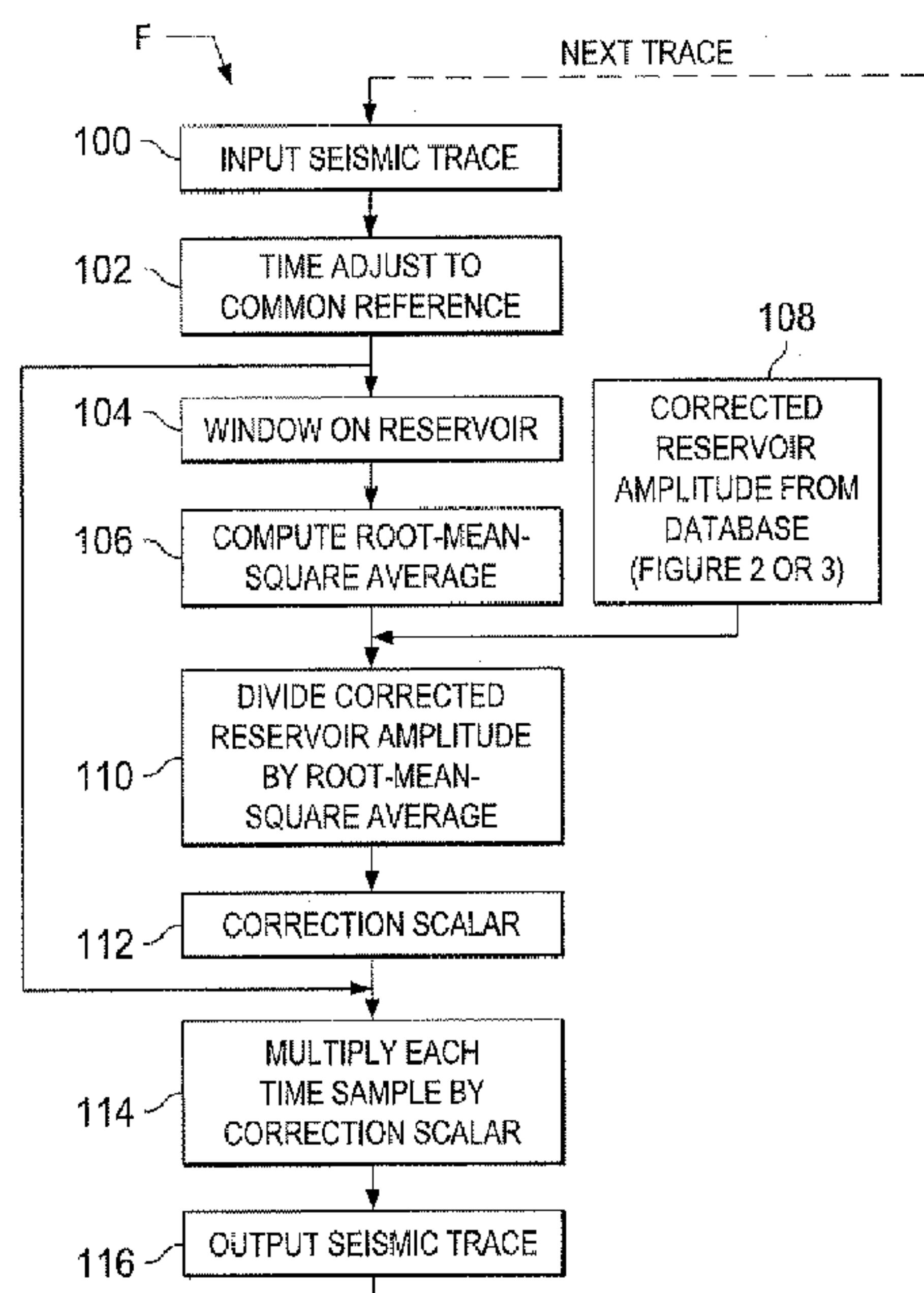


FIG. 1

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CORRECTING TIME LAPSE SEISMIC DATA FOR OVERBURDEN AND RECORDING EFFECTS

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The present to geophysical exploration, and more particularly to processing of time lapse or 4D seismic data for evaluation of features of interest regarding subsurface formations and their contents.

2. Description of the Related Art

[0002] Seismic reflectivity, also known as seismic amplitude or reflection strength, is related to differences in acoustic impedance between reservoir rock and overlying strata. Changing reservoir fluids can modify reservoir acoustic impedance which is calculated by multiplying seismic energy travel velocity and rock density. Seismic reflection strength at a reservoir boundary can vary due to fluid changes such as injection of gas or steam, causing changes in either density, velocity or both. Changes in temperature and pressure also influence the reservoir acoustic impedance. Monitoring movement of these dynamic changes between wells is made possible by conducting repeated time lapse seismic surveys. In this way fluid position is tracked over time by differencing the reflection amplitude between two or more surveys at different times. Other seismic attributes can be differenced but reflection strength is the most commonly used. Further descriptions of these types of surveys and data processing are contained, for example, in "Spectral analysis applied to seismic monitoring of thermal recovery", SEG Expanded Abstracts 12, 331-334 (1993), Eastwood et al. (1993); "Processing for robust time-lapse seismic analysis: Gulf of Mexico example, Lena Field", SEG Expanded Abstracts 17, 20-23 (1998), Eastwood et al.; "Time lapse processing: A North

Sea case study”, 68th Ann. Internat. Mtg., SEG, Expanded Abstracts, 1–4, Harris et al. (1998); “Schiehallion: A 3-D Time - Lapse Processing Case History, SEG 1999 Expanded Abstracts; Altan et al. (1999); and “4D seismic monitoring of CO2 flood in a thin fractured carbonate reservoir”, The Leading Edge, July 2003, 691-695, Li (2003).

[0003] Reservoir characterization based on seismic observations has required a highly accurate seismic acquisition and processing system. For the specialized case of integrating time lapse seismic surveys with reservoir monitoring, accuracy requirements have become even more crucial since dynamic reservoir changes such as fluid movement or pressure changes are related to subtle differences in seismic observations. See, for example, “Time Lapse Seismic Reservoir Monitoring”, Geophysics, Vol. 66, No. 1 (Jan.-Feb. 2001); P. 50–53, Lumley.

[0004] Under ideal conditions, differencing two seismic observations has been a straight forward process so long as the resultant value is assumed to only reflect changes at the reservoir level. Since recorded seismic energy propagated through a geologic overburden, and was also subject to the recording response of the acquisition system, two key assumptions have been used to interpret reservoir amplitude change. These were that propagation effects in the geologic overburden remained the same, and that seismic recording systems responded identically during independent monitoring surveys at different times.

[0005] Field studies have routinely shown these basic assumptions to be false. One only needs to consider the recording system can never be placed exactly in the same surface position, and that changes in the overburden do in fact occur. For example, near surface seasonal variations such as water table elevation changed the overburden response. Even

daily temperature and moisture changes in the first few feet of soil affected repeated seismic observations.

[0006] To improve repeatability in recording, systems have been developed that feature permanently cemented sources and detectors, an example of which is described in “Reservoir monitoring using permanent sources and vertical receiver antennae”, The Céré-la-Ronde case study, The Leading Edge, June 2001, 622-629, (Meunier et al.). Unfortunately there still existed possible overburden changes, especially in the near surface, that occurred above and below the level of permanently installed recording systems. An example of seismic energy above a buried system was the effect of reflections from the air/surface interface commonly known as “ghost energy.”

[0007] Changes in overburden propagation response are routinely compensated for during 4D seismic data processing. Although there may be several causes, overburden changes are usually treated as a single effect. This has been done by conditioning the data using processing techniques that forced overburden measurements to be the same between surveys, or to be the same with those recorded in an initial survey. This processing method prior to differencing is commonly referred to as “cross equalization of a monitor survey to the base survey.” Once cross equalization of the overburden was applied, corrected reservoir amplitudes were differenced between surveys to observe dynamic changes in the reservoir, such as movement of injected fluids, pressure fronts and temperature fronts. Examples of cross equalization are described in “Inside the cross-equalization black box”, The Leading Edge, 15, 1233–1240, (Ross et al., 1998); “A cross-equalization processing flow for off-the-shelf 4-D seismic data”, 68th Ann. Internat. Mtg., SEG., Expanded Abstracts, 16–19,

(Rickett et al., 1998); and “Seismic Low-Frequency Effects in Monitoring Fluid-Saturated Reservoirs”, Geophysics, Vol. 69, No. 2 (Mar.-Apr. 2004); p. 522–532, Korneev et al.

[0008] Performed as a frequency dependent process, cross-equalization can be robust if the frequency bandwidth is similar between two surveys. If not, then cross equalized surveys are limited to a common bandwidth between surveys which may lower resolution of the data. Another key assumption is that signal-to-noise ratios at each processed frequency are the same. While this may be the case for certain types of repeatable noise, such as source generated noise, it does not address frequency dependent noise variations between time lapse surveys.

[0009] Non-repeatable frequency dependent noise may be caused by seasonal or daily changes in near surface overburden layers. As such, cross-equalization tends to propagate noise present in one survey into other surveys. This effect tends to decrease repeatability outside the cross-equalization design window which makes it more difficult to observe small seismic amplitude changes caused by dynamic fluid, pressure or temperature changes in the reservoir.

[0010] Another state-of-the-art 4D data processing normalization technique employs overburden time domain windows to correct the target reservoir. The procedure calculates an average amplitude value from an overburden window that is divided into the average amplitude value of the reservoir window. Since the correction is computed in the time domain, all frequencies contribute to the final correction factor. Similar to cross equalization, deficiencies in this method arise when certain frequency bandwidths are dominated by noise events that vary across time lapse surveys.

SUMMARY OF THE INVENTION

[0011] Briefly, the present invention provides a new and improved computer implemented method of correcting time lapse seismic data for overburden and recording variations present in the data, the data being obtained in a succession of seismic surveys over a period of time from an area of interest regarding a subsurface reservoir beneath an overburden. The computer implemented method according to the present invention forms a measure of average amplitude of seismic energy at the reservoir in a trace in the data of a selected one of the time lapse surveys, and forms a measure of corrected reservoir amplitude of seismic energy at the reservoir in the trace in the data of the selected one of the time lapse surveys. A correction scalar measure is formed indicating the ratio of the measure of corrected reservoir amplitude to the average amplitude at the reservoir in the trace of the selected one of the time lapse surveys, and the correction scalar applied to the trace of the selected one of the time lapse surveys to form a corrected amplitude seismic trace. A record is then formed of the corrected amplitude seismic trace.

[0012] The present invention also provides a new and improved data processing system for correcting time lapse seismic data for overburden and recording variations during the course of acquiring the time lapse seismic data from an area of interest regarding a subsurface reservoir in a succession of seismic surveys over a period of time in the area of interest. The data processing system includes a processor which forms a measure of average amplitude of seismic energy at the reservoir in a trace in the data of a selected one of the time lapse surveys. The processor also forms a measure of corrected reservoir amplitude of seismic energy at the reservoir in the trace in the data of the selected one of the time lapse surveys, and forms a correction scalar measure indicating the ratio of the measure of corrected reservoir amplitude to the average amplitude at the reservoir in the trace of the selected one of the time lapse surveys. The data processing system according to the present invention

applies the correction scalar to the trace of the selected one of the time lapse surveys to form a corrected amplitude seismic trace, and forms a record of the corrected amplitude seismic trace.

[0013] The present invention further provides a new and improved data storage device having stored in a computer readable medium computer operable instructions for causing a data processing system comprising at least one processor unit and an output display to correct time lapse seismic data for overburden and recording variations during the course of acquiring the time lapse seismic data from an area of interest regarding a subsurface reservoir in a succession of seismic surveys over a period of time in the area of interest. The instructions stored in the data storage device cause the data processing system to form a measure of average amplitude of seismic energy at the reservoir in a trace in the data of a selected one of the time lapse surveys, and to form a measure of corrected reservoir amplitude of seismic energy at the reservoir in the trace in the data of the selected one of the time lapse surveys. The instructions stored in the data storage device cause the data processing system to also form a correction scalar measure indicating the ratio of the measure of corrected reservoir amplitude to the average amplitude at the reservoir in the trace of the selected one of the time lapse surveys, and apply the correction scalar to the trace of the selected one of the time lapse surveys to form a corrected amplitude seismic trace. The instructions stored in the data storage device according to the present invention also cause the data processing system to form a record of the corrected amplitude seismic trace.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Figure 1 is a functional block diagram or flow chart of a sequence of correction of time lapse seismic data according to the present invention.

[0015] Figure 2 is a functional block diagram or flow chart of a portion of the sequence of correction of time lapse seismic data of Figure 1.

[0016] Figure 3 is a functional block diagram or flow chart of an alternative portion of a sequence of correction of time lapse seismic data of Figure 1.

[0017] Figure 4 is a schematic diagram of a computer system for correction of time lapse seismic data according to the present invention.

[0018] Figure 5A is a plot of a simulated time lapse seismic survey at a location above a producing hydrocarbon reservoir.

[0019] Figure 5B is a plot of root-mean-square (RMS) amplitude as a function of time obtained from a window in the plot of Figure 5A.

[0020] Figure 6A is a plot of a simulated time lapse seismic survey at the same location above a producing hydrocarbon reservoir as Figure 5A with seasonal variations in near surface seismic velocity added.

[0021] Figure 6B is a plot of root-mean-square (RMS) amplitude as a function of time obtained from a window in the plot of Figure 6A.

[0022] Figure 7A is a plot of a simulated time lapse seismic survey at the same location above a producing hydrocarbon reservoir as Figure 5A with seasonal variations in the near surface overburden layer added.

[0023] Figure 7B is a plot of root-mean-square (RMS) amplitude as a function of time obtained from a window in the plot of Figure 7A.

[0024] Figure 8A is a plot of a simulated time lapse seismic survey at the same location above a producing hydrocarbon reservoir as Figure 5A with seasonal variations in the near surface overburden layer normalized according to conventional cross-equalization techniques.

[0025] Figure 8B is a plot of root-mean-square (RMS) amplitude as a function of time obtained from a window in the plot of Figure 8A.

[0026] Figure 9A is a plot of a simulated time lapse seismic survey at the same location above a producing hydrocarbon reservoir as Figure 8A with seasonal variations in the near surface overburden layer normalized according to conventional cross-equalization techniques.

[0027] Figure 9B is a plot of root-mean-square (RMS) amplitude as a function of time obtained from a window in the plot of Figure 9A.

[0028] Figure 10A is a plot of a simulated time lapse seismic survey at the same location above a producing hydrocarbon reservoir as Figure 6A with seasonal variations in the near surface overburden layer normalized according to conventional time domain normalization techniques.

[0029] Figure 10B is a plot of root-mean-square (RMS) amplitude as a function of time obtained from a window in the plot of Figure 10A.

[0030] Figure 11A is a plot of a simulated time lapse seismic survey at the same location above a producing hydrocarbon reservoir as Figure 6A after processing in accordance with the present invention.

[0031] Figure 11B is a plot of root-mean-square (RMS) amplitude as a function of time obtained from a window in the plot of Figure 11A.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0032] According to the present invention, time lapse or 4D seismic data are corrected for geologic overburden and seismic recording system effects. The method normalizes each time lapse survey within itself rather than across surveys. The data from a survey at one time of interest is processed within a selected frequency band, and the survey data is normalized to corrected reservoir amplitude. As will be set forth, the present invention uses a limited range of frequencies to derive the corrected reservoir amplitude.

[0033] The corrected time lapse amplitude results are used to extract reservoir amplitudes from the data of that same survey. Frequencies where overburden signal-to-noise ratios vary dramatically between time lapse surveys may then be avoided in processing of other data from the area of interest.

[0034] Processing according to the present invention is performed on pre-stack seismic data. The present invention also does not require a baseline survey. The present invention in addition does not require a cross equalization procedure between time lapse surveys. Further, the present invention does not require a coordinate adjustment procedure.

[0035] In the drawings, a flow chart F (Figure 1) composed of a set of correction steps illustrates the structure of the logic of the present invention as embodied in computer program software. The flow chart F is a high-level logic flowchart which illustrates a method according to the present invention of correcting time lapse seismic data for overburden and recording system effects. Those skilled in the art appreciate that the flow charts illustrate the structures of computer program code elements that function according to the present invention. The invention is practiced in its essential embodiment by computer components

that use the program code instructions in a form that instructs a digital data processing system D (Figure 4) to perform a sequence of processing steps corresponding to those shown in the flow chart F.

[0036] The flow chart F of Figure 1 contains a preferred sequence of steps of a computer implemented method or process for correcting time lapse seismic data for overburden and recording effects according to the present invention is illustrated schematically. The flow chart F uses, as will be set forth, a measure of corrected reservoir amplitude from either a set of transform processing steps T (Figure 2) or an alternate set of transform processing steps T-1 (Figure 3). The process of the present invention provides several improvements to the conventional normalization techniques.

[0037] The flow chart F is a high-level logic flowchart illustrates a method according to the present invention of correcting time lapse seismic data for overburden and recording effects. The method of the present invention performed in the computer 20 (Figure 4) of the data processing system D can be implemented utilizing the computer program steps of Figures 1, 2 and 3 stored in memory 22 and executable by system processor 24 of computer 20. The input data to processing system D are time lapse or 4D seismic survey data of the conventional type obtained from an area of the earth overlying a subsurface reservoir of interest. As will be set forth, the flow chart F illustrates a preferred embodiment of a computer implemented method or process for correcting time lapse seismic data for overburden and recording effects. As shown in the flow chart F of Figure 1, a preferred sequence of correction steps based on corrected reservoir amplitude determined in accordance with the present invention, either in the form of transform processing steps T (Figure 2) or T-1 (Figure 3).

[0038] During step 100 (Figure 1) of the flow chart F, an input seismic trace such as shown at 64 (Figure 6A) from a simulated time lapse survey of the area of interest regarding a subsurface reservoir beneath an overburden is read from database storage in the data processing system D. Figure 5A, as well as Figures 6A, 7A, 8A, 9A, 10A and 11A, represents a simulated time lapse seismic surveys collected every other or on an alternate day basis over an acquisition time lasting 720 days from an area of interest. During step 102 (Figure 1), the arrival times of the seismic traces are adjusted to a common arrival time. During step 104, a time window in the time lapse survey data known to be at the time of a target reservoir event in the data is selected. An example target reservoir event is illustrated at a time window 64 in the time lapse survey data of Figure 6A.

[0039] Processing then proceeds to step 106, where an average, or root mean square (RMS), amplitude of the seismic energy amplitude over the time window 64 in the input trace of current interest is determined. The amplitude determined during step 106 represents the uncorrected reservoir amplitude.

[0040] During step 108, a measure of corrected reservoir amplitude determined in a manner to be described during the transform processing T (Figure 2) or T-1 (Figure 3) is obtained from memory 22 of data processing system D. During step 110 (Figure 1) the uncorrected reservoir amplitude from step 106 is divided into the corrected reservoir amplitude obtained during step 108 to derive a correction scalar, which is also stored in memory 22 as indicated at step 112. During step 114 the individual time samples in the input seismic trace obtained in step 102 are then multiplied by the correction scalar from step 112.

[0041] During step 116, a record is formed of the corrected seismic trace. The record is formed by storing the corrected seismic trace in database memory 22, and an output display may also be formed. Processing returns to step 100 and the sequence shown in Figure 1

continues on the next input trace from the time lapse survey data. Processing of the input traces over the duration of the time lapse survey of the area of interest continues until all traces in all time lapse surveys are processed.

[0042] The computer implemented processing sequence for correction for transform processing T (Figure 2), begins at step 200 where an input seismic trace such as shown at 64 from one time lapse survey of the area of interest for a reservoir is read from database storage in the data processing system D. The selected seismic trace and the others from the surveys have preferably been pre-processed with conventional relative amplitude processing procedures. The relative amplitude processing is performed to retain as far as possible reflection amplitudes that represent the acoustic impedance of each geologic layer in the overburden and reservoir while attenuating random noise.

[0043] During step 202 of the transform processing T (Figure 2), the arrival time of the target reservoir event in the selected seismic trace is adjusted to a common arrival time. Processing then proceeds to two sequences which are preferably performed in parallel, as shown in Figure 2, to select two time windows from the selected seismic trace. During step 204, a time window such as that shown at 64 known to be at the time of a target reservoir event in the data is selected to represent the target reservoir window. During step 206, a time window such as that shown at 93 (Figure 10A) known to be at the time of overburden of earth structure above the target reservoir event in the data is selected to represent the overburden window.

[0044] Steps 208 and 210 (Figure 2) follow steps 204 and 206, respectively. During steps 208 and 210, a Fast Fourier Transform (FFT) processing technique is performed on the data in the respective selected time windows 64 and 93. The output data 208a and 210a from steps 208 and 210 are as indicated in Figure 2, in the form of a reservoir frequency spectrum

and an overburden frequency spectrum. Each of the spectra is now referenced in frequency versus amplitude.

[0045] During step 212, the target reservoir amplitude at each frequency of the reservoir frequency spectrum is divided by the overburden amplitude at that same frequency over the same spectrum. During a step 214, a target frequency range in the respective spectra is chosen which is designed to avoid those frequencies contaminated by non-repeatable noise. During step 216, for the target range of frequencies in the respective spectra selected during step 214, a measure of the root mean square (RMS) amplitude for the spectra selected as a result of step 212 is determined. The RMS amplitude determined during step 216 represents the corrected target reservoir amplitude.

[0046] During step 218, the corrected reservoir amplitude determined during step 216 is then stored in the seismic database in the data processing system D. During step 218, quality control plots may also be generated of the corrected reservoir amplitude. These plots may be profiles plotted above the seismic traces or maps referenced to recording position and calendar day of the seismic survey. The corrected reservoir amplitude determined and stored for a trace during the transform processing steps T (Figure 2) is then available as an input corrected reservoir amplitude for that trace during step 108 (Figure 1). Processing to determine corrected reservoir amplitude for another input trace is then begun by return to step 200 and the sequence shown in Figure 2 continues on the next input trace from the time lapse survey data. Processing of the input traces over the duration of all time lapse surveys of the area of interest continues until corrected reservoir amplitude for all traces in all time lapse surveys are processed.

[0047] Figure 3 illustrates an alternative set of transform processing steps T-1 which may be used in place of those shown in Figure 2. In the set of steps T-1, an input seismic trace

such as shown at 50 from one time lapse survey of the area of interest is read during step 300 from database storage in the data processing system D. The selected seismic trace and the others from the time lapse survey have preferably also been pre-processed with conventional relative amplitude processing procedures. During step 302, the arrival time of the reservoir event in the selected input seismic trace is adjusted to a common arrival time.

[0048] During step 304 a time frequency transform is performed of the data in the selected input trace. The time frequency transform may be any of several conventional types, including, for example, Fast Fourier Transform (FFT); Short Time Fourier Transform (STFT); Wigner-Ville Distribution (WVD) Transform(s); Morlet Wavelet Transform; Complex Wavelet Transform (CWT); and Adaptive Wavelet Transform (AWT). Next, during step 306 an average trace is formed from a range of selected range of frequencies of the transformed data from step 304. The selected target frequency range is preferably one chosen to avoid those frequencies contaminated by non-repeatable noise. During step 308 an average or RMS reservoir amplitude is determined for the average trace data resulting from step 306 at a time known to be at the time of a target reservoir event in the data. During step 310 an average or RMS overburden amplitude is determined for the average trace data resulting from step 306 at a time window known to be at the time window of overburden in the data.

[0049] During step 312 the RMS reservoir amplitude determined during step 308 is divided by the RMS overburden amplitude determined during step 310 to form a measure of corrected reservoir amplitude. During step 314, the corrected reservoir amplitude step 312 is then stored in a seismic database in the data processing system D. If desired, quality control plots are generated of the corrected reservoir amplitude. These plots may be profiles plotted above the seismic traces or maps referenced to recording position and calendar day of the seismic survey. The corrected reservoir amplitude is available from database memory for the

correction processing sequence of Figure 1 during step 108. Processing of the input traces over the duration of the time lapse survey of the area of interest continues until corrected reservoir amplitude for all traces in all time lapse surveys are processed.

[0050] As illustrated in Fig. 4, a data processing system D according to the present invention includes the computer 20 having processor 22 and memory 24 coupled to the processor 22 to store operating instructions, control information and database records therein. The computer 20 may, if desired, be a portable digital processor, such as a personal computer in the form of a laptop computer, notebook computer or other suitable programmed or programmable digital data processing apparatus, such as a desktop computer. It should also be understood that the computer 20 may be a multicore processor with nodes such as those from Intel Corporation or Advanced Micro Devices (AMD), or a mainframe computer of any conventional type of suitable processing capacity such as those available from International Business Machines (IBM) of Armonk, N.Y. or other source.

[0051] The computer 20 has a user interface 26 and an output display 28 for displaying output data or records of processing of seismic data survey measurements performed according to the present invention for correcting time lapse seismic data for overburden and recording system effects. The output display 28 includes components such as a printer and an output display screen capable of providing printed output information or visible displays in the form of graphs, data sheets, graphical images, data plots and the like as output records or images.

[0052] The user interface 26 of computer 20 also includes a suitable user input device or input/output control unit 30 to provide a user access to control or access information and database records and operate the computer C. Data processing system D further includes a

database 32 stored in computer memory, which may be internal memory 22, or an external, networked, or non-networked memory as indicated at 34 in an associated database server 36.

[0053] The data processing system D includes program code 38 stored in memory 22 of the computer C. The program code 38, according to the present invention is in the form of computer operable instructions causing the data processor 20 to correct for time lapse seismic data for overburden and recording effects according to the processing steps illustrated in Figures 1 and 2 (or 3) in the manner described above.

[0054] It should be noted that program code 38 may be in the form of microcode, programs, routines, or symbolic computer operable languages that provide a specific set of ordered operations that control the functioning of the data processing system D and direct its operation. The instructions of program code 38 may be may be stored in memory 22 of the computer C, or on computer diskette, magnetic tape, conventional hard disk drive, electronic read-only memory, optical storage device, or other appropriate data storage device having a computer usable medium stored thereon. Program code 38 may also be contained on a data storage device such as server 36 as a computer readable medium, as shown.

[0055] The method of the present invention performed in the computer 20 can be implemented utilizing the computer program steps of Figure 4 stored in memory 22 and executable by system processor 24 of computer 20. The input data to processing system D are the input field seismic record and other data including, for example, preprocessed data with relative amplitudes preserved; two way arrival time of the target reservoir; analysis time window length about the target reservoir; and analysis time window length about the overburden section.

[0056] Figure 5A illustrates a group of simulated time lapse seismic surveys collected every other day over of an acquisition time of 720 days. Figure 5B is a plot of reflection

strength 54 present over the same time as a result of a target reservoir whose presence is indicated in the seismic survey at window 52. The RMS amplitude 54 from the window 52 around the target reservoir indicates a measurable change (7%) in the reflection amplitude of the target reservoir over the time interval in which the data were plotted.

[0057] Figure 6A illustrates the same time lapse survey data as Figure 5A, with seasonal variations in the near surface velocity added ($\pm 5\%$ over the first six meters). A reservoir event 64 has been adjusted to a common arrival time. The RMS amplitude 66 (Figure 6B) of the reservoir event 52 is plotted above the time lapse survey traces of Figure 6A. The reservoir amplitude 66 now varies by 25% over time interval in which the data were plotted. It is to be noted that the variations in amplitude do not correspond to those indicated by the expected trend or magnitude plotted at 66 in Figure 6A.

[0058] Figure 7A illustrates the same time lapse survey data with seasonal variations in the near surface velocity as in Figure 6A. The RMS amplitude 72 measured from overburden window 70 is plotted in Figure 7B above the time lapse survey traces of Figure 7A. Although overburden RMS amplitude should be expected to be constant for each trace in the survey data of Figure 7A, it should be noted that the determined RMS amplitude 72 varies according to seasonal changes in the near surface velocity. The expected reservoir RMS amplitude is also plotted at 74 in Figure 7B.

[0059] Figure 8A illustrates a data plot obtained by conventional industry standard cross-equalization techniques to the time lapse survey data of Figure 7A. The time lapse surveys of Figure 8A have been cross-equalized to the starting day of the time lapse survey, using the same overburden window 70 of Figure 7A and 8A as a reference. After cross-equalization, a plot 80 from the overburden window is, as would be expected, constant. This response is

consistent with the geologic overburden model. The expected reservoir amplitude is also plotted at 82.

[0060] Figure 9B contains a plot 90 of reservoir amplitude after application of industry standard cross-equalization techniques to the time lapse survey data of Figure 7A. The plot is displayed again over the trace data of Figure 9A. Despite the overburden being successfully cross-equalized as discussed above regarding Figures 8A and 8B, near surface variations in the form of large amplitude variations are still present in the data obtained from the reservoir level indicated at 90. The expected reservoir amplitude at reservoir event 91 is also plotted at 92.

[0061] Figure 10B begins with a measure of reservoir amplitude from time lapse survey data of Figure 10A after application of industry standard amplitude normalization techniques. The time lapse surveys with near surface variations are then each normalized on a day to day basis by dividing the RMS reservoir amplitude 94 for that day by RMS amplitude of overburden 93. The resultant RMS amplitude for the reservoir plotted at 95 can be seen to be more accurate than the results obtained from conventional cross equalization of Figure 9A which are plotted at 90 in Figure 9B. The RMS reservoir amplitude plotted at 95 can be seen to be more accurate, but large amplitude variations due to near surface velocity changes are still evident. The expected reservoir amplitude is also plotted at 92.

[0062] Figure 11B contains a plot 96 of RMS reservoir amplitudes according to the present invention on time lapse survey data of Figure 11A. The RMS reservoir amplitude plotted at 96 can be seen to more closely track expected reservoir response plotted at 97 than the plot 90 obtained from conventional cross equalization (Figure 9B) and the plot 95 obtained from time domain normalization (Figure 10B). The processing techniques according to the present invention can thus be used to produce the best match of the expected

reservoir response among the three methods. Further, the results of the present invention do not show residual amplitude anomalies caused by variations in the near surface.

[0063] It can be thus be seen that using the present invention to select a frequency band within one survey to extract reservoir amplitudes can avoid those frequencies where overburden signal-to-noise ratios vary dramatically between time lapse surveys.

[0064] Another advantage of the present invention is that it does not require a surface coordinate adjustment procedure. This affords advantages over conventional procedures comparing two surveys, such as cross equalization, which require additional processing for surface coordinate adjustment. The present invention thus represents a cost savings in project turnaround time and an opportunity to avoid adding processing errors into the data.

[0065] Further, as has been noted, using the present invention on model data (Figure 11B) has shown that dynamic reservoir amplitude changes on the order of 7% can be recovered in the presence of overburden amplitude variations in the range of 25%. The same models show that current-state-of-the-art methods such as cross-equalization and time domain normalization are not successful in determining the correct 7% amplitude change at the reservoir (Figures 9B and 10B).

[0066] From the foregoing, it can be seen that correcting time lapse seismic data for geologic overburden and seismic recording system effects according to the present invention provides improvements over state-of-the-art normalization techniques. The present invention is especially beneficial to reservoir monitoring observations that employ time lapse seismic surveying. By improving the accuracy of time lapse seismic measurements a positive effect is created for production decisions made by reservoir management, especially during enhanced oil recovery operations. A potential operating cost saving during seismic

monitoring may also be available by relaxing the requirement for burying sources and detectors below near surface problem zones.

[0067] As has been set forth, the present invention normalizes each time lapse survey within itself rather than across surveys. The present invention uses a limited range of frequencies to derive the corrected reservoir amplitude. The present invention works on pre-stack seismic data. The present invention does not require a baseline survey. The present invention does not require a cross equalization procedure between time lapse surveys. The present invention does not require a coordinate adjustment procedure.

[0068] The invention has been sufficiently described so that a person with average knowledge in the matter may reproduce and obtain the results mentioned in the invention herein. Nonetheless, any skilled person in the field of technique, subject of the invention herein, may carry out modifications not described in the request herein, to apply these modifications to a determined structure, or in the manufacturing process of the same, requires the claimed matter in the following claims; such structures shall be covered within the scope of the invention.

[0069] It should be noted and understood that there can be improvements and modifications made of the present invention described in detail above without departing from the spirit or scope of the invention as set forth in the accompanying claims.

CLAIMS

What is claimed is:

1. A computer implemented method of correcting time lapse seismic data for overburden and recording variations present in the data, the data being obtained in a succession of seismic surveys over a period of time from an area of interest regarding a subsurface reservoir beneath an overburden, the method comprising the computer implemented steps of:

forming a measure of average amplitude of seismic energy at the reservoir in a trace in the data of a selected one of the time lapse surveys;

forming a measure of corrected reservoir amplitude of seismic energy at the reservoir in the trace in the data of the selected one of the time lapse surveys;

forming a correction scalar measure indicating the ratio of the measure of corrected reservoir amplitude to the average amplitude at the reservoir in the trace of the selected one of the time lapse surveys;

applying the correction scalar to the trace of the selected one of the time lapse surveys to form a corrected amplitude seismic trace; and

forming a record of the corrected amplitude seismic trace.

2. The computer implemented method of Claim 1, wherein the step of forming a measure of corrected reservoir amplitude of seismic energy at the overburden comprises the step of:

performing a transformation of the trace from a time domain measure to a frequency domain measure to obtain an amplitude spectrum of the seismic energy at the overburden as a function of frequency.

3. The computer implemented method of Claim 2, wherein the step of forming a measure indicating the ratio comprises the step of:

forming a ratio of the amplitude spectrum at the reservoir to the amplitude spectrum at the overburden.

4. The computer implemented method of Claim 1, wherein the step of forming a measure of corrected reservoir amplitude of seismic energy at the reservoir comprises the step of:

performing a transformation of the trace from a time domain measure to a frequency domain measure to obtain an amplitude spectrum of the seismic energy at the reservoir as a function of frequency.

5. The computer implemented method of Claim 4, wherein the step of forming a measure indicating the ratio comprises the step of:

forming a ratio of the amplitude spectrum at the reservoir to the amplitude spectrum at the overburden.

6. The computer implemented method of Claim 1, wherein the step of forming a measure of average amplitude of seismic energy at the overburden comprises the steps of:

performing a time frequency transform of the data in the trace;

forming an average trace from a selected range of frequencies in the time frequency transform;

forming a measure of average amplitude of the seismic energy at the overburden;

forming a measure of average amplitude of the seismic energy at the reservoir; and

forming a ratio of the average amplitude of the seismic energy at the reservoir to the measure of average amplitude of the seismic energy at the overburden.

7. The computer implemented method of Claim 1, wherein the step of forming a record of the corrected amplitude seismic trace comprises the step of:

storing the corrected amplitude seismic trace in memory.

8. The computer implemented method of Claim 1, wherein the step of forming a record of the corrected amplitude seismic trace comprises the step of:

forming an output display of the corrected amplitude seismic trace.

9. The computer implemented method of Claim 1, further including the steps of:

selecting another seismic trace from the data of the selected one of the time lapse surveys; and

repeating the steps of forming a measure of average amplitude, forming a measure of corrected reservoir amplitude, forming a correction scalar measure, applying the correction scalar and forming a record of the corrected amplitude seismic trace for the selected another trace.

10. A data processing system for correcting time lapse seismic data for overburden and recording variations during the course of acquiring the time lapse seismic data from an area of interest regarding a subsurface reservoir in a succession of seismic surveys over a period of time in the area of interest, the data processing system comprising:

a processor performing the steps of:

forming a measure of average amplitude of seismic energy at the reservoir in a trace in the data of a selected one of the time lapse surveys;

forming a measure of corrected reservoir amplitude of seismic energy at the reservoir in the trace in the data of the selected one of the time lapse surveys;

forming a correction scalar measure indicating the ratio of the measure of corrected reservoir amplitude to the average amplitude at the reservoir in the trace of the selected one of the time lapse surveys;

applying the correction scalar to the trace of the selected one of the time lapse surveys to form a corrected amplitude seismic trace; and

forming a record of the corrected amplitude seismic trace.

11. The data processing system of Claim 10, wherein the processor in performing the step of forming a measure of corrected reservoir amplitude of seismic energy at the overburden performs the steps of:

performing a transformation of the trace from a time domain measure to a frequency domain measure to obtain an amplitude spectrum of the seismic energy at the overburden as a function of frequency.

12. The data processing system of Claim 11, wherein the processor in performing the step of forming a measure of indicating the ratio performs the steps of:

forming a ratio of the amplitude spectrum at the reservoir to the amplitude spectrum at the overburden.

13. The data processing system of Claim 10, wherein the processor in performing the step of forming a measure of corrected reservoir amplitude of seismic energy at the reservoir performs the steps of:

performing a transformation of the trace from a time domain measure to a frequency domain measure to obtain an amplitude spectrum of the seismic energy at the reservoir as a function of frequency.

14. The data processing system of Claim 13, wherein the processor in performing the step of forming a measure of indicating the ratio performs the steps of:

forming a ratio of the amplitude spectrum at the reservoir to the amplitude spectrum at the overburden.

15. The data processing system of Claim 10, wherein the processor in performing the step of forming a measure of average amplitude of seismic energy at the reservoir performs the steps of:

performing a time frequency transform of the data in the trace;

forming an average trace from a selected range of frequencies in the time frequency transform;

forming a measure of average amplitude of the seismic energy at the overburden;

forming a measure of average amplitude of the seismic energy at the reservoir; and

forming a ratio of the average amplitude of the seismic energy at the reservoir to the measure of average amplitude of the seismic energy at the overburden.

16. The data processing system of Claim 10, wherein the processor in performing the step of forming a record of the corrected amplitude seismic trace performs the steps of:

storing the corrected amplitude seismic trace in memory.

17. The data processing system of Claim 10, wherein the processor in performing the step of forming a record of the corrected amplitude seismic trace performs the steps of:

forming an output display of the corrected amplitude seismic trace.

18. The data processing system of Claim 10, wherein the processor further performs the steps of:

selecting another seismic trace from the data of the selected one of the time lapse surveys; and

repeating the steps of forming a measure of average amplitude, forming a measure of corrected reservoir amplitude, forming a correction scalar measure, applying the correction scalar and forming a record of the corrected amplitude seismic trace for the selected another trace.

19. A data storage device having stored in a computer readable medium computer operable instructions for causing a data processing system comprising at least one processor unit and an output display to correct time lapse seismic data for overburden and recording variations during the course of acquiring the time lapse seismic data from an area of interest regarding a subsurface reservoir in a succession of seismic surveys over a period of time in the area of interest, the instructions stored in the data storage device causing the data processing system to perform the following steps:

forming a measure of average amplitude of seismic energy at the reservoir in a trace in the data of a selected one of the time lapse surveys;

forming a measure of corrected reservoir amplitude of seismic energy at the reservoir in the trace in the data of the selected one of the time lapse surveys;

forming a correction scalar measure indicating the ratio of the measure of corrected reservoir amplitude to the average amplitude at the reservoir in the trace of the selected one of the time lapse surveys;

applying the correction scalar to the trace of the selected one of the time lapse surveys to form a corrected amplitude seismic trace; and

forming a record of the corrected amplitude seismic trace.

20. The data storage device of Claim 19, wherein the instructions stored in the data storage device cause the data processing system in performing the step of forming a measure of corrected reservoir amplitude of seismic energy at the overburden to perform the following step:

performing a transformation of the trace from a time domain measure to a frequency domain measure to obtain an amplitude spectrum of the seismic energy at the overburden as a function of frequency.

21. The data storage device of Claim 20, wherein the instructions stored in the data storage device cause the data processing system in performing the step of forming a measure indicating the ratio to perform the following step:

forming a ratio of the amplitude spectrum at the reservoir to the amplitude spectrum at the overburden.

22. The data storage device of Claim 19, wherein the instructions stored in the data storage device cause the data processing system in performing the step of forming a measure of corrected reservoir amplitude of seismic energy at the reservoir to perform the following step:

performing a transformation of the trace from a time domain measure to a frequency domain measure to obtain an amplitude spectrum of the seismic energy at the reservoir as a function of frequency.

23. The data storage device of Claim 22, wherein the instructions stored in the data storage device cause the data processing system in performing the step of forming a measure indicating the ratio to perform the following step:

forming a ratio of the amplitude spectrum at the reservoir to the amplitude spectrum at the overburden.

24. The data storage device of Claim 19, wherein the instructions stored in the data storage device cause the data processing system in performing the step of forming a measure of average amplitude of seismic energy at the overburden to perform the following steps:

performing a time frequency transform of the data in the trace;

forming an average trace from a selected range of frequencies in the time frequency transform;

forming a measure of average amplitude of the seismic energy at the overburden;

forming a measure of average amplitude of the seismic energy at the reservoir; and

forming a ratio of the average amplitude of the seismic energy at the reservoir to the measure of average amplitude of the seismic energy at the overburden.

25. The data storage device of Claim 19, wherein the instructions stored in the data storage device cause the data processing system to further perform the following step:

storing the corrected amplitude seismic trace in memory.

26. The data storage device of Claim 19, wherein the instructions stored in the data storage device cause the data processing system to further perform the following step:

forming an output display of the corrected amplitude seismic trace.

27. The data storage device of Claim 19, wherein the instructions stored in the data storage device cause the data processing system to further perform the following steps:

selecting another seismic trace from the data of the selected one of the time lapse surveys; and

repeating the steps of forming a measure of average amplitude, forming a measure of corrected reservoir amplitude, forming a correction scalar measure, applying the correction scalar and forming a record of the corrected amplitude seismic trace for the selected another trace.

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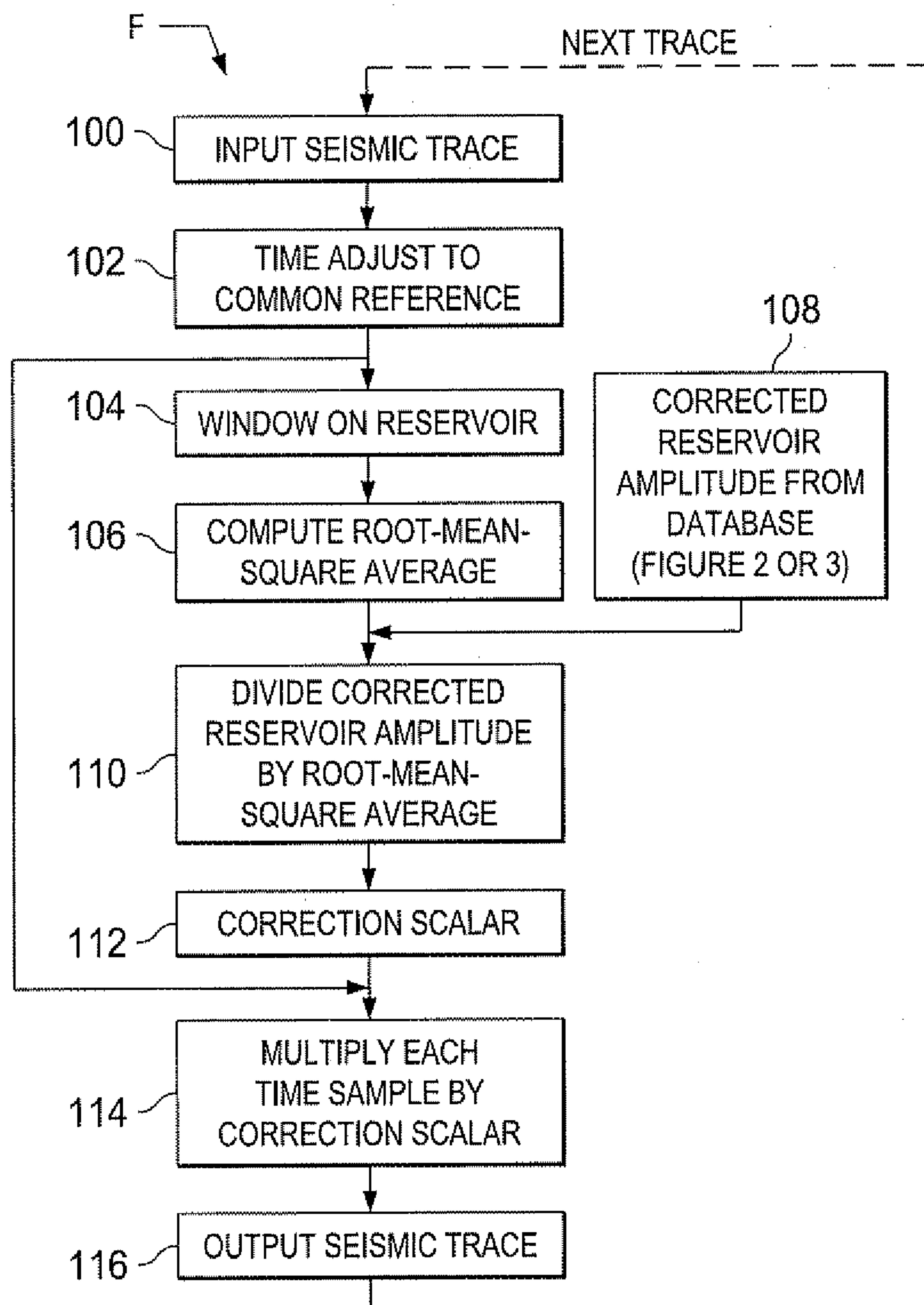


FIG. 1

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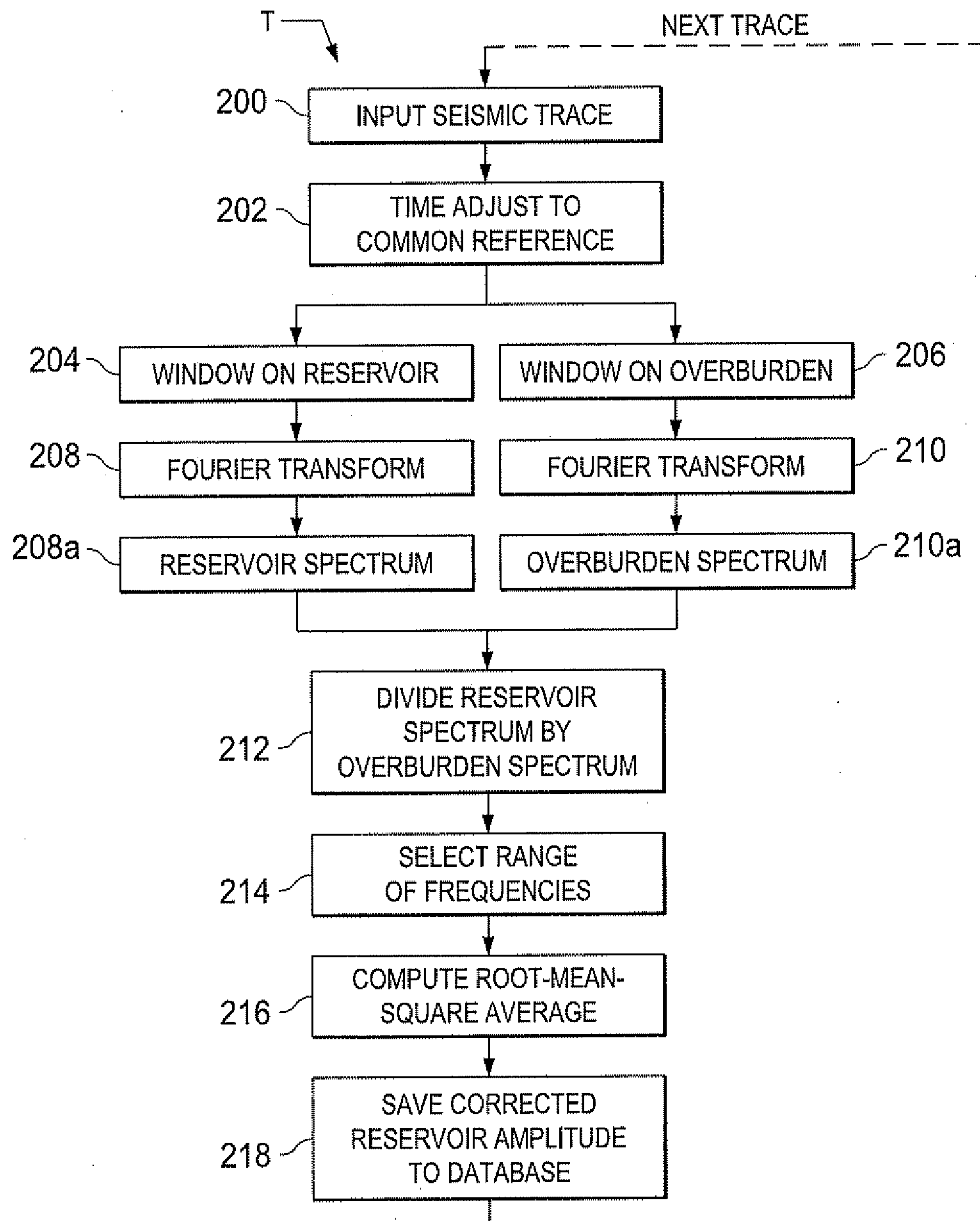


FIG. 2

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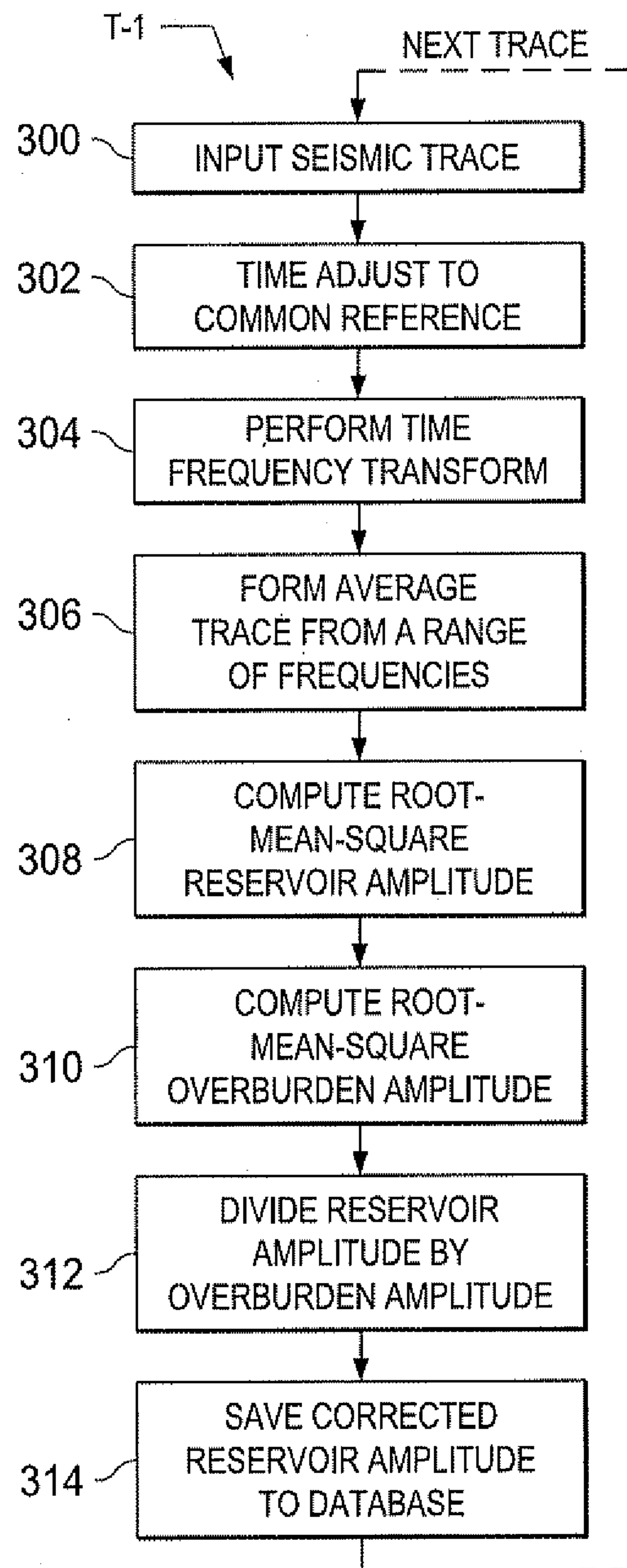


FIG. 3

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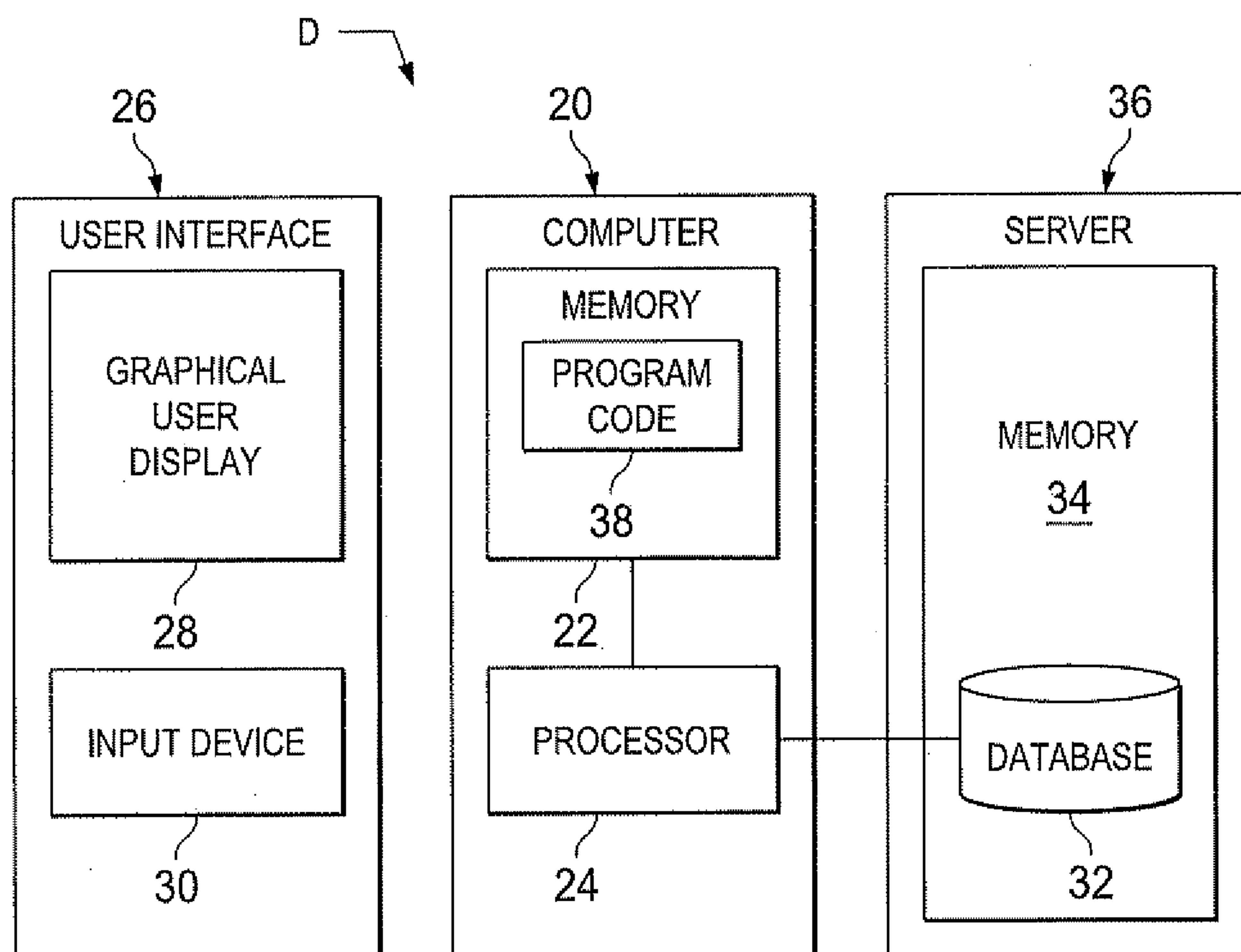


FIG. 4

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FIG. 5A

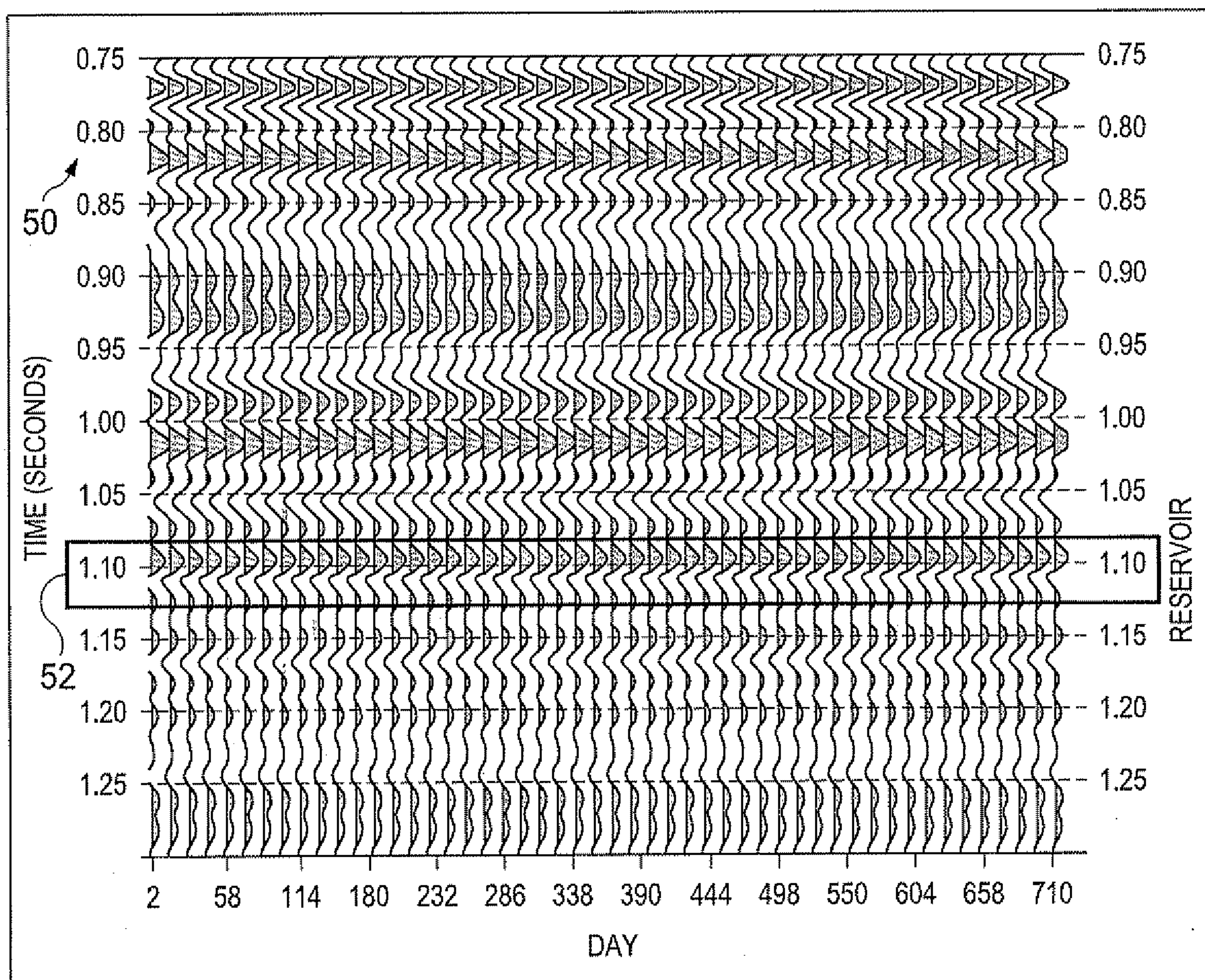
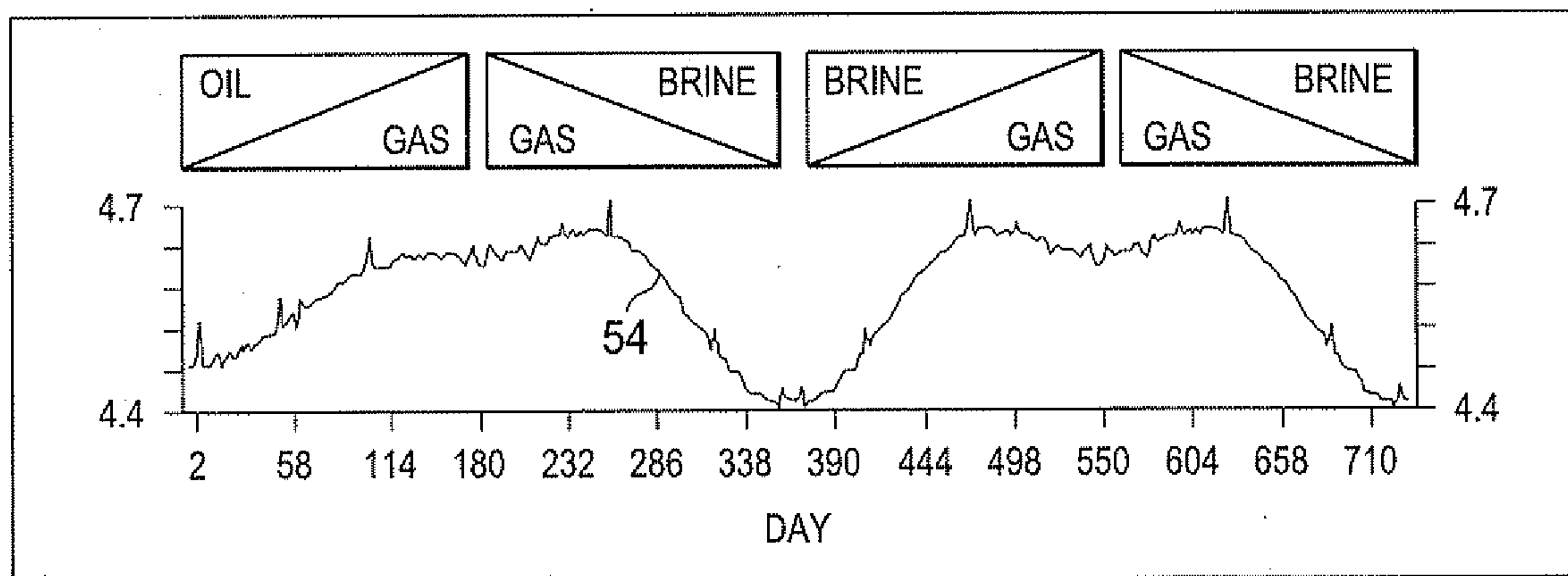


FIG. 5B



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FIG. 6A

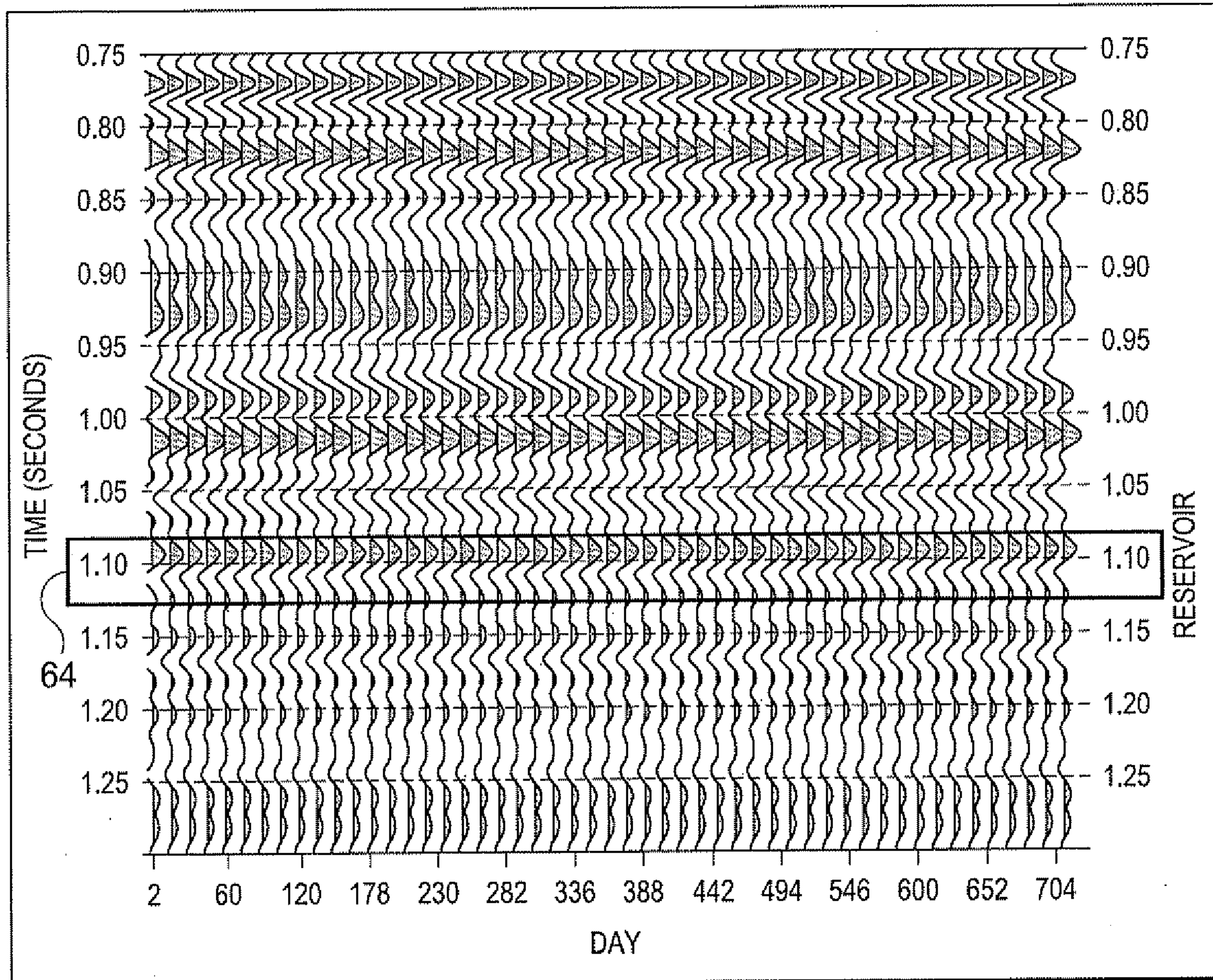
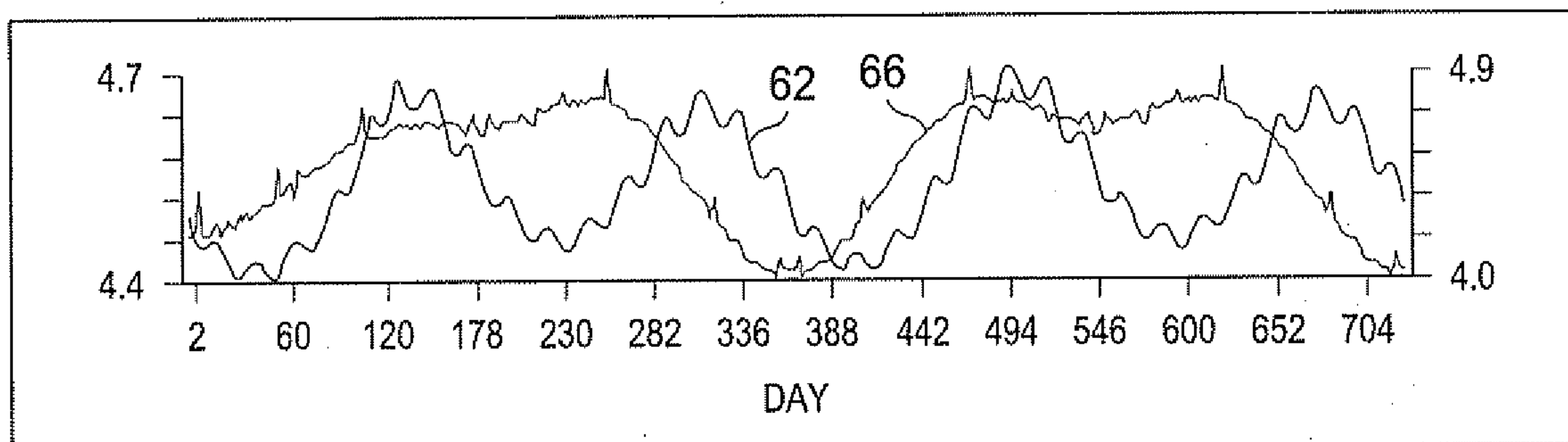


FIG. 6B



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FIG. 7A

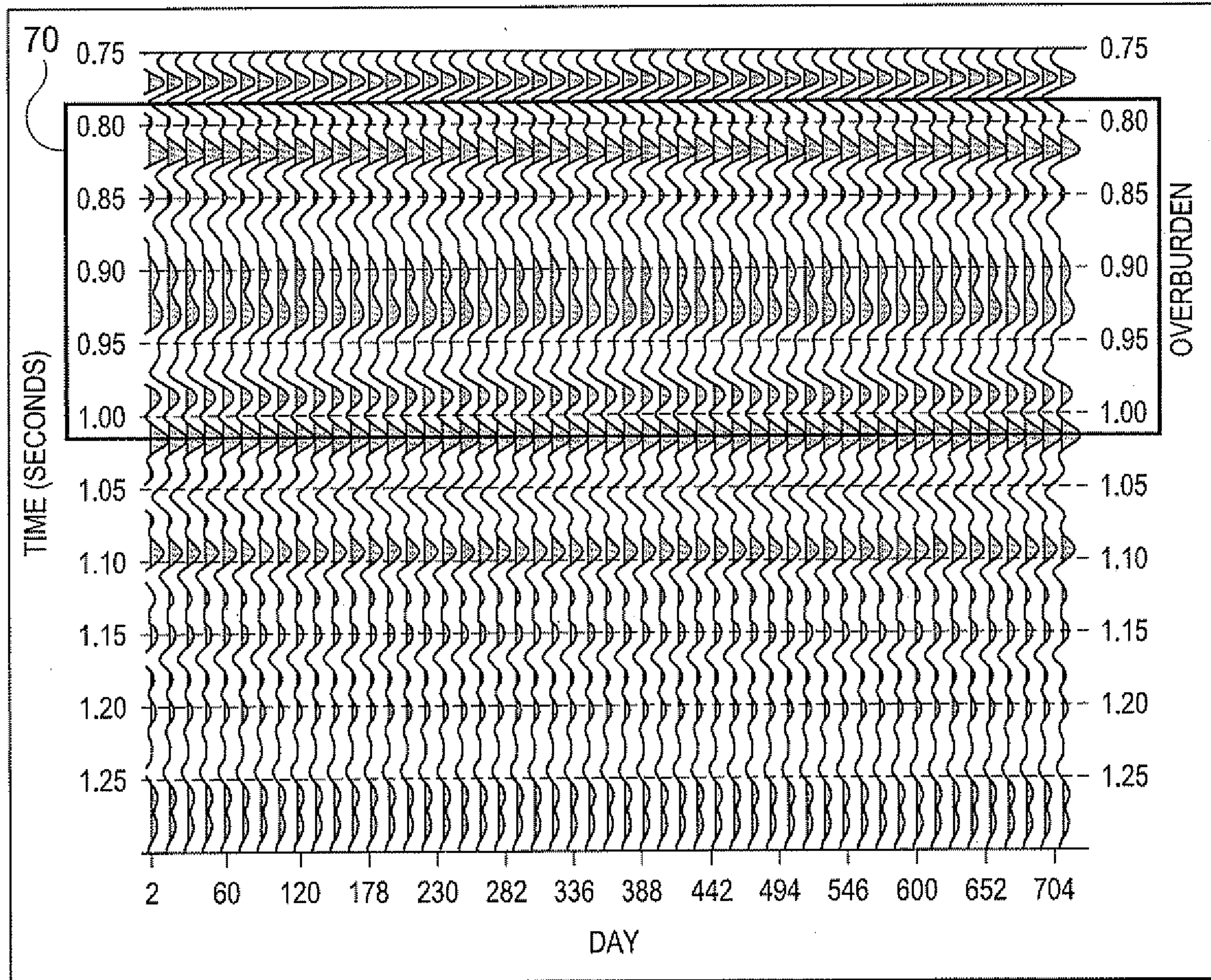
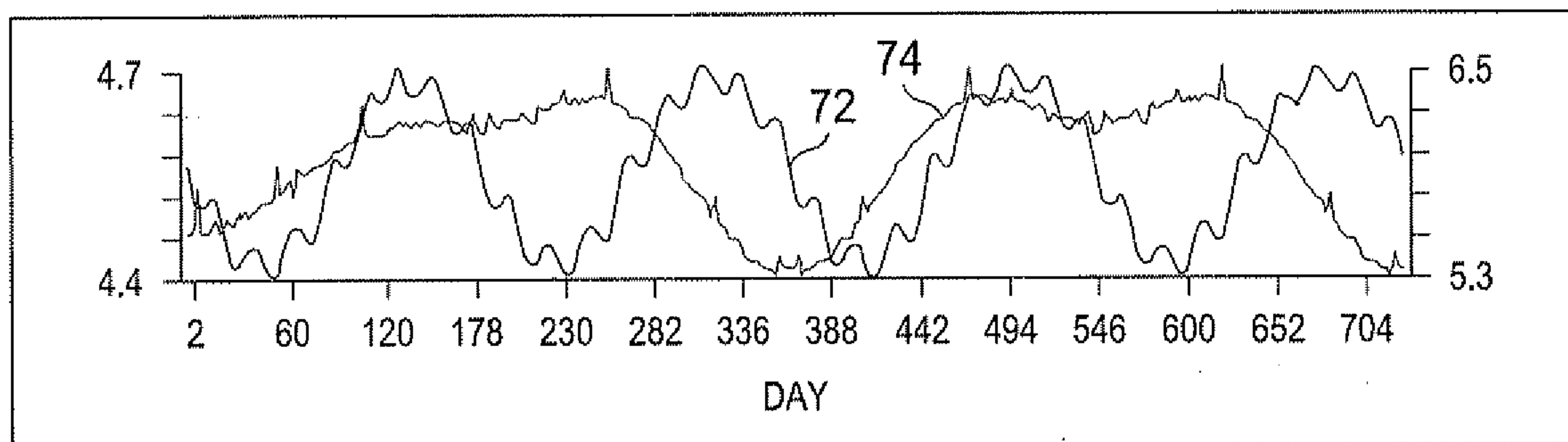


FIG. 7B



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FIG. 8A

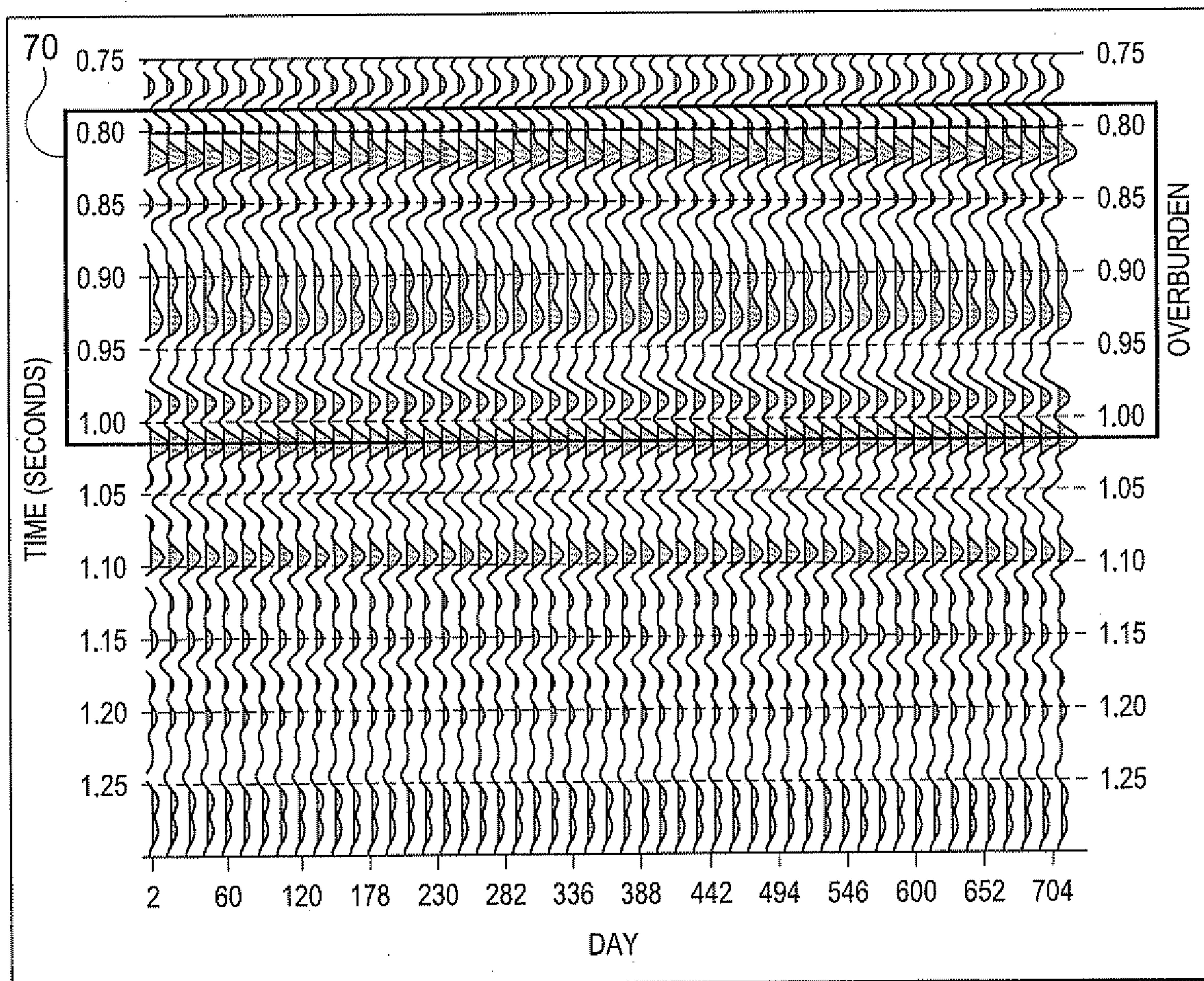
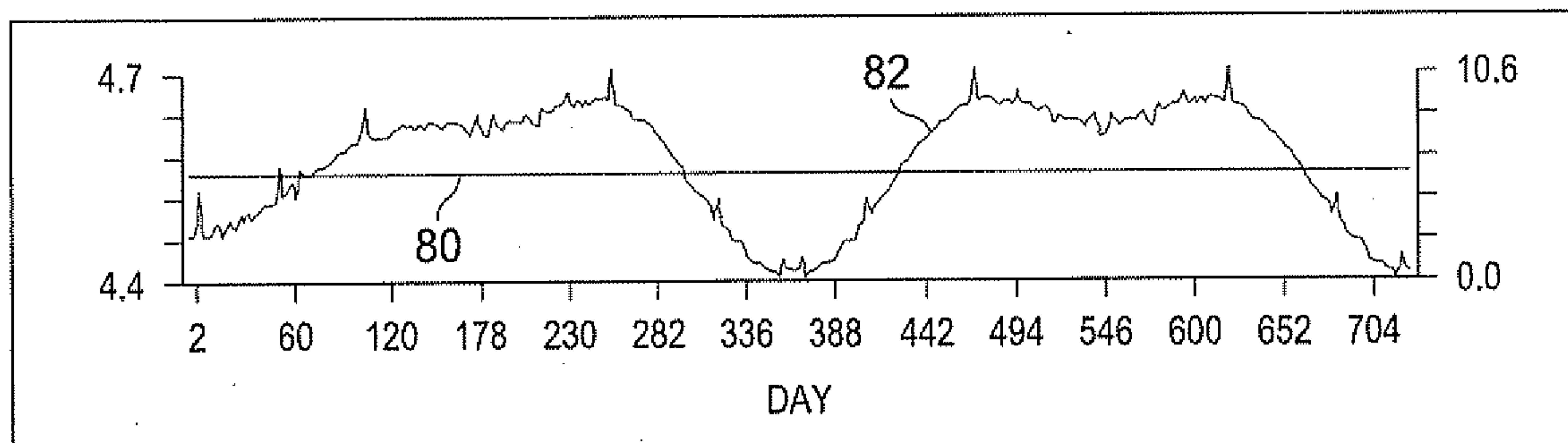


FIG. 8B



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FIG. 9A

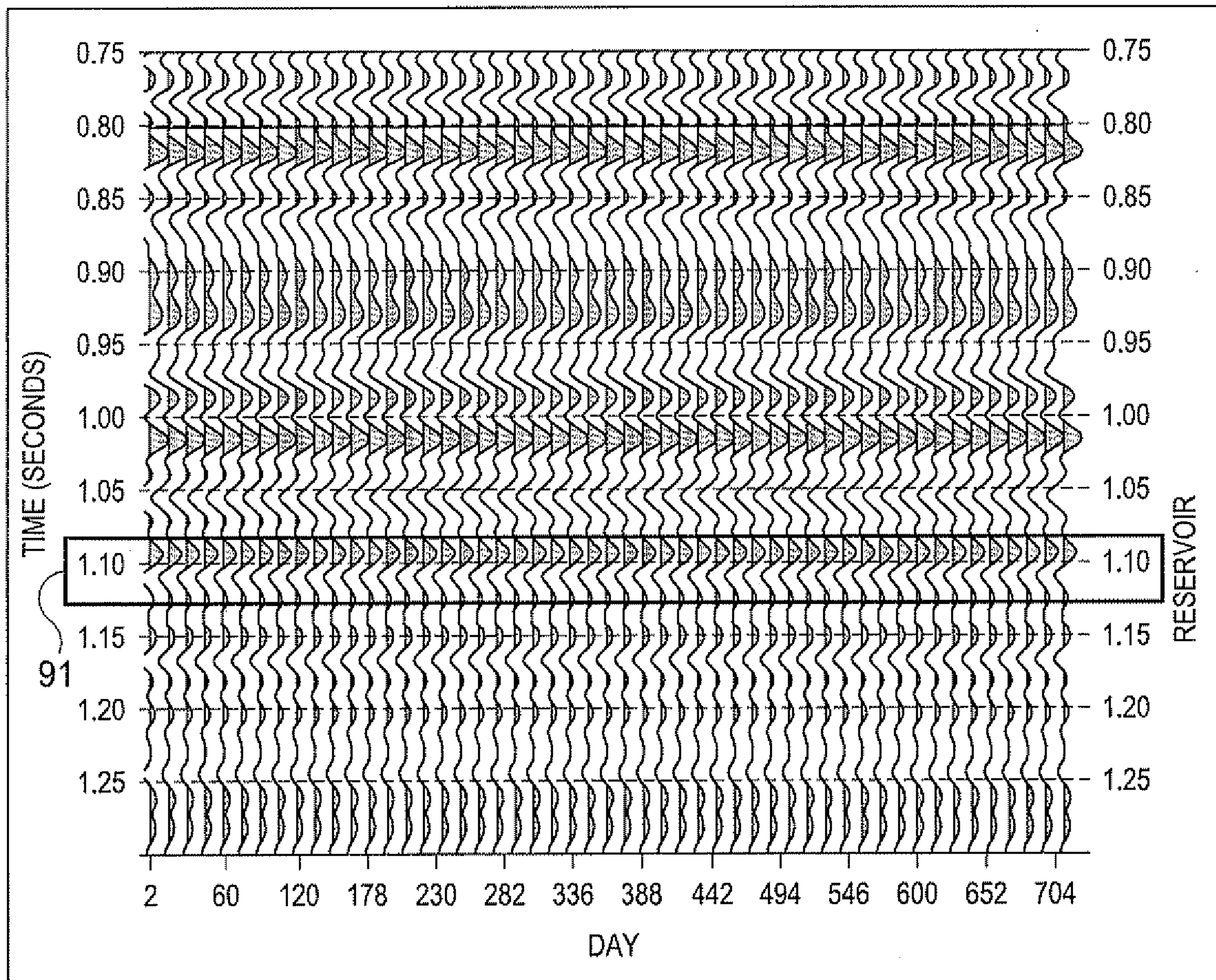
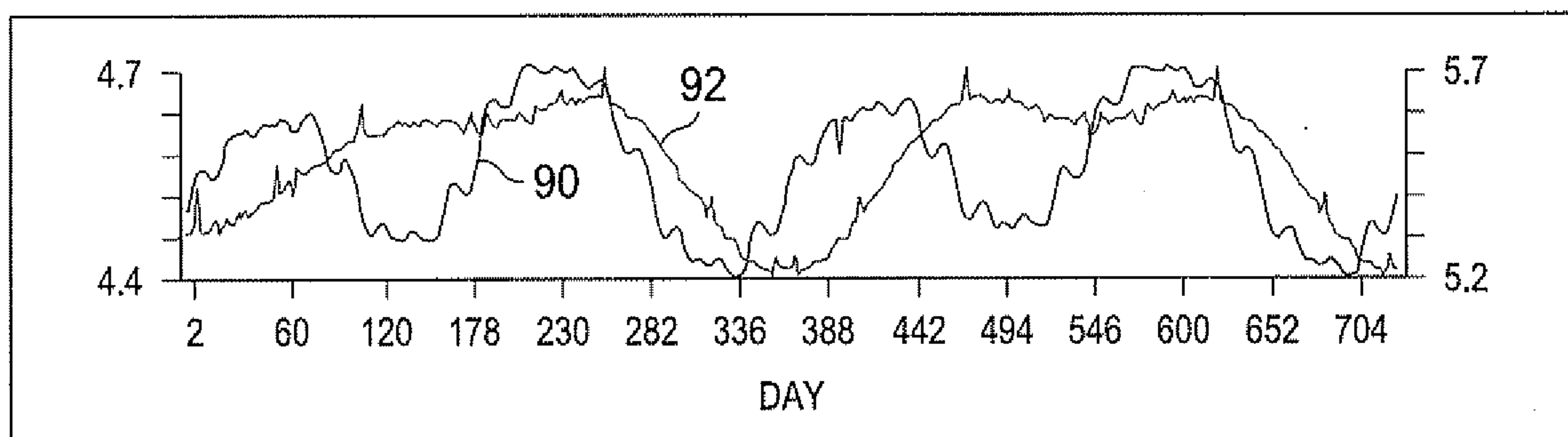


FIG. 9B



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FIG. 10A

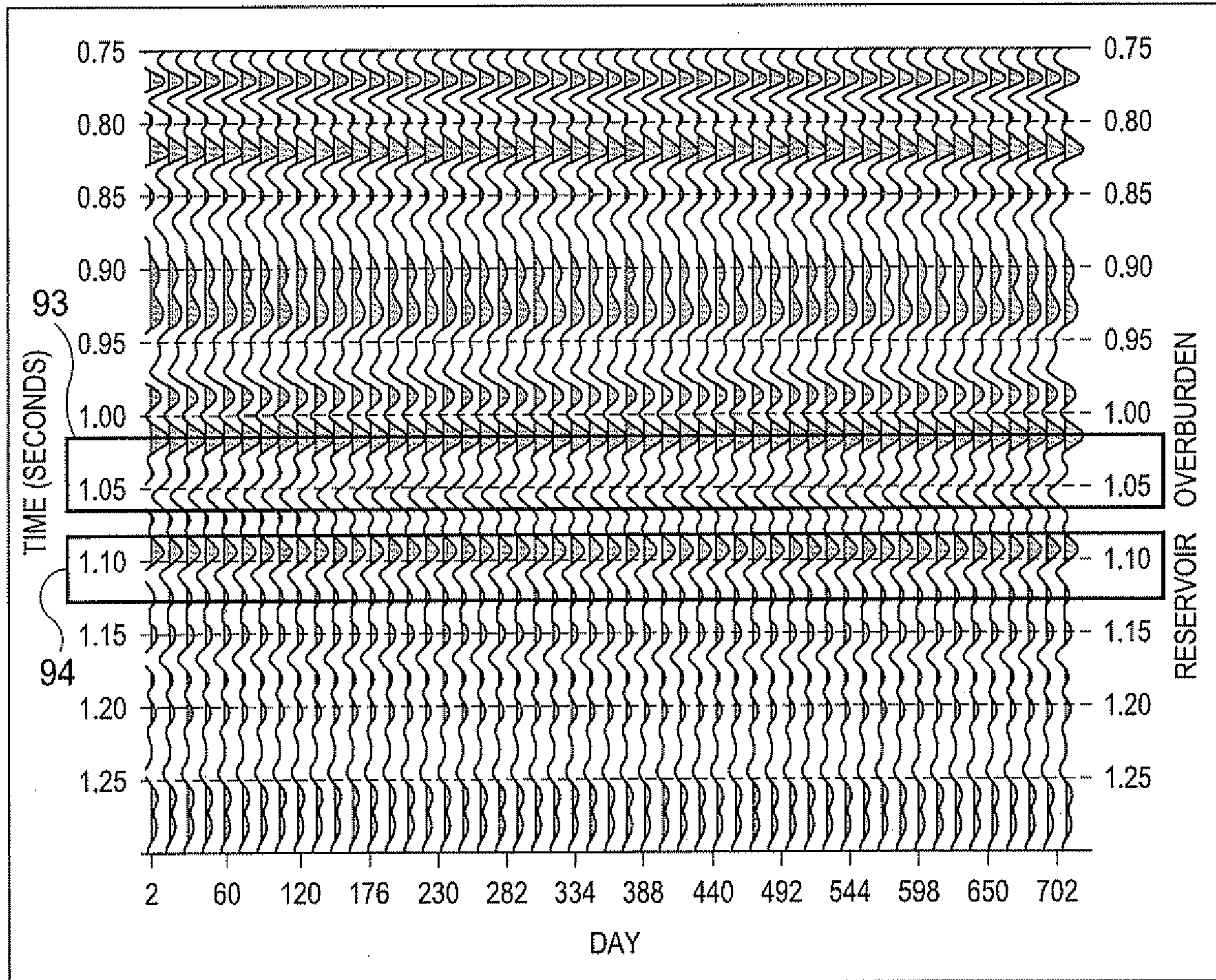
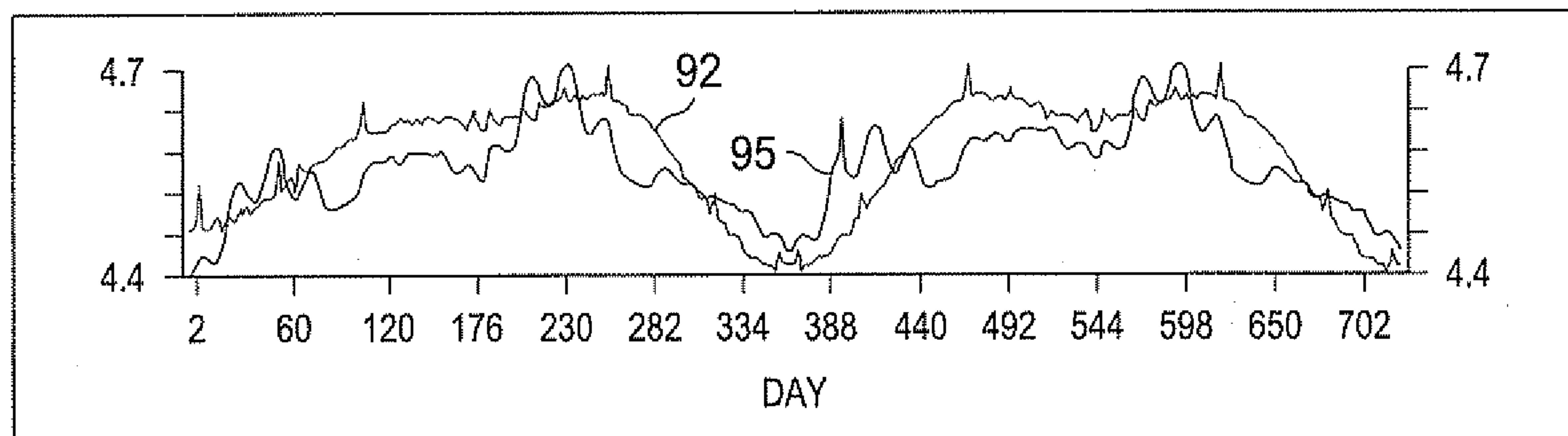


FIG. 10B



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FIG. 11A

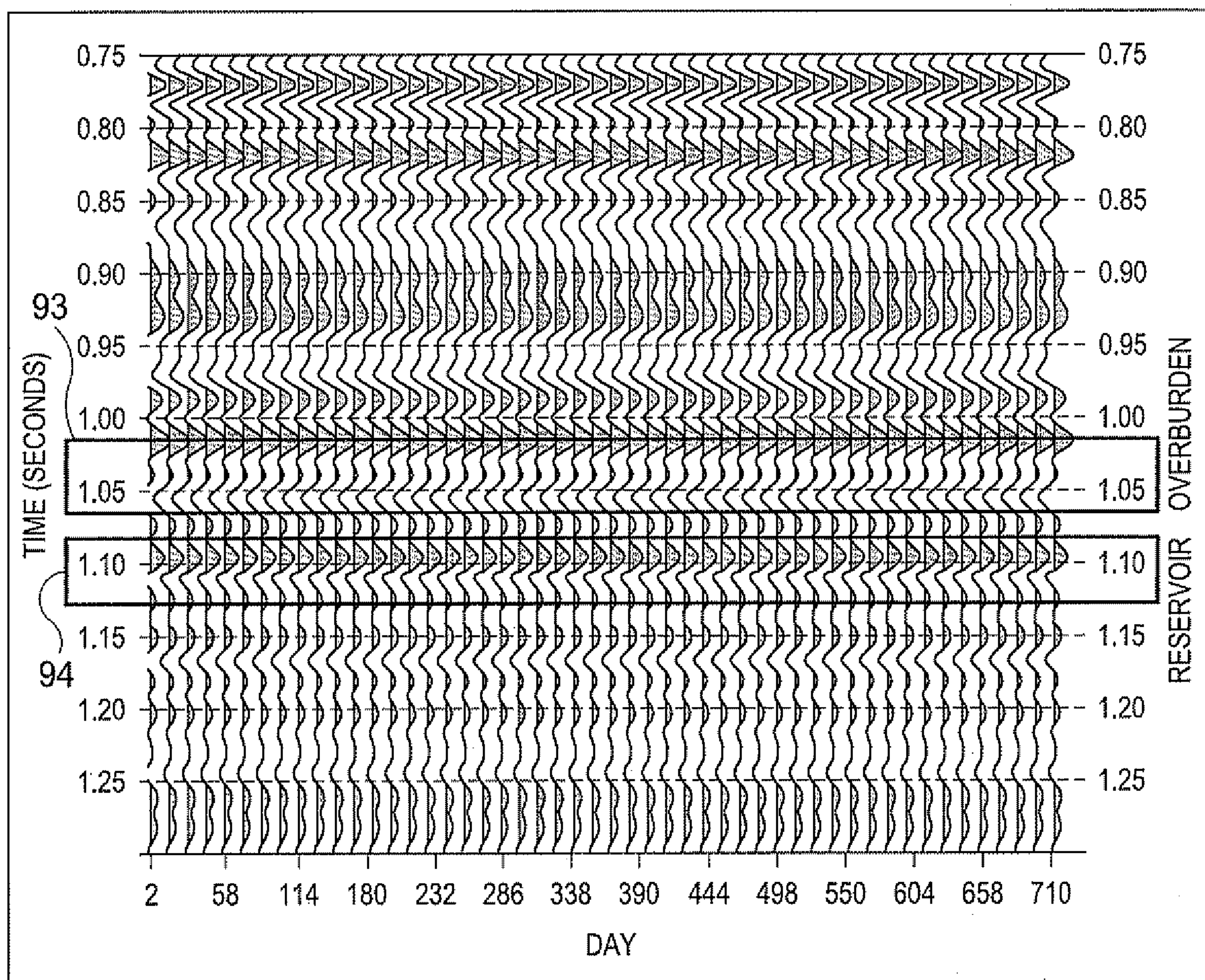
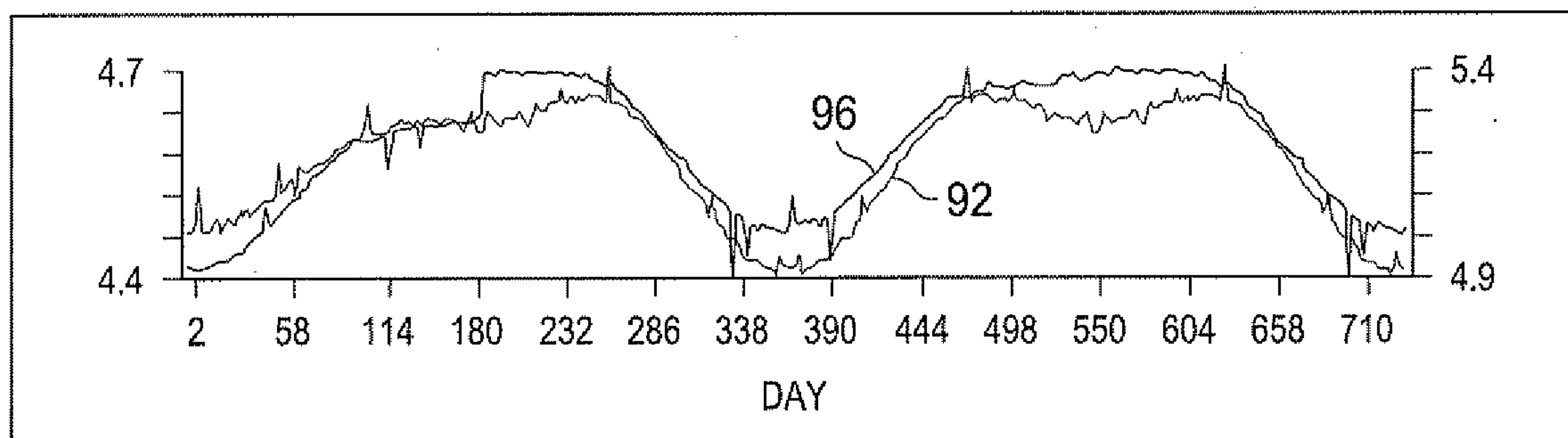


FIG. 11B



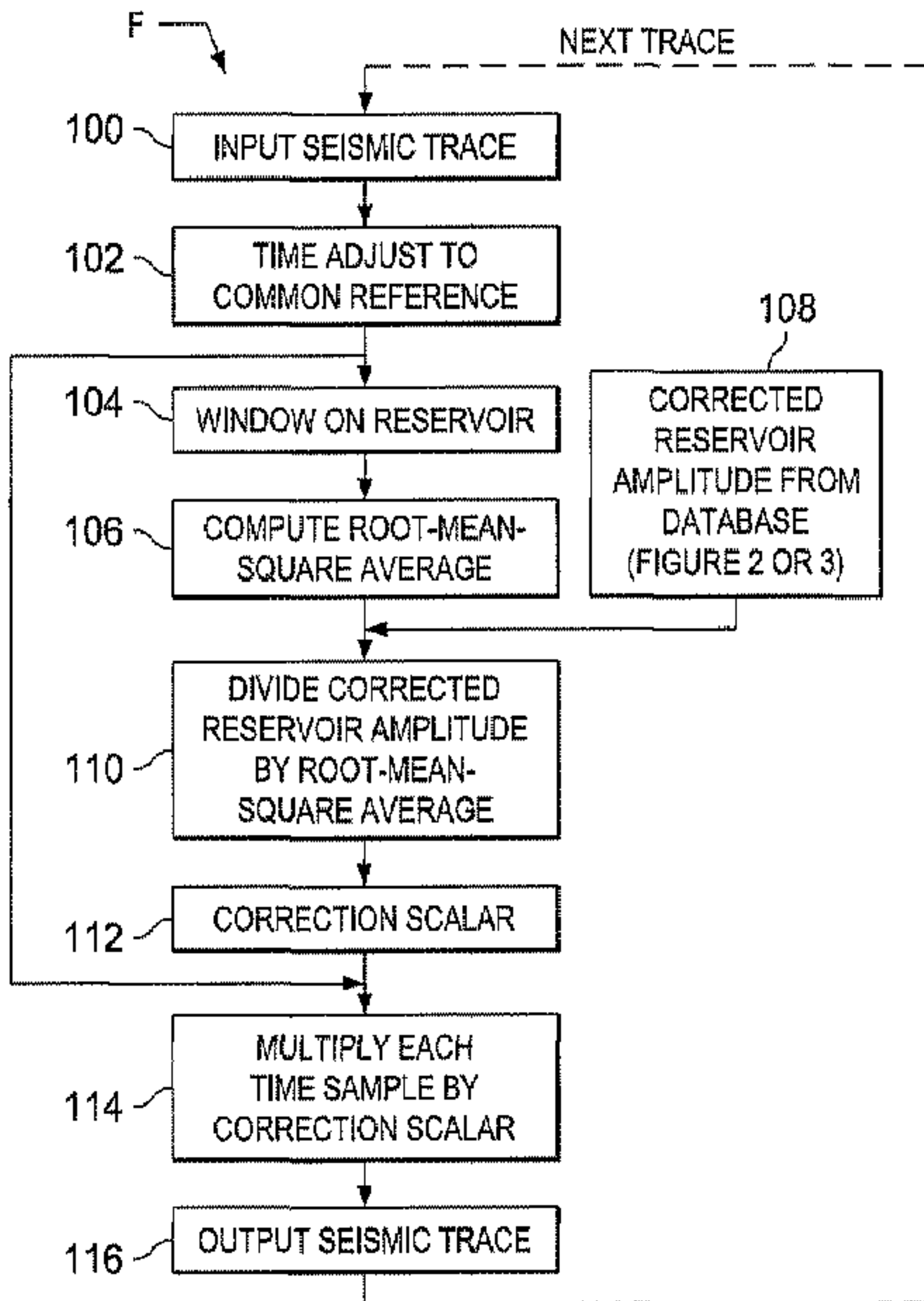


FIG. 1