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(54) Title: METHOD OF MONITORING DEFORMATION OF GEOLOGICAL STRUCTURES AND PREDICTING GEODYNAMIC EVENTS

(57) Abstract

A method of monitoring short-term and long-term deformation changes in a geological space and predicting geodynamic events, such as earthquakes, landslides, dilatations and subsidence events, in a region, said method comprising the steps of performing measurements of one or more hydrosphere parameters using a network of observation wells covering the region, calculating various mathematical parameters and preparing various diagrams, and using the diagrams prepared as a basis for detecting and predicting the time of a possible future geodynamic event.

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Method of monitoring deformation of geological structures and predicting geodynamic events.

The present invention relates to a method of monitoring short-term deformation changes in a geological space and predicting seismic events, such as earthquakes and landslides, in a region.

Geological observations have shown that in the earth's crust volumetric deformation continuously gives rise to the formation and destruction of either compacted or expanded subsurface structures of increased tension or stress-strain (Vartanyan-Kulikov's effect). Such structures are usually formed and destroyed in a matter of days or months, and they are commonly referred to as short living structures of deformation.

Such short living structures may appear all over the globe and they may periodically cover an area of hundreds and sometimes thousands of square kilometers.

As mentioned above short living structures of deformation are formed and destructed continuously, i.e. also during geodynamically quiet periods, and usually in a chaotic manner.

Spatial volumetric stress-strain state microvariations of the lithosphere developing in real time and registered through subsurface variations in hydrosphere parameters are commonly referred to as the hydrogeodeformation (HGD) field. The visualization of the HGD field development is based on the application of special equipment and procedures.

Methods and apparatus, which allow a measurement of the relative deformation of subsurface structures of the order of magnitude of $1 \cdot 10^{-7}$ to $1 \cdot 10^{-9}$, have been developed for use in connection with the monitoring and study of short living structures of deformation.

The invention is characterized in that it comprises the steps of:

(a) performing at different times (t = 0, t = t1) measurements of one or more parameters, X, Y, Z .... in an aquifer in a number

of locations throughout the area of the region using a corresponding number of observation wells;

(b) calculating the Relative Deformation Coefficient, e, for each location and for each parameter X, Y, Z ... on the basis of the measuring values obtained and using the formulas

$$e_{t1} = \frac{X_{t=0}}{X_{t=t1}} \quad (1); \quad e_{t1} = \frac{Y_{t=0}}{Y_{t=t1}} \quad (1); \quad e_{t1} = \frac{Z_{t=0}}{Z_{t=t1}} \quad (1) \ldots$$

wherein

$X_{t=0}$, $Y_{t=0}$, $Z_{t=0}$ are the values of parameter X, Y, Z respectively at time t = 0 (reference time),

$X_{t=t1}$, $Y_{t=t1}$, $Z_{t=t1}$ are the values of parameter X, Y, Z respectively at time t = t1;

(c) preparing a contour map of e-isolines for each parameter X, Y, Z ... on the basis of the calculated e-values and using the contour maps prepared to identify short living deformation structures of potential seismic danger;

(d) calculating the Relative Deformation Parameter, D_e, for each structure having been identified as being of potential seismic danger, said D_e-parameter being defined as

$$D_e = \frac{1}{2 \cdot S_{ref} \cdot e_{ref}} [(e_1+e_2)(S_1-S_2)+(e_2+e_3)(S_2-S_3)+\ldots+(e_{n-1}+e_n)(S_{n-1}-S_n)] \quad (2)$$

wherein e_1, e_2, e_3, ..., e_{n-1} and e_n are e-values of e-isolines in the structure,
S_1, S_2, S_3, ..., S_{n-1} and S_n are the areas delimited by isolines e_1, e_2, e_3, ..., e_{n-1} and e_n respectively,
S_{ref} is a reference area,
e_{ref} is a reference e-value, and
n is a positive integer;

(e) calculating the Parameter of Seismic Attack, A_e, defined as

$$A_e = \frac{\partial D_e}{\partial t} \quad (3), \text{ and}$$

(f) preparing a diagram of D_e vs. t and a diagram of A_e^m vs. t, wherein m is a positive integer, drawing a subsidiary curve through the top points of the peaks of the latter diagram and using the two resulting diagrams in combination as a basis for predicting the time of a possible future seismic event.

The method of the invention has provided a possibility of predicting the time, magnitude and position of a future possible seismic event. In particular, it is very valuable to be able to predict strong and catastrophic seismic events, i.e. seismic events having a Magnitude, M, of 4,5 or higher.

The invention is based on the discovery that by monitoring a HGD-field over vast regions it is possible to assess the state and development of short living structures of deformation and to forecast future seismic events.

Thus, during the period preceding a seismic event, the size of the short living structures of deformation and the intensity of tension within said structures are increasing, thereby forming well-defined bodies within future epicentral zones.

The invention is further based on the discovery that both a D_e-curve and an A_e^m-curve for a given short living structure of deformation has a characteristic course during a build-up within the structure of tension leading to a strong and catastrophic seismic event, and that said two curves in combination can be used to predict the time of a future possible seismic event with high accuracy, i.e. within a matter of days.

The basis of the method of the invention is a system of specialized observation wells, which are used to collect the measurements of parameters X, Y, Z ... . Thus, the observation wells are equipped

with measuring apparatus designed to perform measurements of parameters X, Y, Z ... .

The individual observation wells are preferably connected to a central automatic data processing unit capable of automatically registering, storing and processing all data. Preferably, steps b) - f) of the method of the invention is performed by said data processing unit.

The observation wells are placed throughout the region with due consideration to the dynamic characteristics of individual geological structures and tectonic blocks. Preferably, at least one observation well is used for each mesostructure. In seismic-active regions, preferably at least one well is used for an area of 10,000 square kilometers, whereas in platform regions and other stable regions, at least one well is used for an area of 40,000 square kilometers.

The measuring parameters X, Y, Z ... may be any measurable parameter, such as water level, water pressure, concentration of dissolved chemical substances, equilibrium of chemical substances, concentration of gases, water temperature, electrical conductivity of water, water density, seismic noise, electromagnetic emission, gravity variation or other.

Examples of dissolved chemical substances are Cl^-, F^-, SO_4^{2-} and Li^+.

Examples of gases are CO_2, He, methane, H_2S and Rn (radon).

When measurements of more than one parameter are used to determine an e-value, the individual parameters are evaluated in respect of their relative suitability. The evaluation is made by the user of the method of the invention on the basis of experience, analysis of historical data and knowledge of the measuring uncertainty of the different measuring methods used.

A preferred embodiment of the invention is characterized in using the water level, h, as a measuring parameter and calculating e using

the formula

$$e_{t1} = \frac{h_o}{h_{t1}} \qquad (4)$$

wherein h_o is the water level at t = 0, and
h_{t1} is the water level at t = t1.

The calculated e-values are used to draw up a contour map. The contour map is prepared in a traditional manner by interpolating between the locations at which the e-values have been determined and subsequently drawing e-isolines.

The contour map prepared is used to identify short living deformation structures of potential seismic danger within the region monitored. The identification is made on the basis of observations of the temporal development of the isoline pattern of the structure and of the magnitude of the e-values of the isoline pattern. An isoline pattern having e-values which deviate highly from unity indicates that a large deformation has taken place in the corresponding structure as compared to the reference time t = 0.

Then, the D_e- and A_e-values are calculated for each structure identified as being of potential seismic danger.

The calculated D_e- and A_e-values are then plotted as a function of time in a (t,D_e)-diagram and a (t,A_e^m)-diagram, respectively.

Preferably, a diagram of A_e^m vs. t, wherein m is an even positive integer, is used, and most preferably, a diagram of A_e^m vs. t, wherein m is 2 or 4, is used.

As mentioned above, the D_e-curve and the A_e^m-curve both have a characteristic course, which when the two curves are viewed in combination render it possible to predict a) whether a seismic event will occur and b) if so, the time of said event.

The appearance of said two curves will in part depend on the number

of e-values used in formula (2). Therefore, the same number of e-values must be used in the calculation of each D_e-value of a D_e-curve. However, when a D_e-curve is determined in this manner, the general course and thus the characteristic course will not depend on the number of e-values used in formula (2).

The D_e- and A_e^m-curve for the potentially dangerous short living structures of deformation of the region should be monitored continuously as the general appearance of the HGD-field in a region will change continuously. Thus, at one moment in time a region usually comprises structures with increasing tension as well as structures with decreasing tension, and the tension of a potentially dangerous structure with a D_e-value rising over a period of time may well start to decrease without reaching a critical level. Also, the deformation rates of compaction and expansion for the structures vary greatly as a function of time.

In case the D_e- and A_e^m-curve for a structure show that a seismic event will occur the approximate position of said event, i.e. the epicenter, can be determined. Epicenters of seismic events coincide either with the axial zones of short living structures of expansion or, in the case of a region comprising two relatively closely situated short living structures of deformation one of which is expanding and one of which is compacting, with the interface zones of high tension gradient between said two structures.

In any event the tectonic conditions of the region in question should be taken into consideration when determining the epicenter, since when the earth's crust of the region contains e.g. a fault, the epicenter is likely to be situated within the fault zone.

Furthermore, the intensity of a future seismic event predicted can be assessed from the magnitude of the parameter D_e. Thus, the higher D_e-value, the higher Magnitude, M.

In the following, the invention is described in further detail with reference to the drawings, wherein

Fig. 1 shows two examples of typical D_e-curves having a similar

course,

Fig. 2 shows an example of a typical A_e^m-curve,

Figs. 3-5 show contour maps of the region, in which the Spitak earthquake occurred in 1988, for three different dates,

Fig. 6 shows a diagram of D_e vs. t for the period during which the Spitak earthquake occurred,

Fig. 7 shows a diagram of A_e^2 vs. t for the period during which the Spitak earthquake occured, the diagram being supplemented with a subsidiary curve E drawn through the top points of the peaks,

Figs. 8- 16 show contour maps of the region, in which the Loma Prieta earthquake occurred in 1989, for nine different dates,

Fig. 17 shows a diagram of D_e vs. t for the period during which the Loma Prieta earthquake occured,

Fig. 18 shows a diagram of A_e^2 vs. t for the period during which the Loma Prieta earthquake occurred, the diagram being supplemented with a subsidiary curve E drawn through the top points of the peaks,

Fig. 19 shows a diagram of K_e vs. t for the period during which the Spitak earthquake occurred,

Fig. 20 shows a diagram of K_e' vs. t for the period during which the Spitak earthquake occurred, and

Fig. 21-29 show diagrams of Δg_{av} vs. K_e for nine different dates in the period during which the Spitak earthquake occurred.

In the following, the manner of interpreting the D_e- and A_e^m-curve is described in further detail with reference to Figs. 1 and 2.

As mentioned above both the D_e-curve and the A_e^m-curve have a characteristic course during the build-up of an earthquake.

In the following it is explained how the time of a future earthquake may be determined from said curves.

As will appear from Fig. 1, the D_e-curve increases in phase A corresponding to a build-up of tension within the structure observed. At the end of phase A, the D_e-curve reaches a local maximum LM at $t = t_s$, after which the D_e-curve decreases sharply and markedly during the first stage of phase B. In the last stage of phase B the D_e-curve may decrease vaguely or rise sharply depending on the nature of the structure in question. At the end of phase B, i.e. at $t = t_e$, an earthquake will occur and empirical data have shown that the duration of phase B is from about 3 days to about 10 days.

During the period of phase B, the tension resistance limit of the structure is reached, and fissuring of the structure is initiated.

As will appear from Fig. 2, the A_e^2-curve comprises a number of high peaks having a progressively increasing height with time and progressively diminishing intervals with time. In the time periods lying between the peaks only relatively small values of the A_e^2-parameter are occuring.

As mentioned above an A_e^m-curve, wherein m is 2 or 4 is preferably used. Such curves are used in order to reduce the influence of errors due to measuring noise, which will influence values of A_e lying between the peaks. These values are usually smaller than 1. A m-value of 2 or 4 further increases the heights of the peaks, the A_e-values of which usually are higher than 1. Also, it is convenient to use curves having only positive values.

The physical meaning of the peaks of the A_e^m-curve is that at those moments the rate of deformation of the structure in question is especially high.

If a curve is drawn through the top points of the peaks, a curve having approximately the course of an exponential function is

obtained (curve E, Fig. 2). The part of the E-curve, where the direction of the tangent is approximately vertical (part S of the E-curve), corresponds to the local maximum LM of the D_e-curve and thus from the time corresponding to point S of the E-curve, i.e. from $t = t_s$, an earthquake will occur within a period of from about 3 days to about 10 days as it has been shown empirically.

As mentioned above, the D_e-curve and A_e^m-curve must be used in combination in order to make a certain and accurate prediction of the time of a future seismic event. Thus, the D_e-curve alone is not a sufficient basis for making such a prediction, since the D_e-curve having the general course described above exhibits an irregular zig-zag pattern in said general course, and correspondingly the D_e-curve exhibits a large number of sharp declines, which may be mistaken for the first stage of phase B.

The above-mentioned zig-zag pattern of the D_e-curve is due to fluctuating influences of small magnitude, such as gravitational influences (daily tidal fluctuations) and barometric pressure influences, whereas the general course of the D_e-curve is determined by endogenic influences, i.e. the build-up of tension within the structure due to compacting or expanding of the structure.

In the monitoring and assessment of the state of the structure, it is the sum of the individual natural and anthropogenic, if any, influences, i.e. the resulting influence, exerted on the structure, which should be taken into account, and the D_e-parameter expresses the response of the structure on precisely said resulting influence.

Examples of anthropogenic influences include the influence of high pressure dams, which increase the pressure exerted on subsurface structures, and the extraction of oil, gas and other fluids from subsurface structures.

In connection with the present invention the expression "short-term changes" means changes developing within a structure over a period of days to months.

Furthermore, the terms "D_e-curve" and "A_e^m-curve" refer to a curve

of a diagram of D_e vs. t and a curve of a diagram of A_e^m vs. t, respectively.

The invention further relates to a method of monitoring long-term geodynamic processes, such as slow "earth-quakes", long-term dilatations, plastic deformation of rocks and subsidence events, in a region.

This further method of the invention is characterized in that it comprises the steps of:

(o) performing at different times (t = 0, t = t1) measurements of one or more parameters X, Y, Z ... in an aquifer in a number of locations throughout the area of the region using a corresponding number of observation wells;

(p) performing measurements in a number of locations throughout the area of the region of gravity change, Δg_1, Δg_2, ..., Δg_k, wherein k is a positive integer, and calculating the average gravity change, Δg_{av};

(q) calculating the Relative Deformation Coefficient, e, for each location and for each parameter X, Y, Z ... on the basis of the measuring values obtained and using the formulas

$$e_{t1} = \frac{X_{t=0}}{X_{t=t1}} \quad (1); \quad e_{t1} = \frac{Y_{t=0}}{X_{t=t1}} \quad (1); \quad e_{t1} = \frac{Z_{t=0}}{Z_{t=t1}} \quad (1) \ldots$$

wherein

$X_{t=0}$, $Y_{t=0}$, $Z_{t=0}$ are the values of parameter X, Y, Z respectively at time t = 0 (reference time),

$X_{t=t1}$, $Y_{t=t1}$, $Z_{t=t1}$ are the values of parameter X, Y, Z respectively at time t = t1;

(r) calculating the Parameter of Imbalanced Deformation K_e for the region, said K_e-parameter being defined as

$$K_e = \frac{e_{p,\ t1} + e_{c,\ t1} - 2}{e_{p,\ t1} - e_{c,\ t1}} \qquad (5)$$

wherein

$e_{p,\ t1}$ is the average e-value at t = t1 for all locations showing expansion (e > 1),

$e_{c,\ t1}$ is the average e-value at t = t1 for all locations showing compaction (e < 1);

(s) preparing a diagram of K_e vs.t, a diagram of $K_e' = \frac{\partial K_e}{\partial t}$ vs.t and a diagram of Δg_{av} vs. K_e and using the three diagrams in combination as a basis for detecting possible future geodynamic events.

This further method according to the invention is based on the discovery that by monitoring HGD-fields over vast regions it is possible to assess the state and development of short living structures of deformation and to forecast future geodynamic events.

Also, the further method according to the invention is based on the discovery that the K_e-parameter expresses the overall tendency of the whole region monitored in respect of expansion and compaction and that the K_e-parameter may therefore be used as a means of monitoring long-term deformation changes within the region.

Finally, the further method of the invention is based on the discovery that a (K_e, Δg_{av})-curve has a characteristic course during a period preceding a major geodynamic event of the type mentioned above, and that a K_e-curve, a K_e'-curve and a (K_e, Δg_{av})-curve in combination can be used to detect and forecast possible future geodynamic events.

The further method according to the invention is e.g. useful in identifying the existence of risk zones of geodynamic activity near industrial installations of particular safety and environmental

risks, and in performing a continuous monitoring of said zones in order to detect long-term changes of safety-risk. Thus, said method provides the user thereof with such information, which allows him to take precautions in order to minimize potential damages on existing industrial installations of said type and to select the most suitable site for positioning a new industrial installation. Such industrial installations include bridges, tunnels, nuclear power plants, high pressure head dams, sites for disposal of highly toxic and radioactive waste materials, mines serving as sites for waste material disposal, chemical plants, oil refineries, underground gas and oil tanks etc.

The K_e-values are in the range of -1 to +1, and negative and positive values signify an overall tendency in the region monitored of compaction or expansion, respectively.

The K_e'-parameter expresses the rate of deformation for the region taken as a whole, and the K_e'-curve serves to make it possible to identify the periods during which said rate is high. The K_e'-curve usually comprise a number of peaks corresponding to the periods of high deformation rate and a number of interjacent parts having relative small values of K_e'.

Solar and lunar influences give rise to variations in gravity for subsurface structures. When a subsurface structure is in its relaxed state, i.e. when the tension of the structure is non-existing or small, a (K_e, Δg_{av})-curve for a period of one day (24 hours) will have the approximate form of an ellipse elongated in the direction of the K_e-axis, the curve starting and ending at approximately the same point.

However, it has now been shown that during a period preceding a major geodynamic event of the type mentioned above, the shape of the (K_e, Δg_{av})-curve changes in such a manner that the curve becomes elongated in the direction of the Δg_{av}-axis and that the curve becomes irregular or even chaotic in shape. Such a change signifies that the subsurface structure monitored has lost its elasticity.

The information derivable from the K_e-curve, K_e'-curve and (K_e,

Δg_{av},)-curve in combination allows the user of the present method to make an evaluation of the level of geodynamic activity in the region and to assess the state of the structures in the region with respect to accumulated tension and thus to assess the risk level of the region in respect of geodynamic events. Thus, it allows the user to identify the geodynamically most stable region of a territory and to forecast future geodynamic events within the region monitored.

When the further method of the invention is used to select the most suitable site for positioning a new industrial installation within a territory, the territory is preferably divided into two or more regions, and then analogue diagrams of K_e vs.t, K_e' vs.t and Δg_{av} vs. K_e are prepared for each region. Then, the geodynamically most stable and safe region may be identified by comparing said three diagrams of each region with the diagrams of other regions.

A preferred embodiment of the further method according to the invention is characterized in

(t) preparing a contour map of e-isolines for each parameter X, Y, Z ... on the basis of the calculated e-values and using the contour maps prepared as an additional information forming the basis for detecting possible future geodynamic events.

In connection with the present invention, the expression "long-term changes" means changes developing within a structure over a period of one year or more.

Furthermore, the terms "K_e-curve", "K_e'-curve" and "(K_e, Δg_{av})-curve" refer to a curve of a diagram of K_e vs.t, a diagram of K_e' vs.t and a diagram of Δg_{av} vs. K_e, respectively.

The K_e-value may also be used in the method of the invention described in the first part of this specification.

Thus, another preferred embodiment of said method of the invention is characterized in

(g) performing measurements in a number of locations throughout the

area of the region of gravity change, Δg_1, Δg_2, ..., Δg_k, wherein k is a positive integer, and calculating the average gravity change, Δg_{av};

(h) calculating the Parameter of Imbalanced Deformation K_e for the region, said K_e-parameter being defined as

$$K_e = \frac{e_{p,\ t1} + e_{c,\ t1}}{e_{p,\ t1} - e_{c,\ t1}}^{2} \qquad (5)$$

wherein

$e_{p,\ t1}$ is the average e-value at t = t1 for all locations showing expansion (e > 1),

$e_{c,\ t1}$ is the average e-value at t = t1 for all locations showing compaction (e < 1);

(i) preparing a diagram of K_e vs.t, a diagram of $K_e' = \frac{\partial K_e}{\partial t}$ vs.t

and a diagram of Δg_{av} vs. K_e and using the three diagrams in combination as an additional information forming the basis for predicting possible future seismic events.

The physical meaning of the parameters K_e, K_e' and Δg_{av}, the manner of preparing diagrams of K_e, vs.t, K_e' vs.t and Δg_{av} vs. K_e and the nature of information derivable from said diagrams are explained above.

This information is also valuable in the process of interpreting and making predictions of possible, future seismic events from the D_e- and A_e^m-curve.

In both methods of the invention, a central automatic data processing unit is preferably used to register and store all measuring values and to automatically perform all the subsequent calculations and preparations of contour maps and various diagrams.

In the following, the methods of in the invention will be described in further detail with reference to the examples below.

Example 1

During a period from August 1988 to December 1988, a region covering the southern part of Georgia and the northern part of Armenia was monitored using a number of observation wells to measure the water level in an aquifer of the region. On December 7, 1988 the so-called Spitak earthquake having a Magnitude, M, of 6.9 occurred.

On the basis of the measuring values and using an integrated central computer system the e-values were calculated, contour maps were prepared, D_e- and A_e-values were calculated and diagrams of D_e vs.t and A_e^2 vs. t were prepared and subsidiary curves E were drawn through the points of the peaks of the diagrams of the latter type.

Figs. 3-5 shows contour maps of the region monitored for August 10, 1988, December 7, 1988 and December 10, 1988, respectively. In the Figures, observation wells are indicated with dots, and the Figures show the e-isolines and indicate e-values for both observations wells and e-isolines.

Figs. 6 and 7 show diagrams of D_e vs. t and A_e^2 vs.t, respectively, for the period from August 1988 to December 1988, the latter diagram being supplemented with a subsidiary curve E drawn through the top points of the peaks.

As will appear from the contour maps, a short living structure of expansion has developed during the period from August 10, 1988 to December 7, 1988 the date of the Spitak earthquake, at which date the tension of the structure is very high, the center of the structure having an e-value of 1,968. Three days later, on December 10, 1988 the tension of the structure has decreased somewhat. The epicenter of the earthquake is located near the centre of the structure in the axial zone thereof.

From Fig. 6 the time t_s after which an earthquake will occur within a period of from about 3 to about 10 days may be found as the time

corresponding to the local maximum LM of the D_e-curve, and t_s is found to be approximately November 27, 1988.

Also, from Fig. 7 the t_s-value may be found as the time corresponding to the part S of the E-curve having a tangent, which is approximately vertical, and t_s is found to be approximately December 3, 1988.

As will appear from the above there is a time difference between the two t_s-values determined from the D_e-curve and the A_e^2-curve, respectively, and this shows the significance of using both curves in order to make a reliable determination of t_s.

Example 2

During a period from July 1989 to November 1989, a region covering the territories located adjacent to the San Andreas fault in California, U.S.A. was monitored using a number of observation wells to measure the water level in an aquifer of the region. On October 18, 1989 the so-called Loma Prieta earthquake having a Magnitude, M, of 7.1 occurred.

On the basis of the measuring values and using an integrated central computer system the e-values were calculated, contour maps were prepared, D_e- and A_e-values were calculated and diagrams of D_e vs.t and A_e^2 vs. t were prepared and subsidiary curves E were drawn through the points of the peaks of the diagrams of the latter type.

Figs. 8-16 show contour maps of the region for a number of dates over the above mentioned period of time. In the Figures, observation wells are indicated by dots and the thick intersecting line indicates the San Andreas fault, and the Figures show e-isolines and indicate the e-values thereof.

Figs. 17 and 18 show diagrams of D_e vs.t and A_e^2 vs.t, respectively, for the period of September and October 1989, the latter diagram being supplemented with a subsiary curve E drawn through the top points of the peaks.

As will appear from the contour maps, tension is building up in the region in the period preceding October 18, 1989, the date of the Loma Prieta earthquake. The region comprises a zone of expansion (e-values above unity) having two centres located approximately at observation wells 10a and 7 and a zone of compaction (e-values below unity).

From Fig. 17 the time t_s after which an earthquake will occur within a period of from about 3 to about 10 days may be found as the time corresponding to the local maximum LM of the D_e-curve, and t_s is found to be approximately October 8, 1989.

Also, from Fig. 18 the t_s-value may be found as the time corresponding to the part S of the E-curve having a tangent, which is approximately vertical, and t_s is found to be approximately October 13, 1989.

Example 3

During a period from October 1988 to June 1989, a region covering the southern part of Georgia and the northern part of Armenia was monitored using a number of observation wells to measure the water level in an aquifer of the region. On December 7, 1988 the so-called Spitak earthquake having a Magnitude, M, of 6.9 occurred.

On the basis of the measuring values and using an integrated central computer system the Δg_{av}-values, the e-values, the K_e-values and the K_e'-values were calculated and diagrams of K_e vs. t. K_e' vs. t and Δg_{av} vs. K_e were prepared.

Fig. 19 shows a diagram of K_e vs. t for the period from the beginning of October 1988 to the end of June 1989.

As will appear from the K_e-curve, in the period preceding the earthquake compaction is going on in the region, the K_e-values being negative. Approximately at the time of the earthquake, the overall tendency of the region changes from compaction to expansion corresponding to a release of tension accumulated in the period of compaction, said release being effected through the earthquake. In

the period following the earthquake expansion continues.

Fig. 20 shows a diagram of K_e' vs. t for the period from November 25, 1988 to December 10, 1988. The small vertical arrows signify times of earth tremors and the large vertical arrow signifies the time of the earthquake.

As will appear from the K_e'-curve, the rate of deformation is very high on December 3, 1992 four days prior to the earthquake.

Figs. 21-29 show diagrams of Δg_{av} vs. K_e for nine different dates during the period from August 1986 to December 1988.

In the following, reference to the (K_e, Δg_{av})-curves of Figs. 21-29 is made. On August 19, 1986 (Fig. 21) the curve had a substantially oval shape elongated in the direction of the K_e-axis. On October 25 and 26, 1988 (Fig. 22 and 23) the curve assumed a substantially oval shape elongated in the direction of the Δg_{av}-axis. This irregular shape of the curve means that the elasticity of the subsurface structure monitored is reduced due to a build-up of tension in the structure.

On November 27, 1988 (Fig. 25) and December 6, 1988 (Fig. 26), the curve assumed the approximate shape of two closely adjacent lines having an orientation in the direction of the Δg_{av}-axis, the shape signifying an almost complete loss of elasticity of the structure.

On December 7, 1988 (Fig. 27), the day of the Spitak earthquake, the two lines of the curve have become more spaced, the curve having a U-shape. This shape signifies that the tension of the structure has decreased partly.

On December 8 and 9, 1988 (Fig. 28 and 29) the curve had regained an irregular oval shape signifying the fact that the structure had regained most of its initial elasticity, i.e. the accumulated tension of the structure had been released through the earthquake.

C L A I M S

1. A method of monitoring short-term deformation changes in a geological space and predicting seismic events, such as earthquakes and landslides, in a region, c h a r a c t e r i z e d in that it comprises the steps of:

(a) performing at different times (t = 0, t = t1) measurements of one or more parameters, X, Y, Z .... in an aquifer in a number of locations throughout the area of the region using a corresponding number of observation wells;

(b) calculating the Relative Deformation Coefficient, e, for each location and for each parameter X, Y, Z ... on the basis of the measuring values obtained and using the formulas

$$e_{t1} = \frac{X_{t=0}}{X_{t=t1}} \quad (1); \quad e_{t1} = \frac{Y_{t=0}}{Y_{t=t1}} \quad (1); \quad e_{t1} = \frac{Z_{t=0}}{Z_{t=t1}} \quad (1) \ldots$$

wherein

$X_{t=0}$, $Y_{t=0}$, $Z_{t=0}$ are the values of parameter X, Y, Z respectively at time t = 0 (reference time),

$X_{t=t1}$, $Y_{t=t1}$, $Z_{t=t1}$ are the values of parameter X, Y, Z respectively at time t = t1;

(c) preparing a contour map of e-isolines for each parameter X, Y, Z ... on the basis of the calculated e-values and using the contour maps prepared to identify short living deformation structures of potential seismic danger;

(d) calculating the Relative Deformation Parameter, D_e, for each structure having been identified as being of potential seismic danger, said D_e-parameter being defined as

$$D_e = \frac{1}{2 \cdot S_{ref} \cdot e_{ref}} [(e_1+e_2)(S_1-S_2)+(e_2+e_3)(S_2-S_3)+\ldots+(e_{n-1}+e_n)(S_{n-1}-S_n)] \quad (2)$$

wherein e_1, e_2, e_3, ..., e_{n-1} and e_n are e-values of e-isolines in the structure,

S_1, S_2, S_3, ..., S_{n-1} and S_n are the areas delimited by isolines e_1, e_2, e_3, ..., e_{n-1} and e_n respectively,

S_{ref} is a reference area,

e_{ref} is a reference e-value, and

n is a positive integer;

(e) calculating the Parameter of Seismic Attack, A_e, defined as

$$A_e = \frac{\partial D_e}{\partial t} \quad (3), \text{ and}$$

(f) preparing a diagram of D_e vs. t and a diagram of A_e^m vs. t, wherein m is a positive integer, drawing a subsidiary curve E through the top points of the peaks of the latter diagram and using the two resulting diagrams in combination as a basis for predicting the time of a possible future seismic event.

2. A method according to claim 1, characterized in using as measuring parameters X, Y, Z ... one or more of the parameters water level, water pressure, concentration of dissolved chemical substances, equilibrium of chemical substances, concentration of gases, water temperature, electrical conductivity of water, water density, seismic noise, electromagnetic emission, gravity variation or other.

3. A method according to claim 2, characterized in using the water level, h, as a measuring parameter and calculating e using the formula

$$e_{t1} = \frac{h_o}{h_{t1}} \quad (4)$$

wherein

h_0 is the water level at t = 0, and
h_{t1} is the water level at t = t1.

4. A method according to any of the preceding claims, characterized in using a diagram of A_e^m vs. t, wherein m is a positive, even integer.

5. A method according to claim 4, characterized in using a diagram of A_e^m vs. t, wherein m is 2 or 4.

6. A method according to any of the preceding claims, characterized in

(g) performing measurements in a number of locations throughout the area of the region of gravity change, Δg_1, Δg_2, ..., Δg_k, wherein k is a positive integer, and calculating the average gravity change, Δg_{av};

(h) calculating the Parameter of Imbalanced Deformation K_e for the region, said K_e-parameter being defined as

$$K_e = \frac{e_{p,\,t1} + e_{c,\,t1} - 2}{e_{p,\,t1} - e_{c,\,t1}} \qquad (5)$$

wherein

$e_{p,\,t1}$ is the average e-value at t = t1 for all locations showing expansion (e > 1),
$e_{c,\,t1}$ is the average e-value at t = t1 for all locations showing compaction (e < 1);

(i) preparing a diagram of K_e vs.t, a diagram of $K_e' = \frac{\partial K_e}{\partial t}$ vs.t

and a diagram of Δg_{av} vs. K_e and using the three diagrams in combination as an additional information forming the basis for predicting possible future seismic events.

7. A method of monitoring long-term geodynamic processes in a region, c h a r a c t e r i z e d in that it comprises the steps of:

(o) performing at different times (t = 0, t = t1) measurements of one or more parameters X, Y, Z ... in an aquifer in a number of locations throughout the area of the region using a corresponding number of observation wells;

(p) performing measurements in a number of locations throughout the area of the region of gravity change, Δg_1, Δg_2, ..., Δg_k, wherein k is a positive integer, and calculating the average gravity change, Δg_{av};

(q) calculating the Relative Deformation Coefficient, e, for each location and for each parameter X, Y, Z ... on the basis of the measuring values obtained and using the formulas

$$e_{t1} = \frac{X_{t=0}}{X_{t=t1}} \quad (1); \quad e_{t1} \frac{Y_{t=0}}{X_{t=t1}} \quad (1); \quad e_{t1} = \frac{Z_{t=0}}{Z_{t=t1}} \quad (1) \ldots$$

wherein

$X_{t=0}$, $Y_{t=0}$, $Z_{t=0}$ are the values of parameter X, Y, Z respectively at time t = 0 (reference time),

$X_{t=t1}$, $Y_{t=t1}$, $Z_{t=t1}$ are the values of parameter X, Y, Z respectively at time t = t1;

(r) calculating the Parameter of Imbalanced Deformation K_e for the region, said K_e-parameter being defined as

$$K_e = \frac{e_{p,\ t1} + e_{c,\ t1} - 2}{e_{p,\ t1} - e_{c,\ t1}} \quad (5)$$

wherein

$e_{p,\ t1}$ is the average e-value at t = t1 for all locations showing expansion (e > 1),

$e_{c,\ t1}$ is the average e-value at t = t1 for all locations

showing compaction ($e < 1$);

(s) preparing a diagram of K_e vs.t, a diagram of $K_e' = \frac{\partial K_e}{\partial t}$ vs.t and a diagram of Δg_{av} vs. K_e and using the three diagrams in combination as a basis for detecting possible future geodynamic events.

8. A method according to claim 7, c h a r a c t e r i z e d in preparing a contour map of e-isolines for each parameter X, Y, Z ... on the basis of the calculated e-values and using the contour maps prepared as an additional information forming the basis for detecting possible future geodynamic events.

9. A method according to any of the preceding claims, c h a r a c t e r i z e d in using a central automatic data processing unit to register and store all measuring values and to automatically perform all the subsequent calculations and preparations of contour maps and various diagrams.

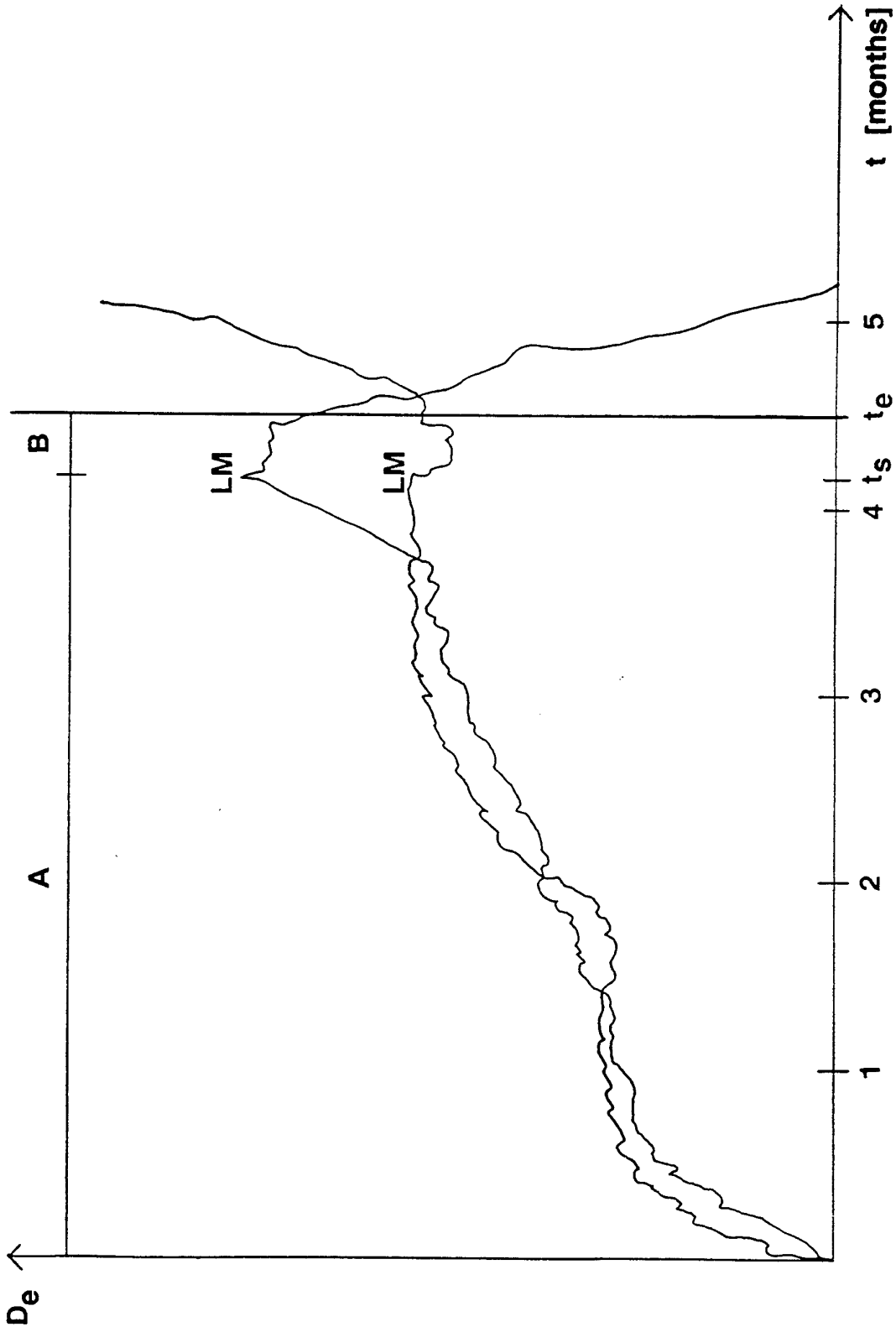


FIG.1

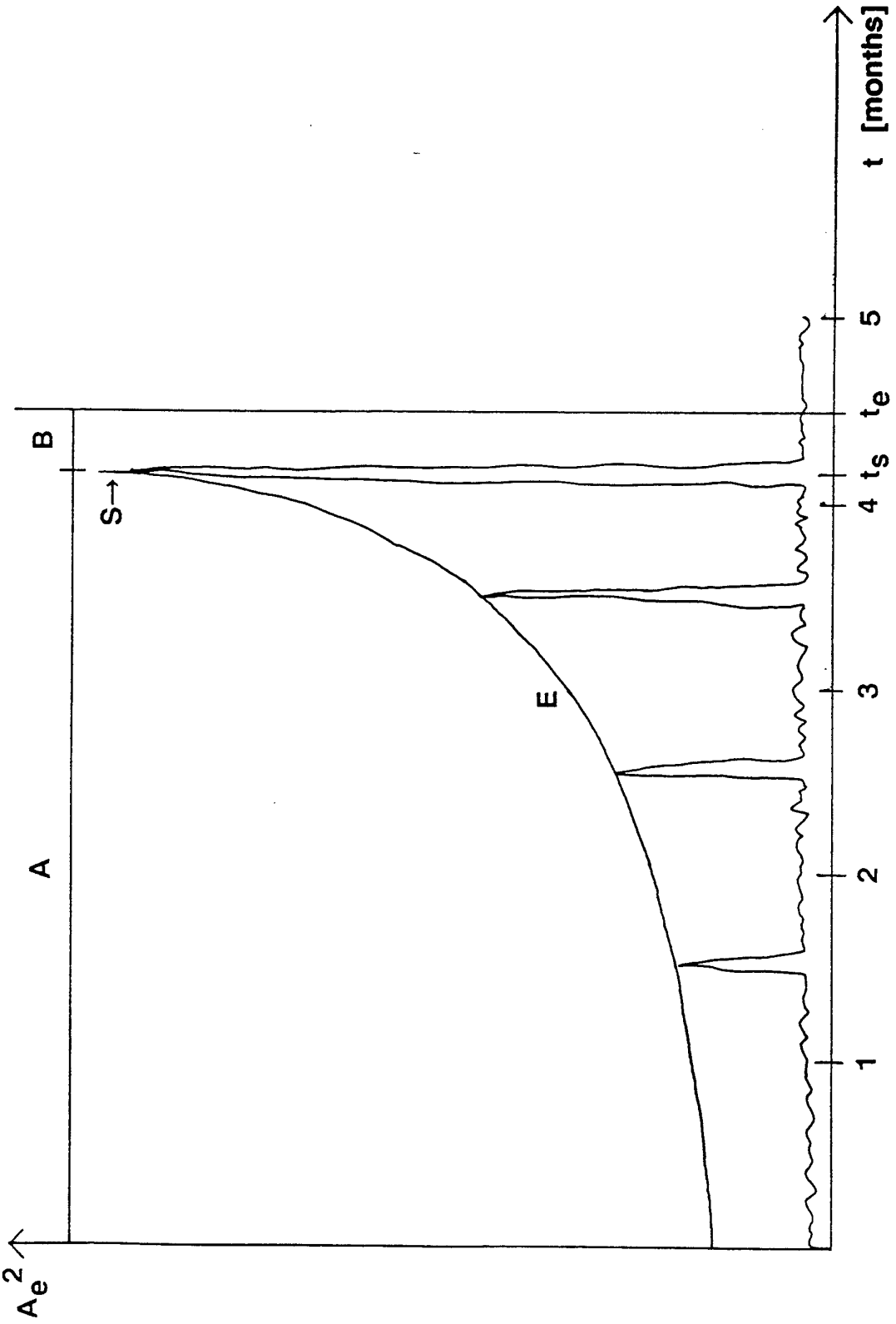
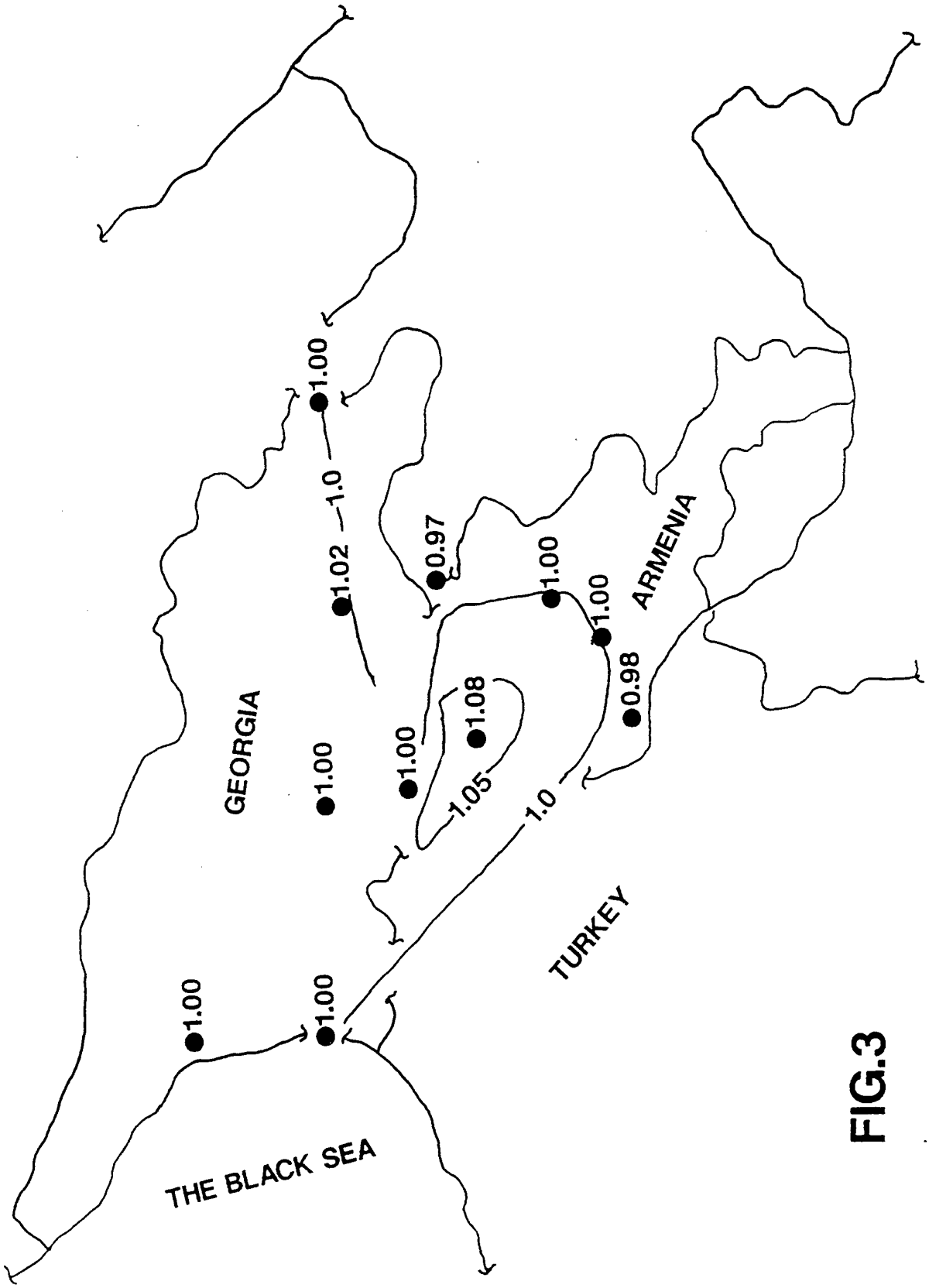


FIG.2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1.0
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0.97
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ARMENIA
0.98
1.08
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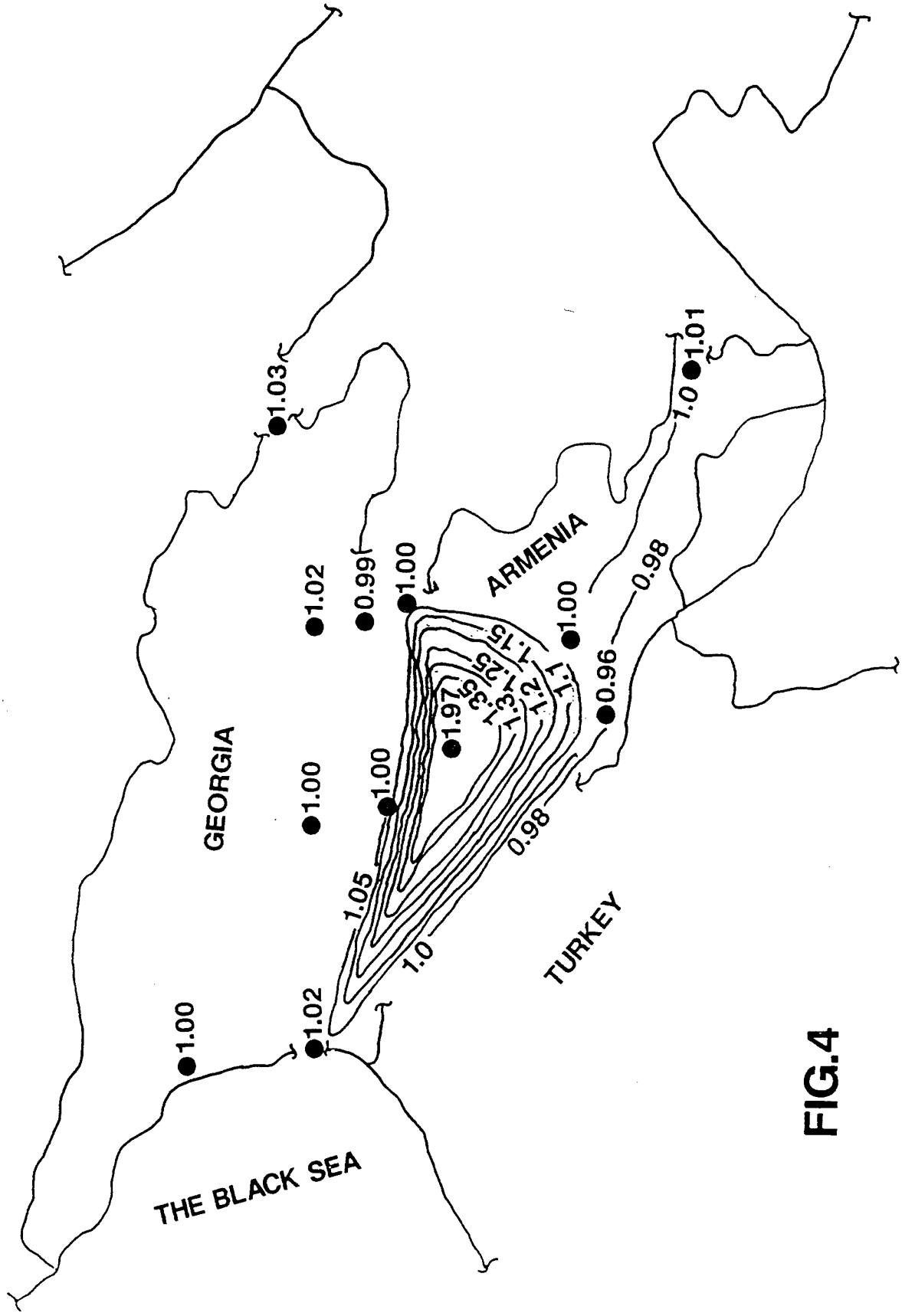
1.00
GEORGIA
1.05
1.0
TURKEY
1.00
1.00
THE BLACK SEA

FIG.3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ARMENIA
1.01
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1.25
1.15
1.1
1.2
GEORGIA
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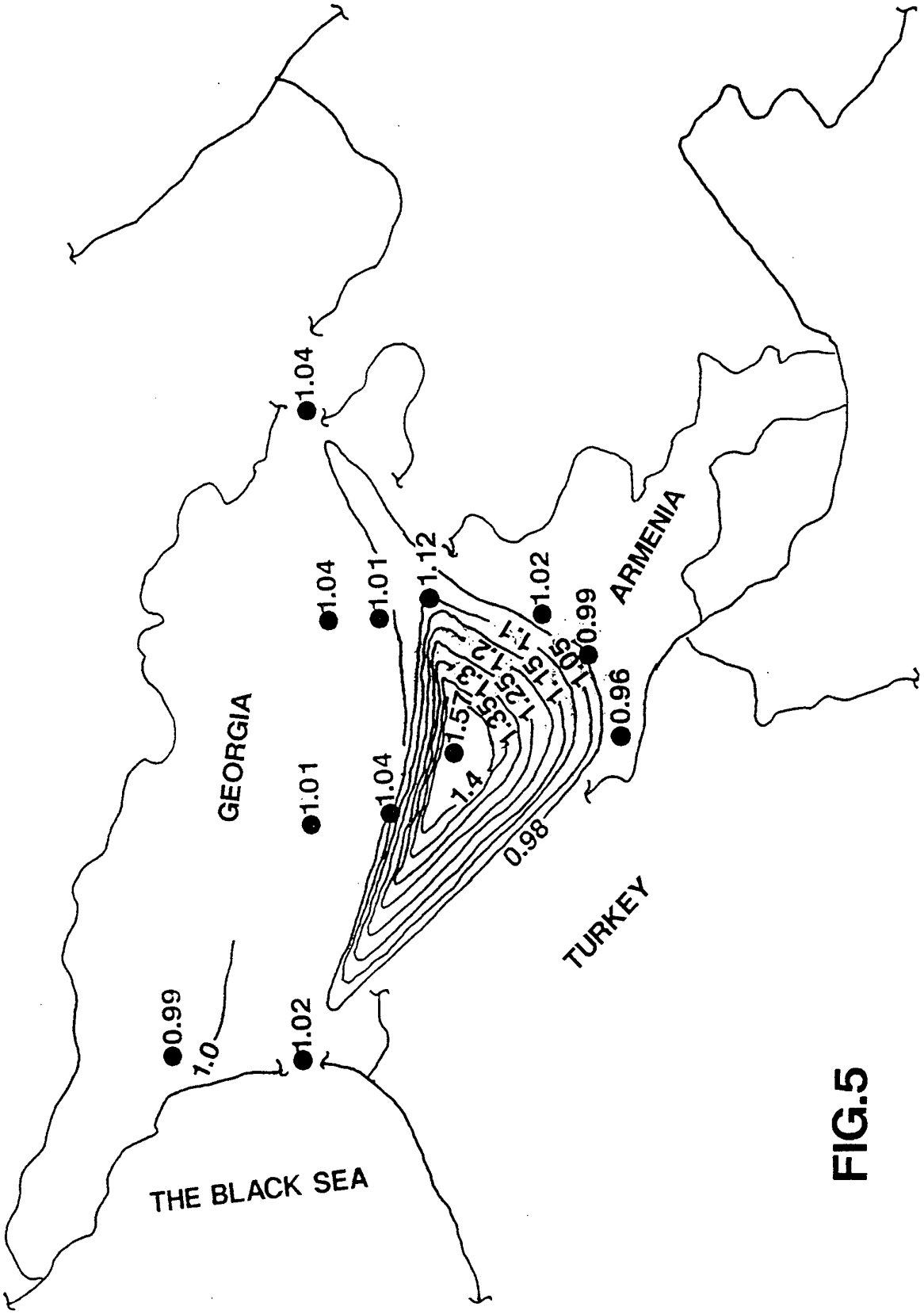
1.00
1.05
1.0
0.98
TURKEY
1.00
1.02
THE BLACK SEA

FIG.4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1.57
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0.99
1.0
GEORGIA
ARMENIA
TURKEY
THE BLACK SEA
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1.25
1.3
1.35
1.05
0.98

FIG.5

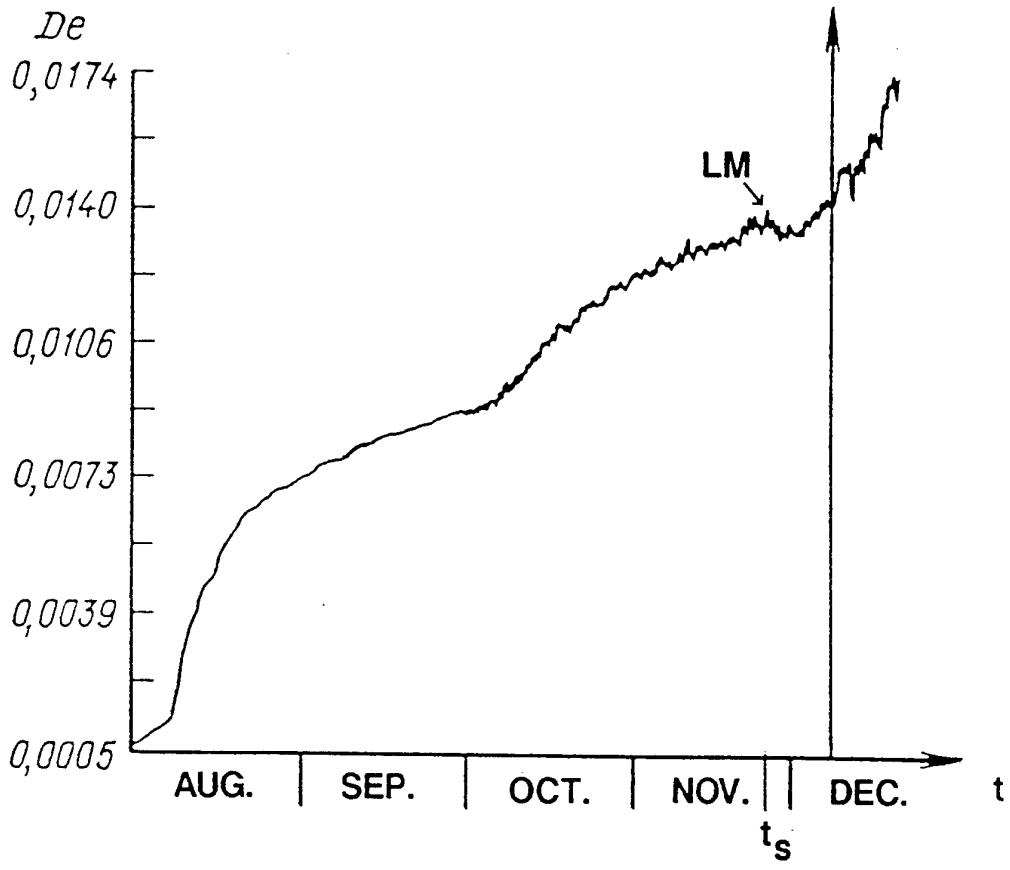
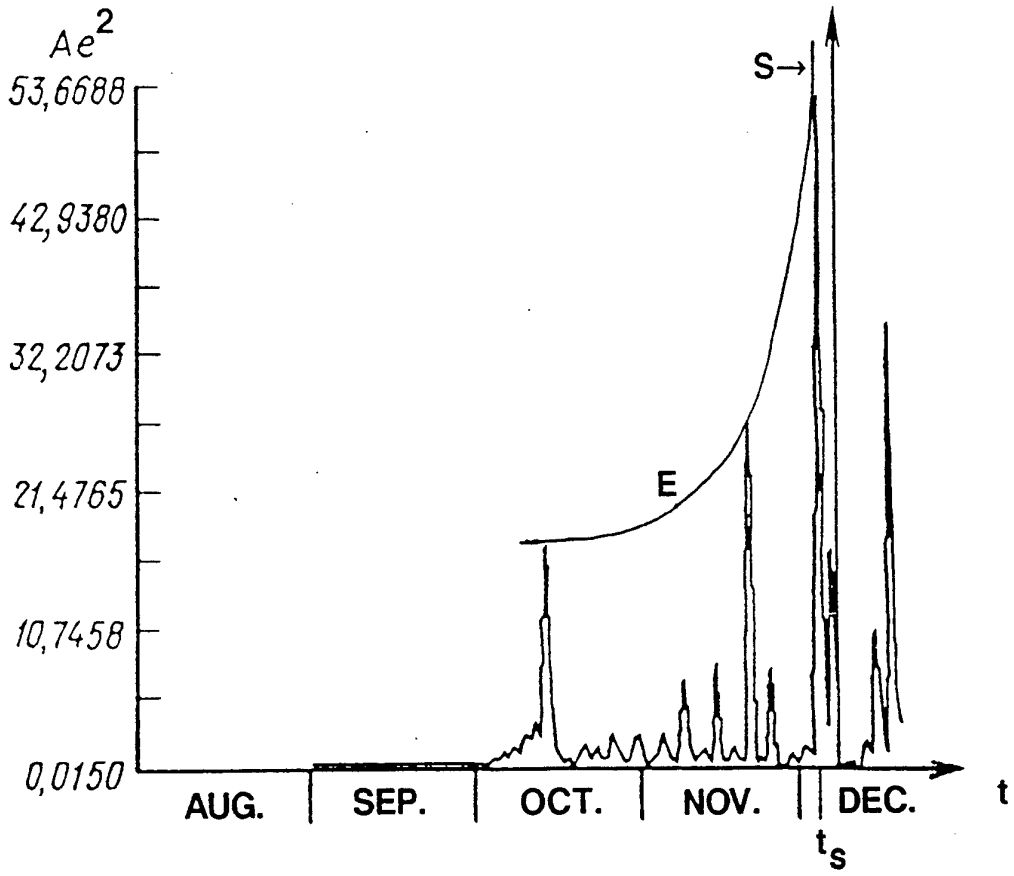

De
0,0174
0,0140
0,0106
0,0073
0,0039
0,0005
LM
AUG.
SEP.
OCT.
NOV.
DEC.
t
t_s

FIG.6


Ae2
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32,2073
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S→
E
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SEP.
OCT.
NOV.
DEC.
t
ts

FIG.7

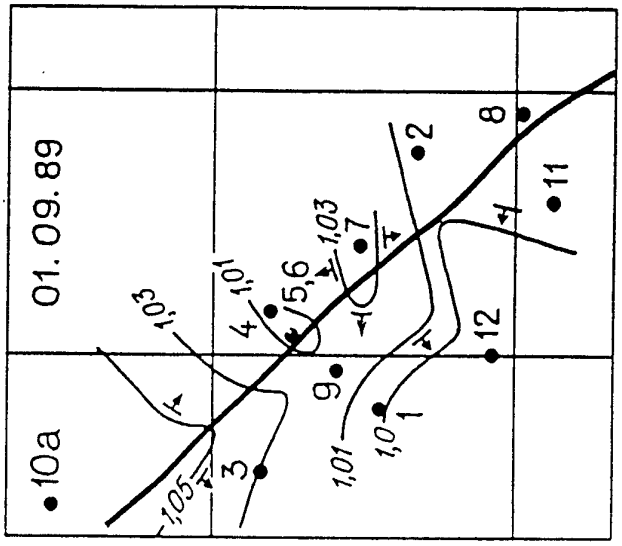


FIG.10

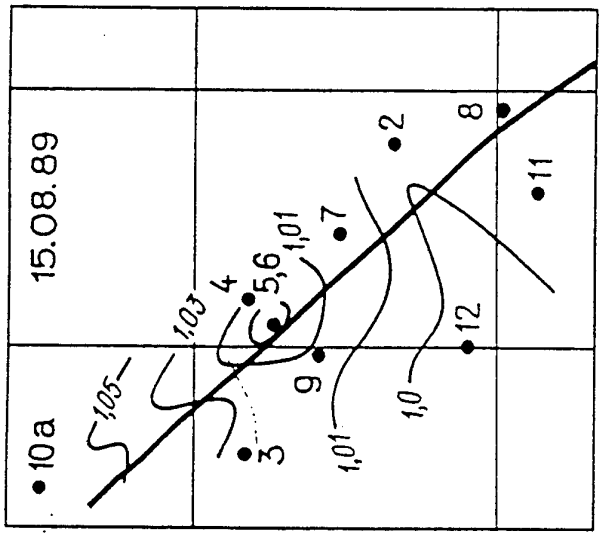


FIG.9

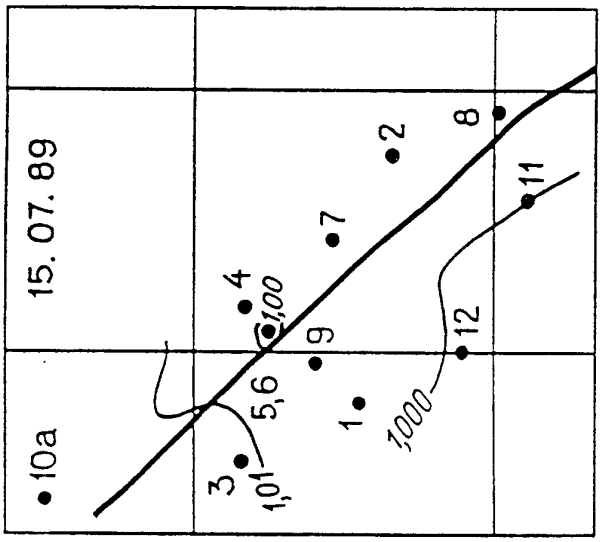


FIG.8

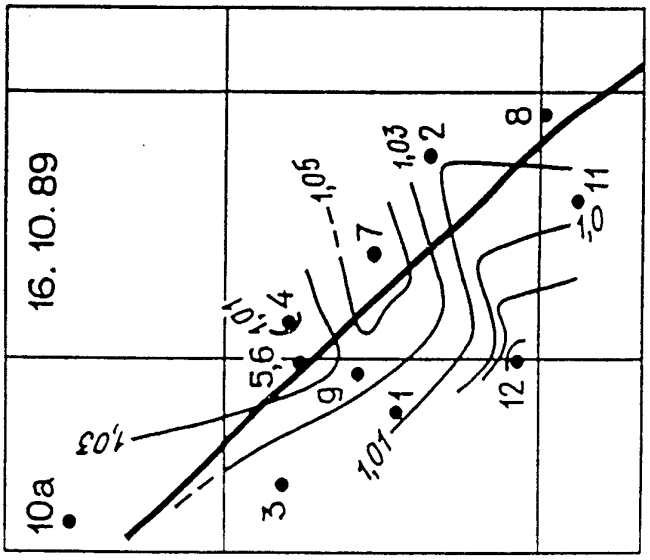


FIG.13

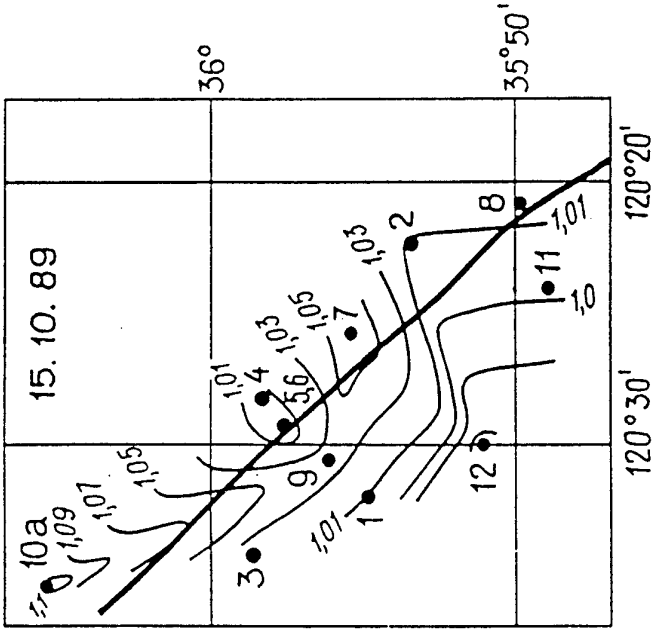


FIG.12

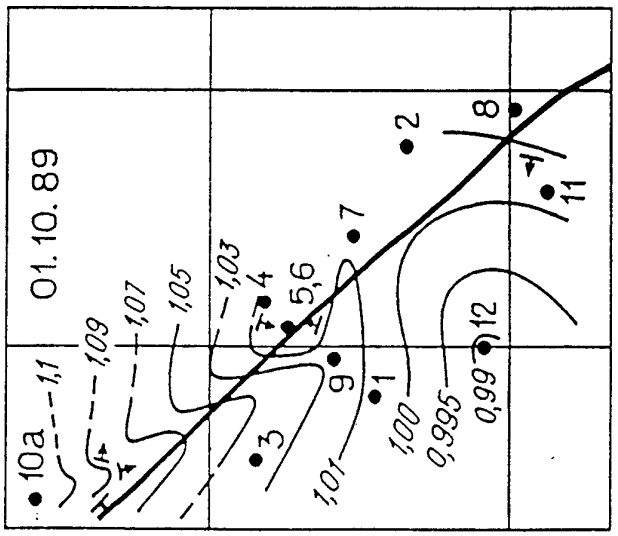


FIG.11

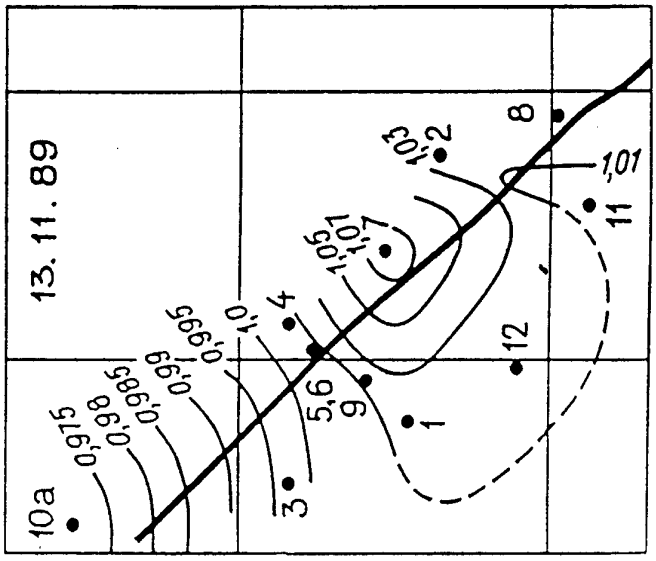


FIG.16

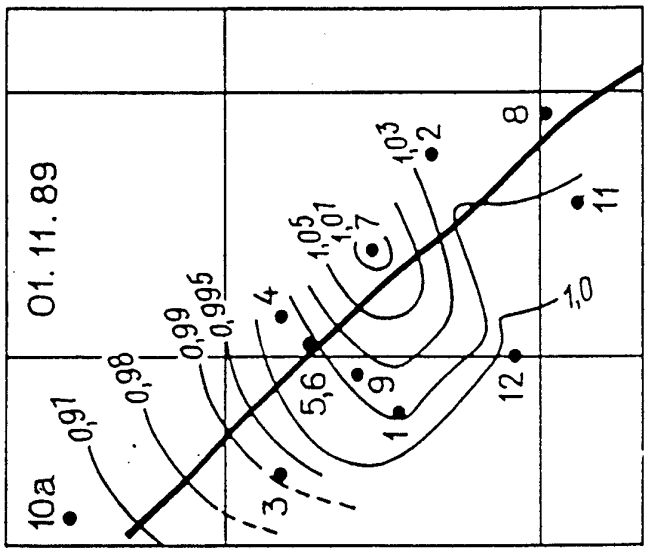


FIG.15

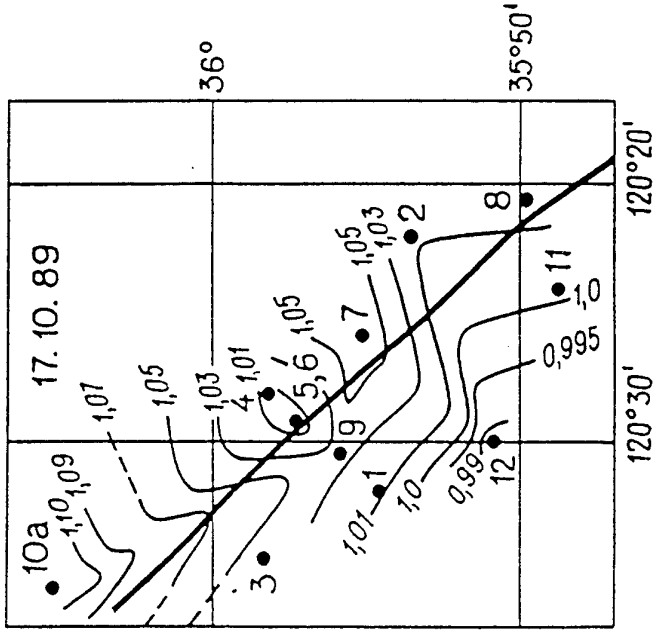


FIG.14

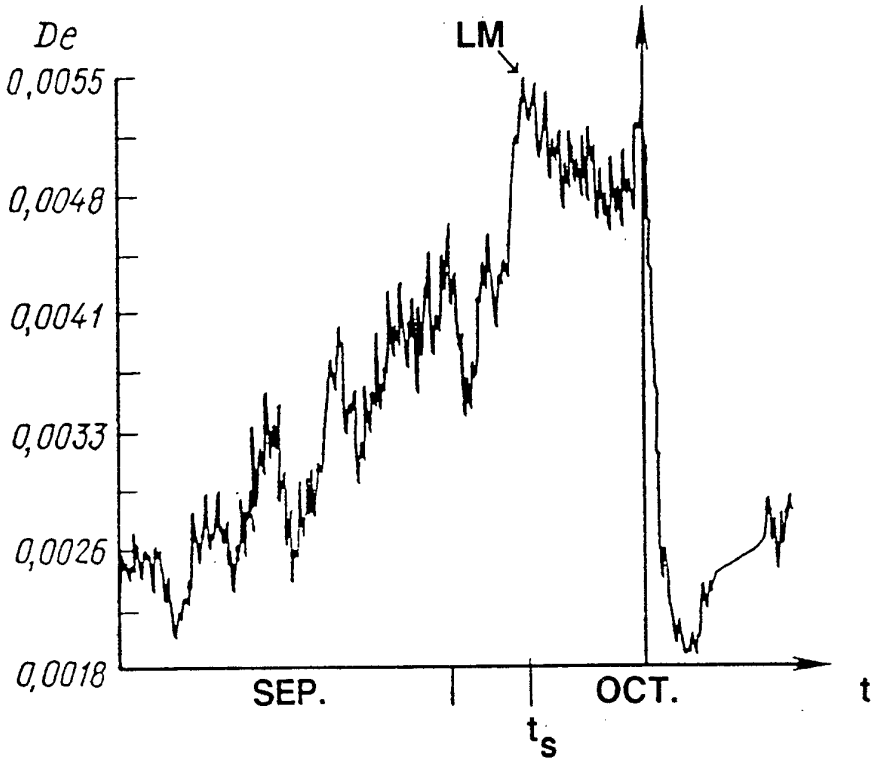


FIG.17

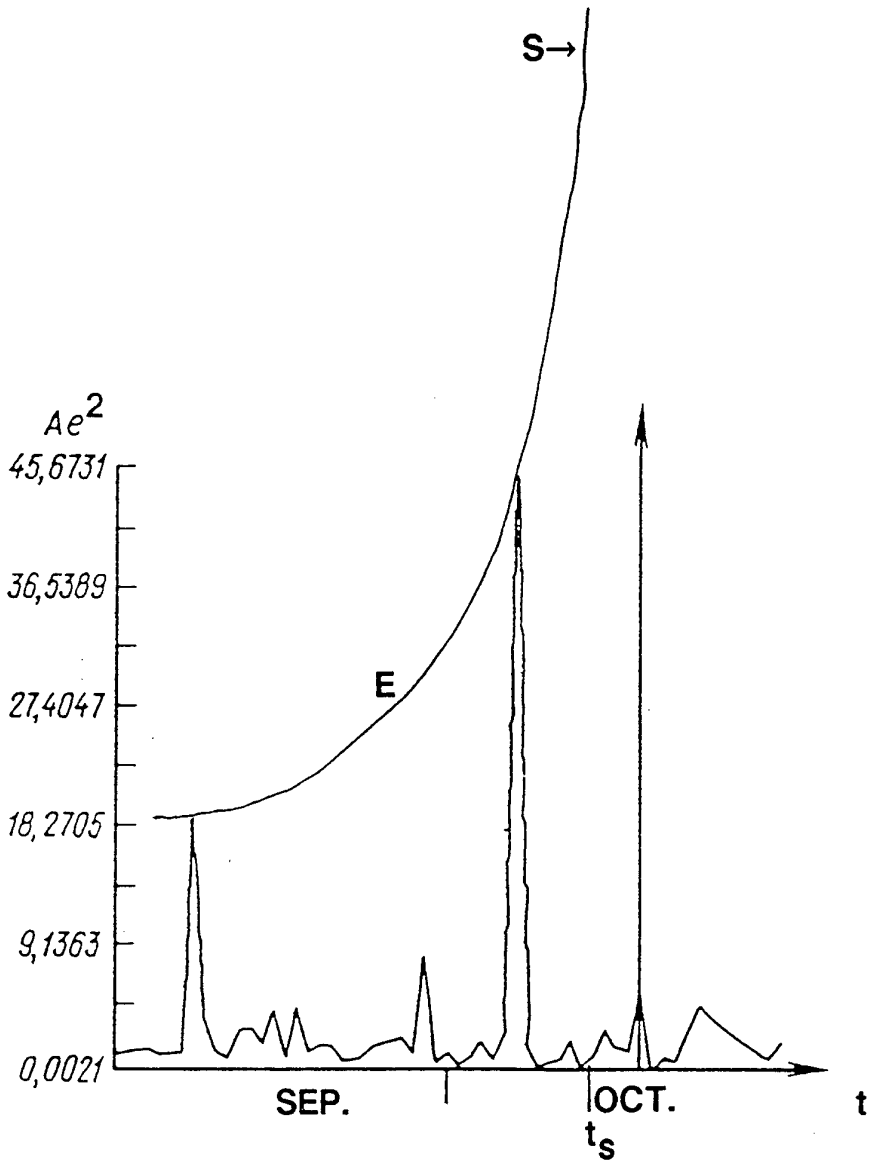


FIG.18

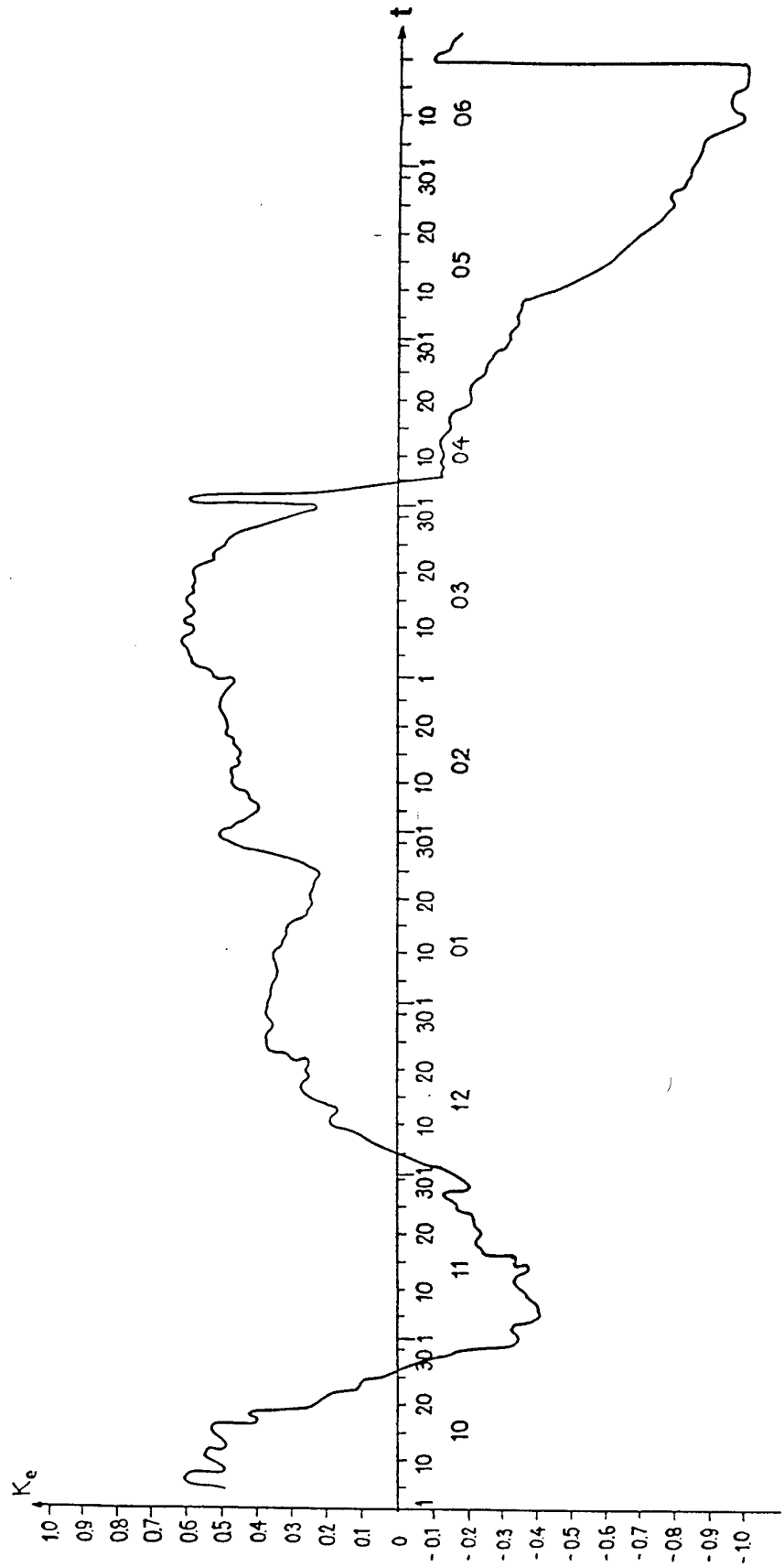
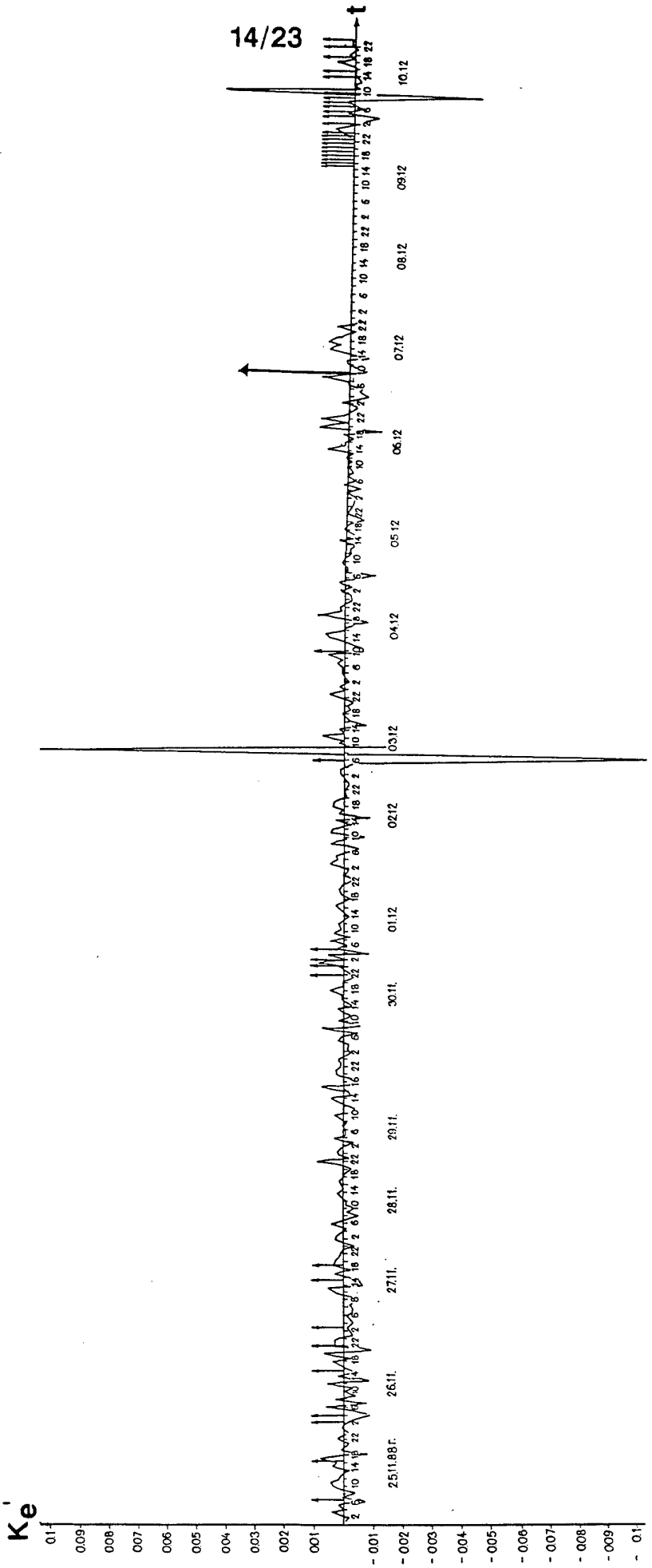

t
K_e
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
01
02
03
04
05
06
10
11
12

FIG.19


t
Ke'
25.11.88 г.
26.11.
27.11.
28.11.
29.11.
30.11.
01.12.
02.12.
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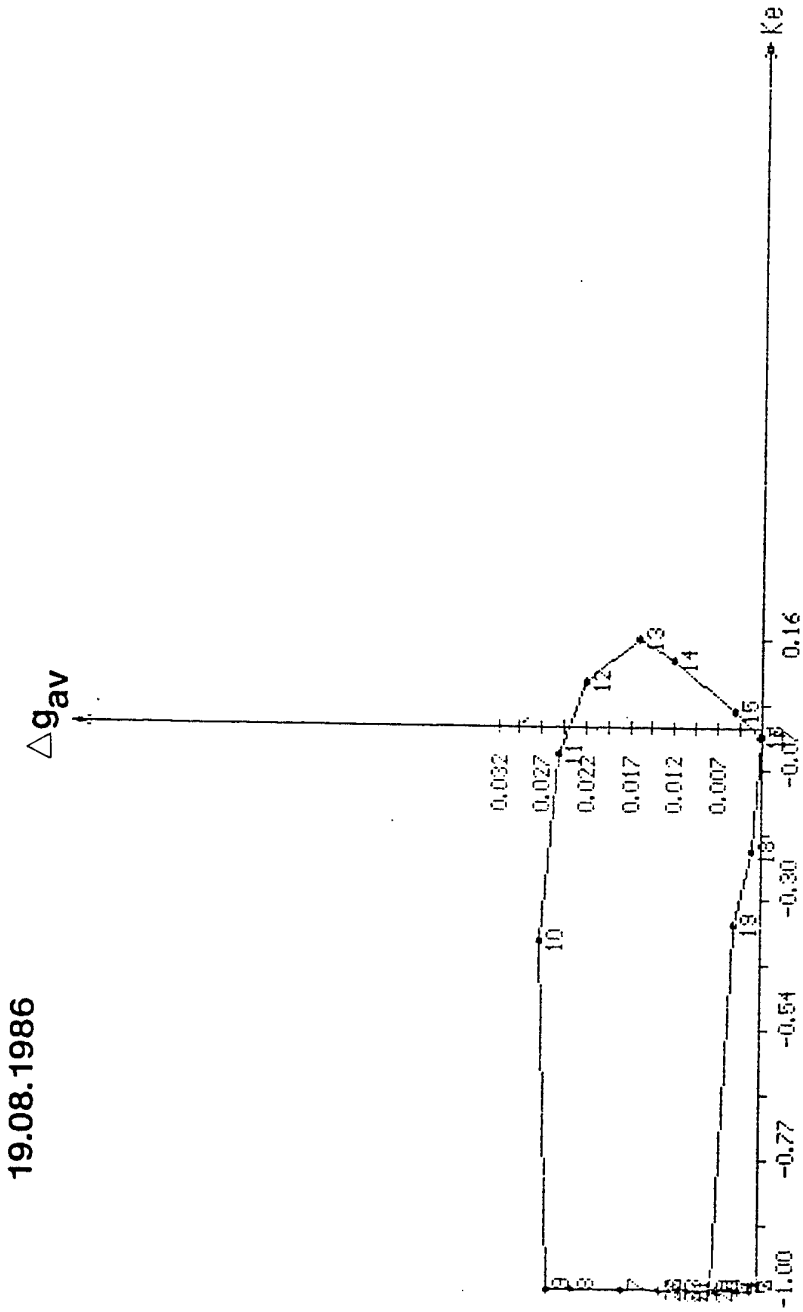
06.12
07.12
08.12
09.12
10.12

FIG.20


Ke
Δg_{av}
0.16
-0.07
-0.30
-0.54
-0.77
-1.00
0.032
0.027
0.022
0.017
0.012
0.007
10
11
12
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16
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19
19.08.1986

FIG.21

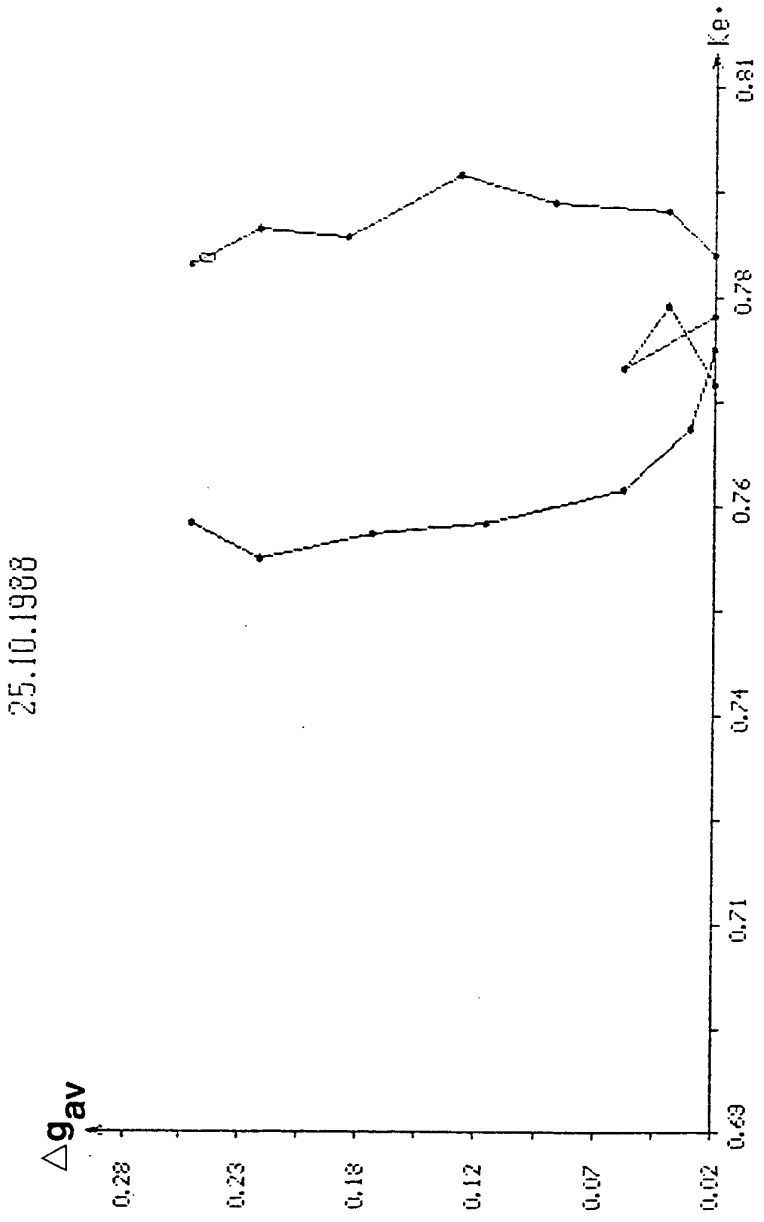
25.10.1988
Δg_{av}
0.28
0.23
0.18
0.12
0.07
0.02
0.69
0.71
0.74
0.76
0.78
0.81
ke.

FIG.22

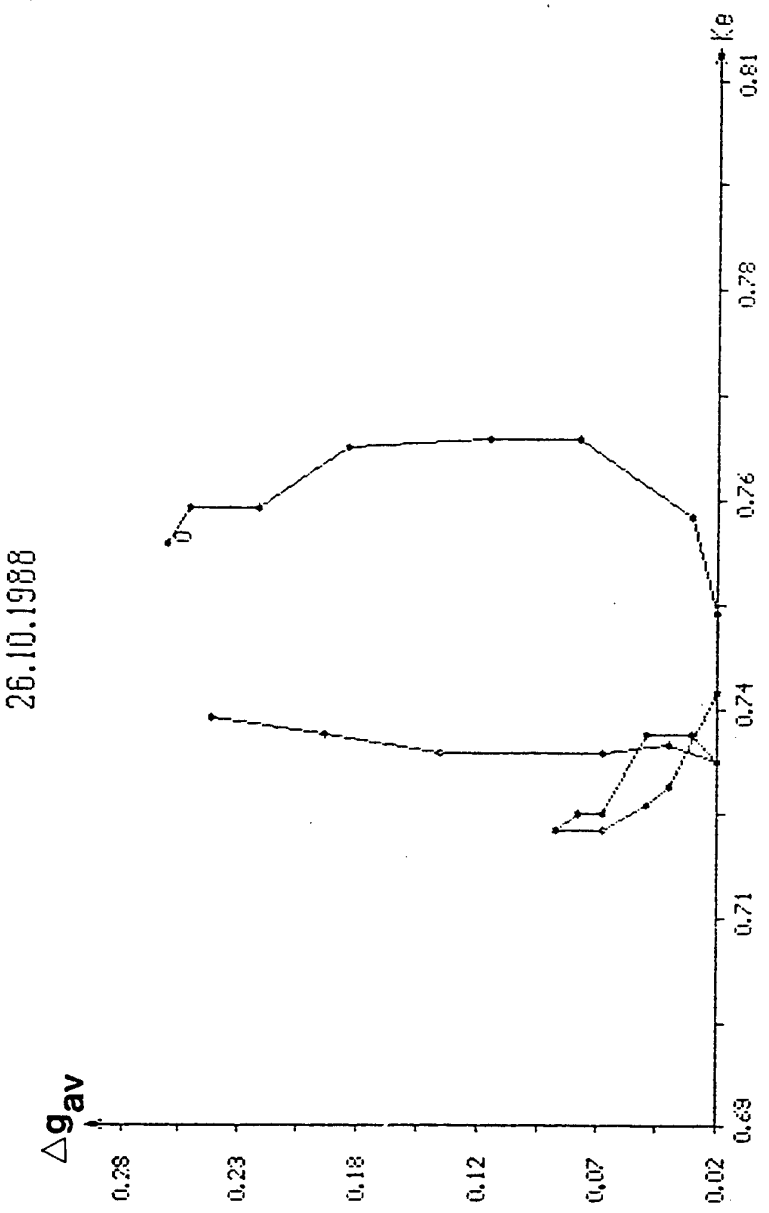
26.10.1988
Δg_{av}
0.28
0.23
0.18
0.12
0.07
0.02
0.69
0.71
0.74
0.76
0.78
0.81
Kø

FIG.23

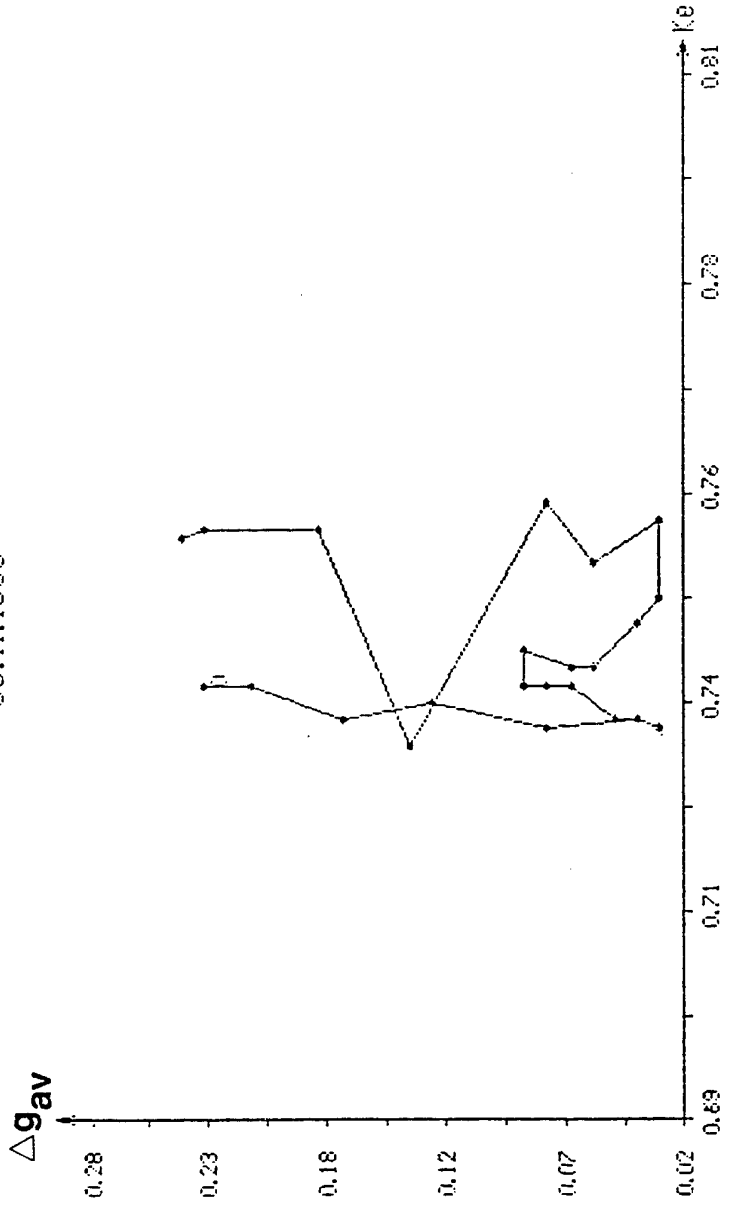
09.11.1988
Δg_{av}
0.28
0.23
0.18
0.12
0.07
0.02
0.69
0.71
0.74
0.76
0.78
0.81
Ke

FIG.24

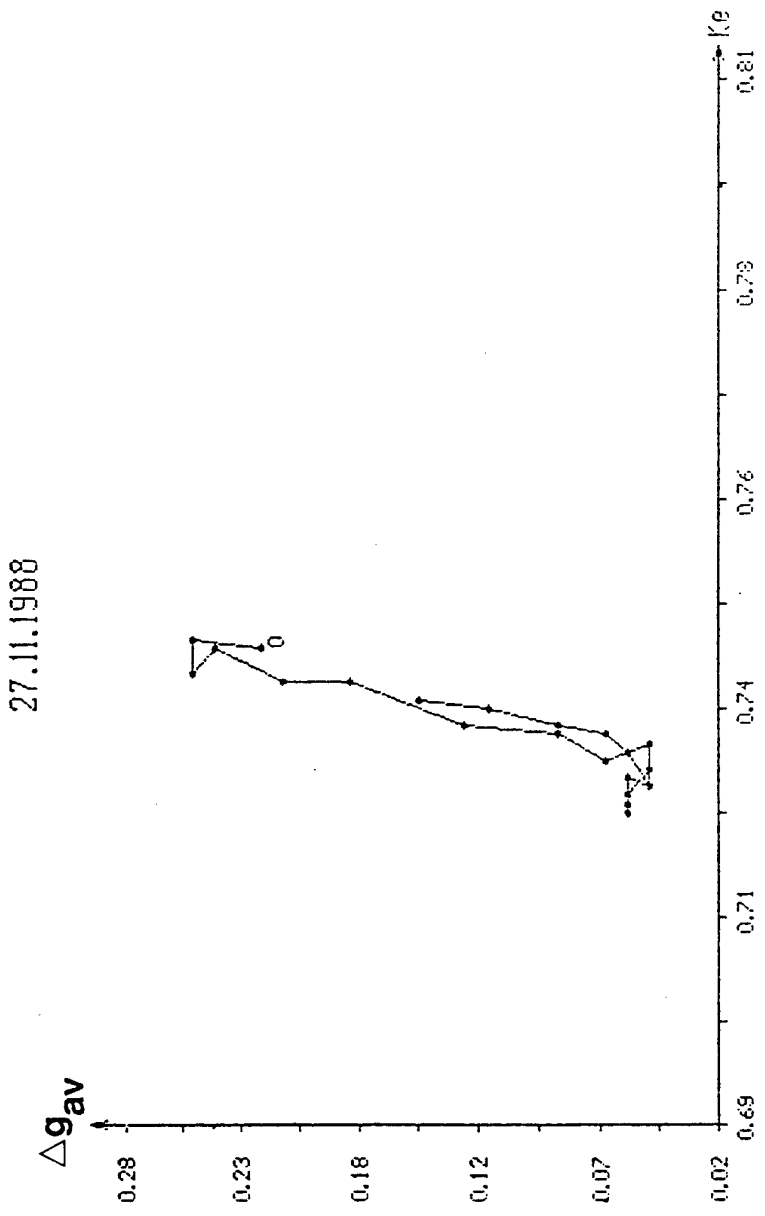
27.11.1988
Δg_{av}
0.28
0.23
0.18
0.12
0.07
0.02
0.69
0.71
0.74
0.76
0.79
0.81
Ke

FIG.25

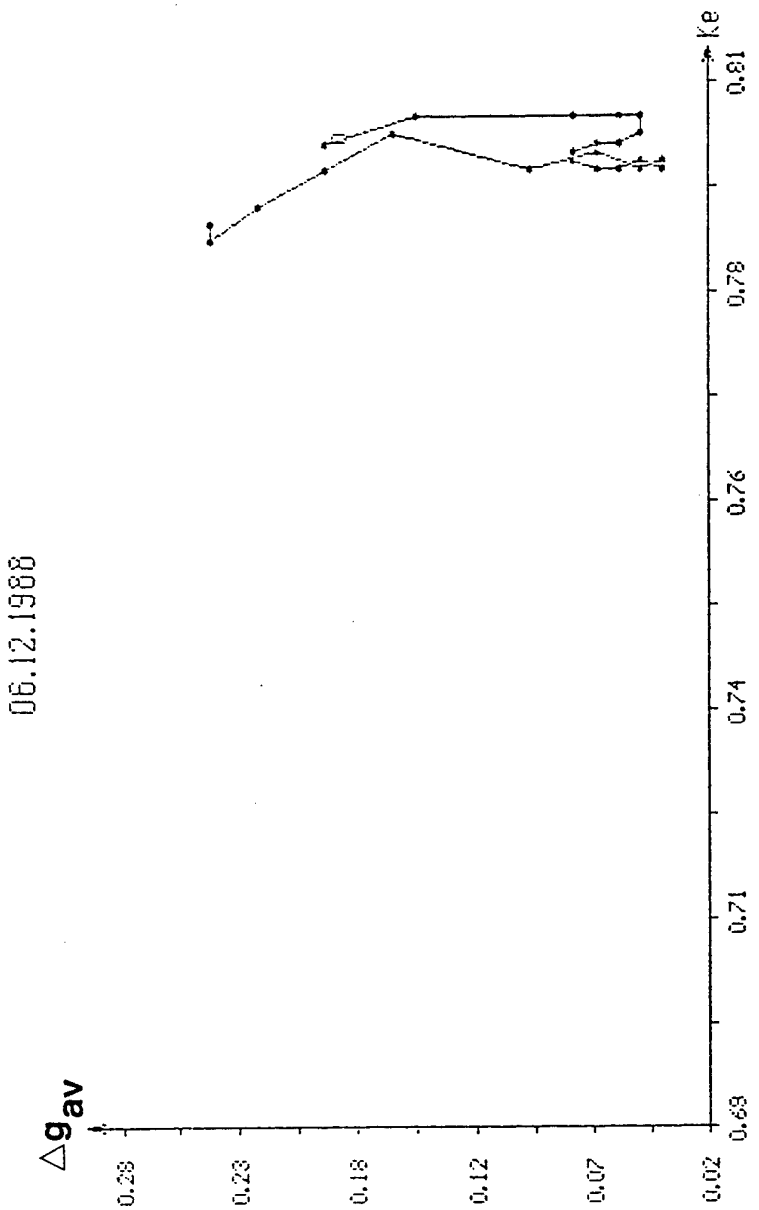
06.12.1988
Δg_{av}
0.28
0.23
0.18
0.12
0.07
0.02
0.69
0.71
0.74
0.76
0.78
0.81
Ke

FIG.26

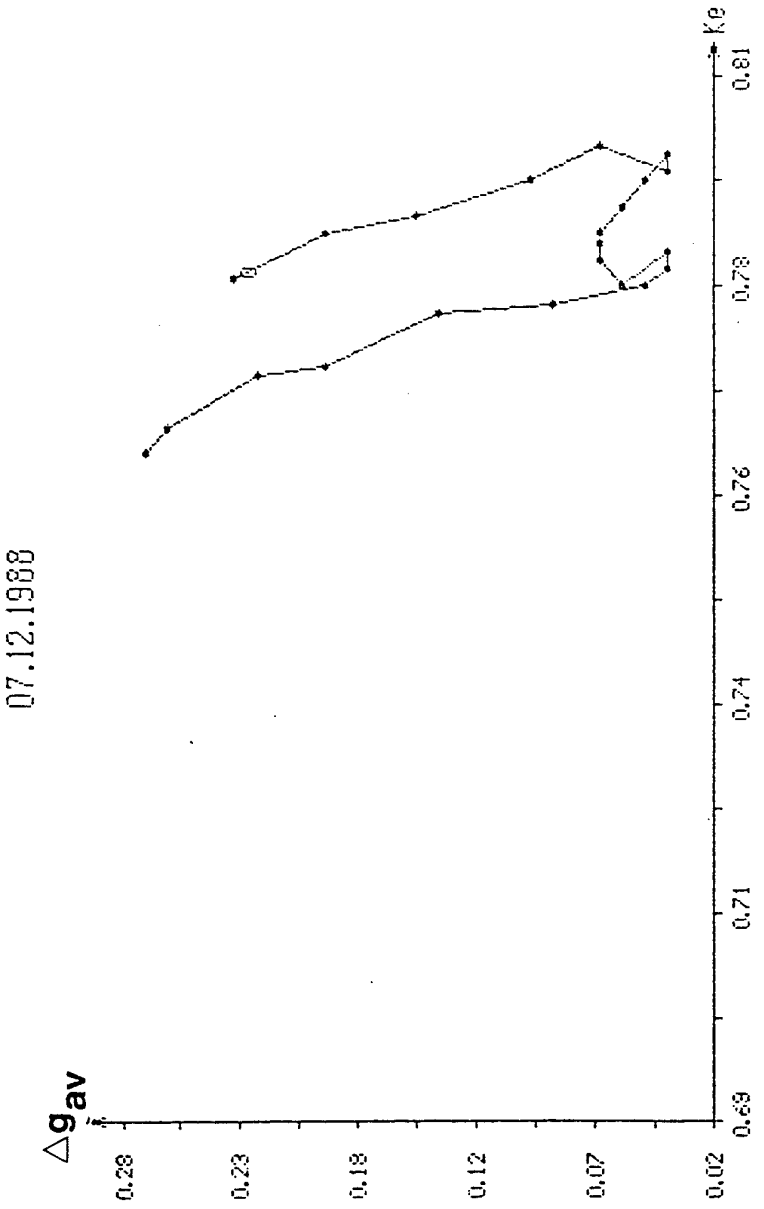
07.12.1988
Δg_{av}
0.28
0.23
0.18
0.12
0.07
0.02
0.69
0.71
0.74
0.76
0.78
0.81
Ke

FIG.27

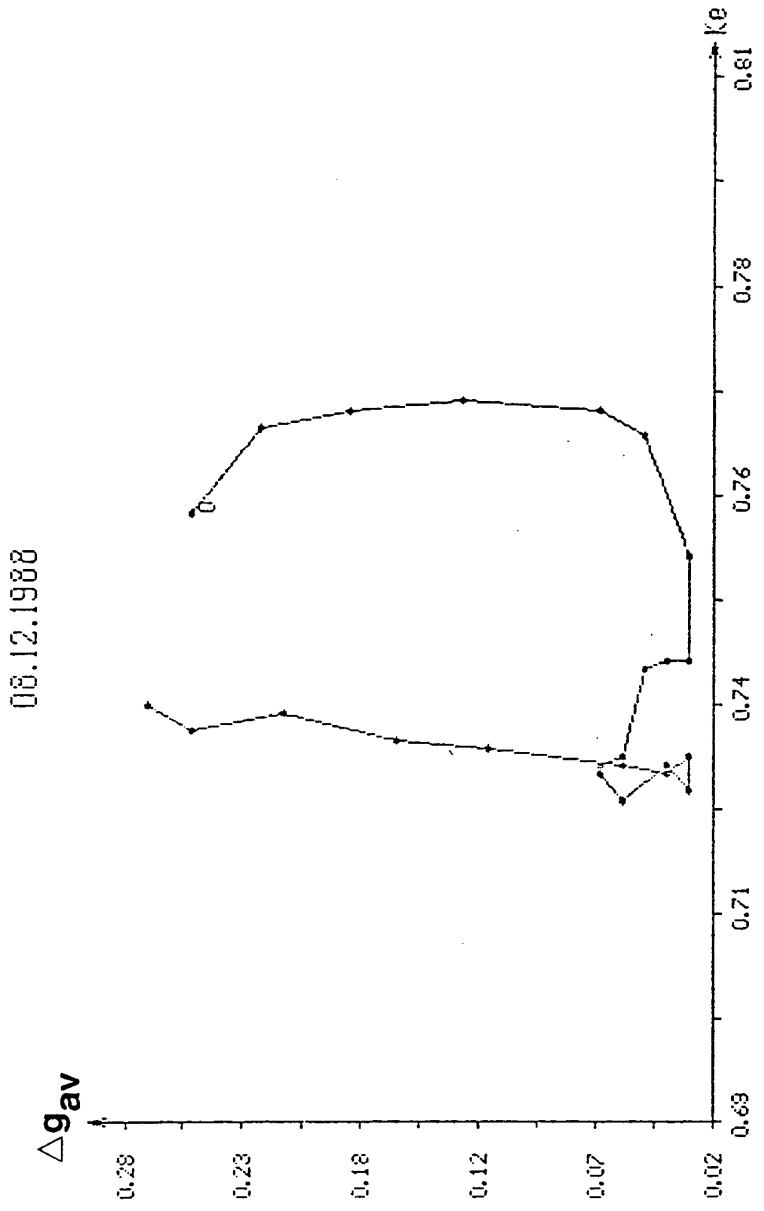
08.12.1988
Δg_{av}
0.28
0.23
0.18
0.12
0.07
0.02
0.69
0.71
0.74
0.76
0.78
0.81
Ke
0

FIG.28

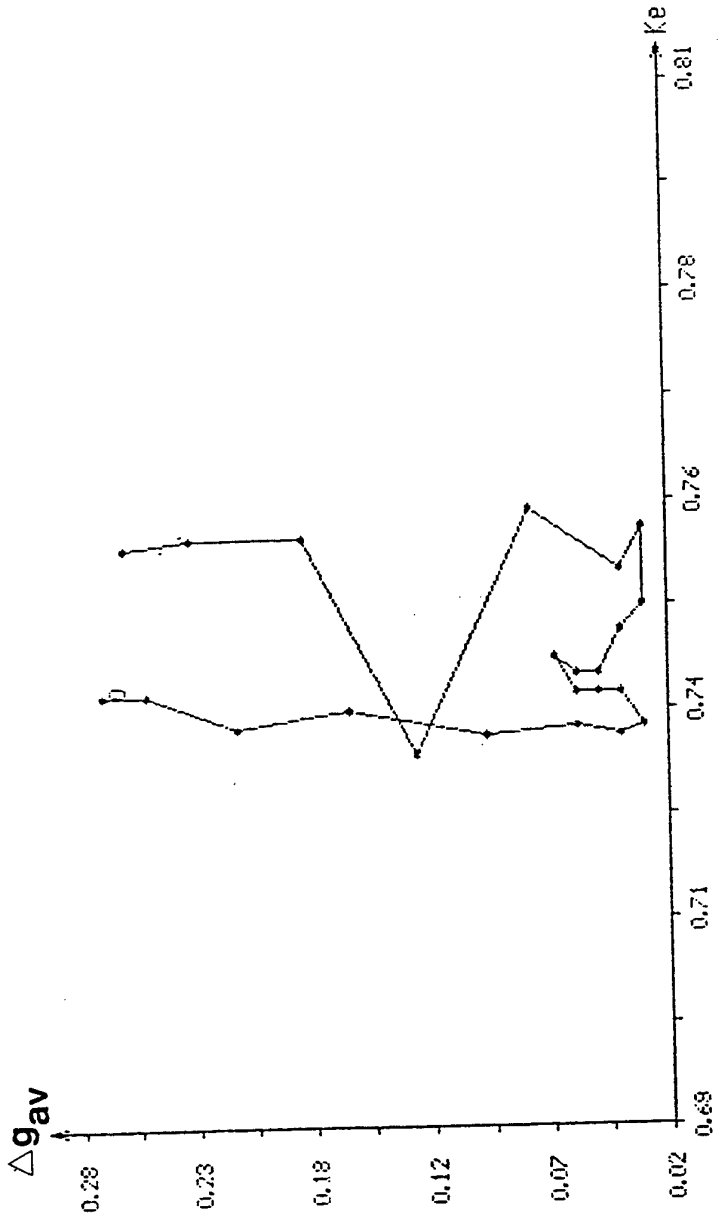
09.12.1988
Δg_{av}
0.28
0.23
0.18
0.12
0.07
0.02
0.69
0.71
0.74
0.76
0.78
0.81
Ke

FIG.29

INTERNATIONAL SEARCH REPORT

International application No.
PCT/DK 93/00337

A. CLASSIFICATION OF SUBJECT MATTER

IPC5: G01V 1/00, G01V 11/00, G06F 15/20
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC5: G01V, G06F, G08B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

DIALOG: WPI, CLAIMS; QUESTEL

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 4727488 (BRUCE E. FLINCHBAUGH), 23 February 1988 (23.02.88) --	
A	US, A, 4884030 (CHARLES NAVILLE ET AL), 28 November 1989 (28.11.89) --	
A	US, A, 4904943 (KOZO TAKAHASHI), 27 February 1990 (27.02.90) --	
A	GB, A, 2183038 (ANTAL ADAM), 28 May 1987 (28.05.87) --	

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" erlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
1 February 1994	04 -02- 1994
Name and mailing address of the ISA/ Swedish Patent Office Box 5055, S-102 42 STOCKHOLM Facsimile No. +46 8 666 02 86	Authorized officer Stefan Svahn Telephone No. +46 8 782 25 00

INTERNATIONAL SEARCH REPORT

International application No.
PCT/DK 93/00337

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	Derwent's abstract, No C7600 E/10, week 8210, ABSTRACT OF SU, A, 834649 (AS TADZ SEISMOLOGY), 10 June 1981 (10.06.81) -- Derwent's abstract, No 92- 22657/03, week 9203, ABSTRACT OF SU, A, 1628026 (AS UZB SEISMOLOGY), 15 February 1991 (15.02.91) -- --------	

INTERNATIONAL SEARCH REPORT

Information on patent family members

30/12/93

International application No.
PCT/DK 93/00337

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A- 4727488	23/02/88	CA-A- 1249876	07/02/89
		EP-A- 0181216	14/05/86
US-A- 4884030	28/11/89	DE-A- 3865998	12/12/91
		EP-A,B- 0286518	12/10/88
US-A- 4904943	27/02/90	JP-A- 1094286	12/04/89
		JP-B- 5036000	27/05/93
GB-A- 2183038	28/05/87	JP-A- 62118287	29/05/87