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RECORD No. 1965/73

VISIT TO CANADA AND THE USA, 1964

by

A. J. FLAVELLE

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SUMMARY

The writer visited Canada and the United States of America for a period of four months to investigate the latest developments in gravity interpretation. Two months were spent with the Dominion Observatory of Canada on the study of the relations of gravity to crustal structure and tectonics. The relation between gravity data and seismic and aeromagnetic data was studied at Lamont Geological Observatory, the United States Geological Survey, and the Institute of Geophysics, University of Hawaii. Some time was spent at the Bedford Institute of Oceanography and the Lamont Geological Observatory in studying the techniques of shipborne gravity measurements. Techniques relating to the interpretation of detailed and semi-detailed gravity data over sedimentary basins were briefly reviewed at Geophysical Associates Inc. of Houston and the Colorado School of Mines.

1. INTRODUCTION

During the early part of 1964, a number of organisations in the USA and Canada were contacted with respect to a proposed overseas tour by A.J. Flavelle of the Gravity Group of the Bureau of Mineral Resources (BMR). The object of the tour was to be the study of the latest developments in the interpretation of gravity data. Particular emphasis was to be given to interpretational techniques that related to the structure of sedimentary basins.

Approval to undertake the tour was given by the Overseas Travel Committee on 10th June 1964. The tour lasted approximately eighteen weeks, from 30th June 1964 to 29th October 1964. Details of itinerary and the organisations visited are given in Appendixes 1 and 2 respectively.

2. DETAILS OF THE TOUR

The organisations visited and the time spent at each one are listed in Appendix 2. This Section gives a description of the visits to these organisations in chronological order.

Geophysical Associates Inc.

The type of interpretational work being carried out by Dr Nettleton and his associates is routine. They do not use any methods that have not already been used or studied by members of the BMR Gravity Group. The main benefit to be derived from the visit was an opportunity to study some confidential gravity maps of the Texas area. Discussions were also held with Dr Nettleton about shipborne gravity techniques.

A review of the techniques used by staff of Geophysical Associates Inc. showed that these techniques are not new and are well known in the profession. An example is the use of automatic computors for calculating the gravitational effect of a two-dimensional geological section. The technique adopted by Geophysical Associates Inc. differs somewhat from the method developed by the BMR Gravity Group. The BMR technique is more general and has definite advantages over that of Geophysical Associates Inc.

Some time was spent examining a gravity map covering a part of the Gulf of Mexico. The stations were established by means of an underwater gravity meter on a 1-mile by 1½-mile grid. The survey covered an area of about 8000 square miles. Subsequent drilling showed the area to be one of thick Mesozoic and Tertiary sediments. There are numerous salt domes in the area and the gravity investigation was outstandingly successful in finding and delineating them. In Australia there are many areas in which sedimentary structure could be delineated by semi-detailed surveys.

The survey in the Gulf of Mexico was made in two stages:

(a) A review was made of the possible density contrasts in the area, followed by a test survey for the purposes of establishing an optimum station spacing.

(b) The remainder of the area was gridded at the optimum station interval.

Although (b) possibly does not fall within the scope of the BMR, consideration should be given to doing a survey of the type described in (a).

Shipborne gravity techniques were discussed in some detail with Dr Nettleton. It is claimed that an accuracy of ± 2 mgals can be achieved. The main sources of error are errors in reading caused by rough seas and errors in navigation that cause an error in the computation of the 'Eotvos effect'. Geophysical Associates Inc. are at present making a commercial shipborne gravity survey off the coast of California. They are not using underwater meters for the establishment of base values, but consider it better to use cross-traverses to tie the lines together. The resultant loops are then examined and adjustments made to the loops in order to prodice a zero (or small) misclosure around each loop.

Dr Nettleton also discussed an interesting feature of gravity profiles over some buried faults. Often a Bouguer anomaly profile shows a small displacement in the curve over a buried fault. The magnitude of the displacement is about 0.2 - 0.4 mgals. This displacement is always observed vertically above the fault plane. It will appear when there is no appreciable density contrast within the sedimentary column, and has been observed over a large number of buried faults. Dr Nettleton could offer no explanation for this phenomenon, although it is possible that compaction could cause it in some way.

United States Geological Survey, Washington Office

Four days were spent discussing interpretational techniques with Dr La Fehr, gravity-magnetic correlation with Mr Zietz, and programming techniques with Dr Anderson.

Dr La Fehr is at present analysing data (semi-detailed scale) from an area in northern California. The general objects of his investigation are:

(a) To establish whether the area is compensated on either a regional scale or a local scale. He uses the well-known criteria that if the area is compensated then the average free-air anomaly over the area should be close to zero.

(b) To establish the level at which local disturbing masses occur. Dr La Fehr has used some formulae developed by Bott and Smith (1958) for this work and in addition has made important modifications to their formulae. The results of this work will be published in the Journal of Geophysical Research.

(c) To develop general methods of computing the masses of bodies that cause individual anomalies.

Mr. Zietz, the Chief of the Regional Geophysics Branch has been studying a geophysical feature known as the Mid-continental Ridge. It is expressed as a ridge both gravimetrically and magnetically and runs south from Lake Superior to north Texas, but is not expressed as a surface geological feature.

The correlation between the gravity and magnetic data is made on a qualitative basis. The source of the 'ridge' is thought to consist of a band of basic igneous rocks (40 - 60 miles wide) within the basement, with metamorphic and acidic rocks on either side.

The results of drilling and aeromagnetic depth estimations show that the relative negative gravity anomalies occurring on both sides of the gravity 'ridge' are not caused by sediments. The mode and degree of isostatic compensation is not known. There is very little elevation variation in the area. It would appear that a careful but qualitative assessment of the magnetic and gravity data has resulted in a comprehensive picture of the 'ridge' and its bordering areas, although seismic work will be needed to investigate crustal thicknesses in the area.

The geophysicists of the United States Geological Survey have considerable confidence in their aeromagnetic data. In areas adjacent to the abovementioned 'ridge', the metamorphic and igneous complex is partially covered by glacial sediments. They have used the aeromagnetic data to delineate the various geological units within the complex by extrapolating from areas of outcrop. A geological map can then be compiled from the aeromagnetic data.

The United States Geological Survey has an Automatic Computing Branch, which undertakes all programming for the Regional Geophysics Branch. A number of programmes relating to gravity interpretation have been written. They are of a routine nature and are similar to the programmes written within the Gravity Group of the BMR.

United States Coast and Geodetic Survey (USCGS)

A short visit was made to the USCGS for further discussions concerning shipborne gravity work. The USCGS operates a La Coste & Romberg meter mounted on a 300-ft, 2600-ton vessel.

The work done by the USCGS has shown that the main source of error for shipborne gravity work is in the varying weather and oceanographic conditons. If two adjacent traverses are run in opposite directions, in some cases the gravity values cannot be compared. Although the first derivative of each profile is similar, it is necessary to add a constant to the gravity values of one or both of the traverses to obtain absolute gravity values. For this reason, Dr Orlin of the USCGS suggests that any shipborne survey should be planned so that a certain number of cross-traverses are run or, if the sea is shallow enough, a number of underwater gravity stations are read.

Dominion Observatory, Gravity Division

Automatic data processing. A study of the Gravity Division's field techniques has shown that they differ from those used by the BMR. Because of these differences, it would not be feasible to use any of their programmes written for data processing. A paper describing the Gravity Division's data processing system has just been written and will be published.

The Division first investigated data processing in 1958 and at present their system appears to be working well. A comprehensive data storage and retrieval system is being developed. For this system, a combination of cards and magnetic tapes will be used. Although work commenced in 1958, a complete, foolproof data processing system was not developed until 1963. At least two systems were completely developed and then discarded because they could not handle all possible types of data. During its five years of development, the project was under the direction of Mr Tanner. Of the twenty members of the professional staff in the Division, nine can programme with a fair degree of facility and three are skilled programmers. One geophysicist works full time on data processing and programming. The scientific programming is usually carried out by the geophysicist who wishes to apply the mathematical technique to a specific interpretational or geodetic problem. Specialised help is provided by one of the three skilled programmers.

Special programmes. A programme has been developed that will generate Bouguer anomaly values at grid points using a three-dimensional geological model. The area of interest is specified in terms of vertical rectangular blocks. Each particular block can be given a number of density contrasts (positive and negative) and depths; thus, for any particular block, density discontinuities can be introduced at various levels. If necessary, the blocks can be drawn right down to the bottom of the crust, thus giving a total Bouguer anomaly and enabling isostatic investigations to be made by using the Bouguer anomaly alone. The estimated cost of the programme development (including salaries) was 10,000 US dollars.

Interpretation of regional gravity data. Most of the systematic gravity mapping so far carried out by the Gravity Division has been over the Precambrian Shield. It is considered that if any attempt be made to explain the large-scale gravity features in terms of structure, then the features that occur over the oldest rocks should be studied first. The reasons for this are:

(1) Tectonic activity of a particular geosyncline or orogen has been completed.

(2) Because of erosion, the surface geological section is usually a deep-seated one.

(3) The number of previous orogens in the area is reduced to a minimum, thus reducing the general complexity of the section.

The main interest of the Gravity Division is the geological significance of large-scale gravity features (gravity 'ridges' and regional gravity 'lows'). A number of such features have been mapped in Northern Ontario and Quebec and occur over Precambrian igneous and metamorphic rocks. The object is to present a regional geological picture of such areas, taking into account considerations of isostatic equilibrium. An investigation of major gravity features in northern Quebec has just been completed (Tanner and McConnell, 1964) and the following is a summary of the results of the analysis.

The major gravity features in the area are an east-trending gravity 'ridge' and two linear gravity 'lows' that border the 'ridge' to the north and south. It is considered that the two gravity 'lows' are actually part of a single 'low' caused by crustal thickening. It is assumed that the crustal thickening is caused by dense material which occurs near the surface and which generates the gravity 'ridge'. The main advantage of an interpretation of this type is that a group of major anomalies can be considered together as a whole; for instance, the three major 'lows' in Central Australia (the Ngalia Gravity Trough, the Amadeus Regional Gravity Low, and the Ayers Rock Regional Gravity Low) could be considered as a single gravity 'low'. Although this is a very interesting possible interpretation, it is of course only one of a number of ways in which these major features may be analysed.

Dr van Boekel has completed the study of an area in central Canada. He has used the three-dimensional model technique, which has enabled him to produce a three-dimensional geological model that is compatible with the gravity data.

Fossil meteorite craters. The Gravity Division has a small group making studies on fossil meteorite craters. Magnetic and seismic, as well as gravity, techniques are employed in this study. In addition, a considerable amount of petrological work is done. This project is a good example of how geophysics can be used to elucidate some of the rarer natural phenomena.

A careful study has been made of about ten circular features that range in diameter from one to forty miles. Most of these craters occur on the Precambrian Shield and have been subjected to erosion and glaciation, so that no prominent rims remain. The present expression of the crater is usually a very slight circular depression filled with Phanerozoic (post-Precambrian) sediments. Drilling has shown that shattered and brecciated rock lies below the Phanerozoic sediments.

For the smaller features, a circular gravity minimum coincides with the slight topographic depression of the fossil crater. The larger craters (five-miles diameter or more) exhibit doming in the centre of the depression and have a gravity 'low' over the centre of the crater. The doming is believed to be caused by impact of a large meteorite on the crust. Subsequent central uplift and tilting of any surface sediments could give rise to a surface geological feature that resembles a salt dome.

Data plotting. The Gravity Division makes use of an automatic data plotter. Cards containing the principal facts of gravity stations are processed by the system and plotted automatically by the machine. The plotter marks the station position and Bouguer anomaly for each particular station. It is possible to plot between twenty and thirty stations per minute.

The quality of the print-up by the machine is probably not high enough for BMR publication standards. However, the plotter is very useful in speeding up the use of some of the interpretative programmes. For example, the three-dimensional-anomaly programme produces Bouguer anomalies at grid points. The output from the computer can be fed into the plotter, which will automatically plot positions and print-up values.

Marine gravity. The Division has an active programme of marine gravity measurements. Tests of the La Coste & Romberg and Askania surface gravity meters have just been completed. The results of these tests indicate that the La Coste & Romberg meter is superior to the Askania instrument, but the La Coste & Romberg Horizontal Accelerometer stabilising system has serious weaknesses. Dr La Coste is now engaged in building a stabilised platform for the La Coste & Romberg meter. Mr Bower, of the Dominion Observatory, believes that the La Coste & Romberg surface meter plus a stabilised platform will give results with an accuracy close to ± 2 mgals. At present, this degree of accuracy cannot be obtained consistently. A paper on these tests is due to be published by the Dominion Observatory before the end of the year. The Gravity Division has done a considerable amount of work using a La Coste & Romberg underwater gravity meter. An 8-mile by 8-mile grid coverage has been used and at this station spacing 15 stations are read per 24 hour day. A survey of this type could be somewhat cheaper than shipborne coverage along ten-mile profiles.

Helicopter gravity techniques. A visit to a Dominion Observatory helicopter gravity party operating in Newfoundland was made in company with Mr Tanner. During the visit, the field techniques employed by the party were compared with BMR procedures. The field techniques employed by the Gravity Division do not appear to be superior to those used by the BMR. The party is equipped with a small portable Varian proton magnetometer, which is being used to make measurements over some ultra-basic masses in northern Newfoundland. It would seem that magnetic measurements could also be made over any steep gravity gradient whose source cannot be confidently deduced from other existing information.

The 'Alert Anomaly'. A major gravity 'low', called the 'Alert Anomaly' has been mapped on north-west Greenland and Ellesmere Island. The area also corresponds with a zone of anomalous geomagnetic activity. It has been postulated that the anomalous gravity field correlates in part with a giant superconductor within the upper mantle. The geophysical investigations of this anomalous area were studied with interest as it is an example of how two quite different programmes of scientific investigation can be used to elucidate coastal structure. Work on the 'Alert Anomaly' is continuing and includes gravity, seismic, geomagnetic, aeromagnetic, and heat flow investigations. The geomagnetic work is described in a paper by Whitham and Andersen (1962). The gravity work has been described by Spector in an unpublished thesis submitted to the University of Toronto.

Bedford Institute of Oceanography

Two days were spent at the Bedford Institute of Oceanography in discussions on marine geophysics with Dr B.D. Loncarevic and Mr D. Barrett. The Institute operates an Askania shipborne gravity meter, Alpine gas-explosion seismic gear, and a Varian magnetometer, all mounted on the Canadian survey ship 'Baffin'. The 'Baffin' is a ship of 4500 tons and length 285 feet. It cost approximately 7,000,000 US dollars to build.

The programme of seismic, gravity, and magnetic measurements has been in operation for six weeks. Considerable teething troubles have been experienced with the seismic gear and only six hours of satisfactory work has been done. The Askania gravity meter is operating satisfactorily. The magnetic measurements have given no trouble at all (in comparison with the seismic and gravity work), and they are very easy to obtain.

Two of the operational factors that affect the accuracy of shipborne gravity meters are the speed and size of the boat.

(a) Boat speed. Ten knots seems to be the optimum speed although no systematic experiments have been done at lower speeds (six knots or less). Dr Loncarevic of the Bedford Institute believes that the accuracy would not be greatly affected by cruising at six knots. However, Mr Bower of Dominion Observatory, Gravity Division, believes otherwise. In any case, considerable experimentation would be necessary before operating at six knots. The meter would have to be run over an underwater gravity range for various sea conditions. There are only two such ranges in the Western World: at Halifax and San Francisco. All operators agree that when using a Decca system for navigation, errors would be too high when cruising at six knots. Thus, it is not advisable to operate a shipborne gravity meter at speeds much less than ten knots because of navigational difficulties and the unknown nature of the errors due to ship movement.

(b) Boat size. Most of the test work done on the shipborne gravity meters has been done on ships of 1000 tons or larger. Both Dr Loncarevic and Mr Bower consider that the smallest size ship that should be used is 750 tons.

The Bedford Institute has not had a great deal of success with its marine seismic gear. It has been in operation for six weeks, and is a gas-explosion type, of 50,000 joules output. The maker is Alpine Geophysical Associates of New York. The seismic gear is operated at six knots and gravity measurements are not taken at the same time. An 'eel' containing 20-30 hydrophones is used.

Theoretically it would be possible to operate at ten knots, providing the water is deep enough and the correct hydrophone array is used. The higher the speed of the boat, the greater should be the distance between the 'eel' and the boat; the shallower the water, the smaller should be the distance. The maximum penetration that has been obtained is 800 feet.

Dr Loncarevic also made the following points :

(a) La Coste is converting his gravity meter to the stabilised platform type. It is generally agreed that it will then be the best instrument available.

(b) Texas Instruments Inc. are manufacturing a package instrument for gravity, seismic, and magnetic work.

(c) In its present form the La Coste & Romberg meter is an extremely complex instrument, prone to component failure. Several operators have used the instrument on long voyages, and subsequent detection of electronic-component failure has resulted in all the results being of questionable accuracy.

(d) In order to guard against (c) it would be desirable to take underwater measurements every six to eight hours.

Lamont Geophysical Observatory

Shipborne gravity. Dr Talwani of Lamont believes that an accuracy of ± 2 mgals could only be obtained under ideal conditions. The Lamont group have an Askania meter which uses a stabilised platform. Stabilised platforms are subject to cross-coupling errors (Bower & Watt, 1963) and recent experimental work done by Dr Talwani suggests that errors due to cross-coupling can be as large as 20 mgals. The current La Coste & Romberg meters use horizontal accelerometers for stabilisation and are not subject to cross-coupling errors. However, the new version of the meter will use a stabilised platform and some method of measuring the cross-coupling error will be necessary.

Marine seismic. All oceanographic cruises carried out by Lamont make sonar type seismic reflection profiles. The data from these profiles are used to correct the gravity data for sedimentary thickness.

They have never had any great difficulty in obtaining reasonable seismic data while cruising at ten knots. If a number of hydrophones are available, it is merely a matter of obtaining the optimum hydrophone configuration. If one hydrophone is used, the main problem when cruising at ten knots is excessive noise caused by motion through the water. This is reduced to an acceptable level by hauling in the hydrophone and then 'slackening off' when firing. The speed of the hydrophone through the water is thus reduced for a short time.

The seismic work carried out by Lamont has gone through four stages of development. They have used :

(1) Gas or mechanical sources and a single hydrophone. Frequency of firings is dependent on speed with which the hydrophone can be reeled in and slackened off.

(2) Gas or mechanical sources and multiple hydrophones. No slackening-off needed.

(3) Gas or mechanical source and multiple hydrophone, plus quarter-pound charges detonated every one or two minutes. The explosive charges give penetration of up to 20,000 feet. This work, however, is apparently dangerous and Lamont have decided to discontinue the practice.

(4) Air-gun source and firing every five seconds or less. This technique has recently been developed by Lamont and in their opinion supersedes all other marine seismic techniques.

The air-gun source is a small metal cylinder, about eighteen inches long, and six inches in diameter, into which compressed air is pumped to pressures of between 900 and 3000 lb/in^2. This pressure is released by a special quick-release valve. The rate of firing is determined by the pressure required and the size of the pump being used. A typical set-up is a firing pressure of 1800 lb/in^2 every five seconds for penetration of up to 18,000 feet. At present there is no commercial production of this instrument although Alpine Geophysical Associates are interested in the instrument.

Interpretational techniques. Gravity profiles obtained by shipborne gravity meter are usually interpreted in terms of crustal structure. A correction is made for the sedimentary thickness - this being obtained from continuous 'sonar' profiles. Crustal seismic refraction work is done to establish the local structure of the crust. The densities used for the various crustal layers are obtained indirectly by correlation with seismic velocities. A two-dimensional gravity programme is then used to calculate the effect of various crustal sections. Finally, a section is obtained that fits the observed gravity profile as well as being compatible with seismic and magnetic data.

Most of the gravity interpretation is done by Dr Vajk, who, until he retired recently, was Overseas Exploration Manager for Standard Oil Company (New Jersey). Dr Vajk is at present working on two problems:

(1) Because of their radically different crustal compositions, the oceans and continents show a wide range of Bouguer anomaly values. Dr Vajk suggests that anomalies can be computed on the basis of standard oceanic and continental sections. His so-called 'crustal anomaly' would be :

Observed gravity (corrected for latitude) minus gravitational effect of the standard crust.

It would be somewhat similar to an isostatic anomaly.

(2) Dr Vajk is presenting a paper on the usefulness and use of regionals and residuals at the meeting of the Society of Exploration Geophysicists in November 1964. The main thesis of his paper is that when the Bouguer anomaly field is divided into regional-residual components, the regional component as well as the residual component should be interpreted in terms of geological structure, usually basement structure. In other words, the regional Bouguer anomaly field must be reasonable in terms of geology. Another point made by Dr Vajk is that all mechanical means of separating out regional and residual components are unsuitable for delineation of gravity gradients (i.e. faults). Most methods of regional-residual analysis would show up as two residual features - a 'low' and a 'high'.

United States Geological Survey, Denver Office

Detailed and semi-detailed gravity surveys are done by a group of geophysicists working under Mr Mabey. Most of the surveys are oriented towards specific geological problems and are usually done for other United States Government agencies. A limited amount of automatic computing is used by the group at Denver, mainly for data reduction.

A considerable amount of the work is done in mountainous areas, and terrain corrections are computed for each station. The computation takes about one hour per station and is done by hand. Special circular slide rules based on Swick's tables are used. Satisfactory terrain corrections can only be made when good maps are available, i.e. accurately contoured maps at a scale of 1:62,500 or better. Maps of this scale are available for a substantial portion of the United States.

The interpretative techniques used by the United States Geological Survey are conventional and include qualitative gravity-geology correlation, two-dimensional body fitting, and tests for isostatic equilibrium.

The results of crustal seismic investigations, carried out by the Branch of Crustal Studies of the United States Geological Survey are of extreme interest. They are briefly :

(1) The thickness of the crust east of the Rocky Mountains and including the low flat plains of the mid-west is between 40 and 50 kilometres.

(2) The thickness of the crust west of Denver, which includes areas of high elevations (greater than 10,000 ft), is between 20 and 40 kilometres.

(3) The only area in the western, mountainous part of the continent in which a rise of elevation corresponds with a thickening of the crust is over the Sierra Nevada mountains.

(4) The gravity data are not compatible with a crustal thickness as deduced from seismic data. The two possible explanations of this are that there are significant density variations in the upper mantle or that there are large variations in the thickness of the intermediate layer between the Mohorovicic and Conrad discontinuities.

Work done by the Branch has shown that in the southern United States (Texas and Louisiana) the crust thickens towards the coast (the Gulf of Mexico). Mr Stuart of the Crustal Studies Branch considers that this crustal thickening is associated with sedimentation, but he has not yet fully developed this theory. The above discussions concerning crustal structure took place with Mr Pakiser in Denver and with Mr Stuart, who was in the field at the time of my visit.

Colorado School of Mines

About three days were spent visiting the Colorado School of Mines. Two interesting projects were reviewed :

(1) A small intermontane basin in the Rocky Mountains is being studied by use of gravity and magnetic techniques. The particular gravity technique being used is one of closely spaced (200 ft) stations for elucidation of sedimentary structure. A profile over a fault has shown that the initial fault was an overthrust followed by normal slumping. Some of the gravity features detected in this investigation were most interesting. One gravity 'low' had a magnitude of 6 mgals and a width of 3000 feet.

(2) A visit was made to the Bergen Park Geophysical Observatory run by the Colorado School of Mines. A most interesting piece of equipment in operation at the Observatory is a set of strain gauges. The set consists of two quartz rods, 72 ft long, mounted at right angles to each other and in underground tunnels. By measuring the movements of these rods it is possible to calculate the stress and strain in the adjacent rocks and in particular to detect rock movements associated with earthquakes.

United States Geological Survey, Menlo Park Office

Discussions were held with Dr La Fehr on methods of computing the mass of a body that produces an anomaly. The method he uses is somewhat similar to that used by Bott and Smith (1958). It would seem to the author that the most difficult problem is to delineate accurately an anomaly that can be attributed to a single body. The regional residual method used by Dr La Fehr consists of the qualitative examination of selected profiles.

The results of a recent gravity survey on Puerto Rico were examined. The most interesting aspect of this work was the care with which the terrain corrections were made. Accurate topographic and bathymetric maps were available and an accuracy of better than 0.1 mgal was claimed for the terrain correction.

A review of interpretation of gravity data over the Eastern Cordillera of America was made. The Cordillera is essentially a north-trending zone of folded and metamorphosed Palaeozoic sediments. It was found that in a general way this zone corresponded with a gravity 'ridge'. However, in many places the 'ridge' is of low amplitude. In the north, over New England, the western part of the Cordillera corresponded with a gravity gradient. Further to the south the gradient becomes less intense and occurs between twenty and forty miles east of the western margin of the Cordillera range in age from Ordovician in the north to Devonian in the south. The explanation proposed for the divergence of the gravity gradient from the western margin of the Cordillera is that it marks the western margin of the Ordovician folding and that in the south this folding is masked by later (Devonian) folding.

Stanford University

The interpretation of gravity data from the Sierra Nevada Range and adjacent areas was discussed with Dr Thompson of the Geophysics Department, Stanford University, and Dr Oliver of the United States Geological Survey. The Sierra Nevada Range is a large uplifted granitic complex, elongated in a north-south direction. Gravity and seismic results show that the crust is regionally compensated under the range. The Sacramento Valley lies immediately to the west of the Sierra Nevada Range and is a relatively flat, low-lying area. It is underlain by 30 - 50,000 ft of Tertiary sediments.

Figure 1 illustrates in a general way the crustal structure and the gravity profile. It can be seen that there is a gravity 'high' west of the Sierra Nevada Range in an area where the sedimentary thickness is about 9000 ft. This 'high' does not originate from structure within the sediments. It has been postulated that the 'high' is in fact not caused by a clearly definable geological feature but rather that the gravity 'high' is related to the juxta-position of the gravity 'low' caused by the Sierra Nevada Range and the 'low' caused by the Sacramento Basin. A complicating factor, however, is the presence of intense magnetic anomalies that correspond with the position of the gravity 'high'.

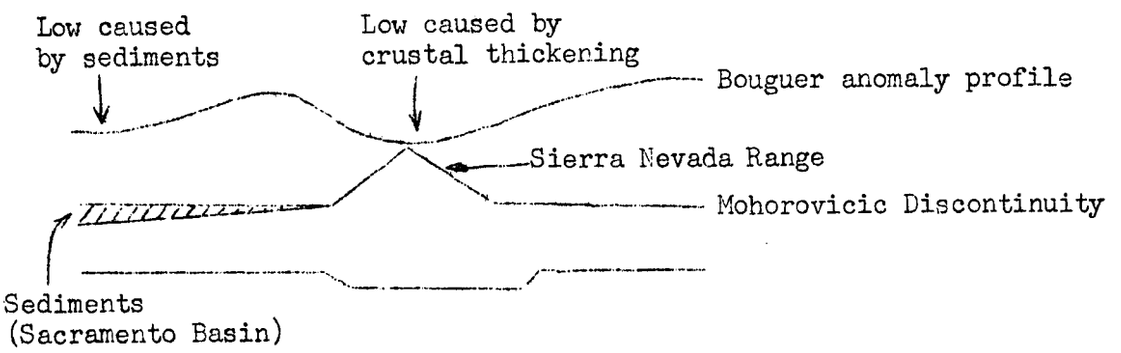

Figure 1

Generalised section showing crustal structure and gravity profile across the Sierra Nevada Range.

University of Hawaii - Institute of Geophysics

The geophysicists of the Institute of Geophysics are concerned mainly with aeromagnetic and gravity studies. A major gravity project involving a study of the relation of gravity anomalies to elevation, geology, and crustal thickness has been completed (Woollard, 1962). It was found that in some areas of the USA there is a reasonable correlation between elevation and Bouguer anomaly. A close study was made of the correlation of the gravity and elevation data from the State of Wyoming.

Most of Wyoming is in the Rocky Mountains, which in general are a core of Precambrian metamorphic and igneous rocks, uplifted during Mesozoic and Tertiary times. There are many small and medium-sized intermontane basins containing Mesozoic and Tertiary sediments. The structure and depth of most of the basins were well known. Gravimetrically, the basins were expressed as 'lows'.

The steps taken in the investigations were : gravity and geology profiles were drawn up; the gravimetric effects of the sedimentary basins were computed and subtracted from the profile; the sediments were replaced with material of basement density and the gravimetric effect of this material added to the Bouguer anomaly profile. The resulting Bouguer anomaly profile is thus the profile one would expect if no sediments were present. After studying a number of profiles in this manner, a basement Bouguer anomaly map of Wyoming was produced. It was found that the basement Bouguer anomaly values correlated well with elevation.

This investigation also showed that for some types of sedimentary basins the best regional anomaly is a straight line joining the Bouguer anomaly value obtained over basement on either side of the basin.

A considerable amount of time was spent discussing the above publication with Dr Woollard. It is strongly suggested that anyone interested in the interpretation of gravity data obtain and read this publication.

3. CONCLUSIONS

Set out below is a list of the main points covered during the tour :

(1) Quantitative interpretation of gravity data can be speeded up and simplified by the extensive use of automatic computing procedures.

(2) The somewhat surprising crustal-thickness results obtained by the United States Geological Survey Branch of Crustal Structures has shown that regional gravity anomalies can originate from below the crust.

(3) Shipborne gravity meters can measure gravity to an accuracy of ±5 mgals. Accuracies of ±2 mgals are possible under calm sea conditions. Technically, the making of shipborne gravity measurements is very complex.

(4) The study of the relations between gravity, elevation, and crustal thickness made by Woollard has shown that if no other data are available, then the gravity-elevation relation can be used to investigate possible geologic structure in the upper part of the crust.

The following comments reflect some general impressions gained during the tour :

(1) The efficiency of the BMR Gravity Group would be considerably enhanced if it possessed, at all times, advanced capability in data processing and computer programming.

(2) The type of gravity work being done by the BMR differs in scope and objective from that being carried out in most overseas organisations. The Dominion Observatory is an exception. Many of the problems that confront the BMR Gravity Group have never been investigated in detail. For this reason it is the firm conviction of the author that the Gravity Group should have the capability and the opportunity of carrying out research into problems relating to its work. No one else is likely to do it for us.

A particular instance relates to the problem of station spacing and optimum contouring methods. To the knowledge of the author there have been very few quantitative papers written on this subject.

(3) The operation of a shipborne gravity meter is a complex matter. If the BMR is to continue shipborne gravity work, a geophysicist should be sent overseas to gain experience in this technique.

4. REFERENCES

BOOT, M.H.P. and SMITH, R.A.	1958	The estimation of the limiting depth of gravitating bodies. Geophysical Prospecting 6 (1), 1-10.
BOWER, D.R. and WATT, P.A.	1963	The second-order errors of sea-surface gravity measurements. J. Geophys. Res. 68, p.245-250.

TANNER, J.G. and McCONNELL, R.K. 1964 The gravity anomaly field in the Ungava region of Northern Quebec, with maps. Gravity Map Series of the Dominion Observatory Nos. 5 and 6.

WHITHAM, K. and ANDERSEN, F. 1962 The anomaly in geomagnetic variations at Alert in the Arctic Archipelago of Canada. Geophys. J. Roy. Astr. Soc. 7(2), 220-243.

WOOLLARD, G.P. 1962 The relation of gravity anomalies to surface elevation, crustal structure and geology. University of Wisconsin, Geophysical and Polar Research Centre, Department of Geology. Research Report Series No.62-9

APPENDIX 1

Timetable

Departed	Hours local time	Date	Arrived	Hours local time	Date
Melbourne	1600	29/6/64	Honolulu	0930	29/6/64
Honolulu	1030	30/6/64	San Francisco	1815	30/6/64
San Francisco	0130	1/7/64	Houston	0800	1/7/64
Houston	0815	5/7/64	Washington	1400	5/7/64
Washington	1600	12/7/64	Ottawa	2100	12/7/64
Ottawa	1800	20/7/64	Gander	2330	20/7/64
Gander	1000	28/7/64	Ottawa	1800	28/7/64
Ottawa	1200	9/8/64	Halifax	1730	9/8/64
Halifax	0900	12/8/64	Ottawa	1300	12/8/64
Ottawa	1000	7/9/64	Toronto	1600	7/9/64
Toronto	1030	9/9/64	New York	1330	9/9/64
New York	1230	20/9/64	Denver	1600	20/9/64
Denver	1430	27/9/64	Hannibal (Missouri)	2100	27/9/64
Minneapolis	1300	1/10/64	Denver	1900	1/10/64
Denver	1800	12/10/64	San Francisco	2100	12/10/64
San Francisco	2000	20/10/64	Honolulu	2200	20/10/64
Honolulu	0200	28/10/64	Melbourne	1730	29/10/64

APPENDIX 2

Organisations visited

Organisation	Period of visit
Geophysical Associates Inc., Houston	1/7/64 - 5/7/64
United States Geological Survey, Washington Office	5/7/64 - 12/7/64
United States Coast and Geodetic Survey	10/7/64
Dominion Observatory, Ottawa	12/7/64 - 9/8/64 12/8/64 - 7/9/64
Bedford Institute of Oceanography, Toronto	8/9/64 - 9/9/64
Lamont Geological Observatory	10/9/64 - 20/9/64
United States Geological Survey, Denver Office	21/9/64 - 8/10/64
Colorado School of Mines	9/10/64 - 12/10/64
United States Geological Survey, Menlo Park Office	13/10/64 - 20/10/64
Stanford University, Department of Geology and Geophysics	16/10/64
Institute of Geophysics, University of Hawaii	21/10/64 - 27/10/64