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MEMORANDUM FOR: Philip S. Justus, Section Leader
Geology/Geophysics Section
Geotechnical Branch
Division of Waste Management

FROM: Richard R. Lee
Geology/Geophysics Section
Geotechnical Branch
Division of Waste Management

SUBJECT: TRIP REPORT - AMERICAN GEOPHYSICAL UNION CHAPMAN CONFERENCE, HARPERS FERRY, WEST VIRGINIA, OCTOBER 22-26, 1984.

On October 24-26 I attended the American Geophysical Union Chapman Conference entitled Vertical Crustal Motion: Measurement and Modeling. The four ½-day sessions I attended consisted of presentations on analyses of vertical crustal motion and new technologies for measuring that motion. Wednesday's presentations were devoted to anaylses of geodetic leveling and gravimetric surveys with emphasis on the modeling potential of the results. Thursday, Satellite Laser Ranging (SLR), Very-Long-Baseline Interferometry (VLBI), and the overall Global Positioning System (GPS) were the topics of presentations.

The major conclusion reached by the conferees was that although very precise measurements of vertical crustal motion are obtainable from laser technology and our emphasis is to improve that precision, we must not abandon the traditional techniques by which all of the historical data has been obtained.

Enclosed is a portion of the meeting abstracts which are considered most relevent to waste management.

/S/

Richard R. Lee
Geology/Geophysics Section
Geotechnical Branch
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Enclosure:
As stated

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Propagation and decay of vertical deformation waves

H.J. MELOSH (Lunar and Planetary Laboratory and Department of Geosciences, University of Arizona, Tucson, AZ 85721).

At first, the earth responds to a suddenly imposed vertical load, such as might be produced by an earthquake or a rapidly filled reservoir, as a thick, elastic shell. Deviatoric stresses generated by the load then relax in the asthenosphere. Long after the load was applied, the surface deformation is given by thin-plate theory. During intermediate times, however, asthenosphere material moves horizontally and vertically from beneath the load, producing time-dependent warping of the surface. Such warping expands the area of initial surface deflection and may allow earthquakes to excite the Chandler wobble if it propagates fast enough.

Finite-element modeling has exhibited this behavior in a number of complex models. The work presented here describes an analytic model similar in concept to Elsasser's stress propagation model, but dealing instead with the vertical deformation of a thin, elastic plate over a (not necessarily thin) asthenosphere. A Newtonian version of the model reduces to the diffusion equation with diffusivity $\rho g h^3/12\eta$ in the thin-asthenosphere limit. Both gravity and flexural modes of propagation can occur, although gravity usually dominates. Non-newtonian extensions for a thin asthenosphere indicate that the vertical warping propagates rapidly away from its source when mean deviatoric stress are high, but slowly when they are low.

This method of analysis, although approximate, gives insight into the nature and causes of time-dependent vertical motions following sudden loading events. It is also applicable to the analysis of tectonic deformation in the presence of a lower crustal asthenosphere. Preliminary computations suggest that plausible non-Newtonian constitutive relations can permit large earthquakes to excite the Chandler wobble.

Modeling Stress and Vertical Motion from Horizontal Density Variations in the Lithosphere

RANDALL M. RICHARDSON (Dept. of Geosciences, University of Arizona, AZ 85721)

Horizontal density variations within the lithosphere may play a dominant role in driving and deforming the lithosphere. The evolution of oceanic lithosphere, giving rise to a ridge push force, is perhaps the best studied case. A horizontal force, proportional to the density moment, arises because the density variation occurs on a horizontal wavelength that is long compared to plate thickness.

New elastic and viscous 2-d finite element models test the roles of rheology and horizontal wavelength on horizontal forces and vertical uplift. Modeled wavelengths cover the range from relatively local phenomena such as the Basin and Range/Colorado Plateau transition through features such as continental shelves up to the mid ocean ridges. A grid with 240 elements in twelve columns extends to a depth of 100 km. Each column has the same total weight, but the density distribution, and hence the density moment, may vary between columns. In most elastic models, the load associated with density variations is supported by shear within the columns of anomalous density. Only minimal horizontal stresses exist in adjacent columns. For most viscous models, however, substantial horizontal stresses exist in adjacent columns, approaching the expected relationship between density moment and stress for long wavelengths.

The predicted vertical uplift rates are linear in the assumed viscosity of 10**23 Pa s for the plate, and are strongly dependent on the horizontal wavelength of the problem. Preliminary results indicate that uplift rates due to horizontal density variations within the North American plate are on the order of 1 mm/yr.

Finite Element Models of Crustal Thickening Due to Continental Collisions

S.C. COHEN (Geodynamics Branch, Goddard Space Flight Center, Greenbelt, MD 20771)
R.C. MORGAN (Business and Technological Systems, Inc., Seabrook, MD 20706)

A finite element implementation of the thin viscous sheet model of England and McKenzie has been used to investigate crustal thickening due to continental collisions. The major parameters affecting the temporal and spatial pattern of thickening and deformation of the crust are the geometry and velocity of the colliding plates, the stress and velocity constraints at various boundaries, and the rheology and densities of crustal and upper mantle rock. In the present analysis we use a linear viscous rheology to model the lithosphere but vary such parameters as viscosity, crustal and mantle densities, initial crustal thickness, sheet dimensions, collision zone length, and boundary conditions to determine the sensitivity of the crustal thickening to these parameters. We find, for example, that boundary conditions which allow for lateral extrusion of crustal material out the sides of the sheet produce significantly different thickening patterns than those which suppress extrusion. The degree to which the models differ depends on the length of the collision zone and the size of the sheet. Our analysis confirms previous findings that viscosity plays only a secondary role in determining the intrasheet velocities and crustal thickening in a laterally homogeneous layer. Horizontal motion is unaffected by the time since initial plate contact but crustal thickness depends strongly on the history of the plate movement.

Modeling the Lithospheric Stresses and the Vertical Crustal Movements in the Southeastern U.S.

JEAN-CLAUDE MARESCHAL (School of Geophysical Sciences, Georgia Institute of Technology, Atlanta, GA 30332)

Analytical and numerical methods have been used to predict the pattern of stress and crustal movements caused by the topography and by density heterogeneities in the lithosphere.

The stresses are determined by analytical methods for a two-dimensional model of the lithosphere consisting of a horizontally layered elastic slab overlying an inviscid fluid. The topography and the variations in crustal thickness are introduced as boundary conditions. The magnitude and the pattern of stress computed for a lithospheric model of the Appalachians are compatible with the observed seismicity. The vertical crustal movements were determined for a model in which the lower part of the lithosphere is viscoelastic. For effective viscosity of the order of 10^{25} Pa.s, the predicted movements are too slow to account for observations which are probably affected by effects on a shorter time scale (e.g., post glacial rebound).

A finite element model has also been investigated to determine the rate of deformation for models of the lithosphere with more complex rheologies or geometries. The observed strain patterns are not readily accounted for by the present topography and lithospheric density heterogeneities, when the rheological parameters are kept within the accepted range. A resolution of this conflict without introducing plate stresses is being attempted by introducing the history of erosion and sediment deposition into the models and by comparing the predictions with long-term trends of vertical deformation.

Wednesday AM
Session V
Analysis of Vertical Motions

① Contemporary Vertical Motions of Plate Interiors

Larry D. Brown (Department of Geological Sciences, Cornell University, Ithaca, N.Y. 14853)

Intraplate tectonics include some of geology's least understood phenomena, and contemporary vertical motions are a case in point. Observed by a variety of means, with geodetic leveling the most commonly used, motions within plate interiors have been ascribed to a variety of processes, including seismogenic strain accumulation, magma inflation, and redistribution of ice, water and sediment loads, not to mention systematic measurement error. In tectonically "active" intraplate areas such as the intermontane western U.S., observed vertical motions are often credibly ascribed to the distributed effects (e.g. fault slip in central Nevada) of the not-so-distant plate boundary, or to incipient plate boundary formation (e.g. magma uplift in the Rio Grande rift). The broad, subtle ups and downs of the nominally "stable" cratonic interior are more problematic. The prominent exception to ambiguity is vertical motion in areas such as Fennoscandia which are rebounding following the geologically recent removal of ice loads. Yet, geodetic observations outside recently de-glaciated regions, if taken at face value, suggest similar rates of vertical motion (up to cms/year). These rates contrast with much lower average values inferred from the geologic record. That the geodetic measurements are sometimes inconsistent both internally and with respect to independent estimates (e.g. sea level monitoring) has greatly undermined the credibility of such motions in the past. However, new corrections, computerized databases, and new techniques such as GPS promise more effective means of discerning motion from systematic error. Although new geodetic techniques like GPS are a major leap foward, it is important that the irreplaceable perspective represented by historical leveling be preserved, corrected and exploited. For some time into the future, crustal motion monitoring networks will by necessity be a hybrid of new and old.

Vertical Tectonics in the Charleston, S.C. Area

PRADEEP TALWANI
C.M. POLEY (both at Geology Dept., Univ. of South Carolina, Columbia, S.C. 29208)

In search for a structural cause of the Charleston earthquake, the shallow 4-7 km deep, NW trending, Ashley River fault (ARF) was defined by hypocentral locations of recent seismicity. Its location is also indicated on available potential field, geomorphic, and stratigraphic data. There is disagreement in the inferred sense of movement on this feature. The fault plane solutions and geomorphic data suggest that the SW side of ARF has been undergoing uplift whereas stratigraphic data suggest that the SW side was downthrown in the Tertiary period.

We examined unadjusted first order releveling data for evidence of vertical movement in the Charleston area. The data were examined for systematic errors and for the effects of water withdrawal. The resulting anomalies appear to be tectonic in origin. On both the NS line between Lane and Charleston (surveyed in 1961 and 1974) and the EW line between Yemassee and Charleston (1960 and 1979) there is evidence of subsidence, which increases to about 5 mm/yr towards the coast. Due to small topographic relief (< 25 m) no systematic corrections were applied. In a block lying between Ashley and Edisto rivers there is a relative uplift of about 2-3 mm/yr. This sense of motion, uplift in a block to the SW of ARF is consistent with that inferred from seismicity, but opposite to that indicated by Tertiary stratigraphy. Dislocation modeling of the observed elevation changes also supports reverse faulting on the ARF.

Modern Uparching of the Gulf Coastal Plain

JIM
J. NI (New Mexico State University)
G. JURKOWSKI (his work)
L. BROWN (Both at Department of Geological Sciences, Cornell University, Ithaca, NY 14853)

A broad doming of the Gulf Coastal Plain between Jackson, Mississippi, and New Orleans, Louisiana, is indicated by leveling surveys carried out in 1934, 1964, and 1969. The progressive arching over a distance of 3.4 ± .5 mm/yr relative to Jackson. Additional leveling of movement could be elongate, with its major axis parallel to the coast. The observed uplift is consistent, at least in sign, with longer term trends indicated by deformed terraces in Mississippi and Louisiana. Oil, gas, and water withdrawal mechanisms as well as systematic leveling errors appear inadequate to explain the wavelength and magnitude of the observed elevation changes. The pattern of uplift resembles that which might be expected from flexure due to sedimentary loading at the mouth of the Mississippi delta. Simple models of flexure of a thin elastic plate overlying a viscous half-space due to sediment loading during the Holocene do predict rates similar to those evidenced by leveling, if relatively low mantle viscosities (~3. x 10^{20} poise) are used. These observations may represent the first in situ measurements of ongoing dynamic flexure at a passive continental margin.

(5) Historical Faulting in the Houston, Texas, Area

T. L. HOLZER (USGS, Menlo Park, CA 94025)

More than 86 faults with an aggregate scarp length of 240 km have offset the land surface in the Houston, Texas, metropolitan area since the 1920's. The affected region, part of the Texas Gulf Coast, is underlain by a complexly faulted, thick sequence of late Mesozoic and Cenozoic miogeosynclinal sediments. Historical offset, which is aseismic, appears to be on preexisting normal faults, many of which have been documented to have long geologic histories of prior offset. The average annual historical rate of vertical offset is about 10 mm/yr. Fault activity temporally and areally coincides with land subsidence principally caused by ground-water withdrawal. Subsidence affects an area greater than 12,200 km^2 and locally exceeds 2.7 m. Ground-water withdrawal, petroleum withdrawal from more than 100 oil and gas fields, and geologic processes have all been considered as potential causes of the historical offset.

Comparison of repeated geodetic measurements of fault offset with fluctuations of the potentiometric surface in the underlying aquifer system suggests that the principal cause of historical fault offset is ground-water withdrawal. Fault displacements correlated closely with man-induced fluctuations of the potentiometric surface; faulting ceased or slowed during periods of partial water-level recovery. In addition, vertical deformation fields near faults were similar to that predicted by elastic dislocation models for normal faulting within the aquifer system. The land surface tilted above both the footwall and hanging wall blocks during faulting to distances as far as 500 m from the scarp. Special sleeved, class A marks were required for the investigation to avoid shrink-swell effects of expansive soils that have caused benchmark instability in parts of the Texas Gulf Coast.

Vertical ground movement associated with volcanism in Hawaii

JOHN J. DVORAK and ARNOLD T. OKAMURA (U.S. Geological Survey, Hawaiian Volcano Observatory, Hawaii Volcanoes National Park, Hawaii 96718)

Repeated level surveys in Hawaii are used to monitor ground movement associated with active volcanism. In the summit regions of the two most active Hawaiian volcanoes, Kilauea and Mauna Loa, vertical changes of 0.5 m are recorded over periods of several years. These changes are related to temporary magma storage in reservoirs 2 to 4 km beneath the surface. Some summit stored magma migrates horizontally into radial rift zones. Level surveys along the rift zones indicate that magma, emplaced as vertical dikes, may reach within 500 m of the surface without erupting.

The accumulation of magma in the summit region and rift zones builds up compressive strain along the flanks of the volcano. The compressive strain is partially released by strike-slip earthquakes that occur between Kilauea and Mauna Loa (e.g., 6.6 M, 16 Nov 1983) and by horizontal, seaward faulting along the coast (e.g., 7.2 M, 29 Nov 1975). Level surveys conducted along the flanks of the volcano are used to estimate the extent of subsurface rupture related to these earthquakes.

Seismic Travel-time Changes without Vetical Movement: an Indication of Aligned Cracks in the Earth's Crust?

R. Kirsch, A. Lambert, G. Buchbinder (Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, Ont. K1A 0Y3)

Since 1974 seismic travel-times and crustal uplift have been measured in the tectonically active Charlevoix region of Quebec, Canada. A significant drop in seismic travel-times was recorded between 1979 and 1980, probably related to an M = 5.0 earthquake in the vicinity. Repeated geodetic levelling and gravity surveys restrict vertical movement to less than 2 cm during this period. The travel-time drop can be explained by the transition from an isotropic to an anisotropic distribution of cracks in crustal rock under the influence of tectonic stress. However, to model the observed travel-time changes a crack-density of .03 for the isotropic and of .06 for the anisotropic state is required. For an assumed crack aspect-ratio of 10^{-3} the calculated increase in crack volume leads to an uplift of about 50cm for a spherically shaped dilatant zone. An attempt is made to explain the discrepancy between the calculated results and the observations by a special uplift pattern due to the opening of aligned cracks. A model simulating the opening of cracks by nuclei of strain and calculating the uplift by means of the corresponding Galerkin-vectors leads, for the case of vertical cracks, to nodal points of uplift near the edge of the dilatant zone.

Vertical Uplift, Mantle Convection, and Dynamic Isostatic Equilibrium: The Case of Fennoscandia

A.J. ANDERSON (Inst. of Geophysics, University of Uppsala, Hällby, S-75590 Uppsala, Sweden)

Dynamical isostatic equilibrium (DIE) of the earth's crust implies the occurrence of large scale uplift and subsidence driven by time dependent horizontal temperature gradients in the upper mantle which are caused by changing patterns in convection.

A DIE model is constructed showing that the present negative topographic height anomaly of the thick Fennoscandian crust is largely a consequence of down-warping isotherms beneath the lithosphere. Vertically-stratified isotherm models, for example, require that the near 60 km thick crust would have to rise on the order of 1 km in order to retain isostatic equilibrium with the surrounding oceanic crust. This is an order of magnitude larger than the estimated remaining glacial rebound for Fennoscandia.

In earlier studies models relating crustal structure to the geoid in Fennoscandia have been produced. These models, which are based upon physically reasonable density variations for the lower lithosphere, imply a depth of compensation for the Fennoscandian crust of between 200-600 km. They imply the existence of horizontally stratified thermal gradients in the mantle down warping between suboceanic and subshield areas with larger gradients forming beneath the shield area. This implies a colder, denser material in the upper mantle beneath the Fennoscandian shield.

Our results are in agreement with numerical models of mantle convection and indicate that the present negative topographic height anomaly for the shield region is evidence of downgoing convective material in the upper mantle.

Uplift and Glacial Isostasy in NW Europe

Nils-Axel MÖRNER (Geol. Inst., Stockholm Univ., S-10691 Stockholm, Sweden)
(Sponsor: W.E. Strange)

Fennoscandia is the classical area for glacial isostasy. New data have shown that the process of uplift is much more complicated than a simple exponential relaxation process (GeoJournal 3:287-318, 1979; Earth Rheology, Isostasy and Eustasy, Wiley 1980, Tectonophysics 71:241-251, 1981)

An uplift has been going on for the last 13,000 years. The geometry of the uplift is an elliptic cone surrounded by a subsidence trough. The maximum uplift amounts 850 m and the maximum subsidence 170 m. The mass in the uplift cone and in the subsidence trough is as 1:1 indicating horizontal subcrustal motions in a low-viscosity "channel", i.e. the asthenosphere. This horizontal transfer of mass began 13,000 BP and ended in mid-Holocene time.

The mode and rate of uplift are clearly divided into two parts; one exponentially decaying uplift (dying out with time and distance from the periphery) and one linear uplift that has remained constant, at least, for the last 8000 years and which is responsible for the present uplift. The exponential uplift factor is of a typical glacial isostatic origin. The corresponding subcrustal viscosity is calculated at 1.5-7 x 10^{20} Poise. The linear uplift factor has an uncertain origin. The corresponding viscosity is calculated at 2-5 x 10^{22} Poise.

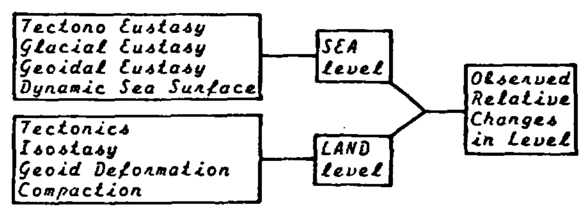
There seems to be a close relation between the crustal thickness and geoid heights over the North Atlantic and Fennoscandia. This concurs with the idea of little or no "remaining uplift" from the glacial isostatic process.

The period of most intensive glacial isostatic uplift has been found also to be characterized by intensive seismic and neotectonic activities (Geology 6: 41-45, 1978).

Vertical Crustal Movements: Multiple Origin

Nils-Axel MÖRNER (Geol. Inst., Stockholm Univ., S-10691 Stockholm, Sweden)
(Sponsor: W.E. Strange)

Vertical Crustal Motions can only be measured with respect to a datum level or a reference level. The more we learn about crustal movements and sea level changes, the more obvious it becomes that our reference levels are also undergoing deformations with time. This is true not only for the sea level zero-points and the levelling zero-points, but also for the gravitational zero level. The deformation of the oceanic (sea) level and the crustal level is controlled by several different variables:



The noval factor is that the geoid level (the oceanic as well as the continental) seems to undergo "constant" and "rapid" changes. This is primarily indicated by paleo-sea-level data, but also by instrumental records. "Rapid" geoid deformations with time are consitent with a "high-dynamic" Earth.

References: (1) J. Geol. 84:123-151, 1976; (2) "Earth Rheology, Isostasy and Eustasy", Wiley 1980; (3) "Mega-Geomorphology", p. 73-91, Oxford Univ. Press 1983; (4) Litoralia 1:1, 1984; (5) "Climatic Changes on a Yearly to Millennial Basis", p. 483-507, Reidel 1984; (6) Marine Geophys. Res., in press, Reidel 1984; (7) Bull. INQUA Neotectonics Comm. v. 1-7, 1978-1984.

Wednesday PM
Session VI

Gravity Determinations of Vertical Motions

DETERMINATION OF VERTICAL CRUSTAL MOTION FROM REPEATED GRAVITY MEASUREMENTS

R.C. Jachens (U.S. Geological Survey, Menlo Park, CA 94025)

Repeated precision gravity surveys are used both to measure vertical crustal motion and to study the subsurface density changes associated with it. Temporal gravity and elevation changes typically are related by a factor of -2 to -3 μGal/cm; the precise value depends on the physical mechanism causing the vertical motion. Most temporal gravity surveys are conducted with spring-suspension electronic-readout gravimeters which measure relative gravity between network stations. Undefined nonlinearities in gravimeter calibration and short-term instrumental drift are major sources of error in relative gravity measurements. Errors from nonlinear calibration functions can be reduced by detailed laboratory and field tests but probably are present at such fine scale that a complete calibration determination is impractical. Errors from drift generally are minimized by measurement procedures which include observations around closed circuits, redundant observations, frequent base-station reoccupations, and the use of multiple gravimeters. Surveys employing well calibrated instruments and following the procedures mentioned above can yield gravity differences with uncertainties of roughly 5 μGal (one standard error) for networks with dimensions of a few hundred km, and smaller uncertainties for smaller networks. Temporal gravity variations caused by movements of mass in the oceans, atmosphere, and underground aquifers complicate interpretations of gravity changes in terms of vertical crustal motion. Adverse effects of small gravity changes from oceanic and atmospheric sources can be minimized by the types of procedures used to treat instrumental drift, but gravity changes resulting from ground water variations can reach 100 μGal or more and present serious problems in the interpretation of temporal gravity data in some areas.

Vertical Crustal Motion at the Plate Boundary of the American and the Eurasian Tectonic Plates

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W. TORGE (Institut für Erdmessung, Universität Hannover Nienburger Str. 6, D-3000 Hannover 1)

The mid-Atlantic plate boundary of the American and the Eurasian tectonic plates in Iceland is expressed by the neovolcanic zone. In North-Iceland this zone has a width of 50 to 80 km. Geotectonic activities of the neovolcanic zone are restricted to a few fissure swarms of several kilometers width; one of them is the Krafla - swarm, which is active since 1975. The current period of activity forms a rifting episode within the kinematic processes at a constructive plate boundary. Measurement types to be considered in this paper determinig vertical crustal motion at the plate boundary since 1965 are conventional leveling and gravity. The geodetic controlled testfield consists of the main profile (length 150 km, 165 stations) determining the regional effect to the recent rifting episode and of 7 local profiles within the Krafla fissure swarm (lengths between 3 and 30 km, 67 stations altogether). From the comparison of the repitition surveys we conclude that

(1) a gravity increase south of the central volcano occurred before the beginning of the rifting episode, possibly a precursor of the later activity;
(2) an extended region (70 km) is affected by uplift and correlated gravity decrease during the rifting process;
(3) the areas south and north of the activity center in the central volcano show a systematic trend characterized by uplift and gravity decrease at the flanks of the fissure swarm and subsidence and gravity increase in a narrow central part.

For geophysical model calculations of the subsurface mass shifts, continous space-time models of height and gravity variations have been developed, using least-squares collocation techniques.

1984-1983 Vertical Distortion of the Long Valley/Mono Craters Region as Deduced by Gravity

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J. R. Rundle (Sandia National Laboratories, Albuquerque, New Mexico 87185)

A network of 40 precise gravity stations has been established in the Long Valley/Mono Craters volcanic region of California. We have made eight occupations of subsets of these stations starting in July 1982. Here we report July 1984-July 1983 gravity differences of the entire network. Significant gravity decreases down to -38 microgals are observed centered on the resurgent dome area of Long Valley caldera. This region of gravity decrease extends northwest and includes the Inyo domes lineation where the gravity decrease is somewhat less. Groundwater change can be eliminated as a cause of the gravity decrease because the key stations have been previously tested for effects of changing ground water table. Test results show insignificant or no groundwater effect. No other significant systematic changes are seen in the network notably to the north in the Mono Craters region where July 1983-July 1982 changes were seen. The gravity decrease is interpreted as an uplift of at least 10 cm resulting from expansion of the deep magma chamber of Rundle and Whitcomb under the central part of the Long Valley resurgent dome. An uplift of at least 7 cm is inferred for the Inyo domes area. The timing of the uplift can be inferred from stations on the margin of the uplift, SHER and USFSM, which were occupied in November 1983 and February 1984. Although the small changes at these stations preclude our attaching a high degree of confidence to timing evidence, we interpret the data to indicate continuous uplift during the July 1983 to July 1984 year with more uplift in the earlier July 1983 to February 1984 period.

Intercomparison of Vertical Movement and Gravity Change Resulting from the Filling of the LaGrande 2 Reservoir, Quebec

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A. MAINVILLE (Geodetic Survey of Canada, Ottawa, Ontario K1A 0E9)

Levelling and precise gravity observations were made along a 60 km profile before and after the filling of the LaGrande 2 reservoir in 1979. Relative vertical movements of 4 cm and relative changes in gravity of 20 microgals (200 nm/s^2) were observed along the profile. The observed changes do not agree with theoretical results for loading of a layered elastic earth. Isotropic, porous, elastic models with reasonable hydraulic properties also cannot explain the observations. In an effort to account for the discrepancies the accuracies and the error sources in the levelling and gravity data were investigated. Corrections were made to the levelling data for refraction errors, rod calibrations, magnetic effects and deflection of the vertical by the water mass. Although the corrections for systematic errors were significant, the discrepancy with reasonable isotropic models remains. The corrected observations show subsidence beneath the reservoir changing to uplift beyond a few kilometers from the edge of the reservoir. The gravity data require a movement of mass in a direction away from the reservoir. Models involving the expansion of cracks under increased pore pressure are being investigated.

Temporal Variations in the Gravitational Field of the Mississippi Embayment

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MENG HUA WEI (Institute of Geology, State Seismological Bureau)
L.D. MCGINNIS (Department of Geology, Louisiana State University)

A network of gravity base stations in the Mississippi Embayment was repeatedly occupied, beginning in November, 1975, although the majority of the occupations were between September, 1976, and September, 1978. Variations in the gravitational difference between most pairs of stations had a standard deviation of 15 microgals and may be attributed to random error. However, the gravitational difference between three station pairs exhibited a temporal change of approximately 45 microgals between the July and November, 1977, surveys, while the difference between three other pairs changed by smaller and less statistically significant amounts. In addition, there is a change in trend at about this time for two other station pairs for which significant, low-order curvilinear regressions were found to fit the observed variations. Neither observed changes in ground water elevation nor regional tectonic activity, as indicated by seismicity, can explain the observed variations. The most probable source is a localized change in elevation caused by the surface loading associated with changes in stage of the Mississippi River.

Observation of Gravity Changes after Earthquakes at The Geysers

J. M. GOODKIND (Dept. of Physics, UCSD, La Jolla, CA 92093)

During April and May of 1984 a swarm of earthquakes occurred at The Geysers geothermal field. Their epicenters were concentrated along a line running to the northwest of the site of our gravimeter at distances between about 3 and 7 km. There were six events of magnitude greater than 2, and each produced a gravity change greater than 1 μgal. The two largest gravity events resulted from the largest event and the third largest, but closest event, respectively. In both of these cases gravity decreased by 3 μgals within 12 hours after the earthquake, and 4 μgals within 3 days. It recovered to its original value within about 18 days. Smaller events took place on a shorter time scale, and large events during the recovery from the two largest ones mentioned produced gravity changes of at most 1 μgal.

Possible models for this behavior, including vertical motion, will be discussed. In addition, data will be presented from earlier measurements with two gravimeters separated by 7 km. These data show that tides and local barometric pressure effects are the same within about 0.3 μgal at these distances. The potential for the use of such differential gravity measurements to determine local vertical crustal motion will be discussed.

Absolute Measurement of the Earth's Gravity

Mark Zumberge IGPP A-025, Scripps Institution, University of California, La Jolla, CA 92093)

The last decade has seen substantial improvements in our ability to make absolute gravity measurements. Several transportable instruments with accuracies of order 100 nms^{-2} (10 μgal), corresponding to a height sensitivity of ≃ 3 cm, have been deployed at a number of sites in North America and Europe. All of these instruments employ laser interferometers to determine the acceleration of freely-falling masses which have been isolated from forces other than gravity. A wide range of both random and systematic effects of instrumental and geophysical origin have been studied. At various times, certain sites have been occupied by more than one instrument. Often, their results agree, but in many cases they do not. Techniques used in these instruments will be described, sources of error in the measurements will be outlined, and absolute gravity data obtained over the last ten years will be reviewed.

Absolute Gravity: A Reconnaissance Tool for Studying Vertical Crustal Motion

T. M. NIEBAUER (JILA, University of Colorado and National Bureau of Standards, Boulder, CO 80309)
J. K. HOSKINS* (JILA, University of Colorado and National Bureau of Standards, Boulder, CO 80309)
J. J. GSCHWIND (Geodetic Survey Squadron, Defense Mapping Agency)
J. E. FALLER† (JILA, University of Colorado and National Bureau of Standards, Boulder, CO 80309)

We are presently constructing six absolute gravimeters. The design of these instruments is based on a prototype which was previously developed at JILA. These instruments use the method of free fall and consist of basically four parts: a drag free dropping chamber, a long period isolation device, a stabilized laser-interferometer and the associated timing electronics. The size (4×4×3.5 feet when the shipping crates are stacked together) and weight (500 lbs for the instrument alone and approximately 800 lbs when packed in the shipping crates) of these units are such that the apparatus can be easily transported and used at a variety of field sites. The required measurement time at any given site is expected to be 1-3 hours. We expect the accuracy of these meters to be 3-5 μgal, an accuracy which translates into an equivalent height sensitivity of 1-2 cm. We believe that field use of these instruments will, among other things, contribute to the study and measurement of vertical crustal motion.

*NBS-NRC Postdoctoral Fellow
†Staff Member, Quantum Physics Division, National Bureau of Standards.

Thursday AM Session VII

New Technologies for Measuring Vertical Motion I

Accuracies of Contemporary Earth Orientation Time Series

M. E. CARTER (National Geodetic Survey, Charting and Geodetic Services, National Ocean Service, NOAA, Rockville, Md. 20852)

Several methods of observations are currently being used to produce Earth orientation (i.e., polar motion and UT1) time series. The International Radio Interferometric Surveying (IRIS) time series, based on multi-station Very Long Baseline Interferometry (VLBI), currently have the highest temporal resolutions and lowest formal errors. Each 24-hour IRIS observing session typically yields estimates of the x and y components of polar motion and UT1 with formal 1-sigma uncertainties of ± 1 millisecond of arc and ± 0.05 millisecond, respectively. Experimental single baseline sessions of only 1-hour duration have typically produced UT1 values with sigmas of ± 0.1 milliseconds. Determining the accuracies of the IRIS time series is difficult because there are no truly comparable series from other techniques. Intercomparisons with lunar and satellite (LAGEOS) laser ranging can place upper bounds on the errors over limited time spans.

Requirements for Determining 5 cm Relative Geoid Heights from Gravimetry

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The error sources which affect the precision of geoid determinations from gravimetry are classed according to their wavelength, and those which have short wavelength (<100 km) features are analysed to find their impact on relative geoid heights (ΔN) over baselines of up to 100 km. Various forms of the Stokes Integral are also reviewed to find their contribution to the error budget.

It is found that ΔN should be computable to ± 5 cm if gravity is available on a 10 km grid to at least ± 3 mGal, provided

(a) systematic errors in
  (i) the gravity are kept below 0.1 mGal per 500 km,
  and in (ii) the height to below 15 cm/100 km
(b) the mean elevation of the region is less than 2 km, and
(c) a circular rings method is used to evaluate the inner spherical cap.

Measurement of the Vertical with Satellite Laser Ranging

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From the analysis of Lageos laser tracking data it is possible to derive the locations of the tracking stations with precision comparable to the data quality. The horizontal position is separable from the radial distance to the center-of-mass of the earth and the latter has a repeatability of 2 or 3 centimeters from year-to-year. Absolute height "accuracy," as inferred from the stability of GM from year-to-year, is believed to be ±3 cm for a Newtonian coordinate system. Analysis of 3 years of data from the Yarragadee, Australia laser indicates monthly consistencies in height (center-of-mass radial distance) of 5 cm. Comparison of the relative heights of six stations in a local region with ground survey confirm the laser capability of 1 to 2 centimeters over extended periods of time. The largest source of error appears to be consistency of data quality followed by gravity model and atmospheric refraction. The long term effect of small errors in the earth and ocean tides does not appear to affect the height accuracy above the centimeter level.

Precision of vertical position estimates from VLBI

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We will examine the prospects of using very-long-baseline interferometry (VLBI) to measure vertical crustal motions. The major limitation of such VLBI measurements will probably be the modeling of the propagation delay through the neutral atmosphere. We will discuss the deficiencies of the currently available atmospheric delay models and the impact of these deficiencies on vertical position estimates.

The repeatability of baseline length measurements are used to infer the precision of the vertical position estimates by examining the projection of vertical position errors into baseline length. These analyses indicate that currently VLBI can only measure vertical positions with a precision of ~ 10 cm for baseline lengths greater than 1000 km (the shortest length baseline we have examined). This precision could be improved by using more accurate 'dry' atmospheric delay models, and by direct calibration of the delay due to water vapor.

Transcontinental Vertical Motion from VLBI

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The vertical component of VLBI measurements for single baseline experiments is directly affected by the earth orientation parameters that are used in data analysis. The effect of uncertainties in earth orientation on vertical measurement has been evaluated for hypothetical baselines across North America.

The dependence of observed delays on the troposphere also introduces uncertainties into vertical measurements. Data from NASA/Crustal Dynamics experiments are analyzed to investigate this effect.

The Accuracy of the Vertical Component of Baselines in Geodetic VLBI

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In geodetic VLBI it is the consistency of baseline length which has been conventionally used as a measure of stability. Changes in the other two baseline components are not usually examined because they are inseparable (or nearly so) from changes in the orientation of the Earth as a whole, in which the baseline is embedded. But these components too would convey valuable information, if we could view them in isolation. In particular, for baselines up to ~ 1 Earth radius, one of these components coincides roughly with the vertical at either observatory. It is this 'vertical' baseline component which would reveal vertical crustal motions, as well as valuable clues to the systematic errors arising from unmodelled atmospheric delays.

For the first time, we have isolated the true vertical component of baseline adjustments by removing the changes in Earth orientation parameters (EOP) as determined from an entirely independent data source — the Satellite Laser Ranging (SLR) results of the U. of Texas Center for Space Research. It has already been shown that these SLR-derived EOP have an accuracy comparable to those derived by the POLARIS VLBI program. Then the resultant vertical components should have an accuracy limited only by errors in the POLARIS data acquisition and reduction process. Results have been obtained for the baseline Westford, Mass.-Ft. Davis, Texas, for several dates during the year 1983. An upper limit is set for vertical motions at the end points of this baseline; comparable results can be obtained for the other sites in the POLARIS network.

Mobile VLBI and GPS Measurements of Vertical Crustal Motion

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Present mobile VLBI technology permits estimation of the baseline vertical coordinate with an accuracy of approximately 10 cm for baselines of length 1000 km or less. The major contributions to the error budget are from atmospheric water vapor (± 6 cm of the baseline vertical error), earth orientation (± 3 cm) and the combination of system noise and unmodeled random error (± 2 cm). Anticipated improvements in WVR technology and lunar laser ranging measurement of earth orientation are expected to reduce the contributions from these sources to approximately ± 1.5 cm and ± 0.75 cm, respectively by the end of 1986, with a total formal uncertainty for mobile VLBI determination of the baseline vertical of ± 3 cm.

Baseline measurements utilizing the GPS system of satellites will have many error sources in common with mobile VLBI measurements. In particular, atmospheric water vapor will remain a major source of error for estimation of the baseline vertical. Covariance analyses will be presented showing that, assuming that the same improvements in WVR technology as for mobile VLBI, uncertainties in the vertical coordinates of GPS determined baselines can be expected to lie between 3 and 4 cm for baselines less than 1000 km in length.

Thursday PM
Session VIII

New Technologies for Measuring Vertical Motion II

Ellipsoidal Height Differences in a 37-Station Network Measured by Interferometry with GPS

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Ellipsoidal height differences among 37 stations in the Eifel region of Germany have been computed from a simultaneous least-squares adjustment of sixty-seven three-dimensional intersite baseline-vector determinations. These vectors had been determined quasi-independently by analysis of doubly-differenced phase observations, by Macrometer (TM) model V-1000 Interferometric Surveyors, of Global Positioning System (GPS) satellites. Thirty-six baselines were observed in September, 1983, and thirty-one others in May, 1984. Six stations were common to both sessions. The average intersite distance was about 10 km. The statistics of the simultaneous network adjustment (which assumed no crustal motion) indicate that the one-sigma uncertainty of the determination of the ellipsoidal height difference between any two adjacent stations was about 20 mm. (The intersite distances were determined somewhat more accurately, with about 10 mm uncertainty.)

For the purpose of monitoring vertical motion, ellipsoidal height differences are no less useful than orthometric height differences, and may be preferable. Certainly, ellipsoidal height differences can be measured much more rapidly and economically than orthometric heights, now that GPS is available. GPS has begun to be used for land subsidence monitoring in the coal-mining region of the Ruhr.

In a companion paper, Engelis et al. will describe the use of gravity data to infer the undulations of the geoid, and thereby to reduce ellipsoidal height differences to orthometric height differnces, for the purpose of intercomparison with traditional leveling data.

Measuring Orthometric Height Differences with GPS and Gravity Data

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Ellipsoidal height differences can be determined with uncertainties of 20 mm or less, over 10-km distances, by interferometry with the GPS satellites (see companion paper by Bock et al.). Geoid undulations can be determined with similar uncertainties, given satellite-derived and terrestrial gravity data. The combination of interferometric and gravity data can yield orthometric height differences. We have tested this procedure on a 37-station geodetic network in the Eifel region of Germany. We compare the orthometric height differences that we derived in this manner with orthometric height differences that had been measured by conventional leveling methods.

Accuracy of GPS for Monitoring Vertical Motions

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Three single frequency Global Positioning system (GPS) geodetic receivers were used in Arizona in March/April 1984 to determine ellipsoid height differences. Observations were carried out over two level lines, one 45 km in length, the other 50 km. Each height difference was obtained using single difference processing of 4 hours of observations with five different satellites observed during all or part of the 4 hours. For one line, with station separations ranging from 8 to 45 km, the maximum variation in independent repeat determinations of ellipsoid height was 2.0 cm. For the second line with station separations up to 50 km the maximum variation was 2.5 cm, despite partial malfunction of one of the receivers. Conversion of the GPS ellipsoid heights to orthometric heights using gravimetric geoid heights and comparison with simultaneous leveling resulted in agreement at the 3 to 7 cm level. Since the geoid heights are not expected to be more accurate than ± 3 to 5 cm this suggests the repeatability of the GPS measurements closely approximates accuracy. Thus GPS appears to be presently capable of monitoring vertical motions with an rms accuracy of 1 to 2 cm using data from a single 4-hour measurement period.

A Canadian Evaluation and Analysis of the MACROMETER™ Interferometric Surveyor

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A field trial with the MACROMETER GPS positioning system was made in the vicinity of Ottawa, Canada during July and August 1983, using two V-1000 single frequency receivers. Twenty-nine observing sessions were held on a variety of baselines, ranging from 30m to 66 km. Reduction of the data using Macrometrics' software showed an agreement with conventional values on the short baselines, 30 and 2200 m, of 4 and 9 mm respectively. On longer baselines from 13 to 66 km. the standard deviation of a single base line determination ranged from 0.3 to 3.0 ppm of the baseline length in all three coordinates. Eight observing sessions were rejected from this data set due to hardware malfunction. Latitudes and longtitudes on the longer baselines also agree with currently available conventional values to within a few ppm of the baseline length. Height differences appear to agree reasonably well with estimated geoid heights. Agreement is generally within the error limits of established data and an improved definition of the conventional geodetic network is required before a more definitive comparison can be made.

The University of New Brunswick independently developed software to process the phase measurements from single or multiple observing sessions. The software yielded baseline components agreeing with the means of those obtained with Macrometrics' software to about 1 ppm. The software is also capable of obtaining a network solution by processing all observation sessions on all baselines simultaneously. The network solution is significantly stronger than the solution based on single baseline processing.

The precision of the observations for horizontal coordinates compares favourably with precise optical methods for horizontal control currently used for crustal motion studies. Unlike optical methods, GPS measurements are not limited to inter-visible stations. Precision in the vertical co-ordinate however ranges up to the specification for second-order levelling. A dual frequency instrument, perhaps with ancillary water vapour observations might be more competitive for vertical control on baselines much longer than those tested here.

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Determination of Geoid Slopes using GPS

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Since early 1983, control survey projects located in various regions of the United States have been performed with satellites of the Global Positioning System (GPS). The GPS surveys were conducted to meet requirements for crustal dynamics, land subsidence monitoring, comparison with measurements performed with other space survey systems, and for connection of new points to the National Geodetic Reference System. All projects have included connections to bench marks with heights determined from differential leveling. The ellipsoidal height differences determined from the GPS measurements and the orthometric height differences between bench marks were used to compute geoid undulation differences. Undulation differences based on unadjusted and adjusted orthometric heights were analyzed. These differences were compared to gravimetrically and astrogravimetrically computed undulations. The comparisons yielded differences of under ±10 cm where the station separations were generally less than 50 km.

A GPS-WVR Baseline Measurement

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We have carried out a Global Positioning System (GPS) baseline measurement including water vapor radiometer (WVR) measurements along the line-of-sight to NAVSTAR satellites. Both a GPS receiver and a WVR were simultaneously operated at each end of a 22-km baseline near Boulder, Colorado. Measurements were taken on three consecutive evenings in July, 1983, during local thunderstorm activity. Macrometer single-frequency receivers were operated by the National Geodetic Survey and NOAA radiometers were used. Excess path corrections to GPS phase measurements resulting from tropospheric water vapor were computed from the WVR data. We found that the repeatability of the baseline length determination, in the horizontal and in the vertical, is improved roughly by a factor of two when the WVR corrections are included.

Progress on Methods of the Future: Hydrostatic Leveling

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Conventional optical leveling can be associated with systematic, height-dependent errors. In an effort to determine elevations that are free of height-dependent errors and based on entirely different phenomena, we have been pursuing the development of a hydrostatic level which uses a tube of water.

We have chosen 10^{-6} times the vertical traverse as our design goal for the maximum permissible height-dependent error. This requires us to maintain the water column at its maximum density at 3.98 ± 0.3°C. This requirement has been met in a prototype 10 m long level and theoretical calculations indicate that it should be possible to do this in a production level about 150 m long.

So far, our efforts have centered on using quartz pressure sensors to measure the pressure generated by the column of water to determine the elevation difference. However, we have found recently that these sensors cannot be relied upon to produce accuracies of better than about 1 mm in the presence of full scale pressure fluctuations. We are investigating alternate methods of determining elevation differences from the column of water, including direct height transfer from a free fluid surface. Paroscientific Inc. is also working on the development of a new pressure sensor which shows great promise of having the required accuracy.

The development of the hydrostatic level would be of great benefit to the geodetic community in that it could provide elevation determinations to a much greater accuracy and precision than is presently possible with optical leveling. It may also prove to be faster along major leveling routes accessible by truck.

Precise Trigonometric-Leveling

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The National Geodetic Survey (NGS) conducted precise trigonometric-leveling tests during March-June 1984, to determine if the procedure is suitable for first- and second-order surveys on the National Geodetic Vertical Network and for vertical crustal motion monitoring surveys. The interest in trigonometric-leveling was generated by problems with conventional compensator leveling surveys caused by refraction and magnetic errors, and by collimation errors that change with temperature. Refraction errors may be reduced in precise trig-leveling by observing parallel to the ground and balancing sight distances. Magnetic errors can be avoided by using instruments that are not sensitive to magnetic fields. Collimation errors are canceled by meaning direct and reverse zenith distances observed to targets.

Two types of surveys were tested. The first used height transfers between a pair of Wild T2000 theodolites by simultaneous reciprocal zenith distances and DI5 slope distances. Height transfers between bench marks and theodolites were made using either zenith distance and slope distance measurements from the instrument to two targets on a leveling rod, or by observing zenith distances to four rod graduations. The second survey used a single T2000-DI5 system and a pair of leveling rods, each equipped with two targets and two small retro-reflectors. Motorized leveling instrument vehicles provided transport for the theodolites. Motorcycles were used to transport the leveling rods.

The Wild T2000-DI5 system met second-order, class I standards for vertical control surveys, over a 38-kilometer test course. Production averaged 11.4 kilometers of single-run leveling per 6-hour day in rolling terrain.