GEODETIC METHODS REGARDING THE CRUSTAL MOVEMENTS AND EARTHQUAKE PREDICTION

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Abstract

In order to make a prediction on earthquakes, it is necessary to determine three mandatory elements: the location, moment and magnitude of the event. For this purpose, a series of information sources must be integrated, including: geological evidence, statistic data, seismic measurements, physical measurements and other data. The knowledge on geology and geological processes, in a certain area, combined with the records of previous earthquakes, involves the execution of seismic hazard maps. The data for the execution of the seismic hazard maps include: the location of active and inactive faults, the fault type, the recent fault movements, the area’s earthquake history, the location of the epicenter of previous earthquakes, the determination of the intensity for previous earthquakes and the correlation of earthquakes with the local faults. Statistic data refers to mathematical relations between an earthquake’s magnitude and the length of the cracked fault. Seismic measurements generally follow earthquake frequency and seismic evidence (previous shocks and shocks subsequent to the occurrence of the seismic event). Physical measurements have as basic idea the determination of amendments related to distances, land elevation or physical properties of the monitored area. Geodesy has been and still is involved in the determination of movements along the faults, by determining the elastic strain accumulations (stress or extensions). Through the geodetic measurements performed repeatedly, between two successive earthquakes of close magnitude, the quantity of energy accumulated in the earth crust is determined. In this article, the performance methodology for the geodetic component of databases related to the execution of seismic hazard maps is approached.

Keywords: *Earthquake prediction, magnitude, leveling.*

1 INTRODUCTION

The study of recent crustal movements is integrated in the overall research on the dynamics of the earth shell, which is a reflection of the phenomena taking place both in the earth shell and in depth. The results obtained by correlating the data provided by geological, geophysical and oceanographic sciences with the results obtained through geodetic measurement, concur to the clarification of the issues related to the earth’s temporal evolution, the understanding of current processes and the attempt to foresee their future manifestation method. Besides from its fundamental nature, research in this field also displays an applied nature, concurring along with geology and geophysics to the highlighting of new sources of energy or useful minerals, the determination of the stability level of the soil in inhabited areas or areas where important industrial and urban sites are to be located. The understanding of the displacements affecting the upper layer of the earth’s shell, movements which occur prior to, simultaneously or after earthquakes, also represents a current issue **(Nacu, 1998).**

2 MAP OF THE RECENT VERTICAL CRUSTAL MOVEMENTS – SHORT HISTORY

The Romanian specialists’ activity in the issue of recent crustal movements was materialized through the execution of a vertical movement rate map in the year 1972 (included in the Map of Eastern Europe, editors Mescherikov, Boulanger, Moscow, 1973) and subsequently in 1973 and 1975 (improved editions), the one from 1975 being printed in 1977 (scale 1:1.000.000) and published in 1978 and 1979 (**Cornea I., Drăgoescu I., Popescu M. N., Visarion M.**).

The map was completed based on the oldest geometric leveling measurements, performed in the rank I network in Banat and Transylvania during the period 1881 – 1896 and afterwards in four distinct time periods: 1895 – 1913, 1919 – 1941, 1949 – 1960 and 1961 – 1972 (Cornea et al., 1978; Cornea et al., 1979). The first measurements from the 20th century were performed by the Military Geographic Institute in Vienna, and the others, by the Military Topography Directorate and later on by IGFCOT (from1958).

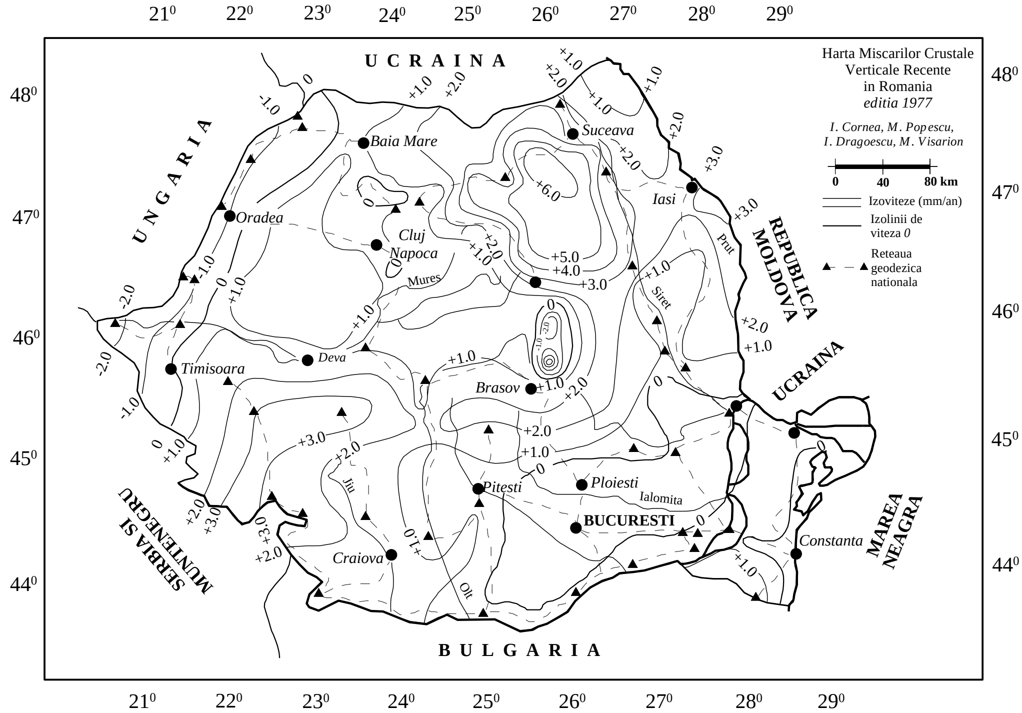

Figure 1. The map of recent vertical crustal movements (after I. Cornea et al., 1978, 1979).

The high precision leveling measurements performed after the earthquake from March 4th, 1977 (1977 – 1983) have allowed the development of new maps for the vertical movement rate on the Romanian territory (Fig. 2), superior to the previous one from a quality perspective, through the implementation of two additional polygon lines, Adjud – Ciceu and Târgu Jiu – Simeria, decreasing the length of polygons surrounding the Oriental and Meridional Carpathian Mountains.

The network of repeated leveling has included 15 closed polygons (including 1328 geodetic landmarks, 59 lines, with a total of 5727 km) and 14 isolated lines (178 landmarks, in total length of 730 km). The length of the polygons was classified between 200 – 400 km (13,3%), 401 – 600 km (40%), 601 – 800 km (40%) and 830 km (6,7%). The values of polygon clearances were ranked between 0,01 – 1,85 mm/year, distributed mainly in the interval 0,42 – 0,69 mm/year (72%). The compensation of the leveling network was performed through the conditioned observation method, the average value of the free terms in the conditional equations being ± 0,27 mm/years. Shares were calculated with the relation:

$$\frac{1}{P} = m_{\Delta h}^{2} \times \Delta t^{-2}$$, where $m_{\Delta h}$ represents the accuracy of rate differences.

(1)

With this measurement data, another series of vertical movement rates was calculated. The new time intervals (between measurements) were 10 – 15 years (47%), 16 – 22 years (36%), 23 – 32 years (15%). On 2 leveling lines, a maximum interval was included in the calculation, of 64 – 69 years (2%).The calculated rate values were related to the fundamental point of Constanţa, for which the absolute movement rate was estimated at -2,51 mm/year, close to the values obtained at the tide gauges at Varna and Burgas (Bulgaria).

The general geodynamic aspect of the Romanian territory is the one highlighted in the previous map: the mountain regions are continuously ascending, while the plains are in a descending process (subsidence).

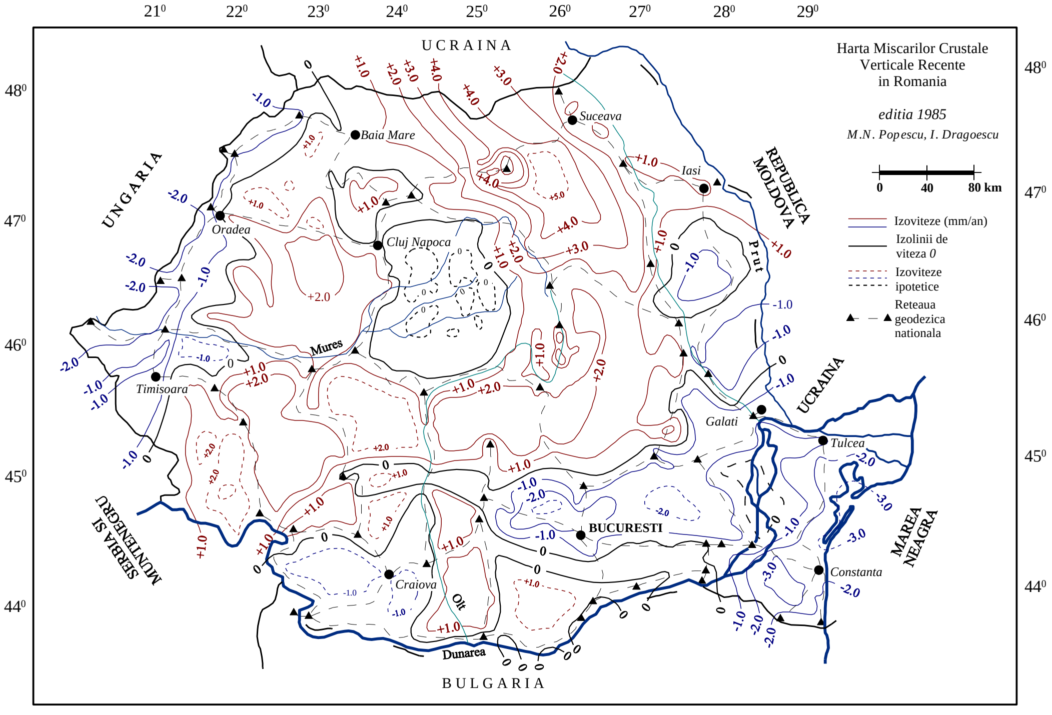

Figure 2. The map of recent vertical crustal movements – edition 1985 (after M.N. Popescu, I. Drăgoescu)

The inclusion of geodesy in the research programs related to crustal movements has been determined and developed simultaneously with the acceptance of the concept of global tectonics. These studies are performed for the purpose of determining a very important precursor of earthquake prediction, namely that of determining crust deviations (such as compressions, extensions and others). Geodesy provides, more and more accurately and promptly, to the other geosciences, data related to displacements, deviations of the earth crust allowing the calculation, within the thresholds determined by the accepted statistical hypotheses, the potential energy quantity accumulated between the series of performed measurements.

A seismic event is characterized by the following geophysical events:

- ☛ the mechanic rupture in the lithosphere;
- ☛ the energy released inside the earth;
- ☛ the radiation of elastic waves.

and can be defined through the following parameters:

- ⦿ the position of the epicenter;
- ⦿ the depth of the hypocenter;
- ⦿ the moment of the earthquake's
- ⦿ the released energy.

The dynamics of the earth crust is investigated through the continuous or periodical tracking of relative displacements, both through geodetic measures, performed near the fault, and through seismologic methods, where the recordings performed at local seismographs are telemetered to central stations, where they are processed and analyzed in the context of neighboring stations. The seismically observed displacements vary from a few centimeters, in the case of small earthquakes, to several meters, in the case of big earthquakes. The duration of the sliding (displacement) is estimated between a fraction of a second, to 10 seconds.

One of the research directions during the last years, maintaining the hope for the reduction of losses and damages caused by earthquakes, is represented by the determination of technologies capable of predicting them, through the study of measurable physical precursors, preceding earthquakes, in general, especially big ones. In the specialized literature (**Rikitake, 1976; Vogel, 1979, 1980; Scholtz,1994**) several classifications of earthquake precursors are presented.

Amongst the over 20 precursors (**Rikitake, 1976, 1979, 1994**) considered in the implementation of the Japanese earthquake prediction program, the ***study of recent crustal movements has an important place***. The vertical, respectively horizontal displacements, or, during the last decades, tridimensional displacements, hades in certain large areas, along with specific measurable deviations, can be considered true study disciplines in this area.

Along with the development of the tectonic plate theory, the geodetic measurements received a new dimension, namely **time**. Geodesy has been requested, along with the other geosciences: geophysics, geology, geomorphology, oceanography and others, to contribute to the confirmation (or completion) of the hypotheses fundamenting this theory. In this context, modern geodesy is characterized by a systematic approach of dynamic phenomena amending the earth's shape and gravitational field, entirely or exclusively for limited areas. As a science in progress, geodesy eloquently contributes to the aforementioned topic, as new technologies, more perfected and especially with larger covered areas, appear and are developed, getting closer and closer to the overall coverage of the entire globe.

Vertical geodetic networks. The first attempts to determine, through geodetic methods, the recent movements of the (terrestrial) crust were based on the high precision geometric leveling, which has continuously evolved during the last years, achieving average quadric errors per double leveling kilometer under 0,3 mm/km (**Ghitau, s.a. 1994**). This accuracy is equivalent to a relative error of $1*10^{-7}$, being one order of error lower than the value of the stress accumulated in the terrestrial crust, at the occurrence of an earthquake with the magnitude of 6,0 degrees on the Richter scale.

In many seismic areas, the repeated leveling measurements have revealed elevations or descents of up to several decimeters. An important change in altitude was calculated, for instance, from repeated leveling measurements (**Mogi, 1985**) near the area where the 1964 Niigata (Japan) earthquake occurred.

Horizontal geodetic networks. The implementation of high precision distance gauges **(Prescott & Lisowski, 1983; Fujii, 1995**) has generated important changes in the structure of geodetic networks, during the last 20 years, as angular measurements (triangulation) were completed or even replaced by distance measurements (trilateration). Recently, it became possibly to measure distances between 1 and 50 km with a relative accuracy around the value 10^{-6} or even better.

Repeated gravity measurements. Amendments occurring over time in the value of an area’s specific gravity can indicate either vertical movements or displacements of the masses inside the earth. Both types of changes can appear not only in in areas with seismic and tectonic activity, but are specific to them through their precursor nature. In the study of determining gravity anomalies (**Vogl, 1980**) both relative and absolute repeated gravity measurements are used. Also, in order to be able to determine the nature of anomalies resulting from high precision geodetic leveling measurements (**Bonatz, s.a., 1994**), it is necessary that they are accompanied by gravimetric measurements, allowing the determination of geopotential figures and dynamic altitudes.

3 SPATIAL GEODETIC TECHNIQUES FOR REGARDING THE CRUSTAL MOVEMENTS AND EARTHQUAKE PREDICTION

The launching of the first satellite can be considered the beginning of the satellite geodesy era. This concept includes all the measuring and processing procedures where (artificial) satellites can be observed and measured from earth or are themselves carriers of the measurement systems. Satellite aided geodesy has generated, first of all, the chance to study this phenomenon in real, tridimensional spaces, on increasingly large areas (groups of countries or continents), and later on, a significant development in the accuracy of measurement results. High scale research programs are known, where the determination of the relative position of two points located on the earth’s surface, at a distance equal to its radius (which can be approximated with the distance between Europe and America), has been performed with a relative error around the value of 10^{-7} **(Reinhart, 1996).**

Global or regional determinations of recent displacements of the terrestrial crust.

Global or regional determinations of the recent displacements of the terrestrial crust refer to large areas from the earth’s surface, including a random number of countries or even continents, overall. The use of the two artificial satellite constellations, launched for navigation purposes, is currently distinguished, for the achievement of the analyzed challenge:

- GPS (Global Positioning System) – having as administrator The US Ministry of Defense, including 18 satellites (phase reached in 1990) at the altitude of 20.000 km;
- GLONASS (Global Navigation Satellite System), under the administration of the Russian Federation, constellation including 14 satellites, located at approximately 19.000 km.

Before the complete implementation of these new technologies also for the civil sector, which led to the increase of the determination speed simultaneously with a significant increase of the determination precision, other specific processes for the spatial geodesy were also utilized (and are currently utilised) by the economically developed countries which are, however, extremely costly:

- VLBI (Very Long Baseline Interferometry);

- SLR (Satellite Laser Ranging).

From these basic notions result the main geodynamic parameters of the global crustal movements:

- the rotation pole’s coordinates;
- the rotation speed of the tectonic plate;
- the borders between the tectonic plates;
- the character of the respective plate’s rotation movement, especially of the points localized on the edge of the considered plates;
- the displacement rate in all of the geodetic points, depending on their position in regard to plate’s rotation pole.

In 1993, at the second International Seminar regarding “GPS in Central Europe”, which took place in Hungary, at Penc, the project **CERGOP (Central European Regional Geodynamic Project)** was presented to the international scientific community.

It referred to the integration of the geo-dynamic researches from the Central Europe’s region through the utilization of the high precision spatial geodetic techniques, especially GPS. Year 1995 marks the beginning of the GPS studies in Romania, within the CERGOP International Project. The project, financed by the European Community, started in 1994, within the CEGRN geodetic network, which initially covered the territories of 10 countries (Austria, Croatia, Czech Republic, Germany, Italy, Poland, Slovakia, Slovenia, Ukraine and Hungary), being including 31 GPS locations. Since 1995 the network also expanded on the Romanian territory, thus including 41 GPS locations. The main scientific objectives of the CERGOP project were the following:

- interpretation of the geodynamic researches in the tectonic context of Central Europe;
- investigation of the structure of the area Tornquist – Teisseire, of the Pannonia Basin and the Carpatic system;
- creation of a reference frame for the subsequent geodynamic studies;
- establishing of extended collaborations and of a data and information exchange;
- mutual publishing of the study results;
- creation of a database regarding the CEGRN network’s points.

The extended CEGRN network was developed within the CERGOP II International Project (Central European Regional Geodynamic Project) (Fig. 3) and is implemented on the Romanian territory in 14 observation stations of which 2 stations (IASI, VATR) were subsequently eliminated and replaced by the site from Suceava (SUCE), so that today not all 12 observation points are operational (Fig. 4).

The location of these stations was chosen in mutual agreement between specialized geologists, geophysicists and geodesists From within the Romanian Geologic Institute (IGR), the National Research Institute – Development for the Earth’s Physics (INCDFP), the Faculty of Geodesies from within the Bucharest Construction Institute (TUCE) and last but not least, Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, Germany (BKG) (**Ghiţău, 2003**).

The locations of the GPS observation stations were determined in order to cover the main tectonic units of the national territory.

The CEGRN network in Romania was designed for the purpose of satisfying a series of mandatory requirements enforced by the geodynamic researches:

 the locations shall cover the majority of the geologic units of the territory on which it is installed;

 the locations shall be installed outside the localities;

 radio obstacles are not allowed located at over 150 degrees hade from the horizontal plan, for a good visibility of the GPS antenna.

Due to the fact that the CEGRN network is a global GPS network, on a national level, it is obvious that it cannot satisfy the requirements specific for the highlighting of the geodynamic features of a small area, as is the Vrancea seismogenic area, in which only the Vrâncioaia (VRAN) observation point is located.

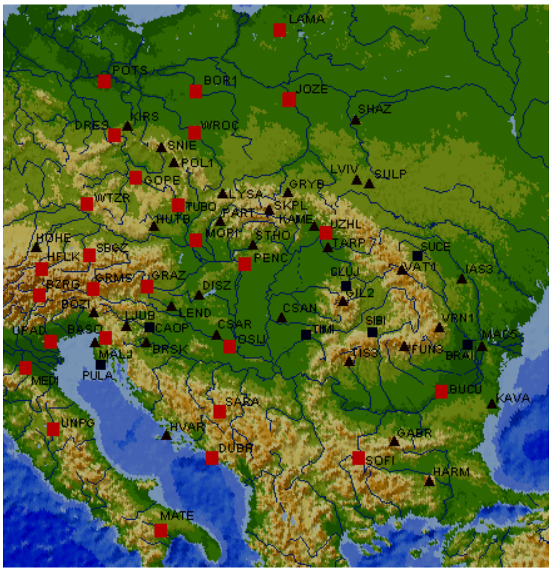

Figure 3. The CEGRN network at the level of Central And Eastern Europe within the GERGOP II International Project

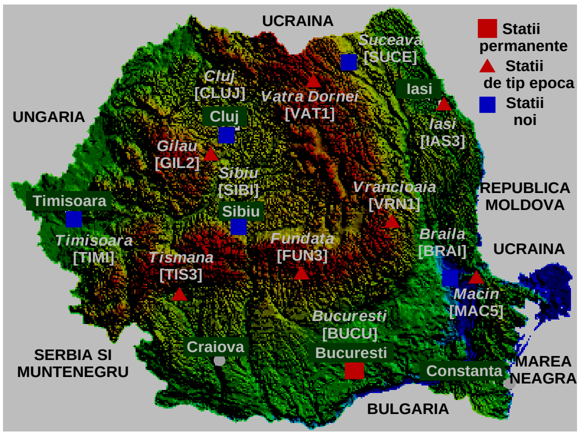

Figure 4. The CEGRN network on the Romanian territory

Thus, the performance of a GPS observation network was enforced, on the level of the Vrancea seismogenic area, network which initially included 25 stations in 1997, after which the network extended every year.

The analysis of the earth behavior over time based on the measurements for determining the displacements and deformations, represents an especially particular complexity and volume of.

4.CONCLUSIONS

The development of modern measurement equipment and geodetic technologies, undoubtedly brought a significant improvement of the determination precision of the position of the geodetic network tracking points, allowed remarkable measurement facilities, but at the same time enforced the necessity of establishment of the trust level in the measurement's results, so that there is no ***ambiguity*** in the interpretation and decision taking regarding the deformations and movements of the earth shell, particularly, highlighting the physical phenomenon which determine the displacements, not the high performance operation of the apparatus, the measurement and processing methods of the data resulting from the measurements, in other words obtaining information regarding the land's behavior over time.

Concretely, depending on the chosen method for the analysis of the displacements and deviations, the performance of the compensation of the measured values is required, individually, for each measurement age, or collectively. ***The performance of the analysis of the displacements and deviations through methods specific for the mathematic statistic is necessary***, due to the fact that the differences between the planimetric position and the altitudes of the tracking geodetic network points on different measurement ages are not only determined, and their significance from a statistic perspective is analyzed. Thus, if these differences include only information regarding the measurement errors, then they will not be considered to be significant, though if the differences contain information regarding the measurement errors and the displacements which the points suffered, then these differences will be considered significant.

The prediction of the land earthquakes has the final purpose of limiting/avoiding the immense damages produced by them, and of the loses of human lives. Approximately 3 decades ago, it was considered that the prediction of the earthquakes cannot be considered a proper scientific research. Although, research programs targeting the prediction of earthquakes appeared in the 60's in Japan and USA (**Rikitaki, 1976; Kislinger, and others, 1975, and others**,), which invalidated the previous hypothesis. The strong earthquakes together with human and material losses, which can be considered catastrophic and which took place during the last years in various parts of the Globe (resembling the one which took place in our country, on 04.03.1977) fully proves the necessity of gradual remedying the extremely complex problematic which is earthquake prediction. In earthquake prediction the following fundamental aspects can be highlighted (**Dambara, 1980**):

- localization of the area where powerful earthquake can occur, with a high probability;
- observance inside these areas of the measurable modifications from within the earthquake precursors, regarding the calculation of the moment in which the earthquake can occur;
- development of some representation models of the earthquake's source for the purpose of performing a correct interpretation of the phenomenon's evolution and of the results of the researches.

The fundamental principle of the earthquake prediction is relatively simple, but not always easily achievable; it can be enunciated as follows: any parameter which can be considered as precursor of a seism, which shows important modifications compared to the normal ones, can be used for the earthquake's prediction, if there is the possibility of tracking/measuring it in its evolution over time.

Regarding the geodetic determinations, the general aforementioned principle can be applied as follows: sudden and important changes in the position of the geodetic points ca be often times associated to a future earthquake. These changes can be without a doubt strongly influenced by the milestone system of the respective points. It needs to be implemented in a way in which the movements from the superficial layer of the crust would not influence the conclusions regarding the position of the landmarks. The implemented studies need to highlight these displacements of the geodetic landmarks which are a consequence of the sudden discharge of accumulated tensions, close to the rupture threshold, of the tectonic forces in action. Also, a real efficiency can only be obtained with a high rate of repeatability of the geodetic measurements and, of course, with a proper coverage with geodetic points of the researched area.

Building the behavior patterns of the studied objectives, which can supply information regarding the displacements and deviations suffered by the tracked objective, the analysis of the previous situations, and also the prediction of the evolution tendency over time require, as shown through the theoretical approach, supported by the practical experiments through the comparison between the usage of various modern and classic apparatus, of the classic and modern measurement techniques, and of the applying of congruence tests between the measurement ages. Thus the ambiguities and their removing procedures can be highlighted.

More exact, there can be found points where displacements take place and the cause of these displacements can be analyzed.

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