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"The Delineation and Interpretation of the Earth's Gravity Field"

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ABSTRACT

In an attempt to understand the mechanical interaction of a growing lithosphere containing fracture zones with small and large scale mantle convection, which gives rise to geoid anomalies in oceanic regions, a series of fluid dynamical experiments is in progress to investigate: (1) the influence of lithosphere structure, fluid depth and viscosity field on the onset, scale, and evolution of sublithospheric convection; (2) the role of this convection in determining the rate of growth of lithosphere, especially in light of the flattening of the lithosphere bathymetry and heat flow at late times; and (3) combining the results of both numerical and laboratory experiments to decide the dominate factors in producing geoid anomalies in oceanic regions through the thermo-mechanical interaction of the lithosphere and subjacent mantle. This work has so far shown the clear existence of small scale convection associated with a downward propagating solidification front (i.e. the lithosphere) and a larger scale flow associated with a discontinuous upward heat flux (i.e. a fracture zone). The flows exist simultaneously and each may have a significant role in deciding the thermal evolution of the lithosphere and in understanding the relation of shallow mantle convection to deep mantle convection. This overall process is reflected in the geoid, gravity, and topographic anomalies in the north-central Pacific. These highly correlated fields of intermediate wavelength (~ 200-2000 km) show isostatic compensation by a thin lithosphere for shorter (≤ ~ 500 km), but not the longer, wavelengths. It is the ultimate, dynamic origin of this class of anomalies that is sought in this investigation.

1. INTRODUCTION

Geoid and gravity anomalies of intermediate wavelength (i.e. 500 - 2000 km) over ocean basins result from the structure and mechanical behavior of a growing lithosphere as it interacts with thermal convection in the underlying mantle. A thin elastic and highly viscous lithosphere giving way downwards to strongly decreasing viscosity in the uppermost mantle - the low velocity zone (LVZ) - followed at greater depths by a significant viscosity increase, provides a veritable garden of possible thermo-mechanical interactions that can distort the geoid. We explain here a set of fluid mechanical experiments intend to investigate a significant part of this interaction.

The mechanical response of the lithosphere to deformational stresses - due to loading and sublithospheric flows and heating - is now a well developed subject in terms of knowledge of the mechanical frequency response of the lithosphere itself (e.g. McKenzie and Bowin, 1976; Watts, 1978; Watts et al., 1980; McKenzie et al., 1980; McNutt, 1988; among many others). (A review and contribution to this subject by Hinojosa and Marsh (1989) is included here as Appendix A.) A great deal of interest has thus concerned the possibility of using the structure in the geoid and gravity fields to infer the nature of the dynamical interaction between the lithosphere and the subjacent convecting mantle. The characteristic length scales of the geoid, lithosphere structure, and mantle convection have emerged as important entities. Small scale convection begins once lithosphere growth has slowed enough to allow instability (Parsons and McKenzie, 1978; Yuen et al., 1981; Yuen and Fleitout, 1986; Fleitout and Yuen, 1984; among others). How near to the ridge this flow may develop has been studied numerically by Buck and Parmentier (1986), how strongly the vertical viscosity structure influences it by Robinson and Parsons (1988), and how it is modulated by fracture zones by Craig and McKenzie (1986) and Driscoll and Parsons (1988). The experiments described herein are designed to augment this numerical work by studying the onset time, scale, and vigor of convection induced by solidification - lithosphere growth - from the top with and without fracture zones (Marsh and Brandeis, 1989).

The nature of small scale sublithospheric convection is suspected to be strongly affected by three features of the lithosphere and upper mantle: (1) The onset of flow is set by the growth rate of the lithosphere and the viscosity structure near its lower leading edge; (2) the depth extent and severity of the low velocity zone, which presumably also reflects the vertical viscosity structure; and (3) the spacing and age offset of fracture zones. Understanding this overall process has been greatly simplified by the realization that convection is strongly partitioned by the viscosity field to regions which are essentially oviscous; that is, regions where the variation in viscosity is less than a factor of about 10 (e.g. Booker and Stengel, 1978; Richter et al., 1983). This fact has been employed in numerical studies to study convection beneath a rigid, constant thickness lithosphere overlying a fluid layer of constant viscosity. This same fact further partitions sublithospheric flows to be contained within the low (seismic) velocity zone, from which viscosity increases both upward and downward (Robinson and Parsons, 1988). Fracture zones within the lithosphere mark significant offsets in plate age, thickness and thermal regime. Because thin lithosphere has a stronger vertical heat flux, it grows faster and more strongly retards convection than does thicker, adjacent lithosphere. This contrast establishes a horizontal temperature gradient in the mantle which encourages flow transverse to the fracture zone and the direction of plate motion.

In essence, then, it is the downward solidification of a lithosphere containing fracture zones into an underlying fluid whose viscosity first decreases and then increases with depth that is reflected in the geoid. It is exactly these features that our present and proposed experiments are designed to investigate.

2. PRESENT AND PAST WORK

We have been conducting over the past year a series (31) of fluid mechanical experiments involving solidification of molten paraffin aimed at investigating the onset and duration of convection beneath the growing crust (or lithosphere), the rate of growth of the crust as a function convective vigor, the history of heat transfer through the crust, and the effect of spatially discontinuous cooling - seeking to emulate a fracture zone - on the pattern of flow. The experimental set up is shown schematically by Figure 1 and some of the flow fields involving the fracture zone cooling setup are shown by Figure 2. The fluid is held by a plexiglass tank (20 X 20 X 20 cm or 20 X 20 X 10 cm) fitted with top and bottom copper plates which are further attached to cooling jackets. Thermally-controlled water is circulated through one or both of the jackets and the resulting fluid motion is observed by passing a sheet of light through the tank whose fluid contains a very small concentration of aluminum flakes. The temperature within the tank is continually interrogated by computer via a stack of 10 thermocouples through the center of the tank. The fluid itself is a compound of two pure paraffins that has a liquidus at about 22°C and a solidus some 5° lower. Between the liquidus and solidus the fluid is a suspension (near the liquidus) or a mush (near the solidus) and at lower temperatures the fluid paraffin is a solid; overall this behavior is rheologically similar to that expected for mantle material. The presence of this liquidus and solidus is what sets these experiments apart from any previous ones (actual or numerical) that of which we are aware. The only broadly similar experimental set up is that due to Curlet (as reported in Parsons and McKenzie, 1978), but there was no liquidus and solidus and thus no change of phase.

A typical experimental run begins by heating the fluid from below until it is isothermal throughout and slightly superheated. After inverting the tank to redistribute the aluminum flakes, which have usually settled to the bottom, the fluid is cooled strongly from the top. In the flow shown by Figure 2 the cooling jacket has been constructed in two, side-by-side compartments such that each compartment can be cooled independently; thus simulating the presence of a fracture zone (Figure 2A). Strong cooling of one side grows a thick crust (or lithosphere). The flow initially begins as a series of small (~0.5-1cm) descending plumes that are soon swept horizontally and downward along the wall by a larger scale flow, which fills the tank (Figures 2B,D). Interestingly enough, however, the small scale instabilities persist in the flow as can be seen by viewing the flow end-on or normal to the fracture zone (Figure 2C). The small plumes and cells, however, become greatly stretched first horizontally and then downward by the large scale flow.

Cooling both compartments causes crust to grow on both sides of the "fracture zone" (Figure 2D), and because thin crust grows faster than thick crust, crust thickness eventually becomes nearly uniform across the tank. Once established, however, the nature of the flow field remains until convection ceases as overall cooling brings the fluid everywhere to its liquidus temperature.

Before discussing the experiments more fully in light of the proposed work, the long term or overall plan of this research in terms to interpreting geoid and gravity fields will be addressed.

Over the past ten years our plan has been first to delineate the gravity and geoid fields in the Pacific, with particular emphasis on anomalies of intermediate wavelength (n,m $\approx$ 18-22, $\lambda \approx$ 2000 km), and then to interpret these anomalies in relation to the dynamics of the lithosphere and upper mantle (e.g. Marsh and Marsh, 1976). The method of satellite to satellite tracking (SST) was used to delineate these anomalies over the central Pacific (e.g. Marsh et al., 1981). This technique allowed verification and closer definition on the regional scale of the global GEM fields, due mainly to F. Lerch and associates at Goddard, as well as of surface data sets due mainly to R. Rapp at Ohio State. And with complimentary data from SEASAT (e.g. Marsh et al., 1984) this anomaly set has become well established. But because some workers (e.g. Sandwell, pers. com.) have felt that these anomalies could, at least in part, be artifacts of truncating spherical harmonic expansions to remove the long wavelength (i.e. regional) effects which we originally tried to guard against (Marsh and Marsh, 1976), we have also continued research along these lines (see Appendix A). Having established this class of anomalies, we have worked at understanding or interpreting them in terms of the isostasy of the lithosphere and convection within the underlying mantle. (Marsh and Hinojosa, 1983; Marsh et al., 1984; Hinojosa and Marsh, 1985; Hinojosa, 1986).

In brief, we have found that the most direct way to show the unequivocal existence of these anomalies is to take the full geoid (untruncated) of the central pacific and remove a simple (first, second, or third order) surface. It is important to realize that the removed surface is not a spherical harmonic field but merely a cartesian surface, which is possible over this limited area. The resultant residual geoid is exceedingly similar to that found by removing a spherical harmonic field model (n, m ≤ 12,12) (See Appendix A). The same has been done for the bathymetry in this region, and the geoid and bathymetry have ben plotted against one another, which gives a clear positive correlation (corre.. coef. = 0.66). The slope of this correlation is also highly significant (i.e. ≈ 7.5 m/km) in that it is very close to the spectrally derived admittance (see below). Altogether we are confident that this class of anomalies is real. Another class of anomalies, of shorter wavelength (~ 100 km), has been singled out by Haxby and Weissel (1986) in the southern Pacific as being indicative of mantle convection, but there is concern about their origin (more later).

The understanding of these anomalies in terms of isostasy has been the subject of Hinojosa's Ph.D. dissertation from which has come the manuscript given as Appendix A. In brief, by treating both bathymetry and geoid in the spectral or wave number domain, the admittance has been obtained from the ratio of the geoid to the topography, which expresses the geoid anomaly in meters for every kilometer of sea-floor topography. The phase has also been found and it is always positive and generally small. Synthetic admittances both for flexural and Airy compensation models have also been calculated and are shown along with the observed admittance (Appendix A). It is clear here that wavelengths shorter than about 1000 km can be compensated both regionally, by the elastic strength of the lithosphere itself, and locally by displacing mantle material to reach isostatic equilibrium. The larger wavelengths, however, cannot be explained in this fashion but must be supported dynamically within the sublithospheric mantle.

To investigate this dynamic process of compensation, Hinojosa (1986) has numerically studied the effect of convection of a variable viscosity fluid, cooled from above and heated from below on deformation of the lithosphere.

Using the mean field method, with and without inclusion of a low viscosity channel, the geoid, topography, and admittance have been calculated as a function of time (see Appendix A). Although the results of this study are far too numerous to be included here, the central result is that small scale convection by itself is not strong enough to produce significant geoid and topographic anomalies that also satisfy the observed admittance. (Buck and Parmentier (1986) show that the geoid can be matched but they did not notice the problem with admittance.) But that regional thermal variations, originating, for example, at the ridge itself, carried along by the flow can cause anomalies of the observed magnitude (see Appendix A). For example, contours of geoid anomaly magnitude as a function of thermal anomaly depth and amplitude. The same has been done for topography and both results have been combined through admittance to reveal the acceptable range of thermal anomaly amplitude and depth. The critical range is 70-100°C at depths of, respectively, 100-200 km.

All of this work is now ready for publication.

To complete the description of our long term research theme, this numerical work led us to the realization of how difficult it is to establish a realistic idea of how small scale convection develops and how it is influenced by the structure of both the lithosphere and the upper mantle viscosity field. It is also clear that these small scale, post-ridge flows probably don't, in and of themselves, cause the observed geoid anomalies. Rather it is the interaction of these flows with earlier, original instabilities that gives rise to the anomalies. We also realized that it is just this same overall process that may play a dominant role in the downward crystallization of magma chambers; the upper solidifying crust of lava lakes, for example, plays much the same role as the lithosphere itself. Two lines of research in this laboratory have thus become intricately intertwined with one area contributing to the other (e.g. Marsh, 1989; Brandeis and Marsh, 1989; Marsh and Brandeis, 1989).

3. NEW RESEARCH

That small scale convection is likely to exist beneath the Pacific plate is hardly anymore doubted. In any experiment of strong cooling from above of an otherwise insulated fluid small scale convection always appears. But its form and how it relates to the structure and dynamics of the lithosphere remains enigmatic. In this regard we plan to investigate three main topics:

1. The interaction of fracture zone modulated flow with the depth of convection and the vertical viscosity structure.
2. The growth rate of the crust or "lithosphere" as a function of convective vigor (i.e. magnitude of Ra), especially in terms of flattening or slowing, or even cessation, of growth at late stages of cooling.
3. The combination of the experimental results with theory and its application to the actual Earth problem itself.

Thorough study of these topics will provide tangible and quantitative insight into the possible flow fields that exist immediately beneath growing lithosphere and how the overall system gives rise to the observed geoid and gravity anomalies.

1. Fracture Zone Effects: As outlined in the introduction, fracture zones delimit significant offsets in plate age and thickness and thus cause horizontal temperature gradients which induce horizontal flow, transverse to the fracture zone and parallel to the ridge. Such a flow has been calculated by Craig and McKenzie (1986) assuming an upper plate of constant thickness (70-75 km) and an underlying low viscosity channel (500-150 km) of viscosity (10^{20} - 10^{22} poise). The flow begins at the fracture zone and propagates throughout the

layer. The time to develop the flow is strongly dependent on the thickness and viscosity of the low viscosity channel. The difficulty with these results is that the lithosphere does not evolve (i.e. thicken) with time to the point of instability and to sustain the lithosphere thickness as constant a high basal heat flux must be employed.

The experiments shown by Figure 2 show how the small scale and layer scale flow develop together early on and interact as the "lithosphere" grows or thickens with time. Just as in the numerical work, the flow field is set by the presence of the fracture zone or the discontinuous outward heat flux. The difficulty with directly applying these results to the Earth is the great depth of the underlying fluid relative to the "lithosphere" thickness. This can be easily remedied (see below) and it is important to do to gauge its effect on the scale of the cell size. That is, in most flows the size of the cells is more or less set by the thickness of interfracture scale or platelet scale. What controls this scale will also be important to investigate. If cell size does shrink significantly as the fluid thickness is reduced, will it at some stage be of an equivalent scale to the small scale plumes that develop - and are swept away by the large scale horizontal flow - just beneath the downward growing lithosphere. Perhaps for a certain thickness of fluid the two scales of flow become similar. That is, horizontally induced flow becomes the same as the small scale lithosphere-growth flow. If so, the effect of the fracture zones becomes simply one of nucleating or ordering the family of cells and does not produce a strong, large scale horizontal flow. This seems to be indicated by the results of Craig and McKenzie (1986), but their work does not include the small scale flow associated with a growing lithosphere.

Because the outward heat flux is inversely proportional to lithosphere thickness, the initial fracture zone flow may reverse itself with rapid growth of new, young lithosphere. That is, in the experiments shown by Figure 2, because horizontally only one side of the cooling plate is cooled, the flow runs horizontally from the isothermal to the cooled side of the system. With growth of crust, however, the upward heat and fluid flow diminish and with commencement of cooling on the other side, cooling may be strong enough actually to reverse the original flow. Such flow reversal may have interesting and observable geophysical (i.e. magmatic) consequences (e.g. Morgan and Forsyth, 1988). (Oddly enough, however, our preliminary work on this possibility shows that once established it is exceedingly difficult to reverse the original flow, but that more structure is added to the flow near the fracture zone itself.)

2. "Lithosphere" Growth: The well known square-root of time decay of bathymetry and heat flow with distance (time) away from the ridges can be interpreted in a number of ways (e.g. Renkin and Sclater, 1988). At long times, greater than about 80 m.y., this dependence is observed to be violated and both bathymetry and heat flow flatten. At least several groups have suggested that this flattening is caused by the onset of small scale convection, which seems to be the time scale sought in the studies by McKenzie and associates and Parson and associates. This flattening, however, may reflect the cessation of the initial small scale flow and reflect the influence of a larger scale flow in providing a deeper mantle heat flux to sustain the necessary heat flow through thick, old lithosphere.

This suggestion, which in part has been made previously, can be appreciated by realizing that the small scale flow may take place at relatively early times relative to distance from the ridge. For example, a number of studies (Jaupart and Parsons, 1985; Smith, 1988) show that on the onset of time (t) of convection in a layer-cooled from above is given by

$$\frac{Kt}{L^2} = \left(\frac{C}{Ra}\right)^{2/3}$$

where K is thermal diffusivity, L is the depth of the layer, Ra is Rayleigh number and C is a constant that depends on the boundary conditions but is about 400. Figure 3 shows this time for a layer of thickness 300 km as a function of fluid viscosity. Unless the viscosity is increasingly large (~10^{22} poise) convection begins early (1-20 m.y.).

The effect of this small scale convection on the rate of thickening of the crust in "lithosphere" is shown by Figure 4 which shows the growth rate with and without convection as measured in our experiments. Convection retards growth by maintaining a high inner temperature near the lower edge of the crust. It is particularly noteworthy that both growth histories show a linear dependence on the square root of time. This is to be expected from the classical Stefan theory of solidification. In the presence of convection, growth is slower than when there is no convection (bottom cooling only). And as convection ceases (near $\sqrt{t}$ ~ 1) there is a distinct change in the rate of thickening. Since the lithosphere follows a $\sqrt{t}$ dependence from the start, it is difficult to say which curve is initially followed (viz. the one with or without convection). The differences do not need to be large. If a small basal heat flux is applied to the flow, at some point as convection wanes, the basal heat flux will become important in maintaining a steady-state heat flux through the entire system which will sustain a constant lithosphere thickness. It is proposed to investigate the combination of these conditions experimentally.

3. Application to Earth: One of the most difficult aspects of understanding this overall process using the presently available research results is that no single study is complete enough to cover the entire process.

That is, the results for small scale flow development (Buck and Parmentier, 1986) don't include fracture zones, whereas the fracture zone convection models don't use an evolving lithosphere thickness. And on the other hand the fluid mechanical experiments (Marsh and Brandeis, 1989) suffer from not being able to observe surface deformations and compute geoid anomalies. We propose to attempt to remedy this situation by not only performing experiments closely scaled to the actual Earth process, but to also evaluate as closely as possible which effects dominate the geoid response and which effects are essentially unobservable. We feel that there will be enough information available from these and other studies to allow this to be done analytically.

METHODOLOGY OF EXPERIMENTAL APPROACH

All experiments performed so far have involved the downward solidification of paraffin possessing a liquidus and solidus. This has enabled us to study the onset and duration of convection as a rigid, solid "lithosphere" grows downward and is influenced by the presence of a discontinuity in outward heat flux (i.e. a fracture zone). The results shown by Figure 2 are preliminary findings, but clearly show that such effects can be modeled in the laboratory. We intend to more fully investigate this overall process by performing experiments in shallower tanks and in a tank where a slightly porous, false floor can be adjusted to control the depth of convection. In this fashion we can reduce the Rayleigh number (now $\sim 10^8$) to 10^4 - 10^5 while at the same time observing the onset of small scale convection and the rate of thickening of the crust.

In addition, because we have found that convection in this fluid ceases once the liquidus temperature is reached (from higher temperatures), Ra can be varied independently of fluid depth by controlling the amount of superheat in the system. This is important in ascertaining the relative roles of small-scale and fracture zone flows in dominating convection.

By attaching a second cooling/heating jacket to the tank the top can be cooled and the bottom heated simultaneously. It is by this method, in both shallow and deep tanks, that we can investigate the long term effect of a low background heat flux in controlling the ultimate thickness of the crust or "lithosphere". Because of this heat input, at some point a steady state will be approached which will be reflected in the crust by attaining a constant thickness. We can investigate this energy balance by monitoring the central tank temperature, the lower and upper plate temperatures, and the thickness of upper crust and temperature gradient across it.

Except for the need of another water chiller and possibly construction of another shallow tank (~ 5 cm), we have all of the necessary facilities to carry out this research. The additional chiller will allow equally strong cooling to all parts of the compartmentalized (i.e. fracture zone) cooling jacket in order to stimulate flow reversal.

In summary, it is the explicit aim of this work to give a heuristic and dynamic understanding to the ultimate origin of a significant part of the geoid field in the Pacific region.

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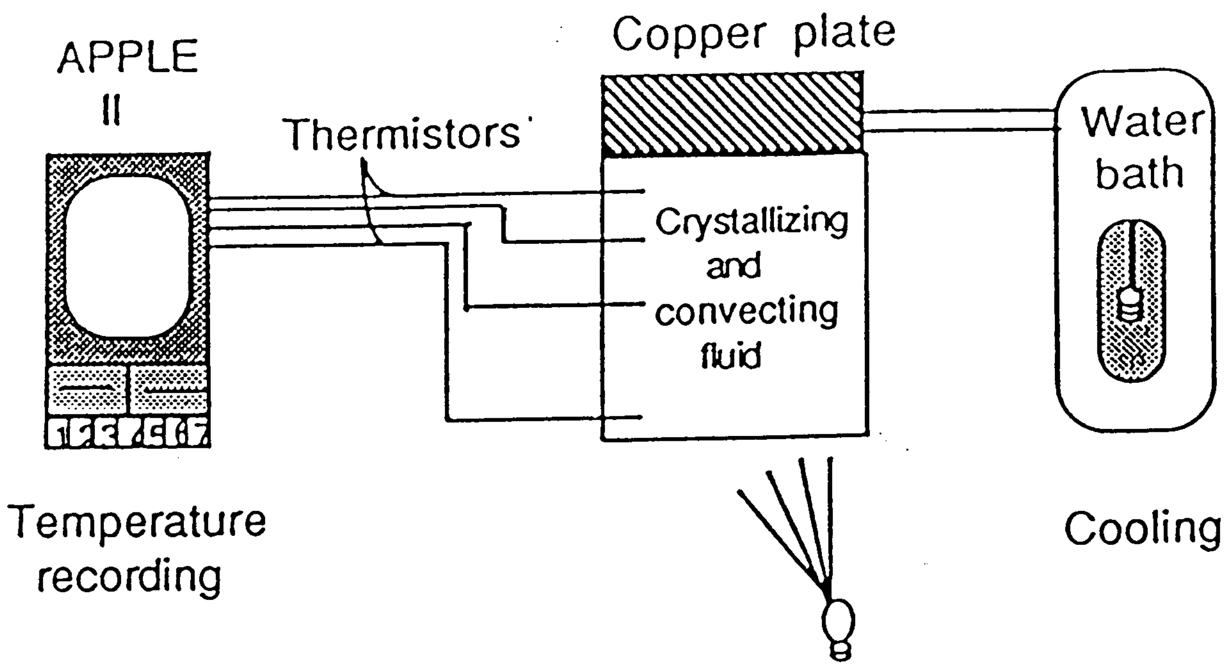
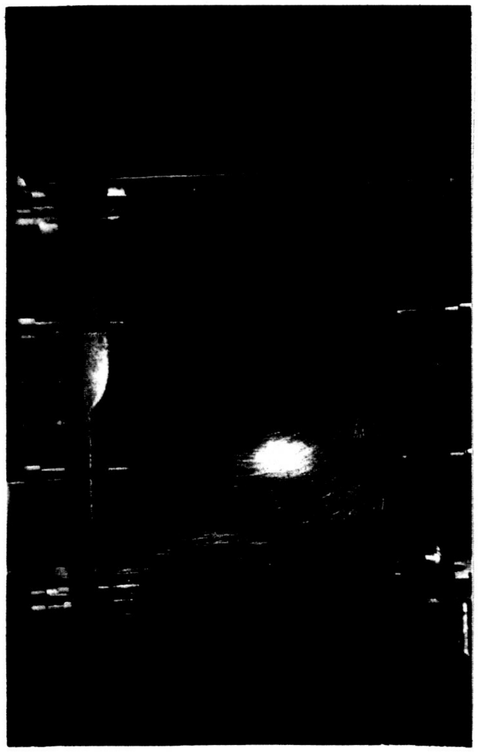


Figure 1: A schematic representation of the experimental setup. A plexiglass tank with a metallic cooling lid and reservoir holds the viscous fluid. The temperature of the lid reservoir is controlled by a water bath. A computer monitors a rack of 8 thermocouples within the fluid. Motion in the fluid is detected by passing a sheet of light through the tank and photographing it at right angles.

Figure 2
(See next page for photos)

Figure 2A	The large tank (20 X 20 X 20 cm) showing the "fracture zone" cooling plate on the bottom before inversion and cooling.
Figure 2B	Top cooling and growth of "lithosphere" (white solid at top) of uneven thickness across" fracture zone", notice the large scale of the flow.
Figure 2C	End on view of flow showing small scale convection near downward growing "lithosphere".
Figure 2D	Slowing of the flow and addition of structure as "lithosphere" on each side of "fracture zone" attains similar thickness.

B



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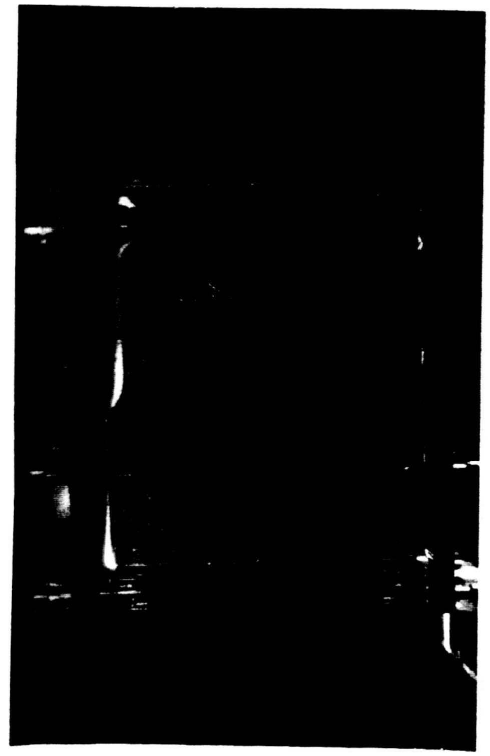

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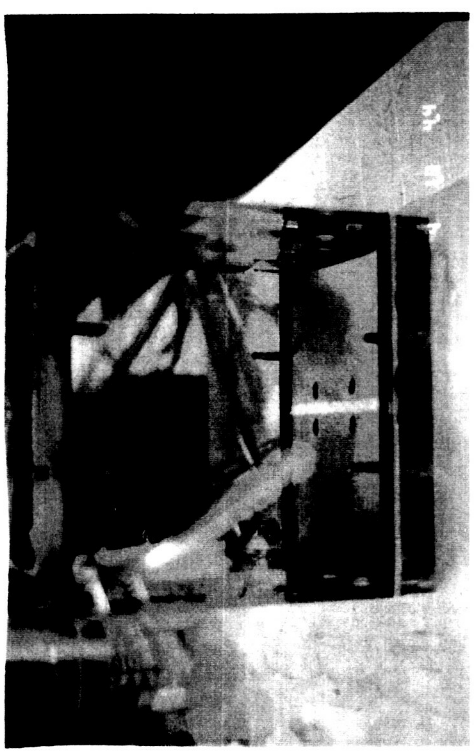

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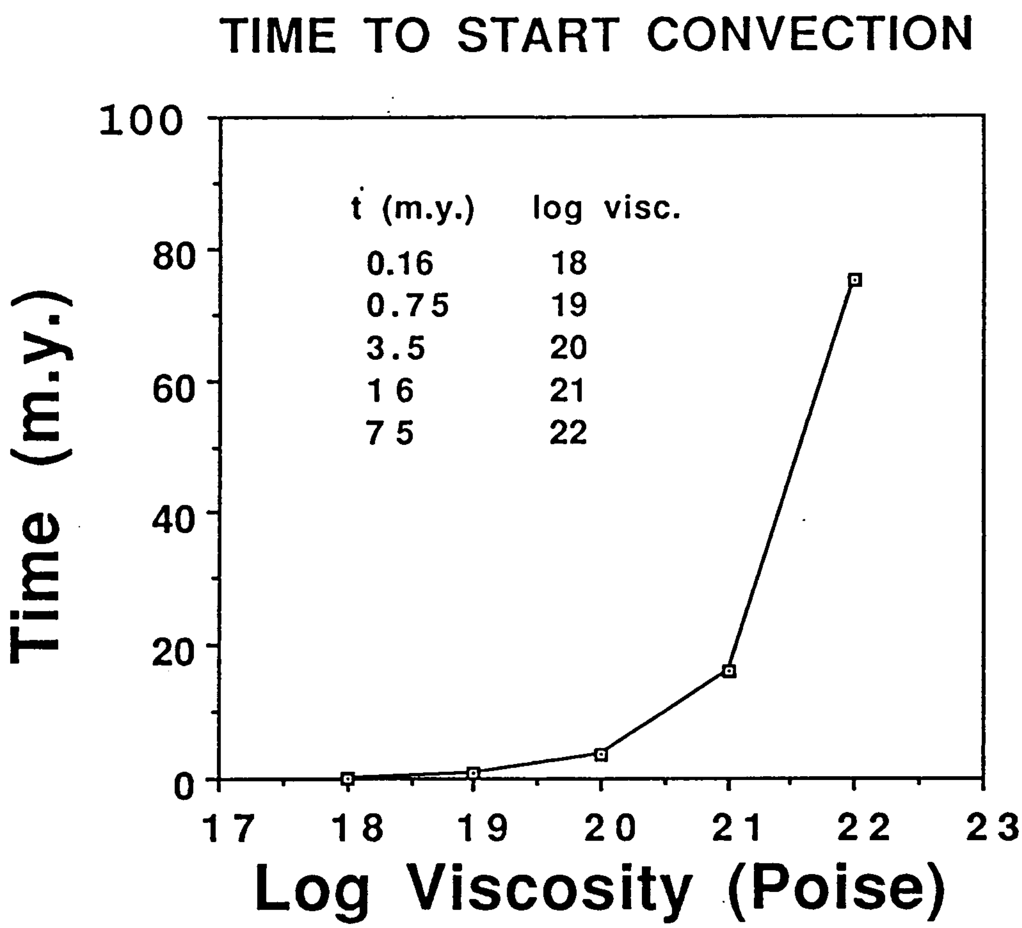

Figure 3: The time to initiate small scale convection beneath lithosphere by cooling from above as a function of upper mantle viscosity. (See text for discussion.)

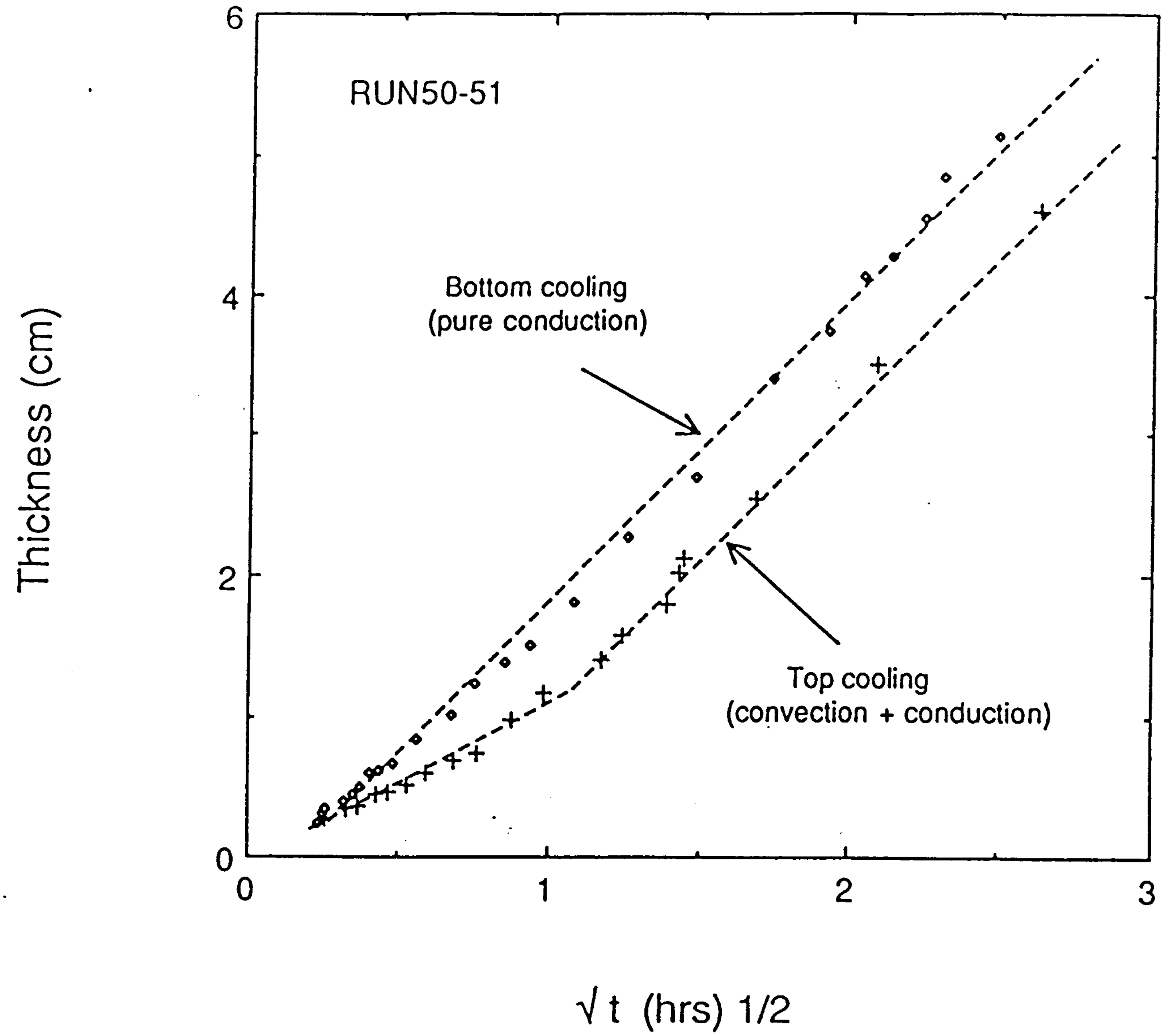

Figure 4: The experimentally determined thickness of the crust on "lithosphere" as a function of the square root of time. All points of the curves are linear. Notice the change in slope as convection ceases (near $\sqrt{t} \cong 1$) for the lower curve.