SEDIMENTARY BASIN RESEARCH: REVIEW AND RECOMMENDATIONS

by

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INTRODUCTION

Sedimentary basins have recently become the object of increased economic and scientific attention in Canada. Economic interest stems from the growing Canadian market for energy resources, the impact of soaring world prices and forecasts of shortages in a few decades; as a result, the Canadian government is encouraging the discovery of additional Canadian natural gas and petroleum reserves. Much scientific interest is currently focused on the nature and causes of vertical motions within the earth in conjunction with the objectives of the I.U.G.G. Commission on Geodynamics which lasts until 1979. Sedimentary basins contain the most complete record of vertical earth motions through geologic time and Canada, with its large Precambrian shield and extensive continental shelf, contains not only a large variety of basin types (cratonic, successor, shelf, marginal, to name a few) but also a record of basin forming activity which spans much of Precambrian time and virtually all of Phanerozoic time including the actively subsiding continental shelf and marginal basins of the present. This situation gives Canadian geoscientists an excellent opportunity to make significant contributions to the knowledge and understanding of long-term vertical movements of the earth and, hence, of basin forming processes.

The Gravity Division, with its data collection and reduction activities and its broad based expertise in analysing problems of crustal structure, regional variations of the earth's gravity field, and long-term mechanical behaviour of the earth, has considerable talent and facilities that have been brought to bear on this problem in the past. This short position paper suggests how the Gravity Division can continue to make specific contributions in the areas cited above.

PREVIOUS BASIN STUDIES BY THE GRAVITY DIVISION

Sedimentary basin studies have been approached in a variety of ways. An early application of gravity methods to such studies in Canada was a torsion balance survey of the Malagash salt deposit in the Cumberland basin in Nova Scotia (Miller and Norman, 1936). Subsequent regional and detailed surveys over the basin were carried out which successfully outlined other accumulations of low density Carboniferous rocks (Garland, 1955). In recent years regional land, sea-ice, sea-surface and sea-floor gravity measurements have been made over sedimentary basins in the Arctic (Sobczak, 1963; Sobczak et al., 1963; Weber, 1963; Berkhout, 1969; Sobczak and Weber, 1970, Hornal et al, 1970; Stephens et al., 1972; Sobczak and Weber, 1973), on the east coast of Canada (Goodacre et al., 1969), in the Great Lakes and Hudson Bay (Innes et al., 1967; Goodacre et al., 1972) and in the Sudbury basin of the Canadian shield (Miller and Innes, 1955; Popelar, 1971). An important use of these gravity data, which in the Arctic and east coast areas have been of particular use to the oil and gas exploration industry, has been to delineate major structures within and beneath sedimentary basins either in a qualitative way or by computer modeling of the gravity field using other geophysical and geological data as constraints. In some areas basement mass variations have been isolated (Sobczak et al., 1970; Stacey, 1975) by removal of the effect of near-surface sedimentary rocks within a basin from the gravity field by computer modeling based on detailed information regarding lithological thickness, density and distribution.

A study has been conducted to determine whether lateral density variations (hence, gravitational attraction) correlate with the occurrence of oil and gas fields and whether vertical density variations can be used to calculate the thickness of denuded sediments in a given area (Maxant,1975).

Another approach has been to model vertical basement motions using an elastic or viscoelastic lithosphere floating on a fluid asthenosphere and, using the model, to estimate mechanical parameters of the lithosphere such as viscosity and flexural rigidity. A thin elastic plate model supporting a sedimentary or topographic load has been used to explain the evolution of arches and uplifts in Canada (Walcott, 1970) and the growth of sedimentary basins at continental edges (Walcott, 1972; Sobczak, 1975 and in preparation). Thin and thick viscoelastic plate models have been applied to the determination of the degree to which mechanical and thermal mechanisms contribute to the formation of given interior basins (Foucher, 1974 and in preparation). Sverdrup basin subsidence patterns and magnitudes have been shown to be consistent with the loading response of a lithosphere modeled as a viscoelastic beam (Sweeney, 1975).

In the shield area, gravity modeling of the structure of Precambrian deformed sedimentary basins, greenstone belts and the circum-Ungava geosyncline (Gibb and Halliday, 1974; Thomas 1974) is being advanced in order to shed light on processes and paths of possible Precambrian plate interactions.

RECOMMENDED DIRECTIONS OF RESEARCH

Basin Structure

a) Economic Objectives

In order to make immediate contributions to economic objectives it is proposed that gravity data gathering and interpreting activities continue to include the delineation and evaluation of the regional structure of sedimentary basins of potential interest to industry.

First of all, the Gravity Division, in keeping with its mandate to complete the regional gravity survey of Canada, should continue to conduct regional gravity surveys in areas not yet explored by industry such as the inter-island waters of the eastern and southern Arctic Archipelago, the Arctic continental shelf north of Axel Heiberg and Ellesmere Islands and Hudson Bay. The resulting gravity data should provide the basis for an initial regional interpretation biased toward identification of possible basin structures within the surveyed regions. In other words, the normal data acquisition activities of the Gravity Division can be immediately employed to help point the way toward sites of future petroleum exploration.

Subsequently, a more thorough and detailed structural interpretation of basins in the explored area can be synthesized combining gravity, seismic and magnetic information and stratigraphic thickness, density and distribution data. The purpose of this would be to delineate major structural features within the basins, determine crustal structure beneath them and provide an interpretation of their tectonic framework.

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This kind of regional evaluation can make the exploration process more efficient by providing timely interpretations of the structural framework of individual sedimentary basins. Such studies will assist the petroleum industry in the selection of favourable areas for more detailed geophysical surveys. This kind of study should also assist government geologists involved in estimating the resource potential of sedimentary basins for government energy policy makers.

b) Current Scientific Objectives

The most prominent gravity features along stable continental shelves (e.g., the Arctic) are the chain of elliptical highs that occur approximately over the shelf break. Several explanations for these anomalies are proposed including the idea (Sobczak, 1975 and in preparation) that sediment loading of the shelf is largely responsible. The anomalies include an edge effect associated with the continental boundary. The amplitude and wavelength of the edge effect depend on the structure of the crust-mantle interface within the transition zone and this is not known very precisely. Any investigation seeking to explain the free-air highs should first remove this edge effect from the gravity field. To do this it is proposed that the crustal structure in the critical transition zone be defined by a multiparameter relatively close-spaced geophysical traverse that includes deep crustal seismic refraction conducted over a stable continental shelf into oceanic crust approximately perpendicular to the margin in a region close to a free air anomaly peak. A first choice of location for this traverse is the Beaufort Sea as it is separated from the Arctic Ocean by an anomaly peak and its underlying stratigraphy is documented by well log and seismic reflection data. A second choice is the shelf north of Ellef Ringnes Island where a short profile line of seismic refraction results exist but little well control. In addition to its scientific value, correlation between free air highs and shelf sediment volumes would also be of considerable significance for oil and gas exploration.

A second problem is to identify factors that determine the location and magnitude of the relatively low troughs between anomaly peaks. Several explanations may be examined. For example: they may be caused by areas of reduced sediment thickness along the outer shelf; they may correspond to sites of mechanical breakup of the shelf; they may result from lithospheric buckling under load stress at characteristic wavelengths (350-400km) that are related to the strength and thickness of the buckled layer. Knowledge of crustal structure (seismic reflection and refraction) and density distribution (gravity and geomagnetism) and bathymetry is necessary to test the above conjectures among others. A geophysical traverse measuring these parameters parallel to the margin across the anomaly minimum would provide the required information. For logistical purposes, the location of such a traverse should be tied to the area chosen for the trans-shelf traverse and therefore can be conducted across the anomaly trough along the margin west of Banks Island or further northeast such as west of M'Clure Strait or to the north of Brock Island.

Basin Evolution

a) Initiating processes

Sedimentary basins are initiated by the creation of depressions at the earth's surface. Observations from Sverdrup Basin in the Arctic Archipelago show that sudden and pronounced increases in subsidence rates are associated with the formation of initial depressions and are explained by signficicant structural and thermal activity affecting the lithosphere. This activity is contemporary with or can be related to major global tectonic events. The existence of a relation between basin subsidence rates and plate motions, therefore, would not be surprising. Accordingly, it is proposed to determine the subsidence histories of several major North American sedimentary basins (the Sverdrup, Alberta, Michigan, Hudson, Williston and Illinois basins) and examine tectonic activity related to their development to reveal the timing and probable causes of creation of initial depressions. This information, when considered in the light of global plate tectonic activity, will indicate the degree to which the two can be related. Given a demonstrable relationship, the sensitivity of subsidence rate changes to variations in plate motion can be determined by comparing the subsidence history of the Canadian Atlantic continental margin or the North Sea basin over the last 80 my to sea-floor spreading rate changes calculated for the well studied North Atlantic Ocean. A signficiant correlation between the two will have important consequences for the analysis of pre-Mesozoic changes in plate motions through the study of Paleozoic basin subsidence rates.

b) Loading response processes

The rapid (about 10^4 years) achievement of isostatic equilibrium within the asthenosphere together with isostatic amplification of the initial depression by loading indicates that sedimentary basin subsidence is principally a record of long term (10^7 - 10^8 years) isostatic adjustment within the lithosphere. Features common to the dynamics of basin subsidence can be determined by examination of subsidence curves from several sedimentary basins (mentioned above) and from geologic evidence of vertical movements around their periphery. These observations, when compared with behaviour predicted by theoretical lithospheric models, can determine, to a first approximation, the mechanical nature of the loading response. Sverdrup basin subsidence data favour a viscoelastic (as opposed to an elastic) lithosphere underlying the Arctic Archipelago but data from several other major sedimentary basins must be tested before this initial result can be advocated as a general property of the lithosphere.

The wavelength and amplitude of deflection and possible changes in these parameters with time combined with available seismic evidence of lithospheric thickness beneath the aforementioned sedimentary basins allow the calculation of the flexural rigidity of the lithosphere and possible decreases in its value with increasing age of the load.

Analysis of loading response dynamics is restricted to the Phanerozoic because of the lack of sufficiently precise Precambrian fossil age control. It is possible, however, to recognize the final geometry of deflection preserved in the pattern of metamorphic facies belts (denoting peripheral uplift) concentric about greenstone belts (denoting central depressions) and from this obtain an estimate of its final wavelength and amplitude. This information can provide values for the thickness and flexural rigidity of a very old lithosphere and thereby, by comparison with Phanerozoic results, indicate the variation, if any, in these parameters over very long (10^9 year) time spans.

Long Term Studies

Sedimentary basins represent an important category of loading phenomena and, as such, are capable of providing useful information regarding the nature of isostatic adjustment mechanisms over a fairly restricted range of load wavelengths and amplitudes. To examine more fully the general problem of isostatic response and processes, not only must a wider wavelength range of loads be examined (for example, the long wavelength topographic loads of shield areas and the short wavelength topographic loads associated with mountain belts) but also a broader age range (e.g., the relatively short lived (10^6 year) loads associated with continental glaciation) and amplitude range (e.g., continental loading).

Gravity as a tool in the investigation of isostatic mechanisms has been well established, most recently by Walcott (1970a,b,1972, 1973), Dorman and Lewis (1970,1972), Lewis and Dorman (1970) and Watts and Cochran (1974). Walcott (1974) has shown that free air gravity (terrain corrected) as a function of the wavelength of topography (Dorman and Lewis, 1972, Fig. 2 - for the gravity field of the United States) can be explained in terms of the flexural hypothesis (long term (greater than 10^6 year) bending a strong lithosphere in response to surface loading). A similar type of spectral analysis of free air gravity vs wavelength of topography over the gravity field of Canada should be undertaken to provide a further test of the flexural hypothesis in particular and to create a uniform and reliable data base for the study of isostatic problems in Canada in general. Application of this technique to selected two-dimensional harmonic topographic features such as the basin and range topography of the Rocky Mountain Thrust Belt and/or the Mackenzie Fold Belt of the western cordillera, whose evolution can be determined by analysis of the stratigraphic and fossil record, should reveal the dynamics of the (long term) topographic loading response process against which mechanical response models may be tested.

Investigation of this broader problem should follow as a consequence and represents a logical extension of analysis of isostatic response to sedimentary basin loading.

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