GRAVITY STUDY OF CAPE COD BAY

Introduction

The geology of the Holocene, Pleistocene, and Tertiary rocks exposed on Cape Cod and the character of those same sediments in the Bay has been treated by numerous workers. The nature of the underlying crystalline basement however has been rarely touched as it is nowhere exposed on the Cape. Depth to basement is shallow both on the Cape and in the Bay. Drill holes penetrating both granitic gneisses and micaceous schists of Paleozoic age at depths less than 0.2 km have been reported by Koteff and Cotton (1962) and Oldale and Tuttle (1965). Geophysical depth determinations, both by seismic and magnetic methods, confirm the same shallow depth (Griscom and Bromery, 1968). Seismic studies in the Bay indicate shallow burial of the crystalline basement with sediment cover ranging from zero at Plymouth to slightly more than 0.2 km in the forearm of the Cape (Hoskins and Knott, 1960; Oldale and O'Hara, 1974; O'Hara and Oldale, 1976).

Gravity and aeromagnetic surveys in Massachusetts (Bromery, 1967; Griscom and Bromery, 1968) show complex Bouguer gravity and magnetic fields over the Cape Cod area suggesting a crystalline basement composed of varied lithologies. Structural trends are consistent with those both observed farther inland and inferred from later geophysical work to the north and east in the continental shelf (Kane and others, 1972). Of particular note is a north trending Bouguer gravity high located east of the Cape Cod canal with maximum values in excess of +35 mgals. In addition a smaller northeast-trending gravity high is present in the eastern part of the Bay. Both gravity anomalies coincide with magnetic highs previously defined by Taylor and others (1968) and Griscom and Bromery (1968). (On a smaller scale, Grow (written communication, 1976) has recently pointed out a very strong relationship between recent aeromagnetic data (GP-804, GP-814) over Cape Cod and the north trending gravity high).

The lack of data from Cape Cod Bay prompted a bottom gravity survey,* and the new data here reported provides a better picture of the gravity field over the Bay. It helps substantiate the extension of previously defined anomalies on land and defines a smaller subparallel gravity low in the northeastern part of the Bay and Cape. The anomalies appear similar to gravity highs and lows elsewhere in coastal New England and offshore (Kane and others, 1972) which are related to intrusive mafic and felsic rock bodies.

Methods of Study

Bottom gravity measurements were made with a LaCoste-Romberg H bottom gravity meter. Forty-seven gravity stations were located along seven east-west traverses at approximately 6 km spacing providing complete coverage of the Bay. A few stations lie off the traverse lines.

Station position was determined primarily by Loran-C navigation and a few visual fixes on navigational aids and man made objects on the Cape (eg. water towers, etc.). All stations are believed to be accurate to $\pm$0.1 minute of latitude. Latitude uncertainty introduces an error not greater than 0.1 mgal.

Water depth was obtained by a pressure transducer in the gravity sphere with an error believed to be less than 1.5 m. The maximum error attributed to depth uncertainties is 0.4 mgal.

Gravity measurements were tied to a base station at the Woods Hole

*The survey was originally defined to provide new gravity data off the New Hampshire and Maine coasts. Due to severe weather conditions work in the open ocean was prohibitive; Cape Cod Bay was protected and had never been surveyed. Data from the northern survey are on file but are insufficient to warrant mapping at this time.

Oceanographic Institution, Woods Hole, Massachusetts, with a value of 980,326.04 mgals (main pier). Because the meter had been reset for work further to the north, only one tie to the WHOI base was made at the conclusion of work in the Bay. Drift of the instrument over the three days in the Bay, therefore, is unknown and cannot be quantitatively evaluated, but is assumed to be very small. Total error from latitude, depth, instrument reading, and drift probably does not exceed 1 mgal.

Observed gravity was reduced by standard methods using a Bouguer density of 2.80 gm/cm^3, consistent with recent gravity work on the continental shelf (Kane and others, 1972; Hendricks and Robb, 1973). Bouguer gravity was hand contoured at a 5 mgal interval. Excellent continuity exists with gravity contours previously drawn for Cape Cod by Bromery (1967). A slight tare is likely present as his data were reduced using a Bouguer density of 2.67 gm/cm^3, though no significant shift is noted with a 5 mgal contour interval.

Discussion

The Bouguer gravity field over Cape Cod Bay (Fig. 1) is dominated by an elongate north-trending positive anomaly. The Cape anomaly is an extension of an earlier defined gravity high across the southern arm of Cape Cod from Martha's Vineyard to East Sandwich, Massachusetts with a maximum Bouguer value in excess of +35 mgal (Bromery, 1967; Griscom and Bromery, 1968). That anomaly is now shown to extend beyond East Sandwich, through Cape Cod Bay and into at least the southern part of Massachusetts Bay. The gravity anomaly along this positive "ridge" decreases northerly away from East Sandwich to the north-central part of the Bay at a rate of approximately 0.8 mgal/km. A minimum value of about +16 mgal is reached near Fishing Ledge (Fig. 1). Beyond this point gravity values increase on the order of 0.4 mgal/km in a northerly direction. More recently, Bowin and Grow (1976) and Grow and others (1976) have shown that the Cape anomaly extends south of Martha's Vineyard.

Approximately 10 km east of the north-trending gravity high in the Bay, contoured Bouguer values define a subparallel gravity trough with a minimum value in the Bay of +5.9 mgal. This anomaly extends northeasterly from a point north of Barnstable Harbor through Truro, Massachusetts. It joins a broader gravity low with closure just east of the Cape and identified as Anomaly IIIA by Kane and others (1972).

The two Bouguer anomalies are believed to reflect largely the general character of crystalline basement beneath Cape Cod Bay. Shallow overlying minor Tertiary and more abundant Pleistocene and younger sediments have little effect on the observed Bouguer gravity field, particularly in the western part of the Bay. As sediment cover increases in thickness eastward (to 0.2 km) the gravity effect correspondingly increases. This effect was removed by approximating a density range for the sediments using Woollard's (1959) and Nafe and Drake's curves (in Talwani, et al., 1959b) relating compressional velocity to density. Ambiguity at low P velocities produces a large range in density for these sediments; from less than 2 gm/cm^3 to as high as 2.6 gm/cm^3 for the older and more consolidated sedimentary rocks. A density contrast of -0.4 gm/cm^3 was chosen to represent the shallow overlying cover. Calculations for this prism show negligible gravity effects in the western part of the Bay with an increase to -3 mgal in the forearm of the Cape where sediment thickness is 200 (?) meters. These values were removed to evaluate the major north-trending anomaly (Fig. 2).

Assumed density values for the crystalline basement rocks of the continental shelf are previously listed by Kane and others (1972) and Hendricks and Robb (1973). These are 2.8 gm/cm^3 for Precambrian and early Paleozoic metamorphic rocks; 2.7 gm/cm^3 for felsic igneous rocks and granitic gneisses (both known from drill holes to exist at shallow depths beneath the Cape and a sample of a probable granite outcrop has been obtained near the entrance to the Cape Cod Canal (X, Fig. 1) by R.N. Oldale (personal communication, 1976) and 3.0 gm/cm^3 for assumed mafic igneous or metamorphic rocks. The granite sample is not used in modelling. Model calculations (Talwani et al., 1959a) using these assumed values permit some simple estimates of the sources for observed anomalies.

Two gravity profiles were drawn: one parallel to 42°N latitude from Plymouth to Long Point for which good subsurface information is available (Hoskins and Knott, 1960); the other from the mouth of the Cape Cod Canal to Orleans (41°47' N. lat.). For both, the regional gravity gradient was taken as 0 mgal from a regional profile from the simple Bouguer gravity map of Massachusetts (Bromery, 1967) supplemented by extension into the gravity field mapped over the continental shelf (Kane and others, 1972). Maximum depth calculations following methods outlined by Kane and others (1972) indicate that the source mass for the elongate positive anomaly is less than 4 km at 42°N and less than 3 km at 41°47' N. Minimum thicknesses range from 1.7 to 3.7 km, respectively for this anomaly causing mass.

While the two models illustrated in Figure 2 are speculative, they do depict a mass of positive density contrast. A roughly rectangular sheet-like model with nearly flat top and flat bottom at 3 and 5 km produces calculated gravity values in good agreement with the observed curve for A-A'. For the B-B' profile, the model requirements are more irregular. The high amplitude (+30 mgal) and steep westerly gradient (3.5 mgal/km) suggest a top at or near the sediment-basement contact. The model found to best approximate the observed curve has a sheet-like form with a block

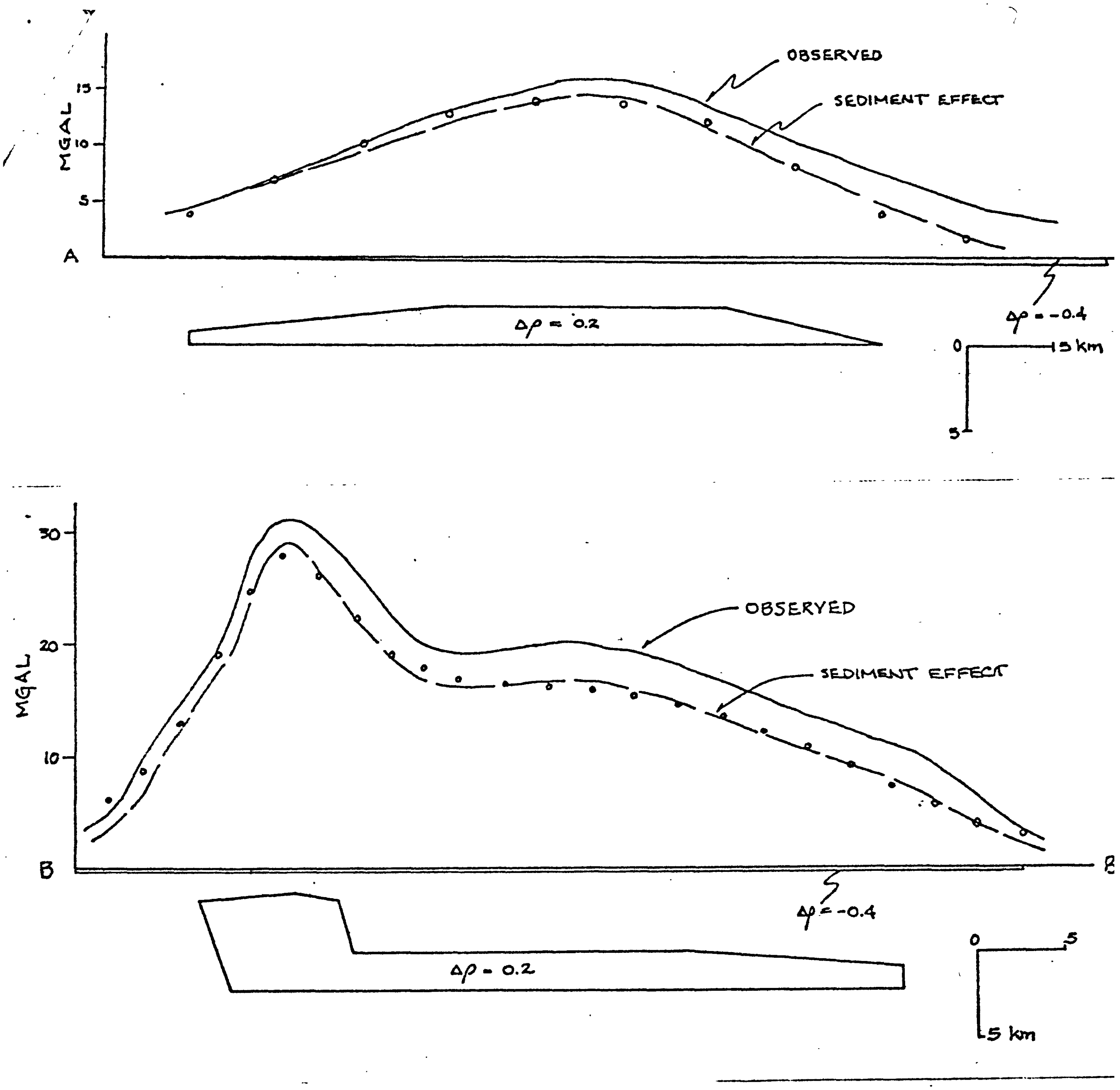

Figure 2. Gravity profiles A-A' and B-B'. Solid line - observed Bouguer gravity; dashed - observed minus effect of sediment prism; circles calculated gravity for model ($\Delta\rho = +0.2$ gm/cm^3).

at the western end extending downward from 1.5 km (top) to 7.3 km (bottom). The western block when projected northerly suggests that at least part of the disturbing mass plunges to the north.

Conclusions

In the absence of rock cores beneath the major positive gravity anomaly and the general lack of bedrock exposures on the Cape, conclusions reached regarding the rock type and (or) structure responsible for the observed anomaly are considered tentative. However, some insight is provided by the similarity of the Cape anomaly and analogous anomalies identified off the New England coast (Kane and others, 1972; Bothner and Harrower, 1973). In addition magnetic highs are coincident with gravity highs in Cape Cod Bay and on the Cape (Griscom and Bromery, 1968; Taylor and others, 1968). These associations support the suggestion of a dense (mafic?) rock mass at a shallow depth. That mass may be represented by an elongate intrusive body extending from Martha's Vineyard through the Cape and the Bay, a band of mafic volcanic or metamorphic rocks, or as suggested by Griscom and Bromery (1968) a folded sequence of similar composition to those mentioned. The preceding two hypotheses imply that the anomaly causing mass is part of the Paleozoic crystalline basement. A third hypothesis that deserves future consideration is the possibility of a Triassic basin (cf., Ballard and Uchupi, 1975) with sufficient basalt infillings to cause the observed gravity and magnetic anomalies from Martha's Vineyard through Cape Cod Bay. Present data precludes distinction among these possibilities. Further geophysical work or drilling will be necessary to define rock type more accurately and unravel the underlying basement structure.

Acknowledgments

The assistance of J.D. Hendricks and C.J. O'Hara in obtaining the gravity data reported here is gratefully acknowledged. Able navigation and good company was provided by the captain of the R/V Asterias. F.S. Birch and J.A. Grow provided thoughtful comments on an earlier draft of this report.

References Cited

Aeromagnetic map of part of the Cotuit Quadrangle, Barnstable County, Massachusetts: USGS Map GP-814, 1971.

Aeromagnetic map of part of the Sandwich Quadrangle, Barnstable County, Massachusetts; USGS, Map GP-804, 1971.

Ballard, R.D. and Uchupi, E., 1975, Triassic rift structure in Gulf of Maine: AAPG Bull., v. 59, p. 1041-1072.

Bothner, W.A. and Harrower, K.L., 1973, Gravity study of the Cape Neddick complex and associated off-shore anomaly in southern Maine: Geol. Soc. America, Abs. with Programs for 1973 (Northeastern Sec.), v. 5, no. 2, p. 140.

Bowin, C.O. and Grow, J.A., 1976, Marine gravity measurements along the Atlantic continental margin (abs): Trans. Amer. Geophys. Union, v. 57, no. 4, p. 265.

Bromery, R.W., 1967, Simple Bouguer gravity map of Massachusetts: U.S. Geological Survey Map GP-612.

Griscom, A., and Bromery, R.W., 1968, Geologic interpretation of aeromagnetic data for New England: in Zen, E-an, and others, eds., Studies of Appalachian Geology: Northern and Maritime: New York, Interscience p. 425-436.

Grow, J.A., C.O. Bowin, D.R. Hutchinson, and K.M. Kent, 1976, Preliminary free-air gravity anomaly map along the Atlantic continental margin between Virginia and Georges Bank: U.S. Geol. Surv. Misc. Field Series Map, MF-795.

Hendricks, J.D., and Robb, J.M., 1973, Gravity measurements in the vicinity of Georges Bank: Geol. Soc. America Bull., v. 84, p. 3911-3916.

Hoskins, H. and Knott, S.T., 1960, Geophysical investigation of Cape Cod Bay, Massachusetts, using the continuous seismic profiler: Jour. Geophy. Res., v. p. 330-340.

Kane, M.F., Yellin, M.J., Bell, K.G., and Zietz, I., 1972, Gravity and magnetic evidence of lithology and structure in the Gulf of Maine: U.S. Geological Survey Prof. Paper 726-B, 22 p.

Koteff, C. and Cotton, J.E., 1962, Preliminary results of deep drilling on Cape Cod, Massachusetts: Science, v. 137, no. 3523, p. 34.

O'Hara, C.J. and Oldale, R.N., 1976, Basement morphology and pre-Holocene sedimentary structure of Cape Cod Bay, Massachusetts: Geol. Soc. America with Programs for 1976 (Northeastern Sec.), v. 8, no. 2, p. 238-239.

Oldale, R.N., and O'Hara, C.J., 1974, Preliminary geologic map of Cape Cod Bay: Adm. Rept. to Commonwealth of Massachusetts.

_______________ and Tuttle, C.R., 1964, Seismic investigations on Cape Cod, Massachusetts: U.S. Geological Survey Prof. Paper 475-D, p. D118-D122.

Talwani, M., Worzel, J.L., and Landisman, M., 1959a, Rapid gravity computations for two-dimensional bodies with application to the Mendicino submarine fracture zone: from Jour. Geophys. Res., v. 64, no. 1, p. 49-59.

Talwani, M., Sutton, G.H., and Worzel, J.L., 1959b, A crustal section across the Puerto Rico Trench: Jour. Geophys. Res., v. 64, no. 10, p. 1545-1555.

Taylor, P.T., Zietz, I., and Dennis, L.S., 1968, Geologic implications of aeromagnetic data for the eastern continental margin of the United States: Geophysics, v. 33, no. 5, p. 755-780.

Woollard, G.P., 1959, Crustal structure from gravity and seismic measurements: Jour. Geophys. Res., v. 64, no. 10, p. 1521-1544.