Present Status of Marine Gravity

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Introduction

The technique of measuring gravity at sea has been greatly improved by the development of spring-type surface-ship gravimeters which can be operated in a wide variety of sea conditions (LaCoste, 1967; Graf and Schulze, 1961). Since about 1961 surface-ship gravity measurements have been obtained on a routine basis in each of the world's major ocean basins. By combining surface-ship gravity measurements with measurements obtained earlier on board submarines (Vening Meinesz, 1948; Worzel, 1965) it is now possible to construct gravity anomaly maps of large regions of the world's oceans. These maps form an important basis for geodetic, geological and geophysical studies.

Since the development of the concept of plate tectonics there have been two approaches to the interpretation of marine gravity data that have proved particularly useful. The first, based on the pioneering studies of Vening Meinesz (1941) and Gunn (1947), uses relatively short-wavelength (wavelength $\lambda \lesssim 400$ km) gravity anomalies in oceanic regions to provide information on the long-term (>10^6 years) mechanical properties of the oceanic lithosphere (for example, Walcott, 1970; Watts and Cochran, 1974; Watts et al., 1975). The second, uses relatively long-wavelength ($\lambda \gtrsim 400$ km) gravity anomalies in oceanic regions to provide information on the forces which operate on the plates and which may ultimately drive them (for example, Anderson et al., 1973; Sclater et al., 1975; Watts, 1976; McKenzie, 1977).

The purpose of this paper is to present a brief review of some of the most recent developments in marine gravity. The extent of marine gravity data coverage is illustrated in a compilation map of the main free-air gravity anomaly maps of the world's oceans which have been published since 1974. A brief discussion of some of the main results in the interpretation of marine gravity is given and some comments made on recent determinations of the gravity field in oceanic regions using satellite radar altimeters.

Gravity Measurements

During the past few years there have been increased efforts to obtain gravity measurements in oceanic regions, particularly aboard U.S., U.S.S.R., and Japanese research vessels (Table 1). Gravity measurements have now been obtained along more than 2 million nautical miles of ship's tracks. Although the accuracy of gravity measurements obtained on individual ship's cruises depends on the types of navigation and instrumentation used, the standard error of these measurements (Table 1) based on studies of discrepancies at intersecting ship's tracks is estimated to be in the range of 5 to 10 mgal.

Figure 1 summarizes the regions of the world's oceans where gravity anomaly maps have been constructed. This figure only includes those maps with an areal extent of 4×10^4 km^2 or greater. These maps are contoured either at 10 mgal or 25 mgal intervals and include a compilation of all available surface-ship, submarine and land gravity measurements. A significant proportion of the data used in these maps is now available from the NGDC*.

Interpretation

Studies have now been carried out which have used marine gravity data to determine information on the deformation (or flexure) of the oceanic lithosphere caused by surface loads such as sediments (Gunn, 1944; Walcott, 1972; Cochran, 1973) and seamounts (Gunn, 1943; Walcott, 1970; Watts and Cochran, 1974; Watts et al., 1975). An important parameter in these studies is the effective flexural rigidity which is determined mainly by the effective elastic thickness of the oceanic lithosphere. By comparing observed gravity anomalies with calculated anomalies based on simple elastic or viscoelastic models it has been possible to estimate the effective elastic thickness and how it may vary with crustal age. The main results of these studies, summarized in Watts (1978), is that surface loads formed at or near mid-ocean ridge crests are associated with relatively small values of the effective elastic thickness while surface loads formed on relatively old lithospheric plates are associated with relatively large values.

Figure 2 is a plot of "isostatic response function" for the East Pacific rise crest and Hawaiian-Emperor seamount chain in the Pacific ocean. This figure shows that the range of wavelengths which provide information on isostasy at the East Pacific rise is 30 to 300 km while that for the Hawaiian-Emperor seamount chain is 200 to 800 km. The importance of these functions, however, (for example, Lewis and Dorman, 1970; McNutt and Parker, 1978) is that they can be easily compared to different models of isostasy. Figure 2 shows that the observed "isostatic response function" for the East Pacific rise crest and Hawaiian-Emperor seamount can be explained by a simple flexure model with values of the effective elastic thickness of the oceanic lithosphere in the range 2 to 6 km and 20 to 30 km respectively.

Recent studies have shown (Detrick and Watts, in preparation; Watts, Bodine, and Ribe, in preparation) that the "isostatic response functions" in Figure 2 can explain gravity data over a wide variety of other geological features. In particular, the ridge

*NGDC. National Geophysical Data Center, Boulder, Colorado.

TABLE 1

Principal Marine gravity Operations Over the World's Oceans 1973 - 1978

Institution	Country	Principal Ships	Gravimeter	Stable Platform	Coverage
Bedford Institute of Oceanography	Canada	Hudson	Graf-Askania Gss-2	Anschütz	Pacific, Atlantic
		Baffin	Graf-Askania Gss-2	Anschütz	Atlantic
Centre National Pour l'explor- ation des Oceans (CNEXO)	France	Jean Charcot	Graf-Askania Gss-2	Anschütz	Atlantic
German Hydrographic Institute	Germany	Komet	Graf-Askania Gss-2	Anschütz	Atlantic
		Meteor	Graf-Askania Gss-2 (also Gss-3)	Anschütz	Atlantic
Institute of Oceanology, Moscow	USSR	Akademik Kurchatov	Graf-Askania Gss-2	Russian built	Atlantic
		Vityaz	Graf-Askania Gss-2	gyrostabilized	Pacific
Lamont-Doherty Geological Observatory	US	Vema	Graf-Askania Gss-2	Alidade	Pacific, Indian, Atlantic
		Robert D. Conrad	Graf-Askania Gss-2	Anschütz, Aeroflex	Pacific, Indian, Atlantic
National Oceanic and Atmospheric Administration	US	Surveyor	LaCoste-Romberg S-51	Gyrostabilized	Pacific
		Researcher	Lacoste-Romberg S-52	Gyrostabilized	Atlantic
Ocean Research Institute, University of Tokyo	Japan	Hakuho-Maru	TSSG (VSA)	Gyrostabilized	Pacific
		Hakuho-Maru*	LaCoste-Romberg S-32	Gyrostabilized	Pacific
Woods Hole Oceanographic Institution	US	Chain	VSA	Sperry MK19	Pacific, Indian
		Atlantis	VSA	Sperry MK19	Atlantic

*Joint United States-Japan cooperative program.

crest function adequately explains gravity data over the Walvis and Ninetyeast aseismic ridges while the Hawaiian-Emperor seamount chain function adequately explains data over some Mid-Pacific seamounts and the Louisville ridge. These results are in general agree-ment with the observation that a number of geological features on the ocean floor orig-inated either at or near a mid-ocean ridge crest (ridge crest and fracture zone topo-graphy, Walvis and Ninetyeast ridges) or as a relatively young load on an old litho-spheric plate (Hawaiian-Emperor seamount chain, Mid-Pacific seamounts, Louisville ridge).

Although these studies have used marine gravity data to provide information on the mechanical behavior of the oceanic lithosphere, they provide little information on the forces which may be operative on the plates. The main problem is that the mechanical and thermal properties of the oceanic lithosphere serve to obscure the gravity effect of deeper processes in the Earth such as mantle convection.

A useful approach to this problem has been to examine the relationship between long-wave-length gravity anomalies and deviations in expected depth of the sea-floor (or residual depth anomalies) for broad regions of the world's oceans (Anderson et al., 1973; Sclater et al., 1975; Watts, 1976). These studies show that a good correlation between gravity and residual depth anomalies exists, at least for the North Atlantic and Central Pacific Oceans. A correlation between long-wavelength gravity and residual depth anomalies makes a good argument for convection. Recently, however, Cochran and Talwani, (1978) concluded

from a global data set that there was, in general, a poor visual correlation between long-wavelength gravity and depth anomalies in the world's oceans. In addition, Detrick and Crough (1977) have proposed the residual depth anomaly in the Central Pacific ocean formed by lithospheric thinning over an underlying "hot spot". Future studies should therefore attempt to establish a relationship between gravity and residual depth anomalies as a function of wave-length since this information appears to be the most likely to constrain models of mantle con-vection (McKenzie, 1977).

GEOS-3 Satellite Altimeter Data

With the advent of satellite altimetry it is now possible to determine the shape of the marine geoid with a great deal of accuracy (Leitao et al., 1975; Leitao and McGoogan, 1975). In the absence of noise, gravity anom-alies derived from GEOS-3 altimeter data, for example, would be equivalent to gravity anom-alies measured on surface-ships. In the presence of noise, however, surface-ship gravity measure-ments provide the best means to determine the short-wavelength gravity field in the oceans while GEOS-3 altimeter data provide the best means to determine the long wavelengths.

In a recent study Rapp (in press) has recovered 1 x 1° average gravity anomalies from GEOS-3 altimeter data and compared them with averages determined from surface ship and land measurements. The RMS difference be-tween predicted and terrestrial 1 x 1° gravity anomaly averages was ±16 mgal for the Philippine sea region and ±8 mgal for the East Coast, U.S.
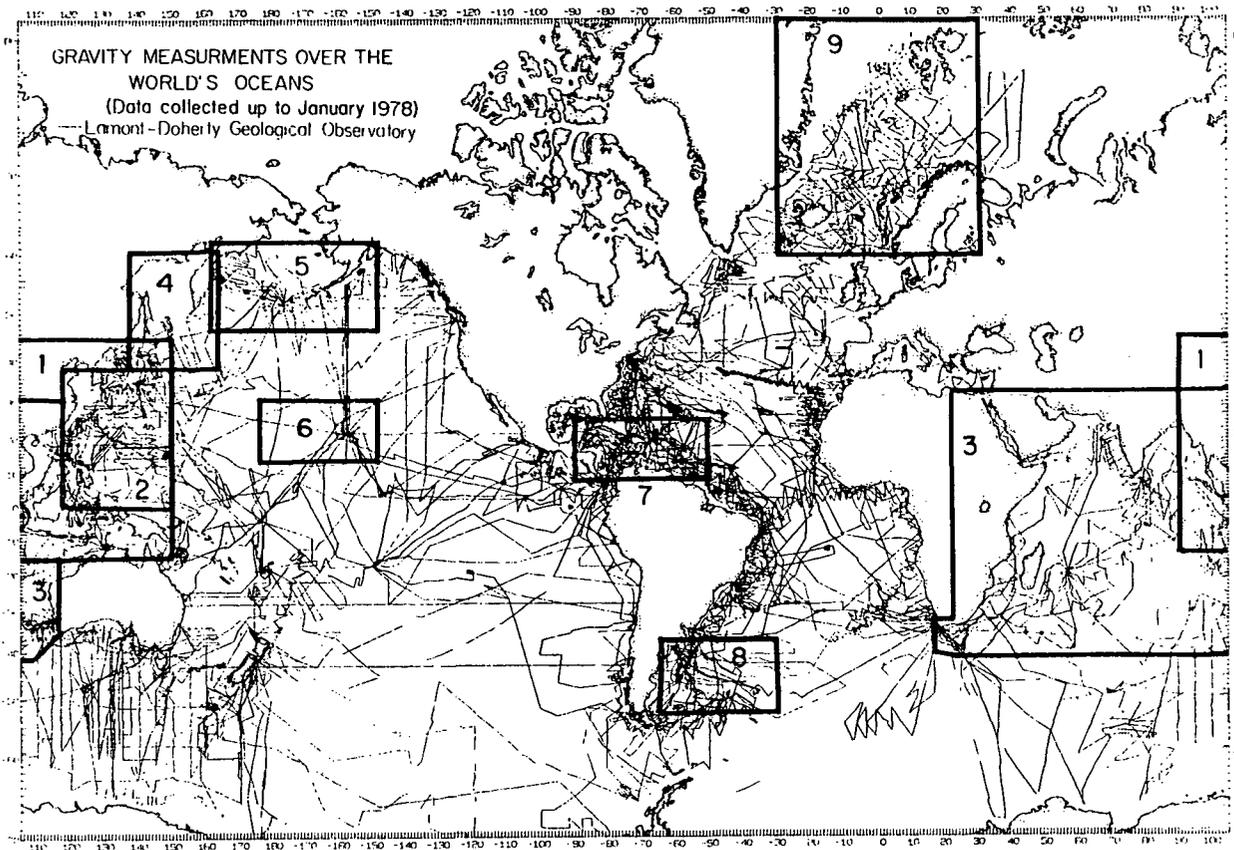
Figure 1. Location map showing coverage of gravity data of Lamont-Doherty
research vessels R/V Robert D. Conrad, Vema and Eltanin (Table 1) up to
October 1978. The heavy lines outline those recently published free-air
gravity anomaly maps of the world's oceans with an area greater than
4×10^4 km^2. The sources of the maps are as follows: 1. Watts, Bowin,
Bodine (1978); 2. Watts (1976); 3. Talwani and Kahle (1975); 4. Watts,
Bodine, Kogan (in press); 5. Watts (1975); 6. Watts and Talwani (1974);
7. Bowin (1976); 8. Rabinowitz (1977); 9. Grønlie and Talwani (1978).

region. Thus, in these regions, which include
a variety of different geological features,
gravity anomalies can apparently be recov-
ered from GEOS-3 altimeter data with a resolu-
tion of about 200 km and a standard error of
about ±12 mgal.

The overall usefulness of GEOS-3 altimeter
data for lithospheric studies can be evaluated
by comparing these estimates of resolution with
those which are required to define isostasy at
the East Pacific rise crest and Hawaiian-Emperor
seamount chain (Fig. 2). The "isostatic response
functions" in Figure 2 explain surface-ship grav-
ity data in the region of the Hawaiian-Emperor
seamount chain and East Pacific rise crest with
an average standard error of ±12 mgal and ±4
mgal respectively. These errors can be attri-
buted to features of the gravity field of
these regions which are not related to isostasy.
Thus in order to provide information on the
state of isostasy of the Hawaiian-Emperor sea-
mount chain, a resolution of at least 200 km
(Fig. 2) with a standard error of better than

±12 mgal is required, while at the East Pacific
rise crest a resolution of at least 30 km (Fig.
2) with a standard error of better than ±4 mgal
is required.

These considerations suggest GEOS-3 altimeter
data may provide useful information on the state
of isostasy of relatively young loads on old
lithospheric plates (Hawaiian-Emperor seamount
chain) but appears unlikely to provide useful
information on isostasy of features formed on
young oceanic crust near mid-ocean ridge crests.

The most promising use of GEOS-3 altimeter
data appears to be in the improved definition
of the long-wavelength gravity field. Of part-
icular interest is the information which may be
present in GEOS-3 altimeter data on deep pro-
cesses in the Earth such as those which may be
associated with mantle convection.

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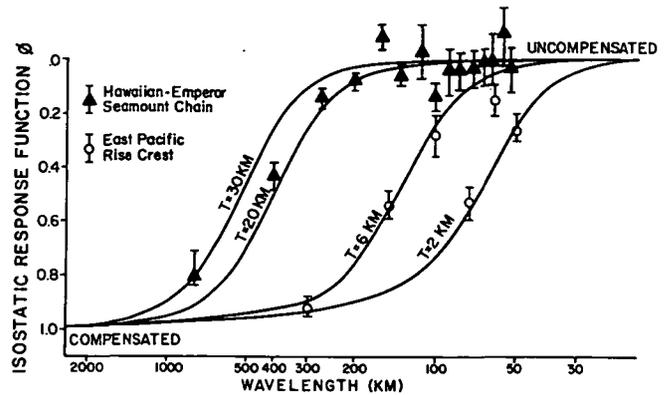
Figure 2. Plot of "isostatic response function" against wavelength for the Hawaiian-Emperor seamount chain and East Pacific rise crest in the Pacific ocean. This figure shows the range in wavelengths for which isostasy is effective at these features. The data in this plot is based on two recent studies by Watts (1978) and Cochran and Watts (in preparation).

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