MAPS OF
NORTH AMERICAN CRUSTAL STABILITY
AND GEOTHERMAL POTENTIAL,
PART ONE

MASTER

by

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"Maps of North American Crustal Stability and Geothermal
Potential"

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ABSTRACT

A three-year program of analysis of crustal movements in North America was planned with the objective of preparing a series of 1:5 million scale maps depicting relative stability/instability. This report only refers to the part of the proposal completed during the first year, though much of this first year's work was preparatory. Three time scales were considered for the data analysis: $1-10^2$ yr., 10^4 yr., and 10^8 yr. Significant differences in sign and rate were suspected between short and long-term motions and these are now confirmed. The first part of the program is now completed. It consisted of two principal activities: (a) data collection for the short and mid-term scales on a U.S.-wide basis, excluding Alaska and Hawaii; all of this material has been reduced to compatible computer language and is stored on tape ready for further study, analysis and final cartography. (b) Map and data analysis of the long-term scale with a completed draft map, applied specifically to the Mid-West and eastern U.S.

A working hypothesis to explain long-term periodicities in crustal motion behavior was presented to the International Union of Geodesy and Geophysics Congress in Grenoble (1974, published 1975 in Tectonophysics, by Rice and Fairbridge).

Reports and displays of the long-period eastern U.S. mapping were presented to the Geological Society of America (Midwest regional meeting for 1975 by Adams), to the American Geophysical Union (Washington, April, 1976, by Fairbridge and Adams), and to the Second International Conference on Basement Tectonics (Delaware, July, 1976, by Fairbridge).

During Fall 1976 and Spring 1977, the Principal Investigator was on sabbatical leave, having been awarded an Alexander von Humboldt prize, studying and giving lectures in West Germany, Netherlands, Belgium, England, Switzerland, Austria, Hungary, Denmark and Sweden. Opportunities have been taken to meet or communicate with members of the I.U.G.G. Commission on Recent Crustal Movements, most of whose activities up till recently have been in Europe. Field trips were made to the North Sea Coast, the Rhine Graben, and to the middle Danube valley (where the first quantitative study of neotectonic motion was made by Pavaï Vajna, half a century ago). The Principal Investigator has been requested by the U.S. national committee of this Commission to form a neotectonic mapping committee for North America, which has been done. He has also been invited (by Prof. V. Magnitzky (U.S.S.R. Academy of Sciences) to join the Working Group on the Interpretation of R.V.C.M. (Recent Vertical Crustal Movements).

INTRODUCTION:

The philosophy behind the proposed program of research is based on the Principal Investigator's 40-year experiences of regional, structural geological studies in each of the continents, and the fundamental but elusive questions that arose during his university teaching of courses dedicated to world regional geology and tectonophysics. The evolution of the theory and practice of plate tectonics during the last decade has furnished new quantitative procedures for handling certain of the questions which could previously be dealt with only by qualitative methods. The new methodology, supported by a prodigious, worldwide effort in field exploration, now provides us with more detailed information on the rates of horizontal plate motion. Variable rates with episodic accelerations are now widely accepted. Very little, however, has been done with respect to vertical crustal motions, except for certain specific areas of notorious hazard to man and man-made structures. Long-term behavior (in terms of 10-1000 years) in crustal motions has, however, become an essential criterion in appraising sites for future construction of nuclear establishments, conventional power plants, dams, and other potentially hazardous major man-made structures.

It seemed, to the Principal Investigator, that his membership in the INQUA Commission on Neotectonics and various other related international commissions, placed him in a position of responsibility to attempt to make some contribution to these problems. A cartographic base for the North American continent

appears to be a prime requirement and accordingly a three-pronged approach was proposed: short-term, on a $1-10^2$ yr. time scale; mid-term, a 10^4 yr. (Holocene) time scale; and a long-term, 10^8 yr. (Cretaceous) time scale. Each map should be eventually expressed in terms of mean annual rate of vertical motion. Because of varied scales, each mapping time scale requires a totally distinct series of data sources, involving a wide range of different disciplines.

Eventually, it would seem possible that some fundamental principles in geosciences will emerge; one basic question is — why are short-term crustal motion rates, even in "most stable" regions, up to three orders of magnitude higher than long term rates? Rice and Fairbridge (1976) voice the possibility of a ratchet process. Another problem is — why are up to 25% of the contemporary RVCMs observed to date (Mescherikov, in Fairbridge 1968) out of phase with the long-range vertical motions? The possibility of pulsatory RVCM related to the passage of a plate over an unevenly heated asthenosphere has occurred to the writer (cf, also discussion by Gass, Chapman, Pollack and Thorpe: unpublished, read at A.G.U., May 1977).

PART II: SHORT-TERM VERTICAL CRUSTAL MOVEMENTS

Referred to in contemporary professional literature (e.g., Pavoni and Green, 1975) as RVCM, these "Recent Vertical Crustal Movements" have been a subject of study and cartography in the U.S.S.R. and eastern Europe for many years. Observed velocities are mainly in the range of 0.1 up to 20 mm/yr. The methodology has been principally by means of (a) repeated geodetic levelling, chronologically spaced at intervals of at least 20 years; (b) correlated geophysical anomalies (mainly gravity and seismic); (c) correlated geomorphic anomalies (mainly river terrace, lake shore and marine shoreline anomalies). The first proven rates of RVCM were obtained along the Danube by a Hungarian geologist, Pavai Vajna, more than 50 years ago. The first example demonstrated in the eastern United States was along the Hudson Valley by Fairbridge and Newman (1968). A number of important papers have been published in recent years by the N.G.S. (see review by Meade, 1975). Holdahl and Morrison (1974), Balasz (1974), Isachsen (1975) and others in North America. The European literature has been synthesized in a series of conference proceedings of the I.U.G.G. Commission on Recent Crustal Movements (Helsinki, Berlin, Grenoble, etc.), the most recent being that edited by Pavoni and Green (1975); a review of the latter has been prepared for publication by the writer. The color-printed map series of Eastern Europe on a scale of 1:2½ million (published in Moscow) were reduced to a 1:10 million scale and included with a special volume

issued by the Commission for the Grenoble meeting of 1975 (edited by Boulanger).

Under our contract, E(11-1)2441, the work on RVCM involved two principal activities, both of which were extremely time-consuming and involved a great deal of essentially raw data handling or in the coordination of otherwise incompatible systems:

1. Geodetic Releveling. It is legitimate to ask: do these geodetic measurements really mean something with respect to crustal motions? There has been extended discussion, ranging from questioning their accuracy, to suggestions of pulsatory gravity fields that simply give the impression of crustal motion. These questions are not totally resolved, but one thing is clear: for more than 75% of observed geodetic anomalies, there are also ancient structural features showing similar trends and mathematic sign (uplift or subsidence). We consider therefore that this is a proper field of study.

The National Geodetic Survey (formerly part of U.S. C. and G.S.) carries out two types of coast-to-coast[#] field surveys: triangulation (including astronomic control) of fixed benchmarks in an azimuthal sense; and secondly, vertical levelling. Unfortunately, the two types of survey have never been coordinated. Thus, a primary task for us was to establish latitude and longitude^d coordinates for the principal horizontal levelling stations.

These were established by careful measurement of horizontal distances on the plotting charts of the N.G.S., taken from known points and reduced to latitude and longitude by a computer treatment. A few cross-over benchmarks between the two surveys were available for quality control. Beginning on the east coast, more than 50% of the country was thus correlated to the latitude/longitude grid, which will permit levelling data for over 15,000 points to be plotted on the same base maps as all other data.

Comparison between the earlier and later surveys have previously been made for selected traverses, referred to in the literature quoted above (by the writer; see also Hodahl, Isachsen etc.). It is our understanding that other contracts are in effect at this time which will furnish these data in due course. At which time, with our geographic coordinates, an analysis integrated by computer technology will be possible with other geophysical and geomorphic parameters. Preliminary plans for this part of the work were worked on in cooperation with the Columbia University Computer Center and our computer consultant J. Lopatin.

2. Continent-wide Geophysical Data Collection.

In anticipation of the completion of the geodetic grid and receipt of RVCM data, and their transformation to tape and graphic form, an extensive search was undertaken to acquire tapes covering other geophysical data, notably sea levels, seismicity, gravity, heat flow, etc. Software computer work was needed to render this material useful for comprehensive multivariate statistical an-

alysis, and now all the relevant tapes are in safe storage and available for ongoing research.

The problem of digitizing existing structural geological maps, as well as with the newly completed satellite-image-based lineament maps, was studied. In order to achieve the highly generalized requirements of a map of 1:5 million scale it was considered that a grid of one degree rectangles would be adequate, to each of which the linear data could be reduced (a) by optical density or (b) by linear measurement (from base maps). It was recognized that such degree rectangles would introduce a variable scale (only roughly 100 x 50 km), the rectangles becoming smaller towards the north. But the advantages of a universally employed coordinate grid that is employed by all existing mapping organizations was deemed to be too great to ignore. It is to be stressed that comparisons may then be made square by square for all available computer taped data and the correlations obtained for known areas can then be extrapolated experimentally to unknown or only partially known areas.

In order to plot, by computer methodology, the collected data now on tape, a series of base maps on varied projections were digitized. Formulae were provided by E. Schmid (N.G.S.) and W.R. Tobler. Available software system CALPLOT utilized a FORTRAN-IV procedure providing rectangular, conic or polar azimuthal projections, compatible with CDC-6600 hardware. Whenever the total data package is readied, it can then be delineated in

cartographic form; cooperation for this action was discussed with Dr. Keller of LASL computer graphics section. An alternative subcontracter with the map displays would be Computer Sciences, Inc. (Richland, WA) which has a possibly comparable capability.

Geologic data for computer storage and mapping was first considered in Sweden, where a GEOMAP program was developed (see Berner et al. 1971). Comparable geologic data bank systems have been developed in Canada and the Canadian Geological Survey (ed. Hutchinson, 1973) has issued an international review of this COGEODATA on behalf of IUGS, UNESCO, and CCGD (Canadian Centre for Geoscience Data). The CCGD also possesses data banks for petroleum and global non-ferrous metals (MANIFILE).

In the United States there seems to be no general geological or geophysical data bank appropriate to cartographic use, although some of the state surveys and oil companies have specialized developed systems. The USGS does, however, hold a Computerized Resources Information Bank (CRIB) that carries 100,000 mineral site data. Its main shortcoming is the difficulty of standardizing definitions and classifications. It was based upon a bibliographic storage and retrieval system known as GIPSY (see USGS Circular 681), which shows the virtue of and methods for interdisciplinary correlations, which is a key to our own methodology.

Another system of interest for interdisciplinary cartography is the GEOCODING technique of the U.S.G.S. (Werner, 1974). It has been developed further for land use (Anderson et al. 1974), and should be useful for handling satellite imagery. A Geothermal Resources Information and Data (GRID) digitized bank is being constructed by Dr. S. Phillips, in cooperation with U.S.G.S..

The high quality of RVCN mapping in the U.S.S.R. makes it probable that they are also employing computerized data banks. In discussions it is clear that integrated data of geomorphology and geophysics are employed, but we have not been able to penetrate to the methodology.

The problems concerning the final statistical analyses of the assembled interdisciplinary parameters were discussed at length in the Columbia University Progress Report for October 30, 1974-July 31, 1975 (Report CU-2441-8, see pp. 14-37, plus annexes), and will not be duplicated here in as much as it refers essentially to preparations for future work and should await proper testing.

PART III: DATA COLLECTION FOR MID-TERM (10^4 yr) SCALE.

The purpose of this time-scale selection is to test the question of RVCM longevity. To what extent does twentieth century activity represent long-term trends? It seems that some features do, some don't. Can we discriminate? And, finally, if we study these Holocene (10,000yr.) structures, to what extent will they prove useful for prediction of crustal motions during the next 100 years?

For convenience, the 10^4 yr. scale can be taken as measured to the exact year 10,000B.P. (measured by convention by radio-carbon from A.D. 1950 as base year). For crustal motion problems, however, some extrapolation will need to be accepted (+/- 2000yr.). Even this objective presents formidable problems, and after considerable discussion, it was felt that this study should be given a second priority by our group, inasmuch as several others are concerned with it.

On the map scale planned (1:5 million) it is believed that a coastal zone deformation map is the only one that can be adequately quantified at this stage. Over interior regions, while it is possible to obtain some relative, qualitative information, it will be difficult to express in cartographic form. On the other hand, the possibility of tracing deformation surfaces up from the St. Lawrence marine datum (Champlain Sea, 10,000 yr. BP) to the Great Lakes littoral terraces seems a reasonable proposal.

The principal area of activity must be concentrated then in the littoral zone and would involve (a) establishing trends of sea level change through the Holocene for as many transverse profiles as possible around the North American continent; (b) establishing a mean eustatic standard for the non-glaciated regions; (c) establishing (by directly collected samples and radio-carbon-dating, or by extrapolation) the mean elevation of the geoid for littoral sites at 10,000 yr. BP. at approximately 100km interval^s; and finally (d) establishing the anomalies between observed and theoretical heights of the geoid at that point in time and from this parameter reducing the mean crustal displacement rate, which will then be cartographically inscribed, ready for comparison with the short and long term map surveys.

None of this work was performed as a direct product of the current contract, but the principal investigator has in one way or another supervised or advised in several key operations, by virtue of his role within the INQUA Shorelines Commission and the INQUA Holocene Commission. The results will thus accrue to the North American crustal stability program with very little cost. Up till now, no budgetary line has been filled for it.

The active research of global significance is being pursued in four principal centers:

1. Queens College (N.Y. City University). Prof. Walter Newman is carrying out a computer analysis of all radiocarbon data hitherto published relating to the behavior of the Holocene sea level on a world-wide basis. Prof. Newman will provide us with his tapes whenever requested. We, for our part, have assisted

him with advice and literature.

2.Cornell University. Prof. Arthur Bloom has been encouraged by UNESCO and INQUA within the IGCP (International Geological Correlation Program) to establish a computer-based analysis of the sites (geological character, meaning and evaluation) mentioned under project 1. He has thus far obtained cooperative assistance from the Netherlands Geological Survey (Haarlem) and the State Survey of Lower Saxony (Hannover) for developing the computer software and field questionnaires required. Preliminary tests by Dr. M. Geyh (Hannover) were studied during a visit to Hannover by the Principal Investigator and the results look promising. Dr. Bloom has also organized a series of regional symposia, to help extract local information and to help publicize the program. The latest field symposium (Dakar, Senegal) was attended by the Principal Investigator. It is recognized that only a world-wide approach will bring about a true understanding of what is commonly called "eustasy" (actually a poorly understood mixture of geodesy, isostasy and other parameters).

3.University of South Carolina. Prof. Donald Colquhoun, as secretary of the INQUA Shorelines Commission, was requested at the IUGS Montreal (1972) meeting to organize and present a global map showing available knowledge of sea-level (and thus relative crustal motion) at three points in time: (a) Present (tide gauge trend in the decade 1950-1960); (b) Mid-Holocene (maximum level reached locally); (c) Eemian or Sangamon (c. 100,000yr. B.P.;

maximum local level). Under the chairmanship of the Principal Investigator the global working group was organized and the preliminary map by Dr. Colquhoun was presented and exhibited at INQUA (New Zealand, 1973); a revised version is in preparation for INQUA (Birmingham, 1977). The original map projection and enlarged black and white prints were provided by courtesy of Dr. Douglas Grant and the Geological Survey of Canada.

This map should serve as a preliminary cartographic base for projects 1 and 2. It will then be possible, by color coding or other technique, to classify broad regions of the earth into gross categories of "stable, rising and falling" littorals, with some quantitative measure (hopefully with a precision of better than 0.1mm/year).

4. University of Quebec (Montreal). The principal investigator is a member of the Earth Science Research Advisory Panel of UQAM and following his suggestions Prof. Claude Hillaire-Marcel has carried out four field seasons in mapping and precise leveling of the Hudson Bay and Ungava Bay Holocene raised beaches. Numbering up to 185 over the period 0-8300 yr. B.P. and reaching to 315m elevation (isostatic emergence), they represent the most detailed and refined climatic-eustatic document in the world. It is hoped to relate this standard scale to the global data furnished in projects 1, 2, and 3; when the precise amplitude and timing of each oscillation is understood, then the regional crustal anomalies can be eventually quantified. (Joint

papers by the Principal Investigator and Hillaire-Marcel have been accepted by Nature for 1977 and other material is in preparation). Dr. Hillaire-Marcel is hopeful that in the future his beach-level survey can be extended in the Champlain Sea area from 8000 back to about 13,000 B.P..

The present status of our 10^4 yr. map project is therefore not unsatisfactory, thanks to vigorous activity by many groups (only a few of whom are mentioned here). We regard the general pattern of eustatic change during the Holocene as now established; there is controversy about the minor oscillations and these are now subject to close study by many workers. It can be clearly seen that mean sea level lay at about -35m at 10,000BP on a global average (excluding glacio-eustatic and highly tectonic areas). It would seem, therefore, to be a simple procedure to collect offshore shell-beach (or oyster-reef) samples dated around 10,000 B.P., and calculate anomalies in depth that are attributed to crustal warping. There are, however, serious unresolved problems: for example, we do not know how far the global spin axis has shifted with respect to the North American Plate and vice versa, during these 10,000 years. There is ^a presently observed secular pole shift towards Greenland, and theoretically this could lead to a slight contemporary regional fall of sea level in the Gulf of Mexico. But this is not borne out by observations (see Hicks, 1973). Relative sea level around

mid-latitude North America is rising, and indeed considerably faster (by 1-2mm/yr.) than the world average. Is this perhaps a delayed result of the postglacial melting from North America, which must have led to polar shift away from Greenland? The consequent large rise of the geoid in the Gulf region would increase water loading (hydroisostasy) the effects of which would be delayed (by 5000-10,000yr.) and could be of much greater amplitude than the present (minor) result of pole shift.

Many other very deep problems of this sort persist and we do not see a rapid solution of them. We can, however, see an approximation for the North American sea-level record, and we can therefore use it for determining gross crustal motions.

Part IV. THE LONG-TERM (10^8 yr) MAP PROGRAM.

The selection of this time scale in the triple program, 10^2 , 10^4 , and 10^8 yr., was not for the sake of "elegant" symmetry, but for several good reasons: (a) it was technically feasible; (b) it would extend the structural behavior history back to a pre-Ice Age era; (c) certain structures show a persistence through this sort of time, e.g. the Cape Fear Arch has shown a secular (or pulsatory) uplift that is recorded not only through the last 10^8 yr. but is geodetically rising today at an astonishing 6 mm/yr. (Richards, 1967; Brown et al. 1972; Balazs, 1974; Oaks and Dubar, 1974; Higgins et al. 1976).

The time scale 10^8 yr., liberally interpreted as dealing with events of about 110 to 85 million years ago, takes us back to one of the turning points in geological history, the mid-Cretaceous revolution that heralded the end of the Mesozoic Era. It was a time of briefly accelerated sea-floor spreading, according to the work of Larson and Pitman (1972), at more than one order of magnitude higher than present mean rates. The calculation has been denied by Berggren et al. (see discussion, *ibid.*), but seems to be supported by other data (Hays and Pitman, 1973). Logically, this would lead to a greatly enhanced heat flow in the mid-ocean ridges and thus to a globally high eustatic level (c. 500m above present). There were nevertheless strong oscillations, even during the Cretaceous (Hart and Tarling, 1974; Petters, 1976). Since that time there have been several systematic crustal behavior trends that have been more or less

continuously operative: (1) a secular (but oscillatory) fall of sea level; (2) an increasing emergence of continents; accompanied by hydroisostatic unloading of margins, leading to (inner) peripheral upwarp; (3) secular filling of marginal basins due to sedimentation, accompanied by (outer) peripheral downwarp (i.e. foot of continental rise); (4) secular but oscillatory change of global climate ("deterioration"), resulting in an increase of continentality, and a progressive build-up of land ice in high latitudes; (5) systematic changes in the mass loading of the lithosphere, due to growth of polar ice caps, continental drift and sea floor spreading, all tending toward relative pole shifts (Liu, Carpenter and Agreen, 1974) and thus to aperiodic adjustments of the geoid.

In the Western part of North America there seems to have been a complex history during this 100 m.yr. interval relating to the plate's advance to and overriding of the Pacific mid-ocean ridge. For the purpose of the present study we have, up till now, totally avoided the western third of the continent, together with Alaska and Hawaii, reserving them for proper study at a later phase of the work. The present survey has been limited to a study of the cratonic region, that is to say, the North American Platform, embracing the Canadian Shield, its subsurface continuation as "basement" as far west as the Rocky Mountain Front, and as far south as the margins of the Gulf of Mexico.

Eastwards we have taken in the Appalachians and Atlantic Coastal plain, though it seems likely that some easterly parts of this belt are ultimately related, not to the American craton but to Africa; however, since separation and rewelding took place back in the Paleozoic, these remnants will be considered as completely integral parts of the North American craton of today.

The relevance of a proposed study of crustal deformation traceable back to a 10^8 yr. era, with respect to an understanding of present-day structural activity, might seem to be marginal at first sight. Quite the contrary, during the course of this work, the principal investigator has become more and more convinced that many of the currently active trends and surfaces may be traced back to remote times. Thus a study of the history of these features may lead us to pin-point their existence today either in buried form or perhaps in well recognized surface features the meaning of which has been in doubt or controversial. The information is contained in either lines ("lineaments") or planes (erosion surfaces, unconformities, paleosols), and may be discussed separately here-

1. Reactivation of Lineaments. The existence of widespread but systematic fracture patterns within the earth's crust have been known since they were first identified (in England) by William Hopkins in 1835 (see Hodgson, 1976). Later they were identified and discussed by Daubrée (in France), and by Kjerulf (in Norway), and by Hobbs (1911, in North America, and worldwide). Lineaments may be described as long rectilinear fract-

ure planes of more or less vertical attitude, comparable to jointing on a planetary scale. The Russian, Schulz, in 1973, described the system as "planetary jointing". Daubrée, following his glass experiments in the last century, recognized them as a product of brittle fracture and the Swiss, R.A. Sonder (1956) has given the process of global jointing the name "rhegmagenesis".

Having given it a name does not necessarily mean that we know anything about it, but it may help focus attention. Present-day attention to the subject was introduced by (a) satellite photography, (b) long-term recognition that many lineaments, or linear intersections, were a clue to ore deposit exploration; (c) deep-sea fracture-zone mapping (J. Tuzo Wilson, 1965, recognized that suboceanic transforms were often co-linear with continental lineaments); (d) general rising interest in global problems prompted by a near-universal recognition of plate tectonics; and (e) increasing public and political awareness of geological hazards, especially when potentially lethal man-made structures such as dams or power stations are built in hazardous areas.

Emerging from these varied interests, a First International Conference on the New Basement Tectonics was organized in Salt Lake City in 1974 (Hodgson, Gay and Benjamins, 1976) and a Second Conference in Newark, Delaware in 1976. The principal investigator submitted a paper to the second meeting (Fairbridge, in press). Arising from it he was tempted into some speculations

on the break-up of Gondwanaland (where he has made personal surveys) and this paper is likewise in press. As a member of one of the Inter-Union Committee on Geodynamics working groups (no. 10, headed by D.A.Valencio), these speculations were not altogether inappropriate. They seem to bring out some useful points with respect to our present contract.

(a) Whereas deep-sea fracture zones are small circles related by Eulerian geometry to poles of plate rotation, the continental lineament are great circles.

(b) As noted by Wilson (1965) and discussed by Scheibner (1976), most of the lineaments go back in history to Precambrian times, but appear to have been reactivated and to have predetermined the loci of deep-sea fracture zones.

(c) When intracontinental rifting takes place (e.g. East African Rifts, Rhine Graben, Basin-Range Province) the Tertiary trends always seem to follow those Precambrian lineaments. Similarly, in the break-up of Gondwanaland, the new continental margins, generated originally as rifts (known from the sedimentary record) today still display the fundamental lineament trends. This is very clear in the Red Sea (Miocene rifting) but less apparent in some of the Gondwanaland coasts that began to open up in the early or late Paleozoic. The writer submits that the idea of a "Mesozoic" break-up of Gondwanaland is false and misleading. Rifting there can be traced easily back into the early Paleozoic

and it continued through the Tertiary up till today. Many of the famous Permo-Carboniferous glacial tillites are found as the first filling in late Paleozoic rifts so it was not the glaciation that caused the rifting. It is interesting that along one and the same lineament, the revived motion has partially been marked by normal faulting, in places by strike-slips, in the oceans by transforms, and then in other places by no displacement at all.

The main point is that rifting and lineament revival has been episodic at least throughout Phanerozoic time. This may be of key importance in understanding the fracture history of the North American craton (see discussions in Saunders and Hicks, 1977;)

Another point of apparently general validity is that rift reactivation propagates over extended periods of time, and in a series of discontinuous jerks. The opening of the South Atlantic, for example, is well-dated stratigraphically and paleomagnetically; it opened rotationally, and was step by step, from south to north over a span of more than 10 million years. We have the analogy of a door with a "creaking hinge". In an analogous way, when two continents collide, it is never "wall-to-wall", but obliquely and in jerks, the "sticky zipper" analogue (Fairbridge, in press). It is interesting that the North Atlantic fracture zones (south of the Azores F.Z.) began to operate c. 180-200 m.yr. ago, but some of the corresponding landward lineaments in both West Africa and in the Appalachians seem to be showing renewed activity through the Tertiary, even Quaternary, up till today, with scat-

tered volcanism, hot springs and local seismicity.

2. Deformation of Erosion Surfaces. It is a characteristic of all mature Phanerozoic orogenic belts that they are today geomorphically modelled into series of stepped erosion surfaces. Recognized by W.M. Davis in the late 19th century as products of humid erosion and identified as "peneplains" (see Brown, in Fairbridge, 1968), in the present century they have been reinterpreted by W. Penck and Lester King as products of headward erosion and explained as more related to semi-arid erosion processes. A third view (Wayland, Büdel) is that they are of humid tropical origin, ie. a largely chemical weathering process, thus the term "etchplain". There is a fourth view (Chorley, Hack) that they are products of a steady-state fluvial process, but this is an idealized model and does not relate to either the field data or the demonstrated historical record.

Each hypothesis, except the last, has something positive to contribute to the general understanding of erosion surfaces, which we are calling "peneplains" in deference to Davis' unequivocal and nongenetic definition of any land surface reduced to a physical plain. Some authorities have spelled it "peneplane" but that was not the original spelling or intent; an erosional surface can never achieve a mathematically planar geometry. The latest comprehensive review and collected classics on the subject is a "Benchmark" volume edited by Professor George Adams (1975, retired, formerly of City College, N.Y. City University). Accordingly Prof. Adams was invited to serve

as a consultant to this contract. The report of that work intended for joint publication is appended to this report. Highlights are discussed below:

(a) The mean surface elevation of the North American craton (whether Precambrian or Paleozoic) is 250m, rising locally to about 500m. Peripherally there are domes, dropping away at the continental margins to deep-sea basins.

(b) This surface is very thinly veneered in places by continental sediments or paleosols of various ages ranging mainly from Permian to Cretaceous. These old soils are "armored" (indurated) by duricrust processes, such as are presently active in the tropics, creating laterites, bauxites, silcretes, and ferricretes. In the north the surface is extensively veneered by Quaternary glacial tills and outwash and in the west partly by loess and sand dunes. In the southwest there are Tertiary calcretes (caliche"). Except for these thin veneers there has been no sedimentary accumulation in 10^8 years.

(c) The net erosion of this cratonic surface since the Cretaceous is limited to major stream valleys that were largely incised during the Quaternary climatic oscillations with their glacial melt stages and so on. The effective general lowering of the surface by erosion has been zero for the period of 10^8 years. Over most of the interior there has been almost zero structural deformation in this period, except along certain specific lin-

eaments (see, e.g. Heyl, 1972).

(d) Freeboard. Inasmuch as the mid-Cretaceous eustatic maximum sea-level is calculated to have been around 500m (Larson and Pitman, 1972; Hays and Pitman, 1973), the entire interior craton would have been inundated if its mean elevation were 250m at time. Of such marine facies there is no trace and the Cretaceous marine sediments of the west were clearly isolated by land from those of the east. Therefore it seems likely that the continent had a somewhat higher "freeboard" at that time (10^8 yr. ago) and that it has subsided during the remaining interval. "Average" freeboard of all the continents, however, has remained relatively stable (Wise, 1972). Such continent-wide subsidence could be predicted from plate motion; The North American plate had just migrated northwestward and would be expected to stand high (with respect to the geoid), with a high regional gravity anomaly. Slow adjustment of the whole continent to an isostatic equilibrium with the new geoid was at an unknown rate, but it must have been constantly revived because it had to drift still another 30° of arc towards the pole and the interior was never invaded by the sea throughout the Tertiary. According to Sharma and Athavale (1975), Disco Bay (in west Greenland at lat. 70° N) lay about 56° N about 60 m.yr. ago, and sea floor spreading in Labrador Sea ceased around 47 m.yr. then so that since the two plates have been locked and moved pole-

ward in unison.

(e) The inner peripheral belt of the craton (King, 1975) is found to be disposed today in a series of domes (e.g. New England, Blue Ridge, Ozarks...), interrupted in places by troughs

(St. Lawrence, Atlantic Geosyncline, Mississippi Embayment, Denver Basin...). Uplift of the domes, relative to the mean craton level, is of the order of 1 km, but in those troughs passing out into oceanic crustal depressions the subsidence has been 5-10 km. It is evident therefore that the rise of the Appalachians, for example, in no way represents a simple balance between isostatic uplift (due to erosional unloading) and basinal downwarp (due to sedimentational loading, which was formerly a favorite explanation (see discussion in Sleep and Snell, 1976).

(f) The present survey shows clearly that the domal areas carry extensive traces of the Cretaceous silcreted surfaces that have become upwarped during the subsequent 10^8 yr. Prior to that upwarping the surfaces were essentially flat ("peneplains"); it is only on very low relief surfaces in the tropics that comparable soil processes operate today. An earlier peneplain of pre-Triassic age had previously reduced the Appalachians to low relief, prior to the crustal stretching, taphrogeny and uplift (augmented heat-flow) that marked the 200-180 m.yr. Atlantic rifting and opening. It has been claimed by Gilluly and others (1970) that the erosion of the Appalachian orogenic belt provided the sediments of the late Cretaceous-Cenozoic Atlantic Coast geosyncline. Evidently those mountains had been degraded already

over 100 m.yr. earlier. While the linear similarities of the uplifts with late Paleozoic, early Paleozoic and even Precambrian orogenic trends speak for inheritance, it is still not understood what is involved. It would appear that the rapid shift of the North American plate through 30° of arc northwestwards and towards the pole in the post-Cretaceous interval may have triggered upper mantle heating processes. The Atlantic and Gulf seaboards are now "trailing edge" geosynclines (Kinsman, 1975) and would hardly retain any of the excess thermal character achieved at the time of rifting.

(g) The planational surfaces of the Appalachians and other domal areas are stepped; that is to say, the margins and main stream valleys are notched and terraced by secondary "partial peneplain" surfaces or "straths". In a joint presentation to AGU in 1971 J. Tuzo Wilson and the principal investigator (Wilson and Fairbridge, 1971) pointed out that these intermediate peneplain surfaces each corresponded to a change in rate of sea-floor spreading, suggesting a tectono-eustatic control (see also Rona, 1973). The surfaces are in part dated by stratigraphic onlap evidence and partly by scattered evidence of terrestrial exposure (leaf deposits, karst, bauxites, high level gravels).

(h) Isobase contours have been drawn on the 10^8 yr. erosion surface. A remarkable change in gradient is observed where a dome passes into a trough, e.g. the slope southeast of the Blue Ridge

dome is 1:200, whereas below -750m off Cape Hatteras, it steepens sharply to about 1:80. In central Texas the Gulf geosynclinal slope is 1:30. According to a personal communication from V.V. Belousov, observations in the USSR show that it is at these inflections where the maximum seismicity and local disturbances generally occur. In the Hungarian plain, where Quaternary sedimentary fill in places reflects over 1000m of downwarping (in 2 m.yr.), it is the inflections that mark the seismic spots (Ronai, 1974). In eastern North America there are four sites where these paleo-slope inflections or hinge lines intersect major lineaments: those areas are in the region of (a) New Madrid, (b) Charleston, (c) Boston, and (d) Montreal. These are the four most seismic areas in this craton. Steepest gradients occur over the transitions into oceanic crust. It is interesting to note in the postglacial uplift isobases of Scandinavia, there is a marked asymmetry, being very steep near the oceanic crustal transition, but quite gentle towards the Russian craton.

(i) Mapping Techniques. Details are given in the Fairbridge and Adams manuscript reproduced in the Appendices, but a few points should be brought out here. The procedure was essentially the same as that developed by the National Research Center for Disaster Prevention, Tokyo (Hatori^{et al.}, 1973) for constructing a tectonic map showing crustal movement since the Plio-Pleistocene transition (c. 2 m.yr. ago). Dated erosional surfaces are assumed to be graded to mean sea level during quiescent structural

phases. In our case we selected the base of the Upper Cretaceous marine transgression which is a widely, accurately dated and well established datum plane in the coastal regions, encountered in numerous borings and thus clearly marked on structure contour maps. Above the marine limit, this surface is followed as an erosion plane, generally indurated by silcretes, that can be followed geomorphically over the uplift areas and down to the marine onlap on the other side. Traverse lines are indicated on the attached map. The results have been digitized for computer comparison with all other geophysical parameters.

QUOTATION:

"Neotectonic maps will have a wide range of usefulness; their preparation should be a challenge to all geologists and to all scientists in related disciplines."

P.B. King (A.A.P.G. Bull.,
1962: p.1950).

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Geodetic releveing - measuring the change of elevation of benchmarks - is the only systematic geophysical parameter directly reflecting crustal stability. At the inception of this program, we were aware that such data was available from NGS (National Geodetic Survey), but we did not know the condition or form of the information. We subsequently learned that out of 10^5 first order (highest precision) benchmarks, data for only 10^4 of them was available. Those were confined to a tier of southern states and the mid-Atlantic coast region. The problem before us was to construct from this restricted information crustal motion maps for the entire U.S. Through his association with the Columbia University Computer Center, a participant in this effort (Alan Rice) was aware that very powerful software for solving a wide variety of statistical problems was supported by the Columbia computer system, and that the Computer Center employed consultants for the use of statistical packages for the social and natural sciences. Inquiries to other agencies indicated that various types of geophysical measurements based on geographic location were available on tape. Running a multivariate analysis to determine, for example, the strength of association between gravity and releveing data would allow prediction of rates of uplift in regions devoid of releveing data but where gravity measurements have been made. We had been concerned about the size of the data base, restrictions on format, and the number of variables that might be correlated. Results of our discussions with consultants at Columbia's Computer Center indicated that collecting and standardizing the data would be the major difficulty. Statistical packages such as SPSS, JOUPAC, DATA-TEXT, and SSP could provide the necessary software tools.

Other advantages were also apparent. Large portions of the data might be suspect (Woolard, 1975). This is a difficulty with which the biological sciences contend on a day-to-day basis. Multitudinous interactions between variables can significantly affect the outcome. The recourse there is to utilize statistical inference to draw out the most probable signal. It also appears that

it will be many, many years before it's either decided what is good or bad in some types of geophysical measurements, or whether stations are to be reoccupied. Hence, we are left only with the same recourse which, however, has the advantage of providing on a formalistic basis measures of confidence for our results.

As there had been in this country no apparent previous effort to run multi-regressions on geophysical information, the opportunity arose to provide fundamental contributions to pure science. The strength of association, say, between gravity and magnetics should yield profound information regarding the dynamics of the earth.

In addition, regressing seismicity and releveilling also allows prediction of seismicity from releveilling data. We have the means to construct a genuine seismic risk map, and many other types. In this context, this effort becomes most valuable to the nuclear engineer concerned with siting problems. A statistical inference from the geophysical parameters dependent on the earth's dynamics yields quantified probabilities with attendant confidence levels with which the engineer is more likely to feel comfortable, both from design and legalistic standpoints, rather than with qualitative assessments and arbitrary guidelines -- in this latter case, we think specifically of one of the current "definitions" of an "inactive fault": one that has not moved for 10,000 years.

Further advantages arise in that prediction may be made from other information in regions lacking measurement of the explicit variable of interest. In the case of releveilling, traverse lines can be separated

by several hundreds of kilometers. Interpolating rates of uplift between lines will only pick up large wavelength structure and the value of this information becomes marginal if the small scale structure (on the order of kms) which is known to have similar amplitudes is the primary concern. Probabilistic predicting (from the multivariate analyses) between traverse lines may bring attention to potential high activity. This possibility brings us to another advantage: the statistical inference provides powerful rationale for putting down instrumentation in regions of hitherto unsuspected instability and serves to optimize data collection strategies.

For precisely the above reasons, the Russians have been pursuing this course for the past ten years. This welcomed confirmation of the feasibility and soundness of the approach on which we had embarked came to our attention at the CRCM (Commission on Recent Crustal Movement) meeting in Zurich, fall, 1974. The Russian map of recent crustal movement presented at this meeting included an inset map depicting confidence levels for their probabilistic inference of uplift from relevelling lines. They employed geological-geomorphological indices (e.g., stream bed configuration; etc.) to correlate against relevelling (Bylmskaya, et. al., 1974). It was learned at this meeting that the Russians had also correlated location of mineral resources with these same and other variables to guide prospecting efforts. We were left with the impression that these techniques had been employed for some time in the Soviet sphere. Interest and attention has apparently just been drawn to these methods in this country as indicated by the new seminars recently fielded by the AAPG

in the combined use of computer processing and statistical analysis to guide oil exploration methods. We were also concerned with producing maps depicting geothermal potential in the same manner as planned for the vertical motion maps, i.e., letting the correlation imply high heat flow or gradients. Both the Russian experience and the AAPG's direction again verified the methodology we were to employ.

The Russians have not been the only ones to correlate their diverse geological indicators. The GEOMAP package employed in Scandinavia has as a subroutine a program with the acronym INTEREST II (Integrated Retrieval and Statistics) which provides options similar to SPSS; in particular relative frequencies, histograms, mean, standard deviation, standard error of the mean, tables of frequency, one way analysis of variance, product-moment correlations, discriminant analysis, factor and principal-component analysis, regression analysis, arithmetic transformations, etc.

In this country, one of the major thrusts in the use of statistical analyses in geographic variables has come from the geographers (e.g. Tobler at Michigan -- use of cross-correlation). Muehecke (1972) in his monograph on Thematic Cartography, refers to random sampling, preprocessing techniques, sifting, filtering and enhancing information, trend analysis and discusses the usefulness of SPSS in spatial analysis. Peucker (1972) cites an evaluation of a potential ski resort with multiple regression analysis against 30 snow sampling stations (over 4 years) and elevation, slope, vegetation, sun intensity, water areas, and

quality (from professional skiers).

We are above simply pressing the versatility of these methods which have seen use in the U.S. for geophysical problems. A bio-medical stat package, BMD, was employed for oceanographic purposes (Ben-Yaakov, 1971). BMD is an "unsupported" (no consulting available, no guarantee there are no systems problems) program at Columbia. For some problems, it is more efficient than SPSS, but lacks its generality.

In this vein, we requested detailed information from the Soviets regarding their procedures but received no reply. Professor Bellousov, head of earth sciences at the State University in Moscow, was aware of our project and asked to visit our office when he was in New York. The conversation was somewhat one-sided, but we did learn that the Russians had constructed a Regional Seismicity Map of the U.S.S.R. under the direction of E.F. Severeyenski, by correlating some 16-17 geophysical variables against seismicity along with geological indices such as fault lengths, crossings, displacement, and slope gradient. A particularly strong correlation exists along "hinge lines": regions of no motion between uplift and downwarp. We found a similar visual correlation in the work of George Adams, who constructed for us a map of total crustal deformation since the upper Cretaceous for the eastern U.S.

This technique has allowed the Soviets to assign seismic risk to areas that had no historical record or surface manifestation of seismic activity. Probable magnitude and location can be assigned but not time of occurrence. Belousov cited several incidents establishing the success of the procedure; the most spectacular being a magnitude 7 quake in a

region of no previous activity. Engineers had ignored the statistical inference with considerable damage the result.

We received word at the spring meeting of the AGU that Frank Press had called for a similar mapping of the U.S. Previous efforts such as Altermisse's epicenter maps indicate frequency of occurrence, intensity, or damage. An overlay of structural elements (e.g. faults) on seismic frequency is provided by the Seismotectonic Map of the Eastern United States by J.B. Hadley and J.F. Devine of the U.S.G.S. (generated by computer cartography). This combining of two maps represents more of a convenience than an advance towards the sophistication of the Russian effort. Quantitative predictions for "aseismic" regions are nonexistent. Such a map may be constructed from our statistical results.

We later heard from Professor Nikolaev in Geological Sciences at the Moscow University that Belousov had brought him up to date on our effort and he was sending along literature that might be useful. The reprints, all in Russian, related to geomorphology and had little to do on mapping or statistics.

In view of the Russian effort, Press's recent statement, and accelerating interest in statistical mapping, it is overwhelmingly apparent that if we did not pursue a similar approach, our effort would shortly have little value. Lack of information from ostensibly the most experienced -- the Russians -- indicated we would have to develop our own procedures, and time/expense dictated that we make use of in-house capabilities. Competent personnel in computerized data manipulation and statistics

are in extreme demand and we were unable to secure any one person who was really qualified from the start. Our attempt to develop our own expertise indicated it would take close to a year to develop finesse of which we would be confident, not long in terms of other projects but too long in terms of our own contract periods. We found that work of this nature is sufficiently mundane that many groups subcontract the data manipulation and statistics out to programming concerns to free investigators from "housekeeping" chores. We include brochures and letters of recommendation from the concern brought into the project. They maintain our files and developed software to manipulate our large data base. From page 60 on is a brief statement of the procedures to be pursued by Calculogic, Inc. and the hardware available to this concern. Also included is a list of variables considered for subjection to the multivariate analysis. Noting the predictor equation, given in the brief statement of procedures, it provides velocity surfaces similar to those employed by Vaníček for inferring motion where relevelling lines are incomplete (see, for instance, the Proceedings of the CRCM Meeting, Zurich, 1974). Vaníček's procedure relies only on relevelling data whereas our velocity surface includes the inference of other geophysical parameters away from traverses. In this respect we should note that the correlation between vertical motion and gravity is so strong that Dr. W. Strange, formerly of the Gravity Branch, NOAA, is now with NGS to provide statistical prediction of regions of high motion from gravity data.

Variables of Study for the Contemporary Mobility Map

Review of types of geoscience data -- geologic, geomorphologic, and geophysical -- dictated that we restrict ourselves to primarily geophysical data as this information was already digitized, or because of its numeric format, it was in a form that provided immediate analysis, and hence was worthwhile to digitize ourselves.

No geologic-geomorphologic data bank is publicly available in the U.S. and an examination of the GEOMAP format given in a previous section should make immediately apparent the huge task of assembling this type of information. Thirty principals were involved in the construction of the Russian map from this type of information. Taking into account supporting staff, the Soviet effort likely exceeds ours in the total number of people involved by two orders of magnitude. There was no hope that we could deal with this type of information at this time.

We provide below a description of each variable we plan to employ, reasons why it may be significant, and problems associated with it. It should be noted that the only temporal variations that are feasible to handle are rates, rates of change, and frequencies.

Position (longitude, latitude)

The position of data in terms of longitude and latitude represents controlling category. These location points are being expressed in standardized form and in a uniform way; incoming data are transformed to meet this format. The position represents the main independent variable and the base for handling the various kinds of spatially dis-

tributed data available. Longitudes and latitude will be used to generate unit areas for multivariate analysis. The coordinates are expressed in degrees and thousands of degrees.

A frequency distribution of data density for the other variables has been run to determine the optimum dimensions of unit areas for the maximum utilization of the statistical analysis. For the moment, this is assessed to be 30 km by 30 km.

For some of the data (e.g., geodetic relelling), latitude and longitude had to be assigned by ourselves at great effort. Other data deemed not crucial were deferred if positions could not be readily assigned.

Oil, water, geothermal well.

This variable allows for distinguishing the type of wells drilled below the surfacial material. Tapped oil and water deposits will have a strong correlation with crustal motion; particular areas of importance being coastal regions in Texas, Louisiana, and California which are undergoing subsidence. Occurance of these deposits are also implicit indices of geologic province; another indicator in assessing crustal motion. We have digitized information on over 30,000 wells obtained from the AAPG.

Ambient average temperature

This variable, amongst things reflects elevation and affects erosion rates. It is potentially an indicator of uplift or downwarp, as is topography; cold temperatures on Mt. Whitney, hot temperatures in Death Valley. The usefulness of this variable as an index will be determined

in the correlation analysis which will yield some indication of the signal strength of its relationship to crustal stability. A reason for including this indicator is that it has been provided in digitized form and is inexpensively included in the analysis. If the indicator is unimportant, useful information is still obtained.

Flow rate of water

The flow rate variable (gpm) is a function of the nature of rock porosity, and structural defects (fractures). It is thus related with past tensions in the crust and with erosional unloading. In the coastal regions of Texas which are subsiding as ground water is drawn off, the value of this indicator is quite obvious.

Geologic setting

Incorporated in the well hole data are types of geologic structure of the region in which the hole is located. They are defined by the following categories:

1. basin
2. mildly folded rocks
3. lightly folded rocks
4. salt domes in vicinity
5. inactive volcanics
6. active earthquake areas
7. shield area

Eventually, geological and geomorphological indicators should be incorporated in this effort. Correlating the above provides an initial step in this direction and should provide a feeling for dealing with a more qualitative data type.

Elevation and topography

Elevations are provided on much of the digitized data. It is available and is readily and cheaply incorporated into the analysis. We do expect this variable to be an indicator and we are employing it -- high areas and areas below sea level may be expected to be active. More useful indicators, however, are likely to be the free air gravity anomaly and a comparison of corrected and uncorrected (for the topographic effect) heat flow data. An important case in point is to compare two mountainous structures which are identical in form. One structure may be relatively stable, and the other undergoing intensive tectonism, i.e., they are both only momentarily identical. A correlation based on elevation only would assign too high a potential motion to the quiet feature and too low a potential motion to the highly active feature. Elevation is, however, a good indicator of activity and is implicitly picked up by the free air anomaly along with the signature of lack of equilibrium manifested in the movement of the active feature. That is, the free air anomaly would be identical for both features if they were both stable. As one is and one isn't, the data will differ, but elevation influence is still included.

Prior to our decision to let free air anomalies and corrected heat flow reflect topography correlation, we had been in contact with USGS and agencies of the U.S. Air Force to obtain digitized topo data. At the time of our correspondence, the USGS data, which was limited, had unfortunately become unrecoverable from their tapes.

The U.S. Air Force apparently has elevation data at every 250 ft horizontal interval obtained by radar overflight. This huge data base might eventually be incorporated in a study of this type. Its inclusion is hardly warranted at the present stage.

Geothermal setting

Four indices categorize this information which describes regional situations; known geothermal setting, etc.

A more accurate regional picture can be obtained from the quantitative information. These categories were provided however, in digitized form by the AAPG and can be incorporated into the analysis with very little effort. They may serve as a check or may yield some interesting correlations.

Water depth

Formations containing considerable quantity of water bear relationships with the rate of heat flow, and the material status of local rock, etc. It may or may not have a significant correlation. Either situation is useful. A strong indicator becomes useful in predicting and would likely provoke research to determine the cause of the relationship.

Permafrost depth

The depth of permafrost is controlled by the equilibrium setting between mean annual air temperature and the geothermal conditions. Cross correlation between temperature (mean annual temperature of air) and permafrost may provide consistent information of geothermal effect where only scarce geophysical data are available. On the data tape, permafrost depth is expressed in meters. This variable is incorporated in anticipation of including Canadian data.

Temperature gradient in the crust

Temperature gradient will likely show some correlation with crustal movements, especially near continental margins and volcanic areas. Regions of recent tectonic activity tend to have higher temperature gradients than stable areas because of warmer buried rock. Heat energy is often connected with deformation.

Likewise, deformation is expected to indicate geothermal potential.

Conductivities are not associated with the AAPG data points, hence direct heat flow cannot be inferred. However, a high temperature gradient would certainly draw attention to the possibility of good geothermal potential.

Thermal conductivity

This variable is dependent on rock type, temperature, water content, stress and other local conditions, which in turn are undoubtedly related to the dynamics of crustal instability. Conductivity was provided by USGS for over 300 stations (Lachenbruch and coworkers).

Heat flow - uncorrected

Heat flow - corrected

Anomalous surface heat flows are indicators of geothermal potential, and have a more pristine value as possible plate boundary markers. Anomalous uplift (or downwarp) are known to correlate strongly with regional heat flow anomalies. Corrected heat flow includes compensation for topographic relief, hence incorporation of both variables implicitly includes a potential indicator of crustal instability, topographic relief, that would otherwise be difficult to employ.

Volcanics

Volcanoes are surface expression of tectonic activity, thermal processes, and are associated with seismicity. Their occurrence and frequency per unit area will be included as variables in the analysis.

Magnetics

Dynamics of crustal stability manifest themselves in residual stress, heat flow, etc., all of which affect the magnetic permeability of the earth's crust.

The dynamics are expected to be anisotropic, hence there will likely be directional trends in local magnetics. Incorporation of all the magnetic variables below into the analysis is readily done; Dr. Fabiano of USGS provided digitized measurements at 14,000 geographic points of the following variables:

- 1) Declination
- 2) Dip
- 3) Horizontal Intensity
- 4) Vertical Intensity
- 5) Total Intensity
- 6) North Component
- 7) East Component

Results given at the Geothermal Session of the Fall AGU meeting indicated correlations of local magnetics with heat flow.

Velocities and accelerations from relevelling and ride gage data

Relevelling offers the most significant and direct data for the study of vertical crustal movements. Relevelling data will be run against all other indices and variables to obtain correlations. They represent direct observation of the positive or negative changes in elevation between two or more series of measurements with geodetic instrumentation. The preparation of the data for the work tape has involved the location of benchmarks and the integration of the network lines so as to provide consistent reference points. The changes are expressed in terms of rates, that is in average change over the last hundred years (cm yr^{-1}). Local accelerations are being inferred where there have been a sufficient number of relevellings (in units of cm. yr.^{-2}).

We initially had been apprised that the relevelling data was not digitized and as this information comprised our prime data base we anticipated having to digitize the information ourselves. In addition we learned that most of the U.S. data was unreduced, meaning that most of the data was really unavailable to us. At this time only some portion of the gulf area and mid-Atlantic states represented useable data. This situation compelled us to assume the direction of attempting to infer crustal movement elsewhere through a statistical correlation analysis.

In August 1974, B. K. Meade, head of the Vertical Network Branch of NGS informed us that the reduced data was digitized and available on tape and that the Geological Sciences Department of Cornell University was processing the data as this effort was halted at NGS due to a lack of funds. He indicated that we would likely be able to obtain this data rather quickly. We were unable to secure the data until late January, 1975.

In the interim, a day's visit to NGS acquainted us with the status, reducing procedures, and problems associated with the relevening data. Sanford Holdahl of NGS was most helpful.

We were taken aback to learn that the benchmarks on which the geodetic relevening data is spatially referenced are not assigned positions according to any amenable reference frame such as latitude and longitude. Each benchmark is located by a rather lengthy description which positions it, say "30' due west of the fire hydrant on the corner of _____, etc." All the other geophysical variables against which we were going to correlate the explicit data base-relevening-are assigned a latitude and longitude. The present method of locating benchmarks has been traditionally employed by land surveyors in this country for the past several centuries. NGS is aware of the impediments presented by this situation and hopes to initiate a program in the next several years to assign latitude and longitude to benchmarks. Not only will such an effort make the relevening data consistent with the rest of the geophysical measurements in this country, but with the accuracies of present satellite navigation, the ability to recover benchmarks or locate the position of benchmarks will be greatly enhanced. There are, however, about 300,000 benchmarks in the country. Whether NGS attempts to assign positions from log book information or by going into the field, the effort will take a long time. Due to the time lapse between the entires in log books and the present, there may be a feeling that locating the benchmarks in the field may be no more difficult than assigning positions from the office. In such case, it would be most economical to assign positions during each new relevening

run in the field. The time factor for assigning positions then runs into decades. We are suggesting to NGS that in the interim, it would be useful to provide positions for only the beginning and ending benchmarks of each traverse. Since the distance between each benchmark is given rather accurately, we will be able to adjust, by computer, our own data to provide the best possible positions for all benchmarks. These positions could be further improved with time by the addition of actual positions to scattered benchmarks between end points and adjusting the whole line again. We have since learned that two separate sets of benchmarks are maintained by the triangulation Branch and the Vertical Network Branch of NGS. The Triangulation Branch benchmarks are assigned position by latitude and longitude and several percent of these benchmarks coincide with those of the Vertical Network Branch. We will later employ these to improve our positions.

NGS has published small maps showing contoured regions of uplift and sinking (e.g., Holdahl and Morrison, 1972). The scales of these maps were such that only a rough approximate of position was necessary for satisfactory representation. These maps we might have used to infer actual uplift data. We chose, however, to attempt to assign positions ourselves as accurately as possible. We did so for the following reasons: (1) Estimations of areas of uplift or downwarp in the NGS maps were rough. To employ this information would introduce before we even attempted our statistical analysis, an "averaging" or bias. Our own statistical procedures would be far more proper and less subject to error if we employed the primary or actual data base. (2) Assigning actual positions provided the foundation for expanding the versatility of our efforts. If regional maps of greater detail were eventually required, the levelling data base would be available to a resolution of several kilometers and possibly finer as positions came to be known with greater accuracy.

(3) Most important, this contribution on our part provides us with an exchange basis between NGS, Cornell, and ourselves. It is particularly important for us to cultivate this mutual cooperation in processing the relevelling data as its reduction is not complete and without the combined efforts of NGS and Cornell, the most important data would be unavailable to us. We will be providing both agencies with our results.

NGS provides maps showing traverses, names of towns at the beginning and end of traverses, and the distance from the beginning of the traverse to each benchmark. With this material we proceeded to assign positions as follows:

(1) A heavy duty polished string was marked off with kilometers identical to the scale given on the map.

(2) The string was pinned along the traverse line--in this manner we could follow loops and bends.

(3) benchmarks along the traverse could then be marked off on the map using the distances provided by NGS from beginning point to individual benchmarks.

(4) A digitizer was then employed to punch out positions of benchmarks on cards.

(5) A computer program transform the positions obtained on the digitizer to latitude and longitude.

(6) To provide an error check, the same computer program determines from the positions obtained by the digitizer, distances from beginning point to individual positions assigned to the benchmarks. These distances are then compared with the distances given by NGS. End point of runs runs also coincide with towns of known geographic position, providing an additional check.

Assigning positions and digitizing could proceed more rapidly if the digitizer we employed had a display showing in addition to coordinates, the accumulative distance from point to point. Acquiring software and hardware for this feature would have cost about \$10,000. This approach however, leaves no permanent visual record on the map. We opted for the hand technique for cost and for the back up provided by the visual record.

We now have a standard manual and computer procedure for assigning positions to possibly all 300,000 vertical network benchmarks in the U.S. The work is easily carried on by undergraduate students at nominal cost.

The digitized data from NGS consisted of elevation changes between releveing and the dates of releveing. The data had to be reformatted for ease in manipulation. In some cases, a line was releveled several times, allowing determination of accelerations. IN many cases, elevations of benchmarks were provided. There were, however, many different types of inconsistencies that required a special treatment. If $\Delta h = y_1 - y_0$ is the change in elevation for a single releveing over some period Δt where y_0 = the base elevation and y_1 = the new elevation, then the velocity for a benchmark is given by

$$v = \frac{\Delta h}{\Delta t} + 0 (\Delta t)$$

If several releveings are made, then three elevations may be inferred for the benchmark, and both velocity and acceleration may be inferred:

$$v = \frac{\alpha^2(y_2 - y_1) + \frac{1}{2}\{\alpha y_3 + y_0 - (1 + \alpha)y_2\}}{\alpha^2(t_2 - t_1)} + 0(\Delta t^2)$$

$$a = \frac{\alpha y_2 - (1 + \alpha) y_1 + y_0}{\alpha^2(t_2 - t_1)^2} + 0(\Delta t)$$

where a is acceleration and $\alpha = (t_1 - t_0)/(t_2 - t_1)$, and t is time, $t_2 > t_1 > t_0$.

When there are enough relevellings to determine accelerations, velocities are "updated" to present time, i.e.

$$V_{\text{now}} = a(t_{\text{now}} - t_{\text{last relevelling}}) + V_{\text{last relevelling}}$$

Otherwise, present velocities are assumed the same as inferred from the last relevellings. Where there are more than several data points with respect to time at a geographic point--this is particularly true for the tide gauge data--a polynomial is fitted.

We include copies of the reformatted relevelling data, and positions that we have assigned to benchmarks. These positions are given to the nearest minute (≈ 1.8 km). Discrepancies in town positions (always beginning and end points of a traverse) inferred from NGS maps and those given in the Times Atlas and estimated error in stringing indicated that we should tolerate no more than a 3 km discrepancy in the positions of towns (beginning or end points) inferred from our computations. We have assigned positions to 15,361 points. 55% of our original assignments met our criterion. The other positions are being corrected. This task should be complete within the month. Our most grievous error was 20 km.

Appendix IX : Sample Printout (Relevelling Positions)

Y	X	LATIT		LONGT		DISTANCE DIG. UNITS	CUMULATIVE DIG. UNITS	DISTANCE KMS	CUMULATIVE KMS
18288	07758	32	2	100	0				
18200	07696	32	1	100	3	107.65	107.65	4.58	4.58
18113	07645	32	0	100	5	100.85	208.49	3.94	8.51
18046	07505	31	59	100	10	155.21	363.70	8.64	17.16
17975	07347	31	58	100	15	173.22	536.92	9.67	26.82
17817	07385	31	56	100	15	162.51	699.43	1.23	28.05
17777	07322	31	55	100	17	74.63	774.05	3.97	32.02
17768	07230	31	55	100	20	92.44	866.49	5.22	37.24
17777	07155	31	55	100	22	75.54	942.03	4.08	41.32
17756	07108	31	55	100	24	51.48	993.51	2.85	44.17
17756	07009	31	55	100	27	99.00	1092.51	5.51	49.68
17767	06921	31	55	100	29	88.68	1181.19	4.78	54.46
17667	06886	31	54	100	31	105.95	1287.14	3.08	57.55
17664	06822	31	54	100	33	64.07	1351.21	3.58	61.13
17575	06824	31	53	100	33	89.02	1440.23	1.05	62.18
17348	06757	31	50	100	37	236.68	1676.91	6.27	68.44
17306	06681	31	49	100	39	86.83	1763.75	4.62	73.06
17270	06638	31	49	100	41	56.08	1819.83	2.74	75.80
17263	06620	31	48	100	41	19.31	1839.14	1.06	76.86
17245	06512	31	48	100	45	109.49	1948.63	6.11	82.97
17227	06411	31	48	100	48	102.59	2051.22	5.72	88.69
17191	05965	31	47	101	1	447.45	2498.67	24.80	113.49
17202	05832	31	48	101	5	133.45	2632.12	7.19	120.68
17204	05706	31	48	101	9	126.02	2758.14	6.89	127.57
17234	05463	31	48	101	16	244.84	3002.98	13.08	140.65
17230	05146	31	48	101	26	317.03	3320.01	17.42	158.07
17235	05072	31	48	101	28	74.17	3394.18	4.02	162.09
17270	04919	31	49	101	32	156.95	3551.13	8.14	170.23
17286	04843	31	49	101	35	77.67	3628.80	4.06	174.29
17326	04747	31	49	101	37	104.00	3732.80	5.00	179.29
17356	04638	31	50	101	40	113.05	3845.85	5.79	185.07
17357	04491	31	50	101	45	152.61	3998.46	7.82	192.90
17434	04376	31	51	101	48	120.81	4119.26	6.10	198.99
17487	04241	31	52	101	52	145.03	4264.29	7.12	206.11
17547	04028	31	52	101	58	221.29	4485.58	11.41	217.52
17570	03899	31	53	102	2	131.03	4616.61	7.01	224.53
17621	03767	31	53	102	6	141.51	4758.12	7.03	231.56
17637	03720	31	54	102	7	49.65	4807.77	2.52	234.08
17645	03670	31	54	102	9	50.64	4858.40	2.73	236.81
17654	03589	31	54	102	11	81.50	4939.89	4.45	241.25
17694	03469	31	54	102	15	126.49	5066.38	6.46	247.71
17761	03300	31	55	102	20	181.80	5248.18	9.07	256.78
17755	03197	31	55	102	23	103.17	5351.35	5.76	262.54
17723	03088	31	55	102	26	113.60	5464.95	6.22	268.77
17674	02963	31	54	102	30	134.26	5599.20	7.18	275.95
17663	02854	31	54	102	33	109.55	5708.75	6.10	282.05
17698	02766	31	54	102	36	94.70	5803.46	4.75	286.79
17764	02664	31	55	102	39	121.49	5924.95	5.42	292.22
17748	02539	31	55	102	43	126.02	6050.96	7.02	299.24
17757	02418	31	55	102	46	121.33	6172.30	6.70	305.94
17760	02363	31	55	102	48	55.08	6227.38	3.05	308.99
17777	02266	31	55	102	51	98.48	6325.85	5.34	314.33
17786	02233	31	56	102	52	34.21	6360.05	1.81	316.14
17795	02172	31	56	102	54	61.66	6421.71	3.37	319.51
17799	02148	31	56	102	55	24.33	6446.04	1.32	320.83

Gravity

A strong correlation between vertical uplift-downward and gravity is already recognized, and is being employed by NGS as an indicator to guide the efforts of its Vertical Network Branch. Some 100,000 points based on geographical position have been obtained to be employed in this analysis and consist of the following variables: (1) Observed gravity

(2) Free air anomaly--this useful parameter has previously been discussed as a means to recognize active or inactive regions of high topographic relief.

(3) Bouger anomaly--this variable may indicate surface manifestations of basement dynamics.

Tectonic stress, maximum or minimum magnitudes

Tectonic stress data depict the distribution of forces acting in the earth's crust and will be definite indicators of crustal stability. This so far is a sparse data base (only 300 geographic points estimated for the U.S.). It's collection for our use as been deferred until development of procedures for dealing with more complete and more numerous types of data, the majority of which is already compiled. We have located all appropriate literature in order to collect this data ourselves.

Principal direction of horizontal stress

The direction of the horizontal stress reveals the pattern of the forces, either tensional or compressional, acting on the crust to deform it, e.g., swells and basins or other relief. Good correlation should appear between stress orientations and long-term isostatic arching and denudation.

Number of seismic events at a given point and average time interval between events

Spatial and temporal clustering of seismic movements will be correlated against sets of other dynamic variables; volcanic activity, stress

arching, heat flow, etc. Particularly important in terms of geologic hazard will be the regression between quake severity and time interval between events.

Focal depth

This digitized information is provided by the Seismic Risk Branch of the USGS. The regression curves should reveal the importance of this parameter; a very useful spinoff of this effort.

Body wave magnitude

This variable will be an implicit indicator integrating effects of the dynamics and regional matter properties of the earth, all important crustal stability parameters.

Intensity (modified Mercalli scale)

Intensity is directly related to stress release which also requires strain. Quake intensity will correlate well with permanent vertical displacement. Correlating intensity against other geophysical variables in turn allows probabilistic assignment of seismic potential from the correlations with the other variables. In constructing a vertical motion map, we also obtain a seismic risk map of much greater sophistication than those presently available.

Diastrophism

This qualitative variable is included in the analysis because it is on hand and is readily treated. It provides a companion correlation to check the seismic and levelling correlations.

Tsunamis

Seismic sea-waves released by earthquakes will correlate with the sudden occurrence of faulting in areas of high seismicity, or with submarine landslides. Most of them are related with rapid vertical movement in the crust. Again

this data in on hand and is readily included as a parameter in the analyses. Correlations may arise for relationships not of specific interest here but still representing valuable spin off which would be useful for a generalized geological risk map.

Seiches

Seiches are associated with large earthquakes of low-frequency energy and may implicitly be a signature of uplift dynamics. We can categorize it with the type of information provided by tsunamis. Its importance should be revealed by the regressions.

Nontectonic - rockburst, coalbump, explosion, collapse

Local non-tectonic accidents at the surface of the crust like rockbursts, coalbump, etc. are sudden failures that reveal accumulated stress and may have a meaningful distribution in terms of the crust's zones of weakness and particular susceptibility to break under applied stresses. Such phenomena may result from unloading and denudation or from man's activity but they can reveal local conditions of the crust, hence are potential indicators of vertical movement.

Surface wave magnitude

The earthquake waves range from large waves to minute omnipresent seismic pulsations and from very fast to very slow movements. In that spectrum of seismic movements, the dispersion and propagation along the earth's surface and the types of particle motion in surface waves bear direct significance in the study of the stability of the crust because this variable is directly related with the crustal structure, hence very likely to correlate highly with crustal movements.

Cultural effects

This variable distantly relates structure and dynamics that might be reflected in different regional response to seismic disturbances. It also provides a basis for weighting seismic activity with respect to actual hazard. Again, this data was readily available and readily incorporated into the study.

Richter magnitude

The characteristic quantity of total energy released by an earthquake is recorded as Richter magnitude, hence reflects potential of permanent strain. This should be a strong correlator.

Local magnitude

Local magnitude reflects local material and structural conditions (e.g. stress, temperature), hence is a potential indicator which is available and readily incorporated into the analysis.

Precipitation

As energy input for dissection of the earth surface and erosion, precipitation may show some correlation with relief, overburden release, etc. Precipitation categories correspond to zones or belts. At least for some geological timespans precipitation may be related to denudation rates and, thus, to isostatic re-adjustments of the crust. It is difficult to estimate from past geological records old precipitation rates, but some facies providing evidence concerning depositional conditions are revealed by the texture of sediments. For the 10^8 year map and for the 10^4 year mpa, only broad categories can be defined, whereas for the 10^2 year map data can be much more refined and devised in numerical categories or used directly as mean annual rain in mm. The correlations obtained for this variable will need careful perusal to infer its

meaning due to the temporal variation of the variable and the response of those parameters it affects.

A tape of digitized data points has been obtained from appropriate government agencies; half of the information is apparently missing and positions need be assigned to data collection stations, hence this information is to be deferred.

Tellurics

The GRID data bank is incorporating telluric information for its geothermal files. This data is most conveniently included when it is finally digitized.

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