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C o n t e n t s
I n h a l t s v e r z e i c h n i s
Part III
Teil III

**Recent crustal movements**

R e p o r t s



P a p e r s

CRCM and KAPG Activity in Recent Crustal Movement Studies

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The interest of Earth's sciences is focused at studies of recent crustal movements of local, regional as well as global importance, during last twenty years. Such studies are a part of problem called Geodynamics, discussed in other papers of our present symposium as well as in its Helmert Commemorative Lecture. In contrary to the problems of Earth's rotation, tidal variations and other special studies, which extend our knowledge on the Earth's core-mantle interaction, elastic properties of the Earth's mantle etc., the research of recent crustal movements is engaged in determination of dynamic parameters of crustal blocks in connection to subsurface structure. The main source of independent numerical data to be analyzed are the repeated geodetic measurements carried out by means either surface or space technique. The world-wide studies of such phenomena are co-ordinated by the IAG permanent Commission on Recent Crustal Movements (CRCM), which is divided in regional Subcommissions covered all dry-lands of our planet with exception of Antarctis. Some special questions of recent crustal movement studies, especially with respect to the needs of national economy are solved in national or regional organizations, as for instance in the KAPG. Let us discusse some results of the work of both organizations in the field of recent crustal movements.

The CRCM is the large international organization and its activity depends on detail activities of regional Subcommissions. The most developed regional studies are covered by three European Subcommissions, North American and Western Pacific Subcommissions. Nevertheless, in other regions as Southern Asia, Africa and Central and Southern America some studies in national scale are carried out.

The results of recent crustal movement studies are published in national or international Journals and presented at special symposia on recent crustal movements. The last CRCM international symposium has been held in Palo Alto, USA, in 1977. Then followed the inter-disciplinary symposia held at the XVII. IUGG General Assembly in Canberra 1979 and at the IAG General Meeting in Tokyo, 1982. The proceedings of these symposia have been published as special issues of TECTONOPHYSICS. In the period of 1983--1987 some regional symposia will be held in Pacific, Europe, Africa and Southern America. The line of these symposia should be finished by the international and interregional symposium, to be held one year before the XIX. IUGG General Assembly, in 1986.

The first regional symposium after the XVIII. IUGG General Assembly was held in Wellington, New Zealand, February 1984. Thematically, this symposium was focused at the recent crustal movement studies in Pacific area. The symposium was carefully prepared by the Royal Society of New Zealand, and accompanied by scientific excursions and business meeting of the CRCM Subcommission for Western Pacific. At the scientific part of the symposium were presented very valuable information on results of monitoring recent crustal movements within the New Zealand, and other parts of Pacific, Philippines, Indian and American as well as Eurasian plates. It exceeds the possibilities of this paper to discuss all results presented at the symposium but the paper presented there will be published soon by the Local Organizing Committee. Summarizing briefly the results presented at the symposium in Wellington we have to appreciate the recent crustal movement



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studies, performed at selected localities covering the main parts of plates' boundaries. Especially, in seismic areas as the Pacific region, the recent crustal move - ments are studied in connection with the main earthquake events occured in areas under study. An overview on Recent crustal movement studies in New Zealand has been given in special issue where the works and main results have been described.

The line of regional symposia continue now in Magdeburg, then in Cairo, Maracaibo and Budapest. We suppose the extension of knowledge as well as more close cooperation by crustal movement studies within the subcommissions. Considering the great importance of the African continent, the regional symposium in Cairo should contribute essentially to the development of research programme for monitoring crustal movements within the region. At the symposium in Southern America we expect the establishment of a group of specialists interested to start with more extensive research of recent crustal movements. The symposium here in Magdeburg and the next in Budapest should be a base to discuse the European problems as well as some common methodological questions. At the world international symposium in USSR, 1986 we shall sumarize the results, presented at the regional symposia, and estimate the continuation of our work and its trends in the next period.

The present stage of crustal movement studies can be characterized as a period of technological improve - ment of methods for monitoring and analysing of recent crustal movements. In contrary to the previous works which consisted in simple comparisons of results the more comprehensive analysis of data available are performed in present stage of research. Using the historical as well as modern results of triangulation/trilateration remeasurements, the model of deformations field was computed, tested and analyzed for the territory of California. Such kind of modelling and analysis seems to be a new approach by solving the problem of time-space properties of recent crustal movements. Moreover, these analysis contribute to the mutual understanding between geodesists and seismologists as well as other specialists of the Earth's sciences. The next feature of present stage of research is the fact that the gravity field is taken into the consideration by practical analysis of repeated measurements. The proper data on non-tidal gravity variations were lacked some years ago. The improvement of the accuracy of present gravity meters extended our possibilities to detect the secular gravity variations, and to consider them by analysis of repeated geodetic measurements carryied out in the actual gravity field. Such a comprehensive studies can contribute effectively by studies of proper - ties of Fennoscandian land-uplift etc. The third feature of present stage is the practical use of the most progressive space technique for monitoring of large, inter-plate movements. As has been reported at the XVIII. IUGG General Assembly the first results of Doppler as well as sattelite laser ranging measurements serve at the first touch to prove the ideas on the movements of main tectonic plates.

It is too difficult to characterize all results available throughout the world in brief report. But pa - pers presented at symposia, or published in journals demonstrate the world-wide activity of our co-workers. It should be point out that the increase of data and results is in good accordance with improvement of systems of analysis and evaluation of final results.

As concerns the KAPG activity, the special crus - tal movement studies are concentrated in the Project



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No. 9. The studies are aimed to the use of recent crustal movement results by prospection of mineral resources, earthquake prediction as well as by evaluation of dynamics of the Carpatho-Balkan region. By means of repeated terrestrial measurements there are studied properties of interaction of surface movement and subsurface deposits of fluid or gas. The results of such a work reveal the capability of geodetic methods to detect zones where a fluid is collected. By means of the experimental measurements across the gas deposit at the depth of 1.5 km with known value of gas pressure the vertical surface changes of about 1 cm were determined by the pressure change of 6 MPa.

The special geodetic networks for monitoring the pre-seismic movements were established in Roumania, Bulgaria and USSR, especially in central Asia and at Sakhalin. In contrary to the classical pre-seismic uplifts the pre-seismic subsidences were revealed by analysis of repeated levelling measurements in Sakhalin seismic area. These phenomena should be studied in connection with the Earth's crust structure and other properties of the locality under study.

In connection with the map of vertical movements of the Carpatho-Balkan region, presented at the XVII. IUGG General Assembly the new map of the vertical movements is going to be prepared. This map will be based on the new relevellings carryied out in 1974-1979 at the territory under study and will be a new addition to data available for studies within the important European region. Moreover, the crustal movements within the Carpathian arc are studied at localities spread at the territory of Roumania, Bulgaria, Hungary, Czechoslovakia and USSR. Some of the results of these works are presented at our symposium, the other will be presented in detail at the next European regional symposium in Budapest, next year. The recent crustal movement studies shall follow the mentioned above trends in order to extend our knowledge of crustal movements and deformations in regional as well as global scale.

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## Über die Aufgaben und Ergebnisse der Untersuchung der rezenten vertikalen Bewegungen in der Karpathen-Balkan Region

I. Joó[1]

### Zusammenfassung

Der Verfasser - als Koordinator der Untersuchung der rezenten vertikalen Erdkrustenbewegungen in der Karpathen-Balkan Region /KBR/ - informiert über das Ziel, die Umstände, Methode und bisherigen Ergebnisse der neueren /1980 begonnenen/ Untersuchung. In Tabellen stellt er die verwendeten geodätischen und ozeanographischen Daten, deren Zuverlassigkeit und die mittleren Fehler der abgeleiteten Geschwindigkeiten und absoluten Höhen vor. Auch die zwischen den mittleren Niveaus der drei Meere /des Baltischen, Schwarzen und Adriatischen Meeres/abgeleiteten Höhenabweichungen werden geschildert. Bis jetzt wurden die gemeinsame Ausgleichung und die Zusammenstellung der nationalen Bewegungskarten durchgeführt. Zur Zeit sind die Zusammenstellungsarbeiten der zusammenfassenden Karte im Maßstab 1:1 000 000 im Gange, deren Herausgabe 1984, Vorstellung im Oktober 1985, am internationalen Symposium in Budapest vorgesehen ist.

Als Ziel der weiteren Untersuchungen werden vom Verfasser die Ableitung der Geschwindigkeitsgradienten der Bewegungen und ihre Darstellung auf der Karte bezeichnet.

## On the Works and Results of Investigations Concerning the Recent Movements in the Karpatho-Balkan Region

### Summary

The author - as coordinator of the study of recent vertical crustal movements in the Carpatho-Balkan Region - gives information on the purpose, conditions and method of recent (starting in 1980) investigations, as well as on the results obtained so far. He presents the applied geodetic and oceanographic data, together with their reliability and the standard error of derived velocities and absolute height data in tabular form. Derived height value differences between the mean sea levels of the three seas considered (Baltic, Black and Adriatic Seas) are also shown. By now joint adjustment, compilation of national maps of movements have been completed. At present compilation of the overall map at scale 1:1 000 000 is under way, with its edition scheduled in 1985, and presentation at the Budapest international symposium in October, 1985.

As far as further investigations are concerned, the author points out the derivation of movement velocity gradients and their cartographic presentation.

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## 1. Einleitung

Das Studium der rezenten Erdkrustenbewegungen erfolgt immer ausgedehnter in den einzelnen Ländern bzw. Kontinenten. Es ist bekannt, daß die zusammenfassende Karte der Erdkrustenbewegungen im Osteuropa im Maßstab 1:2 500 000 schon 1971, an der Plenarsitzung der IUGG in Moskau vorgestellt wurde. Inzwischen hat auch die ausführlichere Untersuchung der rezenten vertikalen Erdkrustenbewegungen in der Karpathen-Balkan Region /KBR/ begonnen. Die aufgrund deren gefertigte Karte im Maßstab 1:1 000 000 wurde in Canberra, am aus Anlaß der XVII. Plenarsitzung der IUGG gehaltenen wissenschaftlichen Symposium vorgestellt. Fast unmittelbar nach der Anfertigung dieses Kartenwerkes wurde es mit der neueren Untersuchung der vertikalen Bewegungen in der KBR begonnen.

Die neuere KBR-Untersuchungen wurden überwiegend dadurch ermöglicht, daß inzwischen neue Präzisionsnivellierungen auf dem Territorium der teilnehmenden Länder durchgeführt wurden. Dementsprechend bot es sich die Möglichkeit, die gegen die Jahrhundertwende bzw. den Anfang des 20-sten Jahrhunderts durchgeführten /und im allgemeinen weniger zuverlässigen/ Messungen wegzulassen. Die Fortsetzung der KBR-Untersuchungen war aber auch deshalb zweckmäßig, weil sich auch einige weitere Änderungen im Vergleich zu der ersten Untersuchung ergaben, namentlich:

- entlang der Grenzen der teilnehmenden Länder wurden neuere Verbindungsmessungen durchgeführt /so war es bei den Anschlußlinien an den Grenzen nicht mehr nötig, Bedingungen bezüglich der relativen Geschwindigkeiten zu benützen;
- neue Verbindungsmessungen und neuer Datenumtausch erfolgten zwischen Ungarn, Österreich und Italien; ferner
- wurde es, veranlassen von den Fachliteraturanweisungen, bestreben, auch die neuesten Ausgleichungsverfahren, namentlich das der gemeinsamen Ausgleichung der Höhen- und Geschwindigkeitswerte im Rahmen der neueren Untersuchung zu verwenden.

Im weiteren werden die laufenden neueren Untersuchungen der rezenten vertikalen Bewegungen in der KBR geschildert, einige Kennzeichen der Untersuchungen, die vorhandenen geodätischen und ozeanographischen Daten, das Ergebnis der bisher durchgeführten Arbeit, die noch zu verrichtenden Aufgaben und die Vorstellungen über die weiteren Untersuchungen vorgestellt. Es ist zu bemerken, daß die Fragen, mit denen sich die anderen beiden ungarischen Vorträge des Programmes dieses Symposiums beschäftigen, in diesem Vortrag nur bis zu dem nötigen Maß verhandelt werden. Diese Themenkreise sind die folgenden:

- Zusammenstellung der Daten der Untersuchungslinien und
- die Methode der Ausgleichung.

## 2. Die neuere Untersuchung der Bewegungen in der KBR

### 2.1 Einige Fragen der Organisation und der Zusammenarbeit

Die Teilnehmer sind die Länder der KBR /Abb.1./ namentlich: Bulgarien, Polen, Rumänien, die Tschechoslowakei und Ungarn. Ferner nimmt die Sowjetunion mit Teilmaterial am Programm teil, und die DDR unterstützt die Untersuchung mit Lieferung von nützlichen Daten.

Das Untersuchungsprogramm befindet sich sowohl im Programm der KAPG /Projekt 9. Thema 5./, als auch in dem der Subkommission Osteuropa der IAG CRCM. Es ist bedeutungsvoll, daß das Untersuchungsprogramm von den geodätischen Diensten der betroffenen Länder wirkungsvoll unterstützt wird.

Obwohl die Koordinierung, Ausgleichung der Daten und die Herstellung der zusammenfassende Karte von Ungarn /Földmérési Intézet = Institut für Geodäsie und Kartographie/ unternommen wurde, nehmen auch die Vertreter der Teilnehmerländer an der Arbeit aktiv teil. Diese werden in der Beilage aufgeführt.

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## 2.2 Ziel und Methode der Untersuchung

Ziel der Untersuchung: Ableitung von zuverlässigeren Charakteristika der rezenten vertikalen Bewegungen in der Region, sich überwiegend auf geodätische und ozeanographische Daten stützend, aber auch Ergebnisse der Geologie, Seismik und Tektonik anwendend.

Diese neuere Untersuchung strebt nicht mehr nur nach der Ausgleichung der Geschwindigkeite und ihrer Darstellung auf der Karte, sondern untersucht die wirkliche Änderungen der Höhen und Geschwindigkeiten zusammen. Dies bedeutet, daß die Teilnehmerländer nicht nur die aus der Wiederholungsnivellierung ableitbaren rohen relativen Geschwindigkeitswerte, sondern auch selbst die Nivellierdaten zu Verfügung gestellt haben. Auf diesem Grund konnte man bei der Ausgleichung unternehmen, die Höhen- und Geschwindigkeitsdaten gemeinsam zu verarbeiten, auszugleichen. Selbst die Ausgleichung hat nicht nur die endgültigen absoluten Geschwindigkeiten, sondern auch die mit einer bestimmten Epoche verbundenen Höhen produziert.

Für die Untersuchung wurden die Mareographdaten von drei Meeren /Baltisches, Schwarzes und Adriatisches Meer/ benutzt.

Bei der Untersuchung wurde angenommen, daß:

- bei den in Frage kommenden Meeren der eustatische Effekt Null ist;
- die Geschwindigkeit der zwischen zwei Zeitpunkten der Nivellierung vorgekommenen Bewegung konstant ist.

## 2.3 Das Untersuchungsnetz und die vorhandenen Daten

Das Untersuchungsnetz wird durch die Abb. 2. demonstriert, zu der die in der Tabelle 1. präsentierten Daten gehören. Demnach gibt es in dem Netz mit einer Gesamtlänge von 40 000 km 432 Linien und 305 Knotenpunkte, die 127 geschlossene Polygone bilden, und die Anzahl der angewendeten Mareographen ist 13.

In der Tabelle 2 sind einige nähere Daten bezüglich der ozeanographischen Daten zu finden. Aufgrund der Tabelle ist es zu sehen, daß die als Ausgangspunkte benutzten Mareographen schon lange funktionieren, die Zuverlässigkeit deren absoluten Höhen ± 1,5 - ± 10 mm, und der mittlere Fehler deren absoluter Geschwindigkeit ± 0,03 mm - ± 0,6 mm/Jahr beträgt. Aufgrund der Tabelle 3 stellt sich heraus, daß die größte Länge der Untersuchungslinien in Polen, bzw. in der Tschechoslowakei vorkommt /8091 bzw. 6543 km/. Darüberhinaus ist das Zeitintervall zwischen der ersten und zweiten Messung /außer den Anschlußlinien/ mindestens 11 Jahre, aber nicht mehr als 72 Jahre.

In der Tabelle 4 wird über die Zuverlässigkeit der verbrauchten geodätischen Daten informiert. Es ist augenfällig, daß fast alle Teilnehmerländer die Zuverlässigkeit der neuesten Nivellierungen bedeutend erhöht haben! Laut der sich in der Tabelle befindlichen Daten ist die Zuverlässigkeit der neuesten Nivellierung in Polen, Österreich, Ungarn und in der Tschechoslowakei am günstigsten.

## 2.4 Bisherige Ergebnisse der Untersuchung

Nach der Kontrolle und Abstimmung der zur Untersuchung zu Verfügung gestellten Daten erfolgte die Ausgleichung /Ausgleichung vermittelnder Beobachtungen, mit voneinander abhängigen Unbekannten/ nach einem Verfahren, dem die von Hazay empfolene Methode [1] als Ausgangspunkt diente.

Vor der endgültigen Ausgleichung wurden zwei vorläufige Ausgleichungen durchgeführt. In die erste vorläufige Ausgleichung wurden nur die gemessenen Höhenunterschiede der zweiten Ausgleichung einbezogen. Infolgedessen konnte man für die Knotenpunkte gute vorläufige Höhen bekommen.

Die zweite vorläufige Ausgleichung erfolgte schon nach demselben Verfahren, wie die endgültige Ausgleichung. In diese wurden die gemessenen Höhenunterschiede der zweiten Nivellierung und die aus den beiden Nivellierungen abgeleiteten relativen Geschwindigkeiten einbezogen. Diese zweite



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vorläufige Ausgleichung hatte das Ziel, einerseits die Grunddaten kontrollieren zu können, andererseits den Einklang der gebrauchten mittleren Meeresniveaus bezüglich sowohl auf die Höhen, als auch auf die vertikalen Bewegungen kennenzulernen. Ausgehend von der letzteren Überlegung war der Ausgangspunkt der Urpunkt Nadap, mit der Verwendung dessen Höhe /in Baltischem System/ und unter der Annahme, daß dessen Geschwindigkeit Null sei:

$$V_{Nadap} = 0.$$

Einige Charakteristika dieser vorläufigen Ausgleichung sind in der Tabelle 5 zu sehen. Bei der Beschauung der in der Tabelle präsentierten Daten sind die folgenden zu berücksichtigen. Für die Höhe und Geschwindigkeit der untersuchten Meere hätte man Nullwerte bekommen müssen, falls sowohl die Ausgangsdaten, als auch die benutzten Meßergebnisse fehlerlos wären, darüberhinaus das Niveau der drei Meere mit derselben Niveaufläche zusammenfiele, und sich die Höhenlage der Meeresniveaus in der Zeit nicht änderte.

Waren die Ausgangsdaten fehlerhaft, hätte man für die einzelnen Meere gleiche Höhen- und Geschwindigkeitswerte bekommen müssen.

Laut der Daten der Tabelle 5 wurden für das mittlere Meeresniveau der untersuchten Meere von Null und auch voneinander abweichende Höhen- und Geschwindigkeitswerte erhalten. Dieser Vortrag hat nicht das Ziel, den Unterschied zwischen den mittleren Meeresniveaus der Meere zu untersuchen. Deshalb wird es nur bemerkt, daß die in der dritten Spalte demonstrierten Niveauunterschiede - mit Berücksichtigung auch auf die in der vierten Spalte der Tabelle befindlichen mittleren Fehler - für signifikant zu betrachten sind.

Bei der endgültigen Ausgleichung der Untersuchungsdaten der KBR bildete sich die Stellungnahme aus, daß die Niveaus des Baltischen und Schwarzen Meeres vom Gesichtspunkt der Untersuchung für identisch betrachtet werden können, das mittlere Niveau des Adristischen Meeres aber von diesen bedeutend abweiche.

Im Hinsicht auf die oben angeführten wurde bei der endgültigen Ausgleichung das mittlere Meeresniveau des Baltischen und Schwarzen Meeres im Wert von 0,000 m, deren absolute Geschwindigkeit im Wert von 0,00 mm/Jahr angenommen. Daneben waren einerseits die geodätischen Daten Österreichs und Italiens, andererseits die sich auf das Adristische Meer beziehenden Mareographendaten wegzulassen.

In der Tabelle 6. werden die mittleren Fehler der aus der endgültigen Ausgleichung erfassenen absoluten Höhen und absoluten Geschwindigkeiten /Spalten 2. und 4./ demonstriert. Es ist festzustellen, daß die Zuverlässigkeit der absoluten Höhen durchschnittlich mit einem Wert von ± 20,5 mm, und die der absoluten Geschwindigkeiten mit ± 1,01 mm/Jahr charakterisiert werden kann.

In den Spalten 3. und 5. der Tabelle 6 werden auch die Durchschnittswerte der bei der Ausgleichung den Höhenunterschieden und den relativen Geschwindigkeiten zugeordneten Kilometer verbesserungen für jedes Land dargestellt. Die vorgestellten Kilometerverbesserungen sind besonders zum Vergleich der Genauigkeit der von den einzelnen Ländern gelieferten Daten geeignet.

Die aus der endgültigen Ausgleichung stammenden absoluten Geschwindigkeiten und deren mittleren Fehler erhielten alle Teilnehmerländer für das ganze Untersuchungsgebiet. Darüberhinaus bekamen alle Teilnehmerländer auch die sich auf die Epoche 1980 beziehenden absoluten Höhen und deren mittleren Fehler für ihr eigenes Territorium. Die Teilnehmerländer haben - mit der Verwendung der von Ungarn zusammengestellten und vorherein zugeschickten Grundkarte - die sich auf ihr eigenes Territorium beziehende vorläufige Landesbewegungskarte zusammengestellt. Diese wurden später abgestimmt.

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## 2.5 Weitere Aufgaben

Im weiteren kann ein jedes Land die ausführliche Analyse, die eventuelle weitere Ergänzung des Untersuchungsmaterials durchführen, und Ungarn stellt die zusammenfassende Bewegungskarte der KBR im Maßstab 1:1 000 000 zusammen.

Das Zusammenstellen und die Herausgabe der Karte ist so geplant, daß sie an dem in Rahmen der IAG 1.-5. Okt. 1985 in Budapest veranstalteten internationalen Symposium über die Untersuchung der Krustenbewegungen, vorgestellt werden kann.

Es scheint zweckmäßig zu sein, in der Periode nach 1985 die Geschwindigkeitsgradienten der vertikalen Bewegungen in der KBR abzuleiten und deren Darstellung auf der Karte durchzuführen, weil die feinere Tendenzen der Bewegungen durch die Geschwindigkeitsgradienten besser zu anerkennen, und in kleineren Bereichen effektiver zu interpretieren sind.

Beilage

Die aktiven Mitwirkenden der neueren Untersuchungen in der KBR

| | |
|---|---|
| Bulgarien: | D. Arabadschijski<br>M. Mladenowski<br>T. Beljaschki<br>T. Burilkow<br>I. Totomanow |
| DDR: | H. Thurm |
| Polen: | T. Wyrzykowski<br>Z. Dziedziuszko |
| Rumänien: | M. Mihailă<br>I. Drăgoescu<br>M. Popescu |
| Sowjetunion: | I.N. Meschtscherskij<br>V.I. Somow |
| Tschechoslowakei: | J. Vanko<br>A. Zeman |
| Ungarn: | I. Joó<br>M. Füry<br>Zs. Németh<br>J. Thury |

Zusammenfassende Daten

Tabelle 1.

| | |
|---|---|
| Anzahl der Linien | 432 /454/ |
| Anzahl der Punkte | 305 /323/ |
| Anzahl der Schleifen | 122 /127/ |
| Gesamtlänge der Linien | 35046 /40 000/ km |
| Anzahl der Mareographen | 13 |
| Meere: | Baltisches M.<br>Schwarzes M.<br>/Adriatisches M./ |
| Anzahl der teilnehmenden Länder: | |
| - mit dem gesamten Landesgrundnetz | 5 |
| - mit Teilmaterial | 2 /4/ |
| - insgesammt | 7 /9/ |

Bemerkung: Die in der Tabelle angegebenen Daten beziehen sich auf die endgültige Ausgleichung, die in den Klammern beziehen sich hingegen auf das am Anfang der Untersuchung zusammengestellte Netz.



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Ozeanographische Daten

Tabelle 2.

| Land | Anzahl der Mareographen | Anfang der Beobachtung | $m_h$ /± mm/ | $m$ absolute Geschwindigkeit /± mm/Jahr/ |
|---|---|---|---|---|
| DDR | 2 | 1900 | ± 1,5 | ± 0,03 |
| Polen | 7 | 1868 | ± /8,0-12,0/ | ± /0,1 - 0,5/ |
| Sowjetunion /Odessa/ | 1 | 1875 | ± 10,0* | ± 0,28 |
| Bulgarien | 2 | 1929 | ± 10,0* | ± 0,4* |
| Italien | 1 | 1944 | ± 10,0* | ± 0,6* |

* Geschätzter Wert

Geodätische Daten

Tabelle 3.

| Land | Gesamtlänge der Nivellierlinien /km/ | Zeitintervall zwischen den beiden Nivellierungen /Jahr/ |
|---|---|---|
| Bulgarien | 3496 | 35-49 |
| DDR | 1604 | 18-22 |
| Polen | 8091 | 13-29 |
| Rumänien | 5438 | 11-69 |
| Sowjetunion | 4031 | 15-72 |
| Tschechoslowakei | 6543 | 12-41 |
| Ungarn | 3858 | 13-27 |
| Italien | 185 | 21-25 |
| Österreich | 1318 | 14-28 |
| Anschlusslinien zwischen den Landern | 482 | 5-26 |

Ergebnis der vorläufigen Ausgleichung

Tabelle 5.

| Meer | Land | Das von Nadap abgeleitete mittlere Meeresniveau | | | |
|---|---|---|---|---|---|
| | | Höhe /mm/ | Mittlerer Fehler /± mm/ | Geschwindigkeit /mm/Jahr/ | Mittlerer Fehler /± mm/Jahr/ |
| Baltisches M. | DDR | - 107/103-111/ | ± /35-36/ | + 1,1 | ± 1,6 |
| | Polen | - 99/ 82-115/ | ± /20-24/ | - 1,0 | ± 1,3 |
| Schwarzes M. | Sowjetunion | + 51 | ± 46 | + 0,4 | ± 2,1 |
| | Bulgarien | - 128/ 98-158/ | ± /26-28/ | + 3,4 | ± 2,0 |
| Adriatisches M. | Italien | - 475 | ± 40 | + 5,3 | ± 3,1 |

Bemerkungen: a/ Die Werte in den Klammern zeigen die Extremwerte!

b/ Die Verbindungsmessung des Mareographen Odessa und des geodätischen Festpunktes wurde nur in einem Fall durchgeführt.

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Zuverlässigkeit der geodätischen Daten

Tabelle 4.

| Land | Mittlerer Fehler der Nivellierungen | |
|---|---|---|
| | Erste Nivellierung | Zweite Nivellierung |
| Bulgarien | /0,70 - 0,85/ /± mm/ √km/ | /0,36 - 0,48/ /± mm/ √km/ |
| DDR | /0,20 - 0,33/ - " - | /0,28 - 0,51/ - " - |
| Polen | /0,17 - 0,56/ - " - | /0,18 - 0,39/ - " - |
| Rumänien | /0,58 - 1,44/ - " - | /0,24 - 0,89/ - " - |
| Sowjetunion | /0,20 - 2,32/ - " - | /0,53 - 1,62/ - " - |
| Tschechoslowakei | /0,17 - 0,72/ - " - | /0,24 - 0,52/ - " - |
| Ungarn | /0,10 - 0,73/ - " - | /0,27 - 0,34/ - " - |
| Italien | /0,63 - 0,64/ - " - | /0,52 - 0,70/ - " - |
| Österreich | /0,46 - 0,64/ - " - | /0,19 - 0,40/ - " - |
| Anschlusslinien zwischen den Ländern | /0,24 - 2,00/ /± mm/ km/ | /0,22 - 0,71/ /± mm/ km/ |

Zuverlässigkeitsmesszahlen aus der endgültigen Ausgleichung

Tabelle 6.

| Land | Mittlerer Fehler der absoluten Höhen /± mm/ | Kilometerverbesserung der Höhenunterschiede /mm/km/ | Mittlerer Fehler der absoluten Geschwindigkeiten /± mm/Jahr/ | Kilometerverbesserung der relativen Geschwindigkeiten /mm/Jahr/km/ |
|---|---|---|---|---|
| Bulgarien | 21,8 | 0,084 | 0,95 | 0,002 |
| DDR | 13,2 | 0,038 | 0,59 | 0,003 |
| Polen | 15,7 | 0,054 | 0,75 | 0,004 |
| Rumänien | 27,3 | 0,094 | 1,70 | 0,009 |
| Sowjetunion | 40,4 | 0,059 | 1,80 | 0,006 |
| Tschechoslowakei | 17,6 | 0,083 | 0,86 | 0,008 |
| Ungarn | 18,7 | 0,029 | 0,96 | 0,004 |
| Durchschnittswert in der KBR | 20,5 | - | 1,01 | - |
| Anschlusslinien zwischen den Ländern | - | 0,102 | - | 0,026 |

Bemerkung: Die angegebenen Daten sind immer Durchschnittswerte!

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DAS TERRITORIUM DER NEUEREN UNTERSUCHUNGEN IN DER KBR

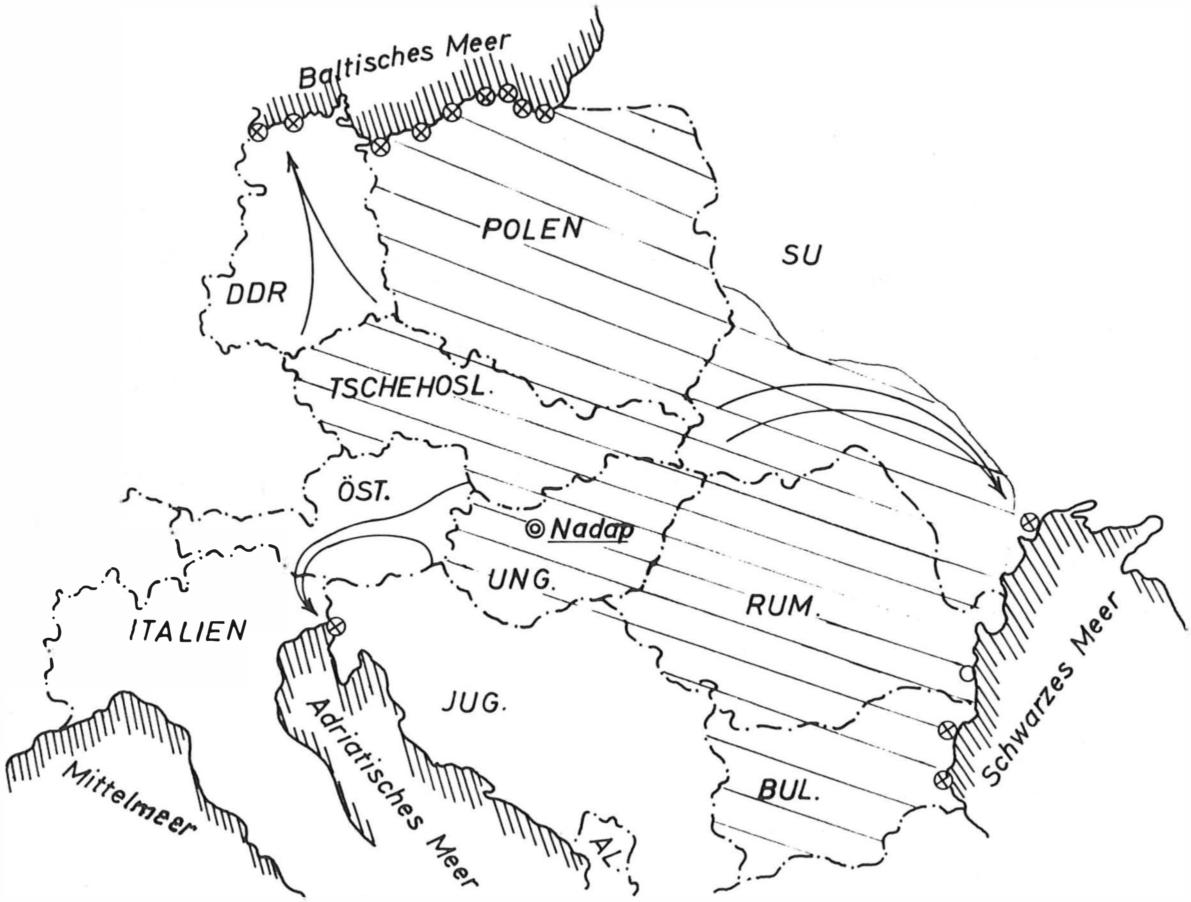


Abb. 1.

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DAS NEUERE WIEDERHOLUNGS-NIVELLIERNETZ DER KARPATHEN-BALKAN REGION


Abb. 2.

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# NORTH SEA COAST LEVELLING NET: A MODEL CASE FOR THE DETERMINATION OF VERTICAL MOVEMENTS IN WESTERN EUROPE

by

W. Augath* und H. Pelzer**

## 1 Short history of coastal subsidence investigations in Northern Germany

In Northern Germany, permanent tide gauge records have been available for investigations since about 1850. As a result of such investigations it was found that in the North Sea the mean sea level (MSL) seems to increase by an amount of approximately 2 mm/year being nearly twice the amount of the eustatic change of the MSL recorded all over the world. This result suggested a coastal subsidence of about 1 mm/year.

In order to study this effect in more detail a special precise levelling net (North Sea Coast Levelling Net, NKN) was established after 1910 and observed repeatedly; see ch. 2 for more information. First results were published in (AdV 1960) more or less confirming the earlier assumption of land subsidence. Strictly speaking, a tendency toward land subsidence was discovered, the amounts determined lying within their statistical confidence regions.

After 1960 the "Niedersächsisches Landesverwaltungsamt, Abteilung Landesvermessung (NLVA), and the Geodetic Institute of the University of Hanover (GIH) continued these investigations, the GIH starting in 1974 within the scope of the "Sonderforschungsbereich 149 - Vermessungs- und Fernerkundungsverfahren an Küsten und Meeren" - being supported by the German Research Council. Efforts have been made towards methodical development and at collecting historical levelling data. In connection with and regarding these investigations, the Subcommission Western Europe of the IAG-Commission of Recent Crustal Movements at its meeting in Karlsruhe in 1981 chose Hanover as computing center for the connection of regional and national networks and for the determination of height changes.

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## 2 Collection of levelling data in Northern Germany

Precise levellings have been carried out in Northern Germany since 1865, initially mainly to solve scientific problems of defining height data (M.S.L.) and to create the first continental levelling nets, which was done by official surveying authorities. The quality of these first precise measurements is based on the European instructions laid down in 1864. Therefore the first extensive levelling net in the lowlands of Northern Germany was established in 1869-76, the whole net being completed by 1894. The problem of different height data was solved by installing a standard bench mark (point of reference, set up in 1879 and transferred in 1912) which defines the reference surface to be nearly identical with the Mean Sea Level of the North Sea.

The levelling lines followed the existing roads and the bench marks were placed at equal intervals by the roadside. Special geological conditions were neglected and as a consequence the stability of the bench marks was extremely influenced by outer effects and inherent motions. The standard deviation of unit weight based on levelling sections measured in the forward and backward directions for Northern Germany was estimated to be 1.30 mm/$\sqrt{km}$.

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This levelling network was renewed constantly, but until 1912 no high accuracy was obtained. It was therefore necessary to carry out precise measurements comprising the whole network, only the point of reference was retained. From 1912 until 1942 the complete first-order levelling network of Germany was established. Taking into consideration the special geological conditions new kinds of marking were installed, as there are fundamental national bench marks, underground bench marks, height marks, wall pins, and the bench marks of the original levelling network. The second part of this extensive first-order levelling network is located in the region of the northern lowlands of the Federal Republic of Germany (FRG), measured from 1912 until 1922. In figure 1, the levelling lines of this area are shown. Only the original observations of these lines are available (RfL, 1927).

It is a well-known fact that in the northern lowlands of the FRG no special geodynamically active regions exist; however, since 1908 (Schütte, 1908) the possibility of the North Sea coast subsiding - an issue of utmost importance to the people of this region - has been discussed from a scientific point of view.

In addition to geological methods it was necessary that precise relevellings check and verify existing theories of crustal movements (Wolf, 1929). For this reason and taking into account the special geological situation in this part of the country, an extensive levelling net had to be established reaching, in this case, from the central highlands to the North Sea and Denmark. This special network was called "North Sea Coast Levelling Net". In view of the main purpose of these measurements this levelling net was an independent one following mainly, however, the existing lines of the first-order levelling network. In addition to the described height marks, many deep-founded pipes were installed. This net is divided into a basic net (first order levelling network of 1912-22) and supplementary lines completing the net near the important re-

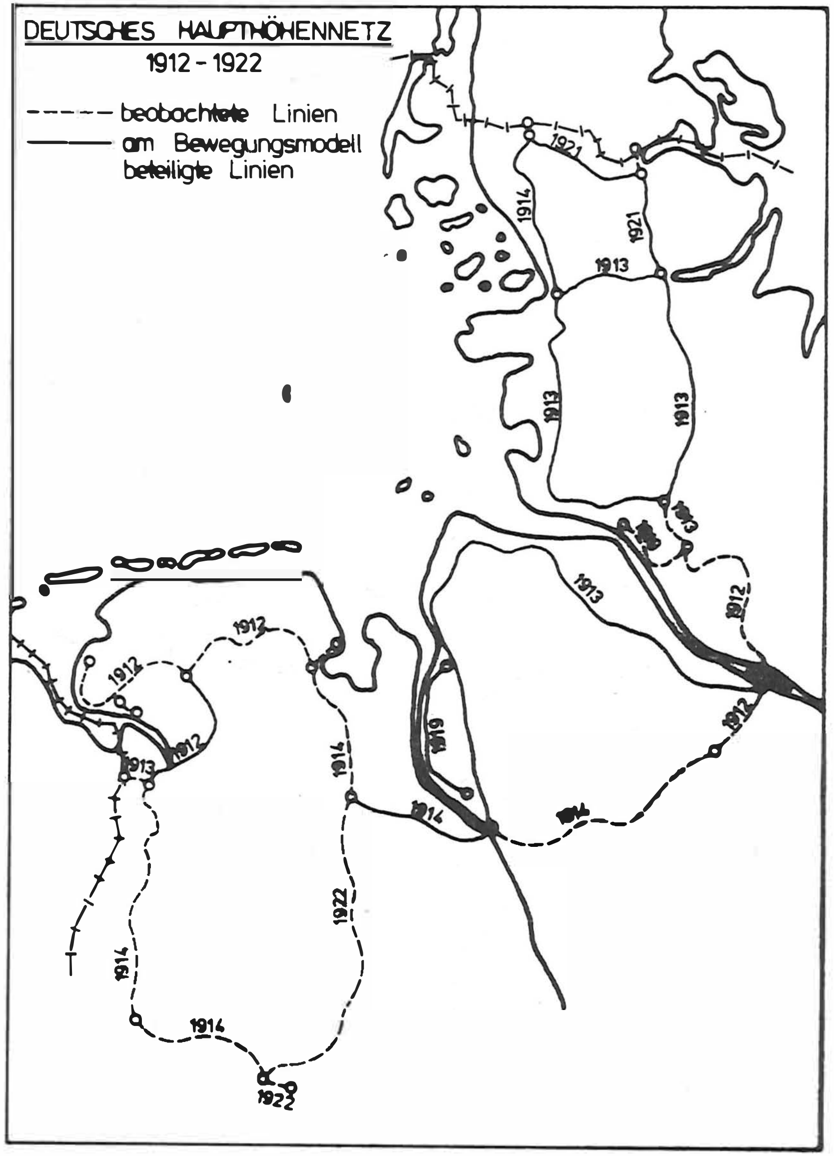


Fig.1: Levelling lines of the First Order Levelling Network - Part II - 1912-22



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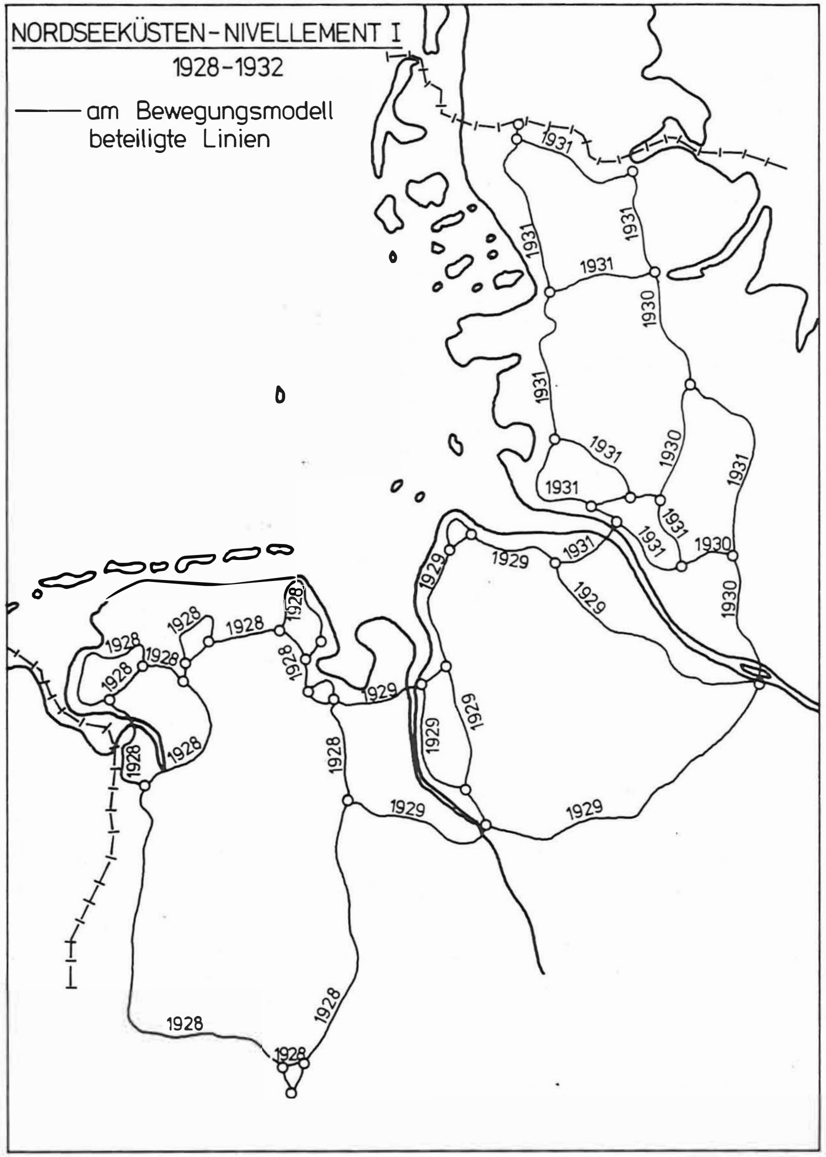


Fig. 2: Levelling lines of the North Sea Coast Levelling Net I - Basic Net, 1928-32

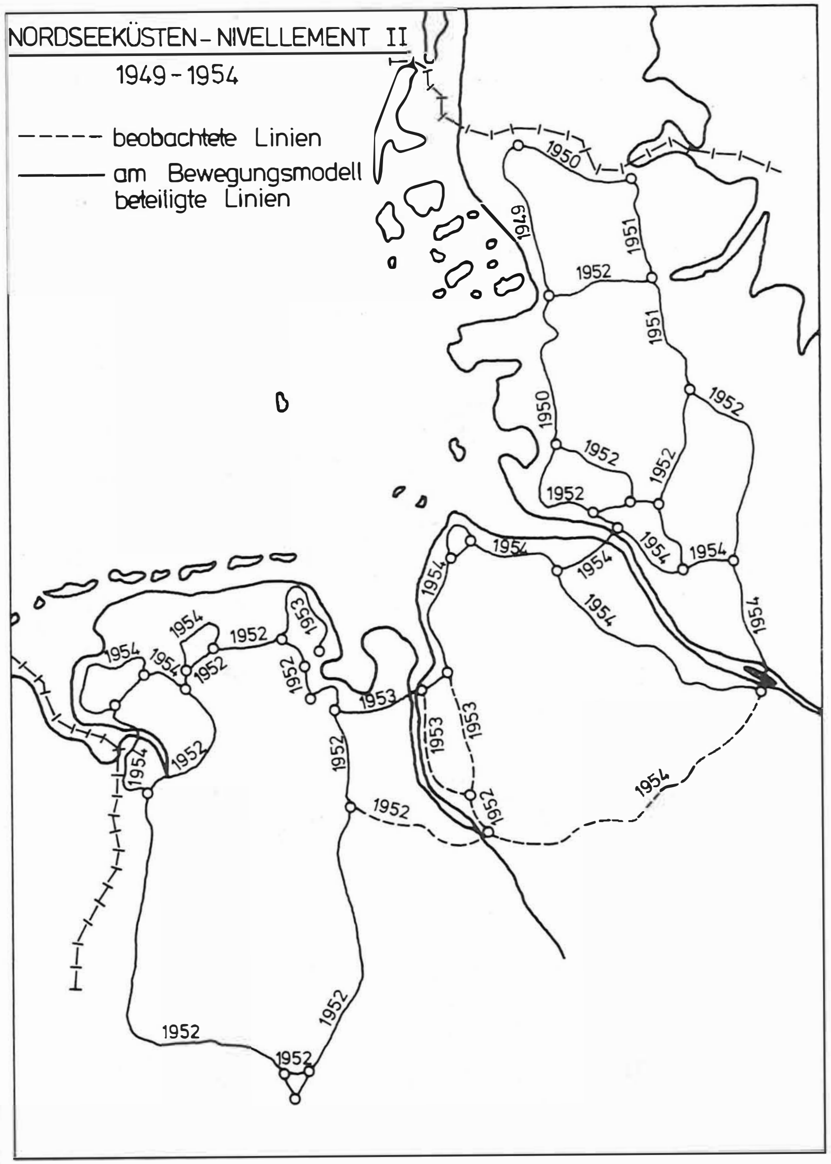


Fig. 3: Levelling lines of the North Sea Coast Levelling Net II - Basic Net, 1949-54

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gion, namely the coast, and connecting the islands. Until then, this net had been measured completely in two periods, from 1928 until 1932 and from 1949 until 1954 (basic net). The levelling lines of the first period are shown in figure 2. Only the original observations of these lines are available (RfL, 1932).

Additionally, the second period is depicted in figure 3. In this case, all levelling observations are available; however, for the first period of studying vertical crustal movements on the basis of the first-order levelling network (1912) to the second period of the North Sea Coast Levelling Net (1954) only the observations of the levelling lines are included in a thorough analysis. The most important facts gained from these three extensive precise levelling measurements are given in table 1.

| | First order Levelling Network(II) | North Sea Coast Levelling Network basic net | |
|---|---|---|---|
| | | Period I | Period II |
| observation time | 1912-22 | 1928-31 | 1949-54 |
| number of levelling lines | 27 | 53 | 49 |
| length of the levelling lines | 1439 km | 1911 km | 1721 km |
| number of points involved in the following investigations (height marks, wall pins and underground bench marks) | 26 | 38 | 35 |
| standard deviation | | | |
| - from sections | .34 | .35 | .38 mm/ km |
| - from adjustment | .43 | .29 | .62 mm/ km |

Table 1: Fundamental data of the First Order Levelling Net and the North Sea Coast Levelling Nets for the first studies of vertical crustal movements

## 3 The Hanover Analysis Approach

The Hanover Analysis Approach (Pelzer 1980; Heer, Leonhard 1982; Leonhard 1984) was established for the computation of vertical crustal movements covering large areas. The computation is done step by step so that the individual results can be checked.

### 3.1 Adjustment and model check in partial networks

All height determinations (spirit levelling, motorized levelling, hydrostatic levelling, high precision trigonometric observations) of one year are regarded as observed simultaneously during a particular epoch. It is assumed that within the rather short observation period - April to October - no observable movements occur.

The observations of one epoch are put together to form one partial net. If there are configuration defects, a corresponding number of partial nets has to be established. Each partial net is adjusted as a static free network. If an individual partial net forms a real network and not just one line, it is possible to perform statistical tests on outliers and on systematic effects and to estimate the observation precision.

The results of the partial net adjustment are listed below:

free heights $\underline{\hat{h}}_i$ (1)

their cofactors $(\underline{Q}_{\hat{h}\hat{h}})_i$ (2)

and the standard deviation $(s_{OT})_i$ (3)

of the partial net № i.



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## 3.2 Connection of the partial networks

### 3.2.1 Preparation of the partial nets

The partial nets to be connected are usually very different in size, design and precision. Therefore it will not be possible to compute rates of movement for each point. Points whose height is determined only once have to be eliminated. A solvability algorithm results with heights, point velocities and accelerations being solvables (Leonhard, Niemeier, Pelzer 1984; Leonhard 1984; Holdahl, Hardy 1979).

If one or more points of a partial net have to be eliminated, this partial net must be reduced to the points which are part of the general system. The matrices with the heights and the cofactors of the points under consideration

$$\underline{\hat{h}}_i^{red}, \ (\underline{Q}_{\hat{h}\hat{h}})_i^{red} \tag{4}$$

are usually regular. With the help of Baarda's S-Transformation the individual cofactors and the free heights can be found (v. Mierlo 1978):

$$\underline{h}_i = \underline{S}_i \ \underline{\hat{h}}_i^{red} \tag{5}$$

$$\underline{Q}_i = \underline{S}_i \ (\underline{Q}_{\hat{h}\hat{h}})_i^{red} \ S_i^T \tag{6}$$

Finally, the Bartlett Test (Höpcke, 1980) checks whether the standard deviations of all partial nets belong to the same population. If this is not the case, the cofactor matrices are homogenized by the average $s_{OT}$ of all standard deviations $(s_{OT})_i$ (Leonhard, 1984):

$$s_{OT}^2 = \frac{\Sigma \ f_i (s_{OT})_i^2}{\Sigma \ f_i} \tag{7}$$

### 3.2.2 Formulation of the Movement Model

The functional model of the general system describes the heights of the partial nets $\underline{h}(t_i)$ with the heights at the reference time $\underline{h}_o$ and with the motion parameters $\underline{g}$ (velocity) and $\underline{b}$ (acceleration):

a) static model:

$$\underline{h}(t_i) = \underline{h}_o \tag{8}$$

b) linear model:

$$\underline{h}(t_i) = \underline{h}_o + \Delta t_i \underline{g} \tag{9}$$

c) quadratic model:

$$\underline{h}(t_i) = \underline{h}_o + \Delta t_i \ g_o + \frac{1}{2} \Delta t_i^2 \ \underline{b} \tag{10}$$

The observations of these models are the free heights of the partial nets (eq. 5). The stochastic model is given by their cofactor matrices (eq. 6) in combination with the observation precision (eq. 7).

The determination of the movement model is done by steps. Starting with the static model the null hypothesis is formulated:

$H_o^s$ : no movements between the epochs. (11)

The general system is solved without using parameters for movements. Then a global congruency test (Pelzer 1980, 1981; Niemeier 1979) verifies whether $H_o^s$ can be applied.

If the static model cannot be accepted and if local disturbances need not be assumed the model of linear movements for all points has to be computed. The null hypothesis is:

$H_o^l$ : all points carry out linear movements. (12)

Again, this model is checked by the global congruency test. If $H_o^l$ is rejected, it is possible to compute a quadratic model. This means that the null hypothesis is given by:

$H_o^q$ : all points have quadratic movements consisting of a velocity and an acceleration term. (13)

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Corresponding tests have to be applied.

Due to the very short time a geodetic measurements takes in comparison with geological processes, the geodynamic meaning of acceleration terms may be doubtful. An extension of the models for movements of a higher degree does not seem to be advisable. It should be avoided to choose a "best approximation" to a given data set without any geophysical relevance.

### 3.2.3 Improvement of the Stochastic Model

The heights of the bench marks may vary constantly in a small range. Paint and corrosion may influence the point definition. The surroundings, for example, are influenced by changing ground water conditions and by a varying traffic load. The uncertainties of the heights can be considered with the help of a point disturbance (Milev, Simeonova, Leonhard, 1984). It seems to be sensible to adopt a point disturbance of

$$\tau = \pm 1.0 \text{ mm}. \quad (14)$$

The introduction of the point disturbance means that the point variances of the covariance matrices of the partial nets will increase. In the following, the movement model has to be computed again with the improved stochastic model. The standard deviation of the general system will improve.

### 3.3 Datum Stipulation

The results of the general system are inner heights and relative movement parameters. They only describe the inner geometry of the model, meaning they represent "shape changes" (Leonhard, Niemeier, Pelzer, 1984). This is of special interest to geologists and geophysicists for interpretation purposes (Reilly, 1981).

If the geological situation requires the adoption of stable bench marks, the free system is transformed on these datum parameters (Leonhard, 1984). In a first step, one stable point is chosen to correct the datum defect of the general system. By an iterative process all moving parameters are found which are not significantly different in relation to the parameters chosen first. For each iteration a global test checks the standard deviation of the datum stipulation against the observation precision.

## 4 Preliminary results of test calculations

For testing purposes the approach described in ch. 3 was applied to a small but typical data set in Northern Germany being a subset of the levelling data available for that region. This means that the results shown below should be considered test results rather than contributions to the issue of coastal subsidence.

In a first test case the approach of ch. 3 was applied to the data set with the following specifications:

case 1: moving model : linear
standard deviation
a priori : $\sigma_o = 0.5 \text{ mm}/\sqrt{\text{km}}$
point disturbance : $\tau = \pm 0.0 \text{ mm}$

The results are shown graphically in fig. 4. There seems to be a stable region in the southern and northwestern part of the investigation area and significant subsidence in the northern and central part.

How well the linear movement model fits can be measured by the standard deviation a posteriori; this yields from the adjustment:

$$s_o = 1.52 \text{ mm}/\sqrt{\text{km}}$$

This high value indicates model disturbances which have to



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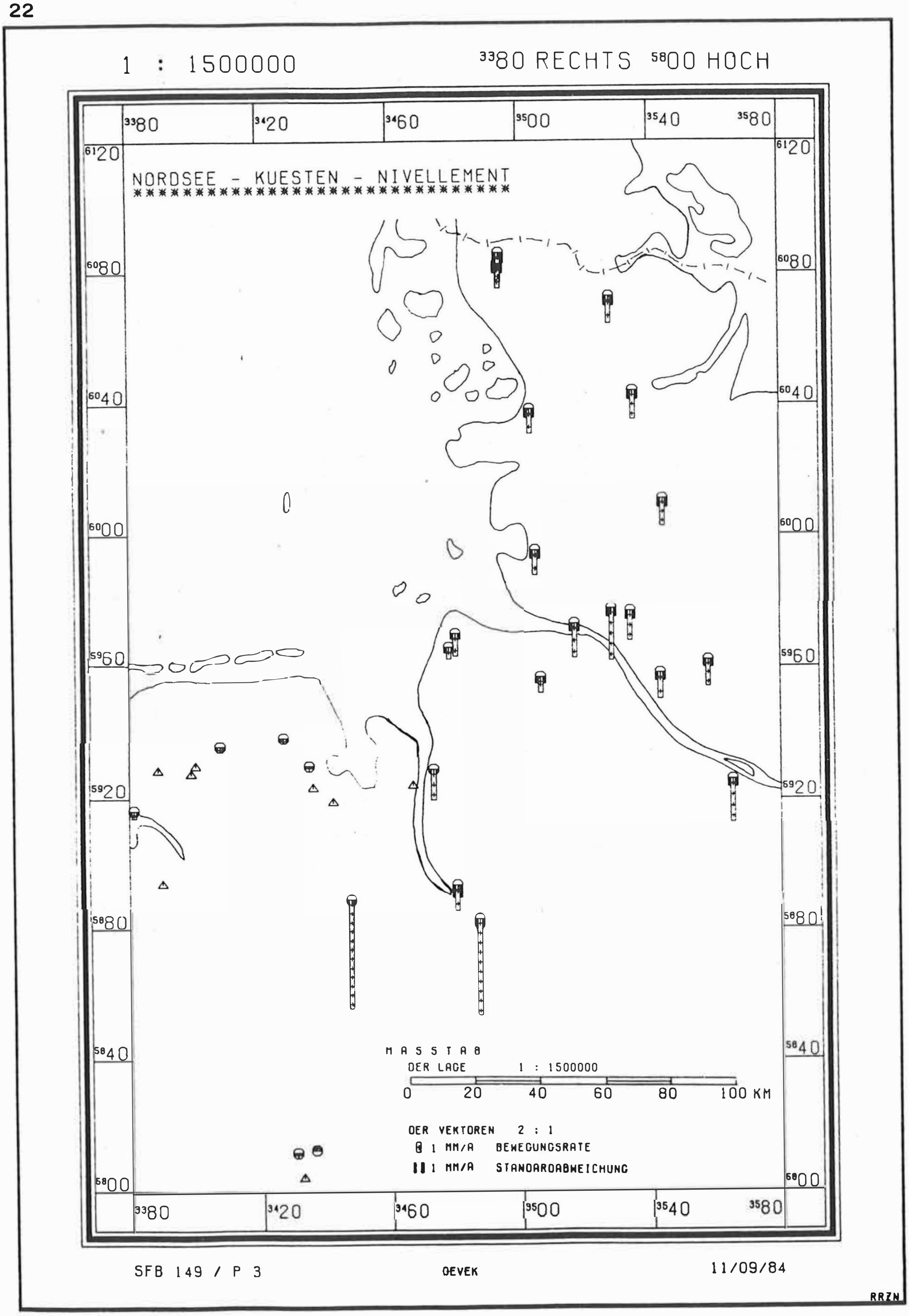


Fig. 4: Height changes in Northern Germany, test case 1 (s. ch. 4)

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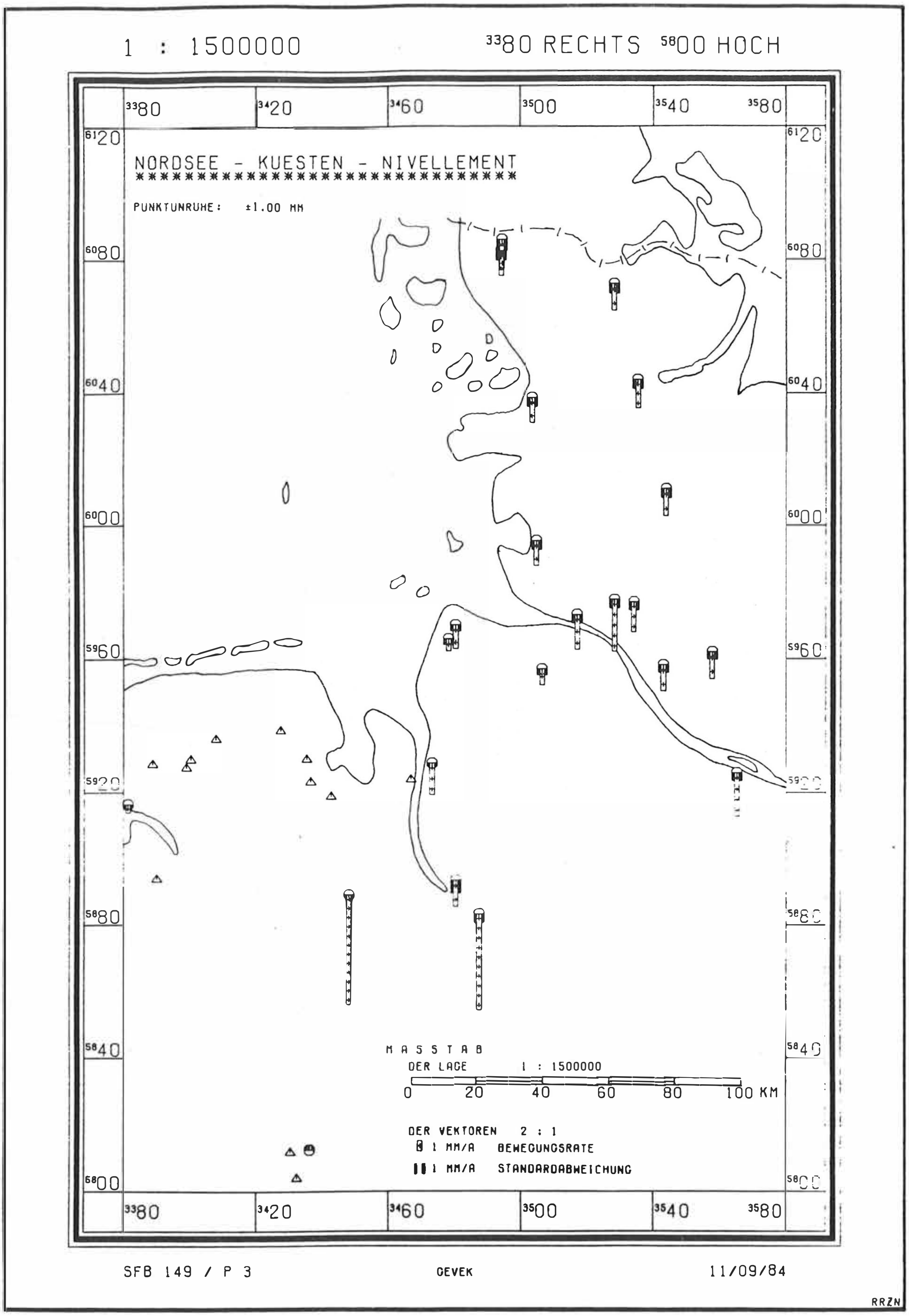


Fig. 5: Height changes in Northern Germany, test case 2 (s. ch. 4)

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be located. In a second test calculation the point disturbance was therefore chosen as

case 2: $\tau = \pm 1.0$ mm.

In case 2 the standard deviation $s_o$ decreases negligibly to

$$s_o = 1.47 \text{ mm}/\sqrt{\text{km}}$$

and the point movements are very similar to the movements in the first case (fig. 5), i.e. the model is robust with respect to the parameter $\tau$. This individual test result, however, should not be generalized without further investigations.

## 5 Conclusion

At the regional meeting in Karlsruhe, the newly selected computation center proposed to start the investigations in the northern part of Germany adding the other Western European countries one by one. In the meantime, we have made good progress with creating the technical conditions and gathering experience. Concerning the adjustment there will be no problems with the capacity after finishing the connection with the adjustment system HANNA (Weise, 1984 ). As regards the data base for points and observations, the results of the national project "ALK" (Elmhorst, Sellge, Steinhauer, 1981)(Augath, 1984) are at our disposal. This data base was created for all geodetic points, the special requirements of levelling points are fulfilled.

The work presented here has shown that a big effort is necessary to register the existing observations. The area of the NKN dealt with in this paper includes about 6000 points in two or three epochs and we had to invest 3 more years for registration. Therefore it will be one of the most important tasks of the members of the subcommission to start or complete these investigations.

## Acknowledgments

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# Space-time variating geological masses by space-time variating geodetic measurements

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Summary

The gravity measurements and the repeated levellings are the space-time variating geodetic measurements which are introduced in the deductions. The plausible hypothesis is presupposed that the recent crustal movement phenomenons which are here to be investigated cover spherical caps of smaller than 1000 kilometer diameter. The other reoent crustal movement phenomenons existing at some other distant places exterior of this cap are approximatively supposed to influence not the space-time geodetic measurements within the considered area. The space-time variating geological masses are represented in terms of some point masses. A relation between these geological masses and the space-time geodetic measurements is derived.

Zusammenfassung

Als geodätische Messungen werden Schweremessungen und Wiederholungsnivellements herangezogen. Es wird die Hypothese eingeführt, daß die rezenten Krustenbewegungen nur Wellenlängen haben, die kleiner als 1000 Kilometer sind. Unter diesen Voraussetzungen wird gezeigt, wie regionale geologische Massenverschiebungen aus regionalen geodätischen Messungen bestimmt werden können.

A combination of levellings and gravity measurements determines the recent vertical movements of the Earth's crust. The concerned mathematical relations require a global coverage by gravity measurements and levellings with utmost accuracy. However, such a coverage is in reality on principle not possible because a third of the Earth's surface only consists of continents giving the opportunity to execute such precise measurements there. On the oceans precise gravity measurements within a /ugal and precise levellings are not possible. The recent crustal movements are computed by

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the following integral, [2], [3], [5],

(1) $$v = \frac{1}{4\pi}\,\frac{R}{G} \iint_{\omega} [\delta g + \frac{2}{R}\, G\, \delta z]\, S_T(\psi)\, d\omega + \delta z \,.$$

Space-time variating potentials are investigated in [4] also. v is the vertical shift of the Earth's surface $\sigma$ caused by the geological phenomena, $\delta g$ is the change of the gravity at a certain surface point, $\delta z$ is the change of the levelled heights above the concerned level surface. R is the radius of the Earth, G the mean global value of the gravity. $S_T$ is the Stokes function and $\omega$ the unit sphere.

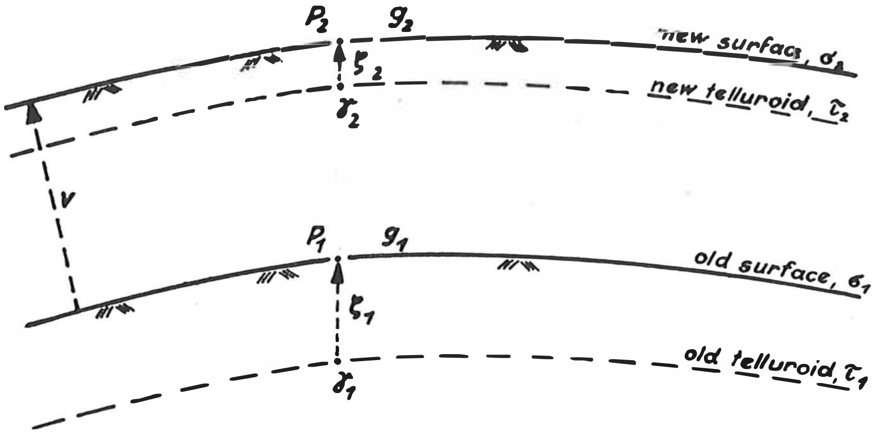


Figure 1.

The height of the quasigeoid above the ellipsoid is denominated by n and the normal heights by z, thus

(2) $$v = n_2 + z_2 - (n_1 + z_1) \,,$$

(3) $$v = \delta n + \delta z \,,$$

(4) $$v = \delta\zeta + \delta z \,.$$

The relations (1) and (4) give the shift of the height anomalies, $\delta\zeta$, and the shift of the perturbation potential at the surface of the Earth, D,

(5) $$D = G\,\delta\zeta = \frac{R}{4\pi} \iint_{\omega} [\delta g + \frac{2}{R}\, G\, \delta z]\, S_T(\psi)\, d\omega \,.$$

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(6) $\delta g = g_2 - g_1$ ,

(7) $\delta z = z_2 - z_1$ ,

(8) $\delta \zeta = \zeta_2 - \zeta_2$ ,

(9) $D = T_2 - T_1$ .

The time shift of the gravity and of the levelled heights are preoisely known along the gravimetric test-lines, $\delta g$, $\delta z$. $\delta g$ and $\delta z$ are known on the continents only. Therefore, it is intended here to try to find a way to determine the time changes of the geological masses by the continental values of $\delta g$ and $\delta z$.

The equation (5) gives

(10) $$\frac{\partial D}{\partial r} + \frac{2}{r} D = - [\delta g + \frac{2}{R} G \delta z] .$$

The potential D at the surface of the Earth has a spherical harmonios development, its convergence at the surface of the Earth is secured, [1],

(11) $$D = \sum_n (\frac{1}{r})^{n+1} D_n Y_n (\varphi , \lambda) .$$

The following presupposition is introduced,

(12) $$n \geq 10 .$$

Thus,

(13) $$\frac{\partial D}{\partial r} + \frac{2}{r} D \cong \frac{\partial D}{\partial r} \cong - \sum_n n(\frac{1}{r})^{n+2} D_n Y_n(\varphi , \lambda ) .$$

The inequality (12) permits only such wavelengthes which are shorter than about 2000 km. In most cases the individual phenomena of the recent crustal movements have a horizontal extension of some hundred kilometers only. A spatial extension up to a size of much more than 2000 x 2000 km square will be very seldom. Otherwise, such low frequencies can be filtered out in any case. Therefore,

(14) $$\frac{\partial D}{\partial r} = - [\delta g + \frac{2}{R} G \delta z] .$$

The potential D consists of two parts, i.e. the potential of the time ohanges of the geological masses in the interior of the Earth and the potential of the masses in the surface layer between the old and the new surfaoe of the Earth, $\sigma_2$ and $\sigma_1$,

(15) $$D = D_{\vartheta} + D_{\sigma} .$$

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The potential $D_{\vartheta}$ is the potential of the geological mass shifts which is to be determined.

(16) $$D_{\vartheta} = D - D_{\sigma} .$$

The surface layer potential has the following shape,

(17) $$D_{\sigma} = f\varrho \iint_{\sigma} \frac{1}{e} v \, d\sigma ,$$

(18) $$\frac{\partial}{\partial r} D_{\vartheta} = \frac{\partial}{\partial r} D - \frac{\partial}{\partial r} D_{\sigma} ,$$

(19) $$\frac{\partial}{\partial r} D_{\sigma} = - 2\pi f\varrho v + f\varrho \iint_{\sigma} v \frac{\partial \frac{1}{e}}{\partial r} d\sigma .$$

The Earth approximates a sphere. Therefore, the following relation is valid,

(20) $$\frac{\partial}{\partial r} D_{\sigma} = - 2\pi f\varrho ( \delta\zeta + \delta z) - f\varrho \frac{1}{2R} \iint \frac{1}{e} v \, d\sigma .$$

All the terms of the order

(21) $$\frac{1}{R} D$$

are always neglected here. Therefore,

(22) $$\frac{\partial}{\partial r} D_{\sigma} = - 2\pi f\varrho ( \delta\zeta + \delta z) .$$

The Bruns' relation

(23) $$\delta\zeta = \frac{1}{G} D$$

leads to

(24) $$\frac{\partial}{\partial r} D_{\vartheta} = - [\delta g + \frac{2G}{R} \delta z] + 2\pi f\varrho [\frac{D}{G} + \delta z] .$$

Again, the amount

(25) $$\frac{1}{R} D \cong 0$$

is neglected. Thus,

(26) $$\frac{\partial}{\partial r} D_{\vartheta} = - \delta g - (\frac{2G}{R} - 2\pi f\varrho ) \delta z .$$

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The expression

(27) $\left(\frac{2G}{R} - 2\pi f\rho\right) \delta z = \Gamma \delta z$

is the Bouguer reduction for a plane plate with the thickness $\delta z$.

(28) $\Gamma = 0.3086 - 0.1119 = 0.1967$ [mgal/m] .

This abbreviation leads to

(29) $\frac{\partial}{\partial r} D_\vartheta = - \delta g - \Gamma \delta z$ .

The potential of the geological masses $D_\vartheta$ is now expressed in terms of the potentials of point masses $m_i$ situated at the points $Q_i$ below the surface of the Earth.

(30) $D_\vartheta (P) = f \sum_i m_i \frac{1}{e(P,Q_i)}$ .

The relations (29) and (30) yield

(31) $\delta g + \Gamma \delta z = - f \sum_i m_i \frac{\partial}{\partial r} \left\{ \frac{1}{e(P,Q_i)} \right\}$ .

The inversion of (31) gives the space-time variation of the geological masses $m_i$ which are the values to be determined.

Finally, the following facts can be pointed out:
In the investigation of the recent crustal movements the determination of the time variations of the geopotential in terms of the space-time variations of gravity and levellings is a difficult problem if it is treated in full universality. In rigorous reasonings the measurements must have a global coverage. Consequently, it is also difficult to determine the space-time geological masses from the space-time potential values.

However, if the radial derivation of the space-time geopotential is introduced and if the constituents with a wave length of more than 2000 km are so small that they can be ignored, in this case it is possible in practice to determine the space-time geological masses of the individual recent crustal movement phenomena.

Here, the Bouguer reduction was obtained theoretically. The relation

(32) $\delta g + \Gamma \delta z = 0$

resulted also empirically by the works of Kiviniemi in Finland and Torge and Kanngieser in Northern Iceland, [6]. These authors found in the mean

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(33) $\quad \Gamma = 0.2$ .

Thus, the investigated recent crustal movements are caused by an influx of new masses which have about the same density as the old masses. Deviations from the equation (32) will show the influx of masses which have another density than the old masses.

The above theoretical investigations show the limits of the empirically obtained result, (32).

It proves, that the shift of the level surface can be neglected in the first approximation in the computation of the Bouguer reduction in our problem.

An eventual refinement of the relation (31) should account for the term of the order

(34) $\quad \frac{1}{R} D$ ,

yielding

(35) $$\delta g + \Gamma \delta z = - f \sum_i m_i \left[ \frac{\partial}{\partial r} \left\{ \frac{1}{e(P,Q_i)} \right\} - \frac{2\pi f \varrho}{G} \frac{1}{e(P,Q_i)} \right] .$$


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# Geokinematic models for the gravimetric W - E profile of the GDR

by

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## Abstract

The gravimetric W - E profile of the GDR is situated between Magdeburg and Frankfurt/Oder. It crosses in its western part the Central German - Polish main fault, which forms the transition from the high-lying crystallin rocks to the mesozoic-kaenozoic sedimentary basin. The net slip of the step fault is about 3 km. The strongest horizontal gradient of gravity in the european region occurs here.

Starting from the geological-geophysical situation simple geokinematic models are built up for the interpretation of possible temporal gravity changes, whereby also movements of the Earth's surface were included: relative movements of different blocks and mass redistributions in different geotectonic levels (Upper mantle, Earth's crust and intrasedimentary processes).

The deep-seated dynamics of the block structure cause in the gravity field a contribution whose extend coincides with a possible subdivision of gravity changes on the W - E profile. The intrasedimentary dynamics may be considered as a noise at the different observation points.

## Zusammenfassung

Die gravimetrische West - Ost - Linie der DDR wurde zwischen Magdeburg und Frankfurt/Oder angelegt. Sie überquert in ihrem westlichen Teil den Mitteldeutsch-Polnischen Hauptabbruch, der den Übergang von hochliegendem Kristallin zum mesozoisch-känozoischen Sedimentbecken darstellt. Die Gesamtsprunghöhe beträgt etwa 3 km. Hier tritt der stärkste Horizontalgradient der Schwere im europäischen Bereich auf.

Ausgehend von der geologisch-geophysikalischen Situation werden einfache kinematische Modelle zur Interpretation von möglichen zeitlichen Schwereänderungen aufgestellt, wobei auch rezente Erdkrustenbewegungen eingeschlossen werden: Relativbewegungen von verschiedenen Blöcken gegeneinander und Massenneuverteilungen in verschiedenen tektonischen Stockwerken (oberer Mantel, Erdkruste und intrasedimentäre Prozesse).

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Die tiefangelegte Dynamik der Blockstrukturen verursacht im Schwerefeld einen Anteil, dessen Beitrag und räumliche Verteilung mit einer möglichen Klassifizierung der zeitlichen Schwereänderungen auf der W - E - Linie zusammenfällt. Die intrasedimentäre Dynamik kann als "Rauschen" an den einzelnen Beobachtungspunkten betrachtet werden.

## 1. Introduction

During the last decade more and more high precision gravity profiles and nets where installed in different regions, where recent geologic-geotectonic movements are supposed and distinct height variations are determined. By repeated gravity observations the correlations are studied between the deformations of the Earth's surface and the synchroneous variations of the gravity field.

Significant results however could be reached up to now in recent active zones, where large movements of the ground are observed mostly restricted to smaller regions of some tens of kilometres, f.i. in Iceland. But also smaller vertical movements (in the order of a few millimeters/a) caused by recent orogenic processes or by the displacements of very extended tectonic units like shields or the roots of mountain chains are connected with observable variations of the gravity field (USSR Alma-Ata, Fennoscandia and Columbia). Finally in districts with artificial released and sufficient extended masses (mining activities, oil or gas exploitations combined with ground water movements) significant gravity variations could be detected (USSR Orenburg, Venezuela).

For the geophysical understanding of the character of the most recent movements of the Earth's crust the main features of the geological evolution must be considered, especially in connection with the forces acting in the different epochs. Fig. 1 shows this situation in Europe. We may see the distribution of the main tectonic cycles both in space and time:

- Proterocoic basement older than $10^9$ years,
- Caledonian cycle, 400 mill. years ago,
- Variscian cycle, 250 mill. years ago,
- Alpide cycle, 100 mill. years ago.

Up to now significant temporal gravity variations only could be detected in regions influenced by most recent force systems:

- Iceland (rifting processes)
- Fennoscandia (disappearance of the ice cap).

In the Middle Europe the most recent forces, generating the geological main features were acting about 100 mill. of years ago. For this reason the reactions of the crust to this forces is nowadays a very small one. In the test areas situated in the region

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of special geological structures, f.i. Rhine graben, margin of the North German - Polish basin, Carpathian mountains and other places, the gravity variations will be expected in the order of a few 0.1 μGal/year[x] and might be detected only by some decades of continuous precise gravity measurements.

For the numerical description of the connection between gravity variations, surface deformations and mass distributions we at first want to give some general remarks.

## 2. Gravity changes, surface deformations, and mass redistributions

The gravity vector $\vec{g}$ in an earth-fixed geocentric coordinate system may be written in the form

$$(1) \qquad \vec{g} = \vec{g}\,(\vec{r}(t),t) = f \cdot \int_{E(t)} \frac{\varrho'(\vec{r},t) \cdot (\vec{r}-\vec{r}\,')}{|\vec{r} - \vec{r}\,'|^3}\, d\tau + (\vec{\omega} \times \vec{\omega} \times \vec{r})$$

The first term represents the gravitational acceleration of the entire earth ($10^9$ μgal) and the second one describes the centrifugal acceleration of the rotation of the earth ($10^6$ μgal). The influence of the direct and the Coriolis-accelerations of the recent crustal movements ($10^{-9}$ and $10^{-5}$ μgal respectively) may be disregarded. Also the EULER-acceleration $\dot{\vec{\omega}} \times \vec{r}$ ($< 10^{-2}$ μgal) is neglected. Polar motions and the variations of the speed of rotation slightly influence the centrifugal acceleration.

The temporal derivation $\delta$ of $\vec{g}$, $\delta\vec{g}$ may be expressed now by

$$(2) \qquad \delta\vec{g} = \frac{d\vec{g}}{dt} = \nabla\vec{g} \cdot \frac{d\vec{r}}{dt} + \frac{\partial\vec{g}}{\partial t}\,.$$

We remark that the instantaneous temporal gravity variation depends on the velocity ($d\vec{r}\ /\ dt = \vec{v}$) of the (recent crustal) movement at the observation point combined with the local structure of the gravity field ( $\nabla\vec{g}$, MARUSSI tensor) and on the redistribution $\delta\varrho\,(\vec{r},\ t)$ of the Earth's masses and variations of the centrifugal force

$$(3) \qquad \frac{\partial\vec{g}}{\partial t} = \frac{\partial}{\partial t}\left[ f \int_{E(t)} \frac{\varrho'(\vec{r}',t)\,(\vec{r} - \vec{r}\,')}{(|\vec{r} - \vec{r}\,'|)^3}\, d\tau + \vec{\omega} \times \vec{\omega} \times \vec{r} \right]\,.$$

The MARUSSI-tensor mainly is determined by $\frac{\partial g_r}{\partial r} \doteq 300$ μgal/m. Each of the other constituents in general is smaller than 1 μgal/m. For the investigation of gravity variations inside regional networks we get for the temporal variation $\delta\Delta g$ of the gravity difference $\Delta g_{21} = g_2 - g_1$ within the limits of error of about 1 %:

x) 1 μGal = $10^{-8}$ m.s$^{-2}$

DOI: https://doi.org/10.2312/zipe.1985.081.03

(4) $$\delta\Delta g_{21} = \frac{\partial g_2}{\partial r} v_{r_2} - \frac{\partial g_1}{\partial r} v_{r_1} + \frac{\partial}{\partial t} \Delta g_{21}$$

For precise interpretations the local gravity gradients along the vertical must be known with an accuracy of about 1 %. The following estimations are performed with $\frac{\partial g}{\partial r} = 3.086$ $\mu$gal/cm as a reasonable mean value. Then we can consider the relative velocity $\Delta v_{r_{21}} = v_{r_2} - v_{r_1}$ and we obtain as a first approximation the well known relation

(5) $$\delta\Delta g_{21} = 3.086\ \Delta v_{r_{21}} + \partial / \partial t\ \Delta g_{21} .$$

In small scale networks the second term in (5) may be restricted to a certain region, which should be found out by numerical studies. The temporal variation of the centrifugal acceleration may be disregarded in repeated relative gravity measurements.

For investigations in a regional scale we can construct the following process model (Fig. 2a): From the geological point of view we have an idea on the tectonic model TMO (extension and driving forces), in our case a germanotype tectonics. The overlying layers react on this forces following the laws of rock mechanics RME. In general we can write the displacement $d_i$ of the i-th layer in an operator equation

(6) $$d_i = TMO_i * RME_i .$$

On the Earth's surface we obtain the deformation of the last layer in form of the results of the repeated levellings $\delta\Delta H$, the temporal height difference variation between the two points 1 and 2.

As mentioned above for temporal gravity variations me must consider both $\delta\Delta H$ as well as $d_i$ in the underground, since the displacements $d_i$ cause temporal density variations $\delta\Delta\varrho$. With N as the NEWTONIAN kernel and $\Delta v_{r_{21}} \cdot t \doteq \delta\Delta H$ in regional models we write formula (5) in the form

(7) $$\delta\Delta g = 3.086\ \delta\Delta H_{21} + \delta\Delta\varrho * N .$$

Our main interst is focused on the possibility to find out the parameters $M_{TMO}$ for the mass redistribution $\delta\Delta\varrho$. Because of the non-uniqueness of the relation between source and gravity field several models for $\delta\Delta\varrho$ are possible. To restrict the possibilities we look for the models, which are valid for $\delta\Delta H$. Since they have a common cause (TMO, $d_i$) we can select these source parameters in the parameter sets of $\delta\Delta H$ ($M_H$) and $\delta\Delta g$ ($M_g$) which are in both sets (Fig. 2b) (section of two parameter sets)

(8) $$M_{TMO} = M_H \cap M_g .$$

It means that for a successful modelling we need both geological and geophysical informations.

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## 3. Geological-geophysical situation on the W - E profile

The general geological situation for the gravimetric W - E profile may be described as follows (Fig. 3): The Eastern Middle Europe is divided by the TORNQUIST-THESSEIRE line, which marks the south-western border of the praeripharic stable complex of the Eastern European platform. Around this platform we see in the Northern Europe the folded structures of the Caledonids (approx. $4.10^8$ years). At the marginal region of the Eastern European platform in the Northern Middle Europe the German basin in post-variscian age and later the North German - Polish depression were built up. Here we have sediments of a few kilometers of thickness. In the Cretaceous age and the Tertiary the southern part of this basin was subjected to the Saxonian fault-fold structure development (approx. $10^8$ years ago). This process results to the uplift of a few blocks like the Harz mountains, the Flechtingen massiv and the Thuringian forest.

The aim of the high precision gravimetric measurements on the W - E profile consists in the investigation of the behaviour of the recent movement at the margin of the North German - Polish depression together with the supposed recent dynamics of the Saxonian block structures. With respect to the old consolidated Variscian mountain range the profile is situated approximately 50 km northern of the Central German crystalline zone, which may be regarded as a guide line for the Variscian mountain chain.

The western points of the profile (Hakenstedt, Irxleben) (Fig. 4) are situated on the Saxonian uplifted fault block. At two fault systems (Haldensleben fault, Gardelegen fault) this block undergoes a subsidence in the north-eastern direction characterized by fault throws of 1.2 km and 3.5 km resp. The observation point Detershagen lies directly in the neighbourhood of the Gardelegen fault. The mesozoic-kaenozoic sedimentary rocks in the direct foreland of the Gardelegen fault doesn't present a horizontal stratification. Salt domes and ridges give rise to a tectonic subdivision, which reflects in a certain sense the tectonic stress situation of this region. The middle and eastern parts are situated in the range of the Berlin gravity minimum which is caused by the thicker upper palaeozoic - mesozoic sedimentary layers. The Saxonian faults loose their significance here.

In the range of the W - E profile the most predominant element of the BOUGUER map is the gravity maximum of Magdeburg - Flechtingen. This maximum might be explained by the high position of the old palaeozoic rocks with respect to the mesozoic ones ($\Delta\rho = 0.15 \cdot 10^3$ kg.$m^{-3}$) on the one hand and on the other by the uplifted position of basic layers of the deeper crust. In the region of the Central German main fault the deeper crust and Upper Mantle are influenced by the Saxonian tectonics also. After gravimetric and seismic investigations the MOHOROVICIC discontinuity shows a jump of approx. 2 km in the direction of NE. It means that an isostatic compensation in this depths does not take place yet. A geotectonic working hypothesis hints on the possibility that this process occurs in the depth of the mountain roots of the Alps, i.e. 60 km approx. A further indication of the stability of the crust and Upper Mantle is the fact that in regions of the Haldensleben and the Gardelegen faults no earthquakes occur.

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## 4. Geodetic-gravimetric modelling

From the point of view of geophysical-geological regional division one can expect for the middle part of the W - E profile two types of mass redistributions:

- in connection with salt tectonics (esp. for observation point Genthin)
- in connection with Rhenish trend of disturbances, caused by deep-seated ( > 10 km) structural elements.

For further decisions on possible models for mass redistributions we look for the results of repeated levellings on the W - E profile (Fig. 5). On this basis we can subdivide three units of mutual height differences or velocities resp.:

Block 1 (stations Hakenstedt, Irxleben, Detershagen (!) and Genthin (!!))
70 km length
no movements of the first three stations in relation to each other, very small movements of the station Genthin

Transition zone (between observation points Genthin and Potsdam)
60 km length
there we have a local minimum (25 km length) and a strong linear trend between Brandenburg and Potsdam (35 km length)

Block 2 (stations Potsdam, Woltersdorf and Diedersdorf)
85 km length
no significant relative motions of the observation points, but an absolut lower value with respect to block 1.

From this statements we can conclude that neither the Central German main fault nor the salt tectonics have an important influence on the repeated levellings. The main variations in the velocities occur in the far foreland of the faults (60 ... 90 km). Using the assumption (which must be proved in a later stage of this investigation) that the spatial dimension of the subsidence is an indication for the depth of the mass redistribution, we can construct three different models (Fig. 5):

Model A: (for the profile section between Genthin and Brandenburg)
Mass redistribution in a lcoal area, say 10 km and in comparatively low depth (5 to 10 km)

Model B: (for the region between Brandenburg and Potsdam)
Mass redistribution in a more extended (20 km) and in a greater depth (20 ... 40 km)

Model C: (for the stable regions: block 1 and 2)
Mass redistributions in a large extension (about 50 km or more) and in a considerable depth (60 km).

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A first interpretation leads to the assumption, that model A can be allocated to crustal process, whereas model B gives a hint to processes in the lower crust and Upper Mantle in connection with the different motions of the block 1 in relation to block 2.

The gravity fields in coincidence with these models show for each model specific spatial dimension of the gravity variation.

## 5. Comparison with observational results

Since 1976 our soviet colleagues four times determined the absolute value of gravity at Potsdam, and they supported seriously by their results also our regional investigations on temporal gravity variations. Using these absolute data we calculated from the results of the yearly performed gravity measurements along our profile gravity values for the single sites referred to 1976 as zero value. Fig. 6 shows the mean gravity values of all the sites computed for the years 1977 to 1983 together with the absolute data at Potsdam. To find out possible differences in the character of the gravity variations along the profile we eliminated a common linear trend. For the period 1976 till 1979 - 15 µGal/y and for the period 1980 - 1984 + 16 µGal/y were eliminated from the data.

The remaining residuals presented in Fig. 7 support the imagination of the different character of the gravity variation in the western and in the eastern part of the profile in accordance with the geologic-geokinamatic model. The amplitudes of the observed residuals are mainly influenced by instrumental effects and cannot yet be used for model comparisons.

## 6. Conclusions

Temporal gravity variations are caused by point movements and mass redistributions. For the detection of the source mechanisms both the influences must be separated by the aid of additional informations on crustal movements and on the local structure of the gravity field. The processes generating the redistribution of masses may be studied by models, whose surface effects agree with the observed gravity and height variations.

From the regional geophysical-geological situation in the district of the gravimetric W - E profile of the GDR and the distribution of the vertical crustal movements a geokinamatic model is most probable, whose parameters are given by a depth from 6 to 7 km, a horizontal extension of ten kilometers and a density variation of $10^{-4}$ $g.cm^{-3}y^{-1}$. This source model produces gravity variations at the surface in the order of 6 µGals.

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At present the scattering of the repeated gravity determinations indicates the influence of the behaviour of the different geological blocks. The continuation of the yearly gravity measurements and the improvement of the instrumentation data processing and statistical decision rules are important for the detection of the estimated gravity variations.

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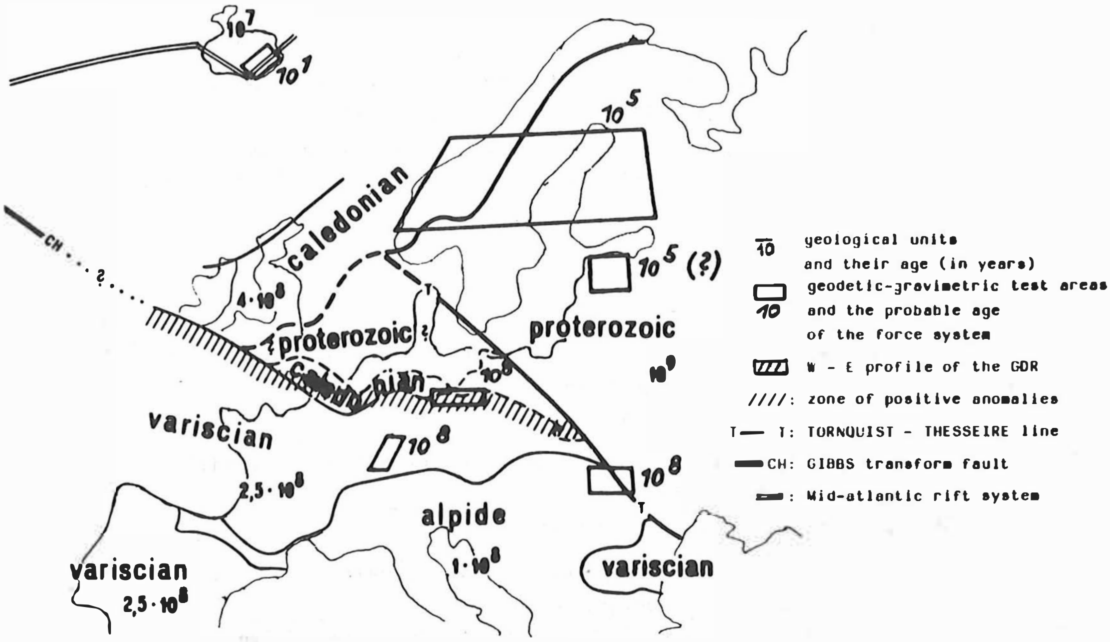


Fig. 1: Consolidation stages of the Earth's crust in Middle Europe (upright numbers) and the probable age of the geological force systems (slanting numbers) in several geodetic-gravimetric test areas

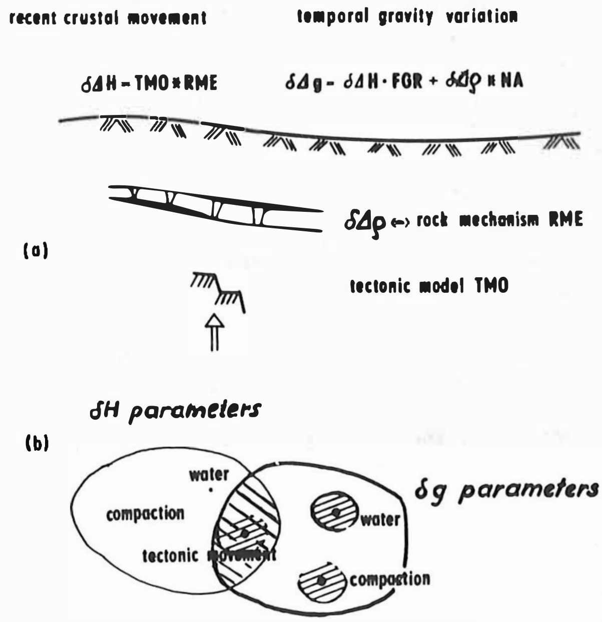


Fig. 2: Working schema for geokinematic models in small-regional and local scales: (a) relations between the geotectonic model for the basement (TMO), the recent crustal movement $\delta\Delta$ H and the temporal variation of gravity $\delta\Delta$ g; (b) selection of the most probable model by the intersection of the parameter sets for geodetic and gravimetric models

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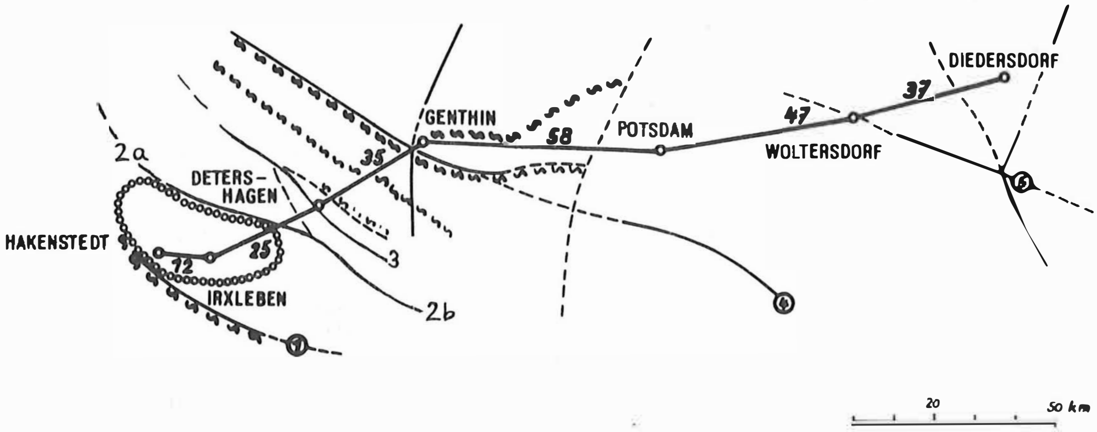


Fig. 3: Tectonic situation in the region of the gravimetric W - E profile of the GDR

25 : W - E profile, observation points and their mutual distances

ooo: Magdeburg gravity maximum

SSS: tectonic salt structures

1 : Allertal fault zone

2a: Haldensleben fault

2b: Wittenberg fault

3 : Gardelegen fault

4 : Genthin fault zone

5 : Freienwalde fault zone

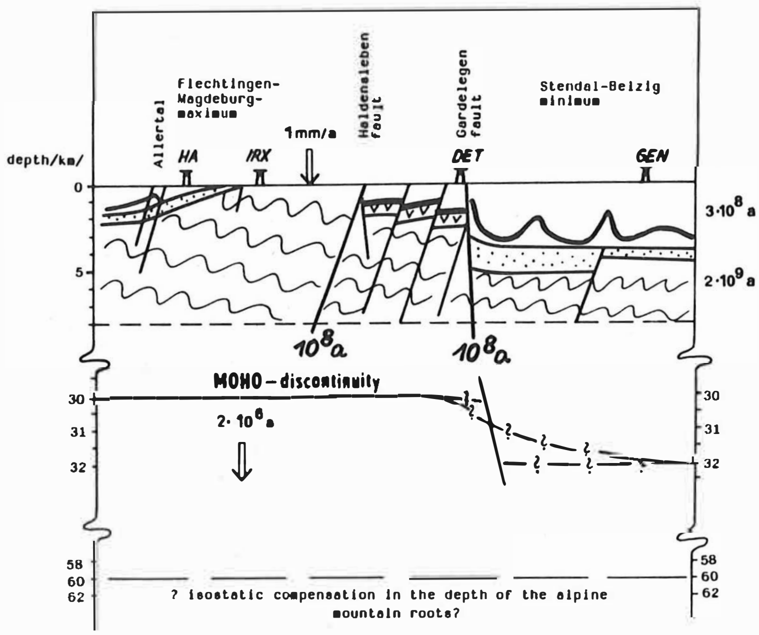


Fig. 4: Schematic geological cross-section of the western part (Central German main fault) of the W - E profile

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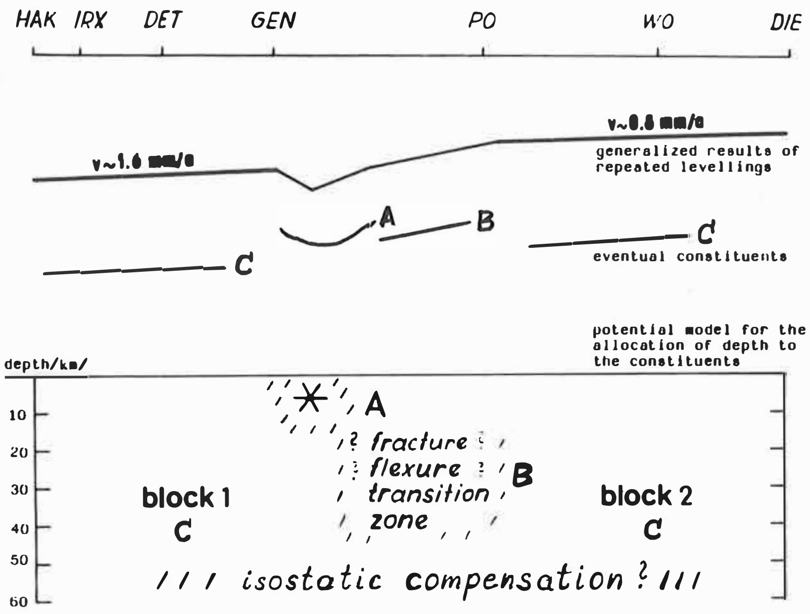


Fig. 5: Simple geokinematic models derived from repeated levellings along the gravimetric W - E profile

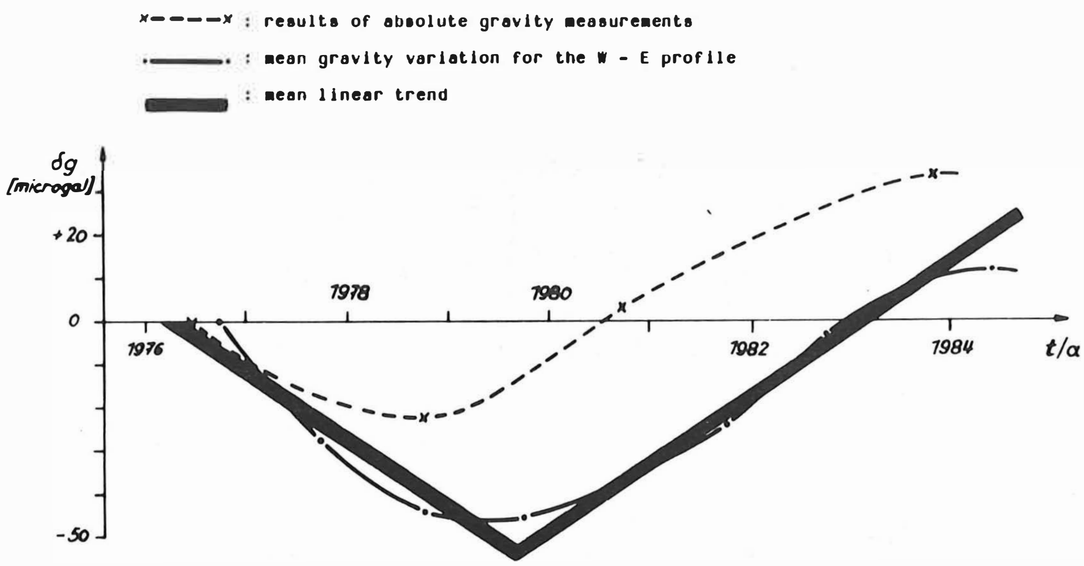


Fig. 6: Absolute gravity measurements at Potsdam and their relation to the results of the W - E profile

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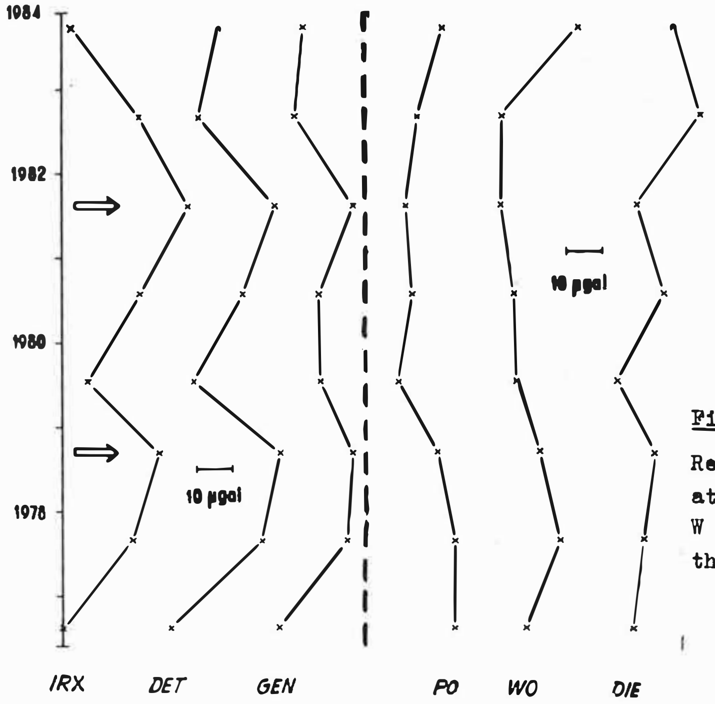


Fig. 7: Residual gravity values at the points of the W - E profile against the mean linear trend

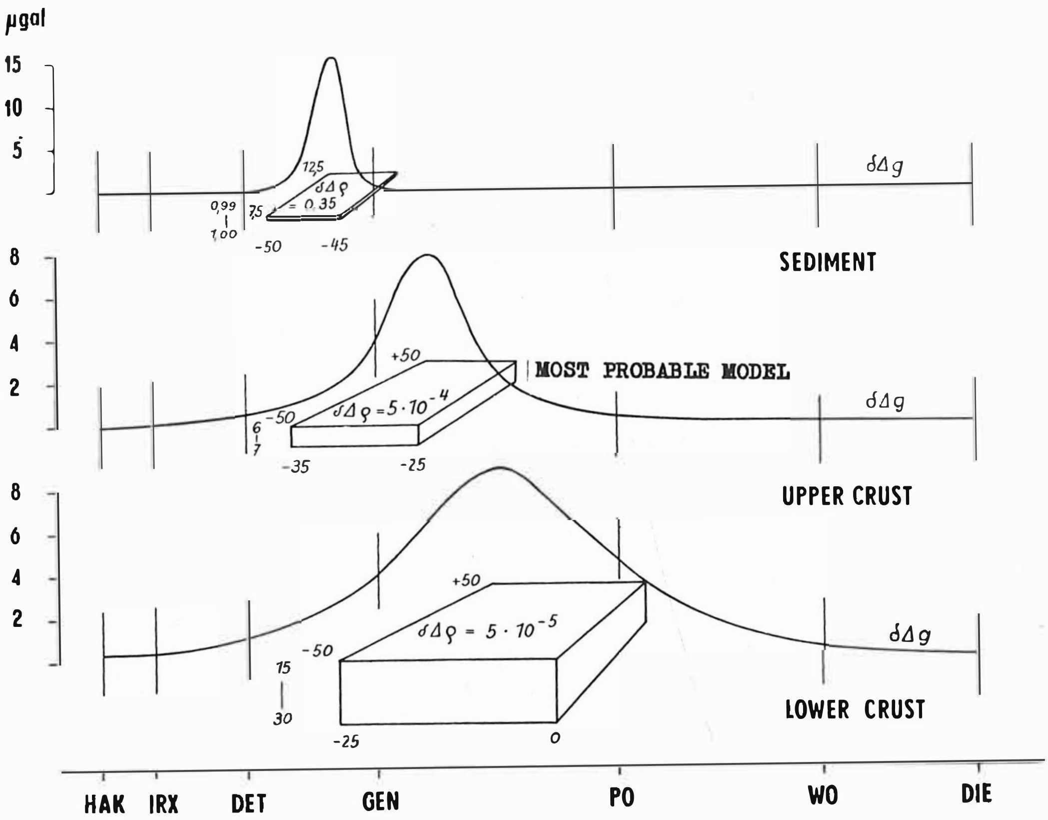


Fig. 8: Variations (f.i. in ten years) of gravity $\delta\Delta g$ due to density variations $\delta\Delta\varrho$

(a) in the sedimentary layer

(b) in the upper crust (model A in fig. 5)

(c) in the lower crust (model B in fig. 5).

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# MATHEMATICAL TREATMENT OF VERTICAL MOVEMENTS

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## Abstract

The vertical movement is an important geodynamic phenomenon both in regional as well as in local scale. Determination of the kinematical parameters /displacement, velocity and acceleration/ is the principal task in the treatment of measured data.

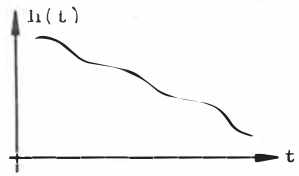
Presently, these parameters are usually determined at measured points and some interpolation method is used between these points.

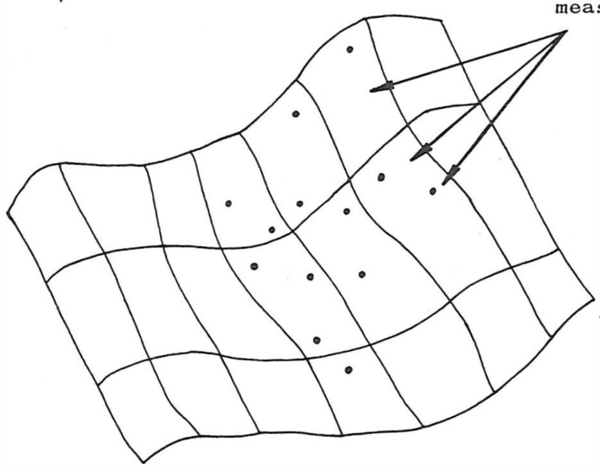
In this paper the problem is tackled by an analytical method. The observed surface is approximated by a 3D harmonic series in space and in time. An application example is given using DFT to describe the surface motion over a working coal-mine.

## 1. Introduction

The main goal of the investigations of the vertical movements is to determine the surface motions with respect to time. This investigations are performed both in small /some square km-s/ and large /regional, continental/ scales. The small-scale investigations are generally used to monitor the effect of artificial activities, first of all of mining, upon the surface motions. The large-scale processes are carried out to solve geodynamic problems. The measuring processes in these investigations are classical geodetic measurements. The observation method is generally to repeat these measurements from time to time. In consequence of this fact we have a "digitized image" of a continuous process /i.e. of the surface motion/ in two senses: 1. in time and 2. in space. To accomplish the mentioned main goal /to describe the motion/ we have to restore the motion from these discrete data as correctly as possible. A generally used method is to describe the kinematical behaviour of every single measured points.

In this paper a method is presented with the purpose to facilitate the treatment of measured data making use of only one analytical form for the total surface to describe the changes of vertical coordinates of the points.



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Since there is no way - due to the measuring techniques - to change the "discrete character" of the measured data, we must use some interpolation method to get informations about the gaps between the measured points. Naturally, in our method, the above mentioned analytical form carries out this interpolation both in space and in time. In an example a DFT /Discrete Fourier Transformation/ method was used to construct the functional form of the surface and applied to a small--scale vertical movement area. We had two reasons to present here a small-scale application: 1. the observed motion was huge as compared to the magnitude of the crustal vertical movement /~ 50 cm/year vs. 1-2 cm/year/ due to mining activity under the surface, 2. we had sufficient data from this area.

## 2. Mathematical background

To obtain the vertical coordinate of a surface point located in the non-measured gap when we have only the point-like information at discrete epochs the traditional method is: a, to determine coordinates of the surrounding measured points $x_i(t)$, $y_i(t)$, $z_i(t)$ at the appropriate epoch t by interpolation /usually by a linear one/, b, then the vertical coordinate $z(t)$ /at given horizontal coordinates $x(t)$, $y(t)$/ will be interpolated from the time-interpolated surrounding points. An interpolation in time generally must be carried out with horizontal coordinates as well as with the vertical one, because vertical motions involve mostly horizontal ones. Kinematical information /velocity, acceleration/ can be computed - even for measured points - also by some numerical process /first or second order numerical derivation, respectively/.

$$\left.\begin{array}{l} x_i(t_1),\ x_i(t_2),\ \dots,\ x_i(t_m) \rightarrow x_i(t) \\ y_i(t_1),\ y_i(t_2),\ \dots,\ y_i(t_m) \rightarrow y_i(t) \\ z_i(t_1),\ z_i(t_2),\ \dots,\ z_i(t_m) \rightarrow z_i(t) \end{array}\right\} \quad i = 1, \dots, n$$

$$\left.\begin{array}{l} x_1(t),\ x_2(t),\ \dots,\ x_n(t) \\ y_1(t),\ y_2(t),\ \dots,\ y_n(t) \\ z_1(t),\ z_2(t),\ \dots,\ z_n(t) \end{array}\right\} \quad x(t),\ y(t) \rightarrow z(t) \qquad /1/$$

It is obvious that an analytical form /a function/ describing the behaviour of the total surface in time would offer many advantages: at first, the interpolation of the vertical coordinate of a point in a gap could be easily obtained from the function, at second, the functions of velocity and acceleration could be analytically derived. It is clear that such a kind of functions must be a 3 dimensional /3D/ one which gives the vertical coordinate with respect to horizontal ones and time, and its derivations determine the velocity and acceleration surfaces.

$$\begin{array}{l} z = z(x,y,t) \\ v = v(x,y,t) = \dfrac{dz(x,y,t)}{dt} \\ a = a(x,y,t) = \dfrac{d^2z(x,y,t)}{dt^2} \end{array} \qquad /2/$$

One of the possibilities to find such a function is to approximate the surface by a 3D harmonic series.

$$z(x,y,t) = \sum_{k=-N_x}^{N_x} \sum_{\ell=-N_y}^{N_y} \sum_{m=-N_t}^{N_t} c_{k\ell m} \times \exp\{ i(k\omega_{x_o} x + \ell\omega_{y_o} y + m\omega_{t_o} t)\} \qquad /3/$$

where $c_{k\ell m}$ are the coefficients of the series.



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We assume that real surface frequencies have a limited range so we use a series truncated at $N_x$, $N_y$, $N_t$.

The velocity and acceleration are derived from the Eq. 3.:

$$v(x,y,t) = \sum_k \sum_\ell \sum_m c'_{k\ell m} \cdot \exp\{\ldots\}$$

$$\text{where } c'_{k\ell m} = im\omega_{t_o} c_{k\ell m}$$

and /4/

$$a(x,y,t) = \sum_{k,\ell,m} c''_{k\ell m} \cdot \exp\{\ldots\}$$

$$\text{where } c''_{k\ell m} = -m^2 \omega^2_{t_o} c_{k\ell m}$$

3. Application example

The above process is applied to the following example: yearly repeated levelling data were collected from a 2.52 x 2.52 square km-s area /Fig. 1./ during a 4 years period, and the kinematical behaviour of this area should be described.

To determine the $c_{k\ell m}$ coefficients of the function $z(x,y,t)$, a DFT spectrum is produced of the surfaces varying in time. DFT needs equidistant data. The periodic measurements produce equispaced epochs, but the vertical coordinates are non-equidistant /the real geodetical network has generally not a grid structure/. A collocation process was used to create a grid using the closest distance between two measured points as basis of the grid.

The DFT spectrum was computed by the following equation /Fig. 2./:

$$c_{k\ell m} = Z(k\omega_{x_o}, \ell\omega_{y_o}, m\omega_{t_o}) =$$

$$= \sum_{k'=0}^{N_x-1} \sum_{\ell'=0}^{N_y-1} \sum_{m'=0}^{N_t-1} z(x_{k'}, y_{\ell'}, t_{m'}) \cdot \frac{1}{N_x N_y N_t} \cdot$$

$$\cdot \exp\{-i(k\omega_{x_o} k' + \ell\omega_{y_o} \ell' + m\omega_{t_o} m')\} \qquad /5/$$

where

$$x_{k'} = k' \cdot \Delta x \qquad \omega_{x_o} = 2\pi/N_x$$
$$y_{k'} = \ell' \cdot \Delta y \qquad \omega_{y_o} = 2\pi/N_y$$
$$t_{m'} = m' \cdot \Delta t \qquad \omega_{t_o} = 2\pi/N_t$$

The velocity and acceleration spectra were derived according to Eq.4. and the velocity and acceleration surfaces were constructed at different epochs with aid of inverse DFT /Fig. 3. and 4./.

We investigated the dependence of the spectrum on the shape of the surface. A very simple model was used: the 3D spectrum of a simulated time-varying hole was computed. The diameter of the hole increased in x--direction. A spectrum plotted at an epoch can be considered as a "section" of the 3D spectrum. It is to be noted that the spectra show a remarkable dependence on the changes of the hole /Fig. 5. and 6./.

4. Conclusions

The described method provides a comfortable, fast process for the kinematical description of a moving surface. In the case of a sufficiently dense grid the interpolation between measured points yields an accurate and quickly obtainable result.

In consequence of applying DFT, a periodical time

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dependence is assumed in the 3D-function z(x,y,t). The period window is limited by the length of the monitored time. Due to this fact the prediction capability of the method is very restricted. An other limitation of the DFT method is the requirement of data in a grid. Both difficulties can be avoided by using some other harmonical expansion method /MEM to search frequencies and space frequencies, Least Squares Adjustment to adjust the harmonic series to the z(x,y,t)/. This generalization will be the continuation of the present work.

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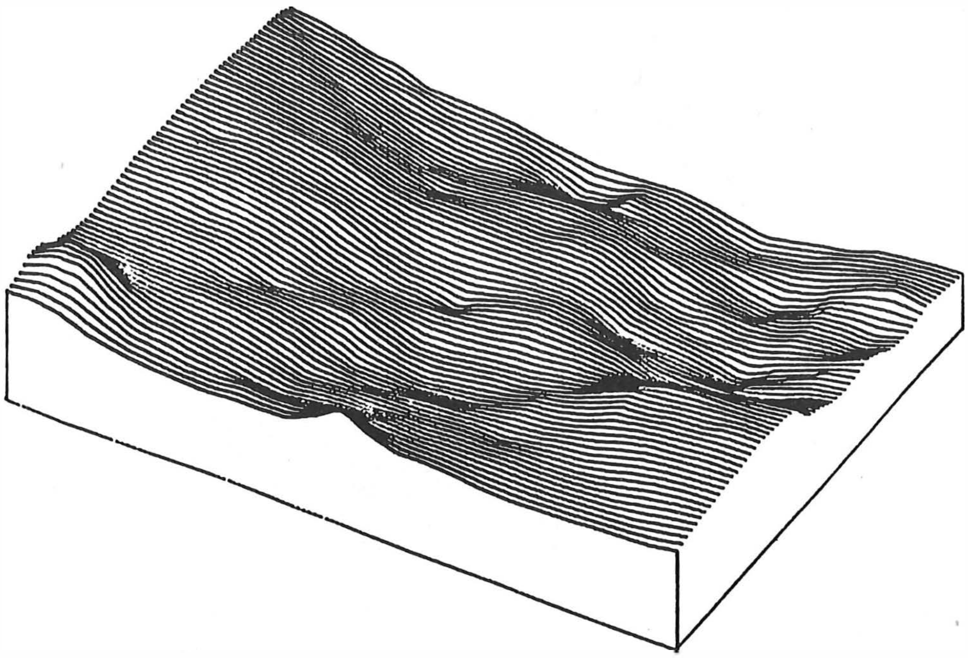

**Figure 1.**
**Sample topographic surface**

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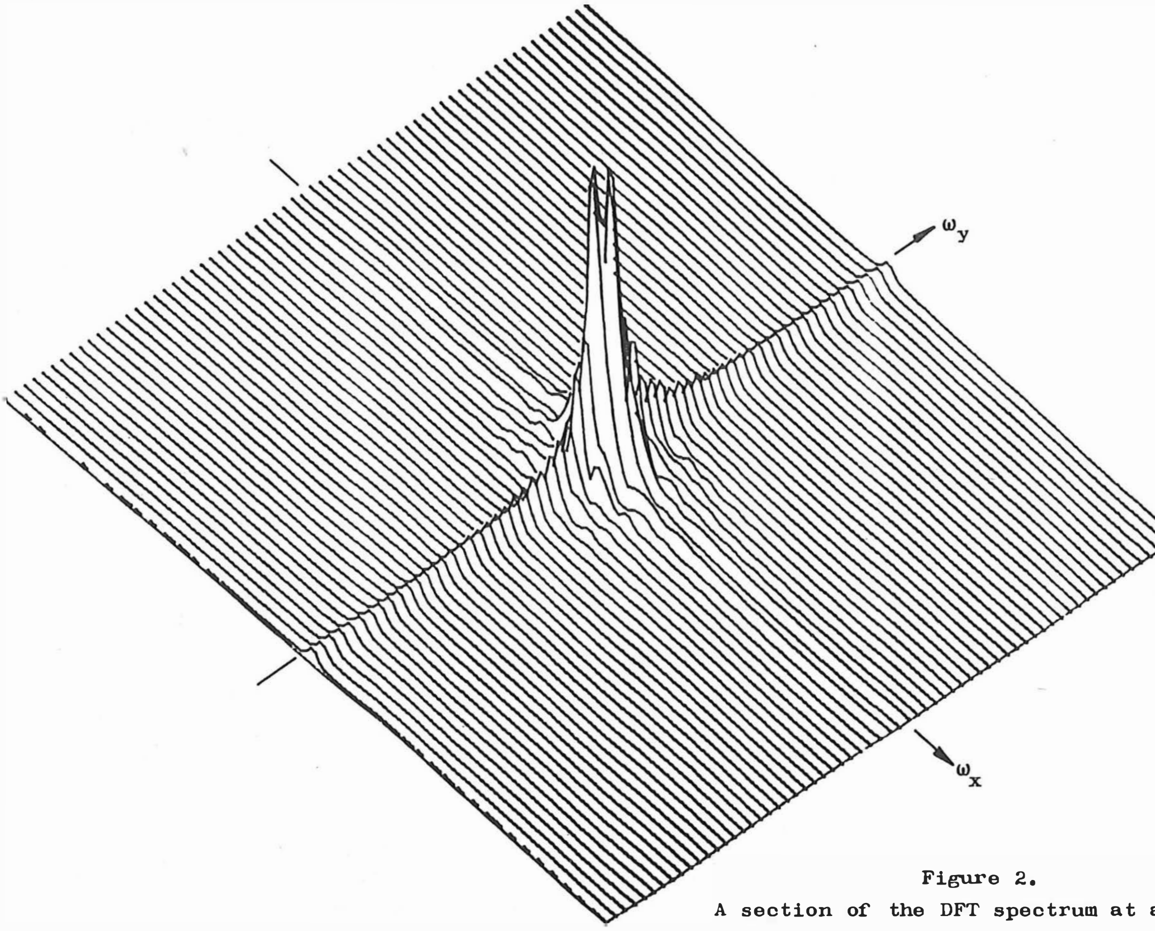


Figure 2.
A section of the DFT spectrum at an epoch

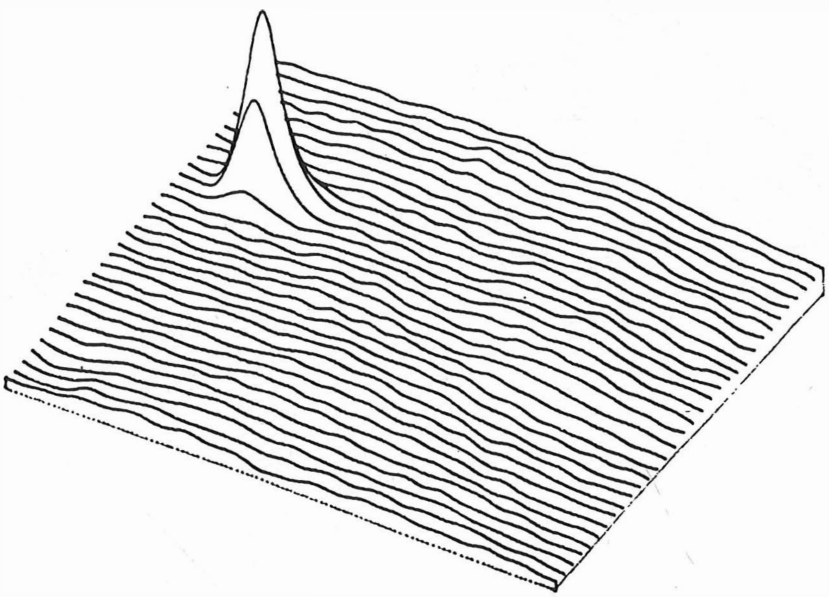

Figure 3.
Velocity surface at an epoch
/with a change of signe/

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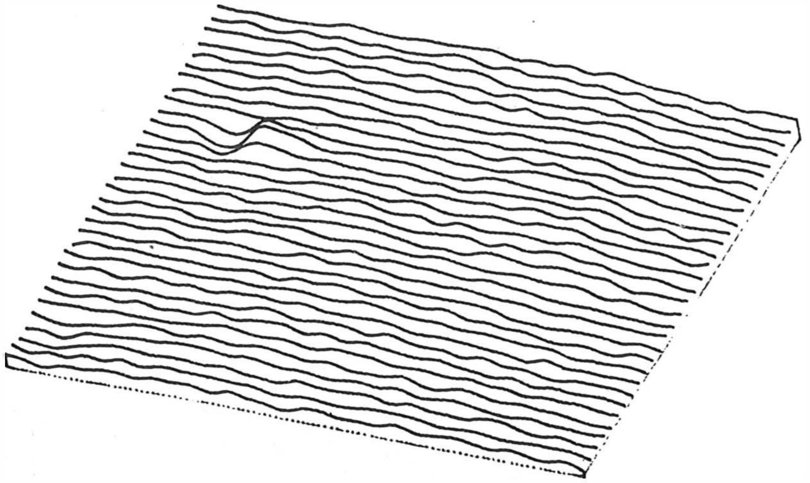

Figure 4.
Acceleration surface at an epoch
/with a change of signe/

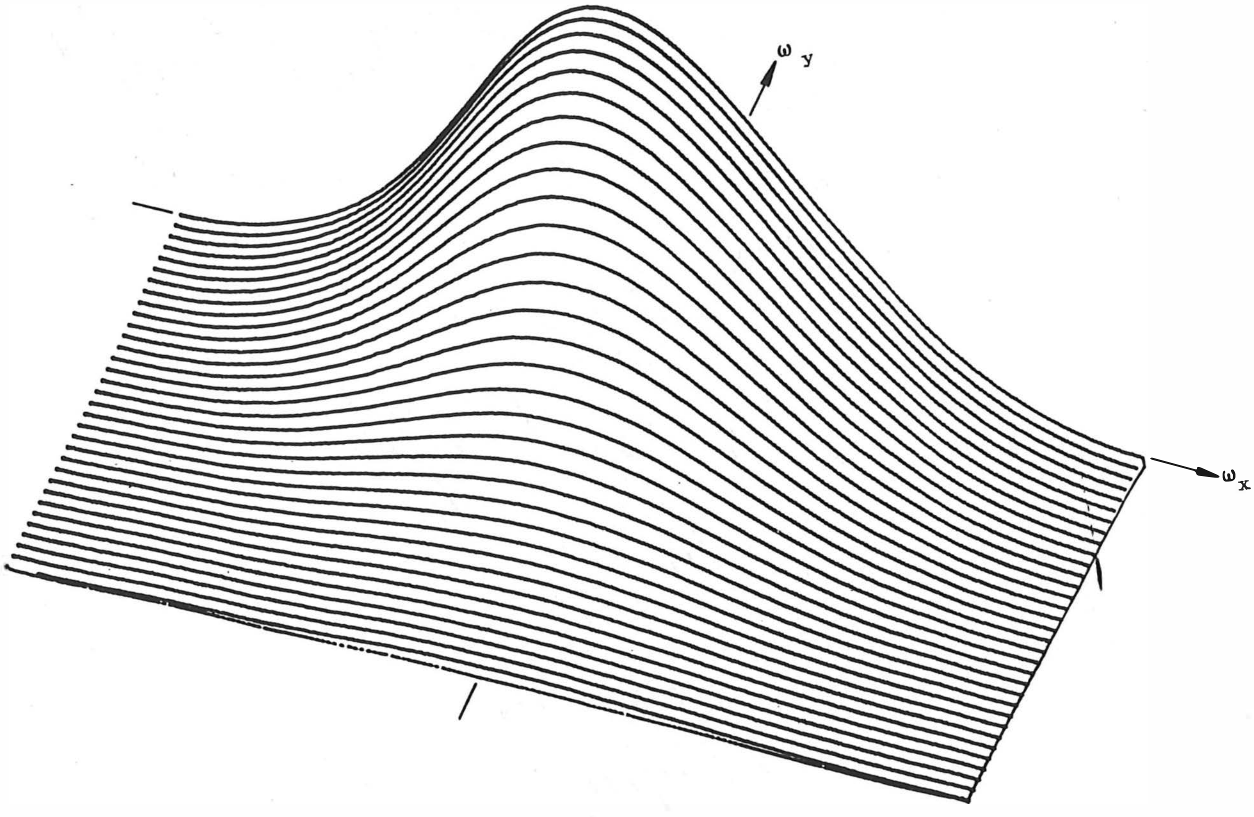


Figure 5.
Spectrum of a circular hole at $t_1$

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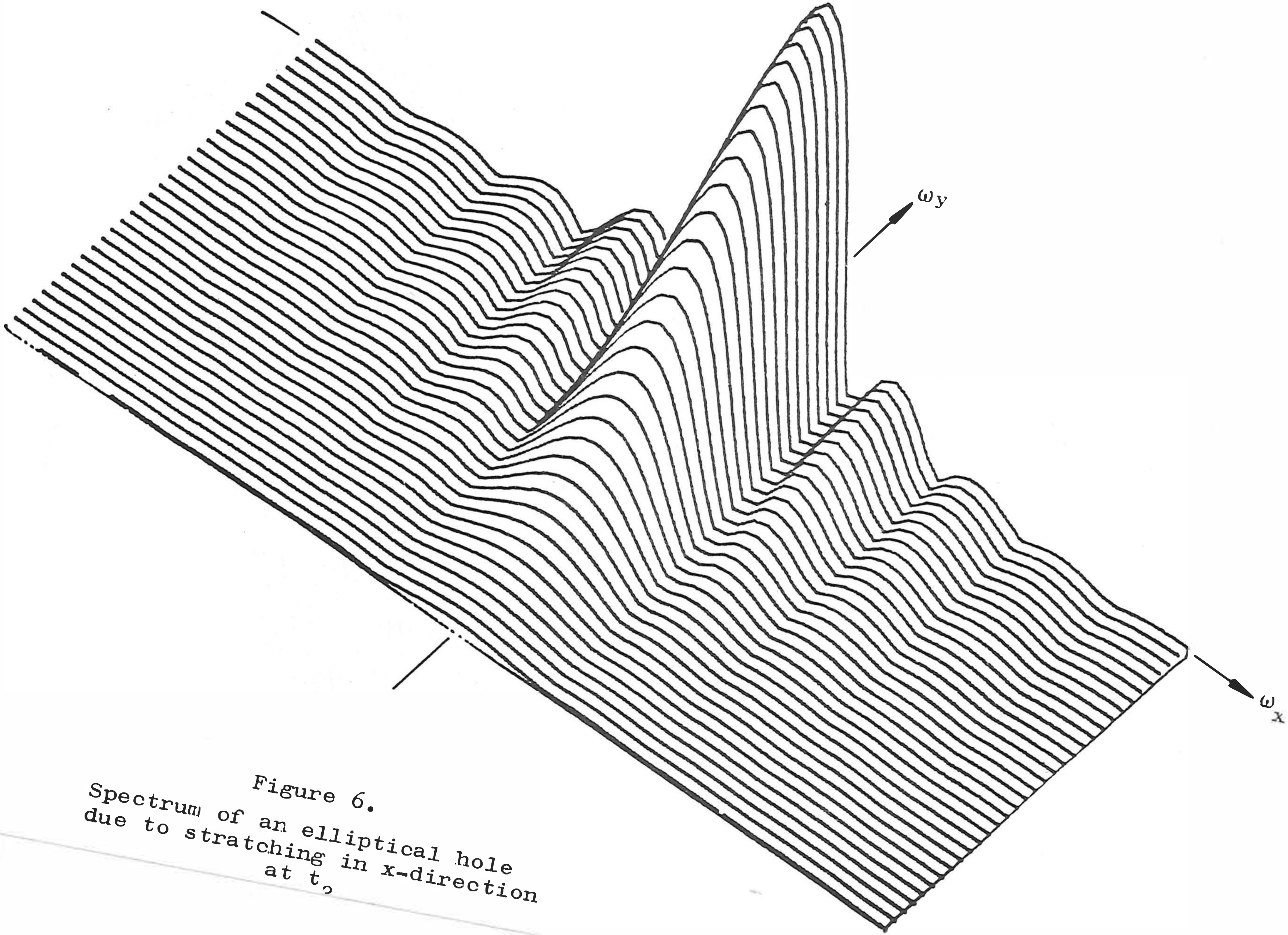


Figure 6.
Spectrum of an elliptical hole due to stratching in x-direction at $t_2$

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## Geodimeter-Netz zur Untersuchung horizontaler Krustendeformationen

Marion Dost u. Günter Lorenz [1)]

**Summary**

In the German Democratic Republic investigations of horizontal Earth's crustal movements referred until now to the derivation of recent horizontal deformations from multiply observed triangulation nets. They were performed for 20 per cent of the territory of the G.D.R. To obtain more detailled information on the dynamic behaviour of the Earth's crust, a special net has been established for the first time. It covers by means of a chain structure the most important geological perturbations of the test field "Elbe valley zone". Special stress was laid upon the reciprocal surface visibility and the identity with numerous points of older triangulations (1890 and 1960). For the most part, the distance measurement has been already finished. The applied GEODIMETER 600 distance meter proved to be successful for these tasks and permits an attempt to receive a new accuracy range. Nevertheless, there are still measuring-methodical reserves in the representative registration of the meteorological field. The mean positional error of $m_p = \pm 10$ mm obtained for the net part measured until now, mekes us optimistically in expecting a considerable more accurate derivation of horizontal deformations and stress.

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**Zusammenfassung**

Untersuchungen horizontaler Erdkrustenbewegungen bezogen sich in der Deutschen Demokratischen Republik bisher auf die Ableitung rezenter horizontaler Deformationen aus mehrfach beobachteten Triangulations-Netzen und wurden bisher für 20 % des Staatsgebietes durchgeführt. Um detailliertere Aussagen über das dynamieche Verhalten der Erdkruste zu erhalten wurde erstmals ein Spezialnetz erkundet, des in Kettenstruktur die wichtigsten geologischen Störungen des Testgebietes Elbtalzone überdeckt. Besonderer Wert wurde auf gegenseitige Bodensicht und die Identität mit zahlreichen Punkten älterer Triangulationen (1890 und 1960) gelegt. Die Sreckenmessung ist in großen Teilen bereits abgeschlossen, das als Streckenmeßgerät eingesetzte GEODIMETER 600 hat sich für diese Aufgabenstellung bestens bewährt und gestattete einen Vorstoß in einen neuen Genauigkeitsbereich, wobei noch meßmethodische und Reserven bei der repräsentativen Erfassung des meteorologischen Feldes vorhanden sind. Der für den bisher gemessenen Netzteil erreichte mittlere Punktfehler von $m_p = \pm 10$ mm stimmt optimistisch und läßt eine wesentlich genauere Ableitung der horizontalen Deformationen und Spannungen erwarten.



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## 1. Einleitung

Die Untersuchungen der rezenten Erdkrustenbewegungen interessieren als wissenschaftliches und praktisches Problem, sie liefern Informationen über den Aufbau, die Dynamik und die Entwicklungsgeschichte der Erdkruste und der oberen Bereiche des Erdmantels. und geben wertvolle Hinweise für die Lagerstättenerkundung. Außerdem können Lebensdauer und Aktualität geodätischer Grundlagennetze durch Krustenbewegungen beeinflußt werden und zu kürzeren Zeiträumen zwischen den Wiederholungsmessungen zwingen. Nicht zuletzt erlaubt die sich stürmisch entwickelnde Meßtechnik einen Vorstoß in neue Genauigkeitsbereiche, die die Schaffung hochpräziser Bezugssysteme und Erdmodelle erfordern.
Nur durch eine interdisziplinäre Zusammenarbeit aller Geowissenschaften, über Ländergrenzen hinweg, können diese Forschungsaufgaben gelöst werden. Von der Geodäsie wird dabei die Erzielung einer höheren Präzision und größeren Zuverlässigkeit in ihrem methodischen Inventar gefordert /1/.

## 2. Das Spezialnetz im Testgebiet Elbtalzone

Die Ableitung von Krustenbewegungen setzt geodätische Wiederholungsmessungen über längere Zeiträume (mehrere Jahrzehnte) auf identischen Festpunkten voraus. Bisher wurden in der DDR vorhandene Triangulationen verschiedener Epochen genutzt, um Verschiebungen abzuleiten. Auf diese Weise wurden 20 % des Territoriums des Landes erfaßt /2/. Um detailliertere Aussagen über das dynamische Verhalten der Erdkruste zu erhalten wurde erstmals ein Spezialnetz erkundet, das in Kettenstruktur die wichtigsten geologischen Störungen des Testgebietes Elbtalzone überdeckt (s. Bild 1).
Die bekannteste Störung ist die Lausitzer Überschiebung. Hier schiebt sich der Lausitzer Granit vom Nordosten her auf den Sandstein des Elbsandsteingebirges auf. Die Westlausitzer Störung trennt das Massiv von Meißen vom Lausitzer Massiv. Dabei sind Existenz und Verlauf dieser Störung im Testgebiet nicht gesichert. Zwischen dem Erzgebirge und dem Elbtalschiefergebirge verläuft die Mittelsächsische Störung. Diese Hauptstörungen schneiden die Netzkonfiguration nahezu senkrecht und werden eine

Das GEODIMETER - Netz

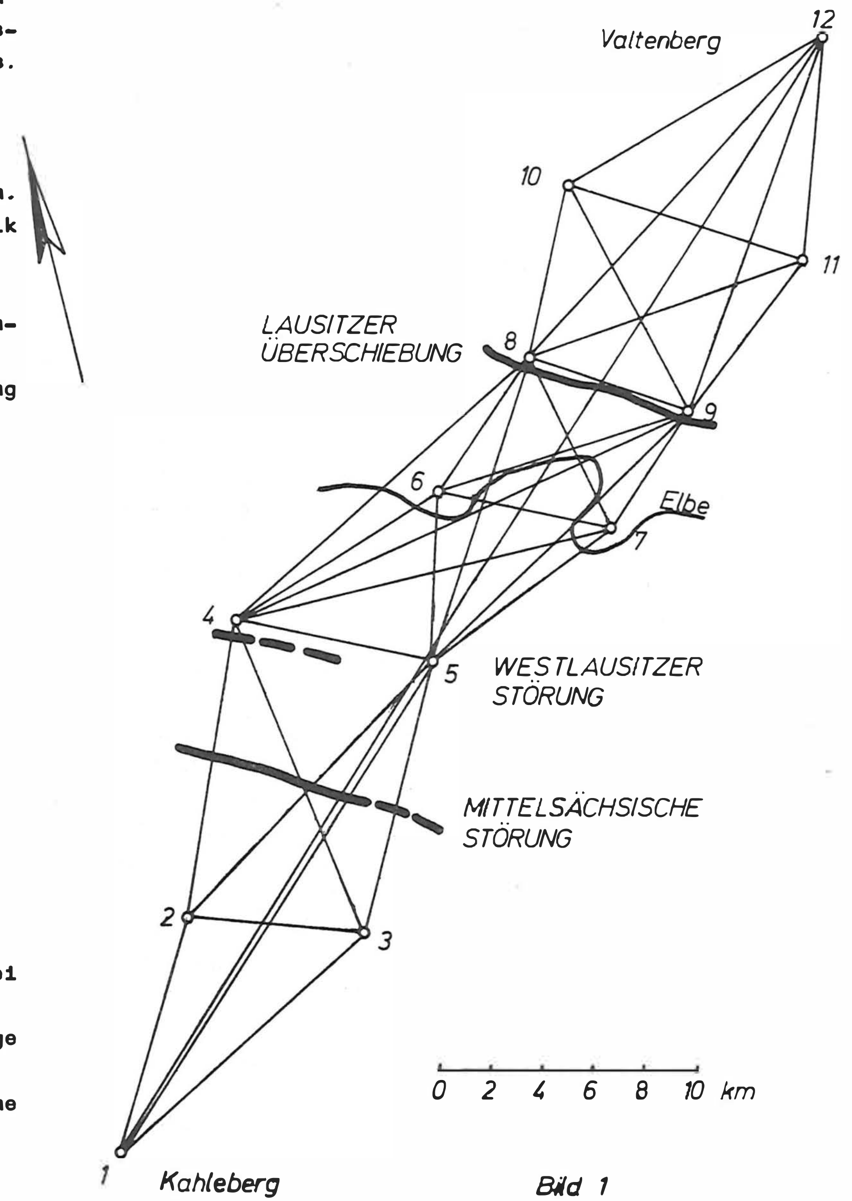


Bild 1

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zuverlässige Interpretation der zu erwartenden Lageverschiebungen ermöglichen, Analysen von LANG /3/,/4/ belegen das.

Die 12 Stationen des neuen Testnetzes wurden so ausgewählt, daß Vergleiche mit älteren Triangulationen, so mit Netzteilen der Königlich-Sächsischen Triangulation von NAGEL (1890) und mit Netzteilen der Staatlich Trigonometrischen Netze I. und III. Ordnung der DDR (1980) möglich werden. Die Vermarkungen der Stationen sind entweder identisch oder mittels Zentrierungen ohne Schwierigkeiten anzuschließen.

Es ist ein besonderer Vorteil, daß zwischen benachbarten Festpunkten (mittlere Seitenlänge 9,4 km) freie Bodensicht besteht, so daß keine zusätzlichen Signalbauten erforderlich wurden. Außerdem sind zahlreiche übergreifende Netzseiten meßbar, die zu einer wesentlichen Genauigkeitssteigerung beitragen.

## 3. Praktische Erfahrungen bei der Messung mit dem GEODIMETER 600

Die Streckenmessungen erfolgten mit dem GEODIMETER 600 der Firma AGA Geotronics AB, Stockholm nach dem Prinzip der "Vier-Phasen-Messung". Eine Strecke wurde jeweils sechs mal im Hin- und Rückgang gemessen. Die reine Meßdauer für einen Meßzyklus betrug eine Stunde.

Für die Messung wurden AGA-Reflektoren verwendet, wobei ein Reflektor aus 24 Einzelprismen zusammengesetzt war. Um die Zielfindung zu erleichtern, wurden Stand- und Zielpunkt mit Scheinwerfern vom Typ TSG 200 des VEB Carl Zeiss JENA signalisiert. Diese Methode hat sich bestens bewährt.

Vereinzelt war die Bestimmung der Feinstrecke problematisch, da Uneindeutigkeiten in den Ablesungen auftreten können.

Das Instrument ist außerordentlich empfindlich gegenüber jeglichen mechanischen Vibrationen, die Folgen der unsicheren Klemmung, des schweren Ganges von Okular- und Strahlengangschalter sind, oder bereits durch das Berühren von Bedienknöpfen entstehen. Der gleiche Effekt wird durch Wind hervorgerufen. Infolgedessen geht die Zielausrichtung des Laserstrahles leicht verloren. Da die Feintriebe sehr grob sind, genügt oft schon ein "antippen" des Instrumentes, um den Laser wieder in das Ziel zu bringen.

Da das Instrument selbst kein optisches Lot besitzt, müssen Zentrierung und Horizontierung separat ausgeführt werden. Leider besteht keine Kontrollmöglichkeit der Zentrierung während der Messung selbst.

Während geringe Überspannungen ohne Einfluß bleiben, führen gerade noch ausreichende Spannungen sofort zu instabilen Frequenzen und damit zu Meßfehlern.

## 4. Die Erfassung der meteorologischen Daten

Elektrooptische Streckenmessungen werden durch Luftdichteunterschiede stark beeinflußt. Daher muß möglichst exakt der von den meteorologischen Bedingungen abhängige wirksame Brechungsindex der Luft bestimmt werden.

Die registrierung der meteorologischen Daten erfolgte für den Messungszeitraum in 5-Minuten Abständen auf Stand- und Zielpunkt. Um ein besseres Bild vom Zustand der Atmosphäre zu gewinnen, wurden die Daten ab 15 Minuten vor Messungsbeginn und bis 15 Minuten nach Messungsende erfaßt. Bereiten die Bestimmung von relativer Luftfeuchte und Luftdruck wenig Schwierigkeiten, bleibt eine zuverlässige Temperaturbestimmung mitunter problematisch.

Es zeigte sich, daß Hin- und Rückmessung einer Strecke unter möglichst unterschiedlichen, aber homogenen Witterungsbedingungen erfolgen sollten.

## 5. Die Messungsergebnisse

Die gemessenen, mit einer meteorologischen Korrektur versehenen Strecken wurden spannungsfrei in eine GAUSZ-KRÜGER-Ebene transformiert. Anschließend wurden alle Beobachtungen einer freien vermittelnden Netzausgleichung unterzogen. Dabei wurden folgende Ergebnisse für den bisher gemessenen Netzabschnitt erhalten /5/:

Die Verbesserungen der Beobachtungen betragen im Mittel ±4 mm. Es besteht keine strenge Proportionalität zwischen der Größe der Verbesserung und der Streckenlänge.

Für den bisher gemessenen Netzabschnitt (s. Bild 2) wurde ein mittlerer Punktlagefehler von ±10 mm erreicht. Alle Netzpunkte weisen einen nahezu gleich großen Punktlagefehler auf. Betrachtet man die Fehlerellipsen, so fällt eine ausgeprägte Richtungs-



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abhängigkeit des Lagefehlers auf. Ein minimaler Fehler ist in Richtung der Kette und somit etwa senkrecht zu den geologischen Störungen zu verzeichnen.

Diese Tatsachen wirken sich vorteilhaft auf die noch anzustellenden geodynamischen Auswertungen aus. Die Ausschöpfung noch vorhandener meßtechnischer Reserven erlaubt eine weitere Genauigkeitssteigerung. Damit können Verschiebungsparameter künftig wesentlich genauer abgeleitet werden.


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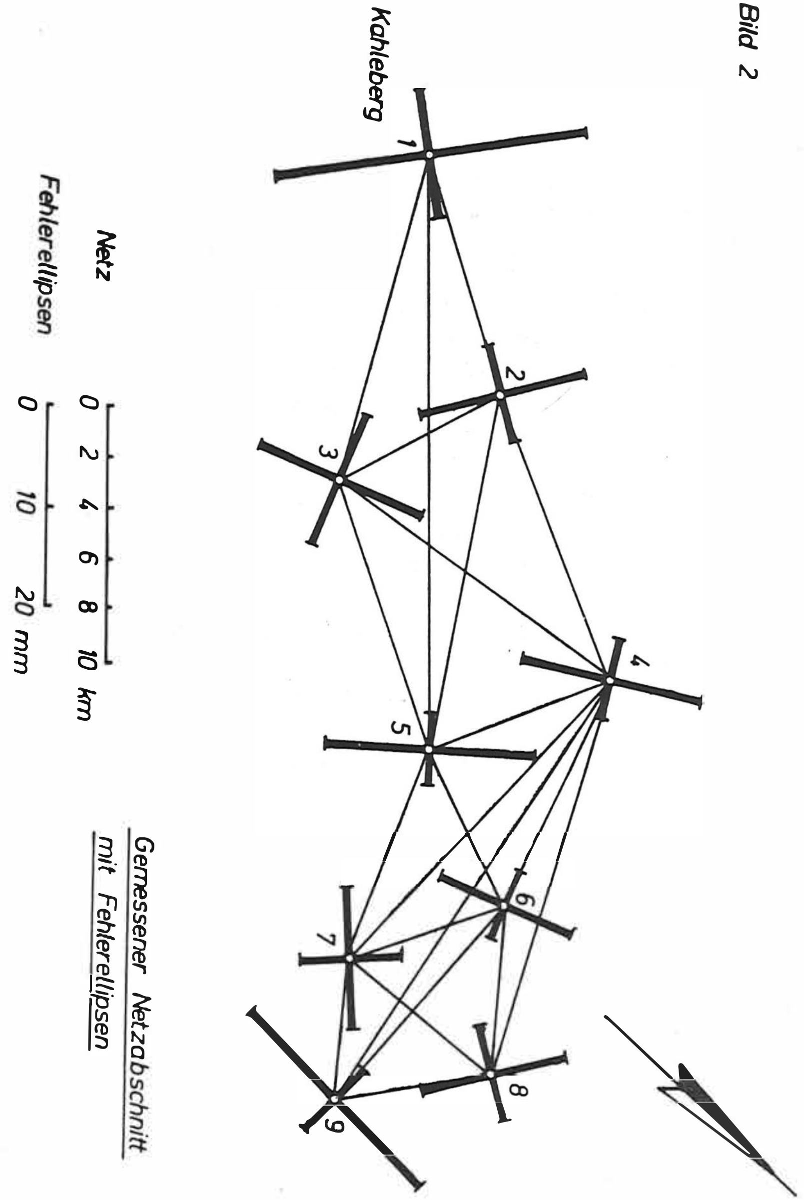
Bild 2

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# GAUSSIAN AND MEAN CURVATURES OF POSTGLACIAL LAND UPLIFT AS EXPANDED IN SURFACE SPHERICAL HARMONICS, AND THE ORIGIN OF EARTHQUAKES IN FENNOSCANDIA

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## ABSTRACT

Formulae for Gaussian and mean curvatures of postglacial land uplift, as expanded in a series of surface spherical harmonics, are derived. These are then applied in investigating if postglacial land uplift is an origin of earthquakes. It is found that the postglacial land uplift of Fennoscandia probably is the origin of the earthquakes along the whole Swedish coast of the Gulf of Bothnia as well as possibly of those in northernmost Sweden (northern Lapland), the earthquakes occurring mainly where the Gaussian curvature of land uplift is great enough. No such relation exists for the earthquakes of south-eastern Norway/ south-western Sweden (Oslo - Vänern area), which then probably do not originate from the land uplift.

## ZUSAMMENFASSUNG

Formeln für Gauss'sche und mittlere Krümmungen der postglazialen Landhebung, dargestellt durch Reihenentwicklung nach Kugelflächenfunktionen, werden hergeleitet. Diese werden daraufhin untersucht inwieweit postglaziale Landhebung ursächlich mit Erdbebenaktivität in Verbindung gebracht werden kann. Mit einiger Sicherheit kann geschlossen werden, dass die postglaziale Hebung Fennoskandiens die Erdbeben längs der gesamten Küste des Bottnischen Meerbusens sowie diejenigen im nördlichsten Schweden (Nord-Lappland) verursacht; diese Beben treten vornehmlich in Zonen ausreichend grosser Gauss'scher Krümmung auf. Für die Erdbeben in Südost-Norwegen/Südwest-Schweden (im Gebiet Oslo - Vänersee) existiert keine solche Beziehung, weswegen sie wahrscheinlich nicht von der Landhebung verursacht werden.

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## 1. INTRODUCTION.

In some earlier publications (Ekman, 1981, 1983) we have studied curvatures of the crust caused by earth tides. Thereby we found, based on certain tidal conditions, a significant tidal triggering of earthquakes.

In the present publication we turn to curvatures of the crust caused by postglacial land uplift. A brief introductory treatment was given in Ekman (1982) where it was said that a full treatment, including an investigation of land uplift and Fennoscandian earthquakes, would be published later. This is now done in the present report. We will first derive formulae for Gaussian and mean curvatures of postglacial land uplift as expanded in a series of surface spherical harmonics. We will then use these in investigating if postglacial land uplift causes earthquakes, whereby the application is made to land uplift and earthquakes in Fennoscandia.

## 2. DERIVATION OF FORMULAE FOR GAUSSIAN AND MEAN CURVATURES OF POSTGLACIAL LAND UPLIFT.

### 2.1. Series expansion of land uplift in surface spherical harmonics.

Postglacial land uplift, like any function on a sphere, may be expanded in a series of surface spherical harmonics (see e.g. Heiskanen - Moritz, 1967),

$$U = \sum_{n=0}^{\infty} \sum_{m=0}^{n} U_{nm}(\varphi, \lambda)$$

$$= \sum_{n=0}^{\infty} \sum_{m=0}^{n} (a_{nm} \cos m\lambda + b_{nm} \sin m\lambda)\, P_{nm}(\sin \varphi) \qquad (1)$$

(A list of symbols may be found at the end of the paper.) As a consequence of the orthogonality relations, the coefficients are given by

$$a_{nm} = (2 - \delta_{0m}) \frac{2n + 1}{4\pi} \frac{(n - m)!}{(n + m)!} \int_0^{2\pi} \int_0^{\pi} U(\varphi, \lambda)\, P_{nm}(\sin \varphi) \cos \varphi \cos m\lambda \, d\varphi d\lambda \qquad (2)$$

$$b_{nm} = \frac{2n + 1}{2\pi} \frac{(n - m)!}{(n + m)!} \int_0^{2\pi} \int_0^{\pi} U(\varphi, \lambda)\, P_{nm}(\sin \varphi) \cos \varphi \sin m\lambda \, d\varphi d\lambda \qquad (3)$$

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If we use normalized harmonics the series expansion is written

$$U = \sum_{n=0}^{\infty} \sum_{m=0}^{n} (\bar{a}_{nm} \cos m\lambda + \bar{b}_{nm} \sin m\lambda)\, \bar{P}_{nm}(\sin \varphi) \qquad (4)$$

The coefficients here are given by

$$\bar{a}_{nm} = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} U(\varphi, \lambda)\, \bar{P}_{nm}(\sin \varphi) \cos \varphi \cos m\lambda \, d\varphi d\lambda \qquad (5)$$

$$\bar{b}_{nm} = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} U(\varphi, \lambda)\, \bar{P}_{nm}(\sin \varphi) \cos \varphi \sin m\lambda \, d\varphi d\lambda \qquad (6)$$

The normalized Legendre functions are related to the non-normalized ones through

$$\bar{P}_{nm} = \sqrt{(2 - \delta_{0m})(2n + 1) \frac{(n - m)!}{(n + m)!}}\; P_{nm} = c_{nm} P_{nm} \qquad (7)$$

In practice the series expansion must obviously be cut off at some large number $n = N$, and the coefficients are calculated by summation over a lot of surface elements (squares) of a suitable size.

The land uplift to be used here is the absolute land uplift, which is the observed land uplift corrected for geoid uplift and general eustatic rise of sea level,

$$U(\varphi, \lambda) = U_{obs}(\varphi, \lambda) + U_g(\varphi, \lambda) + U_e \qquad (8)$$

## 2.2. Curvature formulae of land uplift based on non-normalized harmonics.

We will now derive formulae for the Gaussian curvature and the mean curvature of postglacial land uplift as expanded in the series (1).

Starting from the fundamental formulae (see e.g. Lipschutz, 1969) for the Gaussian curvature

$$K = \frac{\begin{vmatrix} L & M \\ M & N \end{vmatrix}}{\begin{vmatrix} E & F \\ F & G \end{vmatrix}} = \frac{LN - M^2}{EG - F^2} \qquad (9)$$

and the mean curvature

$$H = \frac{1}{2} \frac{\begin{vmatrix} E & M \\ F & N \end{vmatrix} - \begin{vmatrix} F & L \\ G & M \end{vmatrix}}{\begin{vmatrix} E & F \\ F & G \end{vmatrix}} = \frac{1}{2} \frac{EN - 2FM + GL}{EG - F^2} \qquad (10)$$

we can write (cf. Ekman, 1981)

$$K = \frac{\partial^2 U}{\partial x^2} \frac{\partial^2 U}{\partial y^2} - \left(\frac{\partial^2 U}{\partial x \partial y}\right)^2 \qquad (11)$$

and

$$H = \frac{1}{2} \left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right) \qquad (12)$$

These last expressions are valid provided the first order derivatives $\partial U/\partial x$ and $\partial U/\partial y$ are much smaller than 1, which certainly is the case with the land uplift.



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Introducing $U_{nm}$ we get

$$K = \sum_{n=0}^{N}\sum_{m=0}^{n}\frac{\partial^2 U_{nm}}{\partial x^2}\sum_{n=0}^{N}\sum_{m=0}^{n}\frac{\partial^2 U_{nm}}{\partial y^2} - \left(\sum_{n=0}^{N}\sum_{m=U}^{n}\frac{\partial^2 U_{nm}}{\partial x \partial y}\right)^2 \tag{13}$$

and

$$H = \frac{1}{2}\sum_{n=0}^{N}\sum_{m=0}^{n}\left(\frac{\partial^2 U_{nm}}{\partial x^2} + \frac{\partial^2 U_{nm}}{\partial y^2}\right) \tag{14}$$

We now proceed in the following way: For the second order derivatives in (13) and (14) we have (cf. Tscherning, 1976, or Ekman, 1981)

$$\frac{\partial^2 U_{nm}}{\partial x^2} = \frac{1}{R^2}\frac{\partial^2 U_{nm}}{\partial \varphi^2} \tag{15}$$

$$\frac{\partial^2 U_{nm}}{\partial y^2} = \frac{1}{R^2}\left(\frac{1}{\cos^2\varphi}\frac{\partial^2 U_{nm}}{\partial \lambda^2} - \tan\varphi\,\frac{\partial U_{nm}}{\partial \varphi}\right) \tag{16}$$

$$\frac{\partial^2 U_{nm}}{\partial x \partial y} = \frac{1}{R^2}\left(\frac{1}{\cos\varphi}\frac{\partial^2 U_{nm}}{\partial \varphi \partial \lambda} + \frac{\sin\varphi}{\cos^2\varphi}\frac{\partial U_{nm}}{\partial \lambda}\right) \tag{17}$$

Our problem here is to determine the first and second order derivatives of $U_{nm}$ with respect to $\varphi$ and $\lambda$. On inspecting (1) we see that this involves the differentiation of $P_{nm}$ with respect to $\varphi$. Let us first carry out this operation.

We start by noting that, putting $t = \sin\varphi$,

$$\frac{d}{d\varphi}P_{nm}(\sin\varphi) = \frac{d}{dt}P_{nm}(t)\cos\varphi \tag{18}$$

The derivative on the right-hand side is given by (see e.g. Abramowitz - Stegun, 1964)

$$\frac{d}{dt}P_{nm}(t) = \frac{nt}{t^2-1}P_{nm}(t) - \frac{n+m}{t^2-1}P_{n-1,m}(t) \tag{19}$$

Using the recursion formula

$$\frac{n+m}{t^2-1}P_{n-1,m}(t) = \frac{(2n+1)t}{t^2-1}P_{nm}(t) - \frac{n-m+1}{t^2-1}P_{n+1,m}(t) \tag{20}$$

we transform (19) to

$$\frac{d}{dt}P_{nm}(t) = -\frac{(n+1)t}{t^2-1}P_{nm}(t) + \frac{n-m+1}{t^2-1}P_{n+1,m}(t) \tag{21}$$

Inserting (21) into (18) we get, with $t = \sin\varphi$,

$$\frac{d}{d\varphi}P_{nm}(\sin\varphi) = (n+1)\tan\varphi\,P_{nm}(\sin\varphi) - \frac{n-m+1}{\cos\varphi}P_{n+1,m}(\sin\varphi) \tag{22}$$

To find the second derivative most easily we apply Legendre's differential equation. Put $P = P_{nm}(\sin\varphi)$.

DOI: https://doi.org/10.2312/zipe.1985.081.03

Then Legendre's equation reads

$$\cos\varphi \frac{d^2P}{d\varphi^2} - \sin\varphi \frac{dP}{d\varphi} + \left(n(n+1)\cos\varphi - \frac{m^2}{\cos\varphi}\right) P = 0 \tag{23}$$

or

$$\frac{d^2P}{d\varphi^2} = \tan\varphi \frac{dP}{d\varphi} - \left(n(n+1) - \frac{m^2}{\cos^2\varphi}\right) P \tag{24}$$

Inserting (22) into (24) we find

$$\frac{d^2}{d\varphi^2} P_{nm}(\sin\varphi) = \left(-\,n(n+1) + \frac{m^2}{\cos^2\varphi} + (n+1)\tan^2\varphi\right) P_{nm}(\sin\varphi) - \frac{(n-m+1)\sin\varphi}{\cos^2\varphi} P_{n+1,m}(\sin\varphi) \tag{25}$$

Having thus obtained the derivatives (22) and (25), we use these expressions in differentiating $U_{nm}$ with respect to $\varphi$ and $\lambda$. This yields for the first derivatives

$$\frac{\partial U_{nm}}{\partial\varphi} = (a_{nm}\cos m\lambda + b_{nm}\sin m\lambda) \left[(n+1)\tan\varphi\, P_{nm}(\sin\varphi) - \frac{n-m+1}{\cos\varphi} P_{n+1,m}(\sin\varphi)\right] \tag{26}$$

$$\frac{\partial U_{nm}}{\partial\lambda} = m\,(-\,a_{nm}\sin m\lambda + b_{nm}\cos m\lambda)\, P_{nm}(\sin\varphi) \tag{27}$$

and for the second derivatives

$$\frac{\partial^2 U_{nm}}{\partial\varphi^2} = (a_{nm}\cos m\lambda + b_{nm}\sin m\lambda) \left[\left(-\,n(n+1) + (n+1)\tan^2\varphi + \frac{m^2}{\cos^2\varphi}\right) P_{nm}(\sin\varphi) - \frac{(n-m+1)\sin\varphi}{\cos^2\varphi} P_{n+1,m}(\sin\varphi)\right] \tag{28}$$

$$\frac{\partial^2 U_{nm}}{\partial\lambda^2} = -\,m^2\,(a_{nm}\cos m\lambda + b_{nm}\sin m\lambda)\, P_{nm}(\sin\varphi) \tag{29}$$

$$\frac{\partial^2 U_{nm}}{\partial\varphi\partial\lambda} = m\,(-\,a_{nm}\sin m\lambda + b_{nm}\cos m\lambda) \left[(n+1)\tan\varphi\, P_{nm}(\sin\varphi) - \frac{n-m+1}{\cos\varphi} P_{n+1,m}(\sin\varphi)\right] \tag{30}$$

Inserting (26) - (30) into (15) - (17) we obtain

$$\frac{\partial^2 U_{nm}}{\partial x^2} = \frac{1}{R^2} (a_{nm}\cos m\lambda + b_{nm}\sin m\lambda) \left[\left(-\,n(n+1) + (n+1)\tan^2\varphi + \frac{m^2}{\cos^2\varphi}\right) P_{nm}(\sin\varphi) - \frac{(n-m+1)\sin\varphi}{\cos^2\varphi} P_{n+1,m}(\sin\varphi)\right] \tag{31}$$



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$$\frac{\partial^2 U_{nm}}{\partial y^2} = \frac{1}{R^2} (a_{nm} \cos m\lambda + b_{nm} \sin m\lambda)$$

$$\left[\left(- (n + 1) \tan^2\varphi - \frac{m^2}{\cos^2\varphi}\right) P_{nm}(\sin \varphi) + \frac{(n - m + 1) \sin \varphi}{\cos^2\varphi} P_{n+1,m} (\sin \varphi)\right] \quad (32)$$

$$\frac{\partial^2 U_{nm}}{\partial x \partial y} = \frac{1}{R^2} (a_{nm} \sin m\lambda - b_{nm} \cos m\lambda)$$

$$\left[- \frac{(n + 2)m \sin \varphi}{\cos^2\varphi} P_{nm}(\sin \varphi) + \frac{(n - m + 1)m}{\cos^2\varphi} P_{n+1,m} (\sin \varphi)\right] \quad (33)$$

By the combination of (13) - (14) with (31) - (33) we finally arrive at formulae for the curvatures of post-glacial land uplift as expanded in surface spherical harmonics:



The Gaussian curvature of land uplift (34)

$$K = \frac{1}{R^4} \sum_{n=0}^{N} \sum_{m=0}^{n} (a_{nm} \cos m\lambda + b_{nm} \sin m\lambda)$$

$$\left[\left(- n(n + 1) + (n + 1) \tan^2\varphi + \frac{m^2}{\cos^2\varphi}\right) P_{nm}(\sin \varphi) - \frac{(n - m + 1) \sin \varphi}{\cos^2\varphi} P_{n+1,m} (\sin \varphi)\right]$$

$$\sum_{n=0}^{N} \sum_{m=0}^{n} (a_{nm} \cos m\lambda + b_{nm} \sin m\lambda)$$

$$\left[\left(- (n + 1) \tan^2\varphi - \frac{m^2}{\cos^2\varphi}\right) P_{nm}(\sin \varphi) + \frac{(n - m + 1) \sin \varphi}{\cos^2\varphi} P_{n+1,m} (\sin \varphi)\right]$$

$$- \frac{1}{R^4} \left(\sum_{n=0}^{N} \sum_{m=0}^{n} (a_{nm} \sin m\lambda - b_{nm} \cos m\lambda)\right.$$

$$\left.\left[- \frac{(n + 2)m \sin \varphi}{\cos^2\varphi} P_{nm}(\sin \varphi) + \frac{(n - m + 1)m}{\cos^2\varphi} P_{n+1,m} (\sin \varphi)\right]\right)^2$$

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and the mean curvature of land uplift (35)

$$H = \sum_{n=0}^{N} \sum_{m=0}^{n} - \frac{n(n+1)}{2} \frac{1}{R^2} (a_{nm} \cos m\lambda + b_{nm} \sin m\lambda) P_{nm}(\sin \varphi) =$$

$$= \sum_{n=0}^{N} \sum_{m=0}^{n} - \frac{n(n+1)}{2R^2} U_{nm}(\varphi, \lambda)$$

2.3. Curvature formulae of land uplift for the case of normalized harmonics.

The Gaussian curvature formula (34) is valid for non-normalized harmonics. For the case of normalized harmonics, i.e. the series (4), it does not hold any longer. The reason for this is the occurrence of the functions $P_{n+1,m}(\sin \varphi)$. We thus have to modify (34) to fit the normalized harmonics.

$P_{n+1,m}(\sin \varphi)$ enters into the problem through (22) and (25). Let us multiply these equations by the factor $c_{nm}$, and use the relation (7) to convert the equations from non-normalized to normalized Legendre functions. (22) is then replaced by

$$\frac{d}{d\varphi} \bar{P}_{nm}(\sin \varphi) = (n+1) \tan \varphi \, \bar{P}_{nm}(\sin \varphi) - \frac{n-m+1}{\cos \varphi} \frac{c_{nm}}{c_{n+1,m}} \bar{P}_{n+1,m}(\sin \varphi) \tag{36}$$

and (25) by an analogous equation. Here

$$\frac{c_{nm}}{c_{n+1,m}} = \frac{\sqrt{(2-\delta_{0m})(2n+1)\frac{(n-m)!}{(n+m)!}}}{\sqrt{(2-\delta_{0m})(2n+3)\frac{(n-m+1)!}{(n+m+1)!}}}$$

which may be simplified to

$$\frac{c_{nm}}{c_{n+1,m}} = \sqrt{\frac{(2n+1)(n+m+1)}{(2n+3)(n-m+1)}} \tag{37}$$



DOI: https://doi.org/10.2312/zipe.1985.081.03

Thus we get instead of (22)

$$\frac{d}{d\varphi}\overline{P}_{nm}(\sin\varphi) = (n+1)\tan\varphi\,\overline{P}_{nm}(\sin\varphi) - \frac{q_{nm}}{\cos\varphi}\overline{P}_{n+1,m}(\sin\varphi) \qquad (38)$$

and instead of (25)

$$\frac{d^2}{d\varphi^2}\overline{P}_{nm}(\sin\varphi) = \left(-n(n+1) + \frac{m^2}{\cos^2\varphi} + (n+1)\tan^2\varphi\right) \overline{P}_{nm}(\sin\varphi) - \frac{q_{nm}\sin\varphi}{\cos^2\varphi}\overline{P}_{n+1,m}(\sin\varphi) \qquad (39)$$

where

$$q_{nm} = \frac{\sqrt{(2n+1)(n+m+1)(n-m+1)}}{\sqrt{2n+3}} \qquad (40)$$

Consequently we obtain the following formula for the Gaussian curvature of land uplift as expanded in normalized surface spherical harmonics:

$$\begin{aligned}
K = {} & \frac{1}{R^4}\sum_{n=0}^{N}\sum_{m=0}^{n}(\overline{a}_{nm}\cos m\lambda + \overline{b}_{nm}\sin m\lambda) \\
& \left[\left(-n(n+1) + (n+1)\tan^2\varphi + \frac{m^2}{\cos^2\varphi}\right)\overline{P}_{nm}(\sin\varphi)\right. \\
& \left. - \frac{\sqrt{(2n+1)(n+m+1)(n-m+1)}\sin\varphi}{\sqrt{2n+3}\cos^2\varphi}\overline{P}_{n+1,m}(\sin\varphi)\right] \\
& \sum_{n=0}^{N}\sum_{m=0}^{n}(\overline{a}_{nm}\cos m\lambda + \overline{b}_{nm}\sin m\lambda) \\
& \left[\left(-(n+1)\tan^2\varphi - \frac{m^2}{\cos^2\varphi}\right)\overline{P}_{nm}(\sin\varphi)\right. \\
& \left. + \frac{\sqrt{(2n+1)(n+m+1)(n-m+1)}\sin\varphi}{\sqrt{2n+3}\cos^2\varphi}\overline{P}_{n+1,m}(\sin\varphi)\right] \\
& - \frac{1}{R^4}\left(\sum_{n=0}^{N}\sum_{m=0}^{n}(\overline{a}_{nm}\sin m\lambda - \overline{b}_{nm}\cos m\lambda)\right. \\
& \left[-\frac{(n+2)m\sin\varphi}{\cos^2\varphi}\overline{P}_{nm}(\sin\varphi)\right. \\
& \left.\left. + \frac{\sqrt{(2n+1)(n+m+1)(n-m+1)}\,m}{\sqrt{2n+3}\cos^2\varphi}\overline{P}_{n+1,m}(\sin\varphi)\right]\right)^2
\end{aligned} \qquad (41)$$

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The mean curvature formula (35) is not influenced by the above operations; it is valid in the given form also for normalized harmonics.

Looking at the formulae (34) and (41) for the Gaussian curvature we see that they fail at $\varphi = \pm 90^{\circ}$. This is, however, no problem in our case, neither the Fennoscandian nor the Canadian land uplift being situated at the pole.

Finally we may note that the curvature formulae derived here are in principle valid for any surface, e.g. the geoid, developed in a surface spherical harmonic series and fulfilling the requirement on page 8. However, in such a case a better solution might be given by expressions which are a little more complicated but avoid the singularities at the poles. (Concerning the curvature of the geoid in a somewhat different sense, see Burša (1973).)

## 3. LAND UPLIFT CURVATURES AND ORIGIN OF EARTHQUAKES IN FENNOSCANDIA.

### 3.1. Principles of investigation.

The first investigation of a possible connection between postglacial land uplift and seismic activity in Fennoscandia was made by Båth (1954). By estimating the energy of the land uplift and the energy released by the Fennoscandian earthquakes he concluded that the land uplift energy was sufficient to produce the earthquakes. However, the geographical distribution of the earthquakes could not be explained. Later Båth (1978) concluded that the geographical pattern of earthquakes spoke against the land uplift as an origin of the earthquakes, and supported a plate tectonic origin.

Anderson (1980) suggested that the additional uplift due to the deloading of the water masses of the Gulf of Bothnia - going on as a consequence of the Fennoscandian uplift - might cause the seismic activity along the coast of the Gulf of Bothnia.

Most scientists today seem to favour a plate tectonic origin of the Fennoscandian earthquakes, like Båth (1978) and Husebye et. al. (1978). It is often pointed out, e.g. also by Bungum - Fyen (1979), that the earthquakes correlate poorly with both the land uplift and its gradient.

We will now investigate the problem of land uplift and earthquakes in Fennoscandia as follows:

A proper quantity for studying the land uplift as a cause of earthquakes is the land uplift curvature



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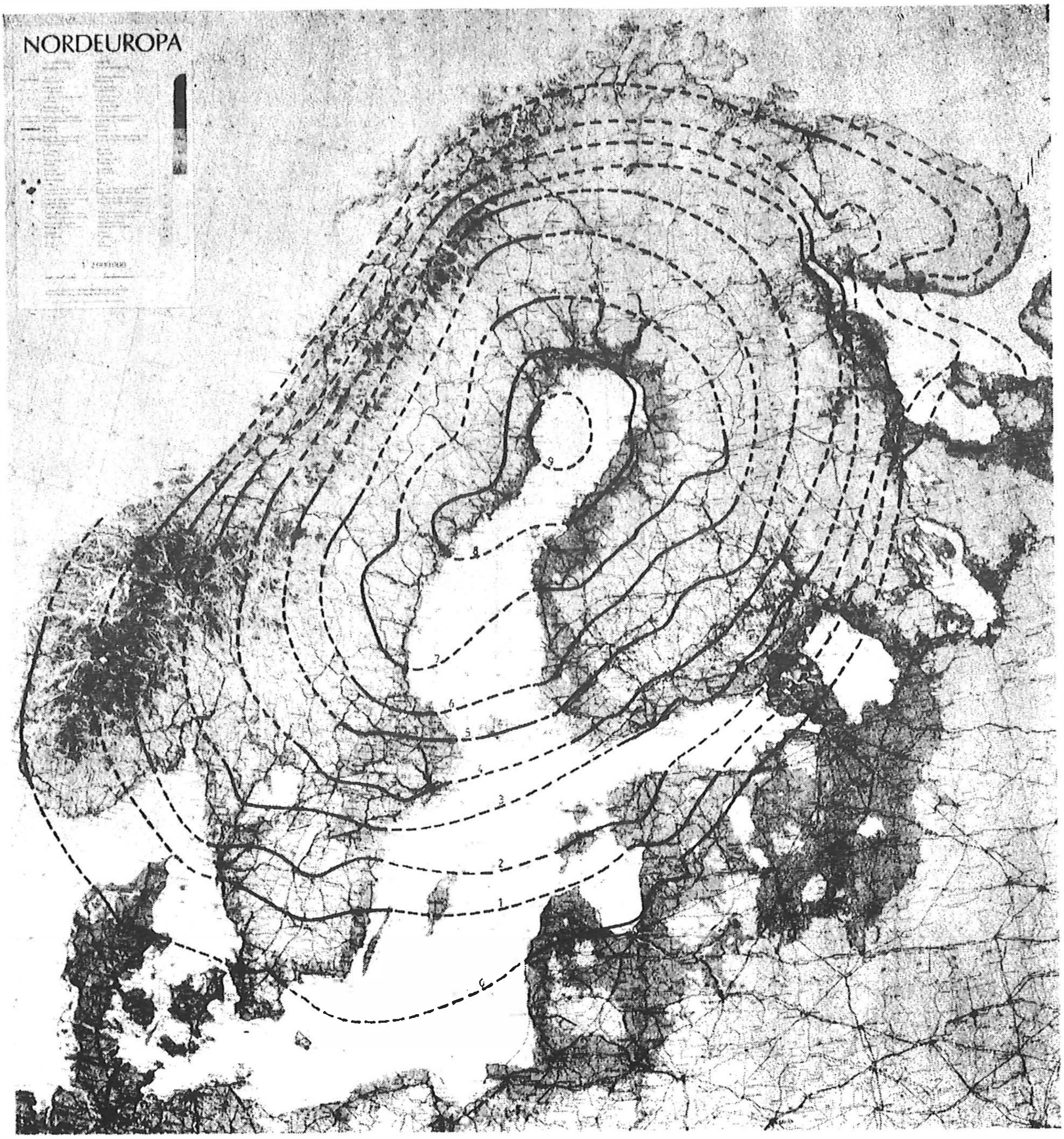


Figure 1: Observed land uplift of Fennoscandia (mm/year).

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[†](rather than the land uplift gradient or tilt, or the land uplift itself). The basic principle may be expressed: If postglacial land uplift causes earthquakes, then these earthquakes should occur mainly in those areas where the land uplift curvature - especially the Gaussian curvature - is great enough. The significance of the Gaussian curvature in this connection may be realized through its geometric interpretation, or through the "Theorema egregium" of Gauss, showing the Gaussian curvature to serve also as a kind of measure of the amount of strain (see e.g. Lipschutz, 1969; cf. also Ekman, 1981 and 1983).

In order to get a picture of the land uplift curvatures and their relation to the earthquake pattern we have proceeded in the following way:

1. A map of the observed land uplift was compiled from maps and data produced by geodetic institutes working in Denmark, Norway, Sweden, Finland, Estonia, Latvia, and the northwesternmost part of the Soviet Union (for references see page 33). These maps are based on repeated levellings and tide gauge (mostly mareograph) observations, in general covering the period 1890 - 1960 approximately. A small version of the compiled land uplift map is shown in Fig. 1. (The northernmost part of the Finnish map has not been used, since that part is based on such a short time period as about 15 years and, therefore, may be disturbed, e.g. by possible small short-time irregularities in the land uplift.)

2. From the compiled land uplift map mean land uplift values within 162 squares of $1^{\circ} \times 1^{\circ}$ ($1^{\circ}$ latitude $\times$ $2^{\circ}$ longitude) were determined. The present knowledge of land uplift does not allow smaller squares than these to be used. The observed mean land uplift values were converted to absolute mean land uplift values through (8), taking

Table 1: Mean values of absolute land uplift (mm/year) within $1^{\circ}$ squares ($1^{\circ}$ latitude $\times$ $2^{\circ}$ longitude). Latitude and longitude are given for the northwestern corner of each square.

| $\varphi_{NW}$ | $\lambda_{NW}$ | U | $\varphi_{NW}$ | $\lambda_{NW}$ | U | $\varphi_{NW}$ | $\lambda_{NW}$ | U |
|---|---|---|---|---|---|---|---|---|
| 71.0 | 23.0 | 1.7 | 66.0 | 27.0 | 8.4 | 62.0 | 23.0 | 6.7 |
| 71.0 | 25.0 | 1.6 | 66.0 | 29.0 | 7.2 | 62.0 | 25.0 | 6.0 |
| 70.0 | 17.0 | 1.9 | 66.0 | 31.0 | 5.9 | 62.0 | 27.0 | 5.0 |
| 70.0 | 19.0 | 3.0 | 66.0 | 33.0 | 3.7 | 62.0 | 29.0 | 3.7 |
| 70.0 | 21.0 | 3.5 | 66.0 | 35.0 | 2.6 | 62.0 | 31.0 | 1.7 |
| 70.0 | 23.0 | 3.8 | 65.0 | 9.0 | 1.7 | 61.0 | 5.0 | 1.7 |
| 70.0 | 25.0 | 3.8 | 65.0 | 11.0 | 4.2 | 61.0 | 7.0 | 3.1 |
| 70.0 | 27.0 | 3.4 | 65.0 | 13.0 | 6.1 | 61.0 | 9.0 | 4.4 |
| 70.0 | 29.0 | 2.8 | 65.0 | 15.0 | 7.7 | 61.0 | 11.0 | 5.3 |
| 70.0 | 31.0 | 2.1 | 65.0 | 17.0 | 8.8 | 61.0 | 13.0 | 6.3 |
| 69.0 | 15.0 | 2.5 | 65.0 | 19.0 | 9.7 | 61.0 | 15.0 | 7.3 |
| 69.0 | 17.0 | 4.3 | 65.0 | 21.0 | 10.9 | 61.0 | 17.0 | 7.6 |
| 69.0 | 19.0 | 5.6 | 65.0 | 23.0 | 10.0 | 61.0 | 19.0 | 7.3 |
| 69.0 | 21.0 | 6.2 | 65.0 | 25.0 | 9.1 | 61.0 | 21.0 | 6.6 |
| 69.0 | 23.0 | 6.4 | 65.0 | 27.0 | 8.4 | 61.0 | 23.0 | 5.4 |
| 69.0 | 25.0 | 6.2 | 65.0 | 29.0 | 6.9 | 61.0 | 25.0 | 4.5 |
| 69.0 | 27.0 | 5.8 | 65.0 | 31.0 | 5.4 | 61.0 | 27.0 | 3.6 |
| 69.0 | 29.0 | 4.9 | 65.0 | 33.0 | 3.3 | 61.0 | 29.0 | 2.1 |
| 69.0 | 31.0 | 3.7 | 65.0 | 35.0 | 1.5 | 60.0 | 5.0 | 1.5 |
| 69.0 | 33.0 | 2.7 | 64.0 | 9.0 | 3.3 | 60.0 | 7.0 | 2.7 |
| 69.0 | 35.0 | 1.9 | 64.0 | 11.0 | 5.4 | 60.0 | 9.0 | 3.9 |
| 68.0 | 13.0 | 1.8 | 64.0 | 13.0 | 7.0 | 60.0 | 11.0 | 4.8 |
| 68.0 | 15.0 | 4.1 | 64.0 | 15.0 | 8.3 | 60.0 | 13.0 | 5.3 |
| 68.0 | 17.0 | 6.4 | 64.0 | 17.0 | 9.5 | 60.0 | 15.0 | 5.8 |
| 68.0 | 19.0 | 7.8 | 64.0 | 19.0 | 9.9 | 60.0 | 17.0 | 5.8 |
| 68.0 | 21.0 | 8.0 | 64.0 | 21.0 | 9.7 | 60.0 | 19.0 | 5.4 |
| 68.0 | 23.0 | 7.9 | 64.0 | 23.0 | 9.2 | 60.0 | 21.0 | 4.8 |
| 68.0 | 25.0 | 7.6 | 64.0 | 25.0 | 8.3 | 60.0 | 23.0 | 4.1 |
| 68.0 | 27.0 | 7.1 | 64.0 | 27.0 | 7.6 | 60.0 | 25.0 | 3.0 |
| 68.0 | 29.0 | 6.3 | 64.0 | 29.0 | 6.1 | 60.0 | 27.0 | 1.8 |
| 68.0 | 31.0 | 5.0 | 64.0 | 31.0 | 4.5 | 59.0 | 7.0 | 2.1 |
| 68.0 | 33.0 | 3.7 | 64.0 | 33.0 | 1.9 | 59.0 | 9.0 | 3.0 |
| 68.0 | 35.0 | 3.0 | 63.0 | 7.0 | 2.4 | 59.0 | 11.0 | 3.9 |
| 68.0 | 37.0 | 2.1 | 63.0 | 9.0 | 4.2 | 59.0 | 13.0 | 4.2 |
| 67.0 | 13.0 | 3.4 | 63.0 | 11.0 | 5.8 | 59.0 | 15.0 | 4.3 |
| 67.0 | 15.0 | 5.8 | 63.0 | 13.0 | 7.4 | 59.0 | 17.0 | 4.3 |
| 67.0 | 17.0 | 7.6 | 63.0 | 15.0 | 8.8 | 59.0 | 19.0 | 4.0 |
| 67.0 | 19.0 | 8.6 | 63.0 | 17.0 | 9.3 | 59.0 | 21.0 | 3.7 |
| 67.0 | 21.0 | 9.1 | 63.0 | 19.0 | 9.0 | 59.0 | 23.0 | 2.9 |
| 67.0 | 23.0 | 8.9 | 63.0 | 21.0 | 8.7 | 59.0 | 25.0 | 1.9 |
| 67.0 | 25.0 | 8.4 | 63.0 | 23.0 | 8.0 | 58.0 | 7.0 | 1.5 |
| 67.0 | 27.0 | 7.9 | 63.0 | 25.0 | 7.1 | 58.0 | 9.0 | 2.1 |
| 67.0 | 29.0 | 6.9 | 63.0 | 27.0 | 6.2 | 58.0 | 11.0 | 2.5 |
| 67.0 | 31.0 | 5.8 | 63.0 | 29.0 | 5.0 | 58.0 | 13.0 | 2.8 |
| 67.0 | 33.0 | 3.4 | 63.0 | 31.0 | 3.1 | 58.0 | 15.0 | 2.7 |
| 67.0 | 35.0 | 1.9 | 62.0 | 5.0 | 1.6 | 58.0 | 17.0 | 2.7 |
| 66.0 | 11.0 | 2.5 | 62.0 | 7.0 | 3.0 | 58.0 | 19.0 | 2.6 |
| 66.0 | 13.0 | 5.0 | 62.0 | 9.0 | 4.6 | 58.0 | 21.0 | 2.2 |
| 66.0 | 15.0 | 6.9 | 62.0 | 11.0 | 5.8 | 58.0 | 23.0 | 1.7 |
| 66.0 | 17.0 | 8.2 | 62.0 | 13.0 | 7.2 | 57.0 | 11.0 | 1.5 |
| 66.0 | 19.0 | 9.4 | 62.0 | 15.0 | 8.4 | 57.0 | 13.0 | 1.8 |
| 66.0 | 21.0 | 10.4 | 62.0 | 17.0 | 8.8 | 57.0 | 15.0 | 2.0 |
| 66.0 | 23.0 | 9.9 | 62.0 | 19.0 | 8.3 | 57.0 | 17.0 | 1.9 |
| 66.0 | 25.0 | 9.2 | 62.0 | 21.0 | 7.7 | 57.0 | 19.0 | 1.7 |



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numerical data for the corrections from (Sjöberg, 1982) and (Lisitzin, 1974).A list of the mean land uplift values $U(\varphi, \lambda)$ is given in Table 1.

3. The coefficients $\bar{a}_{nm}$ and $\bar{b}_{nm}$ of the series expansion were computed according to (5) and (6), using the values of Table 1.

4. Now the land uplift curvatures K and H were computed, applying the formulae (41) and (35). As the series expansion is based on $1^o$ squares, the maximum possible value of N is $N_{max} = 180$, which corresponds to the minimum wave-length $\psi_{min} = 1^o$.

5. In order to examine the stability of the solutions for various values of N several curvature calculations with different N values ($N \leq 180$) were made. They show fairly similar curvature patterns for $180 \geq N \geq 120$ corresponding to $1\overset{o}{.}0 \leq \psi \leq 1\overset{o}{.}5$. For smaller values of N the wave-length $\psi$ gets too large to describe the shape of the land uplift properly enough.

6. Finally curvature maps were constructed for the cases N = 180 and N = 150, and their zones of great curvatures compared with the distribution of earthquakes in Fennoscandia.

## 3.2. Result of investigation.

The results of the Gaussian curvature computations of the Fennoscandian land uplift for the cases N = 180 and N = 150 are shown as Gaussian curvature maps in Figures 2 and 3.

Looking at Fig. 2 (N = 180) we find a zone of great Gaussian curvatures - $|K| > 50$ - along the Swedish coast of the Gulf of Bothnia, with a maximum of $K > 200$ in the northern end and a maximum of $K > 100$ in the southern end. We also find an area with $K > 50$ in northernmost Sweden with a maximum of $K > 100$ in northwestern Lapland. We observe that all curvatures are elliptic (K positive) except for a small area in the middle of the Bothnian zone where the curvature is hyperbolic (K negative).

Looking at Fig. 3 (N = 150) we find areas with great Gaussian curvatures - $K > 50$ - at the Swedish coast of the northern part of the Gulf of Bothnia and at the Swedish coast of the southern part of the Gulf of Bothnia, both with maxima of $K > 100$. A third area with $K > 50$ and a maximum of $K > 100$ is found in northernmost Sweden, i.e. northern Lapland.

We now turn also to the seismic map, Fig. 4, showing instrumentally recorded earthquakes in Sweden and Finland and in Norway apart from the Atlantic coast (usually of magnitudes $\leq 4$, depths $\leq 30$ km). Comparing the curvature pattern of Figures 2 and 3 with the seismic pattern of Figure 4 we find that the zones or areas with great Gaussian land uplift curvatures are characterized by earthquake activity. This is as predicted by the land uplift curvature theory. In addition we find one earthquake area, in south-eastern Norway and south-western Sweden (Oslo Fiord - Lake Vänern area), which is not at all predicted by the land uplift curvature. No statement can be made about the earthquakes in parts of northern Finland since the curvature values there are too unreliable.

The pattern of the mean curvature was found to be rather similar to that of the Gaussian curvature; as expected the relation to the seismic pattern was somewhat less clear.

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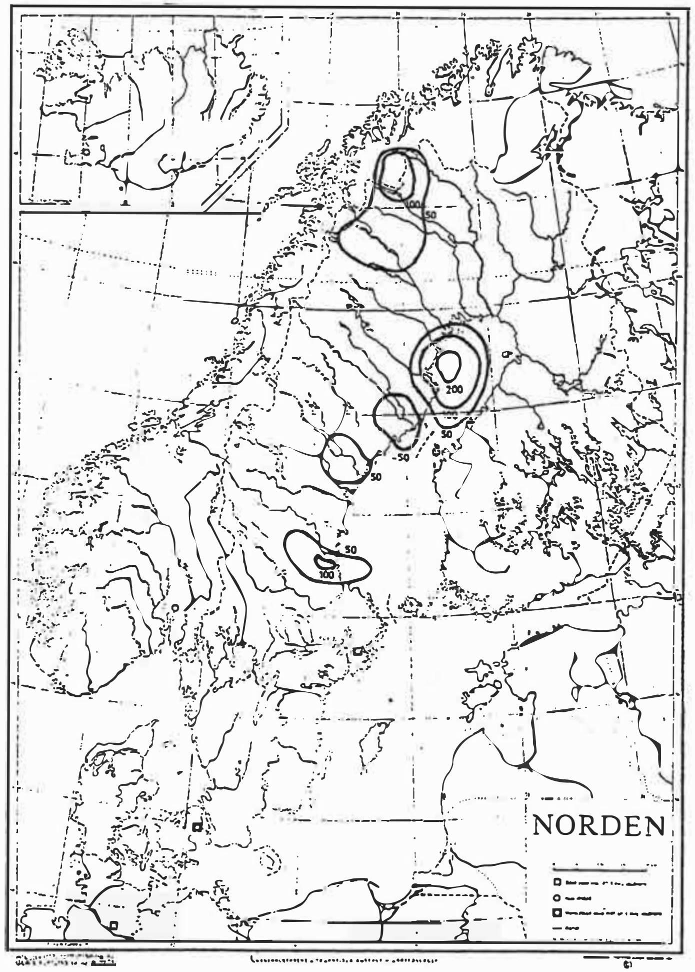


Figure 2: Gaussian curvature K of the postglacial land uplift of Fennoscandia; N = 180. Unit of K (for one century of land uplift): $10^{-30}$ $mm^{-2}$.

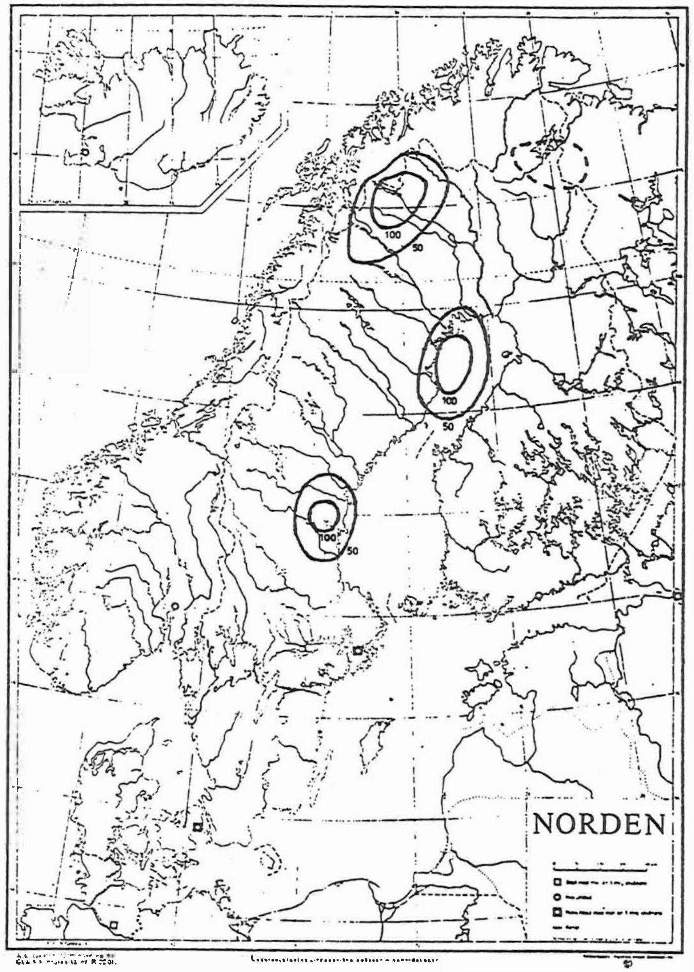


Figure 3: Gaussian curvature K of the postglacial land uplift of Fennoscandia; N = 150. Unit of K (for one century of land uplift): $10^{-30}$ $mm^{-2}$.



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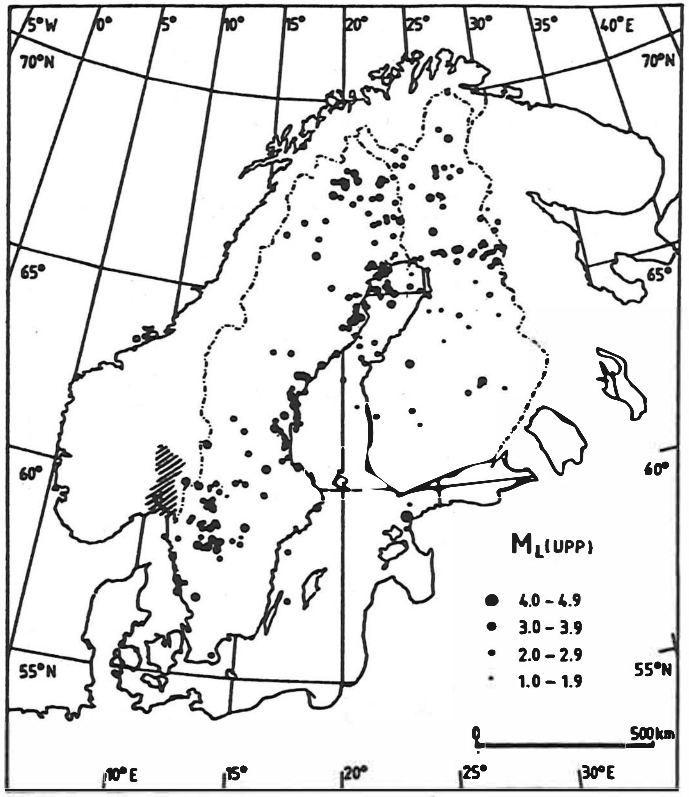


Figure 4: Instrumentally recorded earthquakes in Sweden and Finland (1963 - 1979) and in Norway apart from the Atlantic coast (hatched area). (Mainly from Wahlström - Ahjos, 1982)

<u>We may conclude:</u> The postglacial land uplift of Fennoscandia is probably the origin of the earthquakes along the whole Swedish coast of the Gulf of Bothnia as well as possibly of those in northernmost Sweden (northern Lapland), the earthquakes occurring mainly where the Gaussian curvature of one century of land uplift exceeds about $50 \cdot 10^{-30}$ $mm^{-2}$. No such relation exists for the earthquakes of south-eastern Norway/south-western Sweden (Oslo - Vänern area), which then probably do not originate from the land uplift.

To the extent the secondary effect of deloading of the Gulf of Bothnia contributes to the land uplift wave-lengths larger than 1°.0 (N = 180) or 1°.2 (N = 150) this effect is included in the above solution.

Finally we note that the Gaussian curvature of one century of land uplift is of the order of $3 \cdot 10^5$ times the Gaussian curvature of the earth tide (cf. Ekman, 1983). (This corresponds to the secular land uplift strain being of the order of $10^3$ times the tidal strain.)

A better knowledge of the land uplift through the new Nordic repeated levellings (and longer series of tide gauge data) will be valuable for drawing more definite conclusions in the future than has been possible to do here.

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## List of symbols.

| | | |
|---|---|---|
| E, F, G | = | first fundamental coefficients |
| H | = | mean curvature |
| K | = | Gaussian curvature |
| L, M, N | = | second fundamental coefficients |
| N | = | highest degree of series expansion |
| $P_{nm}$ | = | Legendre function |
| $\bar{P}_{nm}$ | = | normalized Legendre function |
| R | = | mean radius of the earth |
| U | = | absolute land uplift |
| $U_e$ | = | eustatic rise of sea level |
| $U_g$ | = | geoid uplift |
| $U_{obs}$ | = | observed land uplift |
| x, y | = | local Cartesian coordinates |
| $\delta_{0m}$ | = | Kronecker delta |
| $\lambda$ | = | longitude |
| $\varphi$ | = | latitude |
| $\psi$ | = | shortest wave-length of series expansion |

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Professor Lars Sjöberg has supplied me with his computer programme for harmonic coefficients. He has also been helpful in discussions on the subject. My wife Britt Marie Ekman has patiently tried to introduce me into the strange world of computer programming and has made a lot of the programming work. Miss Ingegerd Ohlsson has carefully typed the manuscript. My thanks to all of them.

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# NEAR-SURFACE DEFORMATIONS AND STRESSES IN THE AREA OF THE TOLBACHIK GREAT FISSURE ERUPTION OF 1975-1976 (KAMCHATKA) FROM GEODETIC DATA

A large basalt fissure eruption was active in Kamchatka from July 1975 till December 1976. Four big and several small cones were formed, the highest reaching 310 m. About 2 $km^3$ of deep material was erupted into the surface.

The rise of such an amount of material through crustal rocks could not fail causing considerable deformations. Therefore, geodetic measurements were made in the region. Both the rapid local deformations and opening of cracks and the slow and residual displacements over a large area were studied.

The present paper deals with the analysis of displacements of the points of the triangulation network covering the area of 40x60 km around the region of eruption. Angle and linear measurements were carried out in 1971 (before eruption), in 1976 and 1977 (during and after eruption respectively). The formulas of mechanics were used to determine the parameters of deformations (values and direction of the principal strain axes, maximal shears, dilatation); the basic regularities in the deformation of the region of eruption were analysed; the stress values were calculated with regard to different observation periods. All calculations were made under assumption that the medium is continuous and homogeneous.

Comparison of maps showing deformation parameters in the region of the Tolbachik eruption was carried out from the differences of equated sides for the periods of 1976-1971 and 1977-1976. The accuracy of the difference of sides between measurements in adjacent epochs has an error $\pm 4 \times 10^{-6}$, [1] .

The observation data demonstrate that the zone of horizontal deformations spreads far beyond the fault line where new cones were formed, i.e., in the sub-latitudinal direction to about 30 km (within the network) and in the meridional direction to more than 40 km, thus reaching beyond the network boundary, fig. 1a.

In the period of 1976-1971 the region of new cones experienced considerable strain and the largest strain values, up to $25\text{-}30.10^{-6}$ were observed west and east of the eruption. The strain values from north to south are small, about $+10.10^{-6}$. The strain to the west, north and east rapidly attenuates and at the distance of 5-10 km from the new cones is substituted by compression. In the south, the zone reaches beyond the network boundary. This does not contradict the conclusions, derived from the materials of modelling, [2] ,about the rounded shape of the deformation zone in the region of the Northern Breach caused by the local spherical source of pressure (magmatic focus). North of the eruption area there is a zone of high compression with values up to $-20\text{-}25.10^{-6}$.

Since till June 1975 the region was practically aseismic and seismic activity started with the first earthquake swarm of 27.06.75, it seems apparent that the largest deformations occurred from that moment. Having no measurements exactly before the eruption and assuming the law of accreation of deformations to be analogous to the the law of reduction (obtained from measurement results), the maximal deformations in the region of eruption can be evaluated at $1\text{-}2.10^{-4}$. Residual deformations in 1976 make 15-20% of the maximal. The maximal deformations of $1\text{-}3.10^{-4}$ at the bases 1.5-2.0 km were obtained during formation of cracks on the surface from the results of repeated measurement of lines across the fault zone; these measurements were made by the electro-optical distance device during the bursts of the II and III cones.



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In the period of 1971-1976, the maximal shear deformations up to $50.10^{-6}$ occurred north-west of the Northern Breach and up to $25.10^{-6}$ south-west of the Southern Breach, fig. 1b. The maximal dilatation values reached $35.10^{-6}$ and, probably, the source of deformations is located in the region slightly displaced to the west of the new cones, fig. 1c. The data of seismic prospecting confirm the displacement of focus to the west (2-3 km) from the eruptive fissure, [3]. North of that line the dilatation values are negative.

The study of the mechanisms of earthquake focus in the region of the Kluchevskaya group of volcanoes during the period of eruption has revealed that on the whole the region of eruption experienced an upheaval in relation to the nothern stable zone. The eruption zone itself has two subzones: the eastern one with overthrust movements and the western with shear faulting, [4]. This subdivision is in good agreement with the data of maps showing parameters of near-surface deformations and compiled from geodetic data. Both methods distinguish two zones of different deformations: northern and southern, whose boundary runs between the Tolbachik Volcano and the Northern Breach. The zone of large shear displacements is located west of the fissure on which the new cones appeared.

Comparison between the directions of the principal axes of stresses in earthquake focus of 1975-1976 and of the principal axes of deformations on the surface for the period of 1971-1976 made from geodetic data has revealed as follows. The forces of compression and tension are active in earthquake focus. The averaged position of the compression axes in close to the submeridional and nearly horizontal, whereas that of tension axes is close to sublatitudinal and nearly horizontal. The averaged directions of the axes of compression and tension for 1975-1976 remain the same, expect for the period of 2-6. YII.1975, i.e. from the moment of the most strong earthqoakes (M=5) to the beginning of eruption. From geodetic data, in the time interval of 1971-1976, in the region of eruption only tension was observed; it was highest in the west-east direction and slight in the north-south direction, which testifies in favour of the fact that from the feeding chamber magma rose along a weakened zone of the fault and formed a dyke or a series of dykes. Therefore, the stress of compression at the depth is expressed on the surface by a slight tension coinciding with it approximately along the direction, whereas the stress of tension at the depth also corresponds on the surface to tension with maximal values near the eruption. The change in the direction of the axes of stresses in the period of 2-6.YII.1975 might perhaps be attributed to the earthquakes which started from 27.YI to 2.YII. 1975 and which prepared the way for the magma to flow to the surface. On 2.YII.1975, as the result of strong earthquakes, a fissure appeared, along which the magma started to rise. At the same time, excessive pressure, while pushing the magma along the fissure to the surface, changed the dominating stresses in the region of the breakthrough fissure. And only after the beginning of eruption, when excessive pressure was released, the dominating stresses at the depth in the region of eruption were restored. This is confirmed by the fact that the plane of fracture in the focus of the strongest earthquake is close by strike to the orientation of the breakthrough fissure. Moreover, after the two strong earthquakes on 2.YII.1975 and before the beginning of eruption the energy and depth of earthquakes decreased, [5].

In the period of 1976-1977, compression was observed on almost the entire region, and the highest values (up to $-25 - 39.10^{-6}$) were observed around the Tolbachik Volcano and to the north of it, fig. 2a. The tension around the new cones changed to a slight compression. Compression in the zone of the new cones involved the adjoining regions into the movement, causing a slight tension from west to east of the compression zone. The maximal shear deforma-



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tions, up to $25.10^{-6}$, fig. 2b, as also the maximal dilatation (compression) values, up to $-40.10^{-6}$, fig. 2c, occurred in the same period in the region of the Tolbachik Volcano. Over the remaining territory, the displacement and the changes of area (dilatation) are small and regularity distributed. This feature of deformations can apparently be attributed to the subsidence of the Earth's surface after the outflow of magma under the weight of new cones, lava cones, lava piles and erupted pyroclastic material.

The stresses in the near-surface layers, calculated from geodetic data, corresponded to the maximal deformations of compression and tension in the period of 1971-1976 (the sum of displacements in the preparatory period before the eruption and the Northern Breach activity) and did not exceed 30 kg/cm$^2$. The elasticity module values were derived from the results of seismic sounding of the region,[6].

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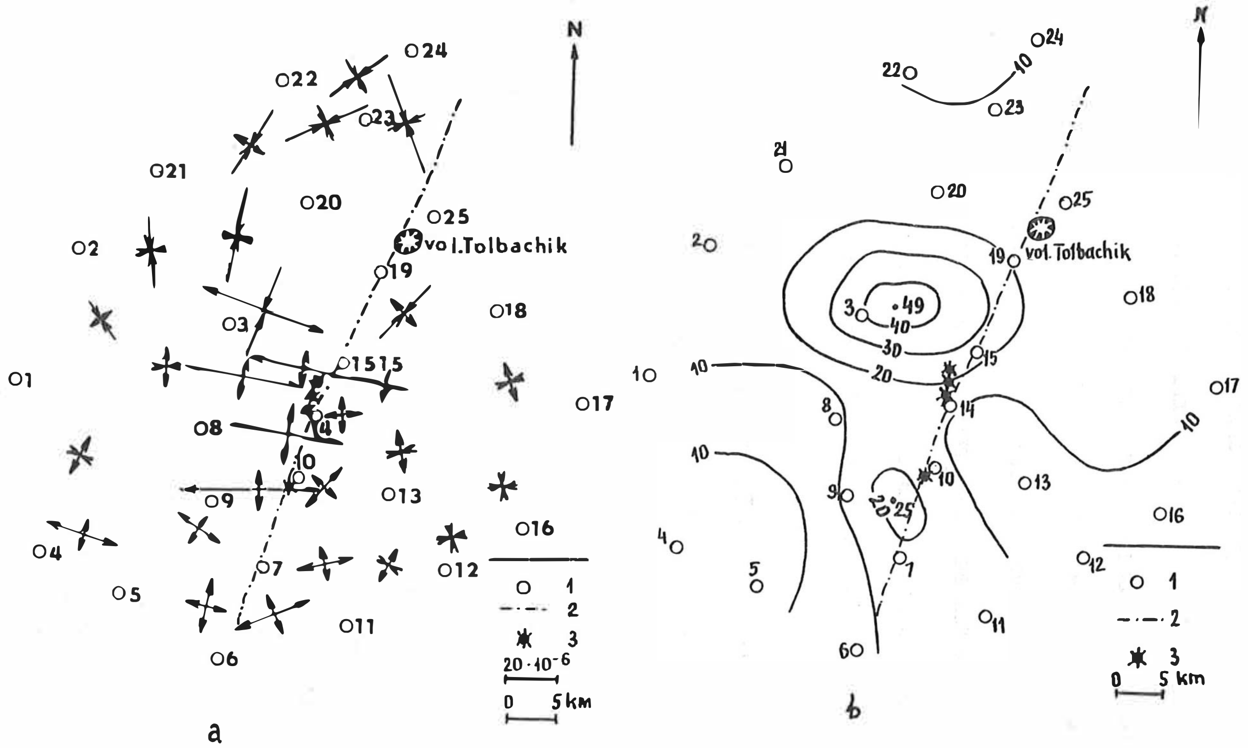


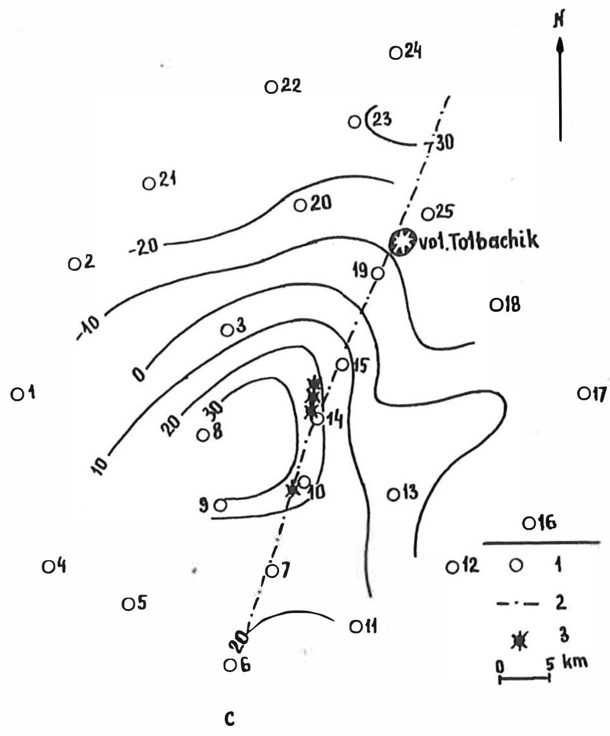


Fig. 1.
The maps of the parameter of deformations of the Tolbachik Great Fissure eruption during the period 1971-1976

a) principal strain axes and their orientation $\varepsilon_1, \varepsilon_2, \vartheta$

b) maximal shear deformations $\gamma \cdot 10^{-6}$

c) dilation $\Delta \cdot 10^{-6}$

1-pointe of the triangulation network

2-the fault

3-the new cratere

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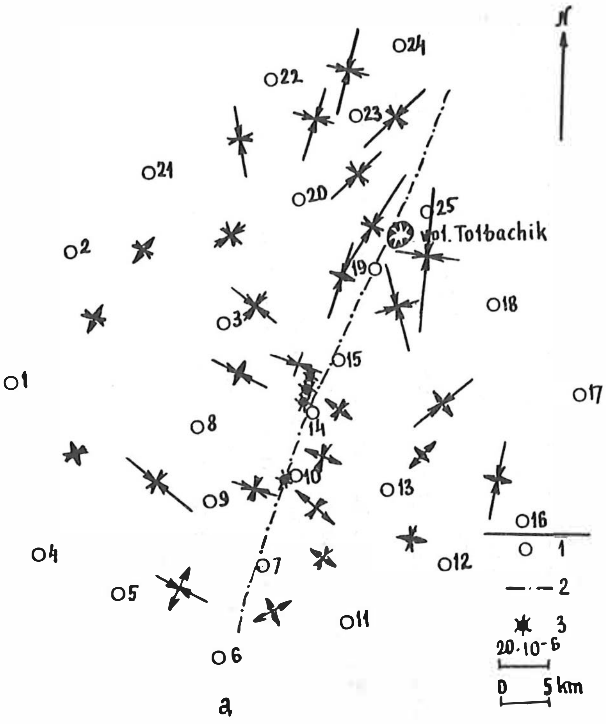


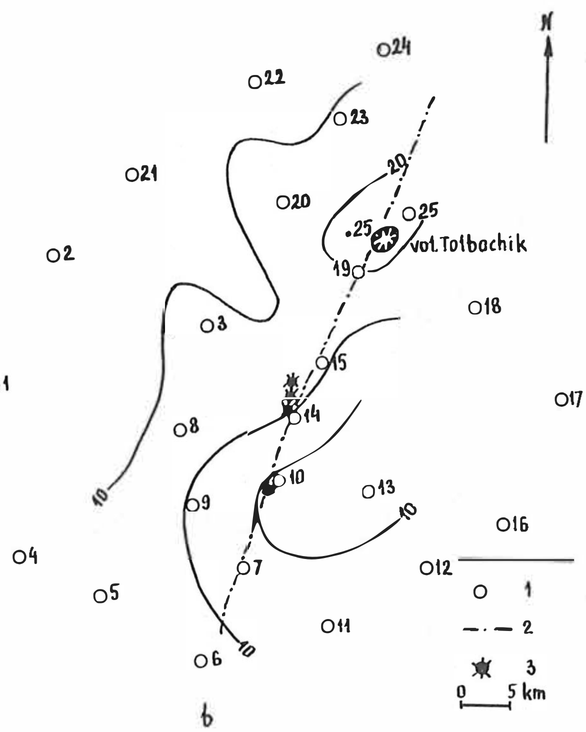


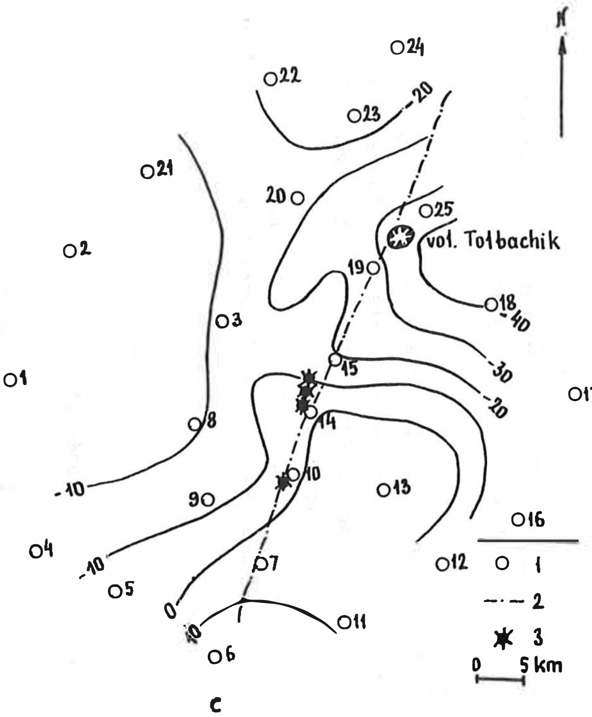


Fig. 2.
The maps of the parameter of deformations of the Tolbachik Great Fissure eruption during the period 1976-1977

a) principal strain axes and their orientation $\varepsilon_1, \varepsilon_2, \vartheta$

b) maximal shear deformations $\gamma \cdot 10^{-6}$

c) dilation $\Delta \cdot 10^{-6}$

1-points of the triangulation network
2-the fault
3-the new craters

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# Method of joint adjustment of height differences and velocities of vertical movements

M.Füry[1] — J.Gergely[2] — Zs.Németh[2]

**Summary**

The preliminary investigations of Carpatho-Balkan Region's repeated levelling network led to the conclusion that the adjustment should be carried out in a way discussed in this paper.

According to this method the height differences of the second levelling were adjusted jointly with the velocities computed from the first and second levellings. The algorithm of the rigorous adjustment and the weighting system of correlated quantities are presented. The computer program and the network are also discussed. The computation run in computer HWB 66/20 in FORTRAN by sparse manner. The normal matrix was factorized by means of Gauss elimination.

## Methode der gemeinsamen Ausgleichung der Höhenunterschiede und Geschwindigkeiten vertikaler Bewegungen

**Zusammenfassung**

Die vorläufige Untersuchung des Wiederholungsnivelliernetzes in der Karpathen-Balkan Region führte zur Schlussfolgerung, dass die Ausgleichung auf der in der Abhandlung geschilderten Weise durchgeführt werden soll.

Nach dieser Methode wurden die Höhenunterschiede gemeinsam mit der von der ersten und zweiten Nivellierung berechneten Geschwindigkeitswerten ausgeglichen. Der Algorithmus der strengen Ausgleichung und das Gewichtssystem der Korrelaten werden präsentiert. Das Rechenprogramm und das Netz werden auch vorgestellt. Die Berechnung wurde auf einer Rechenanlage HWB 66/20 in FORTRAN Sprache mit Sparse-Technik durchgeführt. Das Normalmatrix wurde nach der Gausschen Eliminierungsmethode faktorisiert.

In 1974 the first adjustment of the network established for the investigation of crustal movements in the Carpatho-Balkan Region /CBR/ has been carried out [2]. Then the relative velocities deduced from the levellings performed in the period preceding the World War II and those of the 1950's have been adjusted.

In 1983 a second adjustment was carried out on the base of the levellings of 1950's and 1970's.

On the base of the preliminary investigations [3] a technique has been deduced having the Hazay's approach as a start-point, with the use of which the joint adjustment of height differences and deduced relative velocities of movements of the second levelling was carried out. Applying the joint adjustment method recommended by prof. Hazay in 1967, the measured height differencies of both levellings get a correction [1].

<u>Method of adjustment:</u> adjustment of indirect measures with unknowns depending on each other

<u>Unknowns:</u> absolute height and velocity of the points related to a chosen epocha

Let us introduce the following designations:

$\overline{H}_k$, $\overline{H}_j$ adjusted absolute height of levelled points related to the chosen epocha

$\overline{h}_i$ adjusted height differences related to the chosen epocha

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$h'_i$, $v'_i$; $h''_i$, $v''_i$, measured height differences of the first and the second levelling and their correction

$\Delta\bar{V}_i$ adjusted relative velocities

$\Delta V_i$, $v^{\Delta}_i$ the deduced relative velocities and their correction

$H_{ok}$, $dH_k$; $H_{oj}$, $dH_j$ preliminary value of the height above the sea of the levelled points related to the chosen epocha and its variation

$V_{ok}$, $dV_k$; $V_{oj}$, $dV_j$ preliminary value of the absolute velocity of levelled points and its variation

$t''_i$ time past between the second levelling and the chosen epocha

$\Delta T_i$ time past between the two levellings

$L_i$ length of the levelling line

$m'_i$, $m''_i$ mean square error/ km of the first and the second levellings

Observation equations:

1./ One can get the height difference related to the chosen epocha between two points as the difference of the adjusted absolute heights related to the chosen epocha of the previous and following points

$$\bar{h}_i = \bar{H}_k - \bar{H}_j = /H_{ok} + dH_k/ - /H_{oj} + dH_j/ = h''_i + v''_i + t''_i\,/\Delta V_i + v^{\Delta}_i/ =$$
$$= h''_i + v''_i + t''_i\,[/V_{ok} + dV_k/ - /V_{oj} + dV_j/]$$

2./ One gets the adjusted relative velocity of the vertical movement of a line by forming the difference of the absolute velocity of its both endpoints:

$$\Delta\bar{V}_i = \bar{V}_k - \bar{V}_j = /V_{ok} + dV_k/ - /V_{oj} + dV_j/ = \Delta V_i + v^{\Delta}_i$$

Forming the observation equations from these:

$$v''_i = -dH_j + dH_k + t''_i dV_j - t''_i dV_k + l''_i \qquad /1/$$

where: $l''_i = -H_{oj} + H_{ok} - h''_i + t''_i V_{oj} - t''_i V_{ok}$

$$v^{\Delta}_i = -dV_j + dV_k + l_i \qquad /2/$$

where: $l_i = -V_{oj} + V_{ok} - \Delta V_i$

Assuming the movement to be linear in the period between the two levellings, one gets the relative velocity as the quotient of the realized height variation and the time past:

$$\Delta V_i = \frac{h''_i - h'_i}{\Delta T_i}$$

From the foregoing one can see, that the unknowns belonging to one point don't depend on each other, the weight matrix isn't a diagonal one. Because of the relationship between the unknowns the weight matrix is written as follows:

$$P = Q^{-1} \qquad /3/$$

$$Q/i,i/ = \mu''^2_i = \frac{L_i m''^2_i}{c}$$

$$Q/i+1,\ i+1/ = \mu^{\Delta 2}_i = \frac{L_i/m'^2_i + m''^2_i/}{c\cdot\Delta T^2_i}$$

$$Q/i+1,\ i/ = Q/i,\ i+1/ = \frac{\mu''^2_i}{\Delta T_i} = \frac{L_i m''^2_i}{c\cdot\Delta T_i}$$

The other elements of the weight coefficient matrix is zero.

Let us arrange $dH_i$ and $dV_i$ unknown variations into the vector x, the design matrix A and the constant vector l constructed on the base of /1/ an /2/ . Then the observation equations /1/ and /2/ can be expressed this way:

$$v = Ax + l$$

Be the amount of the measured lines in the network m, the one of the unknown points n/m > n/, so A is a sparse matrix consisting of 2m rows and 2 n columns the matrix contains two or four non zero elements by rows. We want to determine vector x from the condition

$$v^* Pv \text{ minimum},$$

where P a weight matrix defined by [3]. To fulfill the minimum condition, the solution of normal equation

$$/A^*PA/x + A^*Pl = 0$$

is necessary.



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The matrix of the system of normal equation

$$N = A^*PA$$

is a symmetrical, positive definite sparse matrix.

For construction of the matrices A and N, and for solving the system of normal equation the sparse matrix technique was used, so only the non zero elements were stored and operations were carried out only with non zero elements.

The system of normal equation

$$Nx = b = -A^*Pl \qquad /4/$$

was solved as follows: the matrix N was factorized using the sparse matrix technique into the form

$$N = L \cdot R ,$$

where L left side , and R right side triangle matrices. Then the equation /4/ turns to two systems of equations.

$$Ly = b \qquad /5/$$
$$Rx = y$$

Since L and R are triangle matrices too, so /5/ can be solved by resubstitution.

By putting the i-th unit vector $e_i$ in place of b in the first equation of /5//the i-th component of $e_i$ is 1, the rest is 0/ and solving the /5/ /i.e. by subsequent resubstitution/ one gets the i-th column of the inverse of matrix N, $Q = N^{-1}$. For calculation of the value of reliability one needs the i-th element of the i-th column of the inverse, $q_i$/diagonal elements i=1, ......2n/.

Adding the x got by solving the normal equation to the preliminary value of the parameters /heights and velocities/ one gets the adjusted values of the parameters:

$$\overline{H}_i = H_{o,i} + dH_i, \qquad \overline{V}_i = V_{o,i} + dV_i$$

The value of reliability:

$$\mu_i = \mu_o \sqrt{q_i}$$

The average error of unit weight:

$$\mu_o^2 = \frac{V^* PV}{2/m-n/}$$

In the adjustment of the CBR: 2n = 614, 2m = 940.

The adjustment computation was carried out on a computer Honeywell B 66/20. The programmes were prepared in FORTRAN language. The operations performed by the programmes were as follows:

- Construction of coefficient matrix of the observation equations from the input data, computation of the vector of constants, construction of the system of normal equation;
- Factorization fo the normal matrix, solving the system of equation, inversion of the matrix
- Computation of the adjusted absolute heights and velocities of absolute movements related to the chosen epocha, computation of the correction vector, $\mu_o$ and the mean square errors.
- Construction and printing of the output files.

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## Prinzip der Zusammenstellung der Linien der wiederholten Nivellierung zur Untersuchung der vertikalen Bewegungen in der Karpathen-Balkan Region

M.Füry[1] - Zs.Németh[2] - J. Thury[2]

Zusammenfassung

Die in den 1970-er Jahren durchgeführten Nivellierungen haben eine Verbindung zwischen dem Baltischen, Schwarzen und Adriatischen Meer zustande gebracht. Die Linien dieses Nivelliernetzes fielen meistens mit den früheren Nivellierlinien zusammen, so konnten die Messungen zur Untersuchung der vertikalen Bewegungen in der Karpathen-Balkan Region /KBR/ benutzt werden.

Die früheren Nivellierungen wurden mit unterschiedlicher Zuverlässigkeit und in einer langen Periode verteilt durchgeführt. Durch eine Rechnung mit der Summe der Höhenunterschiede der früheren Messungen zwischen den Knotenpunkten und dem Durchschnittswert der Zuverlässigkeit und der Messtermine der Nivellierung wird das Endergebnis laut der Versuchsausgleichung sichtlich beeinflusst. Diese Wirkung kann so beseitigt werden, dass die Ausgleichung des wiederholten Nivelliernetzes mit Nivellierstrecken gleicher Zuverlässigkeit und kurzer Messzeit durchgeführt wird, was aber die Arbeit der Ausgleichung beträchtlich erhöht. Ähnliches Resultat kann auch so erreicht werden, wenn zusammen mit den Höhenunterschieden der zweiten Nivellierung die von den beiden Nivellierungen abgeleiteten Geschwindigkeitswerte ausgeglichen werden. Die Geschwindigkeiten und ihre Gewichtsreziproke können zwischen den Knotenpunkten ohne Vernachlässigung summiert werden. Deshalb wurden für jede Linie zwischen den Knotenpunkten in der KBR der Höhenunterschied der zweiten Nivellierung, seine Zuverlässigkeit und der Zeitpunkt seiner Messung, sowie die Summe der für jede Strecke abgeleiteten Geschwindigkeitswerte und deren Gewichtsreziproken zusammengestellt.

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## Principle of the construction of the lines of the repeated levelling for the investigation of the vertical movement in the Carpatho-Balkan Region/CBR/

Summary

The levellings carried out in the 1970's have established junctions to the Baltic, Black and Adriatic Sea. The lines of this levelling network mostly coincide with the former ones, accordingly the measurements provided a possibility of use in the investigation of the vertical crustal movements in the Carpatho-Balkan Region /CBR/.

The former levellings were carried out with different relisbility and protracted for a long time. The final result is doubtlessly influenced by the calculation carried out using the sum of the height differences on the lines led between the knotpoints, the mean reliability and the time of measurement of the levellings, as the experimental adjustment showed. This effect can be overcome by carrying out the adjustment of the repeated levelling network with use of levelling sections of same reliability and in a shorter time interval, which extremely increase the volume of the work. Similar result can be obtained by the joint adjustment of the velocity values deduced from both levellings and the height differences of the second levelling. The velocity values and their reciprocals can be summed up between the knotpoints without neglecting. It is why the height difference of the second levelling, its reliability and the time of the measurement, as well as the sum of velocity values deduced for each section and their weight reciprocals have been drawn up for each line between the knotpoints in the CBR.



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In den 1970-er Jahren wurden Präzisionsnivellierungen durchgeführt, die zwischen dem Baltischen, Schwarzen und Adriatischen Meer Verbindung zustandegebracht haben. Es lag an der Hand, diese Messungen zur Untersuchung der rezenten vertikalen Erdkrustenbewegungen zu verwenden. Da die Nivellierlinien so geführt wurden, dass sie meistens mit den früheren Nivellierlinien zusammenfielen, ergab sich die Möglichkeit dazu.

Die bei den Erdkrustenbewegungsuntersuchungen benutzten wichtigsten Formeln, die angeben, was für Daten zu den Untersuchungen nötig sind:

$$\Delta V_i = \frac{h_i'' - h_i'}{\Delta T_i}, \qquad /1/$$

$$\mu_i^{\Delta 2} = \frac{L_i \,/\, m_i'^2 + m_i''^2 /}{\Delta T_i^2}, \qquad /2/$$

wo

- $\Delta V_i$ die abgeleitete relative Geschwindigkeit der vertikalen Bewegung einer Strecke oder Linie der Wiederholungsnivellierung,
- $h_i', h_i''$ der aus der ersten, bzw. zweiten Messung stammende Höhenunterschied einer Strecke oder Linie der Wiederholungsnivellierung,
- $\Delta T_i$ das Zeitintervall zwischen den beiden Nivellierungen,
- $\mu_i^{\Delta}$ der quadratische mittlere Fehler der abgeleiteten relativen Geschwindigkeit der vertikalen Bewegung,
- $L_i$ die Länge der Nivellierstrecke oder-Linie,
- $m_i', m_i''$ der quadratische mittlere Fehler der ersten bzw. zweiten Nivellierung einer 1 km langen Strecke ist.

Die zu den früheren Untersuchungen gebrauchten Nivellierungen wurden mit unterschiedlicher Zuverlässigkeit und auf eine lange Periode verteilt durchgeführt. Bei den Untersuchungen der Erdkrustenbewegungen wurden zur Rechnung der obenstehenden Formeln die auf die zwischen den Knotenpunkten geführten Linien summierten Höhenunterschiede, deren durchschnittliche Zuverlässigkeit und das durchschnittliche Zeitintervall benutzt, was eine Vernachlässigung bedeutet und das Endergebnis der Ausgleichung beeinflusst. Um die Grösse dieses Einflusses zu bestimmen, wurde eine Versuchsausgleichung von zwei benachbarten Polygonen des Nivelliernetzes Ungarns durchgeführt [4] . Die Polygone wurden so ausgewählt, dass eines von ihnen ein ruhiges Gebiet, das zweite ein mit kraftvollerer Bewegung/technogener Bewegung/gekennzeichnetes Gebiet deckt.

Das Netz der beiden Polygone wurde in zweierlei Zusammenstellung ausgeglichen. Im ersten Fall wurden die auf die zwischen den Knotenpunkten geführten Linien summierten Höhenunterschiede, die durchschnittlichen Zeitpunkte und die durchschnittlichen mittleren Fehler benutzt.

Im zweiten Fall wurden Linienteile zusammengestellt, die in kurzer Zeit mit gleicher Zuverlässigkeit gemessen wurden. Die Höhenunterschiede wurden auf diese Linienteile summiert und die Ausgleichung wurde mit diesen durchgeführt.

Die Ausgleichungen wurden mit der Methode von Hazay [2] durchgeführt, d.h. die Höhenunterschiede der ersten und der zweiten Nivellierung wurden auf dieselben Epochen reduziert ausgeglichen.

Das Netz mit den beiden Polygonen ist durch die Abbildungen veranschaulicht.

Auf der Abb.1. sind die mit Hilfe der auf die zwischen den Knotenpunkten geführten Linien summierten, zweimal gemessenen Höhenunterschieden und der auf die Linien gerechneten durchschnittlichen Zeitintervalle mittels der Gleichung /1/abgeleiteten relativen Geschwindigkeitswerte presentiert. Die Richtung der Steigungen wird durch Pfeile bezeichnet. Die Schlussfehler wurden im Uhrzeigersinn gerechnet. Die Ausgleichung erfolgte mit den zwischen den Knotenpunkten summierten, wiederholt gemessenen und reduzierten Höhenunterschieden, das dem ersten Fall entspricht.

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Auf der Abb.2 sind die in kurzer Zeit mit gleicher Zuverlässigkeit gemessenen Linienteile und die betreffenden, mit der Formel /1/ abgeleiteten relativen Geschwindigkeitswerte dargestellt. Die Ausgleichung erfolgte mit den zweimal gemessenen und reduzierten Höhenunterschieden der Linienteile, das dem zweiten Fall entspricht.

In der Tabelle sind die auf die Linien zwischen den Knotenpunkten auf zweierlei Weise abgeleiteten relativen Geschwindigkeitswerte und deren ausgeglichener Wert gezeigt.

Die Unterschiede in der Tabelle zeigen, dass das zwischen den Knotenpunkten durchgeführte Zusammenfassen der mit verschiedener Zuverlässigkeit in grösserem Zeitintervall gemessenen Strecken der Wiederholungsnivellierung schon spürbaren Fehler verursacht, den zu vermeiden zweckmässig sei.

Dieser Effekt ist so zu eliminieren, wenn die Ausgleichung nicht auf die Linien zwischen den Knotenpunkten , sondern auf die in kurzer Zeit mit gleicher Zuverlässigkeit gemessenen Linienteile erfolgt. Dies erhöht hingegen den Arbeitsumfang der Ausgleichung. Besonders grossen Arbeitsmehrbetrag würde dies bei der Ausgleichung des Versuchsnetzes der Karpathen-Balkan Region /KBR/ bedeuten, bei dessen Linien die Gesamtlänge etwa 35 000 km beträgt. So war eine andere Lösung zu suchen.

Auf dem Gebiet der KBR erfolgte die in den 1970-er Jahren durchgeführte Nivellierung in kurzer Zeit und mit gleicher Zuverlässigkeit. Die vorhergehende Nivellierung zog sich hingegen in die Länge, und erfolgte mit verschiedener Zuverlässigkeit [3]. Auf der Linien zwischen den Knotenpunkten ist so die zweite Nivellierung einheitlich, dementsprechend sind die Höhenunterschiede der zweiten Nivellierung auf die ganze Linie zu summieren, die der ersten Nivellierung hingegen nicht. Es wurde deshalb aufgeworfen, dass statt der Höhenunterschiede der ersten Nivellierung die aus den beiden Nivellierungen abgeleiteten relativen Geschwindigkeitswerte in die Ausgleichung eingezogen werden sollten.

Die nach der Formel /1/ für die Linienteile berechneten relativen Geschwindigkeitswerte sind nämlich vom Knotenpunkt bis Knotenpunkt ohne Vernachlässigung zu summieren, die nach der Formel /2/ berechneten Quadrate der quadratischen mittleren Fehler der Geschwindigkeiten ebenfalls. Das letztere ist nichts anderes, als $\frac{c}{P_i}$ , wo c ein Koeffizient, und $\frac{1}{P_i}$ der nach der Fehlerfortpflanzung gerechnete Gewichtsreziproke des abgeleiteten Bewegungswerts ist. Die von der zweiten Nivellierung stammenden Höhenunterschiede der Linien und die aus den beiden Nivellierungen abgeleiteten relativen Geschwindigkeitswerte sind zwar voneinander nicht unabhängig, doch dies kann in der Ausgleichung in Betracht gezogen werden.

Die Ausgleichung des auf der Abb.2. dargestellten Netzes wurde auch mit den zwischen den Knotenpunkten gerechneten Summen der Höhenunterschiede der zweiten Nivellierung und der aus dem wiederholten Nivellement für jedes Linienteil abgeleiteten relativen Geschwindigkeitswerte durchgeführt. Diese Ausgleichung gab das gleiche Ergebnis, wie die nach der Methode von Hazay auf Linienteile durchgeführte Ausgleichung /Fall 2./.

Mit der Zustimmung der in der Untersuchung teilnehmenden Länder wurde deshalb das Versuchsnetz der KBR mittels der gemeinsamen Ausgleichung der Höhenunterschiede und der Geschwindigkeiten der vertikalen Bewegungen ausgeglichen. Diese Methode wird durch [1] geschildert. Dementsprechend wurden für alle Linien des zur Untersuchung der vertikalen Bewegungen der KBR zustandegebrachten Wiederholungsnivelliernetzes

- die zwischen den Knotenpunkten summierten gemessenen Höhenunterschiede,
- das Jahr und der quadratische mittlere Fehler der Messungen,
- die zwischen den Knotenpunkten gebildete Summe der auf die Linienteile abgeleiteten relativen Geschwindigkeitswerte und deren Gewichtsreziproken.

zusammengestellt.



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Tabelle

| Nummer der Linie | Länge der Linie km | abgeleitete relative Geschwindigkeitswerte (mm/Jahr) vor der Ausgleichung | | | nach der Ausgleichung | | |
|---|---|---|---|---|---|---|---|
| | | erster Fall | zweiter Fall | Unter-schied | erster Fall | zweiter Fall | Unter-schied |
| 1 | 73 | + 0,07 | + 0,23 | + 0,16 | - 0,15 | - 0,06 | + 0,09 |
| 7 | 56 | + 0,09 | + 0,11 | + 0,02 | - 0,07 | - 0,10 | - 0,03 |
| 11 | 118 | + 1,03 | + 1,24 | + 0,21 | + 0,65 | + 0,66 | + 0,01 |
| 12 | 151 | - 0,36 | - 0,32 | + 0,04 | - 0,24 | - 0,36 | - 0,12 |
| 13 | 167 | + 2,70 | + 3,12 | + 0,42 | + 2,52 | + 2,69 | + 0,17 |
| 14 | 83 | - 2,20 | - 2,20 | 0 | - 2,28 | - 2,33 | - 0,05 |
| 26 | 152 | - 0,01 | - 0,06 | - 0,05 | - 0,48 | - 0,65 | - 0,17 |
| 27 | 30 | - 0,11 | - 0,11 | 0 | - 0,19 | - 0,21 | - 0,02 |
| Summe: | | | | + 0,80 | | | - 0,12 |
| Durchschnittswert der absoluten Werte der Unterschiede | | | | 0,11 | | | 0,08 |

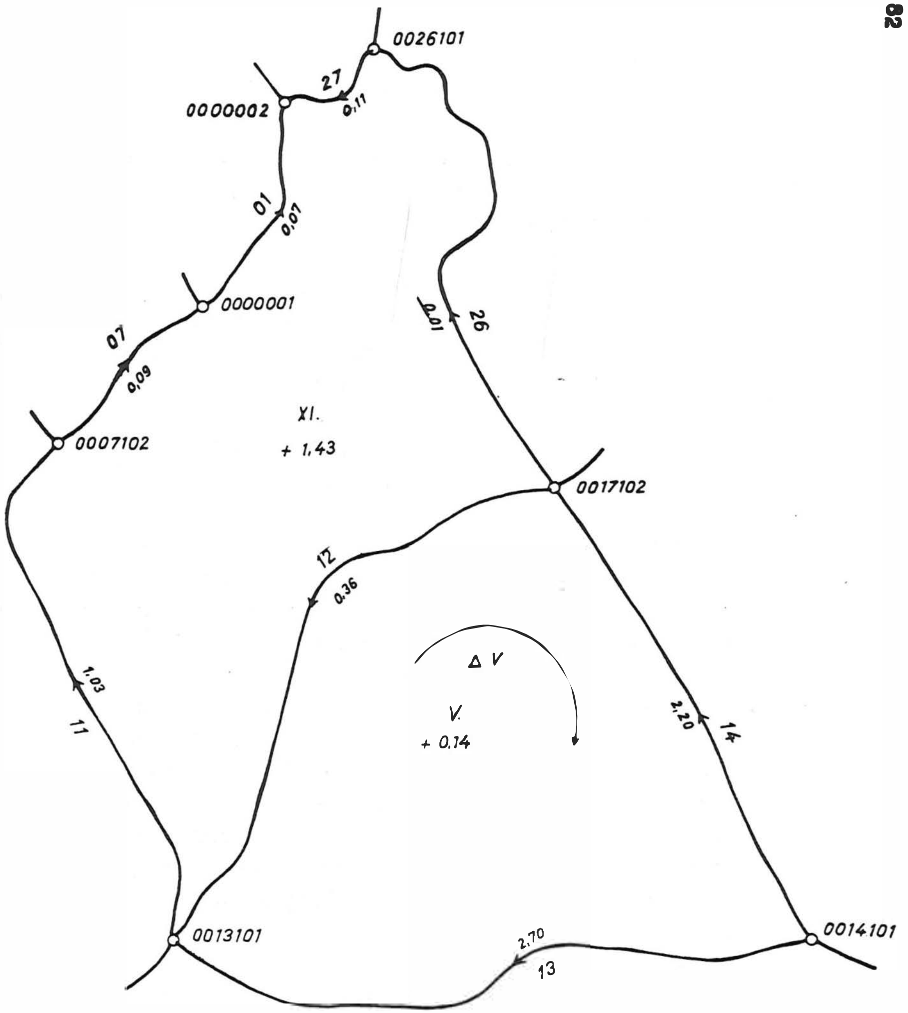


Abb. 1.

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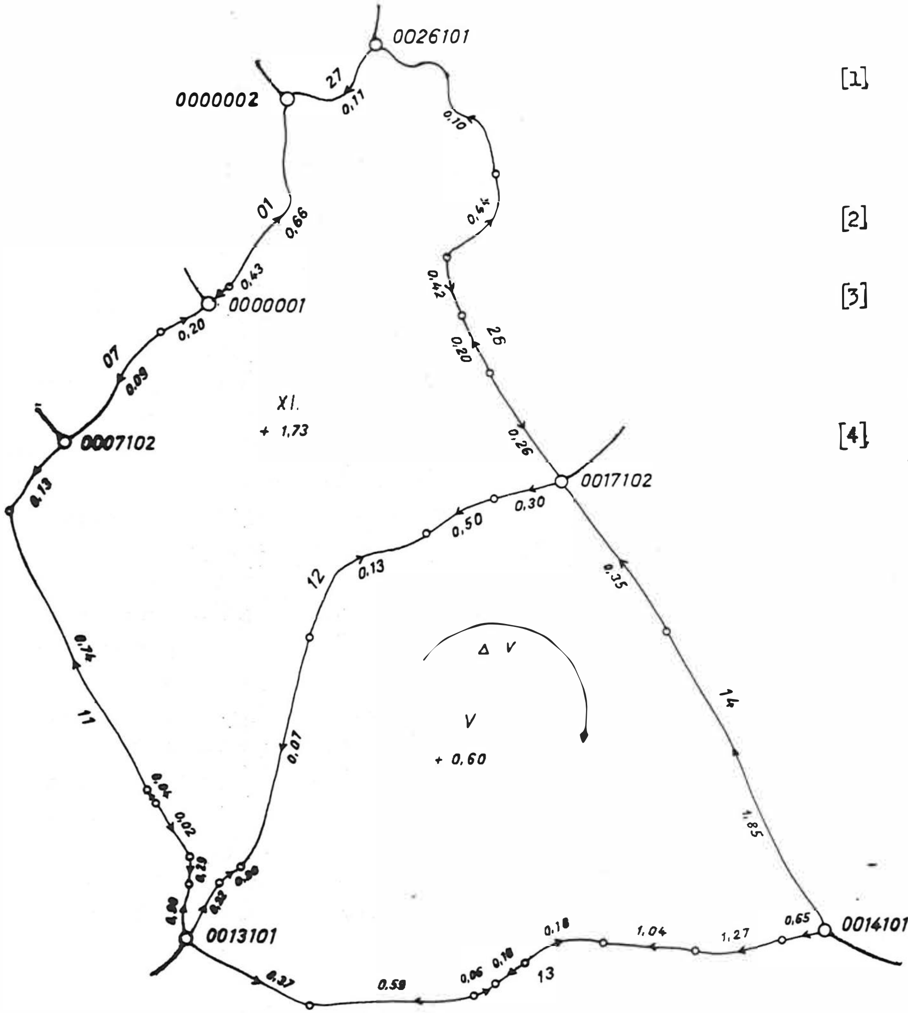


Abb. 2.

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# SOME GEODETIC ASPECTS OF THE PROBLEM OF CHECKING THE PLATE-TECTONIC MODEL OF SEISMICITY IN SOUTHEASTERN EUROPE

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Résumé: On présente le modèle récent de l'hypothèse du néomobilisme pour l'interaction des grandes plaques tectoniques dans la région de l'Europe de Sud-Est expliquant la localisation des foyers d'activité volcanique et de tremblements de la terre. On discute des questions méthodiques pour le rôle possible d'un réseau régional international d'observatoires géodynamiques - astro-géodesiques, spatiales et terrestres de destination complexe pour la vérification de cet modèle de l'hypothèse de tectonique des plaques dans la Méditerranée de l'Est et dans la région Ponto-Caspienne.

L'Observatoire géodésique "Plana", situé non loin de Sofia a été achevé et inauguré dans une région d'un astroclimat particulièrement favorable. On décrit l'équipement de cet observatoire avec des instruments et des appareils astro-géodésiques et spatiaux, de pavillions d'observation etc. et son rôle possible dans le programme international de l'INTERCOSMOS pour l'étude de la géodynamique regionale.

Резюме: Представлена современная неомобилистическая модель взаимодействия крупных тектонических плит в районе Юго-восточный Европы, объясняющая локализацию очагов землетрясений и вулканическую активность. Обсуждаются методические вопросы о возможной роли региональной международный сети из астрономо-геодезических, космических и комплексных наземных геодинамических обсерваторий в Восточном Средиземномории и в Черноморско-Каспийском районе для проверки этой модели тектоники плит.

Окончена и открыта Геодезическая Обсерватория "Плана", расположенная недалеко от Софии, в районе с особо благоприятным астроклиматом. Описывается оборудование этой обсерватории астрономо-геодезическими и космическими приборами, апаратами, наблюдательными павильонами и др. и выясняется ее возможная роль в международной программе ИНТЕРКОСМОС для исследования региональной геодинамики.

In the last years, due to the increased accuracy and applicability of the laser range-finders of III generation and radio-interferometric measuring systems of stationary and mobile types, the satellite geodesy, with its own methods and means, enters in the regional geodynamic investigations. One of the most actual problems, to which the efforts of great international and national groups of specialists are directed, is the determination of the recent movements of large Earth's crustal blocks in seismoactive regions, in order to elucidate the mechanism of generation and manifestation of strong earthquakes. The suitability of a special international programme of satellite geodetic studies in the area of the planetary Mediterranean-Transasian seismic belt, and in particular - in the regions of the Eastern Mediterranean sea, the Balkan peninsula and Caucasus, was stressed by the Central Laboratory for Geodesy at a number of international conferences ( Тотоманов и Георгиев, 1982; Георгиев и Тотоманов, 1982; Totomanov and Georgiev, 1983).

Here on the basis of the modern geological-geophysical conception on the mechanism of generating strong earthquakes and volcanic activity in Southeastern Europe (McKenzie, 1970; Radulescu and Sandulescu, 1973; Бончев, 1980; Bončev, 1982; Дачев, 1980), some methodical aspects of possible geodetic investigations in this region are discussed.

In the region of Southeastern Europe and in Asia Minor the contact zone between the two ancient supercontinents

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Laurasia (presented in the recent epoch by the Eurasian plate) and Gondwana (parts of which are the African, the Arab and the Indian plates) forms a large mobile orogenic belt between the East-European platform (situated in the north of the Carpathians and Caucasus) and the partially submerged in the modern epoch neighbouring section of Gondwana (which embraces the Adriatic sea together with Italy, the Tirentian and Ionian seas and the eastern section of the Mediterrenean sea). The Alpian -Himalayan orogen is presented in this zone by two large structural belts - n o r t h e r n b r a n c h (its western part are the Carpathians, and in the east it is divided to the following two strips:

a) one is verging northwards and is composed by the Craistidians, Balcanides and the Pontian mountains, and

b) the other is verging southwards and represents the Crimean -Caucasian structural zone) and a s o u t h e r n b r a n c h (the Dinaridian-Helenidian-Taurician orogen). This whole orogen area is characterized by high recent seismicity, by which all deep-focus (mantle) earthquakes are concentrated round its southern and northern borders. All said above, together with a number of other geological and geophysical reasons, gives grounds for the hypothesis, in the terms of the new global tectonics (plate tectonics), that in Southeastern Europe a process of an active recent subduction is manifested: a) of Gondwana beneath Laurasia, which generates the strong deep focus earthquakes and the recent volcanic activity in Italy, on the Southwestern border of the Balkan peninsula, in Aegean sea and in Asia Minor, and b) of the East-European platform beneath the northern border of the respective section of the Alpian-Himalayan orogen, which generates the deep-focus Carpathian earthquakes. At these destructive (convergent) boundaries between the plates, the cold Earth's crust is consumed (disappearing) in the mantle, by which a relative approaching of East-European and African plates should be expected with a velocity of the order of 1-2 cm/a (Fig. 1).

The geodetic satellite observatories in this region according to their possible role in the investigations to check this geokinematic model of seismicity, could be divided into two large groups as follows:

1. Observatories located on stable plates of Laurasia (the Eastern-European one) and Gondwana (the African and the Arab plates) the measuring data of which will check just the existence of the recent subduction process in this region, and in case of corroborating it - to determine the general kinematic characteristics of this process. Here two subgroups of such observatories should be distinguished:

- in proximity of the subduction regions (near to the southern border of the Eastern-European platform and, correspondingly - on the northern coast of the African continent), and

- in the central parts of these stable plates, at a distance of the order of 1000-1500 km from the zones of the first subgroup.

By means of this differentiation and utilizing the respective observations, it will be possible to estimate the effect supposed of the inner-plate tectonic deformations, which would contribute to obtain some averaged, but more realistic characteristics of the general kinematic behaviour of these two plates as a whole.



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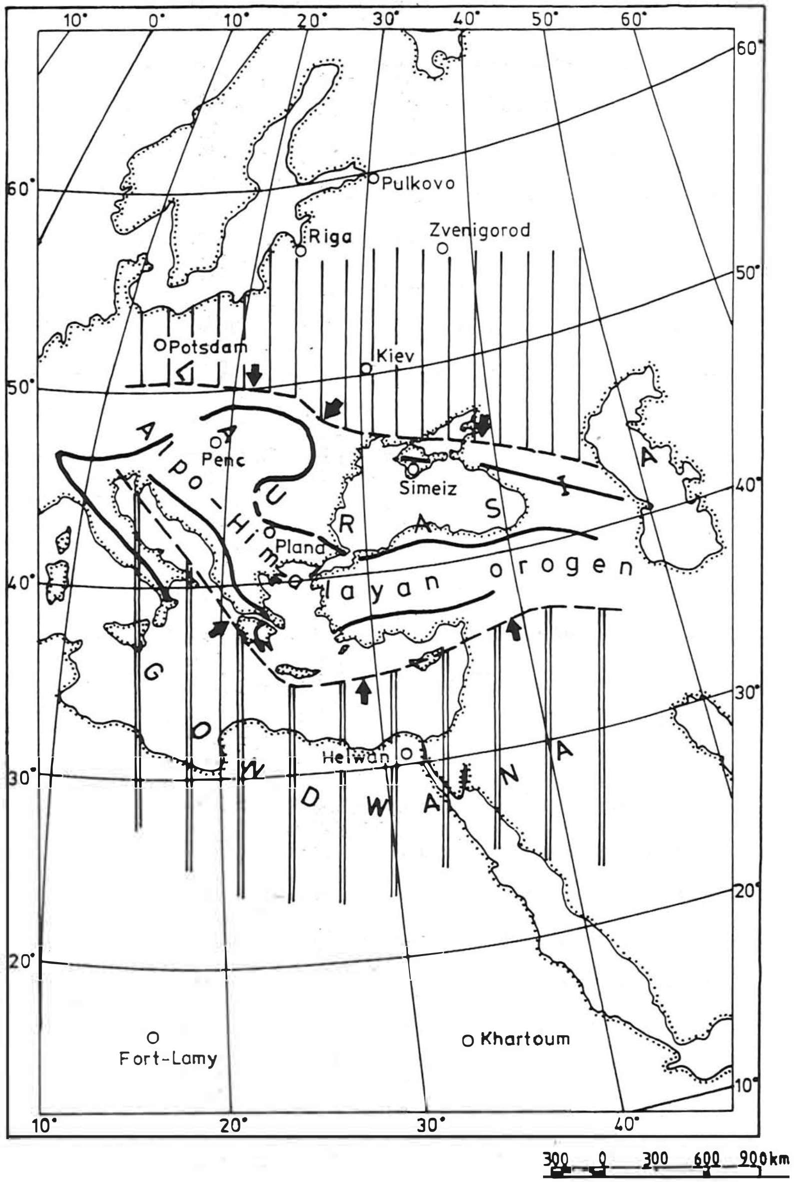


Fig. 1 - Interaction in Southeastern Europe between the Alpian-Hymalayan orogenic belt and the stable plates: hatched areas by single-lines (Eastern-European platform of Eurasian plate) and by double-lines (the respective parts of the African and Arab plates).

2. Observatories situated in the mobile seismic belt, the measurements of which will promote both to elucidate its own geokinematic role in this process and to determine the intrabelt movements generating the strong normal-focus earthquakes in this region and the proper differentiated velocities of the two subductions supposed.

In this way the satellite geodetic technique can successfully contribute to elucidate the recent geodynamic processes in Southeastern Europe and their role in strong earthquake generating.

On the basis of the above mentioned geological and geophysical considerations on the dynamics of the region discussed, some model investigations were performed in the Central Laboratory for Geodesy, in order to determine the observatories where the location of the necessary astro-geodetic and modern space apparata will be appropriate. When carrying out these investigations, special attention was paid both to the optimal location of the stations and to the expedient satellite height and inclination, in the framework of a future experiment planned by the international programme INTERCOSMOS. The preliminary condition, that some basic observatories equipped both by classic and modern space apparata (laser rangefinders of II and III generation, Doppler receivers and antennae for satellite radiointerferometry) should be available, is taken under consideration.

Moreover, additional studies were performed (Georgiev et al., 1984) on some systematic differences obtained by the values determined when estimating the pole motion and the irregularity of the Earth's rotation. It was corroborated once

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again that the differences between the classic and the modern methods are provoked, in first line, by the different coordinate systems to which the observation data obtained are referred. It was demonstrated that some number of observatories of an equal distribution on the areas subjected to such a study - mobile zones and stable plates - should be available which observatories should be equipped both by classic and by most recent space apparata - such as laser rangefinder of a centimeter - accuracy, Doppler receivers for continuous observations and, in the case examined, by antennae for satellite radiointerferometry.

In accordance with these model investigations on the optimal geometry of these observatories and their respective apparata equipment, the following opinion could be expressed on the possible participation of the stations in the framework of the international programme INTERCOSMOS in such a regional geodynamic observation campaigne aimed to check the plate-tectonic model of seismicity in Southeastern Europe:

A) The observatories in Potsdam (GDR), Kiev (USSR) and Helwan (Egypt) located on the near-subduction part of the respective stable plates and these in Plana (Bulgaria), Simeiz (USSR) and Penc (Hungary) located in the mobile area of Alpian-Hymalayan orogen should be equipped by all possible high accuracy apparata, including antennae for satellite radiointerferometry, the last recommendation being grounded on the circumstance that the baselines among these observatories are most expedient according to the satellite planned orbit inclination of 70-80$^{\circ}$, in the future geodetic space experiments of INTERCOSMOS /Северный и Татевян, 1983/;

B) The observatories in the inner parts of the respective stable plates, i.e. these in Pulkovo, Riga and Zvenigorod (USSR) and, as far as possible, in Khartoum (Sudan) and Fort-Lamy (Chad) be equipped by high precision laser rangefinders and Doppler receivers.

One of the possible geodynamic stations of the second type mentioned is the Geodetic Observatory "Plana" in Bulgaria, the exceptional favorable natural conditions of the region of which were demonstrated by a respective analysis of the ten stations operating in studies of Section 6 "Space physics" at the international organization INTERCOSMOS. It was this that provoked the Central Laboratory for Geodesy to initiate its building in 1980, achieved in 1983. Being southwards in the vicinity of Sofia, at a height of more than 1000 m above the sea level, it is situated on the terrain of the former Artificial Earth's Satellite Observation Station "Plana".

This observatory in Bulgaria is a modern complex base aimed to study the geodynamical phenomena by means both of the classic astro-geodetic (astrometric) methods and apparata and the methods of the present-day satellite geodesy and gravimetry. The observations will be used to solve some specific problems of fundamental astrometry, geodetic astronomy and geodesy, to investigate the local effects in the observations and the observation errors of personal-instrumental and thermo-refractional character. At present a laser rangefinder, a photographic camera to observe the artificial Earth's satellites, a visual meridian transit instrument, a zenith telescope for Talcott method and an astronomic universal instrument are available at this observatory; in the immediate future it will be



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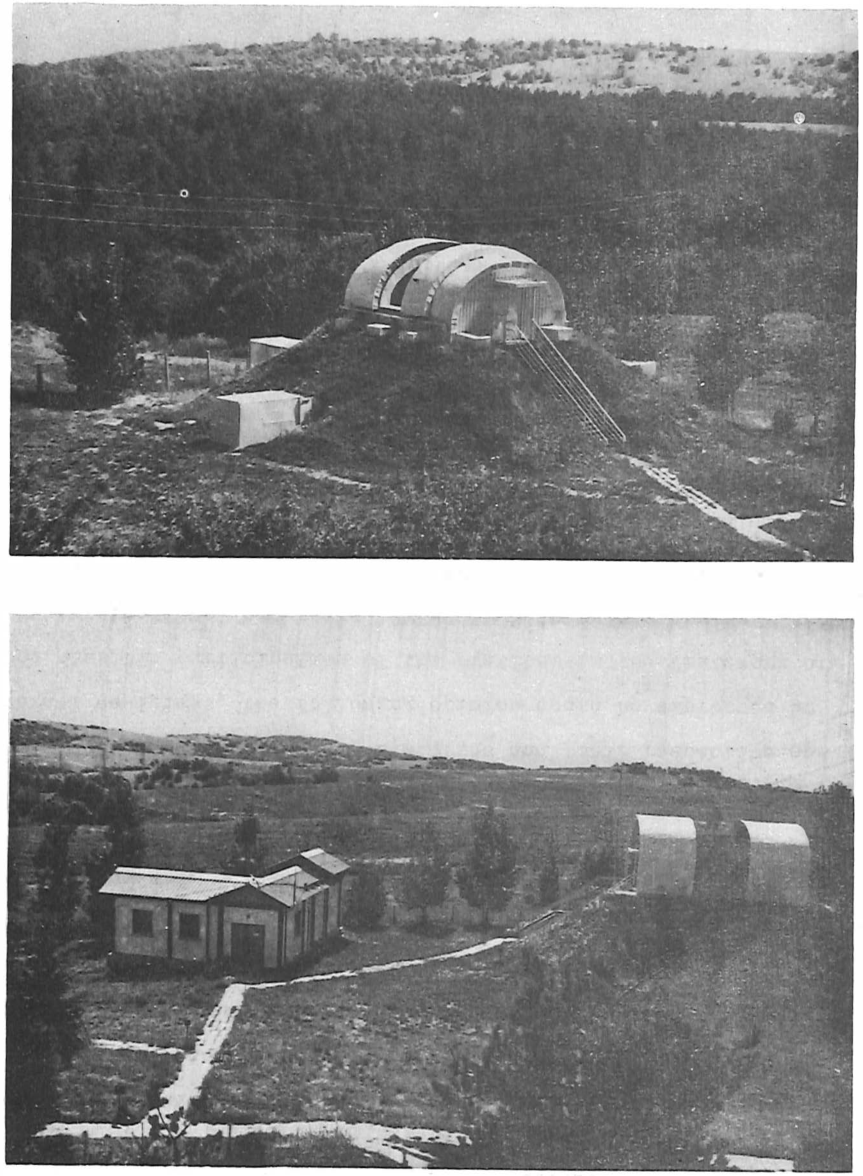

Fig. 2 - Some of the pavilions of the Geodetic Observatory "Plana" at the Central Laboratory for Geodesy-BAS.

equipped with a circumzenithal, and the meridian transit instrument - with a photorecording television device. At the disposal of this observatory is an Exact Time Service of very good possibilities to compare and to conserve the time, equipped with atomic- and quartz-standards of high precision.

When building the observatory, great attention was paid both to the choice of terrain and to the construction type of the astronomic pavilions. All the pavilions now available are modern and are in accordance with the present-day requirements of eliminating the thermo-refractional effects of the astronomic observations which is a necessary prerequisite to obtain results of a high quality. It could be said, in general, that the astronomic pavilion construction applied ensures a maximum diminishing of harmful mechanical influences on the instrument provoked by ground vibrations and by the wind, of different thermal deformations and of different kinds of refractional anomalies inside and above the pavilion (Fig. 2).

The observatory is situated on a relatively plane terraine, far away from industrial powers, and some great settlement.

The favourable geographic situation of the observatory for studying the regional geodynamics, which is corroborated by the theoretical investigations, too, makes it appropriate to be transformed for the investigations envisaged, in a fundamental INTERCOSMOS observatory.

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RECENT CRUSTAL MOVEMENTS AND GEOPHYSICAL INTERPRETATION OF GEODYNAMIC PROCESSES IN THE ALPINE MOUNTAIN BELT[1]

by

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## 1 Introduction

It is a well-known fact that the surface phenomena of global plate tectonics are most convincingly seen and felt along the boundaries of the moving lithospheric plates. These boundaries are morphologically expressed as mid-ocean ridges or as subduction zones such as deep sea trenches or Himalayan/Alpine fold belts, the latter of which are the subject of this paper. The major seismicity zones follow almost exactly the so-called creating and consuming plate boundaries. Even on a global scale, it can be seen that quite a few earthquakes cluster around the Adriatic Sea. If this portion of the world-wide seismicity zone is enlarged, this zone follows precicely the Azores - Gibraltar fracture zone, North Africa, and circles around the Appenines, Alps and Dinarides (UDIAS, 1982; WANIEK et al., 1982), thus defining the so-called Apulian or Adriatic promontory of the African plate (CHANNELL et al., 1979).

On a global scale, there are kinematic models giving an idea of what kind of rates can be expected. Concentrating on the Apulian plate, it is recognized that there is almost no information available for that region. This is due to the fact that magnetic sea floor spreading anomalies are missing in the Alpine environment. On the other hand, the structure and kinematics of the Apulian microplate are of major interest to Switzerland because its northern boundary seems to be formed by the Alpine chain (MUELLER, St., 1982).

In Switzerland there are some 14 special study groups actively working in this field of geodynamics. This paper is restricted to the geodetic and gravity studies. Besides purely national activities, Switzerland is participating in NASA's Global Dynamics Project (COATES, 1984) aimed at determining the plate movements and deformations using

- satellite laser ranging
- very long baseline interferometry and recently also by
- space-borne radio wave techniques, such as the GPS system.

The European core of this project is formed by a group called WEGENER, which stands for Working Group of European Geo-scientists for the Establishment of Networks for Earthquake Research. In its original concept, WEGENER covers the entire Alpine/Mediterranean system and is subdivided into 3 geographic areas (WILSON, 1984):

1. Eastern Mediterranean
2. Central Mediterranean, including the Apulian microplate and the Alps
3. Western Mediterranean

A scientific evaluation of the central part was made during a workshop held in Zurich in 1983. The proceedings of that workshop were published in Annales Geophysicae (1984).

## 2 The Swiss Geotraverse

With emphasis on the assumed northern boundary of the Apulian microplate, the kinematics of relative plate movements in the Alpine area were investigated first. A simplified tectonic map (ROD, personal comm. 1980) of this region is shown in Fig.1. Furthermore, this sketch indicates 2 profiles, the first of which, the Swiss Geotraverse (RYBACH et al., 1980), extends from Bâle (west of Zurich) to Chiasso (north of Milano) and will be described in greater detail later on. The second traverse crosses the Alps further east in the vicinity of the Hohe Tauern (here denoted as Austrian-Italian Traverse) between south of Munich (FRG) and Trieste (Italy).

The uplift rates obtained from repeated 1st order levellings along the Swiss Geotraverse in the period from 1915 to about 1970 are shown in Fig.2 (GUBLER et al., 1981). They refer to a more or less arbitrarily chosen reference bench mark in Aarburg in the Swiss Molasse basin, south of Bâle. Between Bâle and Lucerne, no significant changes in elevation have been observed up to now. Going further south, however, the uplift rates increase systematically. In Lucerne, where the Molasse submerges underneath the Helvetic nappes, a yearly uplift of 0.2 ±0.11 mm/year was observed. Between Lucerne and the Rhine-Rhone line (indicated by RRL) the uplift reaches 0.7 ±0.15 mm/year. The region where the NW-SE Swiss Geotraverse crosses the E-W Rhine-Rhone line near Andermatt is called the Urseren zone. It is associated with almost vertically inclined layers of Mesozoic sediments along which visible recent vertical displacements occur (ECKARDT et al., 1983). In some places the relative displacements encountered along the Urseren zone reach up to 20 m within the last 10'000 years. This active zone has recently been covered by precise 3-D geodetic networks in order to determine the present-day uplift and displacement rates across the Rhine-Rhone line between benchmarks in the Aar and Gotthard massifs respectively. These investigations have become of practical relevance since the 1970s, when construction on the new Gotthard Tunnel began and particularly in 1980 when it was opened to public traffic. Even though the central Aar and Gotthard massifs terminate at the southern end of the tunnel, the uplift still increases further to the south, reaching a maximum of 1.1 ±0.18 mm/year in the southern part of the Lepontine zone (canton Ticino, Switzerland) where the highly metamorphized Penninic nappes are exposed.

Further south the Insubric line (denoted as IL) is traversed. This line has been a major tectonic lineament in the past and sharply cuts off the central Alpine structures in the north from the pre-Alpine structures in the south (GANSSER, 1968). (In some places the IL separates metamorphized rocks only a few 100 m apart but showing a metamorphic age difference of 300 million years). The IL does not seem to show up as a present-day major boundary in the uplift pattern. It merely belongs to a zone of fairly constant uplift rates which gradually decrease further south in the vicinity of the sediments of the southern Alps. Keeping these uplift rates in mind, the following questions arise:

1) What is the driving mechanism of kinematic activity? Is it controlled by isostatic rebound forces as a result of past Alpine subduction processes which have ceased or is it caused by continuing compressional plate tectonic activity?

2) What does the deep underlying crustal and upper mantle structure look like compared to observations made at the surface?

To answer these questions, considerable efforts have been made in Switzerland in the past decade. Some of the results are compiled in the 'Final Report of Switzerland' for the International Geodynamics Project, edited by St. Mueller and Oberholzer (1979).

In the mid-1970s, only one detailed gravity profile (KAHLE et al, 1976) was available (Fig.2), which follows the extensively studied Swiss Geotraverse. This profile revealed a pronounced Bouguer minimum in the vicinity of the Aar and Gotthard massifs, centered over the Urseren zone of the Rhine-Rhone line which separates these two massifs. While the decrease in gravity coincides with an increase in the uplift rates in the northern flank of the central massifs, this correlation is interrupted south of the Gotthard in the Lepontine area where the gravity values increase beyond the maximum of the uplift.

A great part of this discrepancy can be explained by the pronounced edge effects of the high-density Ivrea body which contributes significantly to the Bouguer anomalies in the Lepontine zone (KISSLING, 1980). The gravity anomalies caused by the Ivrea body are shown in Fig.3 (WIRTH, 1982). The maximum values reach +180 mgal. In order to constrain the possible models of the Ivrea body, an international measuring campaign (Fig.4) in the scope of the Swiss National Committee of the International Lithospheric Project (CHILP) was initiated to determine deflections of the vertical using zenith cameras (BUERKI et al., 1983). The structure and nature of this anomolous zone have been designated as a prime target of interest by the Inter- Union Commission on the Lithosphere (ICL). An international symposium dealing with this problem will be held in Switzerland in 1986.

## 3 Alpine traverses proposed by the Swiss National Committee for the International Lithospheric Project (CHILP)

Besides the Swiss Geotraverse, CHILP has recently designated other traverses of interest (Fig.5): One covering the Engadine and the nappe structure there more extensively as part of the European Geotraverse (EGT). The other, extending from north of Besançon (France) to Verbania on Lago Maggiore (Italy), the so-called western traverse.

As part of the western traverse, the relevelling line between Berne and Gampel has recently been analyzed, including the Lötschberg Tunnel north of Gampel. The measurements made from 1909 to 1915 were compared to those from 1982/83. The gradient of uplift rates found in the Lötschberg Tunnel (Fig.6) coincides precisely with the one found along the Swiss Geotraverse, as well as with those detected along a traverse passing through the Tauern Tunnel in Austria (SENFTL and EXNER, 1973).

## 4 Spatial distribution of uplift and gravity in the Alps

### 4.1 Uplift rates

So far only traverses perpendicular to the strike of the Alps have been considered. In the last part of this paper, an attempt is made to present a better spatial view of the current Alpine processes. This approach opens up a broader aspect of the phenomena of recent Alpine kinematics. The Federal Office of Topography of Switzerland is continuing the remeasurement of 1st order levelling circuits. The initial measurement was made between 1905 and 1927, reaching a standard deviation of 1.4 $mm/\sqrt{km}$. The remeasurement has been going on since 1943 and attains a standard deviation of 0.8 $mm/\sqrt{km}$, covering 80% of the lines up to now. From these measurements, uplift rates



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relative to the reference benchmark in Aarburg were computed. Relative height changes of 5 to 10 cm were found in these computations. They show a detailed uplift pattern of the whole country (Fig.7). The uplift or subsidence rates larger than two times their standard deviation are printed in black, the others in outline form. This distinction corresponds to a level of significance of 95%.

To the east and west of the Swiss Geotraverse, the uplift increases more rapidly a l o n g the Rhine-Rhone line than to the south towards the Lepontine zone. It reaches a maximum of 1.4 ±0.16 mm/year near Chur towards the Canton of the Grisons as well as near Brig in Canton Valais. Particular attention should be paid to the Chur uplift: 4 levelling lines from the north, east, south and west indicate a systematic increase in uplift rates when approaching the area of Chur. The question now arises: How does the gravity field correlate to the pattern of recent crustal movements?

### 4.2 Bouguer anomalies and uplift

It is interesting to note that the regions around Chur and Brig are also associated with the most negative Bouguer anomalies (-180 mgal). This was clearly revealed after the new Bouguer gravity map of Switzerland had been completed (KLINGELE and OLIVIER, 1980). The map is based on more than 2000 new gravity stations. The main feature of the Bouguer anomaly map is the pronounced decrease in gravity when approaching the central Alpine chain. Between Bâle and Lucerne there is a linear horizontal decrease of about 10 mgal/10 km. The lowest Bouguer values coincide almost perfectly with the Rhine-Rhone line, reaching -180 mgal near Chur and -160 mgal near Visp/Sion. South of the Rhine-Rhone line in the Cantons Valais, Ticino and the Grisons, the gravity pattern is quite irregular. Positive Bouguer anomalies are only observed in Canton Ticino, west of Locarno in the Centovalli between Borgnone and Piz Gridone. This high is caused by the high-density Ivrea body, the gravitational effect of which has been shown before. An interesting observation is made when the columns for the uplift rates near Chur are superimposed on the Bouguer map. It can be clearly seen that the increase in the uplift rates from all directions corresponds to a systematic relative decrease in Bouguer gravity anomalies.

### 4.3 Isostatic anomalies and uplift

In addition to the Bouguer reductions, 3-D isostatic corrections were applied (KLINGELE, 1979), leading to isostatic anomalies with a minimum of -50 mgal around Chur. From a comparison with the uplift pattern (Fig.7), it is tempting to postulate that the uplift there is strongly influenced by buoyancy forces originating from mass deficiencies underlying this zone. It may therefore be concluded: A part of the uplift of the central Alpine chain is controlled by isostatic forces. The region further south, however, even the area beyond the IL, is strongly affected by compressional forces most likely attributed to the continuing collision process between the Apulian and Eurasian plates (MUELLER, St., 1984). The IL itself does not seem to play a major role at the present.

## 5 Conclusion

It is recognized that the terrestrial geodetic measurements of the pattern of recent crustal movements in the Alps do reveal various effects which depend on space and time.

1) Local scale
   Neotectonic differential vertical displacements such as along the Urseren zone separating the Hercynian Aar and Gotthard massifs reach more than 1 mm/year from geological evidence and have a wavelength smaller than 1 km within the last 10'000 years.

2) Regional scale
   Perpendicular to the strike of the Alps an uplift can be shown, or in other words, a tilt of the entire Alpine chain with a relative uplift rate reaching 1 mm/year over a distance of 100 km ($10^{-8}$), corresponding to a wavelength of 300 km. This north-south oriented tilt extends all the way from Switzerland to Austria, covering a distance of at least 500 km.

3) Differential movements
   In a west-east direction along the strike of the Alps, the uplift increases from 0.7 mm/year to 1.4 mm/year near Chur with a wavelength of 50 - 100 km.

Last but not least it can be stated that these results are essential data in defining a kinematic model for the crust and upper mantle. However, they must be supplemented by space-borne techniques in order to relate them to a global reference system and to detect the large-scale movements. This kinematic model then forms the basis for the interpretation of other geophysical data such as electrical conductivity, the temperature field and the seismic structure of the earth's crust and lithosphere. These physical parameters are controlled by magneto-tellurics, analysis of the dispersion of Rayleigh waves and seismic measurements. All of these data are transformable to gravitational effects (gravitational anomalies and deflections of the vertical) which are to be interpreted as a function of wavelength. While the long wavelength components must be extracted from geodetic satellite observations, the short and intermediate wavelengths can be interpreted from terrestrial measurements. The investigations summarized in this paper reflect some aspects of this concept which will be continued in the future, forming an integral part of the activities of the Swiss National Committee for the International Lithosphere Project.



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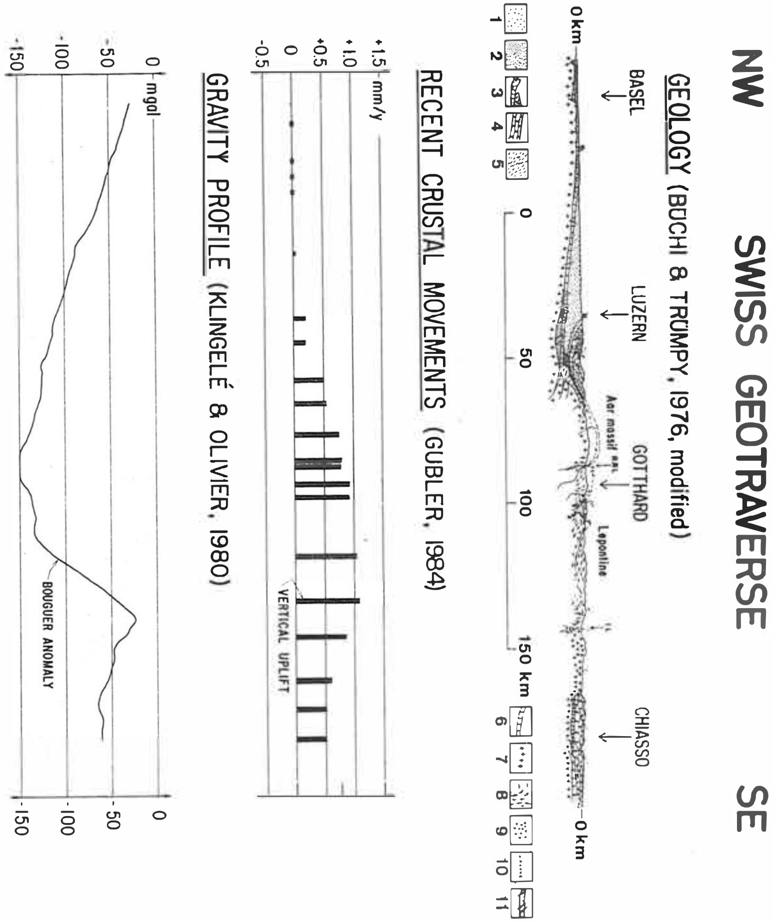


**Fig. 2:** Geological, geophysical data and uplift rates along the Swiss Geotraverse

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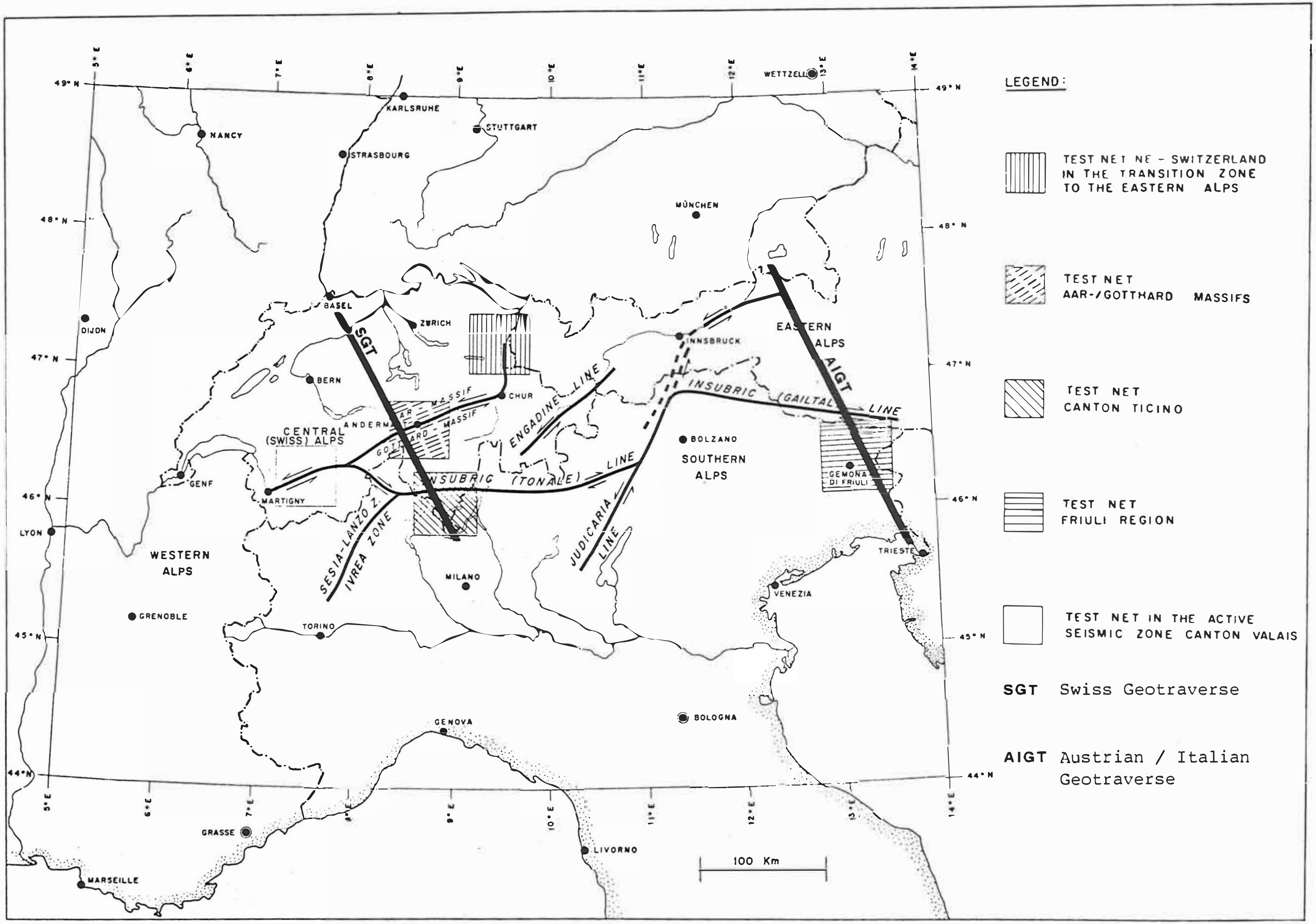


Fig.1 : Major tectonic lineaments in the Alpine Region after ROD (1980)

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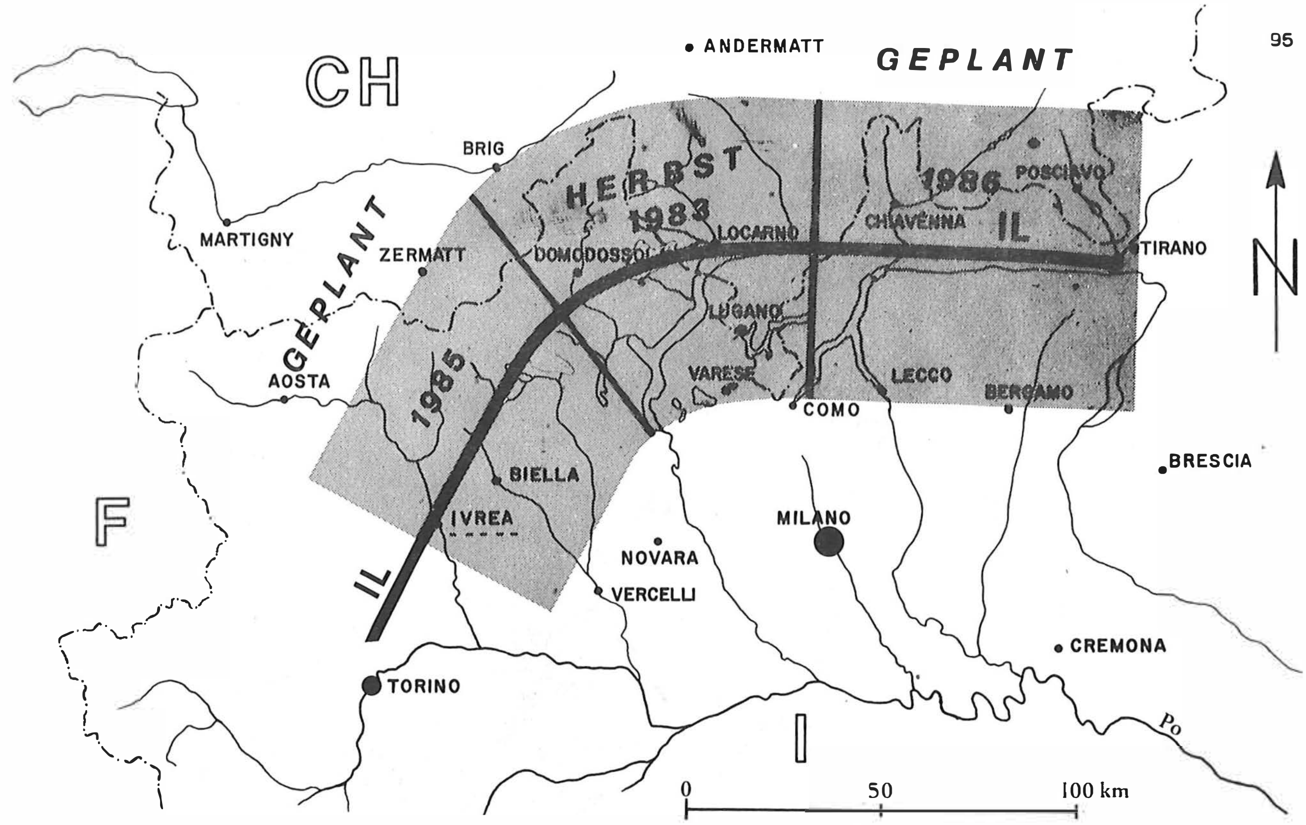


Fig. 4: International measuring campaign to determine deflections of the vertical by zenith cameras

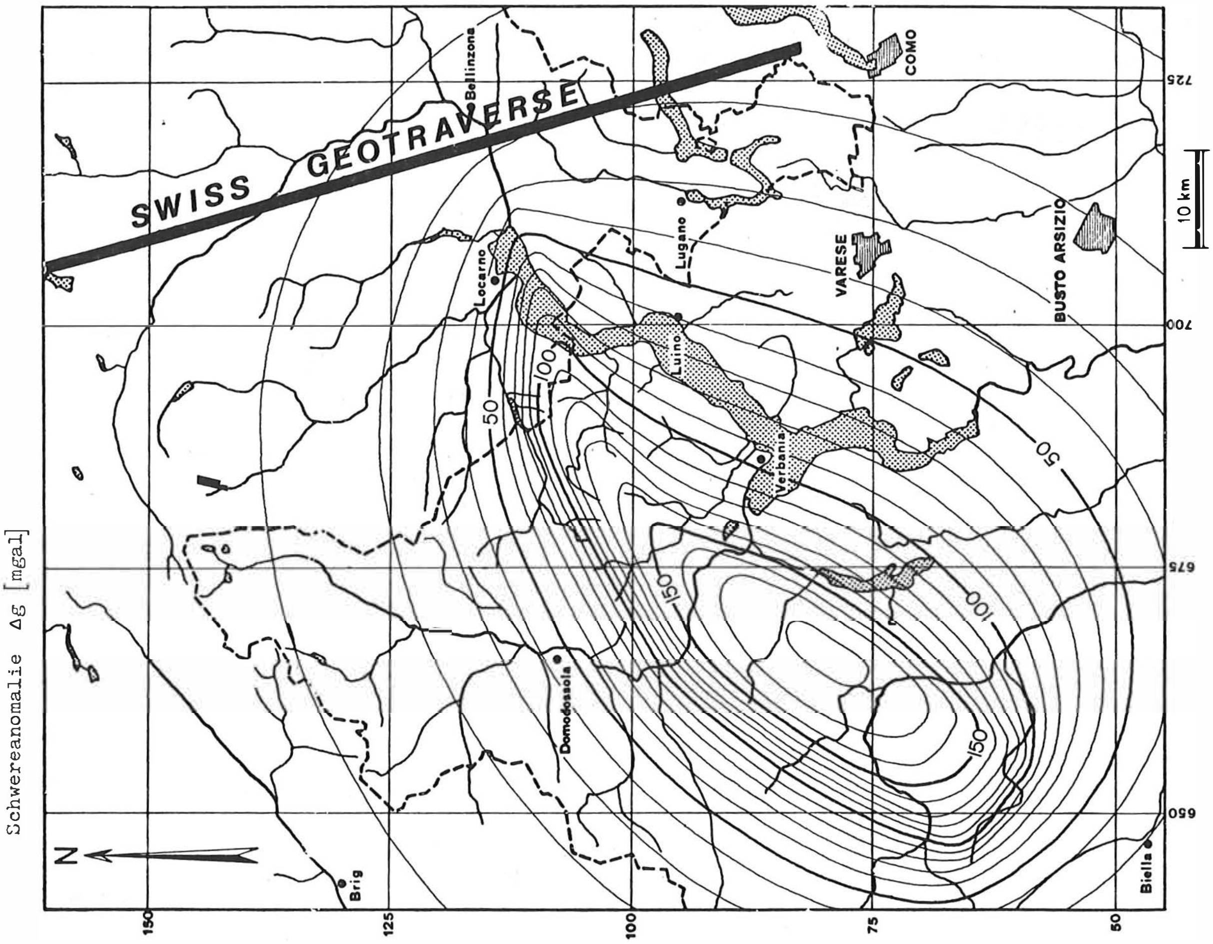


Fig.3 : Gravity anomalies caused by the Ivrea body

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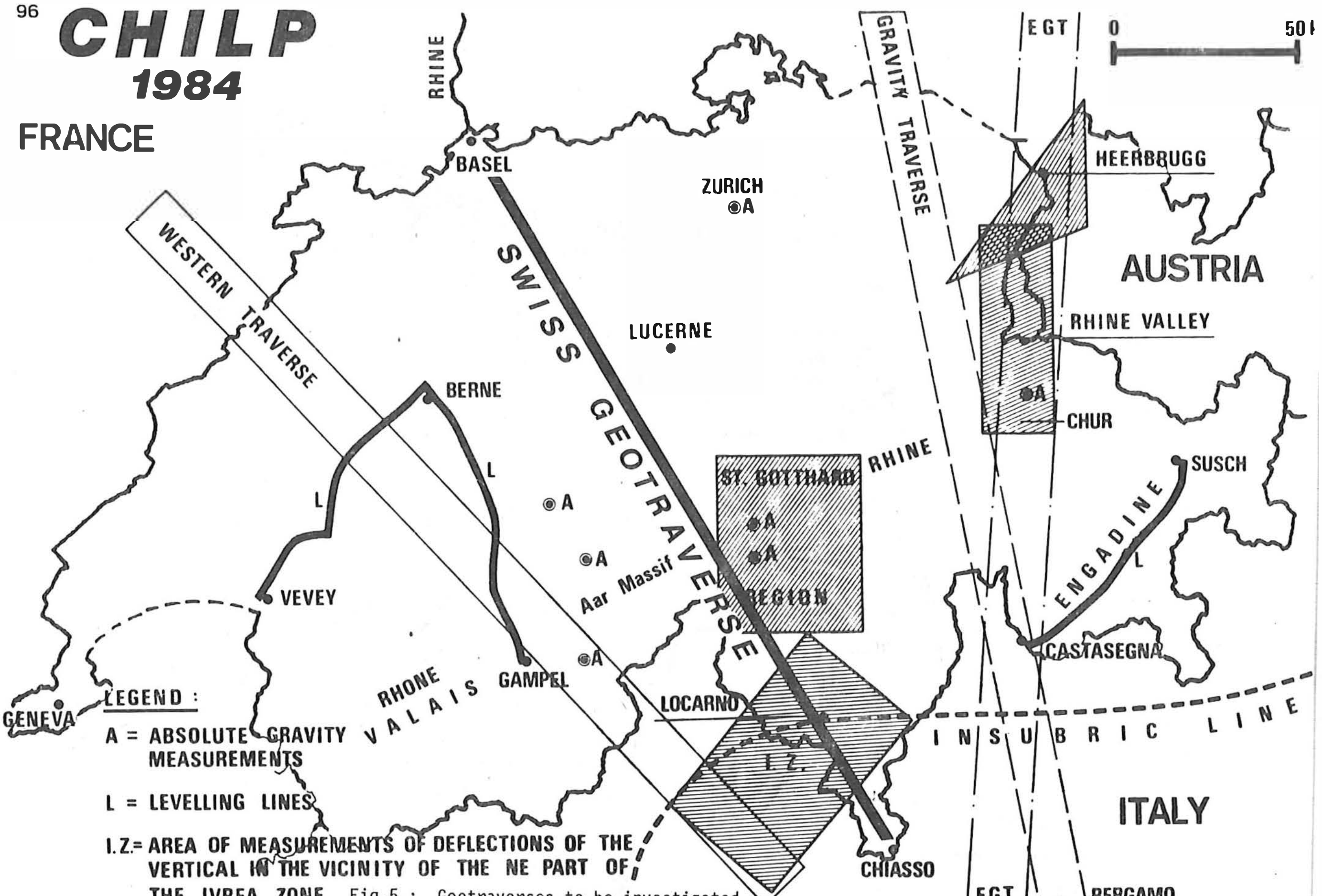


Fig.5 : Geotraverses to be investigated in the scope of the International Lithospheric Project

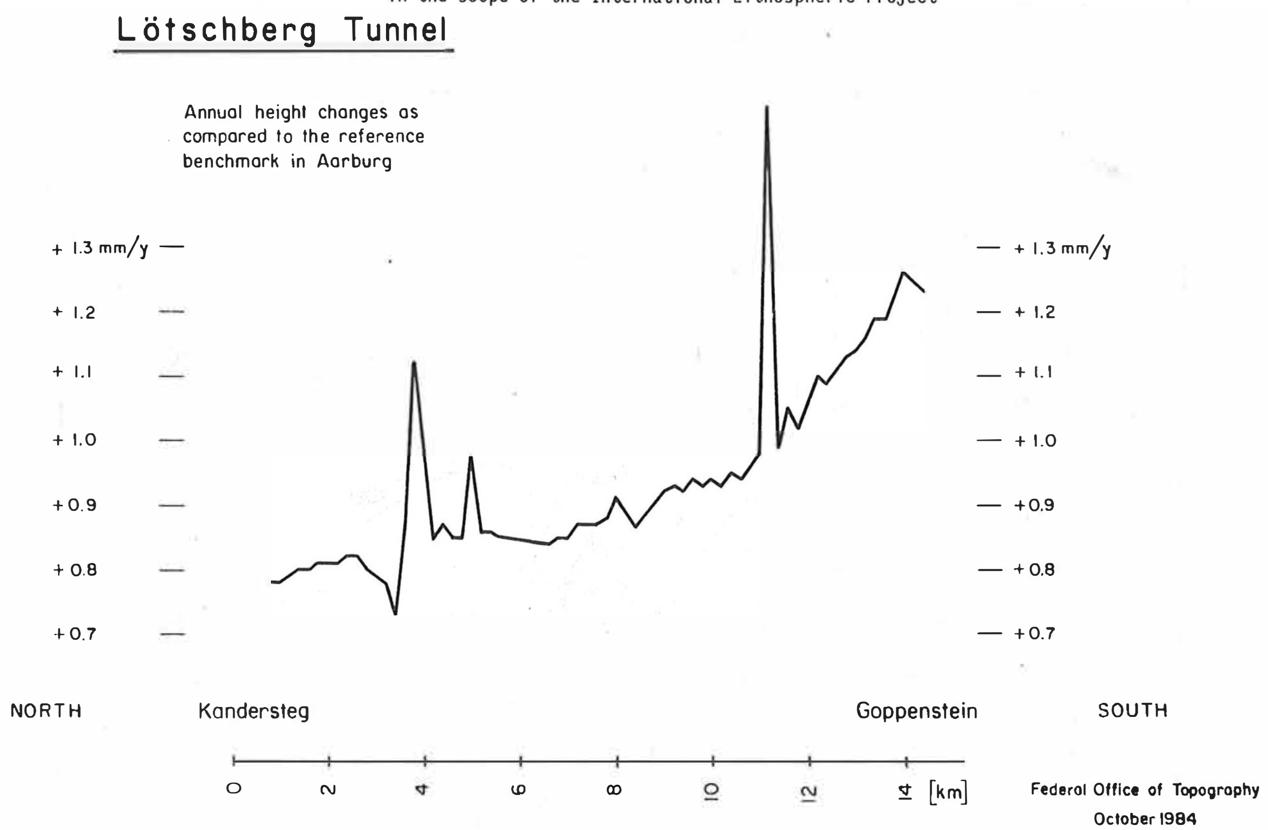


Fig.6 : Uplift rates determined from relevellings in the Lötschberg Tunnel

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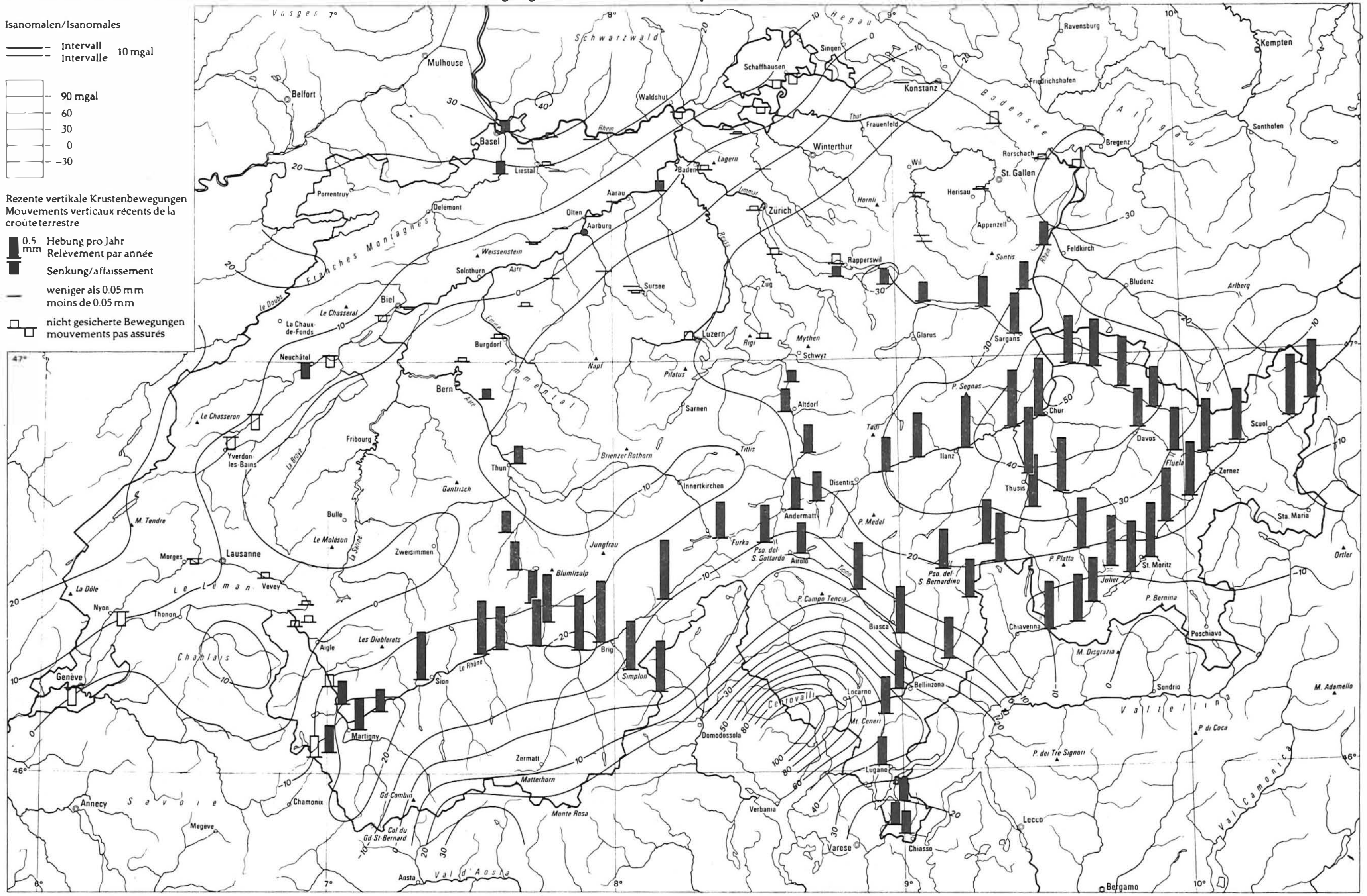
## 2. Isostatische Schwereanomalien und rezente vertikale Krustenbewegungen/Anomalies isostatiques et mouvements verticaux récents de la croûte terrestre




● Aarburg: Bezugspunkt für alle Hebungen und Senkungen / Point de référence pour tous les exhaussements et affaissements

0 10 20 30 40 50 60 70 80 90 100 km

Autoren/Auteurs: Emile Klingelé, Erich Gubler



Fig.7 :

Isostatic gravity anomalies and uplift rates
(Reproduced with the permission of the Federal Office of Topography from November 7, 1984)



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DETERMINATION OF CRUSTAL MOVEMENTS IN THE HIGH TATRA MOUNTAINS

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Summary: A method for determination of the crustal movements in the regions of high mountains ridges has been presented.

Резюме: Предлагается метод определения движений земной коры в областях высокогорных хребтов.

A method of three-dimensional triangulation may be used for determining the crustal movements in the regions of the high mountains ridges where the geodetic levelling cannot be performed. The method is based on integrated observations of both horizontal and vertical angles, distances, spirit levelling lines, deflections of the vertical, and on combine processing of all observed data. As a result of a long-term research into three-dimensional triangulation, comments on the three-dimensional procedure are as follows.

## 1. The Design of a Three-Dimensional Network

The design of a three-dimensional network should be elaborated in cooperation by geodesists and geologists considering all preliminary geologic and geodetic information. The network should be vertically oriented by three levelling points with elevations converted into ellipsoidal heights. In a local network (diameter $\leq$ 15 km), one or two spirit levelling points may be replaced by one or two known components of the deflections of the vertical.

When considering the geological, geotectonical and topographical conditions of the area involved, the locations of observation sites in the network have only a limited number of choices. The station points should be spaced 2 - 6 km apart and chosen to define a convenient geometric shape of the net. The signaling of the standpoints should correspond to the precise pointing and determining of eccentricities even if the lines of sight are inclined significantly.

The geologist is responsible for the stabilisation of network points and/or for their witness points. He also estimates the possibility of local, i.e. of non-tectonical movements. The detailed 1st and 2nd order design depends on the measuring equipment available, in the first place on the range of the rangefinder used, as shown briefly in the following subsections, a,b,c.

a) If, for instance, a rangefinder of an accuracy 2.5 ppm is available only for measurement of distances between the end points of the spirit levelling traverses with the stations at the neighbouring mountain peaks, the observations of both horizontal and zenith angles provide the bulk of information in the network. At each station, a number of 5 - 8 zenith angles should be observed with lines of sight differing significantly both in their lengths and azimuths. The zenith angles should be reobserved at least twice to obtain enough information for solving the refraction problem. The deflections of the vertical should be determined by an independent method on at least a quarter of observation stations, and interpolated at the other standpoints by the adjustment. The covariance **function** C of the deflections of the vertical may be designed in the form $C(d) = C_o e^{-(ad)^2}$, where d denotes the separation of standpoints and $C_o = 1.4$, $a = 0.15$.

b) When a rangefinder of accuracy 1 ppm is available for the whole network, the measured distances become the main source of information, provided two or more distances at each station are so much inclined that the difference between their zenith angles makes at least 20°. Observations of zenith angles are of only a subsidiary significance, and the horizontal angles need not to be observed if the measured distances ensure the horizontal position of network points. There are no big problems with refraction, and the deflections of the vertical can be excluded completely.

c) If a rangefinder of an accuracy better than 0.5 ppm is available for the whole network, the measured distances may be the unique source of information provided more than three distances are measured at each station and, at least two distances are considerably inclined ( > 15°). In this case refraction and



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deflections of the vertical are not considered at all.

## 2. The Data Processing

The data processing is more complicated in the case a) than in the csse b), and it is quite simple in the case c).

In the procedures a) and b) the data are corrected for eccentricities, for preliminary values of refraction and the deflections of the vertical, and are tested for bias before the adjustment. The refraction hypothesis is checked by the changes in the reobserved zenith angles. A three-dimensional geodetic coordinate system (O; $\varphi$, $\lambda$, h) is suitable for the combined adjustment of all observations. For local networks (diameter $< 15$ km) a topocentric Cartesian coordinate system is also used as conventional.

In the case b), the observed horizontal angles and zenith angles may be transformed into spatial angles. The adjustment of spatial angles and distances does not consider the deflections of the vertical and it significantly diminuishes the influence of refraction.

In the case c), the data processing consists only in calculation of eccentricities and compilation of observation equations. The observations are tested by the results of the adjustment. The procedure of the adjustment is repeated provided some of the measured distances failed the test.

## 3. Estimates of Standard Errors After Adjustment of a Local Network

| Procedure | a) | b) | c) |
|---|---|---|---|
| Horizontal coordinates | 12 mm | 2 mm | 1 mm 1) |
| Elevation differences | 12 mm | 8 mm | 5 mm |

1) Results obtained by an adjustment of simulated data. The adjustment of distances measured according the procedure b) proved the method c) to be the most promising one.

## 4. Crustal Movements in the High Tatra Mountains

The procedures a) and b) combined with a geodetic levelling determined the uplift of the mountain peaks Ráztoka, Prieslop and Baranec reaching 5.9, 6.0 and 6.1 mm/year, in the Slovakian reference system of "fixed elevation points" within a time interval of 21 years.

## Reference

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# FINNISH MEASUREMENTS OF THE FENNOSKANDIAN LAND UPLIFT GRAVITY LINES IN FINLAND 1966 - 1984.

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Summary. According to the isostatic theory, land uplift reduces gravity. In Finland the connection between land uplift and gravity has been studied with high precision gravity measurements over the past 18 years. The results show that, although there are significant variations in gravity, the variations are not linear with the time but rather periodic ones.

## 1. Introduction

In Finland the connection between land uplift and the secular variation in gravity has been studied with high precision gravity measurements since 1966. Similar studies were begun in Sweden and Norway in 1967 and in Denmark in 1977. The present test field consists of four land uplift gravity lines running approximately at latitudes 65, 63, 61 and 56 °N (Fig. 1). The study is expected to throw fresh light on the mechanism of land uplift. The origin of the land uplift phenomenon is commonly attributed to the after-effects of the ice age. Consequently the linear variation in gravity with time has been taken as the first approximation, and the variation in gravity with respect to land uplift is expected to provide information on the compensation of the land uplift phenomenon.

## 2. The Finnish sections of the land uplift gravity lines

As land uplift does not take place at an equal rate through out the country, the variation in gravity is not equal either. Consequently the gravity differences between the observation sites also vary. This effect can be measured with gravimeters and has been done so in Finland over the past 18 years.

All the observation sites are level planes on the bedrock and are indicated with steel markers. To reduce the error caused by the instruments the gravity differences are smaller than 0.5 mgal, usually in the order of 0.1 mgal. A car is used to transport the instruments between the stations.

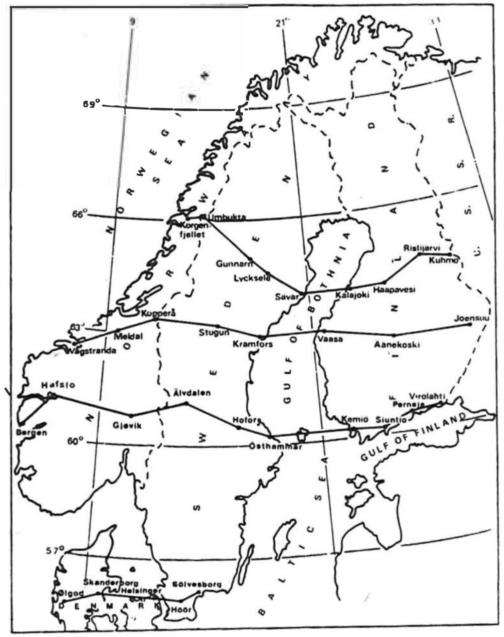


Fig. 1. The Fennoskandian land uplift gravity lines.

## 3. Measurements

Measurements on the Finnish sections of the lines and junction measurements to the Swedish stations were done as follows:

| | Number of measurements | Time interval, years |
|---|---|---|
| Kalajoki - Kuhmo | 2 | 6 |
| Vaasa - Joensuu | 7 | 18 |
| Kemiö - Virolahti | 2 | 7 |
| Kalajoki - Sävar | 2 | 6 |
| Vaasa - Kramfors | 6 | 17 |
| Kemiö - Östhammar | 2 | 7 |

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The measurements were carried out with LaCoste and Romberg G gravimeters. Since similar methods were used for all measurements, it is likely that the variation in gravity observed is not affected by systematic error. The author supervised all the expeditions. Special attention was paid to handling the instruments and to keeping the external conditions of the instruments as similar as possible throughout the measurement.

## 4. Results

The results are presented in Figs. 2 - 4 and in Tables 1 - 4. The expected variation in gravity, g(t), was estimated with known constants based on the isostatic theory 0.308 µgal/mm and 0.171 µgal/mm.

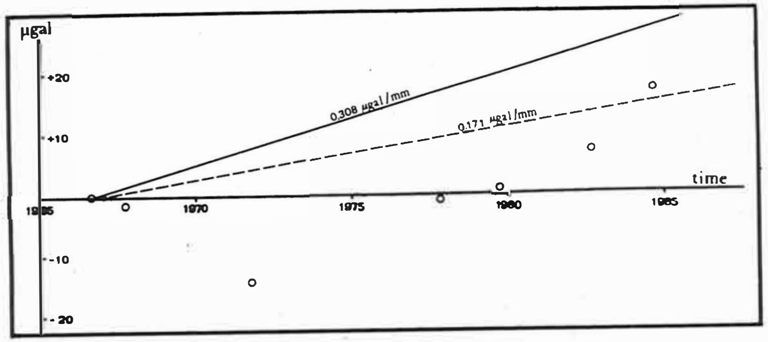


Fig. 2. The measurements Vaasa - Joensuu in 1966 - 1984.

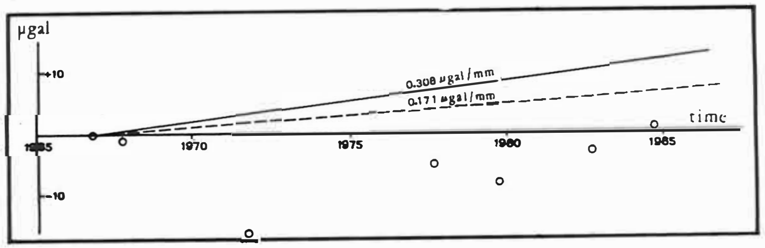


Fig. 3. The measurements Vaasa - Äänekoski in 1966 - 1984.

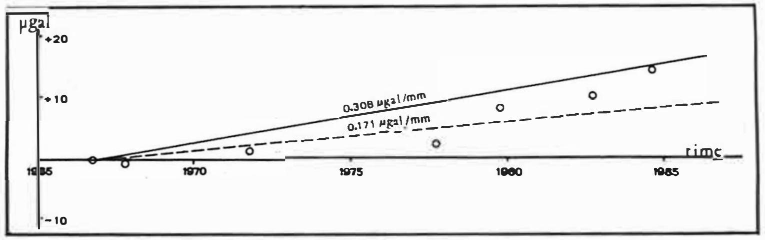


Fig. 4. The measurements Äänekoski - Joensuu in 1966 - 1984.

Table 1. The measurements Kalajoki - Kuhmo in 1975 - 1981.

| Station | Δg, µgal 1975 | Δg, µgal 1981 | µgal Difference | mm Δλ | µgal g(t) |
|---|---|---|---|---|---|
| Kalajoki | | | | | |
| Haapavesi | -44.0±3.8 | -38.2±2.0 | +5.8 | -1.0 | 1.0...1.8 |
| Ristijärvi | -60.0±5.3 | -56.8±0.6 | +3.2 | -0.6 | 0.6...1.1 |
| Kuhmo | -89.2±6.0 | -92.5±2.4 | -3.3 | -1.4 | 1.4...2.6 |
| | | Total | +5.7 | -3.0 | 3.08..5.54 |

Δλ = differences in the land uplift values
g(t) = expected variations in the gravity

Table 2. The measurements Östhammar - Virolahti in 1976 - 1983.

| Station | Δg, µgal 1976 | Δg, µgal 1983 | µgal Difference | mm Δλ | µgal g(t) |
|---|---|---|---|---|---|
| Östhammar | | | | | |
| Kemiö | -139.4±2.3 | -128.5±3.9 | +10.9 | -1.8 | +2.2...3.9 |
| Siuntio | + 22.5±3.4 | + 27.2±4.8 | + 4.7 | -1.0 | +1.2...2.2 |
| Pernoja | - 12.5±4.4 | - 13.2±5.6 | - 0.7 | -0.5 | +0.6...1.1 |
| Virolahti | +106.8±1.0 | +100.4±5.6 | - 6.4 | -0.5 | +0.6...1.1 |
| | | Total | + 8.5 | -3.8 | +4.55..8.19 |

Δλ = differences in the land uplift
g(t) = expected variations in the gravity



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Table 3. The measurements Vaasa - Kramfors in 1967 - 1984.

| | year 1967 | 1971 | 1977 | 1979 | 1982 | 1984 |
|---|---|---|---|---|---|---|
| Vaasa Kramfors | 375.2 ±5.8 | 373.6 ±4.4 | 376.3 ±1.2 | 374.4 ±4.0 | 380.1 ±0.5 | 367.8 ±4.3 mean 374.6 ±1.6 |

Table 4. The measurements Kalajoki - Sävar in 1975 - 1981.

| | year 1975 | 1981 |
|---|---|---|
| Kalajoki Sävar | -128.8 ±3.3 | -129.7 ±3.2 mean 129.2 ±0.6 |

Besides the Finnish measurements many international teams carried out similar measurements. All the observations, both the Finnish and the international ones, will be recalculated with uniform methods as a part of a Nordic project in the course of half an year. The results of this recalculation, with original observations, will be published by the Finnish Geodetic Institute in 1985. We do not consider it likely that the recalculation will alter the results above by more than a few microgals at most.

## 5. Accuracy

The error of the results can be estimated from the discrepancies between the results obtained with different instruments during a measuring period, as given in Tables 1 - 4. However, it is expected that this method gives the precision only. As the land uplift values are very similar in Vaasa and Kramfors and in Kalajoki and Sävar the yearly results of the measurements can be used to study the accuracy of one measuring period. According to Table 3, the standard error of one measuring period is ±4.0 μgal and according to Table 4 it is ±0.6 μgal. Their weighted mean is ±3.3 μgal, which can be taken as the accuracy of one measuring period.

## 6. Conclusion

This study shows that gravity has varied significantly in the Fennoskandian land uplift area. The main findings, given in Fig. 2, show a periodic variation in gravity with time rather than a linear one. The time interval, 18 years, was too short to reveal any systematic variation in gravity. The same periodic character can be seen in the results for the line Vaasa - Äänekoski, whereas the variation in gravity for the line Äänekoski - Joensuu is consistent within the limits of accuracy with the isostatic assumption. This implies that land uplift does not progress evenly. Tables 1 - 2 indicate variations in gravity that can be explained by the isostatic theory. However, the time interval was short and only two measurements are available for the period 1975 - 1983. On the basis of the above, the measurements will be continued, and they will focus on the line between Vaasa and Joensuu with a time interval of about two years.

## Publications

Groten, E., Becker, M., Hausch, W., Stock, B.: Numerical models of the Fennoskandian land uplift based on repeated measurements and potential changes. IUGG, XVIII General Assembly, Hamburg 1983.

Kiviniemi, Aimo: High precision measurements for studying the secular variation in gravity in Finland. Veröff. d. Finn. Geod. Inst. N:o 78, Helsinki 1974.

## Stationäres hydrostatisches Präzisions-Neigungsmeßsystem

G. Lorenz Technische Universität Dresden

**Summary**

**About twenty years ago, a tiltmeter station has been established for investigations of recent crustal movements in the most important test area of the G.D.R. The station is located in a sandrock tunnel system of more than 50 m, the measuring components are orientated in NNW- and ENE-direction.**

**Standard sets of the precision instruments were used with some new constructions and auxiliary equipment. By a decrease of measuring expenditure the following increase of precision was made:**

| | |
|---|---|
| **1966 - 1972** | $m_{\Delta h} = \pm\ 0.020$ mm |
| **1974 - 1979** | $m_{\Delta h} = \pm\ 0.003$ mm |
| **ab 1982** | $m_{\Delta h} = \pm\ 0.001$ mm |

**The reliability of the present measuring system is proved if the earth-tides are compared with measuring data. This system is qualified for the investigations of tectonic block tilting.**

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Im bedeutendsten der Testgebiete der Deutschen Demokratischen Republik für die Untersuchung rezenter Erdkrustenbewegungen - dem Testgebiet Elbtalzone - wurde vor fast 20 Jahren der Versuch begonnen, durch geodätische Messungen Detailinformationen über lokale tektonische Bewegungen zu erhalten. Da man insgesamt gesehen im Gebiet der DDR nur mit geringen tektonisch bedingten rezenten Veränderungen der Erdoberfläche rechnen kann [1] war dies eine echte Herausforderung an die geodätische Meßtechnik.

Für die Untersuchungen wurde ein Stollensystem ausgewählt, das gegen Ende des zweiten Weltkrieges in alte 50 - 70m hohe Steinbruchwände eingetrieben worden war. Von Anbeginn wurde der Grundsatz vertreten, Seriengeräte zum Einsatz zu bringen und - wenn möglich - aufwendige Neu- oder Zusatzkonstruktionen zu vermeiden. Die Wahl fiel zum damaligen Zeitpunkt auf den Gerätetyp der Präzisionsschlauchwaage nach MEISSER [2].

1. Etappe

Mit einer transportablen Ausrüstung, hergestellt vom VEB Präzisionsmechanik Freiberg, wurden durch unterschiedliche Institutionen anfangs für drei, später für fünf Meßstellen zwischen 1966 und 1972 insgesamt 23 ungleichmäßig über den gesamten Zeitraum verteilte Messungsprogramme realisiert.

Die erreichte Genauigkeit kann durch den mittleren Fehler des Höhenunterschiedes zwischen zwei Meßstellen, abgeleitet aus einem Messungszyklus, dargestellt werden. Er beträgt für diesen Zeitraum

$$m_{\Delta h} = \pm 0{,}020 \text{ mm}$$

Dieses Ergebnis zeigte, daß das Schlauchwaage-Meßprinzip grundsätzlich für die Feststellung tektonischer Bewegungen geeignet ist.

2. Etappe

Als Ziel der weiteren Untersuchungen wurde nun die Steigerung der Meßgenauigkeit anvisiert. Auf den gemachten Erfahrungen aubauend, wurde im Jahre 1974 unter Leitung von THURM ein stationäres Schlauchwaagemeßsystem installiert, das alle fünf Meßstellen der beiden Richtungskomponenten durch annähernd horizontal verlegte Flüssigkeitsschläuche in Messungsniveau miteinander verband, gleichzeitig kamen erstmals syphonartige Verbindungen der Schläuche an den Meßstellen zur Anwendung. Dieses System wurde 1974 durch IHDE und LESKE [3] erprobt und in [4] beschrieben. In den folgenden Jahren wurden 16 Normalmessungen ausgeführt und von HAUPT in einem großzügig angelegten Intensivprogramm 1979 nochmals vielfältige spezielle Untersuchungen vorgenommen. [5]

Neben den technologischen Vorteilen des stationären Systems zeigten die Ergebnisse, daß es gelungen war, die Genauigkeit der Höhenunterschiedsbestimmung um fast eine Größenordnung zu erhöhen. Der mittlere Fehler für einen Höhenunterschied ergab sich für diesen Zeitraum zu

$$m_{\Delta h} = \pm 0{,}003 \text{ mm}$$

Die Auswertungen zeigten weiter, daß der Sandsteinblock, in dem die Station liegt, weiterhin eine signifikante Kippung in NE-Richtung ausführt um eine NW-SE-Achse, die mit der tektonischen Hauptrichtung übereinstimmt. Bemerkenswert war, daß sich eine deutliche Verlangsamung der Kippung zeigte.

Die Analyse des umfangreichen Datenmaterials der Intensivmessungen 1979 zeigte jedoch auch, daß mit der Bestimmung von Höhenunterschiedsänderungen im Mikrometerbereich eine Grenze erreicht wurde, die neue Fragestellungen aufwarf und die die Untersuchung und Eliminierung oder Abschwächung einer Vielzahl weiterer Faktoren erforderlich machte [6].



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3. Etappe

Auf der Grundlage der genannten Datenanalyse erfolgte unter Leitung von LORENZ im Jahre 1982 eine Neuinstallation der gesamten Station unter Beachtung folgender Gesichtspunkte:

- Aufspaltung des Meßsystems in zwei getrennte Meßkomponenten zur Vermeidung instrumentenbedingter Einflüsse, die gleichzeitig auf beide Meßkomponenten wirken können,
- Verbesserung des Auflösungsvermögens durch Verlängerung der Meßkomponenten, vorrangig in ENE-Richtung,
- Vergrößerung der Anzahl der Meßstellen von 5 auf 8 zur Verbesserung des Studiums lokaler Bewegungen innerhalb einer Meßkomponente,
- Gewährleistung der Gleichgewichtslage der Meßflüssigkeit durch exakte Horizontalverlegung der Schläuche und Verwendung neuartiger Syphonteile,
- Verbesserung der Temperaturmessung an allen Meßstellen durch neue konstruktive Lösungen und zur Vermeidung evtl. Staueffekte,
- Verbesserung des Druckausgleichsystems durch Querschnittsvergrößerung der Schlauchverbindungen,
- Verringerung der von außen einwirkenden thermischen Einflüsse durch eine Spezialisolierung des gesamten Meßsystems.

Hauptziele waren:

- die Erhöhung der Zuverlässigkeit der Meßergebnisse und
- die Optimierung der Meßtechnologie.

Die von GAMPE und REINHOLD [7] erfolgte Erprobung der neu ausgestatteten Station und die bisherigen Wiederholungsmessungen zeigten und zeigen, daß es gelungen ist, eine Reihe von Einflußfaktoren wesentlich sicherer zu beherrschen und die Genauigkeit nochmals zu erhöhen.

Die Zuverlässigkeit des gegenwärtigen Meßsystems kann am anschaulichsten überprüft werden, wenn die elastischen Verformungen des Erdkörpers zum Vergleich herangezogen werden, denn ein im gleichen Größenordnungsbereich arbeitendes hydrostatisches Meßsystem muß dann in seinen Ergebnissen diesen Gezeiteneinfluß widerspiegeln.

Die nach einem Programm von HEIKKINEN berechneten theoretischen Gezeitenwerte werden uns vom Zentralinstitut für Physik der Erde zur Verfügung gestellt und entsprechend den Verhältnissen der Station Königstein in Höhendifferenzen umgerechnet, dabei werden die in der geophysikalischen Station Tiefenort experimentell ermittelten Amplitudenfaktoren verwendet.

Der abgebildete Meßzyklus soll stellvertretend das erreichte gute Ergebnis belegen. Der Assoziationsgrad zwischen den stündlichen Meßwerten und den theoretischen Gezeitenwerten kommt im Korrelationskoeffizienten zum Ausdruck, sein Betrag schwankt zwischen 0,85 und 0,97. Die mittleren Fehler, der mit Gezeitenkorrektur versehenen Höhenunterschiede betragen für den genannten Zeitraum etwa

$$m_{\Delta h} = \pm 0{,}001 \text{ mm}$$

Die Kippungsrichtung des Blockes hat sich bestätigt, die Kippung selbst weiter verlangsamt. Die Tendenz, die auf eine Umkehr hindeutet muß durch weitere Messungen bestätigt werden. Interessante Fragen ergeben sich auch nach der Größe der zu verwendenden Amplitudenfaktoren. Für die Klärung dieser und weiterer Probleme sollen die Untersuchungen langfristig, kontinuierlich und kooperativ fortgeführt werden. [8]

Mit diesen Ausführungen sollte gezeigt werden:

- daß es mit geringem technischen Aufwand gelungen ist, ein Schlauchwaagemeßsystem für Messungen im Mikrometerbereich weiterzuentwickeln,
- daß durch den Vergleich mit den theoretischen Gezeitenwerten eine ständige exakte Genauigkeits- und Zuverlässigkeitsbeurteilung erfolgen kann.

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# HEIGHT CHANGES AND RECENT CRUSTAL MOVEMENTS IN THE RHENISH MASSIF AND IN THE UPPER RHINE GRABEN RIFT


by

H. Mälzer[1)]



## Summary

Height changes are computed aiming at the investigation of recent crustal movements for the Rhenish Massif and the northern Rhine Graben area. For that purpose results of first order levelling data of the Departments of Ordnance Survey are used.

The Rhenish Massif is not lifting like a rigid block. At the present time uplift is restricted to limited areas. In the eastern part tendencies of alternating uplift and subsidence exist, and the western part is characterized by uplift and stability. The northern Rhine Graben area is not only an area of subsidence but also an area of uplift.

A trend analysis of recent vertical crustal movements shows tilts in the directions NS and WE.

## Zusammenfassung

Im Hinblick auf die Untersuchung rezenter Krustenbewegungen wurden für das Rheinische Schiefergebirge und das Gebiet des nördlichen Rheingrabens Höhenänderungen berechnet. Hierzu dienten die Ergebnisse der Nivellements 1. Ordnung der Landesvermessungen.

Das Rheinische Schiefergebirge ist nicht als ein sich hebender starrer Block zu betrachten. Gegenwärtig bleibt die Aufwärtsbewegung auf begrenzte Gebiete beschränkt. Im östlichen Teil wechseln Tendenzen von Hebung und Senkung, während der westliche Teil durch Hebung und Stabilität gekennzeichnet ist. Im weiteren Bereich des nördlichen Rheingrabens sind nicht nur Abwärtsbewegungen sondern auch Hebungsraten zu verzeichnen.

Eine Trendanalyse der rezenten vertikalen Krustenbewegungen weist auf Neigungen in Richtung NS und WE hin.


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## Introduction

Towards the end of the Miocene a strong uplift of the Rhenish Massif started (Meyer et al., 1983). Consequently the river systems eroded and were fixed in their positions. The uplift is indicated by the terraces of the river Rhine and river Moselle. This regional process was associated with widespread Quaternary volcanic activity mainly in the western part about 600,000 years ago (Windheuser, 1977). The youngest volcanic episode culminated about 11,000 years b.p. with the eruption of the Maar type valcanoes of the Eifel, e.g. Laacher See (Schmincke et al., 1983). The massif is bordered at its southern and northern ends by the active rift segments of the Rhine Graben and Lower Rhenish Embayment which are areas of relative subsidence.

For the determination of height changes in connection with recent vertical crustal movements in the Rhenish Massif and its southern areas - included the northern Rhine Graben - geodetic investigations have been carried out by the Geodetic Institute of Karlsruhe University during a six years Priority Program of the German Research Society (Deutsche Forschungsgemeinschaft) from 1976 to 1982. The title of this multi-disciplinary geocientific program was "Vertical movements and their causes using, as example, the Rhenish Massif" (Fuchs et al., 1983).

## Preliminary remarks: Data-base and modelling

The data obtained by first-order levellings have been provided by the Departments of Ordnance Survey of Baden-Württemberg, Rheinland-Pfalz, Hessen and Nordrhein-Westfalen (Tab. 1). The network is bounded to the north by the Ruhrdistrict and the Lower Rhenish Embayment, to the west and south-west by the border of the Federal Republic of Germany, and to the east by a line running from Paderborn through Frankfurt to Karlsruhe. It contains 4800 relevelled points and the levelling lines are altogether 4000 km long; in Figure 1 only the junction points are represented.

| Department | First measurements | Last measurements | Number of levellings |
|---|---|---|---|
| Baden-Württemberg | 1922-1939 | 1952-1962 | 2 |
| Rheinland-Pfalz | 1934-1957 | 1968-1973 | 2-3 |
| Hessen: | | | |
| Levelling network | 1936-1957 | 1968-1973 | 2-3 |
| Part of former subnet IV | 1936-1938 | 1955-1958 | 2 |
| Nordrhein-Westfalen: | | | |
| Southern part | 1949-1954 | -1973 | 2-6 |
| Northern part | 1921-1925 | -1975 | 2-8 |

Tab. 1. In the different departments different numbers of first-order levellings at different times have been carried out. The time intervals between the first levelling an the relevellings amount to about 20 to 30 years.

The standard deviations of the observations (first levelling and relevelling) amount to $m_1 = (0{,}2\text{-}0{,}5)\ mm/\sqrt{km}$, computed from the differences of the double (forward and reverse) measurements of levelling sections. Because of the inhomogeneity in temporal distribution and the large amount of data, and also from the mathematical point of view, a single point velocity model was the best one to model the height changes (Mälzer et al.,1983).

Several models have been presented in the past years for the determination of "real" recent crustal movements by levelling and gravity data (Biro, 1981; Strang van Hees, 1977; Heck and Mälzer, 1983). Due to the lack of repeated gravity measurements of high precision, which can indicate changes in gravity, the present investigation has been done using orthometric heights. Numerical values of the influence of secular variations of gravity on revelling data are estimated by use of a time dependent orthometric correction (Kistermann and Hein, 1979). It is pointed out that only gravity changes $\geq 5 \cdot 10^{-7} ms^{-2}$ cause deformations in height $> 0{,}2$ mm.

All computed values for the height changes are related to the fundamental bench mark of Rheinland-Pfalz located in a geologically stable plateau of the Hunsrück mountains (Fig. 1).

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## Results of the investigation

For a general description of the recent height changes the estimated velocity quantities can be transformed into coefficients of a trend polynominal describing analytically the relative vertical crustal motion (Fig. 2). Based on a detailed statistical investigation with a confidence level of 95 % in four areas of the Rhenish Massif and the northern Rhine Graben area the height changes come up to a significant trend; the tilts are NS and WE:

- In the north western Eifel (+ 1.6 mm/a);
- in the area of the Bergisches Land (+ 0.7 mm/a);
- in the northern Rhine Graben near the eastern master fault (- 0.9 mm/a);
- in the southern Pfälzer Bergland (+ 0.7 mm/a).

The height changes as a result of detailed investigations are given in Figure 3. At this map the movements dh are classified in connection to their significance. Starting form the estimated (a posterio) variance factor of unit weight $\hat{\sigma}_o \approx 0.9$ mm/$\sqrt{km}$, the values of the point velocities obtain a standard deviation of $\hat{\sigma} \approx 0.4$ mm/a on the average. The presented motions dh, which are not greater than these estimated values, are insignificant. Increasing up towards $dh = 0.8$ mm/a, the motions exceed their standard deviations expressing a trend of height changes without statistical significance. Only those rates of uplift and subsidence exceeding their double standard deviation can be considered as reliable by statistical standards (Mälzer et al., 1983).

The height changes show that the Rhenish Massif is not lifting as a rigid block but the present uplift is concentrated in limited areas. West of the river Rhine the massif is predominantly either uplifting or is stable while east of the river Rhine tendencies of alternating subsidence and uplift occur.

In the north of the Rhenish Massif (Fig. 3) toward western direction a rapid change from uplift of 0.8 mm/a to subsidence of 0.6 mm/a takes place. Entering the Bergisches Land, uplift up to 0.8 mm/a occurs north-east of the Lower Rhenish Embayment. This uplift is not restricted to the Devonian rocks, it overlaps the eastern Quaternary sedimentary series of the Kölner Scholle. In the Lower Rhenish Embayment itself, openearth working and especially the lowering of the groundwater level overlay the tectonic movements. Nevertheless, the recent height changes in this area can still be correlated to the tectonic pattern as already shown by other authors (Quitzow and Vahlensieck, 1955).

In the Nordeifel and Venn-Sattel the greatest rates of uplift up to 1.6 mm/a can be correlated with the Aachen thrust and the presence of a strong seismic reflector at 3 to 4 km depth (Fig.4), indicating a prominent fault zone (Meissner et al., 1981). Investigations of seismicity in the Hohes Venn show that there are earthquake hypocentres at about the depth of this reflector; but the earthquakes have a strong horizontal component as derived by local mechanisms (Ahorner, 1983). In general, this area is characterized by seismic activity, which is not only restricted to the thrust zone (Fig. 5). It seems to be possible that the relativ uplift in the Nordeifel and Venn-Sattel as well as in the Bergisches Land, surrounding the subsiding Lower Rhenish Embayment, indicate a continuos taphrogenesis (Ahorner, 1983).

On both sides of the river Rhine near Koblenz trends of uplift up to 0.6 mm/a exist and may be correlated with recent seismic activity (Fig. 5). In general, the southern border of the Rhenish Massif, marked by the Hunsrück and Taunus fault system, is not recognizable by height changes; only in the south-western part of the massif, in a small area of the Hunsrück near Trier, a tendency of relative uplift is found of up to 0.6 mm/a (Fig. 3).

The Rhine Graben is not only an area of subsidence but also an area of uplift. Subsidence is greatest in the northern part. In this area, tectonic pattern causes shear and extension, which results in an average subsidence of 0.6 mm/a. Maximum values amounting to 1.4 mm/a near Mannheim (river mouth of the river Neckar)



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and Frankfurt are certainly influenced by a subsiding groundwater level. Accordingly, the recent compaction of Quaternary and Tertiary fill has to be taken into account (Fig. 3).

In the central segment of the Rhine Graben north of Karlsruhe an average uplift between 0.3 and 0.5 mm/a has been found. Without doubt, from the geodetic point of view this effect was surprising but in agreement with the geological conceptions of Illies and Baumann (1982):

- It was the first stage extensional rifting which has created a rift valley with a slight zigzag configuration. A nearly NS striking northern part of the graben is followed by a nearly N 35° E striking central segment whereas the southern part trends near N 20° E (Fig. 6).
- The second stage reactivation by sinistral shear caused extensional shear and additional space for subsidence in the northern segment. The central segment between Baden-Baden and south of Heidelberg has reacted by compression shear and uplift. Simple shear occurs in the southern segment.

This geological model is in a certain agreement with the computed height changes in the Rhine Graben area:

- negative height changes in the northern part;
- positive height changes in the central segment west of the river Rhine, but negative height changes along the eastern master fault;
- on the average smaller negative height changes in the southern Rhine Graben.

It is remarkable (Zippelt and Mälzer, 1981) that in the central Rhine Graben segment north of Karlsruhe the western master fault of the graben does not interrupt this uplift (up to 0.8 mm/a) in the direction to the Palatinate Mountains (Pfälzer Bergland).

Over the whole Rhine Graben the computed present-day rates of height changes appear to be to 10 times higher than the mean rates for the Pleistocene periode derived from the thickness distribution of the sediments. In the cases of subsidence, this may be partially explained by the influence of additional factors like lowering of the water table and subsequent compaction of unconsolidated sediments. On the other hand the relative high rate of uplift, as observed in the central segment, cannot be explained by non-tectonic influence. It may be concluded that there is a residual tectonic component of the computed height changes which is higher than the geological rate for the average of the Pleistocene period. Since the vertical movements of the graben floor have been explained to be shear controlled, this concept implies that present-day shear rates are correspondingly higher.

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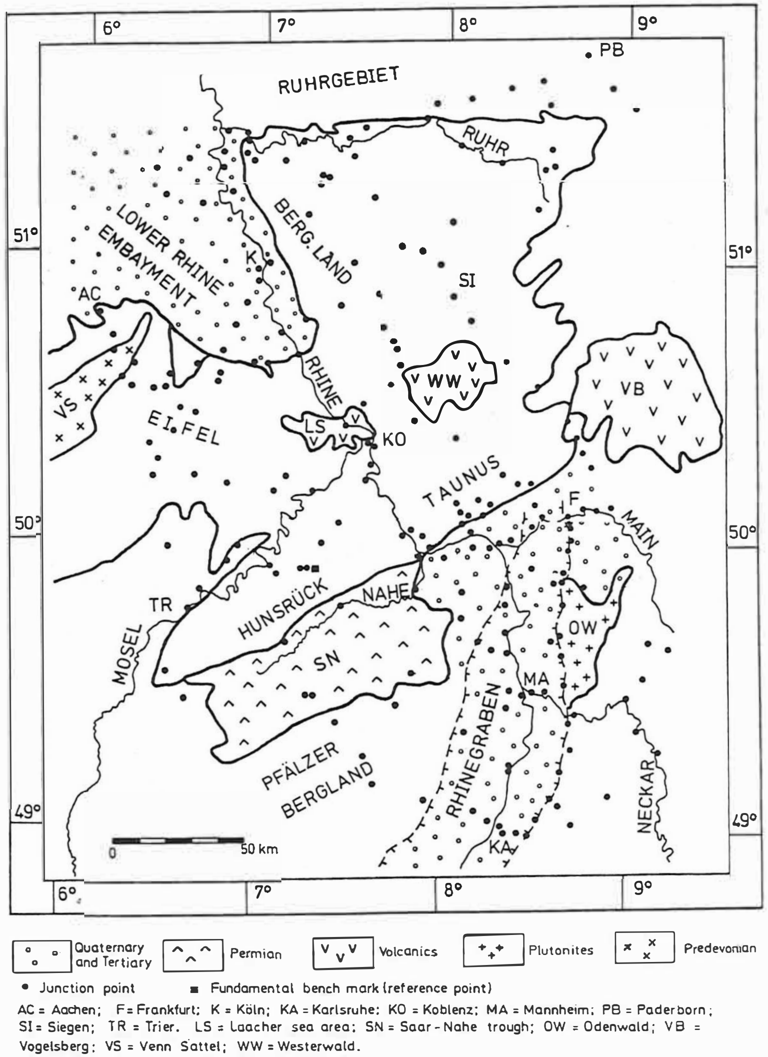


Fig. 1: The Rhenish Massif with the Lower Rhine Embayment and the northern Rhine Graben: Junction points of the used levelling network in association with geological pattern (Mälzer et al., 1983).



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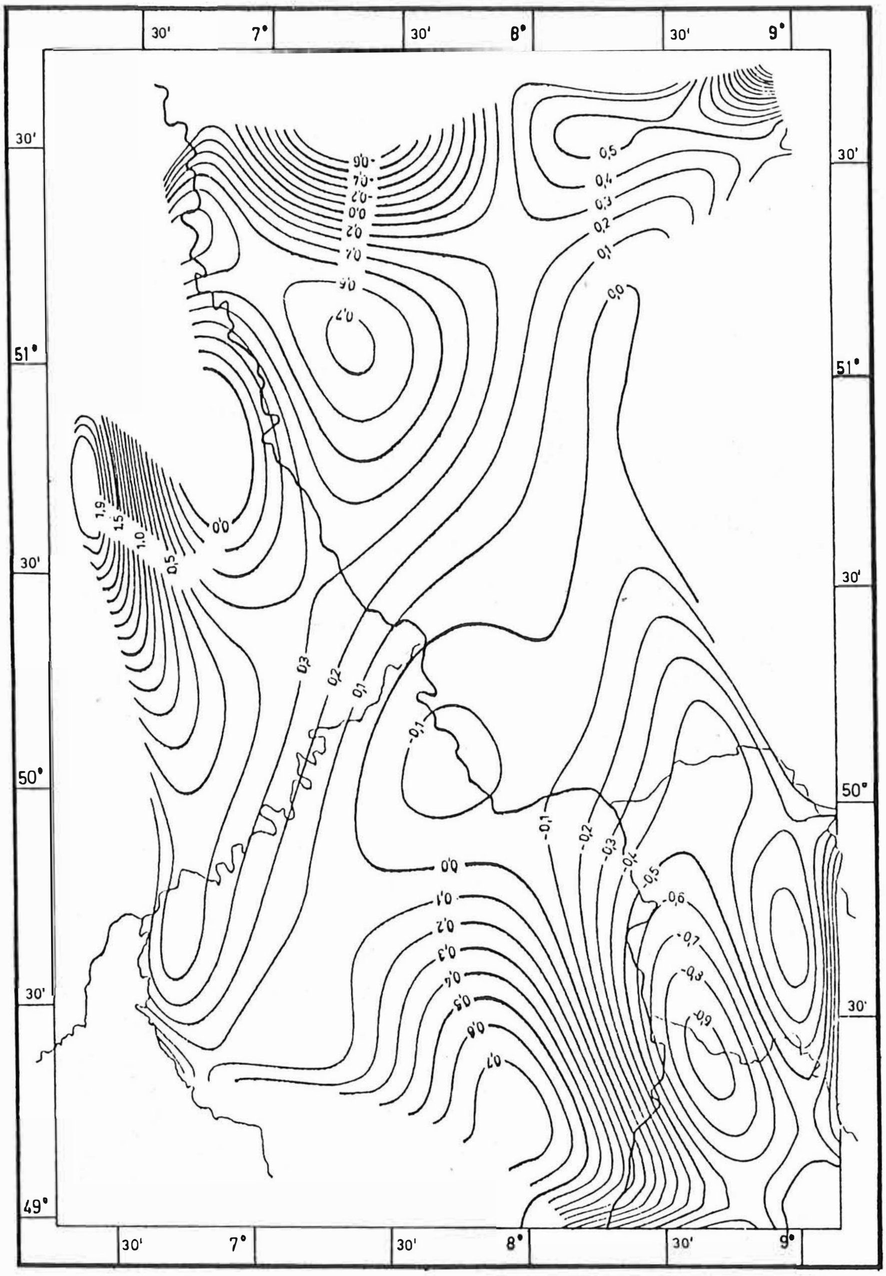


Fig. 2: The trend of the relative vertical height changes (recent crustal movements) in the Rhenish Massif and in the northern Rhine Graben area. The result of this computation based on a trend level of order 9.

Fig. 3: see next page.
Map of height changes. The contour lines are plotted at an interval of 0.2 mm / a using an integrated interpolation and plotting programm (Mälzer et al., 1983).

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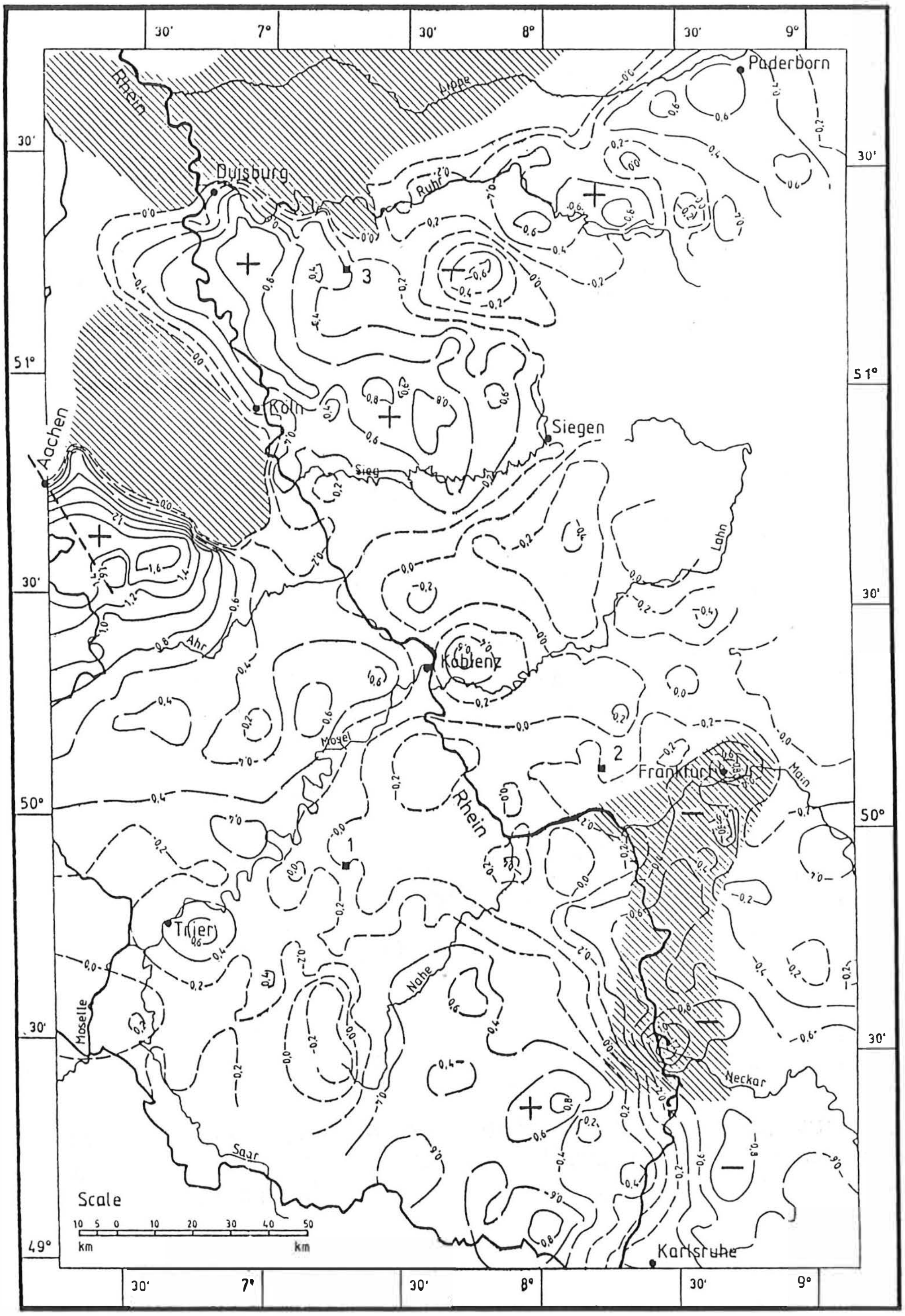


Contour lines of height changes dh (mm/year)

Level of significance :

dh > 2σ

σ < dh < 2σ

dh < σ

International boundary

Area of non-tectonic perturbation

Fundamental bench mark :
1 Rheinland - Pfalz, 2 Hessen
3 Nordrhein - Westfalen

Topographic base data:

Digitale kartographische Datenbank von Europa 1:1 Mio - EURODB des Instituts für Angewandte Geodäsie in Frankfurt am Main.

Cartographic edition:

Institut für Photogrammetrie und Topographie, Universität Karlsruhe (TH)

Fig. 3

DOI: https://doi.org/10.2312/zipe.1985.081.03

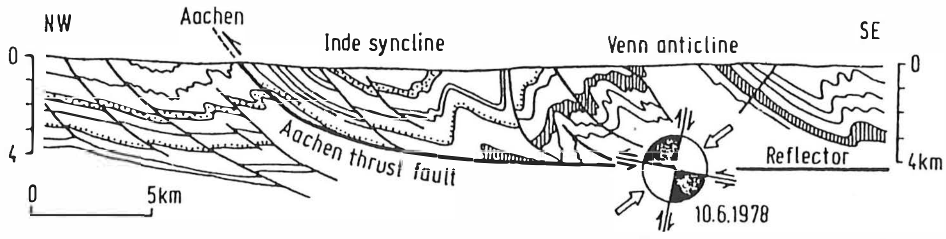


Fig. 4: The geological cross-section with an azimuth of about N 150° E (see Fig. 3) shows the Aachen thrust fault as deduced from seismic reflection data (Meissner et al., 1981). The hypocenter and focal mechanism of the Roetgen earthquake 1978 (M = 3.1) is plotted in it (Ahorner, 1983).

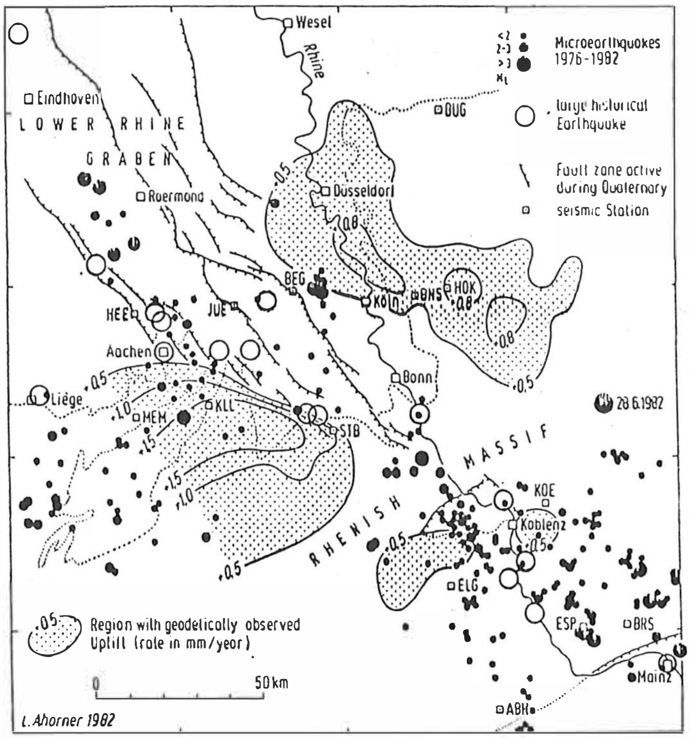


Fig. 5: Microearthquake epicenters 1976-1982 and seismic station network in the Rhenish Massif and its northern foreland. The isolines give relative recent uplift rates in mm/a (Ahorner, 1983).

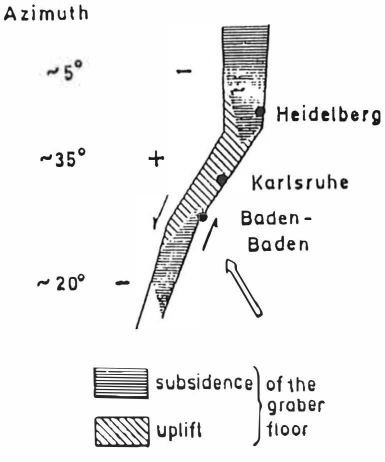


Fig. 6: The Quaternary vertical motions of the Rhine Graben floor are shear controlled. The present seismotectonic activity is that of a sinistral shear (Illies et al., 1979).

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# RECENT VERTICAL CRUSTAL MOVEMENTS OF THE CARPATHIAN-BALKAN REGION AND THEIR RELATIONSHIP WITH NEOTECTONIC MOVEMENTS AND GEOPHYSICAL FIELDS

Abstract

On the base of correlation analysis the high degree of inheritance of recent vertical crustal movements from neotectonic movements has been established as for the whole of the Carpathian-Balkan region, so for a separate structure units with size about $10^4$ - $10^5$ km$^2$. Recent vertical crustal movements, neotectonic movements and crustal thickness have a stable reverse correlation with heat flow. This suggests that thermal heating is a probable cause of neotectonic and recent tectonic activity.

* * *

One of the basic problems of recent vertical crustal movements study is an elucidation of their inheritance from the former deformation of the Earth's crust in the areas of various tectonic regimes. Earlier /1/ we discussed this problem for the East European platform that is a relatively stable block of the lithosphere. However the absence of detailed and reliable data about heat flow values for this region did not allow to make the comparative analysis of tectomic and thermal state of the lithosphere.

Now we have a good opportunity for such a comparison because there are all needed data for the Carpathian-Balcan region. This region including the Pannonian basin with the abjacent mountain rim is a part of the Alpine fold belt. In last decade the origin of the Pannonian basin is widely discussed and that is why the problem of interaction of recent and neotectonic movements and their relationship with geophysical fields is essential.

As a base for comparative analysis we used the new map of recent crustal movements /2/, the map of neotectonic movements in a scale of 1 : 1 000 000, compiled by G.I.Raisner and the international heat flow map of Europe /3/. The boundaries of the studied region and the major structure units are shown in figure 1. The whole territory was divided into equal quadrants 0°30'x0°30' and for every quadrant the next average values were determined: recent crustal movements velocity, amplitude of neotectonic movements and crustal thickness. The 290 measurements have been used for calculation of statistics (mean values and standard deviations), correlation coefficients and factors (principal component analysis) (tables 1, 2 and 3).

As it follows from tables 2 and 3, heat flow values have a stable negative correlation with other variables: recent crustal and neotectonic movements and crustal thickness. It is important that the character of correlation of heat flow with these parameters for the Carpathian-Balkan region and other region of Europe is different /4/.

More interesting results were obtained by principal component analysis application that suggests the reverse correlation of heat flow with other variables (table 3) as a regional pecularity (1 factor accounts for more than 60% of the total variance). However the special meaning presents II and III factors suggesting the existence of regions with direct correlation of heat flow and recent crustal movements (II factor) and heat flow and neotectonic movements (III factor).

Let us consider the results of trend analysis of recent and neotectonic movements, Moho boundary depthes and heat flow values for the Pannonian basin and the adjacent mountain rim. The method applied for computer of the regional and local components of variables was described earlier /1/.



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Figure 2 shows the pattern of regional component for recent and neotectonic movements. The territory of the Carpathian-Balkan region is characterized by the broad minimum that includes the Pannonian basin and the peripherical depressions - Vienna, Transylvanian, West Danube and also the Hungarian Mid-Mountains. The second small low includes the Moesic platform and adjacent spurs of the South Carpathians.

Regional maxima for recent and neotectonic movements are similar and embrace the West, East and South Carpathians, partially the Eastern Alps, Dinarides and also the Apuseni massif separating the Pannonian and Transylvanian basins.

Figure 3 represents the best reverse correlation between Moho depthes and heat flow values.

Thus, the regional trend of recent and neotectonic movements, Moho discontinuity depthes and heat flow values for the Carpathian-Balkan region makes apparent the reverse relation of the first three variables relative to heat flow. The recent crustal movements have a high degree of inheritance from neotectonic deformations; both variables are characterized by the same connection with the crustal thickness and heat flow.

Figure 4 shows the local components of recent and neotectonic movements that have a high degree of coinsidence for the whole region. In both maps one can see the lows of the central part of the Pannonian basin, Transylvanian depression and the highs of the Hungarian Mid-Mountains and the Apuseni massif. The mountain rim is characterized by a positive values of local component.

Correlation between local component of recent crustal movements and local uplifts and lows of the Moho disconinuity is slight in the most part of the region (figure 4 and 5). Such a correlation may be established only for the Transylvanian basin and the Eastern Carpathians.

Local heat flow components are characterized by positive correlation with recent crustal velocities (figure 4 and 5). Lows of both parameters coincide with the Transylvanian depression, the eastern slopes of Dinarides and highs fit the Southern Carpathians, Apuseni massif and Hungarian Mid-Mountains.

Let us consider the isostatic anomalies pattern (figure 6). The isostatic anomalies are variable with total range of about 75 mgals from a low of - 35 mgals in the Eastern Carpathians to high of + 37 mgals in the south-eastern part of the region. Comparison of the gravity variation with recent crustal movements pattern shows that within studied region there are tectonic movements both isostatic and antiisostatic ones.

Positive isostatic anomalies of the Pannonian basin correspond to negative values of recent crustal movements, i.e. the movements have a tendency to restore the isostatic equilibrium. The same trend is marked for the Eastern Carpathians. The northern part of the Moesic platforn (recent subsidence), the Apuseni massif and the Dinarides are characterized by antiisostatic movements.

Thus, the main tendency in recent tectonic activity of the Carpathian-Balkan region, as it follows from above mentioned results, consists in thermal control of crustal thickness and recent and neotectonic movements. It allows to understand why recent crustal movements have a high degree of inheritance from neotectonic deformations. The strong heating of the crust beneath the Pannonian basin along with its thinning and corresponding alkaline basalt volcanism permits to make the conclusion about anomalous conditions in the upper mantle of the studied region.

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From the other hand in some places as it has been remarked there is a reversed character of interrelations between variables in contrast with the main trend. So in some cases we observe the high heat flows in submergence areas with relatively thickened crust. Such a pecularity we can interpret as a result of superposition of different processes.

The recent basalt volcanism of the Carpathian-Balkan region has a special interest for understanding of crustal thinning and heating of the lithosphere. Table 4 shows the averages and CIPW norms of basalts from main volcanic fields of the Carpathian-Balkan in comparison with basalts of the Western USA and the Baikal rift. In all cases basalts refer to the same petrochemical type. In AFM diagram (figure 7) one can see the close trend of differentiation for the Carpathian-Balkan region, Great Basin and Baikal rift basalts and we can make the conclusion about extension stress field during volcanic activity for Pliocene-Quaternary time, i.e. time span of neotectonic movements. It is also important that ultrabasic xenoliths embedded in basalts of the Carpathian-Balkan region have the similar modal and chemical composition as a lherzolite nodules that usually occure in continental rifts.

Thus it is extremely likely that anomalous mantle really exists beneath the crust of the Carpathian-Balkan region and it is responsible for tectonic and magmatic activity beginning from Pliocene when the former compression stress field has been changed by exten-

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Table 4

Averages and CIPW norms of the Pannonian, Western USA and Baikal Rift basalts

| | Pannonian | | | Western USA | | | | | | Baikal Rift | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| $SiO_2$ | 47.70 | 47.29 | 48.08 | 50.60 | 50.56 | 49.88 | 51.29 | 50.38 | 48.39 | 46.92 | 46.20 | 46.24 | 46.40 | 49.36 | 48.34 |
| $TiO_2$ | 2.02 | 2.06 | 1.60 | 1.52 | 1.53 | 1.59 | 1.82 | 1.75 | 2.39 | 2.56 | 2.28 | 2.18 | 2.24 | 2.10 | 2.16 |
| $Al_2O_3$ | 16.88 | 16,28 | 15.89 | 16.23 | 16.75 | 15.26 | 16.20 | 15.54 | 15.71 | 15.35 | 15.42 | 16.16 | 15.36 | 16.17 | 16.24 |
| $Fe_2O_3$ | 3.72 | 3.60 | 3.96 | 2.49 | 1.70 | 1.96 | 1.76 | 2.41 | 3.06 | 4.97 | 4.48 | 5.37 | 4.22 | 4.98 | 2.24 |
| FeO | 5.79 | 5.95 | 5.46 | 7.82 | 7.74 | 8.93 | 8.02 | 6.91 | 8.63 | 7.59 | 7.21 | 6.38 | 7.64 | 5.75 | 8.13 |
| MgO | 7.08 | 6.60 | 7.96 | 6.67 | 6.27 | 8.38 | 6.11 | 7.69 | 7.57 | 7.05 | 7.82 | 7.39 | 8.16 | 5.73 | 7.46 |
| CaO | 9.07 | 9.10 | 9.31 | 8.83 | 8.92 | 9.45 | 8.98 | 8.61 | 8.64 | 7.93 | 8.75 | 8.62 | 8.34 | 7.76 | 7.63 |
| $Na_2O$ | 3.24 | 3.84 | 2.96 | 3.65 | 4.20 | 3.15 | 3.78 | 3.76 | 3.43 | 4.03 | 2.32 | 2.86 | 3.10 | 3.77 | 3.53 |
| $K_2O$ | 1.83 | 2.05 | 1.66 | 1.23 | 1.45 | 0.87 | 1.42 | 1.40 | 1.19 | 2.07 | 1.36 | 1.36 | 1.52 | 1.85 | 2.14 |
| Q | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| OR | 11.11 | 12.48 | 10.11 | 7.32 | 8.67 | 5.19 | 8.46 | 8.39 | 7.12 | 12.42 | 8.39 | 8.32 | 9.26 | 11.22 | 12.92 |
| AB | 24.17 | 21.03 | 25.77 | 31.20 | 28.79 | 26.83 | 32.20 | 31.20 | 28.67 | 22.16 | 20.48 | 25.06 | 24.73 | 32.73 | 24.36 |
| AN | 26.83 | 21.79 | 25.98 | 24.50 | 22.76 | 25.02 | 23.18 | 21.71 | 24.16 | 17.96 | 28.84 | 28.21 | 24.24 | 22.30 | 22.63 |
| NE | 2.17 | 6.78 | 0.04 | - | 3.81 | - | - | 0.62 | 0.33 | 6.76 | - | - | 1.26 | - | 3.34 |
| DI | 15.45 | 19.75 | 17.24 | 16.07 | 17.86 | 17.97 | 17.69 | 17.45 | 15.47 | 17.61 | 13.15 | 10.86 | 13.65 | 13.65 | 13.00 |
| HY | - | - | - | 2.40 | - | 4.80 | 0.09 | - | - | - | 12.12 | 1.89 | 2.09 | 2.09 | - |
| OL | 10.81 | 8.76 | 11.80 | 11.95 | 12.69 | 14.30 | 12.35 | 13.71 | 15.20 | 10.84 | 5.64 | 8.76 | 15.05 | 6.51 | 16.24 |
| MT | 5.54 | 5.39 | 5.92 | 3.65 | 2.49 | 2.86 | 2.57 | 3.54 | 4.48 | 7.52 | 6.78 | 8.06 | 6.31 | 7.41 | 3.32 |
| ILM | 3.94 | 4.03 | 3.13 | 2.92 | 2.93 | 3.04 | 3.47 | 3.38 | 4.58 | 4.94 | 4.52 | 4.29 | 4.39 | 4.09 | 4.19 |
| N | 85 | 145 | 29 | 14 | 12 | 8 | 11 | 11 | 17 | 65 | 32 | 45 | 23 | 40 | 35 |

1 - Balaton region, 2 - Little Hungarian plain, 3 - Transylvanian lowland, 4-7,9 - Rio-Grande Rift, 8 - Great Basin, 10-15 - Baikal Rift.

Note: all data are taken from the Petrobank, compiled by A.F.Grachev.

Table 1

Statistics of recent crustal movements velocities (V), amplitudes of neotectonic movements (N), crustal thickness (M) and heat flow values (q)

| Variable | Mean | Standard deviation | Maximum | Minimum |
|---|---|---|---|---|
| V,mm/year | 0,19 | 1,69 | 5,20 | -3,40 |
| N,m | -33 | 1171 | 1880 | -3200 |
| M,km | 33,31 | 6,26 | 54 | 25 |
| $q, mW.m^{-2}$ | 70,7 | 18,3 | 108 | 29 |

Table 2

Correlation matrix of the same variables as in table 1

| Variable | V | N | M | q |
|---|---|---|---|---|
| V,mm/year | 1,00 | 0,70 | 0,56 | -0,57 |
| N,m | | 1,00 | 0,58 | -0,66 |
| M,km | | | 1,00 | -0,72 |
| $q, mW.m^{-2}$ | | | | 1,00 |

Table 3

Factor loading matrix for the same variables as in table 1

| Variable | Factors | | |
|---|---|---|---|
| | I | II | III |
| V | 0,83 | 0,17 | -0,14 |
| N | 0,88 | -0,09 | -0,31 |
| M | 0,81 | -0,16 | 0,50 |
| q | -0,78 | 0,43 | -0,22 |
| Total variance, % | 61,5 | 15,7 | 7,8 |

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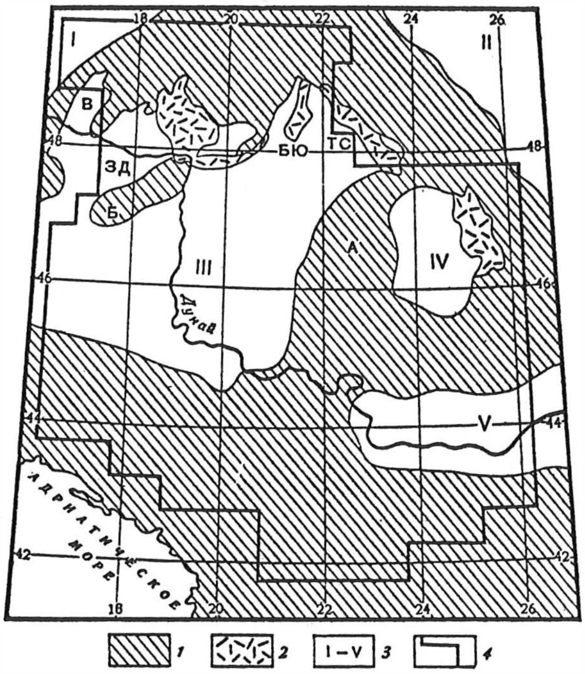


Figure I

Tectonic sketch map of the Carpathian-Balkan region. I - folded complexes of alpine and older age, 2 - early orogenic volcanics, 3 - platform areas and intermountains basins: I - Czechian massif, II - East European platform, III - Pannonian basin, IY - Transylvanian basin, Y - Moesic platform. B - Vienna basin, ЗД - West Danube basin, Б - Bacony mountains, БЮ - Bukk mountains, A - Apuseni mountains, Tc - Transcarpathian basin, 4 - boundaries of the studied area.

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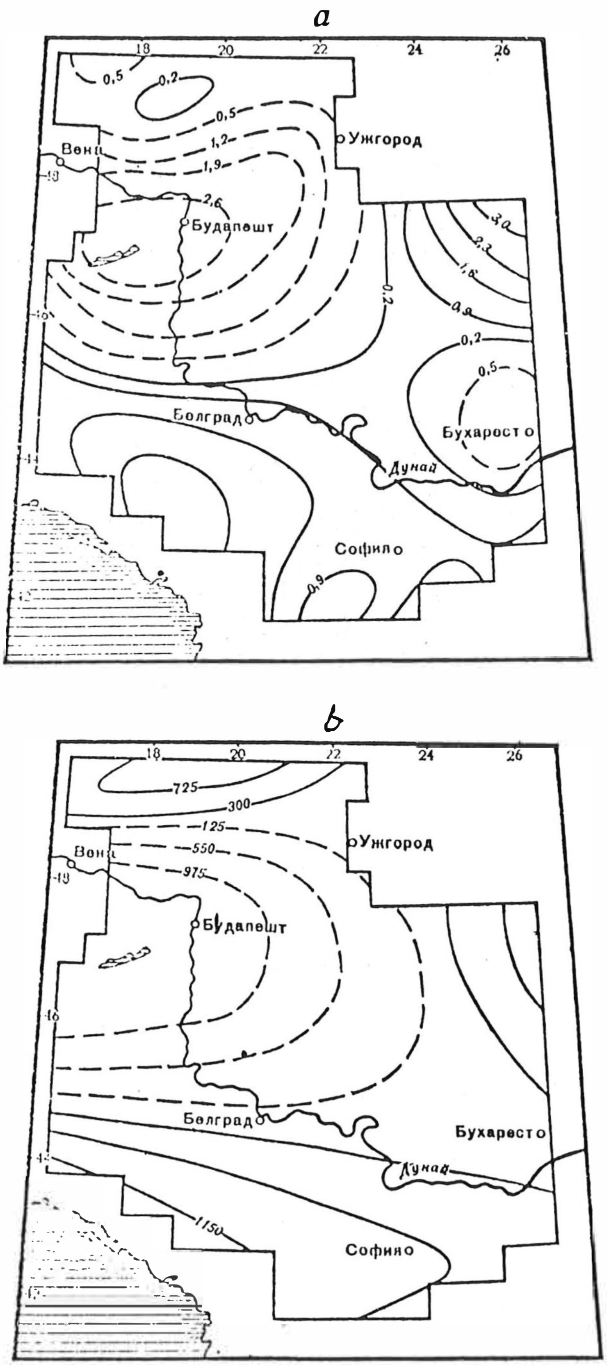


Figure 2

Regional components of recent crustal movements velocity (a) and neotectonic movements (b).

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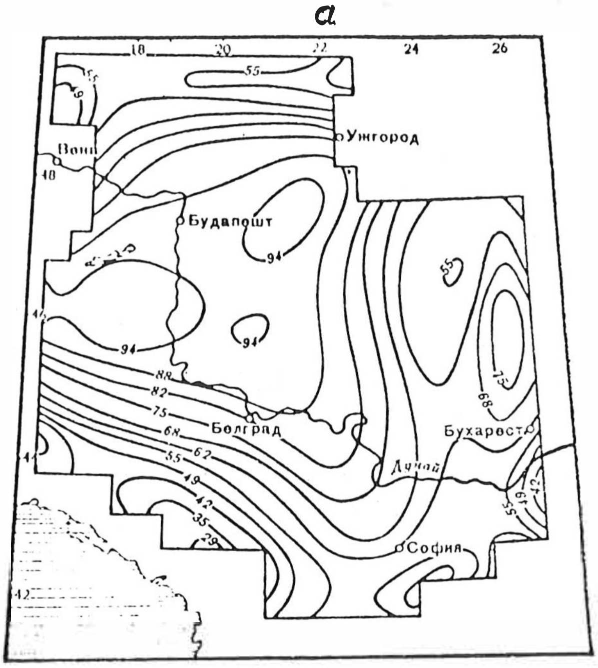


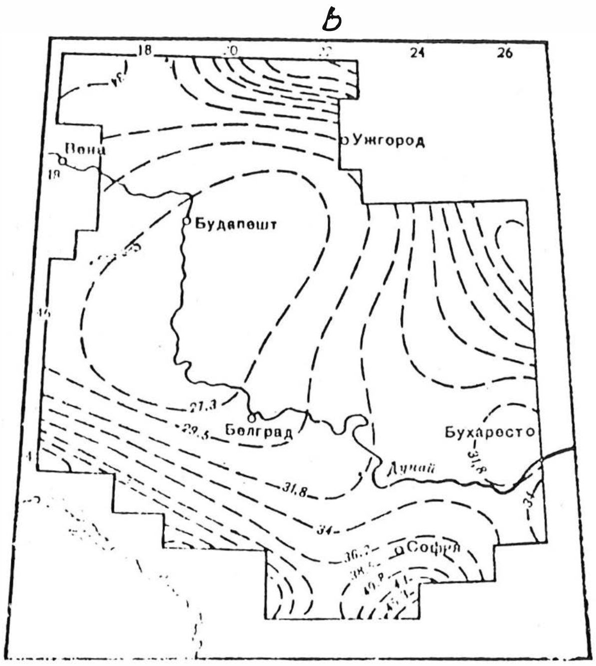


Figure 3 Regional components of heat flow (a) crustal thickness (b).

DOI: https://doi.org/10.2312/zipe.1985.081.03

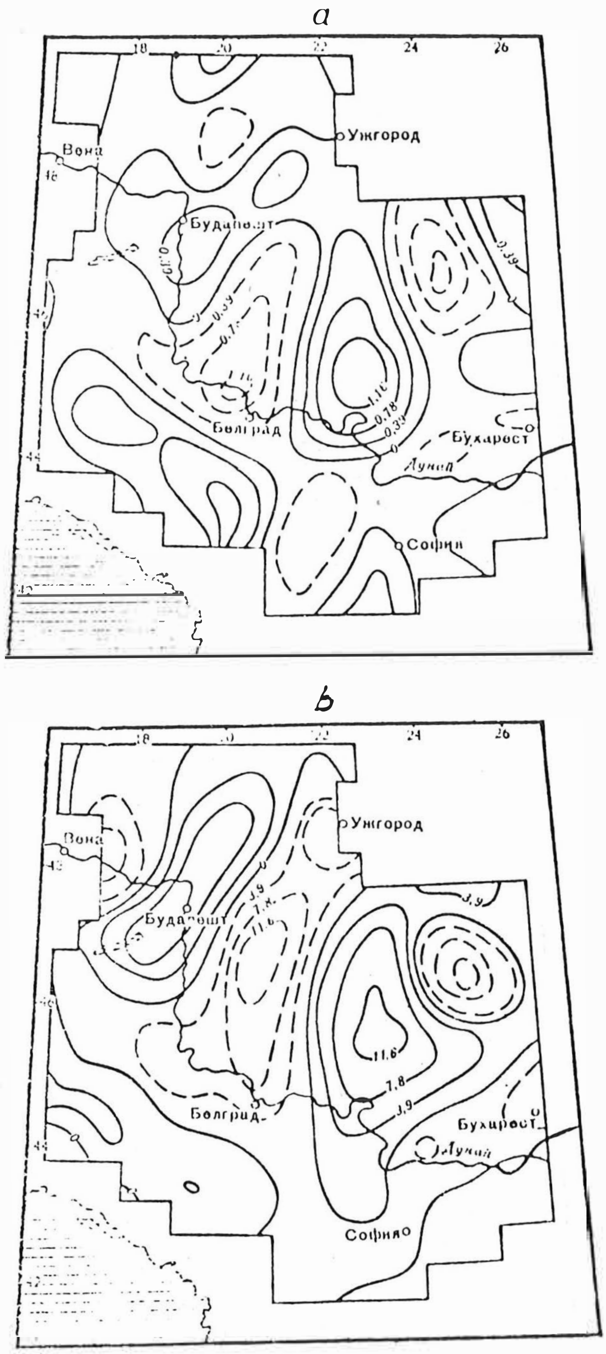


Figure 4

Local components of recent crustal movements velocity (a) and neotectonic movements (b).

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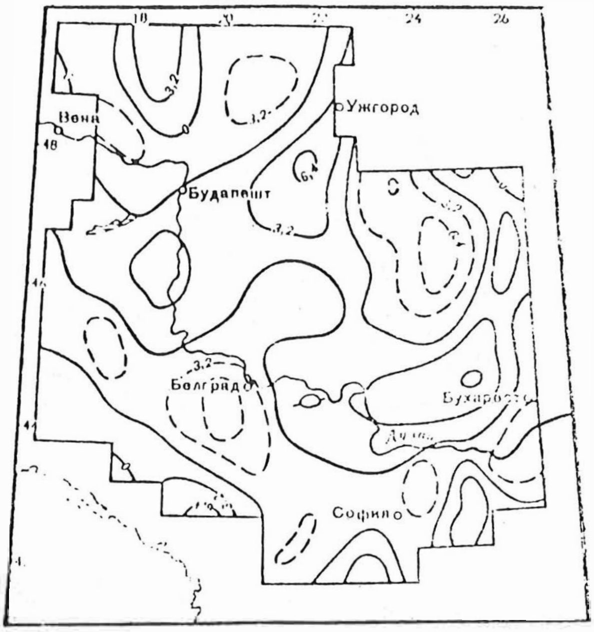
a




b

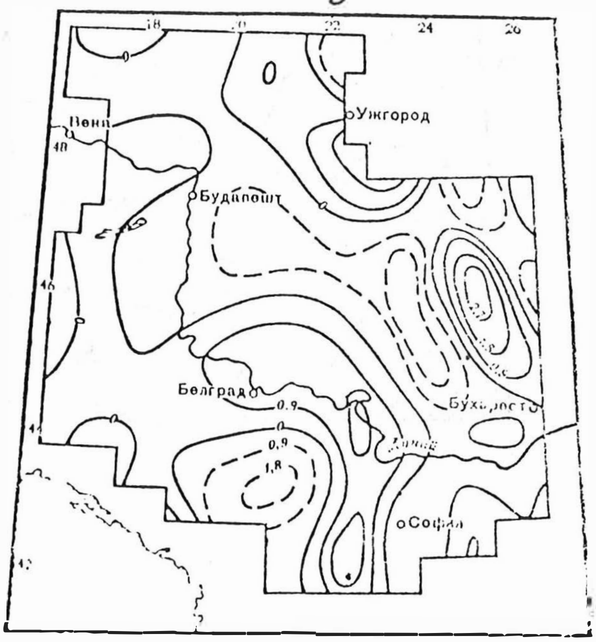



Fig. 5
Local components of heat flow (a) and crustal thickness (b).

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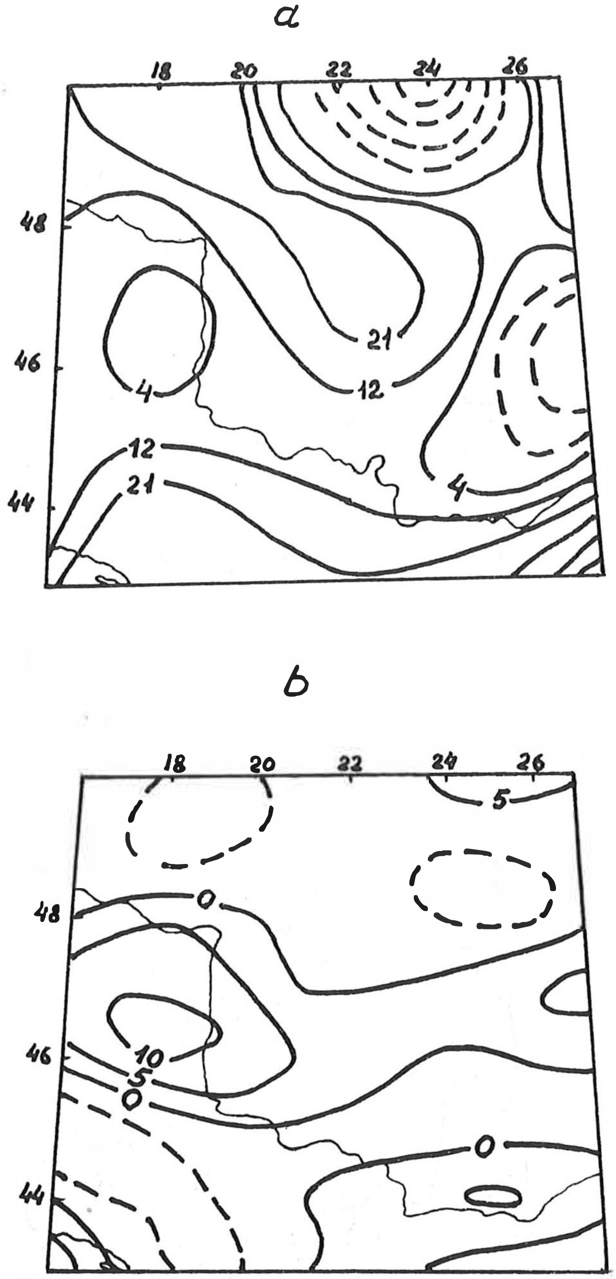


Fig. 6
Regional (a) and local (b) components of isostatic anomalies pattern.

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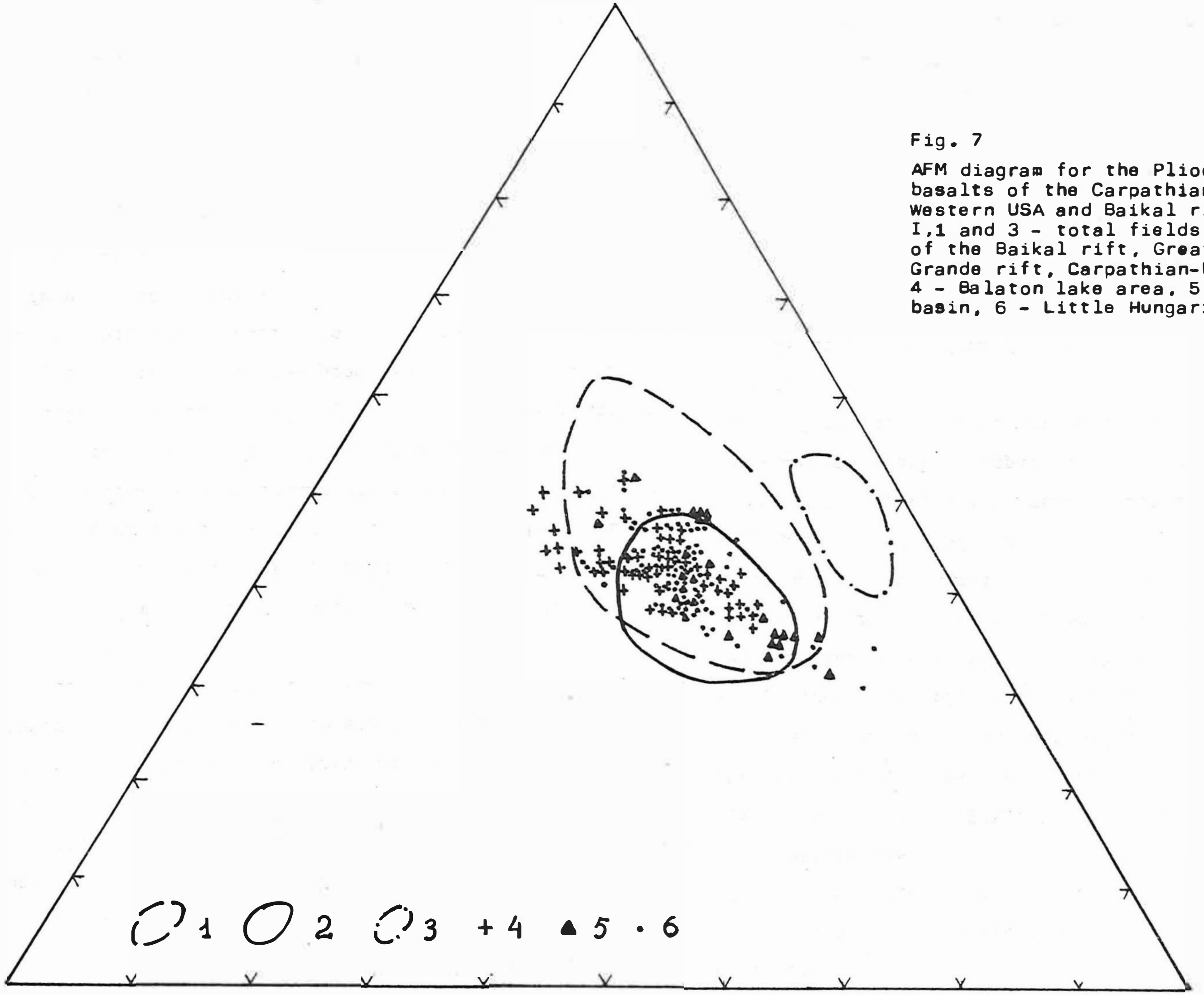


Fig. 7

AFM diagram for the Pliocene-Quaternary basalts of the Carpathian-Balkan region, Western USA and Baikal rift.
I,1 and 3 - total fields for the basalts of the Baikal rift, Great Basin and Rio-Grande rift, Carpathian-Balkan region:
4 - Balaton lake area, 5 - Transylvanian basin, 6 - Little Hungarian plain.



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V.A.Magnitsky, A.F. Grachev, I.V.Kalashnikova, V.Vad.Bronguleev

# ON THE RELATION BETWEEN RECENT CRUSTAL MOVEMENTS, THE SURFACE OF THE BASEMENT COMPLEX AND NEO-TECTONIC DISPLACEMENTS OF THE EAST-EUROPEAN PLATFORM

The problem of the origin of recent crustal movements is one of the most important problems in the field of the Earth's sciences nowadays.

There exist only a few natural phenomena permitting to obtain the direct information about the processes in the interior of the Earth now in action. Recent crustal movements are one of such phenomena.

Everybody knows, that each arbitrary point of the Earth's surface is involved in various recent tectonic movements. Nevertheless the physical causes of these movements are still a mystery. The same concerns the natural laws governing these movements (1.2.3.4.5.) The reasons for such a situation with recent movements are numerous: deficiency of data, insufficiently long periods of instrumental observations, a great number of causes producing crustal movements.

The principal processes leading to the recent displacements of the Earth surface are as follows.

Tectonic processes.

Hydrological processes.

Changes of volume of sediments.

Earth tides.

Temperature changes.

Influence of human technical activity.

To investigate recent tectonic movements one must exclude all kinds of displacements except tectonic ones from total displacements of the Earth surface recorded in data of instrumental observations. Unfortunately this problem has not been solved sufficiently till now.

In the present communication the authors report some results of their investigations of recent vertical movements of the Earth crust within the western part of East-European platform (to the west from longitude 42°E). This region represents an area with slight tectonic activity since Neogen.

The data used in investigations were collected from the following sources (6.7.8). All the mentioned maps of geophysical and geological fields were treated by the method of trend analysis (9).

As a result schematic maps of the regional component and their residuals were obtained for each field respectively (the radius of averaging is 1000-1500 km).

Figures 1, 2, 3 represent regional components of the relief of the basement complex, amplitudes of neotectonic displacements and rates of recent vertical movements respectively for the East-European platform.

As it follows from fig. 1, 2, 3 there exists an apparent similarity for general pattern of regional components of neotectonic and recent movements. The deviations for these two schematic maps are quite unimportant.

Some similarity to the mentioned maps could also be found in the map of regional component of the basement complex with one exception (10). The main meridional swell of the basement surface reduced its height gradually in the direction to the southern part of the platform whereas neotectonic displacements and recent movements form a slight upheaval in that direction. This discrepancy is due to formation of the Dnieper-Donetsk depression that began in the late

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precambrian. On the contrary this depression is not detectable for neogenic and the present times.

Hence it becomes clear that there exists apparent inheritance of general pattern for the movements of the Earth crust beginning at least from the end of the precambrian for the region in question. Especially it is true for neotectonic and recent movements.

Figures 4, 5, 6 represent the residuals of the relief of the basement complex amplitudes of neotectonic displacements and of rates of recent vertical movements respectively.

The most striking and in some way misterious results were obtained from interpretation of the drafts of residuals for the abovementioned fields.

Figure 7a represents the plot of the axis of the residuals for all the fields shown in figures 4, 5, 6. No regularity can be seen in the distribution of axis of different fields.

Figure 7b represents the plot of the same axis. But before plotting the whole diagram the scheme of axis of the neotectonic residuals was rotated by 30° anticlockwise relative to the diagram of the residuals of the basement. The same was done with diafram of axis of the residuals for recent movements but the angle of rotation was 75°.

It is apparent that fig. 7b as compared to fig.7a shows striking regularity in relative position of axis for various fields.

Unfortunately there exists no adequate explanation of this phenomena. The explanation based on the assumption that actual rotation of the platform during geological history exists, is hardly acceptible without corresponding rotation of regional components for corresponding fields.

The following supposition seems more probable. The principal deformation of the Earth crust shown in fig.1, 2, 3 is due to the some long acting source located in the deep interior of the Earth. On the contrary the stripes of undulating sharp deformations shown in fig. 4, 5, 6 are caused by the horisontal stress from adjacent geosinclines which were active in corresponding times (Caledonian, Ural, Kaucasis) (II).

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## Signatures for Figures.

1. Regional component of the relief of the basement complex.
2. Regional component of the amplitudes of neotectonic displacements.
3. Regional component of the rates of recent vertical movements.
4. Local component of the relief of the basement complex.
5. Local component of the amplitudes of neotectonic displacements.
6. Local component of the rates of recent vertical movements.
7. a - the axis of fundamental positive and negative forms of the local components of the recent vertical movements (a), of the amplitudes of neotectonic displacements (b) and of the relief of the basement complex (c). 1 - the axis of positive forms and 2 - the axis of the negative forms; b - position of the axis local component vertical movements, relief of the basement and amplitudes of neotectonic displacements after corresponding rotation. (See explanation in the text).

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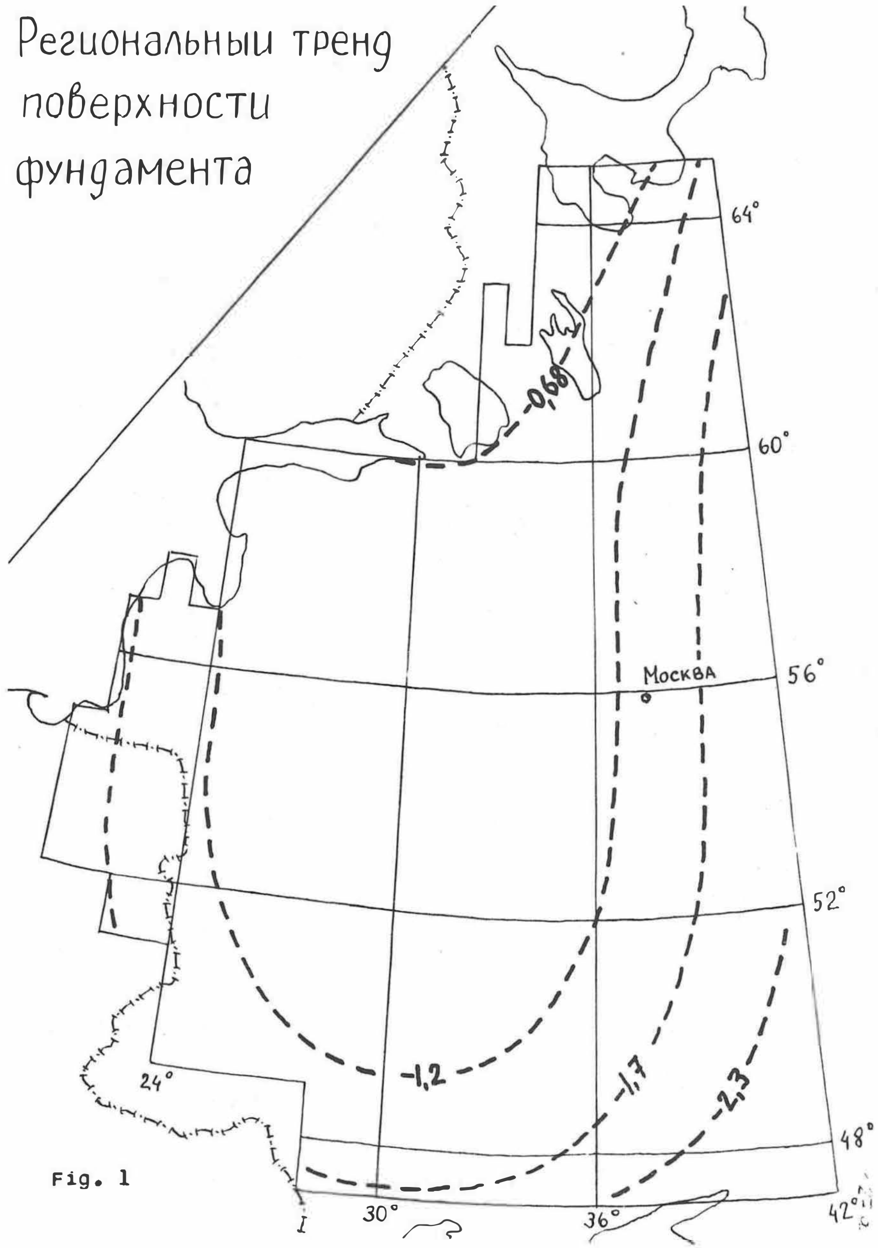

Fig. 1

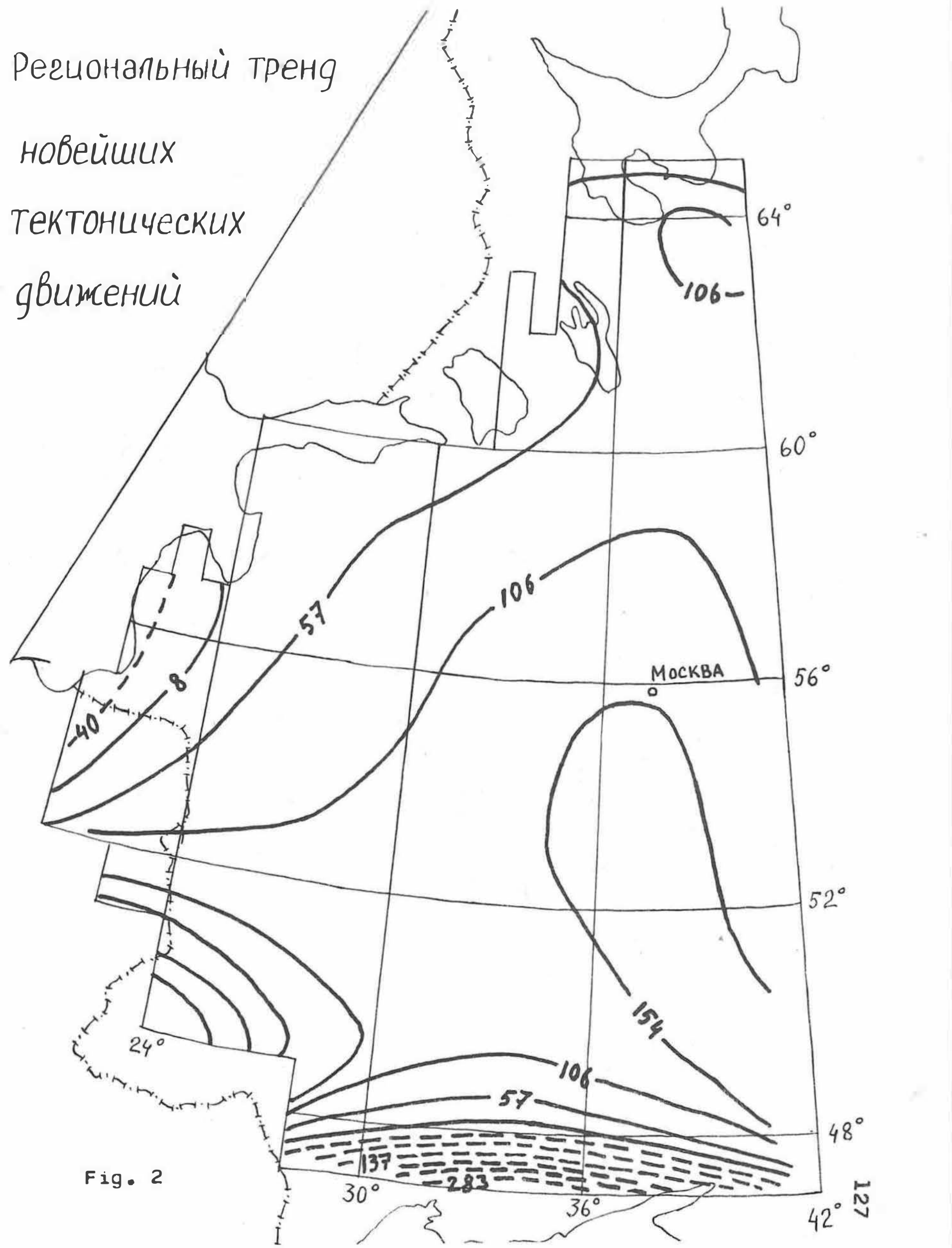

Fig. 2



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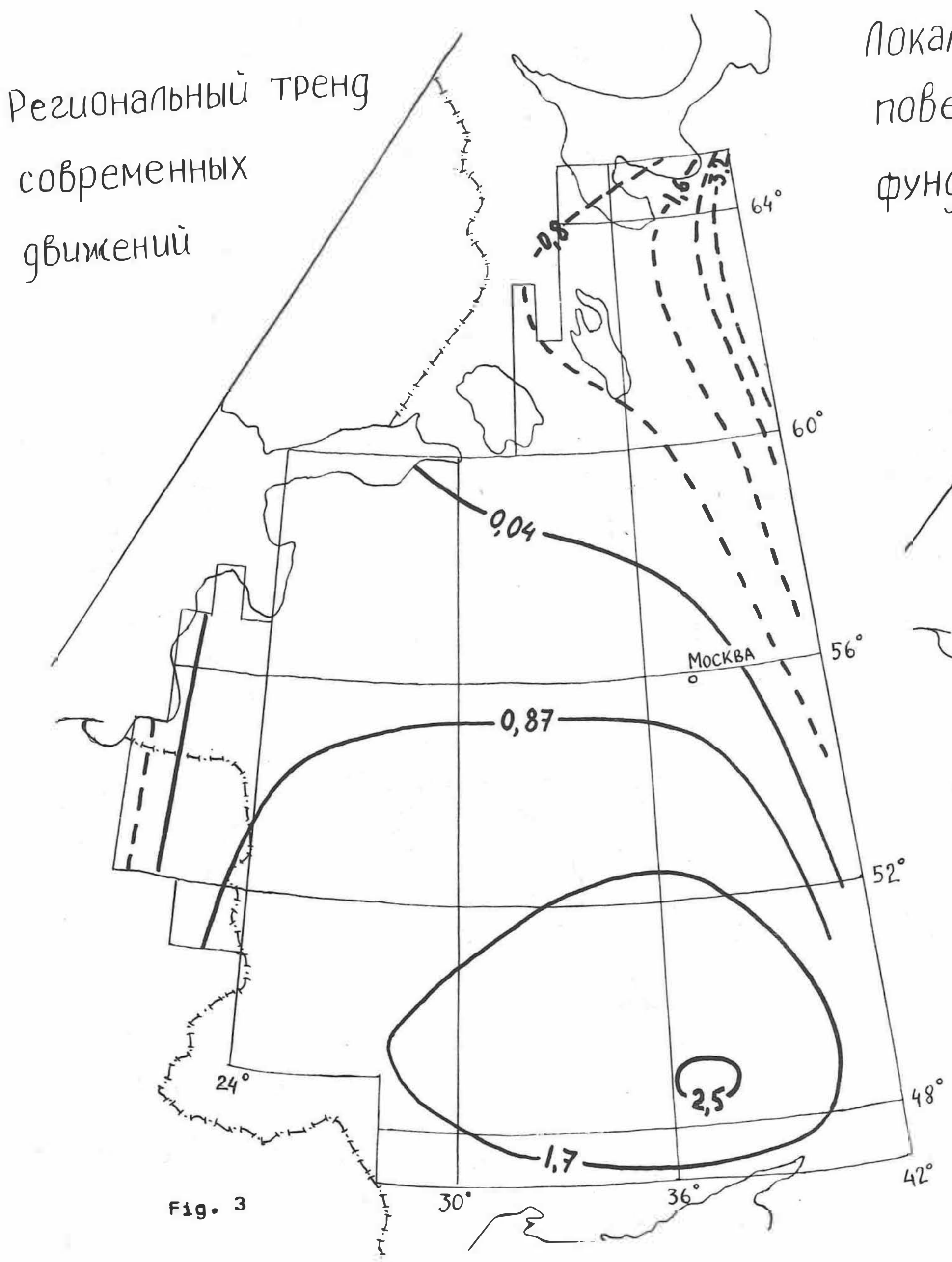


Fig. 3

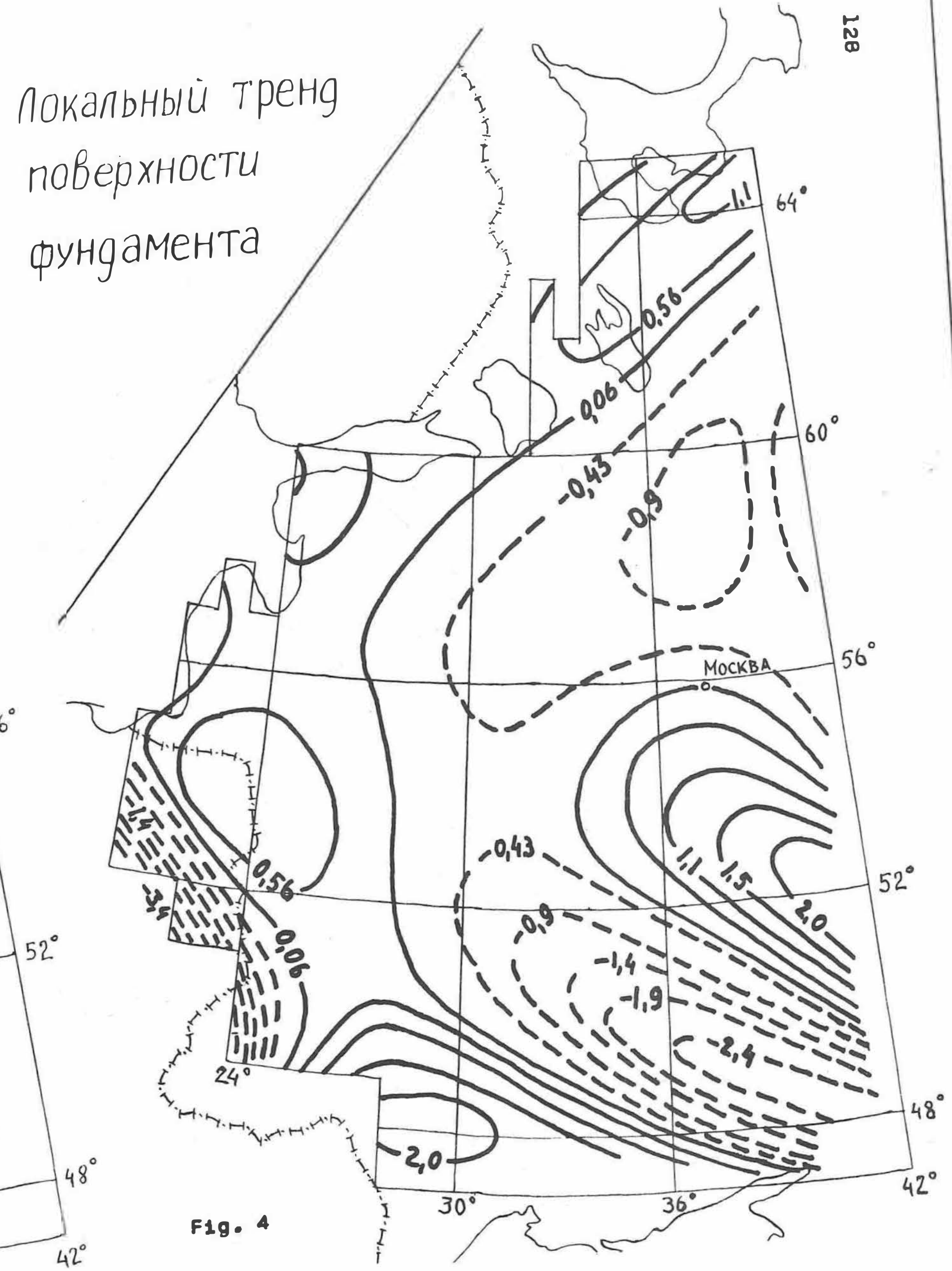


Fig. 4

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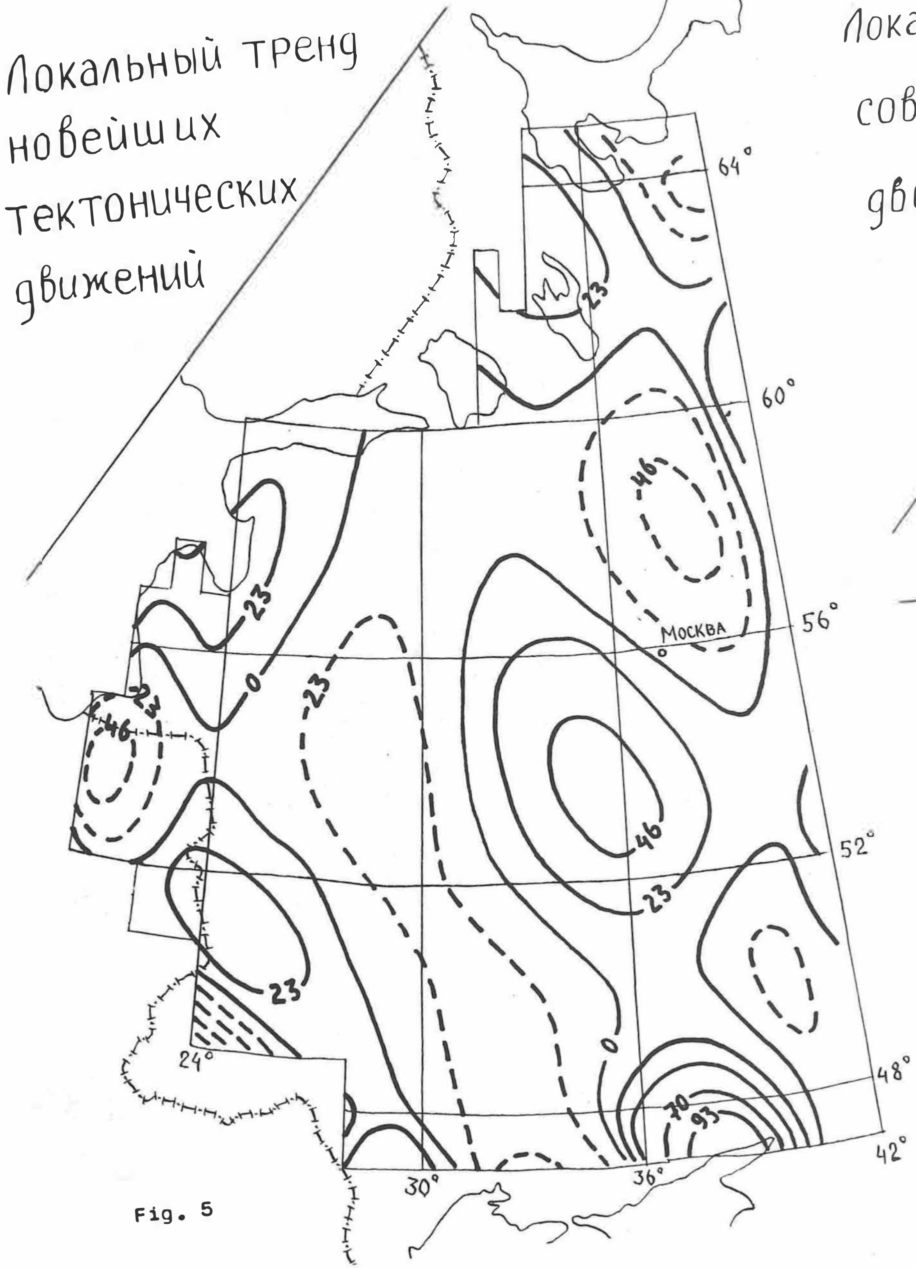

Fig. 5

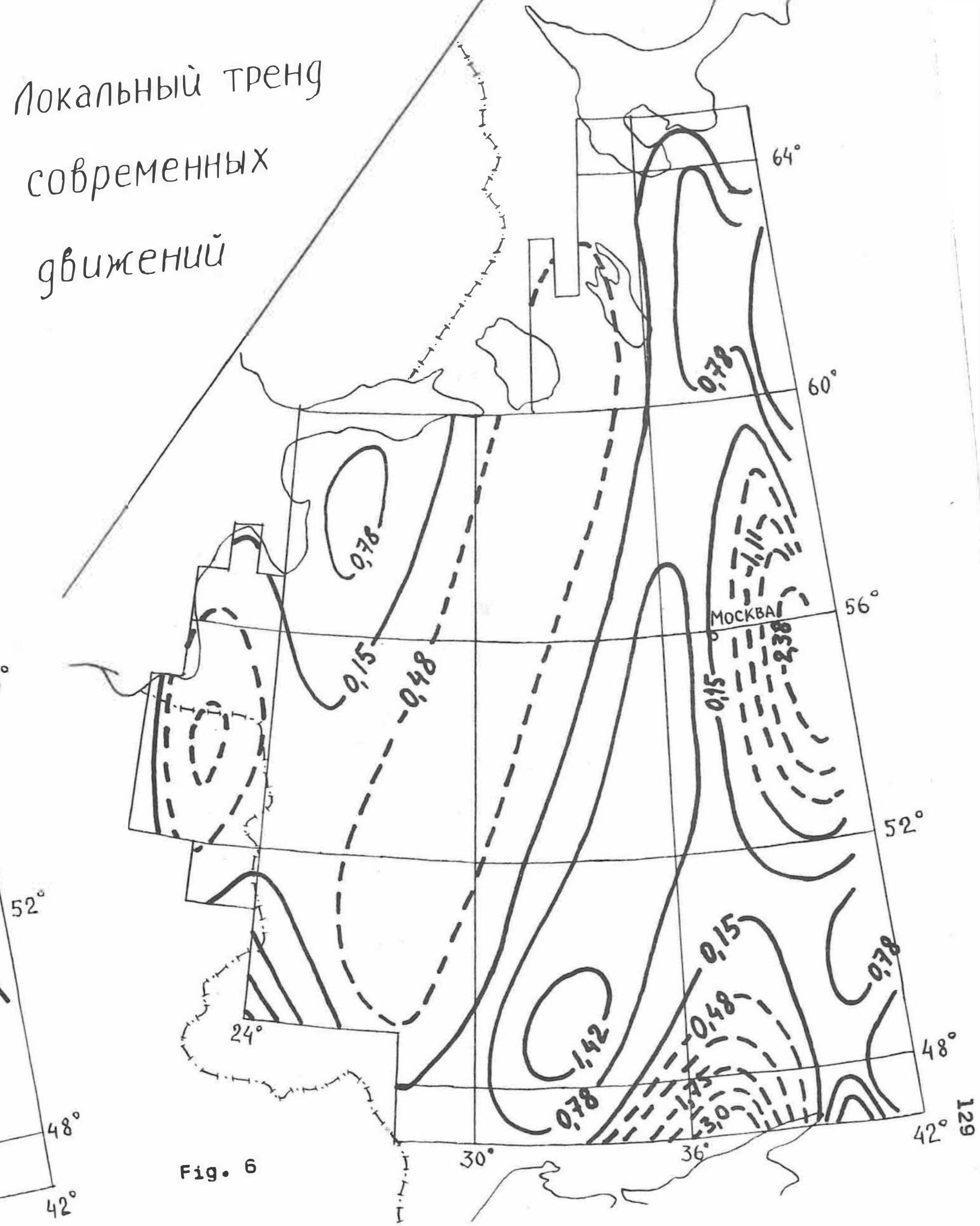

Fig. 6



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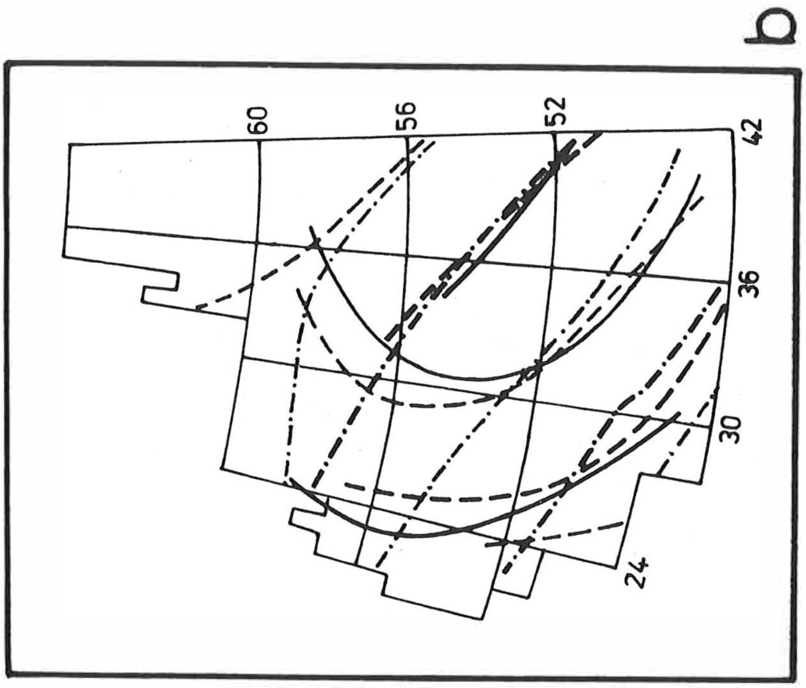
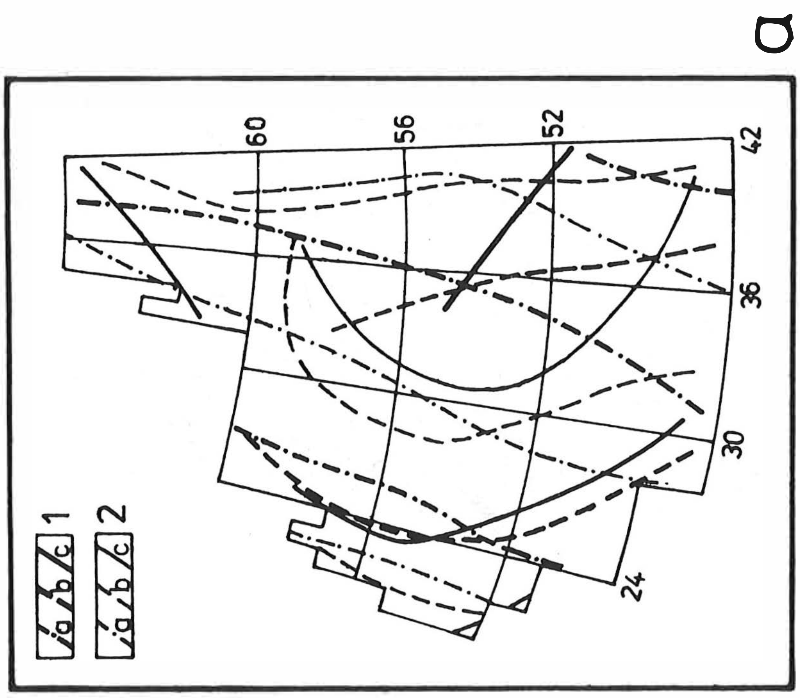



Figur 7 b




Figur 7 a

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SIGNIFIKANZPRÜFUNG REZENTER VERTIKALER KRUSTENBEWEGUNGEN MIT KORRELATIONSFUNKTIONEN (KURZFASSUNG)

Empirisch geschätzte Autokorrelationsfunktionen (AKF) ebener homogen-isotroper Prozesse der Vertikalgeschwindigkeit rezenter Erdkrustenbewegungen in Mittel- und Osteuropa (VYSKOCHIL 1968, HARNISCH 1977, SKRYL' 1981) werden durch Vergleich mit AKF bandgefilterter Nivellementsfehler auf geophysikalische Realität geprüft. Die AKF der Vertikalgeschwindigkeit im Pannonischen Becken läßt sich einem realen Bewegungsprozeß zuordnen, alle anderen sind entweder ohne Einschränkung oder abzüglich eines linearen Trends aus Fehlerkorrelationen erklärbar. Das Datenmaterial,aus dem die AKF geschätzt wurden, enthält mit Ausnahme der genannten Trends, des Teilgebietes Pannonisches Becken und möglicher lokaler Punktbewegungen offensichtlich keine weiteren vorhersagbaren Bewegungssignale. Die zugehörigen Karten mit Linien gleicher Vertikalgeschwindigkeit bedürfen daher einer entscheidenden Revision.

AKF-Modelle bandgefilterter Nivellementsfehler sind behandelt in Vermessungstechnik, Berlin 32 (1984) 4/6, Ergebnisse der Signifikanzprüfung in Vermessungstechnik, Berlin 32 (1984) 8 und in Gerlands Beitr. Geophysik, Leipzig 93 (1984) 5.

SIGNIFICANCE TESTS OF RECENT VERTICAL CRUSTAL MOVEMENTS BY CORRELATION FUNCTIONS (ABSTRACT)

Empirically estimates autocorrelation functions (ACF) of planar, homogeneous-isotropic processes of the vertical rate of Earth's-recent crustal movements in Central and East Europe (VYSKOCHIL 1968, HARNISCH 1977, SKRYL' 1981) are tested by a comparison with ACF's of band-filtered levelling errors concerning their geophysical reality. The ACF of the vertical rate in the Pannonian Basin may be co-ordinated to a real process of movement, the others are explainable, either without restriction or by deducting a linear trend, by error correlations. The data material obviously includes no further predictable movement signals, except the above trend, the partial area Pannonian Basin, and possible local point movements. Therefore, a comprehensive revision of the appropriate maps with isolines of the vertical rate is necessary.

ACF models of band-filtered levelling errors are treated in Vermessungstechnik, Berlin 32 (1984) 4/6, the results of significance tests in Vermessungstechnik, Berlin 32 (1984) 8 and in Gerlands Beitr. Geophysik, Leipzig 93 (1984) 5.



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# COMPARISONS OF DIFFERENT OBSERVATION METHODS OF A LACOSTE AND ROMBERG G GRAVIMETER

by

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Abstract

The LaCoste and Romberg gravimeters can be observed by three different methods: optically, with the gravimeters' own galvanometers and with digital voltmeters together with electronic filters. Field measurements and laboratory tests have been made by these methods with LCR G600 in the Finnish Geodetic Institute for comparing the accuracy of the methods.

## 1. Introduction

According to the manufacturer, LaCoste and Romberg G gravimeters have a reading accuracy of 10 μgal. Investigations of gravity changes in relationship to many geophysical phenomena in fact require accuracy on the microgal level. It is for this reason that the LaCoste and Romberg gravimeters, which may well be the best relative gravimeters on the market, have been widely tested and why auxiliary devices and improvements have been developed for them by both the manufacturer and the users in order to get them to reach microgal level.

Nowadays LCR G gravimeters can be bought with mechanisms to enable observations to be made with various methods. The LCR G600 owned by The Finnish Geodetic Institute has been read in laboratory and field measurements with three different methods: optically, with the galvanometer of the gravimeter and with a voltmeter together with an electronic filter. The best methods for different kinds of measurements can be established by comparing the reading accuracies.

## 2. Observation methods

In the optical reading technique the observer brings the crosshair (i.e. the image of a very fine wire attached to the beam supporting the weight in the gravimeter) seen through the eyepiece to the reading line by turning the measuring screw. With this method the main sources of reading error are

(i) the crosshair is not brought exactly to the reading line,
(ii) the reading line does not (in general) correspond exactly to the vertex of the tilt parabola of the gravimeter,
(iii) the gravimeter is heated by the burning lamps of the levels and the eyepiece, and
(iv) the difficulty of interpolating the reading between two dial divisions.

Error (iv) is common to all reading techniques (unless a nonius scale is fitted to the counter dial, Gerstenecker, 1978, Groten, 1983, p. 364). To eliminate error (iii) the readings have to be taken quickly, permitting the lamps to burn for only about one minute (Gerstenecker, 1978).

Electronic readings are taken with a capacitance readout system, in which a plate moves sith the beam between two fixed plates. A change in the position of the beam changes the voltage, and the variation can be seen in the galvanometer or in a voltmeter connected to the recording socket of the gravimeter. The difference is made zero by turning the dial. The zero point can be adjusted and it can either be chosen to correspond to the optical reading line or determined separately to correspond to the vertex of the tilt parabola.

The galvanometric reading method has an error source similar to (i) above. The stability of the zero of the galvanometer must also be checked.

The voltage can be made zero with a voltmeter (Ducarme et al., 1976). Another method is to take gravimeter readings $l_1$ and $l_2$ corresponding to small negative and positive voltages $V_1$ and $V_2$, respectively, and to interpolate the gravity reading l corresponding to zero voltage using the formula

$$l = l_1 - \frac{l_2 - l_1}{V_2 - V_1} \cdot V_1$$

(Gerstenecker, Groten). The readings are taken as close to zero voltage as possible, at any rate at less than 10 mV, to avoid errors caused by any nonlinearity of the scale. Digital voltmeters (resolution 0.1 mV, accuracy 0.5%,

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response time less than 1 s) were used in the experiments described in this paper.

The voltmeter should not be connected directly to the gravimeter, because the microseism and disturbances in the surroundings cause a noise of a few microgals. Therefore, short-period variations were filtered out with a simple capacitance-resistance circuit with a time constant as about 10 seconds. The filter slowed reading by about one minute. Because of the slowness, only two pairs of readings, i.e. two interpolated zero readings, were taken with the voltmeter method. However, if the zero readings differed by more than 1 μgal in laboratory measurements and by 2 μgal in field measurements, a third zero reading was taken.

## 3. Measurements

The reading methods were compared in both the laboratory and field measurements.

In a subterranean laboratory, where the air temperature could be kept constant and environmental disturbances minimized, the gravimeter was observed 18 times in three hours. The first six readings were taken with the galvanometer, the next six with a voltmeter and the final six optically. The gravimeter was clamped between observations, but it was not moved or even levelled between readings. The levels were checked during measurements, but no major changes were noted in either the length of position of the bubbles. Three readings were taken with the galvanometer and optically; two zero readings were taken with the voltmeter.

The reading methods were also tested on the Malmi calibration line during measurements to determine the periodic error of 1 dial unit. The vertical calibration line, which is located in a staircase in Malmi church in Helsinki, has six stations, distributed evenly over a gravity range of 1 mgal. The optical reading method was used alone twice and together with the galvanometric method once. The reading with the galvanometer was taken first. The galvanometric observations were also made twice with the voltmeter method, which was used alone once. One observation series consisted of 36 observations (6 per point), which means that the gravimeter was carried up and down three times.

Field measurements were made during the densification of the National Gravity Net of Finland. The new gravity points were only observed optically, but the observations on the reference station were done with all three methods to see if the differences between readings obtained with the methods remained unchanged. The reference point was on the outside steps of Punkalaidun church ($\phi$ = 61.12, $\lambda$ = 23.10), which was visited at least three times a day. An average of 18 new net points were measured daily. In addition, the reference point was connected to two other reference points: one at Forssa ($\phi$ = 60.82, $\lambda$ = 23.64) and one at Tyrvää ($\phi$ = 61.35, $\lambda$ = 22.94). These connections, too, were made by reading the gravimeter three times, first with the galvanometer, then with the voltmeter and then optically. The gravimeter was not clamped between readings, but levelling was corrected if necessary. Transport was by jeep. The temperature of the air varied by about ten degrees during the day.

## 4. Results

The readings were converted into microgals according to the table given by the manufacturer. The theoretical tides were calculated and reduced from the observations. The reduced readings of the laboratory measurements can be seen in Fig. 1 a-b. The drift polynomial in the adjustment of the reduced results was first order. The standard errors of the weight unit are given in Table 1 together with the adjusted gravity differences. The differences between the galvanometer and voltmeter readings and between the voltmeter and optical readings in Punkalaidun were calculated and plotted (Fig. 2.).

| Type of experiment | Date in 1984 | f | m (μgal) galvan. read. | m (μgal) volt. read. | m (μgal) optic read. | Δg (μgal) galvan. read. | Δg (μgal) volt. read. | Δg (μgal) optic read. |
|---|---|---|---|---|---|---|---|---|
| laboratory | 10.5. | 4 | 2.5 | 1.4 | 2.2 | - | - | - |
| | 10.8. | 4 | 1.4 | 1.1 | 1.3 | - | - | - |
| 1 mgal | 16.2. | 29 | - | - | 7 | - | - | 1034 |
| calibration | 21.2. | 29 | - | - | 9 | - | - | 1042 |
| line | 22.3. | 29 | - | 4 | - | - | 1031 | - |
| | 15.5. | 29 | 7 | 5 | - | 1036 | 1034 | - |
| | 16.8. | 29 | 4 | - | 3 | 1038 | - | 1035 |
| | 20.8. | 29 | 6 | 3 | - | 1033 | 1035 | - |
| field in Punkalaidun | 12.- 21.6. | 22 | 23 | 21 | 21 | - | - | - |
| Punkal.-Tyrvää | 15.6. | 2 | 11 | 8 | 5 | 27148 | 27135 | 27130 |
| Punkal.-Forssa | 12.& 21.6. | 2 | 20 | 18 | 15 | 16922 | 16918 | 16922 |

Table 1. Standard errors of weight unit of a single observation m, their degrees of freedom f, and the observed gravity differences Δg obtained with different reading methods in different kinds of experiments.



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Though successive readings can easily be taken at the microgal level with the voltmeter method, accuracy is no better than with the other two methods in measurements where errors greater than the reading error are caused by carrying and relevelling the gravimeter. The results obtained with optical reading have almost the same accuracy as those obtained with the voltmeter method if the lamps of the gravimeter are not burning for a long time during observations. In the experiments conducted in August special care was taken to keep the lamps on for only about one minute at each point. The linearity of the drift was better than in the earlier measurements, in which drift polynomials of the second and third order were needed.

The standard errors of weight unit of a single observation are largest with the galvanometric reading method. In addition, the differences between galvanometric and optical readings increased slightly with time during in long-period measurement in Punkalaidun (Fig. 2). The differences between voltmeter and optical readings do not show a clear trend, which implies that the zero of the galvanometer has gradually changed.

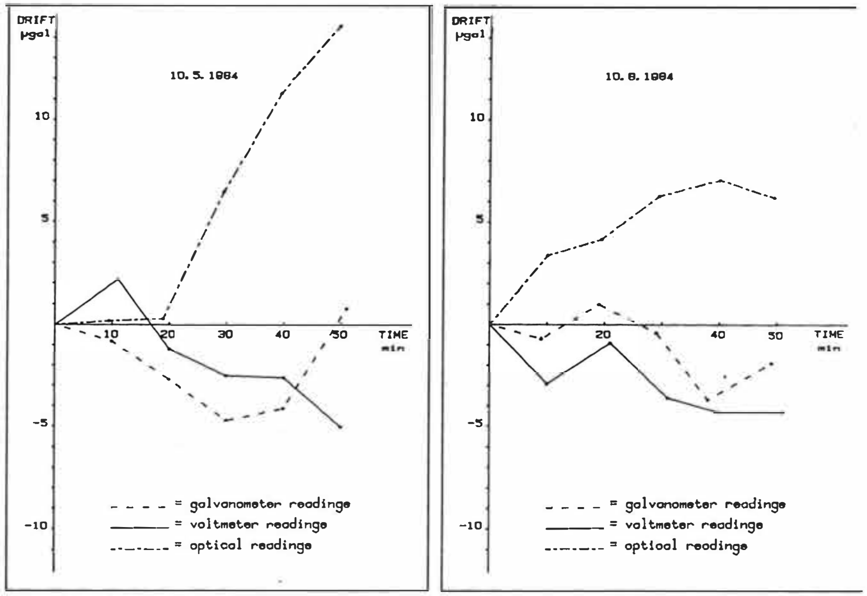


Fig. 1 a-b. The drifts obtained with different reading methods in laboratory measurements. During the first hour the gravimeter was observed with the galvanometer, during the second hour with a voltmeter, and during the third hour optically.

In the first laboratory measurement the displacement sensitivity of the gravimeter was such that about 10 eyepiece divisions corresponded to 0.8 dial units. In the second laboratory test the ratio was about 10 to 0.6. The sensitivity recommended by the manufacturer is 9-11 eyepiece divisions for 1.0 dial units, but this sensitivity does not always seem to be the most suitable for the reading precision.

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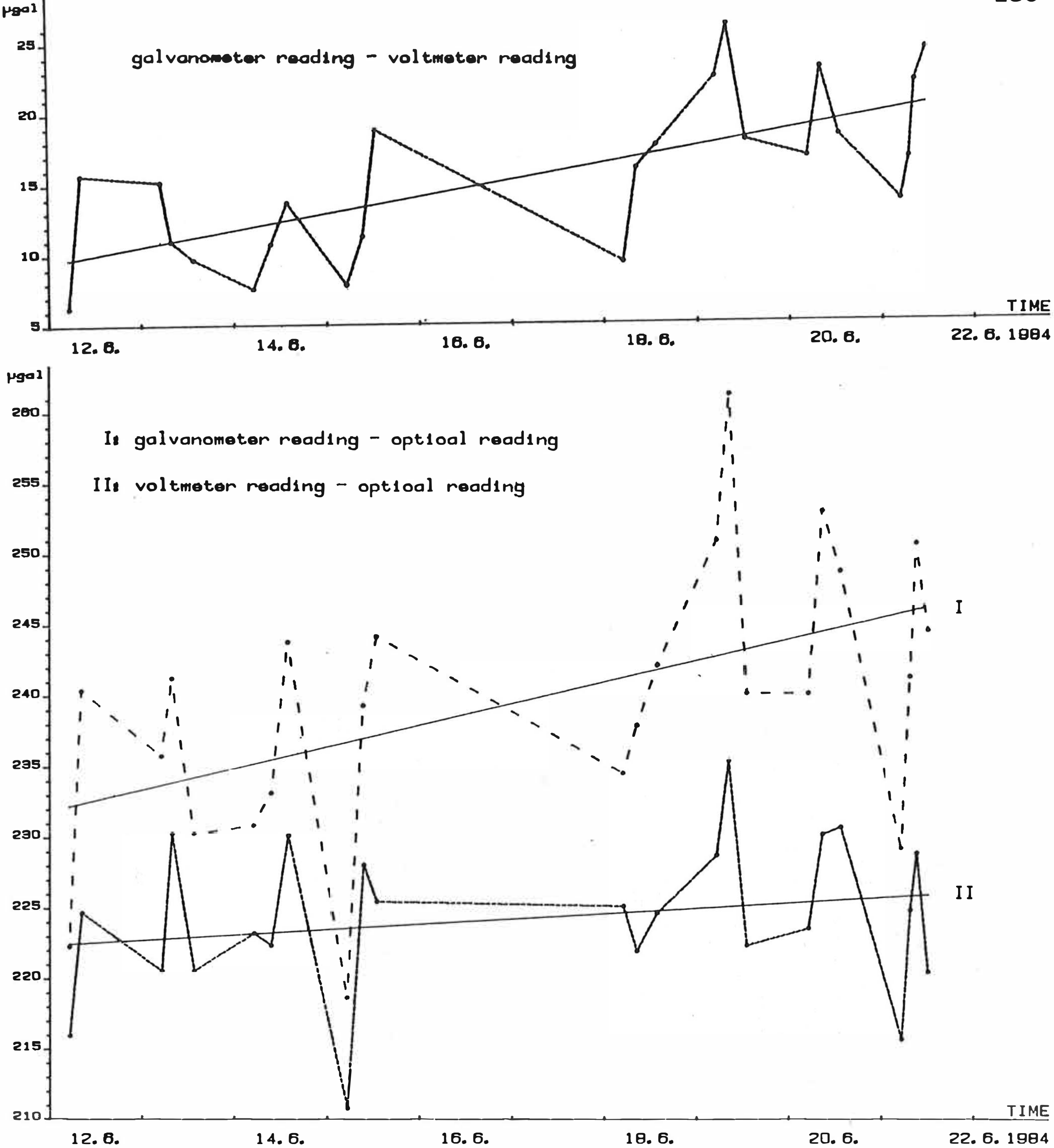


Fig. 2. Differences of reduced readings obtained with different reading methods in field measurements. The slopes of the least squares lines are

1.15 ± 0.27 (galvanometer readings - voltmeter readings)
1.53 ± 0.55 (galvanometer " - optical " )
0.38 ± 0.36 (voltmeter " - optical " ).

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# STATISTISCHE ANALYSE UND INTERPRETATION DER ERDKRUSTENBEWEGUNGEN IN NORDOSTBULGARIEN

Milev, G.[1], Totomanov, I.[2]

A statistical analysis of the changes in height differences of representative bench marks, measured during two periods of the levelling net in Northeast Bulgaria, is made. Considerable differences in exceedings are found which indicate that real changes in the heights of the levelling points exist. By means of velocity maps of the contemporary vertical movements on the same territory, with the aid of a suitable statistical test, it is found that the vertical movements on both sides of Tvardica deeop fault are insignificant. The methods applied and the results obtained are a contribution to the complex investigations of the contemporary dynamics of the region.

Сделан статистический анализ изменений в перевышениях между представительными реперами повторной нивелирной сети в Северо-восточной Болгарии. Выявленные значимые разницы в превышениях подтверждают реальность изменении высот реперов.

При помощи карты современных вертикалных движений той же сети территории и используя подходящую процедуру проверки статистической гипотезы установлено, что разница между вертикальными скоростями двух блоков земной кори, отдельных глубинным Твърдишким разломом, незначительна.

Примененные способы и полученные результаты являеться вкладом к комплексным исследованиям современной динамики в этом районе.

## 1. Vorbemerkungen

Grundlage zur Untersuchung der Vertikalkrustenbewegungen sind die Ergebnisse der wiederholten staatlichen oder speziell-

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[2] Zentrallaboratorium für Höhere Geodäsie der BAdW

gelegten Nivellementsnetze im untersuchten Gebiet. Ihre Zuverlässigkeit und Aussagekraft für solche Zwecke ist im voraus zu überprüfen. Dafür erforderlich sind in der Regel:

- visuelles Studium der Nivellementshöhenmarken entsprechend ihrem Zustand und ihrer Stabilität von geologischen, bautechnischen und anderen Gesichtspunkten;
- Ausschaltung der Nivellementspunkte, unter dem Einfluß von Erdbeben, die größer sind als Stufe fünf nach der Merkali-Kankani-Sieberg-Skala;
- Identifizierung der repräsentativen Höhenmarken.

Zweckmäßig erscheint aber auch noch eine statistische Voranalyse der Differenzen zwischen den Höhenunterschieden der repräsentativen Höhenmarken, gemessen in zwei Beobachtungszeiten. Damit kann festgestellt werden, ob es signifikante Verschiebungen gibt oder diese Unterschiede einen zufälligen Charakter haben.

Gleichzeitig kann angenommen werden, daß das Vorhandensein der Karte der rezenten vertikalen Krustenbewegungen zusätzliche Möglichkeiten anbietet, um die eventuelle Erdkrustenblockbewegungen zu studieren.

Hier werden eine statistische Voranalyse der Differenzen zwischen den Höhenunterschieden, gemessen in zwei Beobachtungszeiten, und die Untersuchung der gegenwärtigen rezenten vertikalen Erdkrustenblockbewegungen in Nordostbulgarien sowie die dafür entsprechenden Methoden dargestellt.

## 2. Statistische Analsyse der wiederholten Nivellementsergebnisse in Nordostbulgarien

In dem zu untersuchenden Gebiet liegt ein Nivellementsnetz, dessen Teile in verschiedenen Beobachtungszeiten $t_i$ gemessen worden sind. Auf Grund schon genannter Voruntersuchungen (1-3) wurden die repräsentativen Höhenmarken identifiziert (Abb. 1). Die durch die Erdbeben beeinflußten Höhenmarken sind aus der weiteren Bearbeitung ausgeschaltet.

Für die statistische Analyse wurden die Abstände $L_i$ in km zwischen den repräsentativen Höhenmarken, das Zeitintervall $\Delta t = t_2 - t_1$ in den Jahren zwischen den zwei Beobachtungszeiten und die Differenzen $\delta h$ zwischen den Höhenunterschieden angewandt. Der maximale Unterschied beträgt $\delta h = +33,30$ mm

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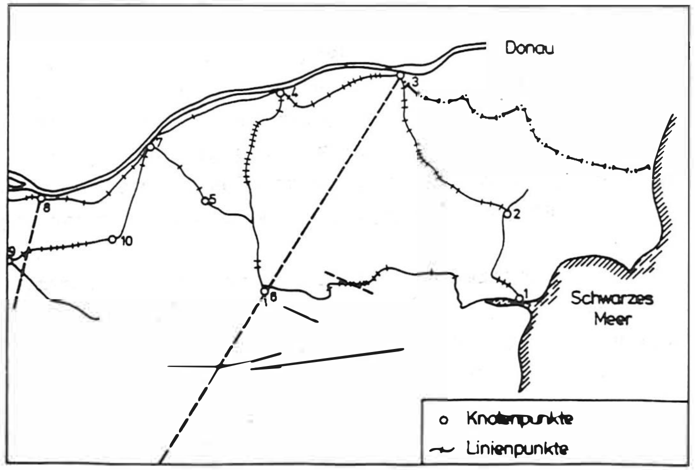


Abb. 1

und die Gesamtzahl der Unterschiede - 176.

Wie bekannt, sind die Ergebnisse der geodätischen Messungen einer Größe nach einer bestimmten Methode normalverteilt, wenn es keine systematischen Einflüsse gibt und eine theoretisch unendlich große Grundgesamtheit vorhanden ist /1/. Die Unterschiede $\delta h$, die aus theoretisch normalverteilten Größen resultieren, können auch theoretisch normalverteilt sein. Theoretisch müssen diese gleich Null sein, oder die Abweichung darf nur in den Grenzen der zufälligen Fehler schwanken. Diese Tatsache wird hier überprüft, um die systematischen Einflußbewegungen nachzuweisen. Die Untersuchung über Normalität erfolgt nach in der mathematischen Statistik gut bekannten Methoden, Kriterien und Charakteristiken - Exzes, Schiefe, Kriterien von $\chi^2$ (Pearson), Kolmogorov-Smirnov und andere /2/.

Die Berechnungen werden zweimal durchgeführt: Zum ersten werden die unveränderten Differenzen $\delta h_i$ eingeführt. Im zweiten Fall werden die $\delta h_i$ mittels der Nivellementsstrecke $L_i$ und dem Zeitintervall $\Delta T$ reduziert

$$\delta h_i^r = \frac{\delta h_i}{L_i \, \Delta T} \qquad (1)$$

$$\Delta T = \frac{\Delta t}{10} \text{ Jahr.}$$

Die Exzes E und Schiefe S sind für solche Zwecke schon früher benutzt worden /4/, /5/, /6/. Die Ergebnisse sind:

$$\begin{aligned} E &= 1,14 & E' &= 5,68 \\ \sigma_E &= 0,37 & \sigma_{E'} &= 0,37 \\ S_K &= 0,35 & S_{K'} &= -0,57 \\ \sigma_{S_K} &= 0,18 & \sigma_{S'_K} &= 0,18 \, . \end{aligned} \qquad (2)$$

Die Grenzwerte, innerhalb derer die Verteilung als normal angenommen werden kann, betragen /2/

$$\begin{aligned} E &\leq 3\sigma_E \\ S_K &\leq 3\sigma_{S_K} . \end{aligned} \qquad (3)$$

Die entsprechenden Ungleichungen ergeben sich hierzu wie folgt:

$$\begin{aligned} 1.14 &\leq 1.21 & 5.68 &\nleq 1.21 \\ 0,35 &\leq 0,54 & 0,57 &\nleq 0,54 \, . \end{aligned} \qquad (4)$$

Im ersten Fall liegen E und $S_K$ innerhalb der zulässigen Grenzen. Folglich kann der Normalverteilung angenommen werden. Im zweiten Fall werden die Grenzwerte überschritten, und es liegt keine Normalverteilung vor. Demzufolge sind systematische Einflüsse vorhanden, die mit großer Wahrscheinlichkeit auf signifikante Erdkrustenbewegungen hindeuten.

Diese Tatsache wird auch durch die $\chi^2$-Kriterien von Pearson und Kolmogorov-Smirnov bestätigt. Benutzt sind die entsprechenden Rechenprogramme von Preston /7/, die im Rechenzentrum der Bulgarischen Akademie der Wissenschaften vorliegen.

## 3. Untersuchung von Blockbewegungen

Das Untersuchungsgebiet Nordostbulgarien läßt sich entsprechend den geotektonischen Verhältnissen /5/, /6/ in drei Zonen (W, C, E) aufteilen, die durch Verwerfungen voneinander getrennt sind (Abb. 2). Zur Untersuchung wurden die Karte der



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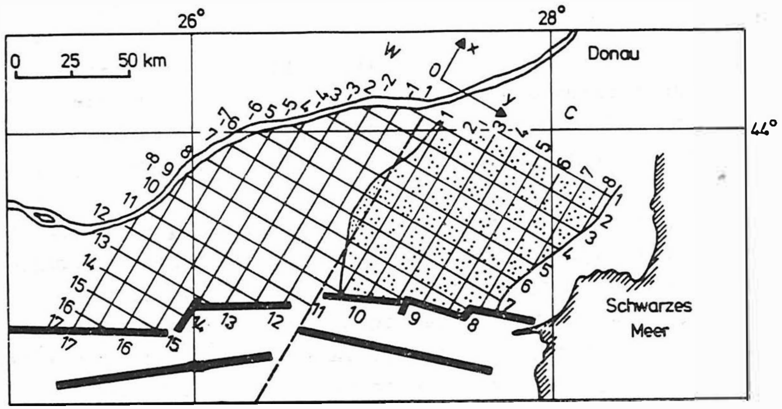


Abb. 2

vertikalen Erdkrustenbewegungen in Osteuropa /3/ uns die dazugehörige Karte der Isolinien gleicher mittlerer Fehler der Geschwindigkeiten hinzugezogen. Die rezente Hebung liegt überwiegend bei 0 bis 2 mm/Jahr. Es treten auch lokale Hebungen bis 3 mm/Jahr (Blöcke W und E) und Senkungen bis -1mm/Jahr (Block C) auf.

Um die gegenseitige Bewegung der Blöcke W und C zu bestimmen, wird ein rechtwinkliges Gitternetz über diese beiden Blöcke in die Karte eingetragen. Für die Gitterpunkte werden durch lineare Interpretation sowohl die Geschwindigkeiten als auch die Standartabweichungen der Geschwindigkeiten abgeleitet. Die Interpolationsergebnisse für beide Blöcke werden als statistische Reihen mit verschiedenen Genauigkeiten betrachtet. Die empirischen Mittelwerte und die Dispersionen beider Blöcke werden bestimmt.

Die Gesamtheit der Geschwindigkeiten eines Blockes ($V_w$ bzw. $V_c$) kann als Grundgesamtheit der relativ gleichartigen Objekte, von denen Stichproben gemacht worden sind, betrachtet werden. Die statistische Aufgabe kann folgendermaßen gestellt werden: Aus den beiden Grundgesamtheiten $V_w$ und $V_c$ sind unabhängige Stichproben zu entnehmen.

Die Stichproben haben den Umfang

$$n_w = 73$$
$$n_c = 59 \qquad (5)$$

Die empirischen Mittelwerte beider Stichproben betragen

$$\bar{V}_w = +\,0{,}90 \text{ mm/Jahr}$$
$$\bar{V}_c = +\,0{,}80 \text{ mm/Jahr}. \qquad (6)$$

Ihre Dispersionen betragen

$$D_w = D_e\,(\bar{V}_w) = \pm\,0{,}12 \text{ mm/Jahr}$$
$$D_c = D_e\,(\bar{V}_c) = \pm\,0{,}39 \text{ mm/Jahr}. \qquad (7)$$

Zum Testen der Gleichheit der Mittelwerte der beiden unabhängigen Grundgesamtheiten /2/ wird die Nullhypothese formuliert:

$$H_o : M(V_w) = M(V_c). \qquad (8)$$

Als Alternativhypothese folgt:

$$H_A : M(V_w) > M(V_c). \qquad (9)$$

Die Teststatistik

$$Z' = \frac{M(V_w) - M(V_c)}{\sqrt{\frac{D_w}{n_w} + \frac{D_c}{n_c}}} \qquad (10)$$

ist näherungsweise normalverteilt, also gilt

$$M(Z') = 0 \quad \text{und}$$
$$\sigma(Z') = 1\,. \qquad (11)$$

Die empirische Testgröße berechnet sich zu

$$Z'_E = \frac{\bar{V}_w - \bar{V}_c}{\sqrt{\frac{D_w}{n_w} + \frac{D_c}{n_c}}}\,. \qquad (12)$$

Der Grenzwert $Z_k$ der Testgröße wird von der vertafelten Laplace-Funktion abgeleitet:

$$\emptyset\,(Z_k) = \frac{1 - a}{2} \qquad (13)$$

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Ist

$$Z_E < Z_k \quad (14)$$

so wird die Nullhypothese akzeptiert und die Alternativhypothese mit

$$M(V_w) > M(V_c) \quad (15)$$

verworfen.

Für das Untersuchungsgebiet Nordostbulgarien ergeben sich folgende Werte auf einem Signifikanzniveau von $\alpha = 0{,}05$

$$Z_E' = 1{,}10$$
$$\phi\ (Z_k) = 0{,}45 \quad (16)$$
$$Z_k = 1{,}65.$$

Die Ungleichung (Gl 14) ist erfüllt und die Nullhypothese (Gl. 8) wird akzeptiert.

Hieraus kann der Schluß gezogen werden, daß sich die Blöcke praktisch gleich bewegen. Unterschiede in den Bewegungen treten nur in der Größenordnung der Genauigkeiten auf.

## 4. Schlußfolgerungen

Die dargestellten Methoden und ihre Anwendung zeigen, daß die Ausgangsdaten für die Untersuchung der rezenten Krustenbewegungen zuverlässig sind und im voraus abgeschätzt werden können. Gleichzeitig erlauben die Methoden ein reelles Bild über Größe und Charakter der eventuell differenzierten Bewegungen im gegebenen Gebiet, wie z. B. Nordostbulgarien, festzustellen.

Die Anwendung der Karte der Geschwindigkeiten der gegenwärtigen Erdkrustenbewegungen mittels geeigneter statistischer Tests ergibt, daß die relativen Bewegungen beider Seiten der Verwertungszone, zwischen den Blöcken W und C, gering sind.

Zweckmäßig ist, mehrere Deten und Fakten anderen Ursprungs - seismotektonische, geomorphologische, geographische usw. zu benutzen, die eine zusätzliche und wichtige Information über die untersuchte Erscheinung liefern.

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# A new apparatus for testing bubble vials, electronic levels and automatic levels

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An important task of geodetic researches is to increase the accuracy. Several significant results have been achieved in this field leading to an increase of the role of geodesy in geosciences /e.g. determination of geometric and physical parameters needed for geodynamical investigations/. That means that the accuracy of astro-geodetic measurements and high precision levelling must be also increased. A part of this task is a more correct qualification of different levels and levelling instruments. For this purpose a new level trier /tiltmeter/ has been constructed in our Institute taking into account earlier experiences. Tárczy-Hornoch /1961 a, 1961 b/, Tárczy-Hornoch et al. /1972/.

The main aspects of the construction of this new apparatus were the following Somogyi and Mentes /1978/:

1/ more accurate measurement of the tilt angle,

2/ more accurate measurement Of the bubble movement,

3/ electronic sensing and digital display of the measured values,

4/ one-line connection to the computer

5/ decrease of the effect of outer disturbances during measurements and comfortable handling.

The level trier enables the step-by-step control of tilt-in or free bubbles of any accuracy, of electronic levels, of automatic levels or any other kind of tilt meters, its main aim is, however, the control of high-precision levels needed in astrogeodetic measurements.

In order to ensure a high precision, the tilt of the level trier is measured by a capacitive transducer, the displacements of the bubble by the movement of an optical system of changeable base using a measuring screw. Both values can be digitally displayed.The smallest rotation angle measurable by the transducer is 0.1 second of arc, the smallest measurable displacement of the bubble is 0.01 mm.

In order to eliminate the effect of the heat radiated from the observer, the upper part of the level trier is covered by a plastic box. This means that outer temperature changes can disturb less the level during the measurements. The comfort of the measurement is ensured by a suitable observing facility.

The main units of the whole apparatus are:

1/ the level trier /tiltmeter/ /Fig. 1/

2/ the electronic unit /Fig. 1/

3/ the measuring collimator /Fig. 2/.

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The tiltmeter coneiste of two parts /Fig. 3/;

a/ fixed unit

b/ moving unit.

The basis of the fixed part is the baeic frame /1/ of the inetrument. It is supported by a fixed foot /2/ and by two foot screws /3/. The following units are connected to the baeic frame: the horizontal rotation axis, the fixed part of the capacitive traneducer and the carriage of the optical syatem with the incremental angular encoder, are settled inside, outside one can see the measuring screw /4/ which followe the movementa of the level and the lifting unit /5/ which can be connected to a remote control unit /Fig. 1/.

The moving unit of the instrument consists of the tiltable rigid plate /6/ for the setting of the level to be controlled /different level holders can be mounted on it/, and of the moveable optical syetem /8/. The pins /9/ of the optical system can be brought to a distance corresponding to the actual bubble length by the base-lenght setting screw /10/.

Operation of the electronic unit of the level trier:

The electronic construction of the tiltmeter is presented in Fig. 4. The changes of the tilt are transformed by a capacitive transducer into electronic signals.

The angular measurements can be carried out in three ranges /Table 1/.

| | Range of the measurements | | |
|---|---|---|---|
| Reeolution power | 400 sec of are<br>0,1" | 200 sec of are<br>0,05" | 40 eec of are<br>0,01" |
| Linearity | non linear | non linear | linear |
| Correction of the meaeured angles | fifth degree polynomial | third degree polynomial | multiplication constant |
| Mean error of the corrected angles | 0,7" | 0,5" | 0,1" |

Table 1.

In the most sensitive range, tilts between + 20 and - 20 eeconds of arc can be measured. This range is used for the control of high precision levels. The other two ranges have scale values set according to the demande of the user. By increasing the measurement range, the reeolution power and the accuracy of the angular measurement decreaee, too.

In case of the control of conventional levels, the rotation of the moving screw of the microscope which followe the movements of the bubble is felt by an incremental angular encoder. The two out-of-phese signals of the angular encoder are processed by the microprocessor using the corresponding software.



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The resolution in the display of the bubble movements is 0.01 mm, the measurement range is 120 mm.

The display of the tilt and of the bubble movement is carried out continuously. If the pushbutton PRINT is pressed, then the built-in microprocessor yields output data about corresponding tilts and bubble positions by the serial RS232 C interface. Thus they can be directly fed into a computer or to a printer, and the characteristic curve of the level can be automatically drawn.

The transfer rate of the serial interface lies between 75 bits/s and 9600 bits/s.

The use of the tiltmeter is supported by the remote control of the lifting unit. In certain cases its use is unavoidable /collimator measurements/. Lifting end lowering can be made with two different speeds, thus arbitrarily small angles can be set.

The measuring collimator is used for testing automatic levelling instruments. The collimator can be set up in a stable position using the big foot screws /1/ /see Fig. 2/. The adjustment of the collimator tube in elevation can be carried out by the setting screw /2/ on the vertical supporting column. The aye-piece micrometer of the collimator /3/ is interchangeable. The presently used eye-piece micrometer is a product of the firm Jenoptik and has divisions of 0.01 mm and the measuring range is 8 mm. The complete error of pointing and reading is obtained if the vertical or horizontal wire of the tested instrument is several times made to be flanked by the double wire of the eye-piece micrometer of the collimator and the standard error of this measurement series is computed. Its a priori value is about 0.3 seconds of arc. In order to increase the reading accuracy, the measuring screw should be read through a hole diaphragm to avoid parallax.



As it has been told, the level trier can be used for different tasks but its main aim is the control of high precision levels. This measurement is made as follows. The level to be controlled is set on the basis frame and one of the extremal pars-divisions is brought into coincidence with the end of the bubble. In the observing system one sees the bubble ends in coincidence and they touch the initial division. The fixed fotation value chosen for the incremental measurement is set on the raising unit, its value appears on the display. One lets the bubble ends once more to coincidence with the aid of the measuring screw and the bubble displacement due to the tilt change can now be measured. Its value appears also on the display. The chosen angular value can be set again on the raiaing unit and the operations are rapeated till the bubble reaches the far end of the divisions.

In order to teet the stability and measuring accuracy of the instrument, a lot of different investigations were

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carried out. The results of these investigations complay with the specified requirements.

The accuracy of the observations has been determined by the bubble of a Horrebow-level belonging to a Wild T4 instrument. In order to exclude environmental effects, ahort measurement series consisting of 10 measurements each were carried out with nine repetitions. The observation accuracy of the bubble lies between ± 0.005 and 0.013 mm; on the basis of 90 measurements, the expected error is ± 0.008 mm /Fig. 5/.

The linearity of the collimator has been controlled by a Wild T3 theodolite. The images of the centres of the wire crosses have been brought into coincidence, then the measuring eye-piece of the collimator has been set at 1.00 mm. The angular values belonging to different positions of the measuring eye-piece have been read on the theodolite /Fig. 6/.

The tilt measure unit was tested with a HP interferometer. The results of this measurements can be seen in Table 1.

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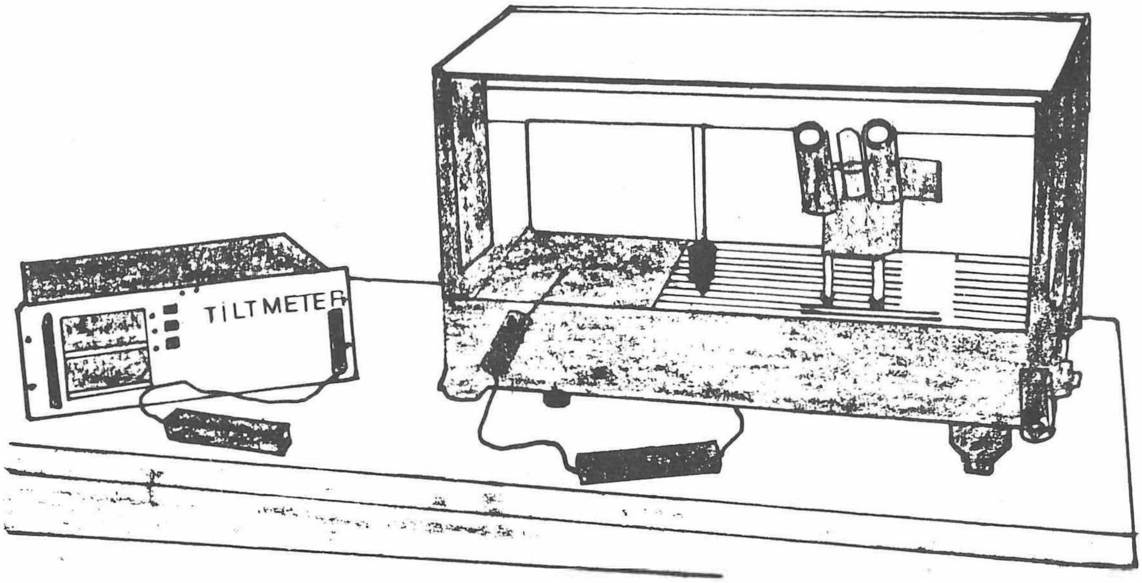


Fig. 1

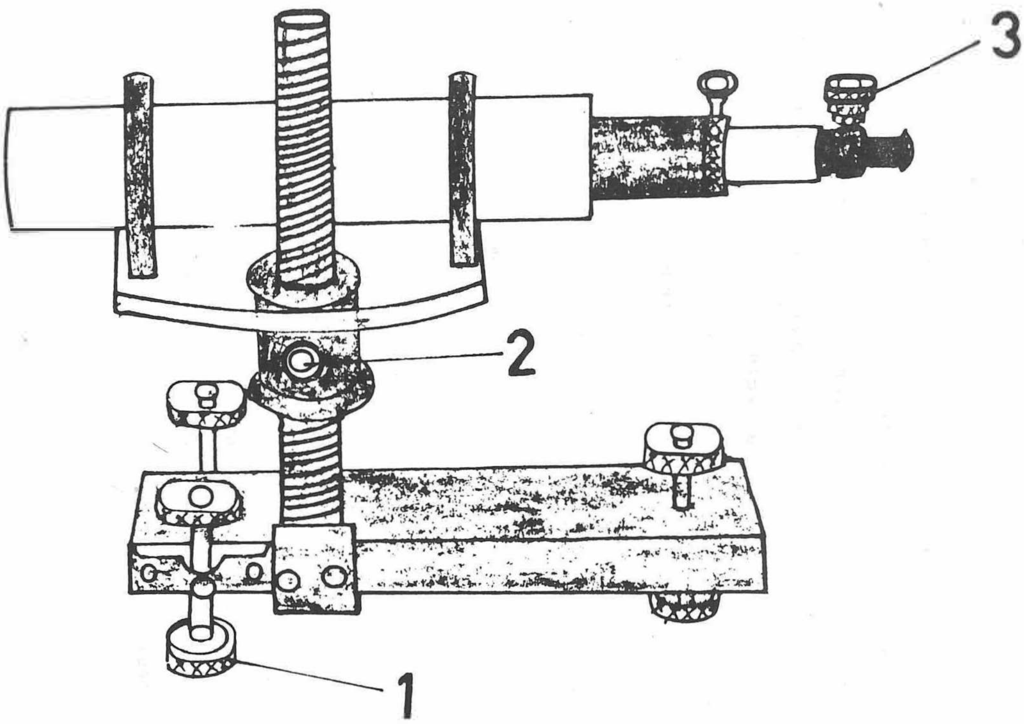


Fig. 2

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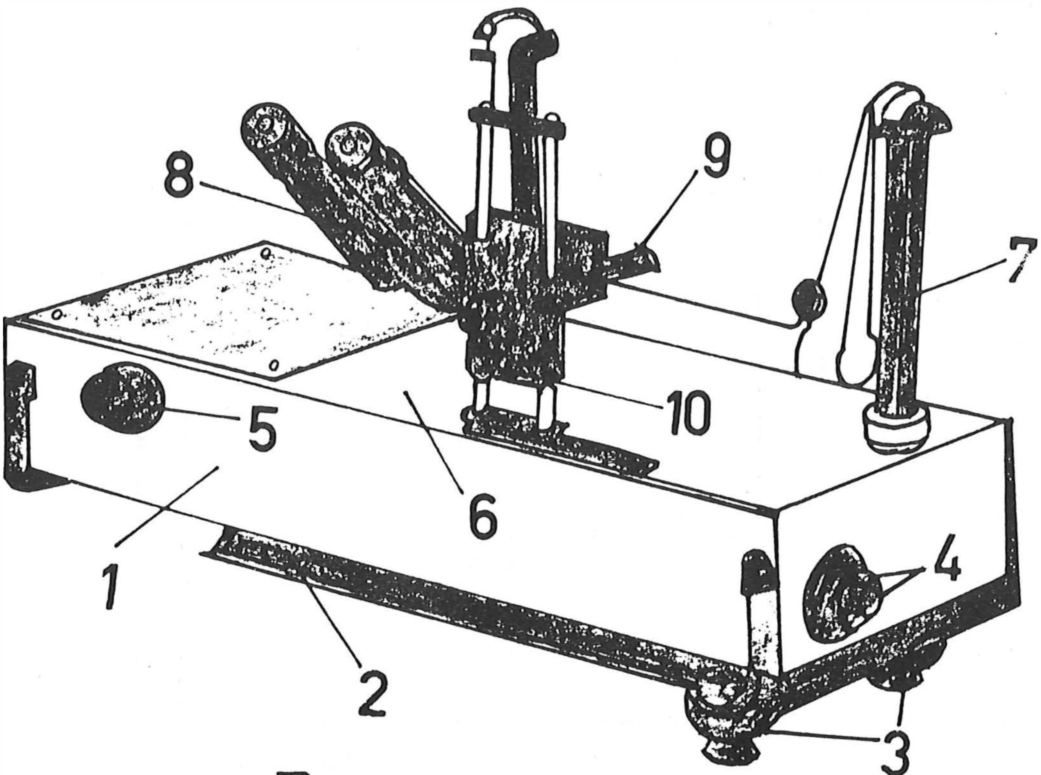


Fig. 3

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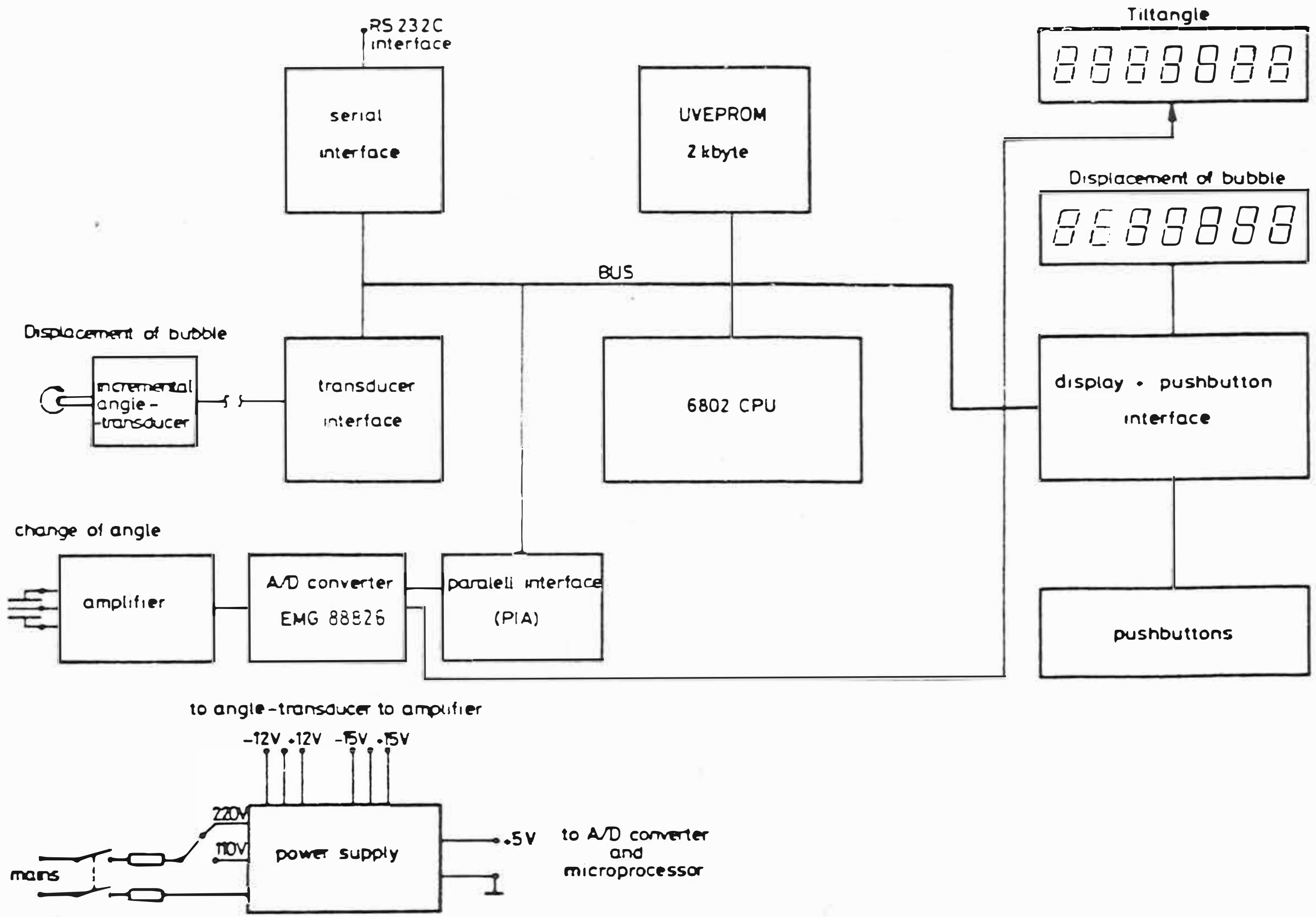


BLOCK DIAGRAM OF THE TILTMETER

*Fig. 4*

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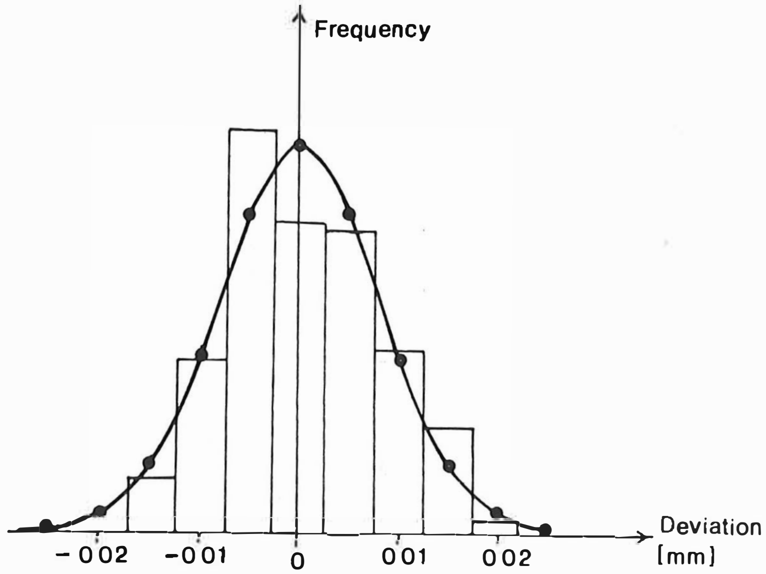


Fig. 5

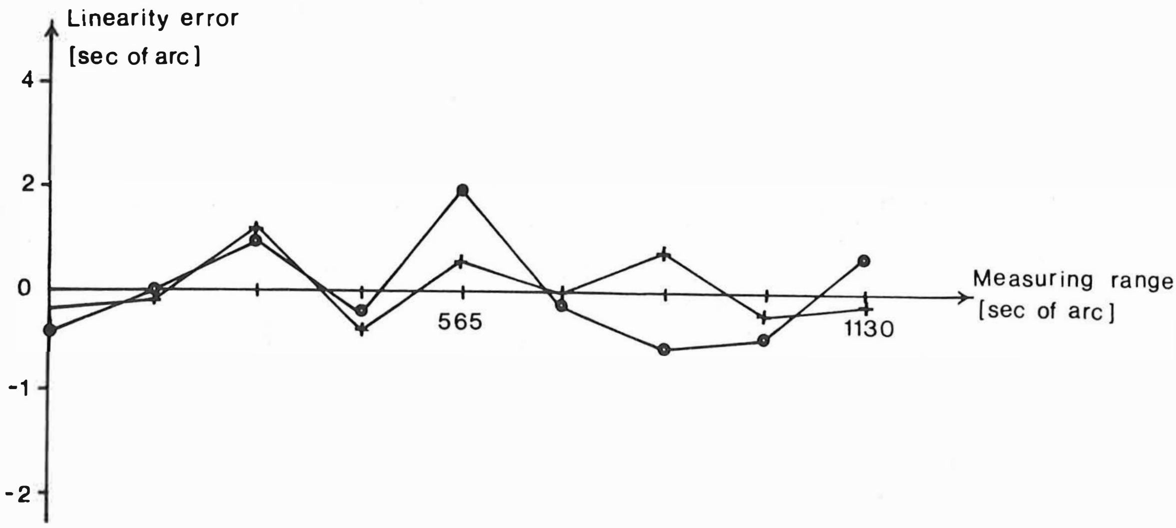


Fig. 6

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# RELATION BETWEEN EARTHQUAKE FOCAL INTENSITY AND RECENT VERTICAL EARTH'S CRUSTAL MOVEMENTS IN THE RILA-RHODOPE SEISMIC REGION

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A b s t r a c t : The stable statistical relation is studied, between the maximum magnitude Y of expected earthquakes with foci in the Earth's crust and the vertical velocity X of recent crustal movements, in the above mentioned mountainous region of Southwestern Bulgaria characterized by a particularly high seismic and tectonic activity. The two-dimensional random variate (X, Y) is presented by its sample $(X_k, Y_k)$, k = 1, 2,..., 60 composed by appropriate smoothed estimates according to data of the most recent investigations. The sampling (joint and respective marginal) distributions of (X, Y) are determined and examined. A number of statistical hypotheses is tested and the respective recent geokinematic and tectonic predestination of the seismic activity in the Rila-Rhodope seismic region is argued in terms of the best fitting, to the empirical data, regression polynomial of Y with respect to X. A comparison between results obtained on the region under examination and corresponding data of earlier studies on the whole country is made.

Р е з ю м е : Исследована устойчивая статистическая связь между максимальной магнитудой У возможных землетрясений с очагами в земной коре и вертикальной скоростью Х современных движений коры в упомянутом районе Юго-западной Болгарии, отличающемся особо высокой сейсмической и тектонической активностью. Двумерная случайная величина /Х, У/ представлена выборкой $/Х_к$, $У_к/$, к = 1, 2,..., 60, составленной из подходящих сглаженных оценок по данным последних исследований. Определены и исследованы эмпирические /совместное и соответствующие одномерные/ распределения /Х, У/. Сделана проверка ряда статистических гипотез и дана количественная вероятностная обосновка конкретной современной геокинематической и тектонический обусловленности сейсмической активности в Рило-Родопском районе с помощью наиболее подходящего /в смысле аппроксимации к эмпирическим данным уравнения регрессии У по отношению к Х. Сделано сравнение полученных результатов с аналогичными данными из более ранних исследований для всей страны.

## 1. Introduction

The Balkan peninsula, in the cental part of which Bulgaria is situated, enters in the Aegean seismic region of the vast, secons by its significance on the planet, Mediterranean-Transasian seismic belt. Even though the strong earthquake frequency of Greece, Turkey, Italy and of some other Mediterranean countries is greater, the seismicity of Bulgaria is considerable: above 600 epicentres are recorded here till now, among which, only dyring the last 80 years - of 13 strong and destructive earthquakes (Григорова и Григоров, 1964); the greater part of its territory falls, according to the most recent complex scientific estimations (e.g. Weltkarte ..., 1978; Reisner et al., 1979; Berz and Smolka, 1983), within this part of the European and Mediterranean region which is marked by the highest (of its expected intensity) seismic hazard. Bulgaria is influenced both by its proper earthquake foci (of an only normal type) and by the Minor-Asian, of the Sea of Marmora, the Aegean, the Adriatic and the Carpathian earthquakes. Its seismicity is connected with two basic positive tectonic structures - the Nort-Bulgarian Swell in Northeastern Bulgaria, to which large and well expressed positive magnetic and gravitational anomalies are refferred to, and the Rhodope massif in the Southwestern Bulgaria, which is marked by the largest and clearly expressed negative gravitational anomalies (Григорова и Григоров , 1964). These structures, as a matter of fact, are elements of the so-called Diagonal Swell - a wave positive tectonic macrostructure of stable Late-Alpine to recent uplift of the Earth's crust during the last 45 million years, along the flanks of which the recorded foci of high-magnitude earthquakes are located (Bončev, 1958, 1982; Бончев, 1971). It could be said that the three basic seismic regions of the country - the Northeastern, this of Sredna Gora Mountain and

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the Rila-Rhodope ones, which are differentiated on the basis of a number of seismologic and tectonic criteria (Григорсва и др., 1980) - have a respective diagonal Northeaster-Southwestern location, too, on its territory. The areas of a stable consedimentational and compensating subsidence - the Lom Depression in Northwestern Bulgaria and the Eastern Rhodope in Southeastern Bulgaria which are characterized by the weakest and of the lowest-amplitude proper seismotectonic potential (Bončev, 1982) -oppose to these seismic regions.

It could be seen that the different parts of the country are not at all equivalent with respect to their seismic activity - both in the common qualitative and in the specifically accepted in the seismic zoning (e. g. Ризниченко , 1979) quantitative sense of this concept. Therefore, the earlier established (Totomanov, 1983, 1984a, 1984b) general statistical interrelation between the seismic activity (resp. hazard) and the recent tectonic movements in Bulgaria will have, inevitably, an averaging sense and significance - the respective parameters of this interrelation, probably, will vary in some quite large intervals: on the one hand - between the marked seismic active diagonal Northeastern-Southwestern positive tectonic structure and the above mentioned opposing to it Northwestern and Southeastern negative structures, and on the other hand - among the indicated seismic regions themselves, within the active diagonal structure.

The present study deals with the Rila-Rhodope seismic region in Southwestern Bulgaria which spreads all over the mountains of Western Rhodope, Rila and Pirin and the mountain massifs in the west of Struma River which region is characterized by a maximum seismic density and activity in the country (Bončev , 1982; Григорсва и др., 1980). According to the above, analogous investigations, both on the other two seismic regions and on the two above mentioned areas of weaker activity in the country, will be expedient.

## 2. Sampling Distribution of Vertical Movement Velocity and Earthquake Intensity

The quantitative distribution of the parameters of the recent Earth's crustal dynamics, including the vertical velocity X of the present-day tectonic movements and the maximum magnitude Y of probable (expected) normal-focus earthquakes, on the Earth surface is a complicated and unknown function of the properties, the structure, the composition and the history of development of the crust. In this respect, when a random hitting onto a given surface element of the territory under examination is treated as an experiment, then both X and Y could be of different values which could not be known in advance. Consequently, in the terms of the theory of probability (e. g. Вентцель, 1964), the pair (X, Y) represents a two-dimensional random variable, which is characterized in this work by the sample $(X_i, Y_i)$, i = 1, 2,..., n. Here $Y_i$ are complex estimates of Y forecasted by means of a computer ( Буна и др.,1982) and $X_i$ are respective locally smoothed estimates of X (Тотомансв и др., 1978; Joo et al., 1980) according to the most recent publications, i is the number in succession of a surface element of dimensions $\Delta\varphi = 10'$ and $\Delta\lambda = 15'$, and n = 60 is the size of the sample.

The joint sampling distribution of (X, Y) in the Rila-Rhodope seismic region is determined on the basis of these data and is presented in Fig. 1, according to which it deviates considerably from the respective distribution for Bulgaria (see Totomanov, 1984b).

The procedure of a study on the statistical relation between two random variables X and Y depends significantly on the type of their joint distribution, and in particular - whether it is normal, or not. With the aim to establish which of these two alternatives is realistic, a number of simple statistical hypotheses is tested: two of them concern the normality of the marginal distributions of X and Y, and other two - the linearity of the respective regressions.



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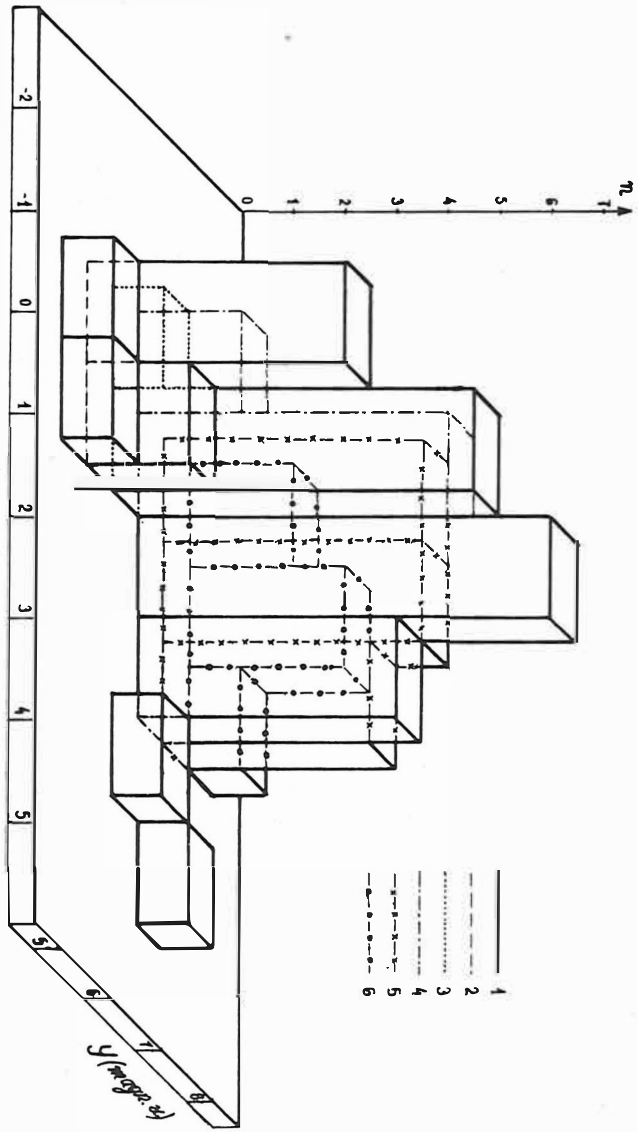


Fig. I. Stereohistogram of the joint sampling distribution of X and Y in the Rila-Rhodope seismic region of Bulgaria. n - sampling frequencies. Cross-section edges of the distribution surface for respective two-dimensional class-intervals: I - visible; invisible /only their front part/: 2 - for $5.5 \le Y < 6.0$, 3 - for $6.0 \le Y < 6.5$, 4 - for $6.5 \le Y < 7.0$, 5 - for $7.0 \le Y < 7.5$, 6 - for $7.5 \le Y < 8.0$.

According to the considerable size of the sample, the method of the straight-lined diagrams (e. g. Aivazian, 1978) is used to check the first two hypotheses. This method is based on the assertion that, for a random variable Z of a normal distribution $N(a_z, \sigma_z)$ with q-fractiles as given by

$$/1/ \quad P(Z < u_q) = \Phi(u_q) = \frac{1}{\sigma_z\sqrt{2\pi}} \int_{-\infty}^{u_q} e^{-(t-a_z)^2/2\sigma_z^2}\, dt = q\,,$$

the system of points $(Z, u_q)$, in a respective rectangular plane co-ordinate system, determine the straight line

$$/2/ \quad (Z - a_z) \,/\, \sigma_z = u_q\,.$$

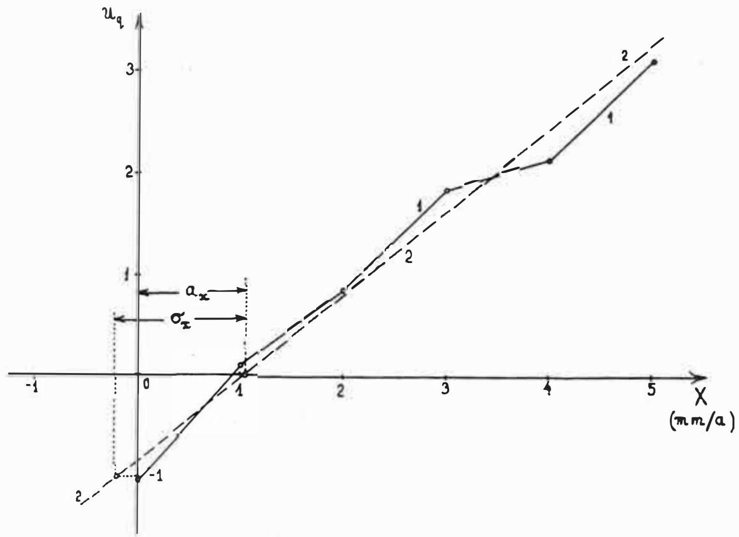


Fig. 2. Test of the normality of the marginal distribution of X: 1 - polygon of the sampling q-fractiles $u_q$, 2 - smoothing straight line and graphical estimation of the parameters $a_x$ = 1.04 and $\sigma_x = \pm\, 1.26$ mm/a of the best fitting normal distribution $N(a_x, \sigma_x)$ of X.

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The results of the computations for the sampling q-fractiles $u_{qi}$ of the marginal distributions of X and Y are represented in Fig. 2 and Fig. 3, respectively, where the determination of the parameters a (mathematical expectation) and $\sigma$ (standard deviation) of the best fitting normal distributions $N(a_x, \sigma_x)$ and $N(a_y, \sigma_y)$ is shown, too.

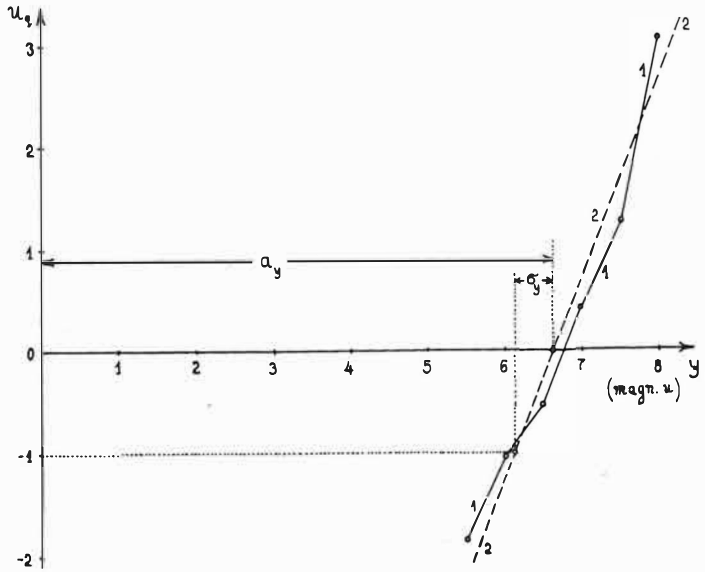


Fig. 3. Test of the normality of the marginal distribution of Y: 1 - polygon of the sampling q-fractiles $u_q$, 2 - smoothing straight line and graphical estimation of the parameters $a_y$ = 6.467 and $\sigma_y$ = ± 0.334 magnitude units of the best fitting normal distribution $N(a_y, \sigma_y)$ of Y.

From these figures a conclusion can be drawn that the integral functions of the two sampling distributions agree with the integral functions of the two respective normal distributions.

The test for the differential functions of these distributions is given in Fig. 4 and Fig. 5 which demonstrate symptoms of bi-modality manifested, too, by the sample for the whole country (Totomanov, 1984b). The data on the type of regression between X and Y are presented in the same figures - it can be distinctly seen that in both cases it is curvilinear. According to these results the hypothesis for a normal two-dimensional distribution of (X, Y) in the Rila-Rhodope seismic region could be rejected.

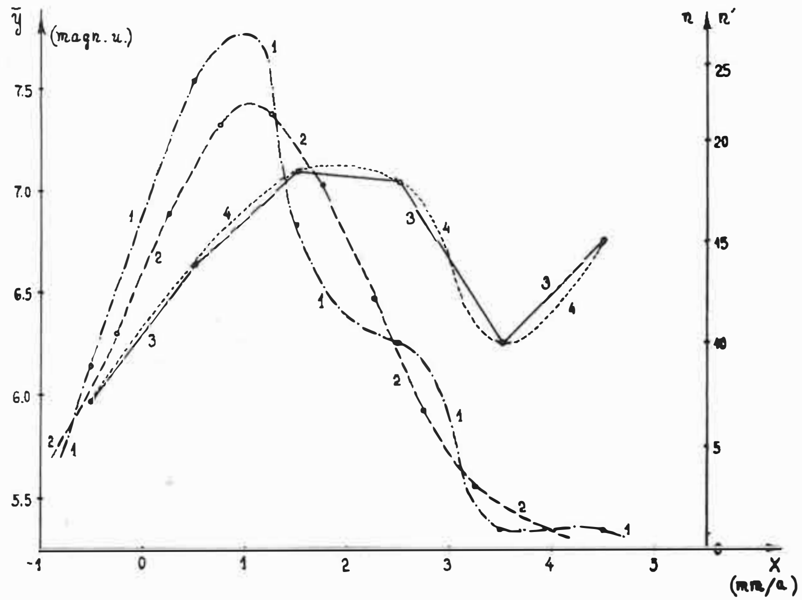


Fig. 4. Frequencies of the distribution of the vertical velocity X for class-intervals $x \pm l_x$ of semi-width $l_x$ = 0.5 mm/a: 1 - sampling curve, 2 - theoretical curve of the normal distribution $N(a_x, \sigma_x)$.

Graph of the regression equation $\bar{y} = \bar{y}$ (X): 3 - sampling polygon, 4 - graphic smooting curve.

It should be noted that the respective hypothesis was earlier rejected, too, for the whole country (Totomanov, 1984a, 1984b).



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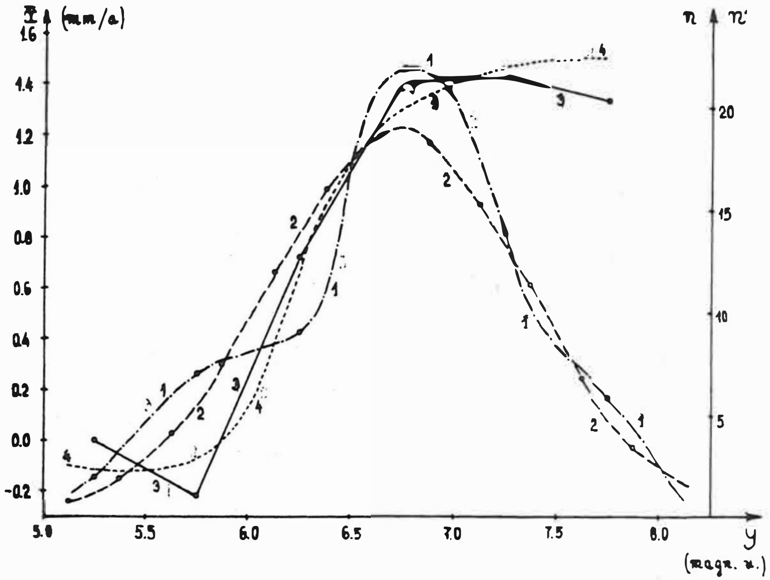


Fig. 5. Frequencies of the distribution of the maximum magnitudes Y for class-intervals $y \pm l_y$ of semi-width $l_y$ = 0.25 magnitude units: 1 - sampling curve, 2 - theoretical curve of the normal distribution $N(a_y, \sigma_y)$.

Graph of the regression equation $\bar{x} = \bar{x}$ (Y): 3 - sampling polygon, 4 - graphic smoothing curve.

### 3. Regression Equation of Magnitudes with Respect to Vertical Velocities

The determination of the regression equation

/3/ $$\bar{y} = \bar{y}\,(X) = \sum_{r=0}^{r=\lambda} a_r X^r$$

is of considerable interest for the seismic zoning; here it is approximated by a power polynomial both the order (the highest degree) $\lambda$ and the coefficients $a_r$ of which being unknown. According to Fig. 4 it could be supposed that $\lambda = 4$ in the Rila-Rhodope seismic region, too, as it was earlier estimated for the whole country (Totomanov, 1983, 1984b).



For a more precise assessment of $\lambda$ in the Rila-Rhodope seismic region, a special study is carried out here: eq. /3/ is approximated at a variable $\lambda$ = 0, 1, 2,..., 5 by the orthogonal polynomial of Tchebicheff

/4/ $$y = \sum_{r=0}^{r=\lambda} k_r \Psi_r (x)\ ;$$

/5/ $$\begin{cases} \Psi_0 (x) = 1, \\ \Psi_1 (x) = x - (m+1)/2 = x - 3.5, \\ \Psi_2 (x) = x^2 - (m+1)x + (m+1)(m+2)/6 = \\ \quad = x^2 - 7x + 9.333\,333, \\ \Psi_3 (x) = x^3 - \frac{3}{2}(m+1)\,x^2 + \frac{1}{10}\left[5(m+1)^2 + (m+1)(m+3)\right] x - (m+1)(m+2)(m+3)/20 = \\ \quad = x^3 - 10.5\,x^2 + 31.7\,x - 25.2, \\ \Psi_4 (x) = x^4 - 2(m+1)\,x^3 + \frac{1}{4}\left[5(m+1)^2 + (m+3)(m+11)/7\right]x^2 - \\ \quad - \frac{m+1}{4}\left[(m+1)^2 + (m+3)(m+11)/7\right] x + (m+1)(m+2)(m+3)(m+4)/70 = \\ \quad = x^4 - 14\,x^3 + 66.714\,285\,x^2 - 124\,x + 72, \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \end{cases}$$

where m = 6 is the number of the class-intervals in the sampling distribution of X and the new variable

/6/ $$x = (X - X_a^{+})/\,C = X + 1.5$$

is introduced by which $X_a^{+} = -1.5$ is the middle of a resp-

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ective, preceding the first real one, class-interval of X and C = 1 is the constant length of the class-intervals of this marginal distribution (e. g. Митропольский , 1971).

It should be noted here, that, in addition to the well known formulae (Андерсон , 1976 - see eqs. /5/ in section No. 3.2.1, by substituting T = m) for $\psi_1(x)$ and $\psi_2(x)$ expressed as functions of m, respective new formulae for $\psi_3(x)$ and $\psi_4(x)$ are deduced and given in the general (first) part of eqs. /5/, the second (specialized) part of which being obtained at the above mentioned value of m for the sample of X under examination.

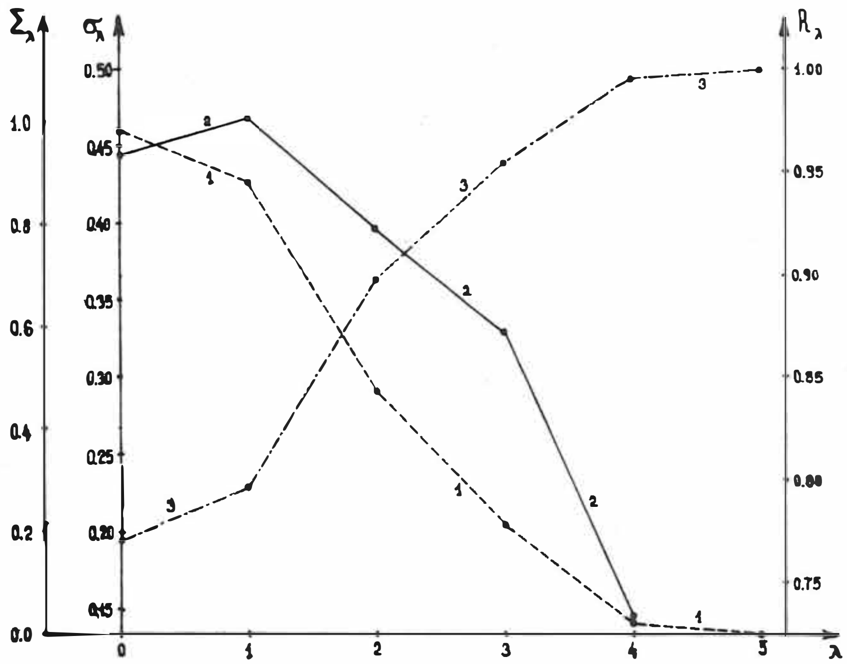


Fig. 6. Dependence of the accuracy of approximation of empiric polygon $\overline{y} = \overline{y}$ (X) on the degree $\lambda$ of the polynomial: 1 - quadratic form $\Sigma_\lambda$, 2 - estimate $\sigma_\lambda$ for the standard deviation, 3 - coefficient $R_\lambda$ of the model determination.

The computations for detemination of the new unknown coefficients $k_r$ in eq. /4/ are carried out by means of statistical tables (e. g. Большев и Смирнов , 1983) as a result of which the following estimates are obtained:

$$/7/ \quad k_0 = 6.626\ 217, \quad k_1 = 0.076\ 323, \quad k_2 = -\ 0.104\ 562, \quad k_3 = 0.062\ 994, \quad k_4 = 0.048\ 665, \quad k_5 = 0.019\ 136.$$

The quadratic form $\Sigma_\lambda$ and the estimates $\sigma_\lambda$ for the standard deviation and $R_\lambda$ for the coefficient of the model determination are obtained for the respective approximations, at $\lambda$ = 0, 1, 2,..., 5, by means of eqs. /5/ - /7/. The results are presented in Fig. 6 which testifies that the most appropriate, according to the three criteria mentioned, order of the regression equation /3/ or /4/ is, once again, $\lambda$ = 4. In this way the earlier established (Totomanov, 1983, 1984b) for the whole country order $\lambda$ = 4 of the regression equation $\overline{y} = \overline{y}$ (X) expressing the quantitative relation between Y and X is also corroborated for the Rila-Rhodope seismic region.

With the help of eqs. /4/ - /7/, at the value $\lambda$ = 4 obtained, the regression equation of Y with respect to X, for the Rila-Rila-Rhodope seismic region, is determined in its common aspect /3/ as follows

$$/8/ \quad \overline{y} = 6.196\ 684 + 0.696\ 008\ X + 0.355\ 208\ X^2 - 0.326\ 326\ X^3 + 0.048\ 665\ X^4$$

where the mean values $\overline{y}$ of Y are obtained in magnitude units when X is introduced in mm/a.

The mean square error $m_{\overline{y}}$ of $\overline{y}$ , as given by eq. /8/, is determined by the following equation

$$/9/ \quad m^2_{\overline{y}} = 0.019\ 750 + 0.014\ 803\ X - 0.028\ 391\ X^2 - 0.047\ 835\ X^3 + 0.108\ 680\ X^4 - 0.076\ 371\ X^5 + 0.025\ 348\ X^6 - 0.004\ 068\ X^7 + 0.000\ 254\ X^8 .$$

The best approximating polynomial /8/ and the respective



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confidence area, at a confidence probability P = 0.683, are presented in Fig. 7 which testifies that the new equation ensures two times higher order of the accuracy of forecasting the maximum earthquake magnitudes Y by means of the vertical velocity X , compared to the accuracy of the respective equation earlier established (Totomanov, 1984a, 1984b) for the whole country.

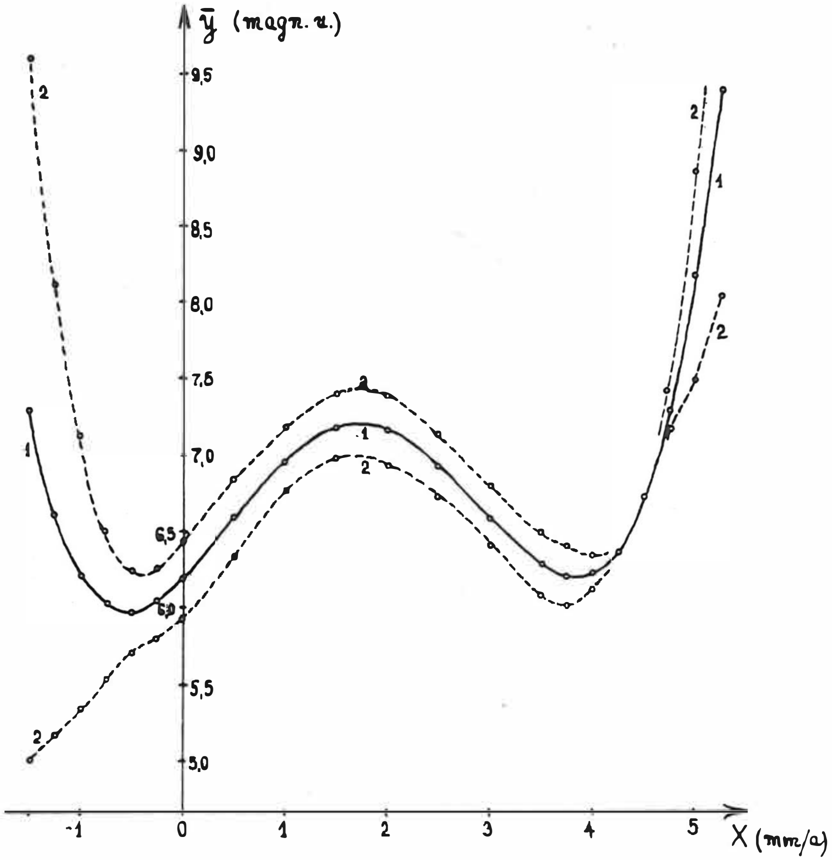


Fig. 7. Regression equation $\bar{y} = \bar{y}$ (X) aimed to forecast the conditional mathematical expectation $\bar{y}$ of Y in the Rila-Rhodope seismic region by means of X: 1 - graph of the best fitting polynomial of order $\lambda = 4$; 2 - limits of the confidence area of $\bar{y}$ , at a confidence probability P = 0.683.

Fig. 6 and Fig. 7 demonstrate that the stable statistical relation between Y and X in the Rila-Rhodope seismic region, being in a general accordance with the earlier established regularities for the whole country (e. g. bi-modality of the marginal distributions, curvilinear type of the regressions, deviation from the two-dimensional normal distribution, order $\lambda = 4$ of the best approximating polynomial of the regression equation of Y with respect to X), has realy its own distinctly expressed individual quantitative features. In this way, specifying the general statistical relation in Bulgaria between the seismic hazard and the recent vertical tectonic movements, for the region under examination, the present study demonstrates at the same time that the parameters of this relation are subjected to a significant space variation. The latter corroborates the above mentioned expediency of future studies on the features of the relation between X and Y in the other two seismic regions of Bulgaria.

The relatively high accuracy of forecasting the maximum magnitude Y by means of the vertical velocity X, according to eqs. /8/ and /9/, demonstrates once again the considerable informativity of the recent tectonic movements when assessing the seismic hazard.

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# Dynamics of the Bohemian Massif

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## A b s t r a c t

The Bohemian Massif is a solid block surrounded by the Alps and Carpathians from south and south-east respectivelly. The main idea of the presented paper is the controlling role of the Alps at the dynamics of the Bohemian Massif. The initial assumption is discussed with respect to the results of new repeated levellings, local horizontal measurements as well as to the disturbance lines determined from sattelite images. In addition the results of local horizontal and vertical remeasurements performed at the test area of Lišov, southern Bohemia, are taken into consideration. The discussion of mentioned data leads to conclusions on the possible role of the Alpine pressure as a driving force in dynamics of the Bohemian Massif.


Looking at the tectonic map of Central Europe, the Bohemian Massif seems to be a stone, standing in a flow of Alps and Carpathians. It can be deduced, that present face and position of the Alps and Carpathian arcs was determined due to the existence of the Bohemian Massif in its position. Obviously, from the other hand, the pressure of Alps and Carpathians affected the solid Bohemian Massif, and was an origin of faults and tectonic movements. Such a way, the tectonics of the Bohemian Massif should be determined by the tectonics of the Alps and Carpathians. Considering the recent crustal movements are the tectonic movements at the present stage of tectonics, all these mutual effects should be reflected in recent dynamics of Central Europe.

As has been stated elsewhere, new first order re - peated levellings were carried at the territory of Czechoslovakia in the period of 1974 to 1979. In addition, the relevellings continue with the some accuracy at the levelling lines of second order. These relevellings will be finished in the years 1985 to 86 and should serve as a base for new, more precise map of vertical crustal movements at whole territory of our republic. Using the first order relevellings, performed up to 1980, the preliminary map of vertical movements of the Bohemian Massif was constructed on request of the Czech geological survey. This map should be consider as a mid-term result to be finished after the finishing of the relevellings at the second order levelling lines. Nevertheless, this first touch with results of new repeated levellings was analysed with re - spect to the previous maps, especially to the map of the year 1971, as well as to the data obtained from the sattelite images.

The results of comparisons of the new map of recent vertical crustal movements with those, based on previous relevelling will be discussed later, after the finishing of the whole work. As concerns the present analyses we can say, that in the map of 1980 are preserved all relative tendencies of movements, given in the map of 1971. Some slight differences can be explained by the various density and quality of the relevellings, used for construction of the map of 1971. In contrary to the previous maps the new map results from consistent comparisons of levellings, performed in 1939 to 1950 and in 1974 to 1980, i.e. both relevellings are similar in accuracy and time interval of performance. It is why this map can be consider as the best representation of the recent vertical movements at the territory of the Bohemian Massif and its contact with the Carpathian arc.

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Summarizing the data on vertical recent movements and those, given by the analyses of sattelite images as well as the information on main tendencies of horizontal deformations determined by the geodetic measurements, we can present the map in Fig. 2. It should be add, that the main axis of deformation at the Czechoslovak territory were determined by our results and the axis shown at the North-western border were determined is known work of H. Thurm. Supposing the main axis of pressure initiating from Alps with approximatively northward direction we can find a good agreement of main lines disturbance with main features of recent movements. The main pressure in distributed through the Bohemian Massif, establishing the arcs in front of its top. The relative subsidences occur in the centre of arcs in contrary to the uplifts at the northern top. In horizontal plane, the axis of deformation determined by H. Thurm are in good agreement with distribution of the initial pressure within the Bohemian Massif to be expected. The main axis of compression at the south-eastern border of the Bohemian-Massif follows the distribution of the main pressure as well, but the effect of the contact with the Carpathians should be taken into consideration here. Last but not least, the mentioned above ideas can be supported by the local studies of both, horizontal and vertical components of movement at the test area of Lišov in southern Bohemia.

The properties of the test area Lišov were described formerly, and the results of repeated horizontal and vertical measurements performed in 1967 to 1981 were analyzed in detail. Using the repeated distance measurements, the main axis of horizontal deformation were determined. More than ten repeated levellings were analyzed by the computation of trends of vertical movements between main bench marks. The test area is situated at the southern end of the fault zone called Blanice furrow. The networks of detail geodetic measurements cross this fault zone and the other of local importance, which is nearly perpendicular to the former. These faults detach morphologically pronounced hills of moldanubicum from the cretaceous sedimentary basin (Fig. 3). The main axis of compression has nearly north-eastern direction which is in good agreement with the direction of supposed pressure of the Alps. The basin relatively subsides according to the moldanubic hills at the north, or the moldanubic hills uplift with respect to the basin. Such a tendency is recorded not only at the north-eastern border but also at single moldanubical blocks sticking out through the sedimentary layers at the western part of basin. On the contrary, the transverse hills of the Blanice furrow direction at the eastern border of the basin tend to the strong subsidence of their single blocks. The prominent subsidence is revealed at the granit block where also the trigonometric station is situated. The deformation results in the shear axis, which follows the direction of Blanica furrow. The origin of these movements can be explained clearly by the predominant effect of the horizontal pressure in front of the Alps.

Obviously, analyzing the dynamics of the Bohemian Massif as a whole we should have in mind its block division. These blocks transfer the main pressure in accordance to their position and shape. But the main features of the disturbance lines with respect to the axis of deformation as well as to the shape of isolines of vertical movements is in good agreement with the initial assumption. From the other hand the situation given in Fig. 2.determine the localities, where additional measurements and analyses are desirable. In addition the control mechanism of the geodynamics should be studied with respect to the neighbouring arc of the Western Carpathians.



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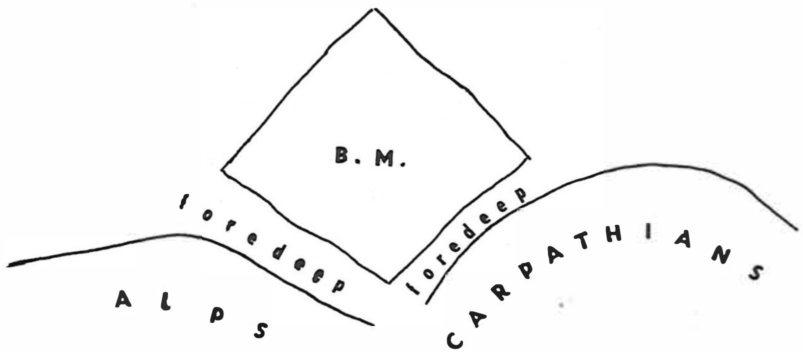


Fig. 1


Fig. 3

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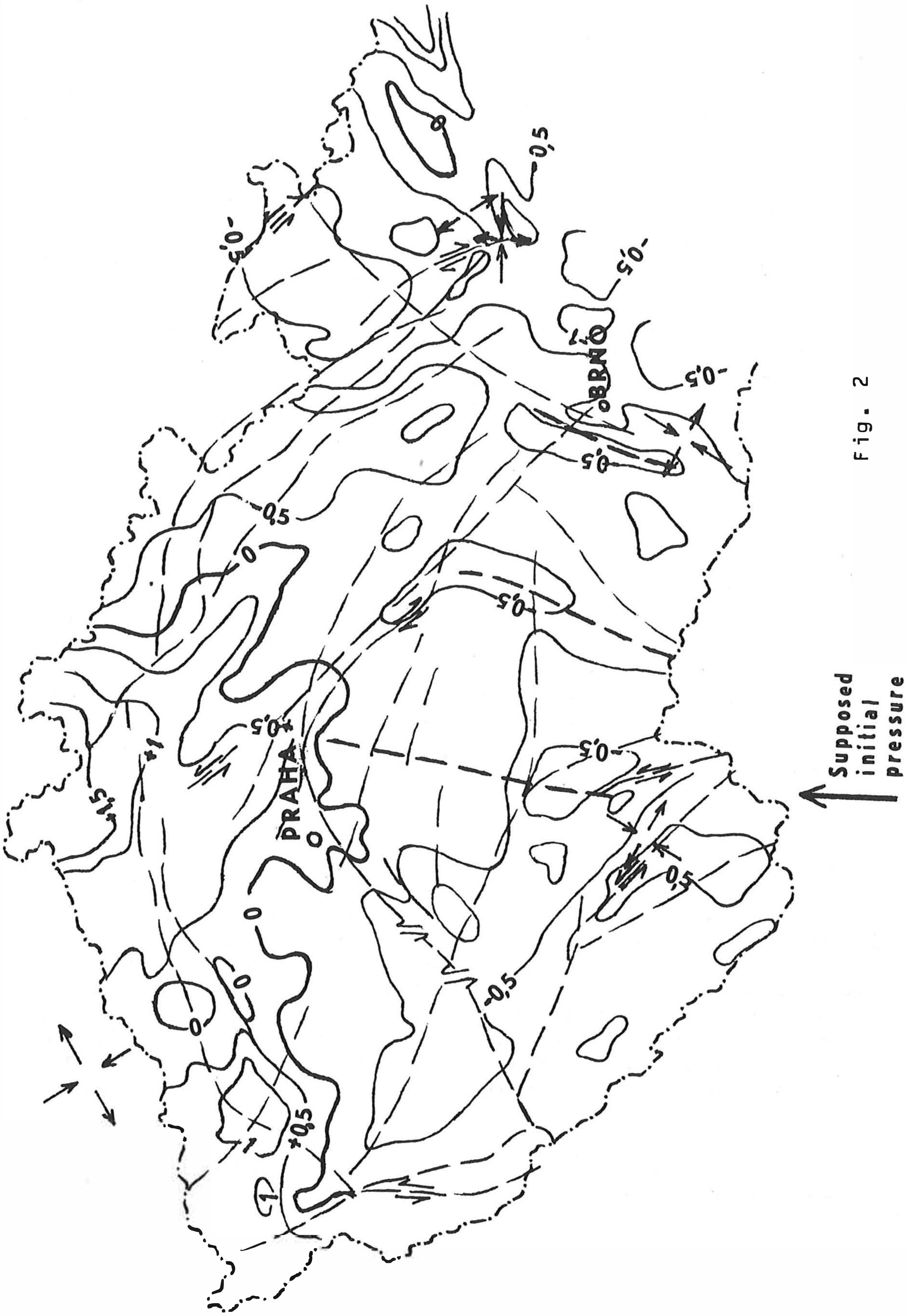


Fig. 2

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# AN OPTIMUM USE OF SEA-LEVEL RECORDINGS

by

H. Weise x)

Summary

A reference niveau is necessary for proof of vertical recent crustal movements. The undisturbed surface of the sea is a suitable reference niveau. It is deduced from continuous sea-level recordings at the adjacent coasts of most countries.

For a significant proof it is necessary to presume

- modern measurement techniques, with adequate resolution in time and area,
- homogeneous data collections for a long time range,
- carefull analysis methods for treatment of measuring data.

Propositions for working modus will be offer ed and in connection with this geo-scientific assertion could be forced up.

Zusammenfassung

Zur Ermittlung von vertikalen Erdkrustenbewegungen bedarf es eines Bezugsniveaus, das durch die ungestörte Meeresoberfläche dargestellt werden kann. Das Bezugsniveau ist aus kontinuierlichen Wasserstandsregistrierungen (Pegel) des angrenzenden Meeres für das jeweilige Land ableitbar.

Ein signifikanter Nachweis von rezenten Krustenbewegungen setzt voraus

- eine moderne Meßtechnik mit angemessener räumlicher und zeitlicher Auflösung,
- ein homogenes Datenmaterial über längere Zeiträume und
- eine sorgfältige mathematische Analyse der Meßdaten.

Es werden Vorschläge für einen Bearbeitungsmodus unterbreitet, der die geowissenschaftliche Aussagekraft der Messungen erhöhen soll.

## 1. Introduction

The forces that act upon the Earth from outside are the same for the mainland, the sea and the atmosphere, but their effect varies with the physical condition concerned: solid, liquid or gaseous. Solid matter will display a much weaker and different response than the liquid medium. A gaseous medium, such as the Earth's atmosphere and its associated properties, is not suited for a significant reflection of the effects brought about by these forces. The surface of the sea, however, has properties which make it very suitable for a demonstration of the cause and the effects of natural excitation mechanisms. It is important to record these effects in quantitative terms

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and assess them from a geophysical angle.

With such an approach in mind, sea water level recordings assume an importance which is much greater than generally believed. Continuously measured, carefully collected and comprehensively analyzed data will probably make it possible to arrive at much more detailed findings of a general geophysical interest than have been made in the past.

However, this paper will deal with these aspects only to the extent that they are directly related to the "recent crustal movements". It should be noted that level-taking alone results in measurements of differences in elevations of land, whereas land elevations proper cannot be derived from them. When absolute information about elevations of land have to be obtained, the level-taking results have to be coupled with the mean sea level recordings.

## 2. Measurement technology

Measurements constitute the basis upon which recent crustal movements can be detected and interpreted. Some remarks should be made with regard to data collection, because all the other stages of data processing depend upon the accuracy of the measurements made.

The instruments which are used for recording the sea level are expected to operate accurately and safely. The term "accurate" is meant to describe a situation where the recording gauges are able to provide a resolution in time and space, which corresponds to the requirements of the objective envisaged. Presently, hourly centimetre readings are considered optimal for the determination of the sea level. The value obtained should not be an instantaneous one, but a mean value computed for observations for a stated period in time.

The recording gauge must be in constant operation and checked at regular intervals, if a safe collection of data is to be ensured. It is important to check whether the reading of the water level is correct in relation to a fixed point of the level (calibration) and whether the fixed point itself is correct in height in relation to a geologically safe and adequately demarcated reference datum.

Whereas major advances were made in the measurement technology for many disciplines of science and technology, this does not apply to water level readings. It should be tried to modify or improve this situation.

## 3. Data collection

Data collection should be modern and unique. The objective should be to collect data in the digital form and store them for electronic data processing. These data (more than others) should be stored in a form which makes them accessible for future generations. The Permanent Service for Mean Sea Level (PSML) constitutes a very

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suitable basis for such a type of data storage. It was introduced internationally in 1976. The water-level data collected should indicate the place, the type and the reference of the values obtained. These include

- name of the gauge station,
- geographic coordinates,
- datum plane in a local reference system,
- data collection frequency,
- type of data obtained (instantaneous, mean or extreme values),
- recording gauge downtime,
- description of the values added.

4. Data analysis

The first useful step in the analysis of the data obtained is to check whether or not they are correct, with the emphasis being placed on finding and removing obvious errors. This can be done by visually comparing the plottings or recording tapes of adjacent gauge stations or by means of correlation calculus. The second step is to decide which of the values are to be further processed: the original values or the mean values of prolonged periods of time.

Where mean values are used, these should largely be freed from random influences, whereas systematic ones should be removed only, if the origin and the periodicity of these disturbing quantities (the effect of the tides, for example) is known and if they are eliminated through averaging.

As far as systematic influences are concerned whose underlying principles are not or insufficiently known, averaging of the set of observations does lead to a smoothing, but it also reduces the disturbing influence so that it is no longer possible to name the individual disturbing quantities.

The sea tides belong to the systematic influences of a known periodicity. Their effect on the sea level depends largely on the location concerned. Whereas the range of short-period tides (periods of up to one day) reaches a value as high as 12 metres on the French Channel coast, it is considerably smaller on the Baltic Sea where it is less than 10 cm. A significant decrease in the tidal range has been proven to exist at the southern coast of the Baltic Sea in West East direction. The determination of the partial tides of a period of up to one day at the gauge stations requires that hourly values have been obtained for a period of somewhat more than one year. As certain properties of the observation location (such as the depth of water and the configuration of the coast) vary, the partial tides derived from the tidal analysis are not constant in size, and it is recommended to repeat the harmonic analysis at intervals of several years.

The half-monthly, monthly, half-yearly and yearly tides belong to the long-period tides, the latitude-dependent effect of which has been assessed theoretically as well as determined by means of measurements. The harmonic constants computed for the data observed in the more distant past are known only for a small number of gauge stations

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located on the coast of the Baltic Sea. This is why the effect of long-period tides on the Baltic Sea can be derived from the values indicated in Table I only in an insufficient manner. What is striking, however, is the fact that significant differences exist between the theoretically determined harmonic constants and those actually derived from the data observed, as can be seen from the amplitude ratio $\frac{a}{\Delta H}$. It can also be seen that the effect of long-period tides is by no means smaller than that of the short-period ones. Sometimes it is even bigger.

Table I Long-period tides according to LISITZIN

| | | | theoretic $\varphi = 55^{\circ}$ | | observed $40^{\circ} < \varphi < 60^{\circ}$ | | |
|---|---|---|---|---|---|---|---|
| Tide | $\omega$ [°/h] | p | $\Delta H$ [mm] | [2] page | a [mm] | [2] page | $\frac{a}{\Delta H}$ |
| Mf | 1,0 | $15^d$ | 14,0 | 45 | 37,7 | 46 | 2,7 |
| $Mf_N$ | 1,0 | | 5,8 | 45 | - | - | - |
| MSf | 1,0 | | 1,2 | 45 | 28,4 | 46 | 23,7 |
| Mm | 0,5 | $30^d$ | 7,4 | 45 | 43,1 | 45 | 5,8 |
| Sm | 0,5 | | 1,5 | 45 | - | - | - |
| SSa | 0,08 | 1/2 a | 6,6 | 41 | 38,0 | 44 | 5,8 |
| Sa | 0,04 | 1 a | 1,0 | 41 | - | - | - |
| $M_N$ | 0,0022 | 18,6a | 5,9 | 39 | 21,4 | 40 | 3,6 |

As can be seen from what has been said above, water-level recordings make it possible to arrive at conclusions about the sea tides, which, in turn, have a bearing on the Earth's tides. High-resolution gravimetric measurements require stepped-up efforts to observe the various disturbing effects which include the effect of the sea tides on the adjacent mainland.

Other periodic phenomena, too, (such as Chandler's effect) can be analyzed, if a sufficient number of data are collected, as have shown the investigations carried through by MAXIMOV [3] into the data collected by the station of Esbjerg in Denmark. Standing at 40 mm, the amplitude found is about six times as high as has theoretically been assumed (Fig. 1). The ratio between the theoretical amplitude and the observed one is estimated to be as high as 1:7 for the Baltic Sea. JESSEN's [4] computation of the duration of Chandler's period was fairly accurate, as he found it to be ± 1.4 d (p = 434.6 d) [2, page 56].

According to LISITZIN [2], Chandler's effect is an interesting problem which is worth studying in more detail. It seems as if this effect is stronger in seas of the landlocked-basin type than in oceans. This would be one of the reasons why the Baltic Sea is a particularly well-suited object for investigations into Chandler's period.

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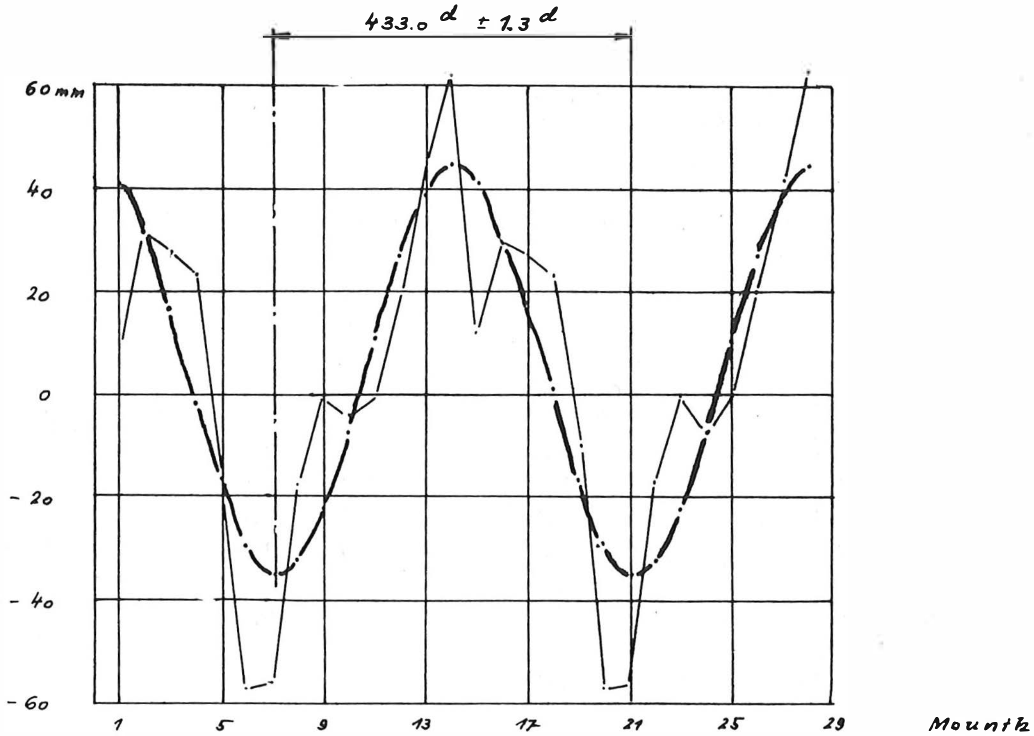


Fig. 1 Effect of Chandler's motion upon the sea level according [3]

As far back as in 1959, HAUBRICH and MUNCK [5] carried out a spectrum analysis on a large number of data observed at 11 different places of the Earth. They found a marked peak of 0.84 cycles per year (CPY), which corresponds to the 14-monthly Chandler's period. They found also that the stations of Świnoujście (Baltic Sea) and Marseille (Mediterranean) - i.e. two stations located on the shores of almost completely landlocked seas - had particularly high peaks. What is more, the mean amplitudes measured at all 11 stations were twice as high as would have been expected on the basis of the tide theory.

In addition to the periodic phenomena, there are other disturbing factors whose effect on the water level is rather strong. These are meteorological and hydrological parameters whose data are incomparably more difficult to collect than the other data, because for them no generally valid theory has been advanced as yet.

The possibilities tried out in an effort to eliminate the wind, which exerts the most disturbing effect on the sea surface, have mainly rested on statistical investigations and have proven their worth, when certain constraints are imposed. These constraints include

a) the duration of the wind's effect;
b) the area affected by the wind's effect;

DOI: https://doi.org/10.2312/zipe.1985.081.03

c) wind velocity, and
d) predominant wind directions at the gauge station concerned.

Hydrologists and oceanologists use such statistical procedures for water-stage forecasts in abnormal weather conditions. In such cases, the constraints are present, sometimes assuming extreme proportions.

However, such statistical procedures cannot be used in non-extreme weather conditions. Another method is used which is directed at exploring the inherent mechanism of meteorological and oceanographic influences and approximating them in mathematical form.

For several decades now, dynamic oceanography has dealt with the water-level changes brought about through the thrust of the wind, with the aim being to make reliable forecasts possible. The mathematical models rest upon the hydrodynamic state-variable equations which include hydrological parameters (depth of water, density of water, friction coefficients at the sea bottom and the water surface, water level and sea current) a meteorological parameter (air pressure) and geodetic parameters (the radius of the Earth, the Earth's rotation and the observational place). Naturally, mathematical models designed to describe the sea surface by means of an undisturbed water level contain some specific information about the place for which the water-stage forecast has to be made.

For the area of the Baltic Sea, some remarkable results have been presented by HÄKKINEN [6]. He used a HANSEN-type one-layer mathematical model and tested it for two prolonged periods each lasting one month. The weather conditions differed largely in the two periods: stormy conditions prevailed in the first period in December involving gauge variations in the metre range (Fig. 2), whereas calm conditions prevailed in the second period in September with only one storm of two to three days duration (Fig. 3). This mathematical model was then used to forecast water-level changes at 11 stations (seven in Finland, four in Sweden). There are at least three points which are very remarkable about the results achieved.

1) About 80 per cent of the water-level changes were forecast correctly.
2) An astonishingly good approximation was reached regarding the water-level-change forecast in terms of time (phase dependence).
3) The degree of correspondence between the forecast level and the actual level recorded varies from region to region. The model simulates the water-level changes in the Gulf of Finland better than those in the Gulf of Bothnia.

The question that arises out of this water-level forecasting situation is:

- how much easier in terms of the approach,
- and how much safer in terms of the findings would be a method which, instead of being used for forecasts, would be used to reconstruct the effect upon the water level from the known meteorological and hydrological data?

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The goal of such a project would be largely to eliminate the disturbing effects upon the sea surface. This would result in improved input data; and even shorter water-level time series would be sufficient for calculations of the trend of shifts in the sea and land levels. This would be a prospective approach which is worth contemplating and discussing.

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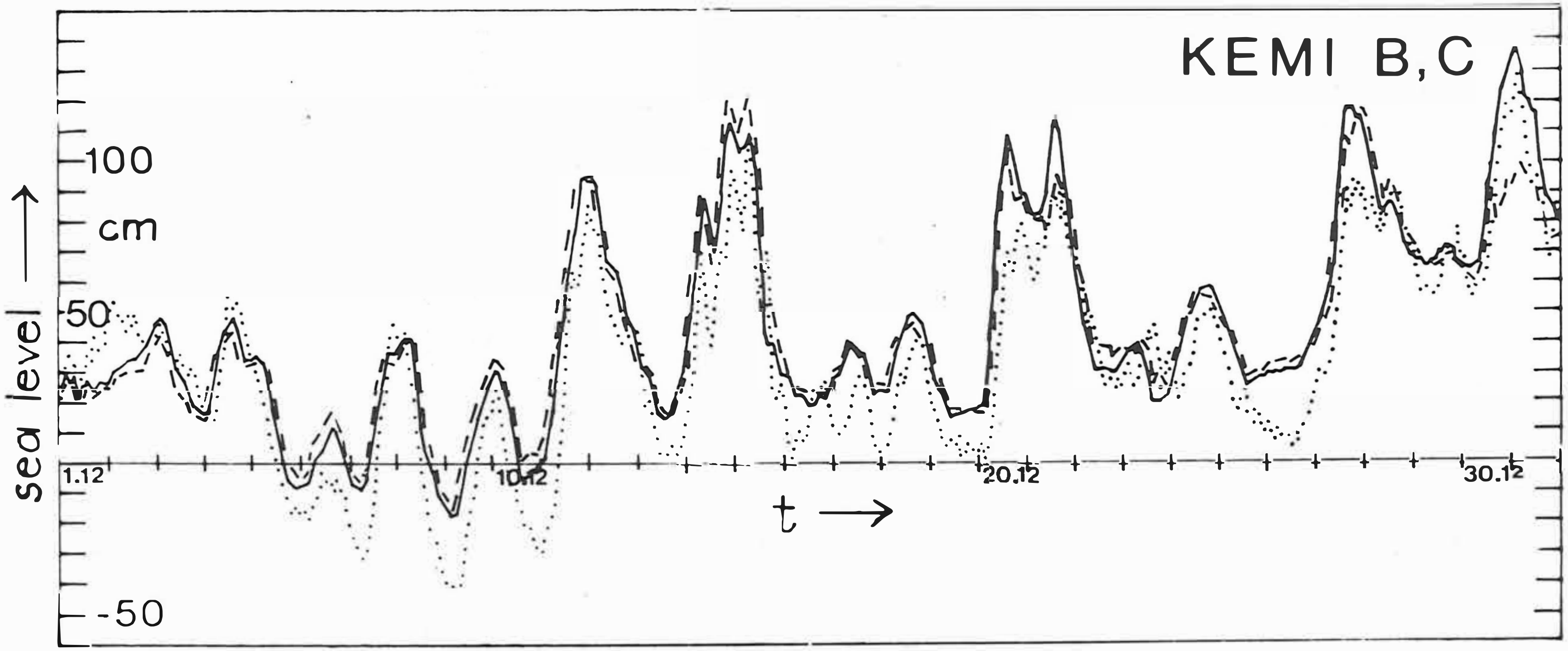


Fig. 2 Computed water levels, stormy conditions [6]
—Model B, ---Model C, ·····observed



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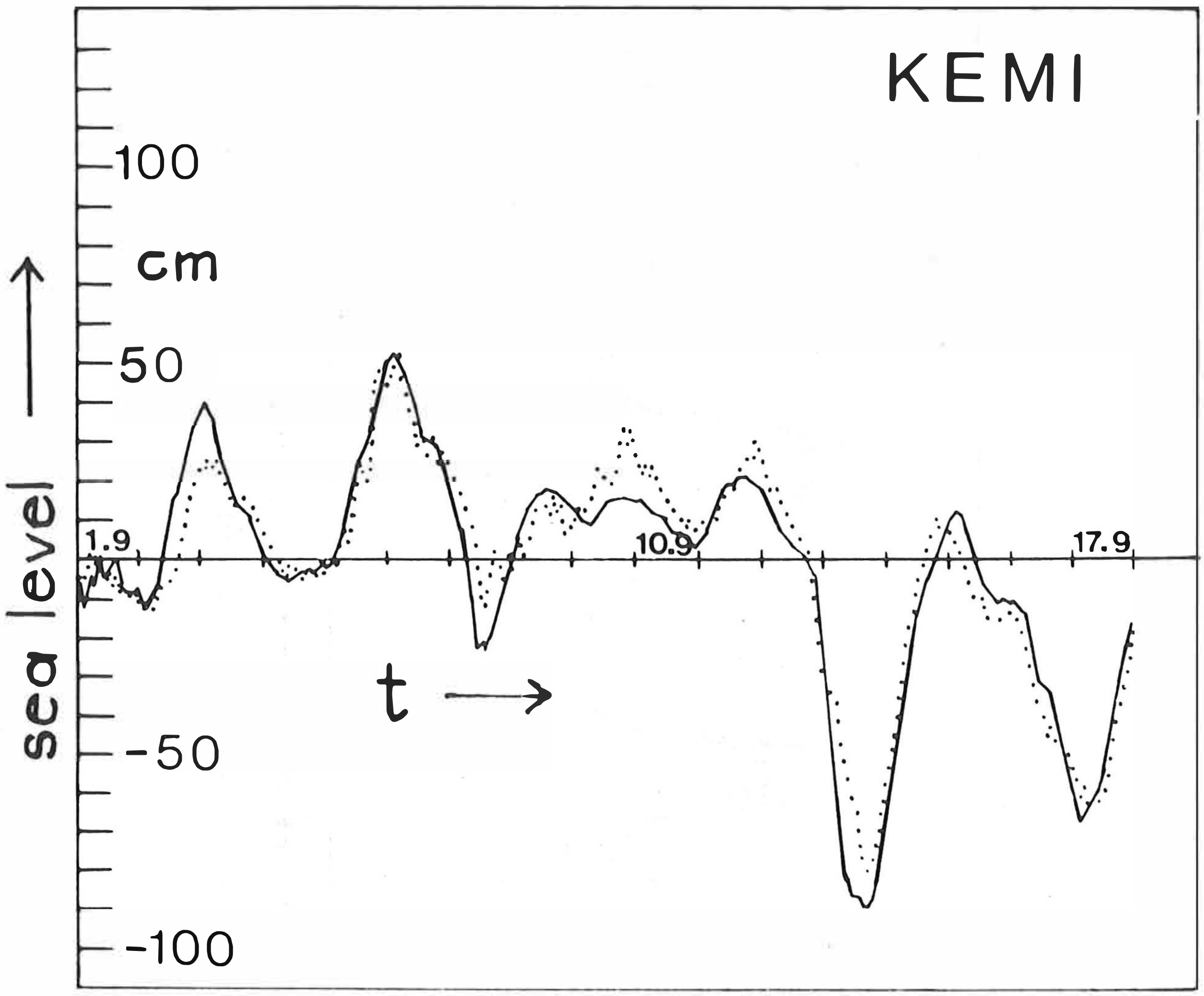


Fig. 3 Computed water levels, calm conditions [6]
—— Model, ····· observed

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