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MONITORING FLUID DEPLETION AT THE GEYSERS BY THE GRAVITY CHANGE/SUBSIDENCE RATIO

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Abstract The ratio of gravity change to subsidence may be a useful indicator of the rate of fluid depletion in vapour-dominated reservoirs. For an average reservoir porosity less than about 10%, this ratio is close to -40 μgals/cm if there is no recharge or reinjection to the reservoir. The ratio is independent of reservoir thickness, pressure drop and porosity. If R is the fractional recharge mass (assumed to be <100°C), the ratio is reduced by a factor $\frac{1 - R}{1 + 0.4 R}$. The rate of injection of condensate into The Geysers reservoir would reduce this ratio to between -24 to -28 μgals/cm. Analysis of the available data at The Geysers (1974-1977) shows the most heavily produced part of the reservoir to have a ratio of -14 μgals/cm. This discrepancy may be significant, and could be due to a component of natural liquid recharge, or to decompression effects at the boundaries of the vapour-dominated zone. A much more negative value for the ratio is implied by the few data points in the smaller pressure sink around power plants 9-10, suggesting little recharge or reinjection is occurring in this area. The very small value of the ratio in the unproduced part of the reservoir could be caused by tectonic subsidence, or could be due to decompression of a predominantly liquid-dominated reservoir.

Introduction During the mid-1970's, monitoring of gravity, and both vertical and horizontal movement at The Geysers, showed significant changes due to fluid withdrawal from the reservoir (Isherwood, 1977, 1981; Lofgren, 1981). More recently Denlinger, et al., (1981) modelled these changes, showing they yield reasonable estimates of the volume of the reservoir.

In this paper the relationship between gravity changes and subsidence is examined more closely to see whether variations within the reservoir may provide useful constraints for monitoring the effects production and reinjection.

Theory *Liquid Depletion Caused by a Pressure Drop.* In a vapour-dominated production zone, steam is the continuous, pressure-controlling phase, but trapped water is usually the dominant phase by mass. As pressure decreases, water boils, and the excess steam volume flows towards the source of the pressure drop. The heat of vapourization extracted from the rock and residual water causes a temperature decline. While water still remains in the rock, temperature and pressure follow the saturation curve. In most vapour-dominated zones (especially at The Geysers and Lardarello) temperature and pressure are in the range 220-250°C and 20-40 bars. Temperature changes (ΔT) and pressure changes (ΔP) are approximately linearly related by (error <10%):

$$\Delta T(^{\circ}C) = 1.8\,\Delta P\ (\text{bars}) \qquad (1)$$

Let x be the fractional volume of water in the rock which boils to steam during a small pressure drop ΔP and a temperature drop ΔT. If S is the fractional saturation of the pore volume before the pressure drop, then heat balance considerations yield:

$$x = [(1 - \phi)\rho_r C_r + \phi S\, \rho_w C_w]\Delta T/\rho_w L \qquad (2)$$

where ϕ = porosity
$\rho_{r,w}$ = density of rock, water
$C_{r,w}$ = specific heat of rock, water
and L = heat of vapourization

For the temperature range considered here, ρ, C, and L can be considered as constant, with ρ_w = 800 kg/m^3; C_r = 1 kJ/kg°C; C_w = 4.8 kJ/kg°C; and L = 1800 kJ/kg. If the porosity is less than about 10% (as at The Geysers) equation 2 simplifies to:

$$x \approx \rho_r C_r \Delta T/\rho_w L \qquad (3)$$

Inserting the appropriate values, with ρ_r = 2650 kg/m^3, gives:

$$x = 0.0018\,\Delta T(^{\circ}C), \text{ or} \qquad (4)$$
$$x = 0.0032\,\Delta P(\text{bars})$$

That is, x is 1% if a pressure drop of 3 bars, and a temperature drop of 5-6°C occurs.

Gravity Change Caused by Liquid Depletion. The average reservoir density change caused by a fractional volume, x, of water being replaced by steam is $x(\rho_s - \rho_w)$, where ρ_s is the density of steam (15 kg/m^3). The one-dimensional gravity change, Δg, due to this density change is therefore:

$$\Delta g = 2\pi G H x(\rho_s - \rho_w) \qquad (5)$$

where G = gravitational constant (6.7 x 10^{-11} Nm^2 kg^{-2}), and H = average production zone thickness. Inserting the appropriate values and substituting for x using equations 1 and 4 gives:

$$\Delta g(\mu gals) = -110 H \Delta P \qquad (6)$$

where H is in km and ΔP is in bars. Because of the one-dimensional assumption, this equation is only valid where the sides of the production zone are a much greater distance from the observation point than the depth of the production zone. When used on its own, the equation may only be a reasonable approximation near the centre of the production zone. A one-dimensional expression for subsidence is also used in this papaer. The one-dimensional assumptions are not as restrictive as first appears, because the ratio of gravity change to subsidence is used in the interpretation.

Equation 6 gives the gravity change for a production-induced pressure drop in a vapour-dominated reservoir. Reinjection of excess condensate will cause an additional pressure drop as the water is heated to reservoir temperature. The reinjection will also decrease the size of the gravity change. If R is the mass fraction of the produced steam which returns to the reservoir, the gravity change will be reduced by a factor $(1 - R)$. The temperature and pressure decline in the reservoir as the reinjected water comes to thermal equilibrium can be estimated if the initial enthalpy of water is known. Assuming the temperature of the water to be $70 \pm 30^{o}C$ (i.e. specific enthalpy of 300 ± 120 kJ/kg), the change in enthalpy after it has reached thermal equilibrium with a $230 \pm 10^{o}C$ reservoir, is 700 ± 160 kJ/kg. However the change in enthalpy caused by boiling trapped pore water to steam for production is 1800 kJ/kg. Therefore the reservoir heat loss, and also ΔT and ΔP, will be increased by a factor of $(1 + 0.4R)$ due to reinjection. That is, the observed pressure drop, $\Delta P'$, is:

$$\Delta P' = \Delta P(1 + 0.4R) \qquad (7)$$

where ΔP is the original pressure drop due to production alone. Since R is small at The Geysers (0.2 - 0.3), the uncertainty in the enthalpy change of the reinjected water becomes relatively small when considered in equation 7. Substituting for the original ΔP and Δg in equation 6, the simplified equation relating gravity change and average reservoir pressure drop becomes (superscript on $\Delta P'$ is also dropped):

$$\Delta g(\mu gals) = -110 H \Delta P(1 - R)/(1 + 0.4R) \qquad (8)$$

where H is in km and ΔP is in bars.

A check that equation 8 is reasonable can be made by substituting published values for The Geysers. The gravity change in the heavily produced part of the reservoir ranged between -150 and -200 μgals between 1974 and 1977 (Isherwood, 1977; corrected for elevation change). Assuming the production zone to be 2 km thick, this implies a pressure decline of 1.2 ± 0.3 bars. Lipman, et al. (1977) show the pressure decline at Cobb Mountain No. 1 well to have been 24 psi, or 1.7 bars, between 1974 and 1977. Considering the uncertainty in production zone thickness, the difference between the two figures is remarkably small.

Equation 8 emphasizes the value of repeat gravity surveys for monitoring depletion of The Geysers reservoir. With modern gravimeters, the standard error for surveys should be around ± 10 μgals. Since changes in production zone thickness should be negligible once the field has been on production for a few years, the theoretical resolution of repeat gravity surveys is equivalent to ± 0.1 bars reservoir pressure. The main factor limiting this resolution is varying near-surface groundwater level. This becomes significant if water level changes are in excess of several metres.

Subsidence The one-dimensional relationship between subsidence, Δh, and reservoir consolidation at depth is (after Geertsma, 1973):

$$\Delta h = 2(1 - \nu).\ [\text{consolidation}] \qquad (9)$$

where ν = Poisson's ratio (0.25 ± 0.15 usually). Reservoir consolidation can occur from both a temperature decline and a pressure decline. Equation 9 therefore becomes:

$$\Delta h = 1.5\ (\alpha H \Delta T + a H \Delta P) \qquad (10)$$

where α is the coefficient of linear expansion, and a is the uniaxial compaction coefficient ($a \simeq 0.5$ (bulk compressibility) $\simeq 0.5$ (bulk modulus)$^{-1}$). For most rocks $\alpha \simeq 10 \pm 2 \times 10^{-6}$ $^{o}C^{-1}$ (Skinner, 1966) and $a \simeq 1 \times 10^{-6}$ bars^{-1} for rocks with low porosity (Birch, 1966). This value for a is also consistent with the elastic properties of The Geysers reservoir inferred from seismic velocities (Majer and McEvilly, 1978). Inserting these values in equation 10, and substituting for ΔT using equation 1 gives:

$$\Delta h(cm) = 2.9\ H\ \Delta P; \qquad (11)$$

where H is in km and ΔP is in bars. It is also evident that the thermal contraction component is an order of magnitude larger than the fluid decompression component. This is a characteristic of a low-porosity reservoir. For high-porosity reservoirs (e.g. $\phi > 20\%$; these are usually liquid dominated) subsidence is mostly due to fluid decompression.

The heavily produced part of the production borefield at The Geysers subsided by 10 ± 2 cm between 1974 and 1977 (Lofgren, 1981). Using H = 2 km again, equation 11 implies a pressure drop of 1.7 ± 0.3 bars. This is also very close to the pressure drop observed in Cobb Mountain No. 1 well during that time.

Ratio of Gravity Change/Subsidence. Combining equations 8 and 12 gives the ratio of gravity change to subsidence as:

$$\Delta g/\Delta h \simeq -38 \frac{1 - R}{1 + 0.4\ R}\ \mu gal/cm \qquad (13)$$

The accuracy of the ratio is difficult to estimate, as it depends on the accuracy of the values chosen for the various physical parameters. The value of Poissons ratio and the uniaxial compaction coefficient have the greatest uncertainty. As a result, the uncertainty in the ratio in equation 13 is probably ±20%. The ratio should be less sensitive to boundary effects than either of the one-dimensional expressions for Δg and Δh, because the two parameters are independent physical properties of the same anomaly. Boundary effects will therefore tend to cancel. The advantage of the ratio is its independence of the actual reservoir thickness or the pressure drop in the reservoir. It is also insensitive to variations in porosity as long as the porosity is less than about 10%, and 2-phase, vapour-dominated conditions exist.

With no reinjection, the ratio of gravity change/ subsidence should be around 38 μgals/cm.

Analysis of the Data Fortunately an overlapping set of gravity and subsidence data has been published for The Geysers reservoir. Gravity changes were measured between 1974 and 1977 over a large portion of the produced part of the reservoir (Isherwood, 1977). Levelling surveys were made in 1973, 1975 and 1977 (Lofgren, 1981). A profile of gravity change and subsidence across the reservoir is shown in Fig. 1. This extends from the produced part of the reservoir onto the unproduced part (Fig. 2). Both the gravity and the subsidence profiles are referred to assumed stable benchmarks 20 km from the reservoir. Fig. 1 shows the main area of subsidence and gravity change coinciding with the produced area of the reservoir.

To ensure that the subsidence corresponds to the same period as the gravity changes, the subsidence between 1974 and 1975 is assumed to be half that between 1973 and 1975. In addition, the gravity changes discussed by Isherwood (1977) are not corrected for subsidence of the benchmarks (pers. comm., W.F. Isherwood, 1982), so the free-air correction of 3 μgals/cm has been applied. Thirty four benchmarks at The Geysers have both gravity change and subsidence measurements for the period 1974-1977. The distribution of the benchmarks is shown in Fig. 2, and the data is plotted in Fig. 3. All 34 points show a weak trend of increasing gravity change with increasing subsidence. However, a much clearer pattern emerges when the points are split-up according to their location in Fig. 2. The data can be divided into 4 groups:

A: Points within the most heavily produced part of the reservoir (near power plants 1-8, 11) having both a large gravity change and a large subsidence value (black circles);

B: Points close to power plants 9, 10, having a large gravity change with only moderate subsidence values (black squares);

C: Points between groups B and D with moderate gravity changeand moderate subsidence (downward triangles) and

D: Points in the unproduced part of the reservoir having little gravity change with moderate subsidence (upward triangles).

Group A, with 15 points, defines a regression line of slope -14 μgals/cm, and intercept -17 μgals, with a regression coefficient of 0.85. This line is compared with 4 theoretical lines in Fig. 3. The horizontal line for R = 1 corresponds to no mass loss from the reservoir; R = 0 corresponds to no reinjection; and the two intervening lines correspond to varying amounts of reinjection.

Despite the scatter in group A data points (each gravity change has an accuracy of about ± 30 μgals, Isherwood, 1977), the fact the regression line passes close to the origin suggests the data may be behaving according to the theory outlined above. A systematic error in the amount of subsidence, such as that caused by the base-station benchmark being unstable, or tectonic tilt occurring, would have caused the line to pass wide of the origin. The slope of the line is equivalent to R = 0.55, which is significantly greater than the R = 0.2 - 0.3 normally cited for The Geysers (Reed and Campbell, 1976; Bufe and Shearer, 1980). This discrepancy is reduced if the reservoir rock is more compressible than originally assumed. However even with an order of magnitude larger compressibility, R is only reduced to 0.4. Assuming the discrepancy to be real, it could be caused by a component of natural recharge to the production zone. If present, this would most likely take the form of water draining down from shallow depth. An alternative explanation is that boundary effects, where the rock is liquid dominated and pressure is greatly in excess of saturation pressure, are biasing the ratio. Appendix I shows that decompression of a single-phase liquid zone

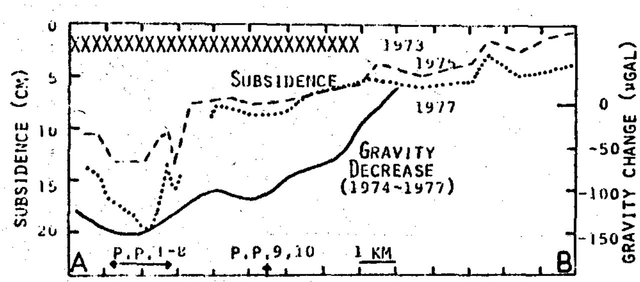

Fig. 1: Profiles of gravity change (Isherwood, 1977) and subsidence (Lofgren, 1981) along a NW-SE line across The Geysers reservoir. The row of crosses denotes the area of production, which also coincides with the area of induced seismicity.

should have a gravity change/subsidence ratio of -1 to -2 μgals/cm. An interesting feature in Fig. 2 is the spread of group A points to the west of the main pressure sink shown by Lipman, et al.(1977). This suggests that draw-down in the reservoir extended further toward Mt Cobb than was recognised at that time.

In contrast to group A points, the average of the four group B points (-155 μgals; 4.5 cm) lies on a line equivalent to R = 0.1. These points are influenced by production from power plants 9 and 10. The reinjection well for these plants is 1-2 km north of the four benchmarks. Possibly very little fluid is returning to the vicinity of the production wells. The fact these four points lie so close to the R = 0 line also suggests that the values assumed for the elastic constants in equations 9 and 10 may be reasonably accurate. This in turn, confirms that the slope of the group A regression is significantly less than the lines for R = 0.2 or 0.3.

Group C benchmarks lie in a transition zone between the produced and unproduced parts of the reservoir. Their gravity changes and subsidence reflect this, being intermediate between groups A, B, and group D points (Fig. 3).

Subsidence of the Unproduced Reservoir Group D points in the unproduced part of the reservoir have negligible average gravity change, and an average subsidence of 4 cm. One explanation for this could simply be that the subsidence here has a tectonic origin. However if true, it is surprising that tectonic subsidence of this magnitude has not also

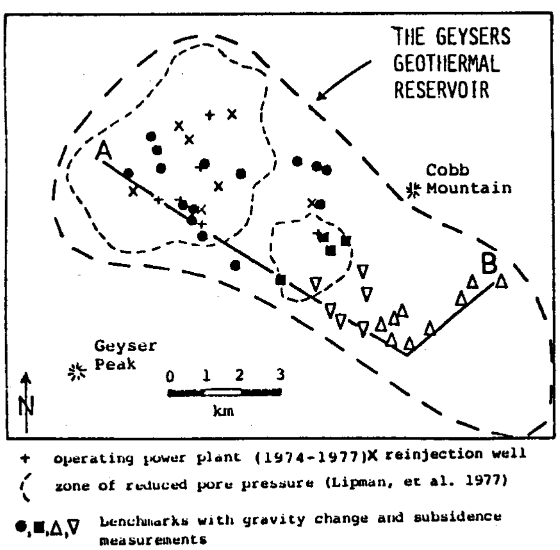

Fig. 2: Location of benchmarks which were monitored for gravity change and subsidence between 1974 and 1977. The benchmarks are divided into four groups according to location in the reservoir.

affected group A points in the produced part of the reservoir. An alternative explanation is that the unproduced part of the reservoir is mostly liquid dominated, with average reservoir pressure greatly in excess of steam saturation (e.g. vertical pressure gradient near to hydrostatic). Decompression of an all-liquid zone with low porosity would cause the ratio of gravity change to subsidence to be between -1 and -2 μgal/cm. (Appendix 1). Subsidence of 4 cm would therefore be associated with a gravity decrease of -4 to -8 μgals, which is too small to have been measured in the 1974-1977 gravity surveys. If the subsidence was due to liquid decompression then the 4 cm of subsidence could have been caused by a liquid pressure drop of 13 bars (equation 4). At this rate, the pressure at production depth would take many years to fall to 30-40 bars saturation pressure (for 230-250^{o}C water).

Allis (1982) has suggested that the induced seismicity in the exploited part of The Geysers reservoir could be partly due to a large fluid pressure drop caused by production. This explanation implies that the initial fluid state of the reservoir was liquid-dominated but that it rapidly became vapour-dominated with production. The presence of subsidence without a significant gravity change in the unproduced part of the reservoir could be additional supporting evidence.

The obvious difficulty with this explanation is the fact that investigation wells in the unproduced reservoir apparently discharged steam after a short period of 2-phase discharge immediately after drilling. Down-hole pressure therefore indicates that an extensive vapour-dominated zone may already exist. The only way this contradiction can be reconciled is if the pressure measured in a well which has been discharged is not representative of average reservoir conditions. This could conceivably occur if the large fractures which represent the primary permeability are finite in volume and, in general don't form an intersecting network through the entire reservoir. For example, the major features could be arranged in an en echelon pattern, which would be consistent with the right-lateral shear at The Geysers. Each fracture must be large enough so that steam wells have a high transmissivity, but also small enough so that on first opening, the pressure drops to steam saturation within the first few hours, or at most, days. Such behaviour is feasible because the hydraulic diffusivity of single phase, 250^{o}C water is 1000 times higher than that of 2-phase, 250^{o}C fluid (derived from Grant and Sorey, 1979). Once depleted of excess water, such fractures may take many years to become liquid-dominated again, because of both the lower, secondary permeability of the surrounding rock, and the 'insulating effects of 2-phase fluid.

Conclusions Combined use of gravity change and subsidence monitoring at The Geysers is capable of providing valuable constraints on reservoir modelling. Both parameters are linearly dependent on the fluid pressure drop. However they are also dependent on assumptions of the size and shape of the reservoir, and the amount of reinjection. By forming a ratio of the gravity change to subsidence, several of the dependent variables cancel. Systematic variations in the ratio are best analysed by plotting the gravity change against subsidence for all benchmarks. Examination of the graph for 1974-1977 data at The Geysers shows lateral variations in the extent of production and reinjection can be identified by this method. However a full understanding of these variations will probably only come when the data is used in conjunction with other reservoir information (such as downhole pressure or discharge enthalpy changes). The additional information would help clarify whether the anomalously low gravity change/ subsidence ratio in the heavily produced part of the reservoir is due to a component of recharge, or some other factor. The accuracy that can be attained with both gravity and precise levelling surveys is such that repeat surveys should be carried out each year.

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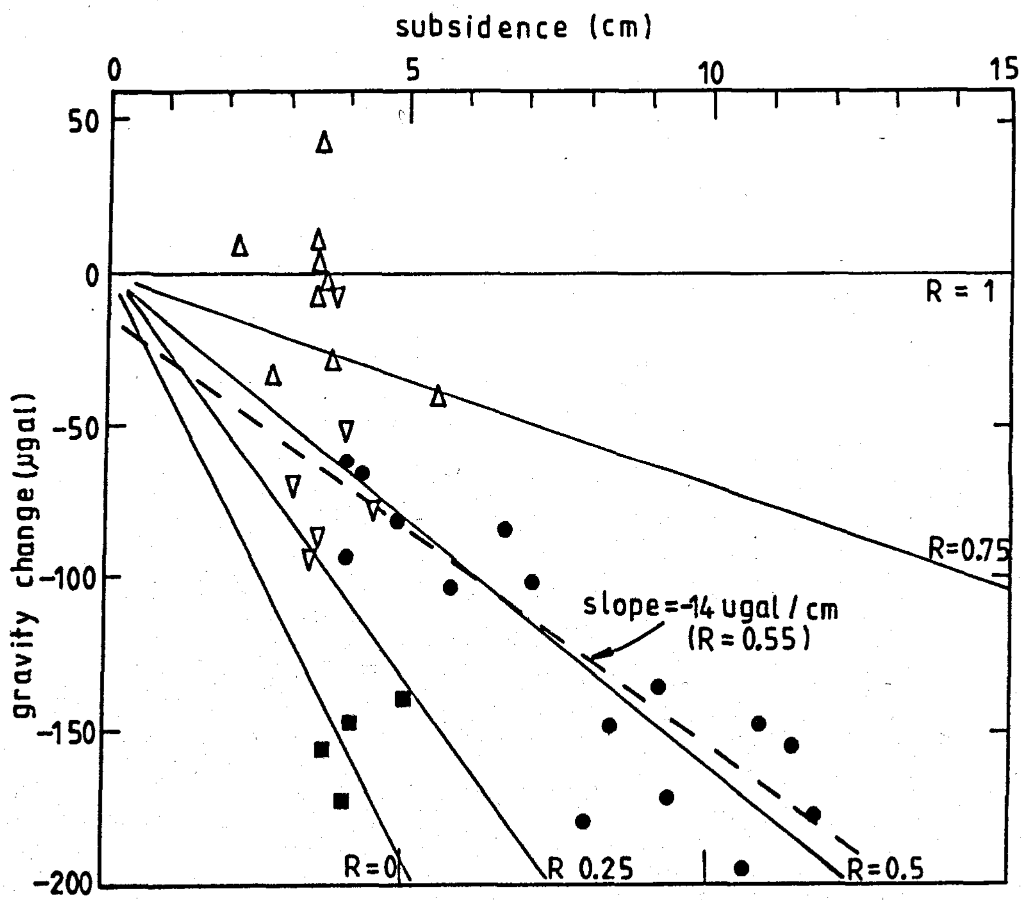

Fig. 3: Plot of gravity change (corrected for elevation change) against subsidence for the period 1974-1977 at The Geysers (from Isherwood, 1977; Lofgren, 1981). The different symbols denote location with the reservoir (Fig. 2). Solid lines are theoretical relationships for varying amounts of reinjection (refer to text). Dashed line is the regression line for the 15 black circles.

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Appendix 1: *Decompression of a single-phase liquid zone*. Consider a reservoir in which the water is under a pressure greatly in excess of steam saturation. When a drop in fluid pressure occurs, the increase in effective pressure on the rock causes a decrease in pore volume, and the pore water also becomes less dense. The fractional volume of water expelled from the rock due to these two effects will be $\Delta P(A + b\phi)$, where A is the bulk compressibility of the rock, and b is the fluid compressibility ($\simeq 1 \times 10^{-4}$ bars^{-1} for 250°C liquid). The one-dimensional expression for the gravity change during a pressure drop is therefore:

$$\Delta g = -2\pi G H \rho_w \Delta P(A + b\phi) \qquad (1A)$$

where all symbols are the same as in the main body of the paper. Inserting a bulk compressiblity value appropriate for the low porosity rock at The Geysers (assumed to be 2×10^{-6} bars^{-1}), and assuming the porosity to be between 0.03 and 0.07,

$$\Delta g = -(0.24 \pm 0.06) H \Delta P \qquad (2A)$$

where H is in km and ΔP is in bars. As before, the subsidence will be:

$$\Delta h = 2(1 - \nu) H \, a \, \Delta P \qquad (3A)$$

where a is the uniaxial compaction coefficient ($\simeq 1 \times 10^{-6}$ bars^{-1}). Therefore $\Delta h(\text{cm}) \simeq 0.15 H \Delta P$, and the ratio of gravity change to subsidence is:

$$\Delta g/\Delta h \simeq -1 \text{ to } -2 \ \mu\text{gals/cm} \qquad (4A)$$