STANDARDIZATION OF GRAVITY AND BOUGUER ANOMALIES IN INDIA

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

GEOSCIENCES

(GEOPHYSICS)

JANUARY 1969

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PREFACE

The standardization of Indian gravity data has been possible through the cooperation among the Hawaii Institute of Geophysics, University of Hawaii, Honolulu, the National Geophysical Research Institute, Hyderabad, India, and the Geodetic and Research Branch, Survey of India, Debra Dun, India. The author started the compilation and the standardization of the data while working for the National Geophysical Research Institute in 1965. During this period, he was also associated with Dr. M. H. Manghnani of the Hawaii Institute of Geophysics who has reoccupied 215 of the old Survey of India gravity stations and established some 380 new stations in India. In 1967 the author continued this project as part of a research program at the Hawaii Institute of Geophysics and occupied some 80 more of the Survey of India stations and established 640 new stations in poorly covered areas in India.

For permission to use other gravity data and related information as well as substantial help in conducting the field work in India, the author is deeply indebted to Dr. Hari Narain, Director, National Geophysical Research Institute, to Col. K. L. Khosla, Director, Geodetic and Research Branch, Survey of India and to Dr. G. P. Woollard, Director, Hawaii Institute of Geophysics without whose interest and help this work would not have been accomplished. Thanks are also due to Dr. Manghnani for allowing the author the use of the gravity data that he had collected in 1965, and to Mrs. Delia Lavin for help in the reduction and the standardization of the data.

Free computer time provided by the Statistical and Computing Center of the University of Hawaii towards the processing of data and computation of anomalies is gratefully acknowledged.

The funds for the support of the writer were from the Aeronautical Chart and Information Center contract AF-23(601)-4375 and for the field work in India from the Army Map Service grant DACA 71-67-c-0080.

ABSTRACT

About 150,000 gravity measurements made in India during the past two decades have been based on various floating datums. In this study an attempt is made to bring all this data to a standard datum by reoccupying some 300 of the old stations and tying them to the standard calibration range in India established by Manghnani and Woollard in 1963. A correlation analysis of the differences between the old and the new sets of gravimeter values indicated a simple regression of the differences in the absolute gravity values, roughly corresponding to the areas and the years of field survey parties. For the standardization of the old values to the national datum of Dehra Dun (979.0640 gals), the Survey of India stations required two corrections: (1) a constant and (2) a term linearly dependent on their absolute values. The Oil and Natural Gas Commission values required only a constant correction term for the base datum.

Simple Bouguer anomalies were computed for about 4,000 of the standardized values together with about 1,000 new gravity stations covering formerly blank areas. The anomaly map does not show consistent correlation with surficial geology but reflects the major tectonic features well. Low and broad anomalies in areas of high density rocks, such as the Deccan Plateau basalts, the Cuddapah basin, etc., point to a dominance of the effects of deeper mass variations in the crust. Regional anomalies were therefore obtained by filtering out the components due to the near-surface and smaller features. Using a three-dimensional

anomaly computation procedure, a structural map of the 'M' surface was derived assuming a sea level crustal thickness of 32 km and a density contrast of 0.4 gm/cc at the Moho boundary.

Two large regions of low gravity are seen in the regional anomalies. One is a semi-circular low with a minimum of -120 mgal, centered over the Mangalore coast, and practically covers all of the triangular peninsula of India. The other lies in the region of northern India where there are steep gradients towards the Himalaya Mountains. The gradients increase from about 60 mgal/100 km over the deeper part of the Indo-Gangetic basin to about 140 mgal/100 km in the Punjab and Kashmir foothills of the Himalaya Mountains. A zone of relative high gravity values covers central India and roughly follows the northern boundary of the peninsula.

The Moho surface shows general depression under the peninsula with a maximum depth of about 42 km under the Mangalore coast. It rises in the central India to form a NW-SE trending upwarp along whose axis the 'M' surface lies at a depth of about 30 km further west under Rajasthan. West of the Ganges delta the 'M' surface lies at a depth of about 34 km. North of this upwarp the Moho surface dips down again to depths of about 40 km under the Himalayan foothills and lies at a depth of about 50 km and more under Kashmir.

This interpretation of the regional gravity field appears to be substantiated by regional uplift over the area of postulated anticlinal uplift of the 'M' surface as delineated by the Satpura Mountains, the Mahadeo Hills, the Maikal Range and the Kaimur Hills trending east-west across central India and the Aravalli Range which appears to lie on a north-south trending spur on the main crustal anticline in western India. The deepening of the 'M' surface as the Himalayan Mountains are approached is to be expected for a major orogenic feature of this type of Alpine age. The only question concerning the interpretation pertains to marked negative gravity values in southern India which may be related at least in part to a major negative mass inhomogeneity in the upper mantle. In the absence of seismic crustal measurements, this uncertainty can not be resolved at this time.

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INTRODUCTION

The sub-continent of India offers a very interesting region for geophysical studies of our earth. It incorporates areas of great geological diversity, viz., a part of the youngest mountain system, a deep sediment-filled geosynclinal trough, one of the world's greatest outpourings of plateau basalts, and a shield area made up of ancient crystalline and metamorphic rocks.

The northern part of the sub-continent is an area of tectonic, highly folded and overthrust, mountains of very recent geological origin. The rocks in the Himalayas are composed of enormous thicknesses of sediments representing practically the whole geologic column which had been deposited in the Tethys geosyncline continuously from Cambrian through early Tertiary time. The strata are marked by complex folds, reversed faults, overthrusts and nappes of great dimensions.

The Indo-Gangetic Plains are broad monotonous and level expanses of recent alluvium, layers of sand, clays and occasional organic debris. These plains owe their origin to sedimentation in a sag in the crust formed in conjunction with the uplift of the Himalayas.

The peninsular region in the south is an ancient shield plateau with mountains of relict-type. It is composed of Precambrian rocks of diverse origin, most of which have undergone metamorphism. The peninsula represents a stable block of the earth's crust which has remained quiescent since practically the close of the Archaean era.

The Himalayan Mountains represent a compression of enormous amounts of sediments that are estimated to have involved a shortening of the crust by about a thousand miles. Paleomagnetic evidence suggests in addition that there was a drift of peninsular India of about 56 degrees of latitude since the end of Paleozoic time. These various facts make this part of the globe an interesting and important area for geophysical and geological study which can contribute to the understanding of the processes associated with continental drift and sea floor spreading.

The present study concerns the gravitational field of India, and it is important since gravity constitutes one of the best preliminary methods for investigating the subsurface structure as it now exists. Even though gravity measurements in India have been made for over a century now, much of the data were of dubious quality and also there were many areas having little or no coverage. Although Glennie (1932) and others have made attempts to interpret the crustal significance of the regional gravity field in India, and although it was on the basis of gravity relations here that Archdeacon Pratt arrived at the Pratt theory of isostasy in the middle of the last century, the data were really inadequate for analytical studies requiring a reliability in excess of 20 mgals. Gulatee (1956a), for example, rejected all observations made in the period 1865-1873. Even on the more modern measurements since 1901, Woollard (1950) showed that there was an uncertainty of 29 mgals in the Indian National Base value.

Also Woollard (in Woollard and Rose, 1963) showed there were relative discrepancies of the order of 12 mgals in the pendulum station network values established since 1926. The most recent summary on the existing gravity work is that by Narain et al. (1964). These authors point out the need for reducing all the gravity values to a national standard datum for any meaningful interpretation of the gravity field.

As a first step in resolving the problems of standardization Manghnani and Woollard (1963) established a north-south line of base stations using gravimeters between Srinagar in northern India and Trivandrum at the southern tip of the peninsula, and in 1965 Manghnani (unpublished) extended this control network into other portions of India.

The present dissertation represents an extension of this work on standardization and also an attempt to collect and standardize the earlier gravity data in India as well as extend the regional gravity coverage into areas where there were few or no data, so that a meaningful geological and crustal interpretation of the data could be undertaken.

REVIEW

GEOLOGY AND TECTONICS

A simplified geological map of India is shown in Figure 1 based on Roy (1963). Comprehensive studies of the geology and the tectonics of the Indian sub-continent have been made by Wadia (1957) and Krishnan (1953, 1956, 1964). They divide the area into three distinct units quite unlike in their physical, geological and structural characteristics.

I. The Peninsula

Nearly two-thirds of the triangular plateau of the peninsular shield is made up of gneisses, schists, granites and other igneous rocks and various sediments, all of Precambrian age, which have been metamorphosed in varying degree. The basaltic lavas of the Deccan Trap series of Late Cretaceous and earliest Cenozoic age cover a large part of western and southern India, while a couple of areas of Gondwana rocks are found in the central and eastern parts of the peninsula. The coastal areas contain thin and narrow fringes of Tertiary formations.

Krishnan has delineated the following major structural trends in the Archaean rocks of the peninsula:

a. Aravalli trend - It is the NE-SW strike of rocks from Delhi to Champaner in Gujerat at the head of the Gulf of Cambay where it tends to splay into two parts, one directed towards Mysore with the intervening area covered by Deccan Trap lavas and the other continuing south into the Laccadives area along the coast of the Gulf of Cambay.

b. Dharwarian trend - This characterizes the formations of the same name in the state of Mysore. It is generally NNW-SSE and more or less parallel to the western coast, but turns to N-S when followed to southern Mysore, and finally veers rather sharply to a ENE-WSW trend south of Mysore City. The rocks defining this trend there are covered and even overthrust by those of the Eastern Ghats province.

c. Eastern Ghats trend - It runs NE-SW between Mahanadi and Krishna rivers. These rocks appear to continue on strike into the sea south of the Krishna valley but can be picked up in the syncline of Ceylon. The western limb of the syncline emerges near Madras City whence the rocks continue in a general WSW-ENE trend to the Shivaroy massif and Nilgiri hills. The rocks of the Eastern Ghats near Vishakhapatnam and further north turn towards the coast, with an ESE or SE strike.

d. Mahanadi trend - It is the NW-SE strike of the ancient crystalline massifs in the area between the Godavari and Mahanadi rivers and in the coastal tracts of the Ganjam and Vishakhapatnam districts.

e. Satpura trend - It is a more or less E-W strike that prevails from the Narbada valley in Gujerat in the west to the Ganges delta in the east.

Superimposed on the Archaean mass of the peninsular India are basins of Cuddapah and Vindhyan rocks, filled mainly with sediments of the Precambrian age. The Cuddapah basin in Andhra Pradesh is crescentic in outline, with its eastern margin greatly disturbed. The Cuddapah basin of Bastar and Chattisgarh is of similar form but the structure is not so well defined as it has been split up into separate segments divided by outcrops of Archaean crystalline rocks. The great basin of Vindhyans in Bundelkhand, occupying the Son Valley and parts of Rajasthan and central India has a complicated structure. Only the southern half is exposed forming a broad band on the west and south around the granite boss of Bundelkhand. The exposed part of the basin forms the southern half of an ellipse whose longer axis would strike in a ENE-WSW direction. The western margin of the basin is marked by a great thrust zone over 800 km long trending NE-SW in which the older rocks are brought against the youngest Vindhyan formations. To the southwest the basin extends beyond Indore.

The Deccan Traps are a series of horizontal basalt flows presumably erupted from numerous fissures in the crust during Late Cretaceous and Early Eocene times. They lie unconformably on the pre-existing peninsular rocks and now occupy some 510,000 square km in the western and central India. They are estimated to be over 1,800 m thick near the western coast and about 750 m thick in Cutch. The base of the lava flows is found at different levels: at 600 m above sea level at Belgaum, at 300 m near Nagpur, at 480 m on the flanks of the Maikal Range, at 750 m south of Sohagpur and in the Ranchi Plateau, at about 900 m in Jashpur, and at 150 to 550 m below sea level in the Narbada Valley and in Kathiawar (Krishnan, 1953). The Traps have also suffered somewhat from faulting and folding and show dip and flexure in various parts.

Several late eruptive centers for the Trap lavas are known in Kathiawar and in the Narbada Valley. Wakhaloo (1967) has studied the Girnar volcanic complex in Kathiawar which he describes as composed of many different rock types but mostly of alkalic varieties, and formed by the doming up of the country rocks. This volcanic dome covers an area of about 160 square km and rises to about 930 m above its surroundings. This is believed to be one of the secondary sources (chamber) of magma for the later lava flows.

The peninsular shield area has been tectonically quiescent since Cambrian times except for some block-faulting in the northeast part along the Son-Damodar, Mahanadi and Godavari valleys. The northern border of the peninsula is irregular and appears to have been thrust under Asia. The two ends of the border extend as sunken wedges into the region of the lesser Himalayas. They have produced two syntaxes, one in the Kashmir-Pamir region in the northwest and the other in the Upper Assam-Southwest China region in the northeast. The wedge in the Punjab-Kashmir region projects far to the north, pushing the Himalayan system towards the Pamir knot. The Assam plateau forms the northeast extension of the peninsular shield and shows fault scarps on its northern and western borders.

The remarkably straight margin of the continental shelf of the western coast of the peninsula lends support to the deduction that it has been formed by faulting in comparably recent times. A series of hot springs along a north-south line parallel to the coast near Bombay suggest a line of fracture. Additional evidence is afforded by the Deccan Traps which are over 1,800 m thick near the Bombay coast and gradually thin eastwards. It is believed that their abrupt termination at the Bombay coast is due to the breaking off of the portion of land that originally lay to the west of Bombay. The age of the faulting postdates the Deccan Traps and may be as late as Pliocene. The Gulf of Cambay within the continental shelf appears to be a step-faulted trough in which the Deccan Traps have been let down to a depth of over 1,800 m below sea level. A major fault just north of the Runn of Cutch has been traced for some 60 km, with a strike partly E-W and partly WNW-ESE.

II. The Extra-Peninsula

This is a region of a series of high, tectonic mountain chains extending from Baluchistan, West Pakistan, in the west to Burma on the east. The rocks here are predominantly composed of enormous quantities of sediments that were laid down in the vast Tethys geosyncline continuously from Cambrian to early Tertiary time and then were compressed and ridged up into mountains only during early or middle Tertiary time. The core of the mountains is composed of granitic intrusions of presumably Tertiary age. The tectonic ranges are arcuate with their convexity towards the rigid crust of the peninsula against which they appear to have been thrust.

III. The Indo-Gangetic Plains

The Indo-Gangetic Plains are broad, monotonous, level expanses of recent alluvium spreading from the Indus Valley in the west to the Brahmaputra Valley in the east. They are built up of layers of sands and clays of Pleistocene and Recent age. The intense mountain building movements produced a depression or a foredeep in front of the convex side of the Himalayan arc because of the bending down and underthrust of the northern edge of the peninsula against the central Asian mass. This foredeep is not a continuous depression throughout the length of the Himalayas, but consists of three parallel strips having the same alignment and separated from each other by transverse ridge-like structures west of Delhi and in the region of Cooch-Bihar. The foredeep, or at least the northern part of it, is doubtless underlain by the Tertiary and older rocks which dip down into it from the Himalayan side. Similarly the rocks on the peninsular side may also be expected to continue below it from the south.

GRAVITY AND SEISMIC STUDIES

Glennie (1935) and Evans and Crompton (1946) studied the isostatic anomalies in the sub-continent and concluded that isostatic equilibrium does not prevail in India. Burrard (1918), Gulatee (1956b), Heiskanen (1958), and Qureshy (1963), on the other hand, are of the opinion that the major parts of the sub-continent are isostatically compensated. Evans and Crompton (1946) believed that the great thickness of Tertiary and Mesozoic sediments in northeast India could account for about + 50 mgal of the low isostatic anomalies found in the Indo-Gangetic plain. Heiskanen (in Heiskanen and Vening-Meinesz 1958) concluded from the average of 22 Free Air, Bouguer and Hayford isostatic anomalies chosen at random over India, that isostatic compensation does exist to a major degree.

Gulatee (1956b) published several isostatic anomaly maps of India based on both the Pratt-Hayford and Airy concepts of isostatic compensation. These maps show alternate east-west bands of anomalies; positive under the high Himalaya Mountains, negative in the Indo-Gangetic plains, slightly positive in central India, and again negative over the peninsula. Gulatee showed that the major part of the isostatic anomalies could be removed by assuming two different values for the depth of Airy-compensation; a larger value (30 km) for the north, and a smaller value (15 km) for the south India.

On the basis of geodetic observations, Burrard (1912, 1918) suggested that the Himalayan folds are the result of under-thrusting of the Indian sub-crust below the land mass of central Asia. He, and later Glennie (1932) also, inferred that a 'Hidden Range' runs practically parallel to the Himalayan trend and is formed due to crustal warping with a downwarp under the Gangetic plains and an upwarp below central India.

It has long been known (Skeels, 1940, Woollard, 1962a) that the gravity in India is not controlled by the observable geology but rather is biased by crustal mass inequalities as evidenced by negative anomalies over the high density Deccan Traps in the western India, and over the dense sediments in the Cuddapah basin in the eastern part, and the markedly negative values over the Indo-Gangetic plains in the north.

Sengupta (1965) compares the gravity minimum over the Gangetic plains, flanked to the north and south by positive isostatic anomalies, to the known gravity profiles across typical 'Pacific-type Arcs' and deep oceanic trenches. His review of the recent geological and geophysical findings suggests a northerly slope of the basement below the Gangetic alluvium accompanied by a thickening of the sediments with a crustal thickness of 30 km below the southern part of the Gangetic plains and a progressive dipping of the underlying mantle surface to about 70-75 km below the high Himalayan peaks.

Qureshy (1964) prepared a Bouguer anomaly map of peninsular India from the published data of the Survey of India, Geological Survey of India, and his own data. He inferred that the Bouguer map probably indicates the structural grain of the peninsula, and concluded tentatively that within the Indian shield large crustal blocks have moved up and down epeirogenically during the geologic past in a rhythmic way.

During the preliminary investigations for the International Indian Ocean Expedition, Caputo et al. (1964) reported a gravity low which seemed to be centered about the southern tip of the Indian peninsula. This agrees with the gravity analyses of satellite orbital data reported by Kaula (1966), Khan and Woollard (1966), Strange (1966) and Köhnlein (1966); all of which show a gravity minimum centered just south of Ceylon.

A number of gravity and other geophysical studies have recently been made in areas of local interest, such as by Takin (1966) on the continental shelf near the Bombay coast, by Reddy et al. (1967) and by Balakrishna et al. (1967) in the Cuddapah basin near Madras, and by Qureshy et al. (1968) in Godavari Valley.

Some surface-wave dispersion studies have been made of several earthquakes recorded in India and elsewhere to decipher the structure of the crust in the Indian sub-continent. These results are summarized in Table I. In general they indicate a crustal thickness of about 40 km under the Gangetic plains increasing to about 60-70 km under the Himalayas. On the other hand, recent studies of P-wave data from shallow earthquakes by Kaila et al. (1968) suggest a quite different structure of the crust under the Himalayan foothills. The crustal section defined is as follows:

Layer	Thickness (km)	Velocity (km/sec)
Sedimentary	6.0 ± 1.0	2.7 ± 0.1
Granitic	8.0 ± 5.0	6.2 ± 0.1
Basaltic	14.0 ± 7.0	6.9 ± 0.1
	H = 28.0	

TABLE I

CRUSTAL STRUCTURE FROM SURFACE WAVE DISPERSION STUDIES

Area	Layers and their thickness (kms)		Source	Reference
Gangetic Valley	Crust	40	Bihar earthquake of 1934	Roy (1939)
Gangetic Basin	Crust	40	East Pakistan/Burma/India border region earthquakes	Chaudhury (1966)
Himalayas	Crust	60	Assam earthquake of 1950	Banerji (1957)
Himalayan foothills	Crust	50	Assam earthquake of 1959 and its aftershocks	Tandon (1954)
Kashmir Himalayas	Granitic Basaltic	26 25-30		
Nepal Himalayas	Granitic Basaltic	25 25-27	Near quakes from 1964 to 1961	Chauhan & Singh (1965)
Assam Himalayas	Granitic Basaltic	23 27		
Lahore-New Delhi region	Crust	38	Various earthquakes	Gabriel & Kuo (1966)
Shillong, New Delhi and Quetta	Crust	45		
Himalayas and Tibetan Plateau	Crust	65-70	Arctic Region earthquakes of 1964	Gupta & Narain (1967)

Kaila et al. attribute the low value of derived crustal thickness to the effect of the thick, low velocity sedimentary section which had been neglected by earlier workers. They report that the oil well data and the results of a refraction profile in the Punjab foothills by the Oil and Natural Gas Commission confirm a thickness of at least about 5.0 km for the sedimentary layer in that area.

PAST GRAVITY MEASUREMENTS

The areas of gravity survey by various organizations in India are shown in Figure 2. The Survey of India has the longest history of activity (since 1865), and has made gravity measurements in most parts of the country. Prior to 1947 only pendulum measurements were made. Starting in 1947 gravimeters were adopted for geodetic studies as well as the establishment of the national gravity network. The accepted Survey of India gravity data (Gulatee, 1956a) suffers from two types of discrepancies:

1. The pendulum values on the basis of gravimeter comparisons involve errors varying from -16 to +14 mgals.
2. The accuracy of gravimeter values depends on that of the pendulum bases they are tied to and on the reliability of the gravimeters used.

The other major groups actively engaged in the gravity surveys in India have been the Oil and Natural Gas Commission and the National Geophysical Research Institute. The Oil and Natural Gas Commission has been doing detailed surveys for petroleum exploration in most of the sedimentary areas of the country while the National Geophysical Research Institute has been interested mostly in the peninsular area. Other groups interested in local areas have been the Geological Survey of India, the Assam Oil Company, Ltd., the Standard-Vacuum Oil Company, and some universities.

Several investigators, e.g., Woollard, Muckenfuss, Bonini, Sanker Narayan, Sparkman, of the University of Wisconsin have in recent years made connections between the World Gravity Network and some of

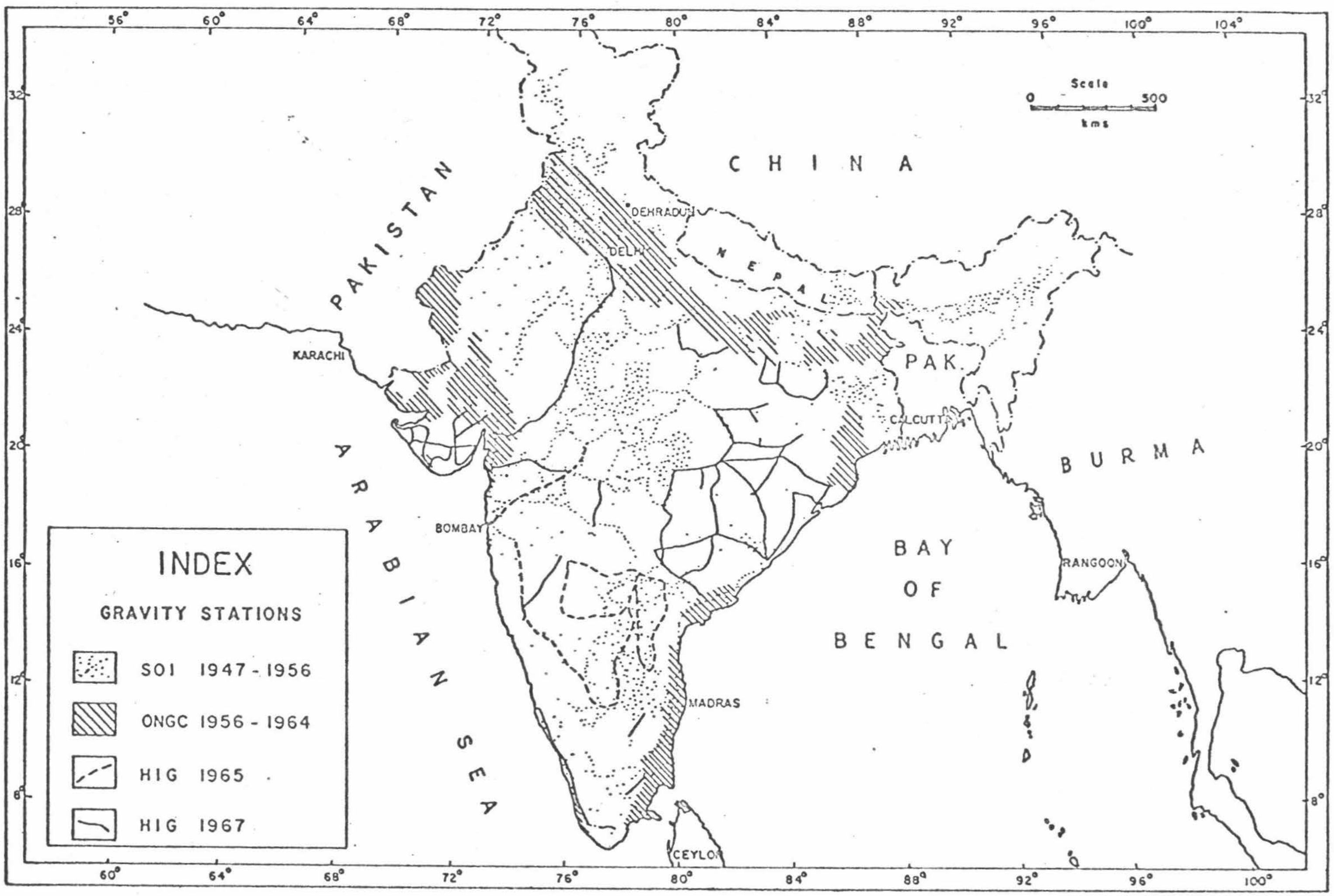

Figure 2. Areas of Gravity Coverage in India.

the pendulum stations in India (Woollard in Woollard and Rose, 1963). Manghnani and Woollard (1963) evaluated the quality of these earlier connections and established a north-south line of gravimeter stations to provide a gravity standardization range in India.

Recently, the Hawaii Institute of Geophysics, under the direction of Dr. G. P. Woollard, has been cooperating with the Survey of India and the National Geophysical Research Institute in a project of standardization of the gravity data in India and sent Dr. M. H. Manghnani in 1965 and the author in 1967 to India to evaluate the old Survey of India pendulum and gravimeter values and to extend the gravity coverage in the country.

FIELD WORK

In order to assess the accuracy of the earlier gravity data, about 300 of the survey of India's old pendulum and gravimeter stations and most of the Oil and Natural Gas Commission's base stations were reoccupied by Dr. M. H. Manghnani and the author, both of the Hawaii Institute of Geophysics, in 1965 and 1967 respectively. A Worden gravimeter was used in 1965 and a La Coste-Romberg gravimeter in 1967. Both of these surveys were tied to the gravimeter stations of the standardization range established earlier with a La Coste-Romberg gravimeter by Manghnani and Woollard (1963). In addition, about 1,100 new gravity stations were established in areas of sparse coverage in various parts of peninsular India as shown in Figure 2. Table II compares the values of the gravity stations common to the two Hawaii Institute of Geophysics surveys. The La Coste gravimeter showed negligible drift but the closure values indicated a few small tares (jumps in values) that had to be allowed for in the reductions. None of these exceeded 0.5 mgal. The Worden data suffered from erratic drift problems. The stations with a significant difference of about 1.5 mgals or more, viz., Delhi, Sonnagar, Dehri-on-Sone, Jetalsar, Rajkot, Junagadh, Shapur, Veraval and Viramgam, all fell on two loops of the Worden gravimeter survey. A reexamination of the ties and drift rates indicated that these values could be easily adjusted to agree with the La Coste values without violating the closure values. In general, though, there was agreement to within ±1 mgal between the 1965 and 1967 values, and the overall accuracy of the Hawaii Institute of Geophysics data is estimated to be this value.

TABLE II

HIG WORDEN (1965) AND LACOSTE (1968) VALUES

Station	HIG	No.	Worden Value gals.	L&R Value gals.	Diff. mg.
Delhi Jn. RS	MM	1A	979.1420	979.1441	+2.1
Dehra Dun Nat'l Base	MM	5	979.0640	979.0640	tie
Dehra Dun RS	MM	5B	979.0722	979.0723	+0.1
Surat RS	MM	27	978.7221	978.7220	-0.1
Secunderabad RS	MM	44	978.3349	978.3347	-0.2
Kazipet RS	MM	46	978.4358	978.4356	-0.2
Dornakal RS	MM	47	978.4413	978.4410	-0.3
Vijayawada RS	MM	48	978.4492	978.4488	-0.4
Madras RS	MM	53	978.2839	978.2838	-0.1
Jalarpet RS	MM	59	978.1288	978.1288	0.0
Baroda RS	MM	72	978.7517	978.7517	0.0
Ratlam RS	MM	99	978.7214	978.7214	0.0
Kanpur RS	MM	138A	978.9773	978.9777	+0.4
Agra Cantt. RS	MM	160	979.0533	979.0534	+0.1
Dehri-on-Sone RS	MM	155	978.8797	978.8812	+1.5
Sonnagar RS	MM	156	978.8784	978.8804	+2.0
Bhusaval RS	MM	172	978.6319	978.6329	+1.0
Jalgaon RS	MM	173	978.6353	978.6367	+1.4
Miraj RS	MM	276	978.2891	978.2890	-0.1
Purna RS	MM	309	978.4543	978.4543	0.0
Wardha RS	MM	320	978.5849	978.5848	-0.1
Suryapet TB	MM	347	978.4018	978.4021	+0.3
Lucknow RS	MM	482	978.9809	978.9810	+0.1
Hardwar RS	MM	490	979.1252	979.1249	-0.3
Rajkot RS	MM	530	978.7527	978.7502	-2.5
Veraval PS	MM	531	978.7146	978.7121	-2.5
Shapur RS	MM	532	978.7388	978.7362	-2.6
Junagadh RS	MM	533	978.7512	978.7487	-2.5
Jetalsar RS	MM	534	978.7353	978.7327	-2.6
Viramgam RS	MM	536	978.8292	978.8268	-2.4
New Delhi AP	WA	2019	979.1343	979.1343	tie
Mangalore AP	WA	2102	978.2316	978.2314	-0.2

Notes: RS = Railway Station
PS = Pendulum Station
TB = Traveller's Bungalow
AP = Air Port

STANDARDIZATION OF GRAVITY VALUES

The absolute gravity value for India (979.063 gals) is that established for Dehra Dun by relative pendulum measurements from Kew, England by Sir Gerald Lenox-Conyngham in 1904. Woollard and Gulatee (Woollard, 1950) found a value of 979.064 gals relative to Madison, Wisconsin (980.3689 gals) as did Manghnani and Woollard in 1963. As subsequent work by Woollard (1963) has shown the Madison value to be about 0.9 mgal high relative to the Potsdam absolute base used as a World Standard Datum, the Indian National Base value is essentially correct. The absolute values for all stations in India were referred to the Dehra Dun base station and as indicated its absolute gravity in turn was established by relative measurements to Potsdam. Although all values in India can be put on an absolute datum by using the pendulum sites as bases, the error in most of the pendulum sites exceeds 3 mgals and as shown earlier some were found to be over 10 mgals in error. Because of these discrepancies in values plus the fact that some surveys were on floating datum it was necessary to make gravity connections to all the surveys in order to put all the data on a single datum.

The first problem, therefore, in making use of the older data was to reference all the earlier gravimeter observations either directly or indirectly to the national standard datum defined at Dehra Dun. The normal procedure in doing this was to reoccupy several of the old stations in each survey dispersed so as to cover the maximum range in gravity involved. This permitted both the datum and calibration standard to be evaluated on a statistical basis through comparisons of the old and the new values.

For each of the reoccupied stations the difference (δ) between the new and the old values was ascribed to one or more of the following:

1. The error in datum value.
2. The erroneous or poor calibration of the old meters used.
3. The effect of the altitude (pressure) on the calibration of the meters due to leakage.
4. The erroneous values.

The first effect results in a constant difference between all values for a given survey; the second, in a linear difference in values that is related to changes in gravity; the third, in a more or less linear difference that is related to elevation; and the fourth, related to observational error. Mathematically, the difference in the new and the old values could then be expressed as a function of the absolute gravity and the elevation of the station:

$$\delta = a_o + a_1 g + a_2 e \qquad (1)$$

where a_o, a_1 and a_2 are constants,
g = absolute gravity,
e = station elevation.

δ would thus be the amount of correction necessary to bring the old gravimeter values to the standard datum. In this study the national base station in Dehra Dun with a value of 979.0640 gals (Manghnani and Woollard, 1963) was used as the gravity standard datum.

The calibration standard was that defined with the Gulf pendulums (Woollard and Rose, 1963) between Point Barrow, Alaska and Mexico City, Mexico.

Survey of India Pendulum Values

The Survey of India pendulum values published in Survey of India Technical Paper No. 10 (Gulatee, 1956a) and the Hawaii Institute of Geophysics gravimeter values for the stations reoccupied are compared in Table III and Figure 3. The differences δ , between the two values range from -7.6 to +11.2 mgals and indicate a possible systematic departure of 9.5 mgals per 1000 mgal change in absolute gravity. This departure is greater than that noted by Woollard in Woollard and Rose (1963) who found an apparent systematic change of about 2.5 mgals per 1000 mgal change for the limited number of pendulum stations that had been occupied at that time. The writer's results based on a different sampling of stations appear to be more representative of average conditions. There is no apparent dependence on elevation, the location of the station, or the year of the survey. As it is not known how representative Figure 3 is of all data, values were only changed for those pendulum stations actually reoccupied. The rest of the Survey of India values were used with caution as no other check observations were available.

Survey of India Gravimeter Values

The Survey of India gravimeter values and their Hawaii Institute of Geophysics reoccupation values are listed in Appendix Table I, along with other relevant data. Assuming that the Survey of India gravimeter

TABLE III

REOCCUPIED SOI PENDULUM STATIONS

Station	SOI No.	Year	SOI Value (gals.)	HIG Value (gals.)	Difference δ (mgal)
Kandla	41I2	1934	978.834	978.8361	+2.1
Veraval	41L1	1934	978.713	978.7121	-0.8
Viramgam	46A2	1934	978.830	978.8296	-0.4
Sholapur	4701	1929	978.341	978.3451	+4.1
Bijapur	47P1	1929	978.288	978.2888	+0.8
Bagalkot	47P2	1929	978.259	978.2627	+3.7
Mangalore	48L1	1933	978.237	978.2461	+9.1
Dharwar	48M2	1933	978.183	978.1942	+11.2
Bijnor	53K3	1932	979.131	979.1324	+1.4
Moradabad	53L1	1932	979.078	979.0852	+7.2
Badaun	53P2	1932	979.060	979.0638	+3.8
Etawah	54N1	1923	978.998	978.9945	-3.5
Raichur	56H1	1930	978.277	978.2822	+5.2
Secunderabad	56K1	1930	978.331	978.3370	+6.0
Cochin	58C1	1933	978.162	978.1724	+10.4
Kottayam	58C2	1933	978.138	978.1482	+10.2
Allahabad	63G1	1910	978.943	978.9429	-0.1
Buxar	6301	1912	978.933	978.9302	-2.8
Moghal Sarai	6302	1912	978.919	978.9180	-1.0
Sasaram	63P2	1912	978.903	978.9043	+1.3
Bhopalpatnam	65B1	1932	978.553	978.5609	+7.9
Bijapur	65B2	1932	978.457	978.4654	+8.4
Bhadrachellam	65C2	1932	978.472	978.4771	+5.1
Jagdalpur	65I1	1931	978.420	978.4310	+11.0
Jeypore	65J1	1932	978.391	978.3982	+7.2
Pottangi	65J2	1932	978.373	978.3806	+7.6
Arrah	72C1	1912	978.918	978.9173	-0.7
Gaya	72D2	1912	978.884	978.8764	-7.6
Mansi	72K2	1937	978.904	978.9048	+0.8
Katihar	7201	1936	978.923	978.9205	-2.5
Angul	73H2	1932	978.675	978.6818	+6.8

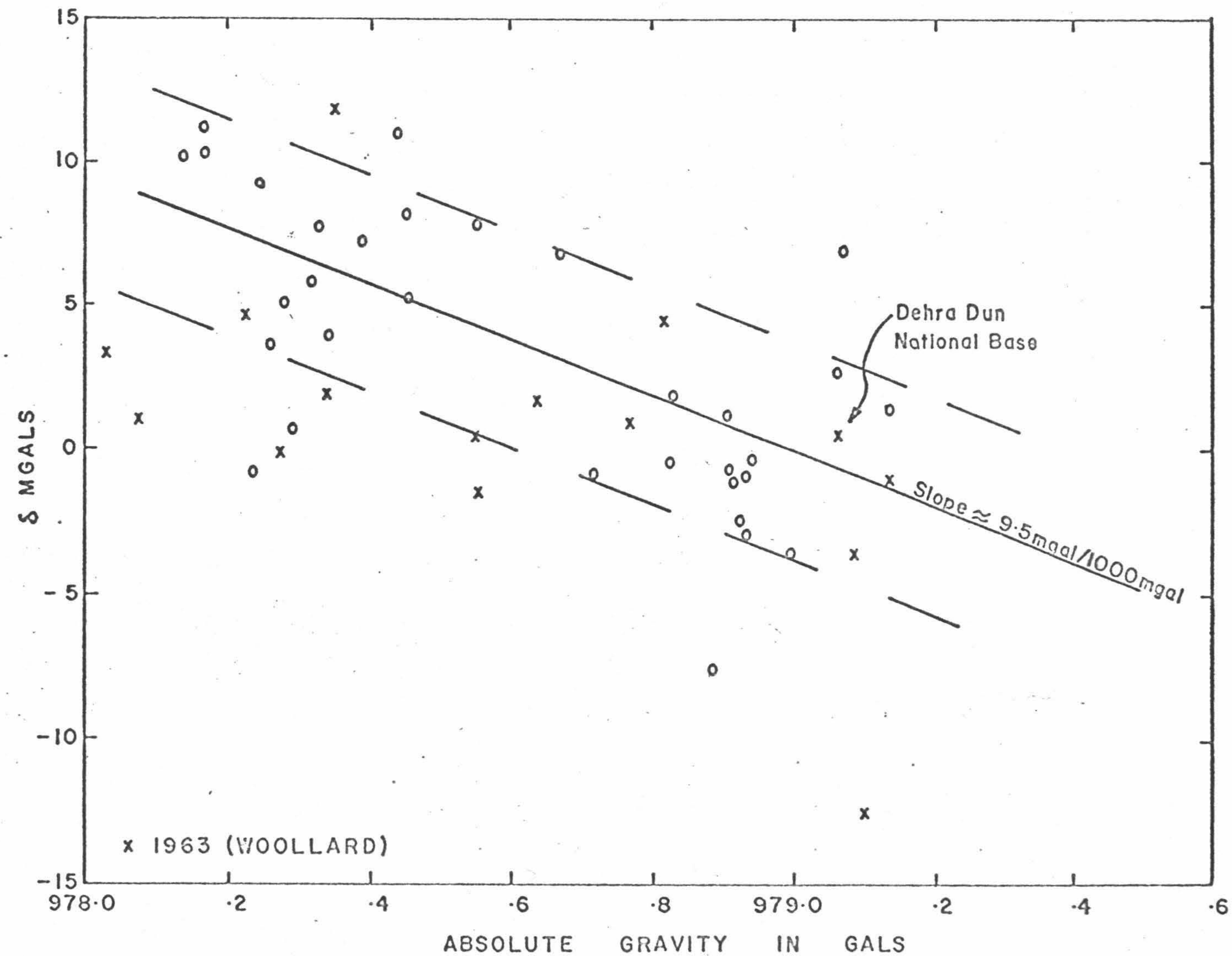

Figure 3. Differences in SOI Pendulum and HIG Gravimeter Values.

observations in a particular section of the country made in one or more field seasons were all tied to a common base, the above data can be divided into nine groups as indicated in Appendix Table I.

Since these data were based on random sampling from a normal population having a Gaussian distribution, linear regression analyses using the method of least squares were carried out to determine simple correlation between δ and g, and multiple correlation between δ and g and e. The sample points with values greater than 3σ(σ = standard deviation) were rejected. The results are shown below:

Group No.	No. of Stations	Correlation coefficient δ and g	Correlation coefficient δ and g and e
I	3	0.74	0.99
II	7	0.81	0.82
III	36	0.27	0.66
IV	13	0.63	0.65
V	10	0.37	0.40
VI	91	0.92	0.92
VII	77	0.47	0.49
VIII	7	0.80	0.80
IX	3	0.99	0.99

It is noted that except for the cases where the number of sample points is small, i.e., where such analysis is invalid, the inclusion of the elevation variable in the regression analysis in most cases did not significantly improve the correlation coefficient. The only exception was Group III. Lacking definite information on the type of gravimeters used, the third term in the equation (1), expressing the elevation dependence, was neglected in adjusting the data for each of the nine groups. A plot of the differences δ against the Survey of

India gravimeter values is given in Figure 4 and Table IV summarizes the results of the simple regression analyses.

On the above basis, the Survey of India gravimeter values for the stations in the different zones as outlined in Figure 5 were adjusted using the simple regression relation:

$$\delta = a_o + a_1 g \qquad (2)$$

and the corresponding values of the constants a_o and a_1 are as in the Table IV.

Oil and Natural Gas Commission Data

During the last decade the Oil and Natural Gas Commission has obtained a closely-spaced network of gravity observations in connection with petroleum exploration. These data were found to be internally consistent to an accuracy of ±0.5 mgal. Since the data for each of the Oil and Natural Gas Commission surveys had been tied to a local Survey of India pendulum or gravimeter station, only the determination of a_o term in the equation (1) appeared to be necessary. The correction was obtained from the reoccupation of the base station used for each survey. The old and the new values are listed in Table V. The Oil and Natural Gas Commission values were adjusted by the amounts shown to put them on a common standard relative to the Dehra Dun national base.

National Geophysical Research Institute Data

As the National Geophysical Research Institute has been using the standardization range of Manghnani and Woollard (1963) for controlling their gravity surveys, no corrections were necessary in their data which amounted to about 50 regional stations.

TABLE IV

RESULTS OF SIMPLE REGRESSION ANALYSIS OF HIG-SOI GRAVITY DIFFERENCES

Group No.	Area Covered (SOI topo map nos.*)	Correlation Coefficient	Constant a_0 (mgals)	Coefficient a_1 (mgals/gal)	Standard error of estimate (σ mgal)
I	43 J,K,L,N,O,P 44 M(1-29)	0.74	2447.60	-2.50	0.11
II	45 G,H,I,J,K,M,N	0.81	3763.80	-3.84	0.23
III	46 A,B,C,D,F,G,H,K,L,O,P	0.27	1337.33	-1.37	0.53
IV	48 L,P 49 M,N 58 B,F	0.63	4630.41	-4.73	0.29
V	52 D,H 53 A,B,C,D,E,F,G,J,K	0.37	-1040.73	1.06	0.37
VI	43 P 44 I,J,K,M,N,O 45 O,P 46 M,N 53 H 54 A,B,C,D,E,F,G,H,I,J,K,L,M,N,O 55 A,B,C,D,E,F,G,H,I,J,K,L,M,N,O,P 56 M 63 B,C,D,F,G,H 64 A,B,C,E,F,J	0.92	5930.45	-6.06	0.54
VII	56 A,C,E,F,G,H,J,K,L,O,P 57 A,B,C,D,E,F,G,H,I,J,K,L,M,N,O,P 58 A,J 65 C,D,H,J,L,O 66 A,B,C,D	0.47	3019.20	-3.09	0.61
VIII	72 F,K,L,N,O,P 73 I,M 79 A,B	0.80	7258.51	-7.41	0.29
IX	78 B,D,F,J,K,N,O 83 B,C,D,E,F,G,I,J,M	0.99	11773.48	12.02	0.29

* As referred in Gulatee (1956a).

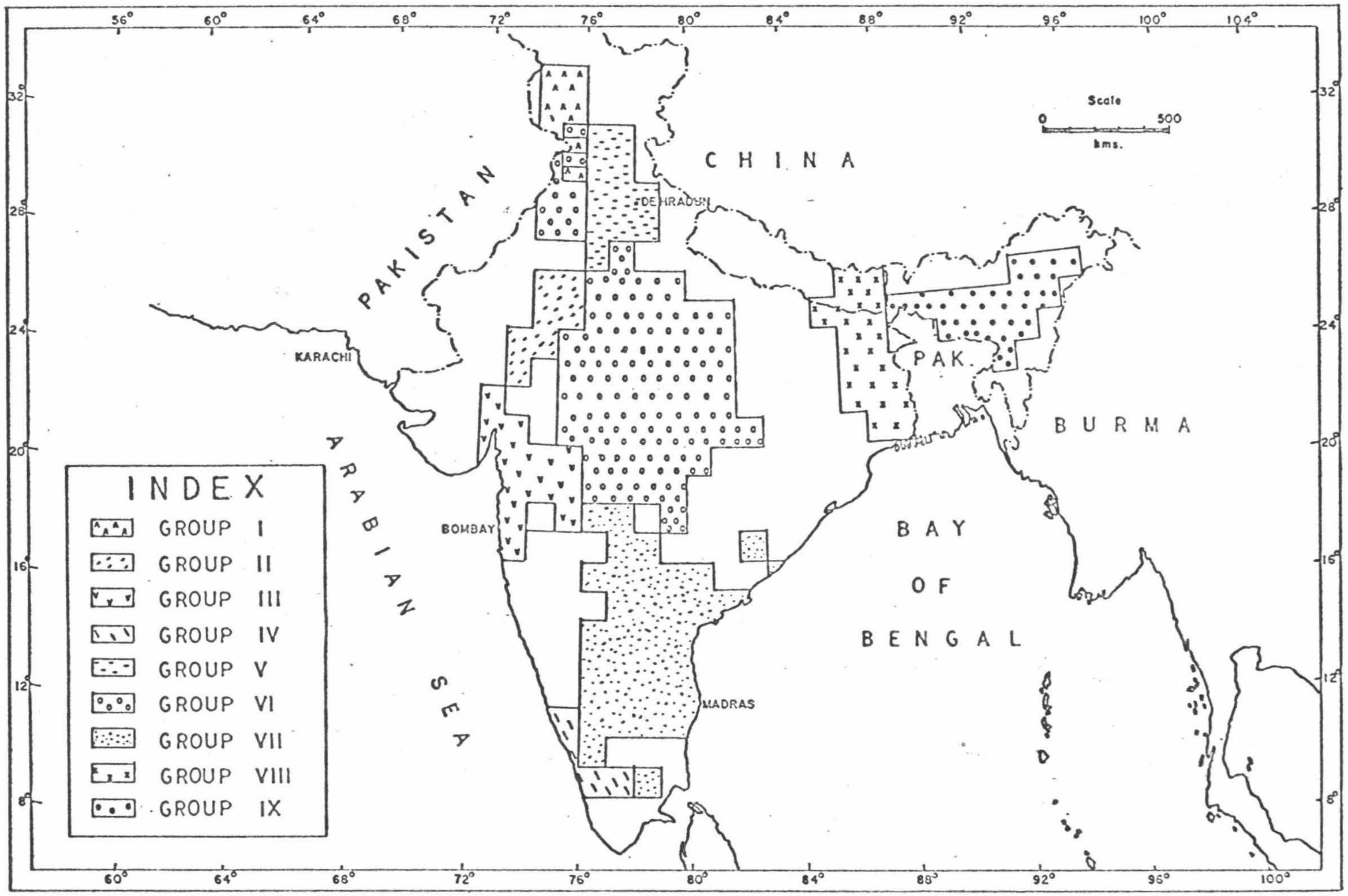

Figure 5. Distribution of SOI Gravimeter Stations for Standardization.

TABLE V

ONGC BASE STATION DATA

Party Nos.	Base Station	Value used by ONGC (gals)	HIG Value (gals)	Correction $(\delta = \alpha_o)$ (mgals.)
Andhra Pradesh-1, A.P.-2, A.P.-3, A.P.-4	Rajahmundry RS	978.4760	978.4759	-0.1
Madras-1, M-2, M-3	Trichinapolly PS	978.1605	978.1591	-1.4[a]
Rajasthan-5, R-6, R-7, R-8, Cutch-2, C-6, Gujerat-4, G-6, G-7, G-9	Ahmedabad PS	978.8368	978.8349	-1.9
Assam-1	Jorhat Engg. College	978.8854	978.8856	+0.2[c]
Cutch-1, C-3, C-4, C-5	Kandla PS	978.834	978.8361	+2.1[a]
Rajasthan-1, R-2, R-3, R-4, R-9, R-10(Sundra) R-10(Harra)	Jaisalmer	979.0294	979.0287[b]	-0.8
Gujerat-1, G-2, G-3(Ankleshwar), G-5	Broach PS	978.7436	978.7421	-1.5
Gujerat-3(Veraval)	Veraval PS	978.7130	978.7121	-0.9
Orissa-1, West Bengal-1, W.B.-2, W.B.-4	Midnapore PS	978.7738	978.7756[b]	+1.8
West Bengal-3, W.B.-5, Bihar-1, B-5	Katihar PS	978.9230	978.9205	-2.5
Bihar-2, B-3, B-4, B-6	Muzaffarpur RS	978.9325	978.9347	+2.2
Punjab-1	Gurdaspur RS	979.2733	979.2735	+0.2[c]
Punjab-2, P-3, P-4, P-5, P-6	Hoshiarpur RH	979.2357	979.2362	+0.5
Punjab-7, Uttar Pradesh-3, U.P.-17	Bijnor PS	979.1310	979.1324	+1.4
Uttar Pradesh-1, U.P.-2	Moradabad PS	979.0780	979.0852	+7.2
Uttar Pradesh-17, U.P.-20	Lucknow RS	978.9813	979.9810	-0.3
Uttar Pradesh-18, U.P.-19	Badaun PS	979.0600	979.0638	+3.8
Kerala-1	Kottayam PS	978.1380	978.1482	+10.2

Notes: [a] Not corrected as the ties are not clear and locations uncertain.
[b] Recent values supplied by the Survey of India.
[c] Neglected because small.
RS = Railway Station
PS = Pendulum Station
RH = Rest House

PROCESSING OF DATA

For studying anomalies in India, about 5,000 stations from all the available gravity data were selected having an average spacing of about 8-10 kms. After standardizing the gravity values, simple Bouguer anomalies were computed based on a density of 2.67 gm/cc. Terrain corrections were not applied. Their neglect, according to Woollard (1966), is not considered serious as might be supposed, since the terrain correction is a function of the actual location of the observation site relative to precipitous topography rather than to the general nature of the topography. Nevertheless, there is certain to be some bias in the simple Bouguer anomaly values at certain stations in the mountainous areas. Figure 6 shows the resulting Bouguer anomaly map contoured with an interval of 10 mgals.

To separate the anomalies of crustal origin from those due to near-surface geologic sources, two-dimensional filtering was used. Various filters have been developed for separating the regional from local effects with data interpolated on square grids. In this case, a very simple filter that has long been in use, was employed. The Bouguer anomaly values were picked on a grid of half degree intervals. The application of the filter consisted in summing two-tenths of the central value and one-tenth of each of the surrounding value over a $1^{\circ}X1^{\circ}$ square grid to obtain a mean value for the square. This process was repeated after moving the filter grid by half degree intervals in both the east-west and north-south directions.

The regional anomalies so obtained are shown in Figure 7. This map also incorporates the data similarly obtained for the Northern

Himalayas from the Figure 2 of Marussi (1963) the data for which he collected during the Italian Karakoram Expeditions of 1954, 1955 and 1961. Marussi's gravity datum (Caputo, 1957) is about 2.5 mgal lower than the standard datum of Dehra Dun used in this study, and in obtaining the regional anomalies this discrepancy was ignored. As the spacing of the data used in deriving the regional anomaly is half a degree, the anomaly components due to local sources having a wave length smaller than one degree, i. e., about 110 km in horizontal extent have been filtered out. The actual suppression of values for features with a wave length of one degree is about 10 percent in averaging over this distance.

Given gridded gravity anomaly values and a mass distribution about a horizontal plane, Cordell and Henderson (1968) have developed a method for calculating automatically a three-dimensional structure model by successive approximations. For a given density contrast and a given position of the horizontal plane, a first approximation of the structure is obtained by means of the Bouguer slab relationship. Subsequent modifications of the model are obtained by calculating the gravity effect of the model and using the ratio of the observed and the computed gravity values at each grid point. The process is iterated until a satisfactory agreement between the observed and calculated anomaly is obtained. Using this method, and assuming the depth of the horizontal plane to be 32 km and a density contrast of 0.4 gm/cc, a model was obtained of the configuration of the crust-mantle interface in the Indian sub-continent. This is shown in Figure 8. All calculations were based on the half degree grid regional anomalies.

As the Indian data was not exactly on a rectangular grid as required by Cordell and Henderson's method, an approximation was introduced by assuming the half degree grid to be equivalent to 53.8 km (the average length of a half degree in the region under study). At the sixth iteration, the agreement between the observed and the computed anomalies was better than 10 percent except in the boundary areas for the data. These errors are believed not to be significant when compared to those inherent in the basic assumptions of a standard sea level column, a constant density contrast between the crust and mantle, and the ambiguous nature of the gravity interpretation.

INTERPRETATION

BOUGUER ANOMALIES AND THE GEOLOGY

Most of the Indian sub-continent shows, see Figure 6, a negative anomaly of magnitude 40 mgals or more. The -40 or sometimes -50 mgal contour follows the boundary of the Precambrian rocks and parallels the coast line of the southern triangular peninsula. Superimposed on this general pattern are several lows having a magnitude of -100 mgals which center over a variety of geological formations:

1. Two elongated lows, one -100 mgal trending NNW-SSE and the other -90 mgal trending E-W, over the high density (2.9 gm/cc) Deccan Traps near the Bombay coast.
2. Three lows over the Dharwar gneisses and schists, of density 2.85 gm/cc, east of Goa, Mangalore and Cochin coasts.
3. One low over the Archaean granites of density 2.67 gm/cc about halfway between Mangalore and Madras.
4. About six small lows over the Cuddapah basin northwest of Madras.

The coastal areas around the peninsula show anomaly gradients of 0.8 mgal/km except in three localized areas on the western coast near Bombay, Mangalore and Cochin where steeper gradients of about 1.6 mgal/km are observed and where the anomalies become positive at the coast.

Gravity measurements made on H.M.S. OWEN during 1961-62 and 1962-63 indicate that the sharply increasing anomaly values at the coast and reaching a maximum of about +70 mgals at Bombay lie on the eastern flank of a small circular off-shore high whose western flank lies in the continental shelf area. Takin (1966) interpreted this high as being caused by the remains in the intermediate layer of a secondary magma chamber that furnished material to Deccan Traps.

A similar gravity high of about +60 mgals is found over the Kathiawar traps and would suggest another magma chamber. Various workers have suggested that the main sources of the Deccan Traps were in the west where studies of the eruptions, such as the one at Kathiawar by Wakhaloo (1967), have been made.

There are two 40 mgal lows observed over the sediments along the peninsular coast northwest of Ceylon. They appear to correlate with the Tertiary sediments in that area. Kailasam (1964) has done a detailed seismic geophysical study of this coastal belt and found several thousand feet of sediments.

The area of low gravity values flanked by a relative high in the Guntur and Rajahmundry districts north of Madras could indicate a faulted basin under the alluvium.

Cuddapah Basins

The large and broad gravity low northwest of Madras encloses the Cuddapah basin. The major portion of the sediments present consists of the Cuddapah series having a density slightly higher (2.75 gm/cc) than that of the surrounding crystalline rocks. Most of the central basin shows anomalies of about -100 mgals. However, a small 40 mgal relative high is seen in the southwestern part of the basin where widespread basic and ultra-basic igneous intrusives are present in the form of flows and sills (Sen and Rao, 1967).

The general low gravity in this region seems to have its origin in the deeper part--a sag in the crust where the basin developed. Reddy et al. (1967) and Balakrishna et al. (1967) have done detailed gravity and magnetic studies of the basin and have at places correlated local gravity highs with Cuddapah rocks and basement features.

The other Cuddapah basin of Bastar-Chattisgarh in the east-central India does not show any outline correlation with the gravity anomalies except for a region of relative high values over the Chattisgarh part of the basin.

The NE-SW trend of the exposed narrow synclinorium of Cuddapah sediments in the Aravalli tectonic belt has expression as steep gradient of gravity with an elongated high over the Dharwar rocks in the east. The parallel gravity low on the west would indicate an extension of the basin under the alluvium. There is some indication in the trend of the anomaly contours that the fault along the eastern margin of the synclinorium may continue into the graben of the Gulf of Cambay.

Gondwana Basins

The NW-SE elongated pair of gravity minimum and maximum in the Godavari valley is related to the graben structure of this Gondwana basin or with a steep fault scarp on its northeastern margin. The minimum of about -80 mgals falls over the Gondwana sediments which have been faulted down with respect to the Cuddapah sediments and crystalline rocks on the northeast side over which a gravity maximum of zero anomaly is indicated. Qureshy et al. (1968) have interpreted the low over the Gondwanas due to a rift zone 50 km wide, 3 to 4 km deep and extending as far as 23° N latitude. The writer believes that the gravity data are insufficient in this area for a clear definition of the maximum.

The Gondwana sediments in Madhya Pradesh can only roughly be correlated with the 30 mgal relative gravity low in that area.

Vindhyan Basin

Only a very general trend in the anomaly contours can be deciphered to follow the great Vindhyan basin in the central India. The western part of the basin shows up as a low while the eastern part roughly corresponds to a high. A zone of steep gradients trending NE-SW parallels the Great Boundary fault on the western margin of the basin.

A broad low is seen in the central India over the faulted trough along the Narbada valley which is mostly covered by alluvium. The steepness of the gravity gradient across the course of the Tapti river would also indicate a faulted trough showing through the Deccan Traps.

Indo-Gangetic Plains

The anomaly contours in the northern part over the Indo-Gangetic basin follow the general trend of the Himalayan chain in the north and show steep gradients of 0.7 mgal/km towards the mountains.

The NNW-SSE trending area of relatively high gravity anomaly values in northwest India extending into the West Pakistan seems to be the effect of the Punjab-Kashmir wedge of the peninsula thrusting into the Himalayan formations which have folded around it. A similar effect due to the Assam wedge in the northeastern India is suggested but there is a lack of gravity data in the area.

It is to be noted that the correlation between the Bouguer anomaly and the geology in the sub-continent is not consistent. Only the structural features such as major faults, larger intrusives, but not the extrusives, and some basinal depressions have expression in the anomalies. Most of the deficit in gravity seems to be related to mass variations associated with the crust and upper mantle.

REGIONAL ANOMALIES AND CRUSTAL STRUCTURE

To have significance for studying the crustal root, Woollard (1962b) has shown that the Bouguer anomaly should be based on the mean crustal density rather than on a value (2.67) that applies only to the surficial geology at the top of the crustal column. A change from 2.67 to 2.9 in making the slab correction would result in Bouguer anomalies about 9.5 mgal more negative for each 1000 meters of elevation, and a change of 9.5 mgal in the anomaly would imply an error of about 0.5 km ($\approx 9.5/2\pi\gamma \times 0.4$) in the crustal root estimate. This error in the Moho depth of about 0.5 km/1000 meters of elevation, however, would be significant only in the high mountain areas of the north.

The regional anomaly map, Figure 7, shows the Bouguer gravity anomaly values from which the anomaly components due to the sources near the surface and smaller than about 110 km in horizontal extent have been filtered out. In the absence of any information concerning seismic refraction velocities and the structure of the crust in the area, it is assumed that the regional anomalies have their origin in the variations in crustal thickness. Using a sea level standard column of 32 km of crustal thickness and a density contrast of 0.4 gm/cc, an estimate of the structure of the 'M' surface was obtained as shown in Figure 8.

The main features of the regional gravity, and consequently of the Moho surface, are:

1. A semi-circular, broad and extensive low covering the whole of the triangular peninsula in the south centered around Mangalore on the west

coast. Only gravity data in the Arabian Sea off this coast would indicate the total extent of this low and its relation to the low found in the Indian Ocean by a few reconnaisance gravity surveys (Caputo et al. 1964) and as defined by satellite observations (Kaula, 1966, Strange, 1966, and others). In relating satellite gravity observations to convection in the mantle, Runcorn (1965) has postulated that the negative gravity anomaly in the Indian Ocean is a place where there is a rising current and horizontal crustal flow radiating from its center outwards.

The writer's analysis indicates that the Moho is depressed under the southern peninsula with a maximum depth of about 42 km under the Mangalore coast.

2. Steep gravity gradients of 0.6 mgal/km toward and following the Himalayan chain occur from West Pakistan to Assam and Burma over the Indo-Gangetic trough. The derived crustal thickness varies from around 35 km under the exposed northern edge of the peninsula to about 40-45 km under the Himalayan foothills. These values are in general agreement with the results obtained from the surface-wave studies.

Evans and Crompton (1946) have postulated that there is a great thickness of low density sediments (50,000 ft $\approx$ 15 km) in Assam and Burma which would require a geologic correction of as much as 100 mgals. Such a correction would raise the regional Bouguer anomalies by this amount. Kaila et al. (1968) also report the presence of about 6 km of sediments (velocity = 2.7 km/sec) on the basis of P-wave earthquake data in the Himalayan foothills. If a density of about 2.5 gm/cc is assumed for the sediments, the regional anomalies in that area could be increased by about 50 mgals and the derived thickness of the crust decreased by about 3 km ($\approx 50/2\pi\gamma x 0.4$).

However, several ridges in the crystalline basement have been reported in the Indo-Gangetic trough, e.g., Delhi-Punjab ridge, and a well drilled near Lahore encountered mica schist at 1300 feet (Krishnan, 1956).

The Punjab wedge of the peninsula also seems to have been rigidly held up with the Moho at 32 km while the compressive stresses developed the Kashmir orocline around it.

The strong anomaly gradients, becoming steeper to 1.6 mgal/km in northern Kashmir, suggest there is a thickening of the crust towards the Hindukush-Karokarom chain of the central Himalayas where Marussi (1963) points out that there are large Bouguer anomalies of the order of -300 to -500 mgals. These in part may be attributed to the presence of great synorogenic granite intrusions forming the core of the mountains. However, it is doubtful if more than 35 to 40 mgals can be attributed to this cause.

3. A broad zone of relative high anomaly values extends from western Rajasthan where the anomalies are about +20 mgal through central India to the Ganges delta where the anomalies are negative. This band from NW to SE roughly parallels the exposed northern edge of the peninsula and is flanked by the large negative anomalies of the peninsula on the south and those of the geosynclinal trough on the north.

It has been widely accepted on the basis of paleomagnetic work on the Deccan Traps and the glacial evidence on the peninsula that the latter drifted from about 37° S to its present position of 19° N, referred to the latitude of Bombay. This drift not only involved northward translation but also an anticlockwise rotation of 25 to 30 degrees opening up the sphenochasm of the Arabian Sea (Holmes, 1965). The northwestern protrusion--Punjab-Kashmir wedge--of the advancing peninsula would be the first to come into contact with and butt against the Asian mass. This movement apparently produced the Baluchistan and Punjab oroclines and could have also produced a NW-SE trending anticlinal fold at the northern edge of the thrusting peninsula. The gravity data in the central India and the derived Moho structure there do suggest the presence of a crustal anticlinal fold which elevates the Moho to about 30 km under the western Rajasthan and with the Moho deeper at about 34 km under Chattisgarh in Madhya Pradesh.

This anticlinal feature, if it is proven to exist by seismic refraction studies, would be what Burrard (1918) and Glennie (1932) described as the 'Hidden Range' on the basis of limited gravity data. However, the anomalies do not indicate the existence of a 'Hidden Trough' in southern India parallel to the range. On the other hand, in a recent study of the Bouguer anomalies in India, Qureshy and Narain (1968) do not believe the evidence supports the concept of a 'Hidden Range' in central India.

CONCLUSIONS

From the foregoing study of the Bouguer anomalies in the Indian sub-continent, the following conclusions can be made:

1. The correlation of anomalies with the surficial geology is good in some areas such as Cuddapah synclinorium of the Aravalli belt, Gondwana trough of the Godavari Valley, sedimentary basins on the eastern coast, basic intrusives in Kathiawar and in Cuddapah basin northwest of Madras, but is rather poor in most other areas. The dominant part of the anomalies seems to have its origin in deep mass variations.

2. The regional gravity field shows two marked areas of low gravity, a wide semi-circular low covering the southern peninsula, and the other, an area of steep gradients towards the Himalaya Mountains separated by a zone of relative high gravity in the central India.

3. The regional gravity features may be interpreted as a depression of the Moho surface under south India, an upwarp in the crust under central India, and a gradual thickening of the crust in the Indo-Gangetic trough towards the Himalaya Mountains.

The thickening of the crust towards the Himalayas is to be expected for a major feature of this type of Alpine orogeny. The fact that the central India is a region of uplift, as represented by Satpura and Vindhyan Ranges, Mahadeo Hills, Maikal and Kaimur Ranges and the Chota Nagpur Plateau trending from west to east, and by the Aravalli Range trending north-south in western India, supports the postulate of a crustal upwarp underneath. But the interpretation of large negative gravity values in southern India in terms of a depression of Moho surface alone may be questioned and at least a part of the anomaly may be related to mass variations in the upper mantle.

It should be reiterated that the interpretation of the gravity anomalies in terms of the crustal structure is based on the assumptions that (a) the Airy concept of isostasy prevails, (b) there is a standard sea level crustal column of fixed structure and thickness, and (c) the density contrast between the crust and mantle is constant. Seismic refraction studies in various areas of the world have, however, shown that none of these assumptions is universally true. Thus the gravity interpretation without seismic crustal measurements offers only one possible solution, rather than a unique one.

APPENDIX

TABLE I

SOI AND HIG COMMON STATIONS

SOI NO.	YEAR	ELEV (ft)	SOI VALUE (GALS)	HIG VALUE (GALS)	DIFF δ (MGALS)
GROUP I					
43P6	1952	875	979.2733	979.2735	0.2
44M3	1952	775	979.3062	979.3065	0.3
44M7	1952	995	979.2357	979.2362	0.5
GROUP II					
45H1	1954	1860	978.8079	978.8135	5.6
45J2	1954	1587	978.9785	978.9836	5.1
45J4	1954	1455	978.9919	978.9965	4.6
45J6	1954	1581	978.9781	978.9833	5.2
45M5	1954	1570	979.0235	979.0283	4.8
45N2	1953	1420	978.9910	978.9957	4.7
45N19	1954	1280	979.0295	979.0344	4.9
GROUP III					
46A3	1953	156	978.8368	978.8349	-1.9
46A4	1953	170	978.8326	978.8295	-3.1
46B3	1953	120	978.8006	978.7994	-1.2
46B4	1953	141	978.7843	978.7825	-1.8
46C3	1953	30	978.7250	978.7237	-1.3
46C4	1953	58	978.7431	978.7412	-1.9

Appendix - Table I - Continued

Group III - Continued

46C9	1953	57	978.7236	978.7218	-1.8
46D3	1953	36	978.7117	978.7107	-1.0
46D5	1953	44	978.6871	978.6862	-0.9
46D7	1953	87	978.6697	978.6689	-0.8
46D10	1953	60	978.6510	978.6504	-0.6
46F1	1953	109	978.7535	978.7520	-1.5
46F4	1953	118	978.7534	978.7517	-1.7
46F12	1953	380	978.7572	978.7556	-1.6
46L9	1955	1943	978.4859	978.4843	-1.6
46L11	1955	1900	978.4894	978.4881	-1.3
4605	1953	691	978.6386	978.6366	-2.0
46012	1953	679	978.6335	978.6319	-1.6
46P16	1955	1143	978.5402	978.5380	-2.2
47A6	1953	52	978.6260	978.6253	-0.7
47A8	1953	22	978.6737	978.6726	-1.1
47A9	1953	15	978.6695	978.6685	-1.0
47A10	1953	50	978.6772	978.6762	-1.0
47A12	1953	12	978.6584	978.6572	-1.2
47A13	1953	10	978.6555	978.6544	-1.1
47A15	1955	26	978.6145	978.6131	-1.3
47B2	1951	34	978.6341	978.6333	-0.8
47B8	1953	9	978.6531	978.6521	-1.0
47E31	1955	27	978.5624	978.5617	-0.7
47E32	1955	50	978.5498	978.5490	-0.8

Appendix - Table I - Continued

Group III - Continued

47E33	1955	70	978.5475	978.5467	-0.8
47E37	1955	750	978.5005	978.4984	-2.1
47E38	1955	950	978.4867	978.4862	-0.5
47E39	1955	1923	978.4299	978.4289	-1.0
47E43	1955	1827	978.4634	978.4618	-1.6
47E44	1955	1842	978.4679	978.4662	-1.7

GROUP IV

48L2	1956	34	978.2949	978.2938	-1.1
48L3	1956	34	978.2561	978.2554	-0.7
48L7	1956	18	978.2595	978.2585	-1.0
48L8	1956	36	978.2630	978.2619	-1.1
48P3	1956	10	978.2350	978.2339	-1.1
48P9	1956	16	978.2730	978.2717	-1.3
48P10	1956	22	978.2499	978.2489	-1.0
48P12	1956	15	978.1953	978.1942	-1.1
49M8	1956	20	978.1961	978.1951	-1.0
49M9	1956	15	978.1846	978.1838	-0.8
49M11	1956	44	978.1707	978.1699	-0.8
49M19	1956	30	978.1699	978.1700	0.1
58B4	1956	98	978.1426	978.1421	-0.5

Appendix - Table I - Continued

GROUP V

53D3	1952	792	979.1112	979.1123	1.1
53F13	1947	985	979.1345	979.1360	1.5
53G3	1947	867	979.1288	979.1303	1.5
53G4	1949	734	979.1517	979.1532	1.5
53G6	1948	900	979.1603	979.1612	0.9
53G9	1949	808	979.1484	979.1498	1.4
53J2	1947	2239	979.0630	979.0640	1.0
53J6	1947	3006	979.0219	979.0224	0.5
53J10	1947	6578	978.8201	978.8215	1.4
53J15	1947	6500	978.8267	978.8274	0.7

GROUP VI

43P24	1955	1088	979.2419	979.2397	-2.2
44I6	1954	759	979.3512	979.3476	-3.6
44I17	1954	755	979.3520	979.3499	-2.1
44N30	1954	810	979.2814	979.2791	-2.2
45018	1952	830	978.8860	978.8871	1.1
45P2	1955	1523	978.7709	978.7722	1.3
45P6	1955	1174	978.8394	978.8406	1.2
46M12	1955	1633	978.7168	978.7183	1.5
46M13	1955	1544	978.7215	978.7229	1.4
46M15	1955	1462	978.7514	978.7529	1.5
46N2	1953	1903	978.6200	978.6214	1.4

Appendix - Table I - Continued

Group VI - Continued

46N7	1953	1887	978.6214	978.6223	0.9
46N8	1953	1806	978.6446	978.6453	0.7
46N10	1953	1745	978.6649	978.6656	0.7
53H3	1950	649	979.0826	979.0806	-2.0
53H18	1951	720	979.1349	979.1343	-0.6
53H20	1952	710	979.1456	979.1441	-1.5
53H21	1952	685	979.1428	979.1416	-1.2
53H29	1952	690	979.1388	979.1382	-0.6
54A10	1952	930	978.9915	978.9916	0.1
54E16	1952	581	979.0711	979.0706	-0.5
54F4	1953	570	978.9860	978.9863	0.3
54I2	1950	587	979.0736	979.0713	-2.3
54I3	1950	612	979.0768	979.0742	-2.6
54I11	1955	520	979.0535	979.0534	-0.1
54J4	1953	694	978.9511	978.9511	0.0
54K4	1953	920	978.8821	978.8810	-1.1
54K6	1953	850	978.9072	978.9073	0.1
54L9	1953	1200	978.8144	978.8135	-0.8
55B2	1953	690	978.6935	978.6950	1.5
55B5	1953	630	978.6913	978.6927	1.4
55C2	1953	1014	978.6879	978.6882	0.3
55C3	1953	1007	978.6869	978.6882	1.3
55D3	1953	912	978.5973	978.5996	2.3
55D4	1953	889	978.6007	978.6032	2.5

Appendix - Table I - Continued

Group VI - Continued

55D5	1953	868	978.6025	978.6051	2.6
55D6	1953	818	978.6068	978.6093	2.5
55E25	1955	1407	978.7409	978.7411	0.2
55H3	1953	1098	978.5994	978.6014	2.0
55H5	1953	1083	978.5873	978.5896	2.3
55H6	1953	989	978.6033	978.6054	2.1
55H17	1953	920	978.5907	978.5929	2.2
55L4	1953	978	978.5893	978.5915	2.2
55L5	1953	886	978.5940	978.5959	1.9
55L7	1953	935	978.5830	978.5849	1.9
55L9	1953	809	978.5926	978.5945	1.9
5501	1948	1019	978.6147	978.6170	2.3
55031	1953	1017	978.6161	978.6176	1.5
55P6	1953	806	978.6043	978.6058	1.5
55P7	1953	820	978.5807	978.5824	1.7
55P8	1953	762	978.5875	978.5893	1.8
55P9	1953	723	978.5871	978.5891	2.0
55P14	1953	652	978.5862	978.5881	1.9
55P15	1953	631	978.5829	978.5849	2.0
56M1	1953	624	978.5687	978.5709	2.2
56M2	1953	608	978.5667	978.5690	2.3
56M3	1953	621	978.5673	978.5696	2.3
63B2	1950	385	978.9813	978.9810	-0.3
63B7	1950	405	978.9778	978.9773	-0.5

Appendix - Table I - Continued

Group VI - Continued

63B14	1955	412	978.9783	978.9764	-1.9
63B20	1955	410	978.9783	978.9779	-0.4
63B21	1955	400	978.9756	978.9749	-0.7
63B22	1955	410	978.9766	978.9762	-0.4
63B23	1955	410	978.9712	978.9709	-0.3
63C2	1955	436	978.9144	978.9147	0.3
63C3	1955	432	978.9138	978.9139	0.1
63C4	1955	465	978.9144	978.9146	0.2
63C5	1955	409	978.9230	978.9230	0.0
63C6	1955	439	978.9253	978.9254	0.1
63C7	1955	430	978.9317	978.9316	-0.1
63C8	1955	415	978.9450	978.9450	0.0
63C9	1955	436	978.9350	978.9351	0.1
63C12	1955	395	978.9645	978.9644	-0.1
63C13	1955	394	978.9545	978.9544	-0.1
63C14	1955	366	978.9520	978.9518	-0.2
63C15	1955	406	978.9448	978.9444	-0.4
63D4	1955	1050	978.8417	978.8420	0.3
63G2	1955	785	978.8837	978.8839	0.2
63G3	1955	591	978.8970	978.8973	0.3
64A6	1955	1254	978.7584	978.7593	0.9
64E8	1955	1586	978.6714	978.6725	1.1
64E9	1955	1691	978.6605	978.6617	1.2

Appendix - Table I - Continued

Group VI - Continued

64F2	1955	1795	978.6424	978.6436	1.2
64F3	1955	2029	978.6343	978.6358	1.5
64F4	1955	1819	978.6409	978.6422	1.3
64F6	1955	1219	978.6766	978.6777	1.1
64J2	1955	1087	978.6942	978.6954	1.2
64J3	1955	1051	978.6850	978.6861	1.1
64J4	1955	938	978.6944	978.6954	1.0
64J5	1955	884	978.6808	978.6819	1.1

GROUP VII

56A2	1955	1505	978.4660	978.4634	-2.6
56A3	1955	1405	978.4632	978.4608	-2.4
56A4	1955	1380	978.4598	978.4572	-2.6
56A6	1955	1340	978.4566	978.4538	-2.8
56C2	1955	1405	978.3223	978.3207	-1.6
56E2	1955	1315	978.4571	978.4543	-2.8
56E4	1955	1180	978.4711	978.4680	-3.1
56E5	1955	1230	978.4687	978.4658	-2.9
56E6	1955	1240	978.4634	978.4605	-2.9
56F2	1955	1130	978.4642	978.4610	-3.2
56G9	1955	1495	978.3454	978.3431	-2.3
56G11	1955	2052	978.3118	978.3104	-1.4
56H8	1955	1276	978.3276	978.3258	-1.8

Appendix - Table I - Continued

Group VII - Continued

56H10	1955	1677	978.3178	978.3154	-2.4
56H11	1955	1216	978.3286	978.3262	-2.4
56H12	1955	1071	978.3255	978.3232	-2.3
56H13	1955	1003	978.3203	978.3192	-1.1
56H14	1955	1065	978.3101	978.3080	-2.1
56H15	1955	1072	978.2980	978.2957	-2.3
56H16	1955	1314	978.2867	978.2850	-1.7
56J1	1955	1255	978.4447	978.4416	-3.1
56J4	1955	1702	978.3954	978.3927	-2.7
56J6	1955	1750	978.3748	978.3723	-2.5
56K5	1955	1960	978.3380	978.3357	-2.3
56K6	1955	1940	978.3322	978.3305	-1.7
56K7	1955	1614	978.3382	978.3366	-1.6
56K9	1955	1350	978.3576	978.3552	-2.4
56K10	1955	1040	978.3826	978.3803	-2.3
56K16	1955	1740	978.3370	978.3349	-2.1
56K17	1955	1608	978.3455	978.3430	-2.5
56K18	1955	1889	978.3215	978.3192	-2.3
56K19	1955	1888	978.3162	978.3140	-2.2
56K20	1955	2114	978.3007	978.2989	-1.8
56L2	1955	1620	978.3027	978.3005	-2.2
56L5	1955	1770	978.3072	978.3050	-2.2
5601	1955	941	978.4378	978.4356	-2.2
5602	1955	907	978.3930	978.3907	-2.3

Appendix - Table I - Continued

Group VII - Continued

5603	1955	695	978.3998	978.3976	-2.2
5604	1955	609	978.4070	978.4048	-2.2
5605	1955	571	978.4040	978.4021	-1.9
56P3	1955	430	978.3986	978.3954	-3.2
56P4	1955	530	978.3858	978.3830	-2.8
57E1	1955	1484	978.2273	978.2243	-3.0
57E8	1955	1473	978.2273	978.2257	-1.6
57E31	1955	1008	978.2917	978.2900	-1.7
57E33	1955	1112	978.2522	978.2506	-1.6
57E34	1955	1389	978.2276	978.2263	-1.3
57E35	1955	1447	978.2274	978.2258	-1.6
57E36	1955	1563	978.2213	978.2210	-0.3
57E37	1955	1593	978.2228	978.2217	-1.1
57G1	1951	3118	978.0315	978.0293	-2.2
57G19	1955	2232	978.1356	978.1339	-1.7
57G21	1955	2061	978.1511	978.1493	-1.7
57G30	1955	2686	978.0958	978.0947	-1.1
57H1	1951	2980	978.0359	978.0346	-1.3
57H2	1951	3002	978.0351	978.0341	-1.0
57I15	1955	555	978.2612	978.2581	-3.1
57I16	1955	949	978.2879	978.2843	-3.6
57I21	1955	700	978.2730	978.2693	-3.7
57I22	1955	602	978.2786	978.2749	-3.7

Appendix - Table I - Continued

Group VII - Continued

57I33	1955	1004	978.2820	978.2796	-2.4
57J2	1955	500	978.2666	978.2633	-3.3
57J13	1955	456	978.2506	978.2475	-3.1
57J18	1955	480	978.2564	978.2528	-3.6
57J20	1955	397	978.2548	978.2526	-2.2
57L15	1955	1323	978.1300	978.1288	-1.2
57L20	1955	870	978.1881	978.1855	-2.6
57N4	1951	40	978.3101	978.3082	-1.9
57N9	1955	63	978.3235	978.3212	-2.3
57O11	1951	293	978.2399	978.2382	-1.7
57P3	1955	700	978.1984	978.1965	-1.9
57P5	1955	580	978.2136	978.2117	-1.9
58J1	1956	267	978.1605	978.1591	-1.4
58J2	1951	260	978.1622	978.1604	-1.8
66A7	1955	25	978.4050	978.4031	-1.9
66C8	1951	25	978.2858	978.2839	-1.9
66D1	1951	40	978.2818	978.2803	-1.5

GROUP VIII

72K5	1953	120	978.9112	978.9146	3.4
72O2	1953	104	978.9166	978.9206	4.0
73I1	1947	761	978.8150	978.8195	4.5
73I19	1952	355	978.8292	978.8333	4.1
73M81	1952	259	978.8516	978.8559	4.3
79B3	1952	36	978.8215	978.8263	4.8
79B10	1952	19	978.8007	978.8051	4.4

Appendix - Table I - Continued

GROUP IX

78N34	1952	159	978.9895	978.9853	-4.2
7801	1952	5021	978.6922	978.6844	-7.8
7805	1952	1783	978.8957	978.8900	-5.7

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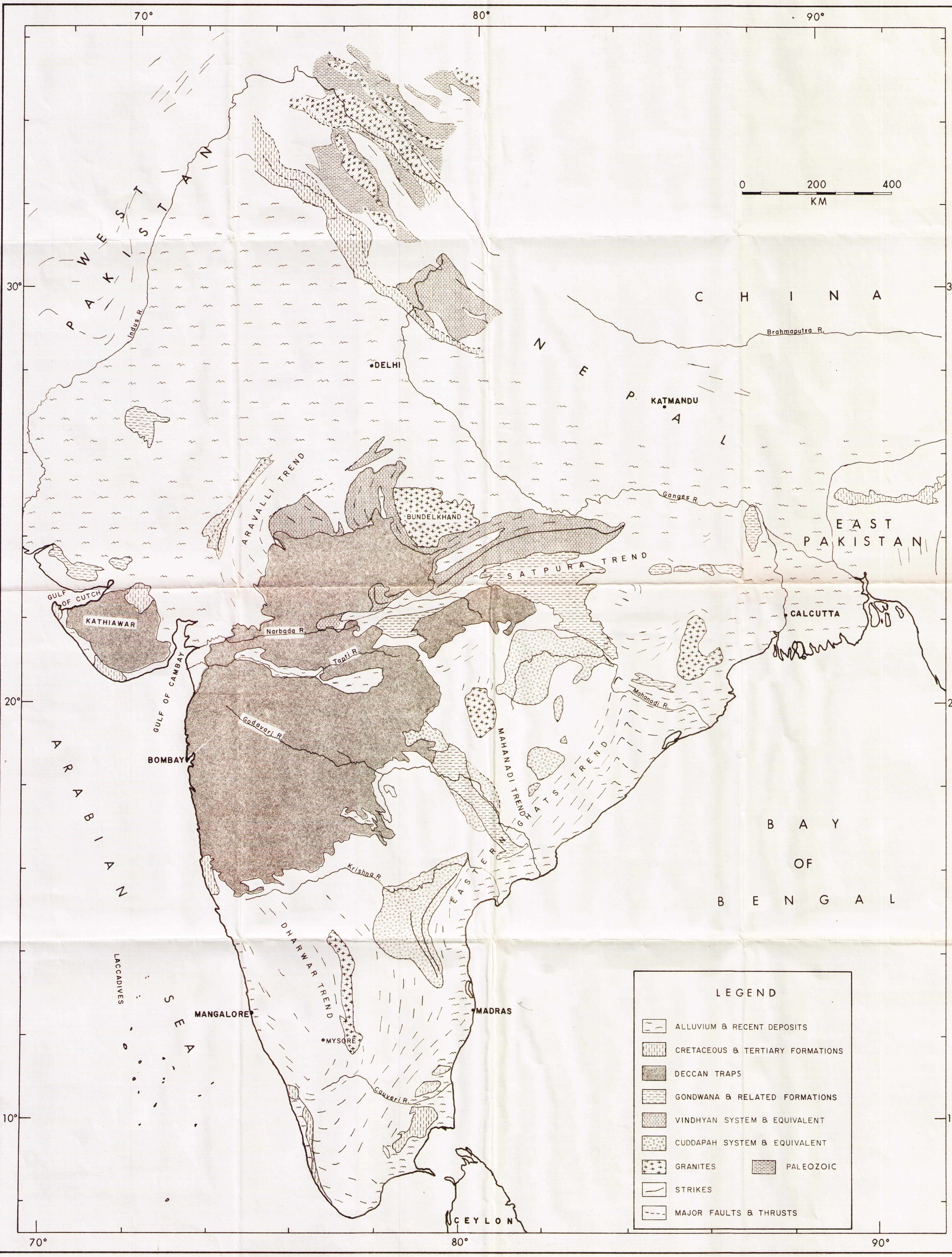
FIG. 2



70°
80°
90°
30°
20°
10°
0 200 400
KM
CHINA
NEPAL
WEST PAKISTAN
EAST PAKISTAN
Indus R.
Brahmaputra R.
DELHI
KATMANDU
Ganges R.
ARAVALLI TREND
BUNDELKHAND
SATPURA TREND
GULF OF CUTCH
KATHIAWAR
Narbada R.
Tapti R.
CALCUTTA
GULF OF CAMBAY
Mahanadi R.
Godavari R.
BOMBAY
MAHANADI TREND
EASTERN GHATS TREND
ARABIAN SEA
BAY OF BENGAL
Krishna R.
DHARWAR TREND
LACCADIVES
MANGALORE
MADRAS
MYSORE
Cauveri R.
CEYLON
LEGEND
ALLUVIUM & RECENT DEPOSITS
CRETACEOUS & TERTIARY FORMATIONS
DECCAN TRAPS
GONDWANA & RELATED FORMATIONS
VINDHYAN SYSTEM & EQUIVALENT
CUDDAPAH SYSTEM & EQUIVALENT
GRANITES
PALEOZOIC
STRIKES
MAJOR FAULTS & THRUSTS

Fig 6

CONTOUR INTERVAL = 10 MGALS.
0 200 400
KM
70°
80°
90°
30°
20°
10°
WEST PAKISTAN
CHINA
NEPAL
EAST PAKISTAN
CALCUTTA
BOMBAY
GOA
MANGALORE
MADRAS
COCHIN
CEYLON
ARABIAN SEA
BAY OF BENGAL

FIG. 7

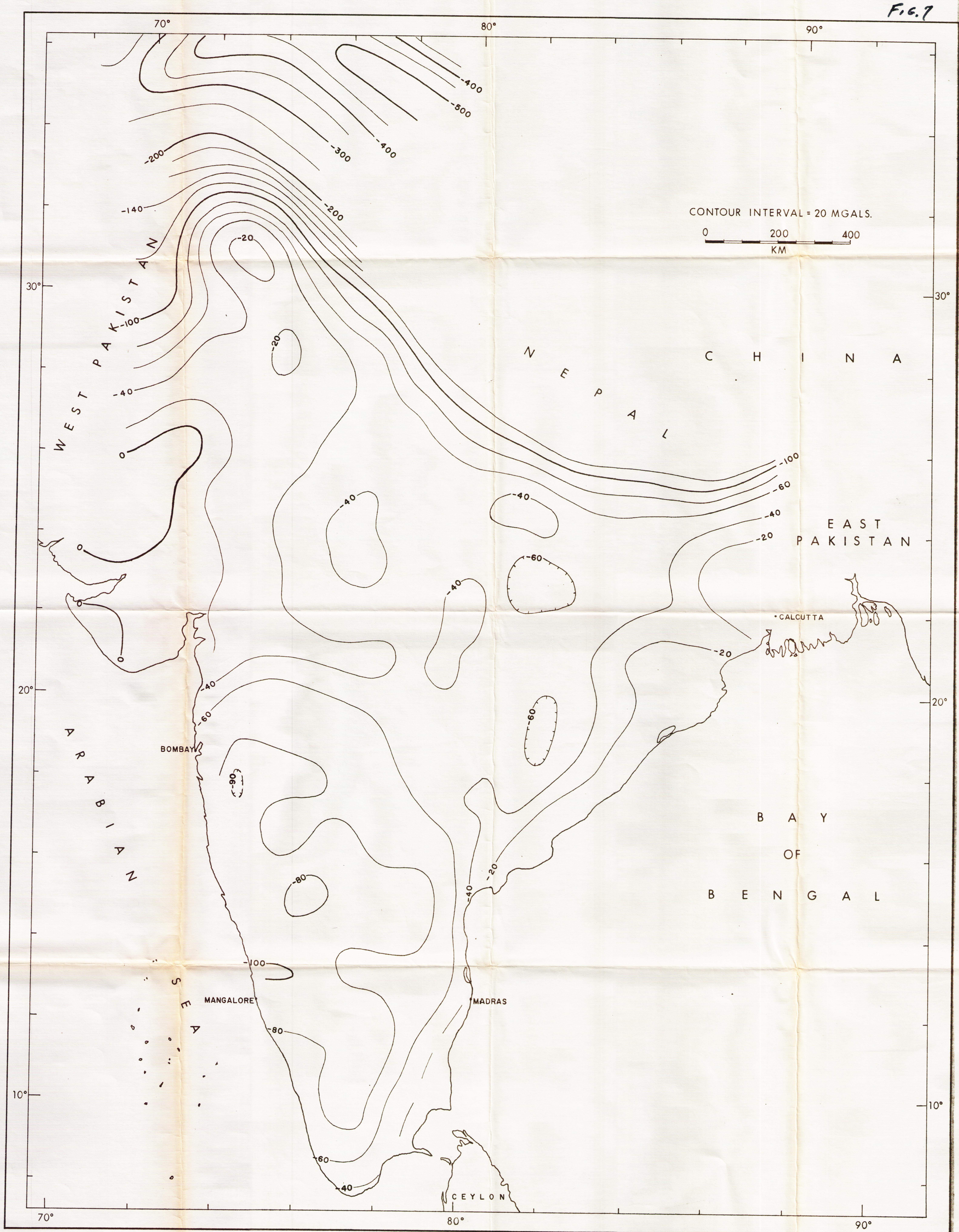
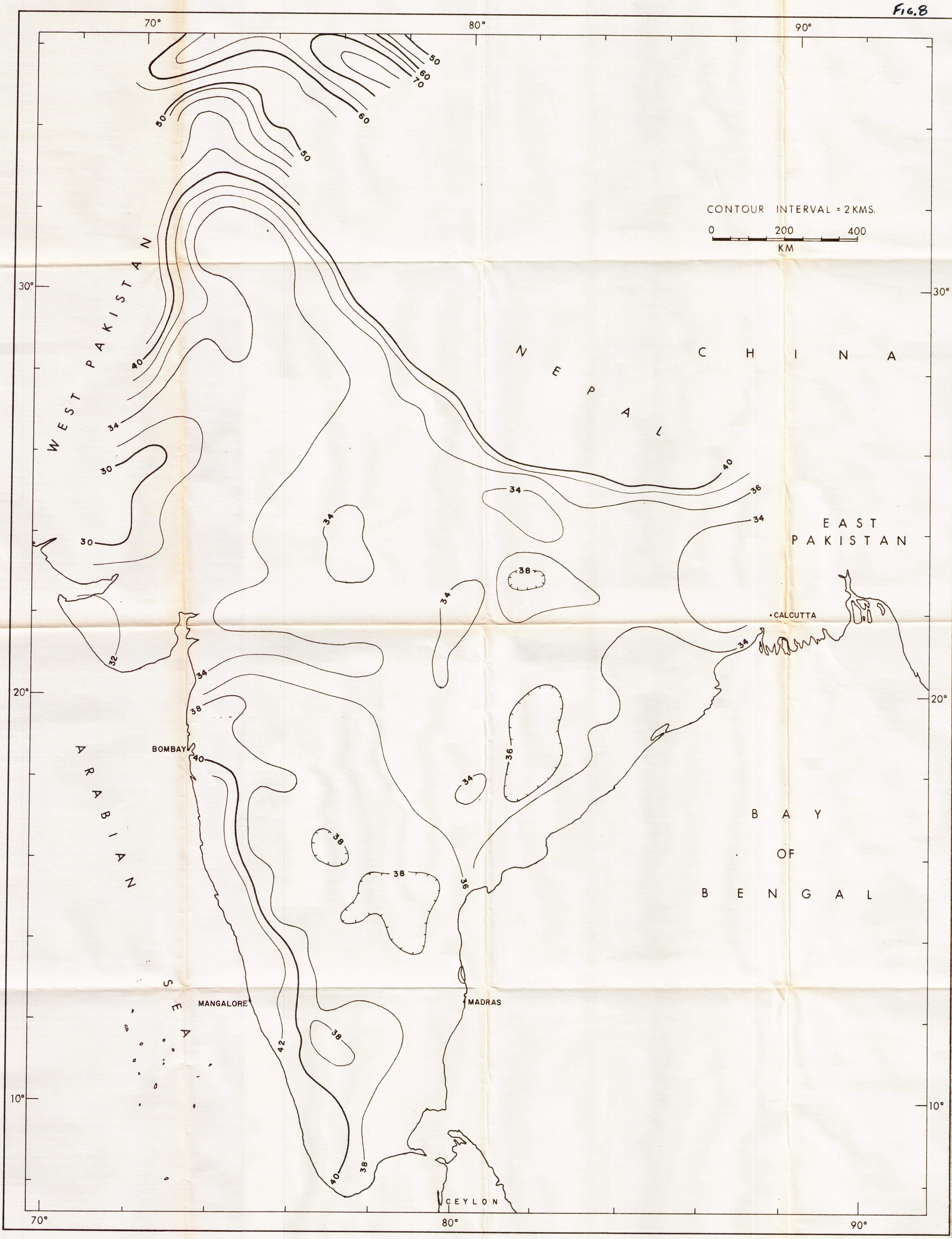

CONTOUR INTERVAL = 20 MGALS.
0 200 400
KM
WEST PAKISTAN
NEPAL
CHINA
EAST PAKISTAN
CALCUTTA
BOMBAY
MANGALORE
MADRAS
CEYLON
ARABIAN SEA
BAY OF BENGAL
70°
80°
90°
30°
20°
10°
-500
-400
-300
-200
-140
-100
-60
-40
-20
0
-80
-90

Fig. 8



CONTOUR INTERVAL = 2 KMS.
0 200 400
KM
70°
80°
90°
30°
20°
10°
WEST PAKISTAN
NEPAL
CHINA
EAST PAKISTAN
CALCUTTA
BOMBAY
MANGALORE
MADRAS
CEYLON
ARABIAN SEA
BAY OF BENGAL