TABLE III

Pressure derivatives of adiabatic and isothermal compressibilities and bulk modulus

	$d\beta_\perp/dp$	$d\beta_\parallel/dp$	$d\beta_V/dp$	dK/dp
	$10^{-21}\,\frac{cm^4}{dyne^2}$			
Adiabatic 298 K	–.0054	–.0117	–.0225	3.22
Isothermal 298 K	–.0052	–.0114	–.0223	3.11
Adiabatic 273 K	–.0046	–.009	–.0180	2.57
Isothermal 273 K	–.0035	–.006	–.0125	1.68

Conversion to isothermal moduli and their pressure derivatives : Because of the anomalous thermal expansion coefficient parallel to the " *c* " axis [11], $\alpha_{\parallel}$, and the relatively large $d\alpha_{\parallel}/d[p] = -d\beta_{\parallel}/dT$ in the temperature range of our measurements, the difference between adiabatic and isothermal elasticity parameters becomes quite significant, as noted in Tables II and III. For this conversion we used the Voigt equations for each of the c_{ij} [12], the zero applied field thermal expansion data of Bozorth and Wokiyoma [11] and the published values of C_p (measured heat capacity) near T_c [13]. The remarkably small $(dK/dp)_T$, where K is the bulk modulus should be noted; this derivative is seldom less than 4, whereas in ferromagnetic Gd it is 1.68.

Discussion

The anomaly in c_{33} *near* T_c : The effects of the transition to the ferromagnetic state on the temperature dependence of c_{33} are of interest because they are typical of the anomalies observed at many higher order phase transitions. In the case of Gd we observe the anomalous effects beginning at approximately 40 K above T_c and the largest effects occurring between T_c and 2.5 to 3 K below T_c (Fig. 4). Since the thermal expansion anomaly also begins about 30 K above T_c it may be presumed that part of the c_{33} anomaly is a result of the increase in volume on cooling through T_c. We

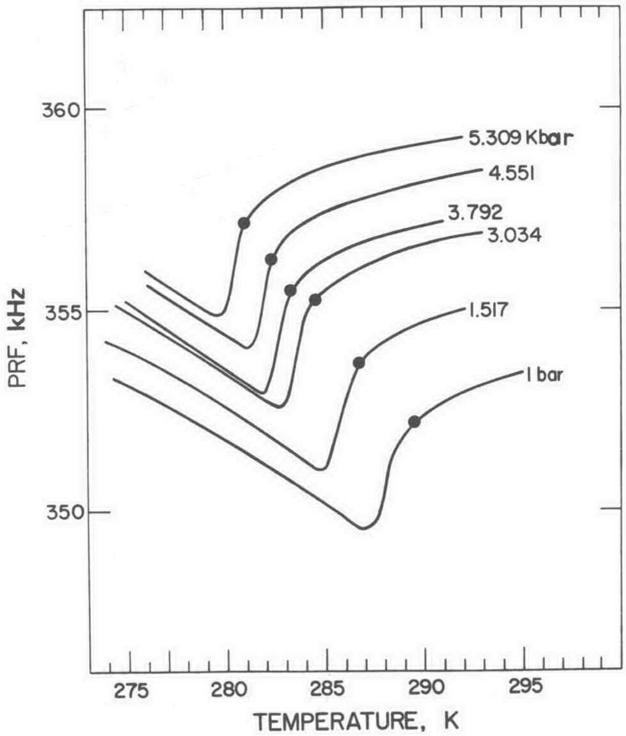

FIG. 4

Variation of pulse repetition frequency for the c_{33} mode through the ferromagnetic transition as a function of hydrostatic pressures (●) corresponds to T_c estimated from changes in slope.

TABLE IV

Evaluation of the intrinsic temperature effect on the c_{ij} *of Gd from Eq. (3) of text.*

Temp.	Modulus	$\left(\frac{1}{m}\frac{\partial m}{\partial T}\right)_p$	$\left(\frac{\alpha_V}{\beta m}\frac{dm}{dp}\right)_T$	$\left(\frac{1}{m}\frac{dm}{dT}\right)_V$
298 K	c_{33}	+ 2.08 × 10⁻⁴	– 1.74 × 10⁻⁴	0.34 × 10⁻⁴
	c_{11}	– 4.00	– .60	– 4.60
	c_{44}	– 4.83	– .06	– 4.89
	c_{66}	– 4.34	– .33	– 4.67
	B	+ 2.14	– 1.58	– 0.56
288 K	c_{33}	97 × 10⁻⁴	– 5.50 × 10⁻⁴	91.5
273 K	c_{33}	– 16.9	– .94	– 17.84
	c_{11}	– 9.8	– .64	– 10.4
	c_{44}	– 10.3	– .31	– 10.6
	c_{66}	– 6.1	– .35	– 6.5
	B	– 8.76	– 1.00	– 9.76

can now investigate this presumption via the pressure coefficients that are given above and the relation

$$\frac{1}{m}\frac{dm}{dT} = \frac{1}{m}\left(\frac{\partial m}{\partial T}\right)_V - \frac{\alpha_V}{(\beta_V)_T}\frac{1}{m}\left(\frac{\partial m}{\partial p}\right)_T \qquad (3)$$

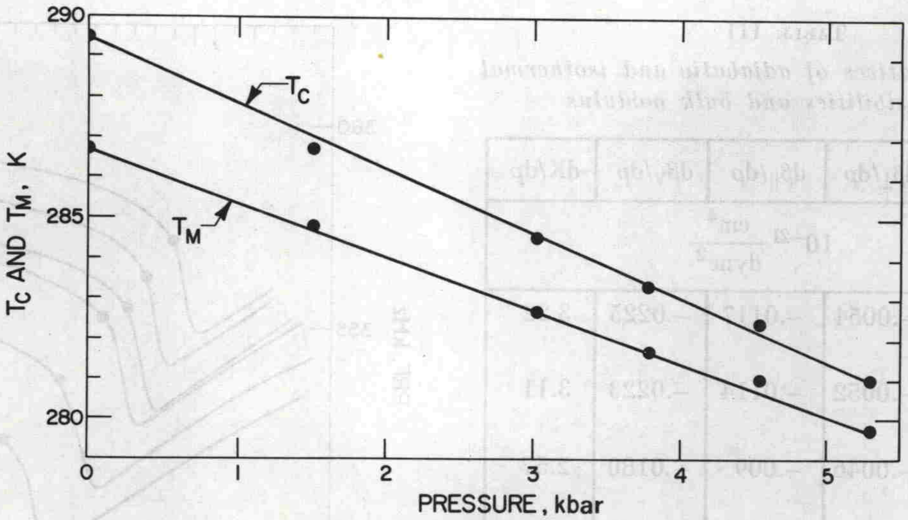

FIG. 5
Variation of T_c and T_m (minimum c_{33}) with hydrostatic pressure.

where m is the modulus and α_V is the volume expansion coefficient. The $(\partial m/\partial T)_V$ term is the intrinsic part of the temperature dependencewhich is due to effects other than static volume change. Table IV gives the evaluations for the three terms of equation (3) as applied to the c_{ij} and bulk modulus. At 298 K the observed temperature derivatives of c_{11} and the shear moduli are almost completely due to the intrinsic effects, whereas the c_{33} and K derivatives are primarily caused by the anomalous thermal expansion. Below T_c, however, the volume change contribution to c_{33} is almost insignificant. The very large dc_{33}/dT between T_c and the temperature of the minimum c_{33}, T_m, is evidently due to a coupling between the compressional wave and the spontaneous magnetic dipole alignment along the " c " axis. The abrupt change to a negative dc_{33}/dT are perhaps associated with a rapid increase in magnetic anisotropy energy at $T < T_m$ and a consequent loss of coupling between the magnetic structure and the " c " axis strain.

The effects of high pressures on the c_{33} curves are shown in Fig. 4. From the data at 1 bar and the magnetization data it is deduced that T_c, noted by (0) in Fig. 4, is that point on each curve where dc_{33}/dT begins to increase sharply on cooling from above T_c. The variations of the T_c and T_m deduced from the data of Fig. 4 are shown in Fig. 5.

The straight line through the indicated T_c connects the two end points. The slope of this line is — 1.60 K/kbar, which is remarkably near the values for dT_c/dp deduced from several sets of magnetization measurements [14]. The pressure dependence of T_m is given by a straight line with a slope of — 1.36 K/kbar. The difference $(T_c - T_m)$ is clearly decreased with increasing hydrostatic pressure.

Gruneisen parameters, γ_L and γ_H : It has been shown that the hydrostatic pressure derivatives of the c_{ij} can be used in deriving average Gruneisen γ's at low and high temperatures, γ_L and γ_H [15]. These computed γ's closely approximate that obtained from the lattice contributions to the thermal expansion coefficients :

$$\gamma_{th} = \frac{\alpha_V V}{c_V (\beta_V)_T} = -\frac{d \ln \bar{\omega}_i}{d \ln V} \quad (4)$$

where α_V is separated from the spontaneous magnetization effects, c_V is the heat capacity at constant volume, V, and $\bar{\omega}$ is the average lattice frequency of vibration. The $(\partial \ln c_{ij}/dp)_T$ values enable the approximation of $(\partial \ln \omega_i/\partial p)_T$ which, in turn, are related to the individual mode γ_i, where i is a given mode of wave propagation. By simple averaging of the γ_i over 300 directions [16] and 3 polarizations using 298 K and 273 K values for dc_{ij}/dp and c_{ij} of Gd, we obtain values of γ_H of 0.35 and 0.26, respectively, compared to values of approximately 0.45 for γ_{th}. Since the γ_{th} calculation involves an estimate of the normal α_V and c_V values near T_c the agreement with the computed γ_H is reasonably good. Both give remarkably small γ's for a metal above its Debye temperature.