rameters computed, the parameters in solution 5 are preferred. Although $(\partial\gamma/\partial T)_v$ is probably nonzero in the vicinity of room temperature, it is interesting that the values for $(\partial K_{0a}/\partial P)_T$ and $(\partial K_{0a}/\partial T)_p$ calculated for stishovite are quite close to those measured by *Manghnani* [1969] and *Chung and Simmons* [1969] for rutile (Table 3), which is isostructural and has nearly the same density as stishovite. *Bassett and Barnett* [1969] and *Liu et al.* [1969] have determined the K_{0t} values for stishovite by fitting their pressure-volume data obtained by X-ray diffraction to the Birch-Murnaghan equation, equation 1. Their value for K'_{0t} [$= (\partial K_t/\partial P)_T|_{p=0}$] was set at 4. However, we have observed that the value for K_{0t} thus calculated depends on the choice of the value for K'_{0t}, as shown in Table 2. If the value for K'_{0t} is chosen to be 7 (solution 5), the K_{0t} values obtained from the X-ray diffraction data are consistent with the K_{0t} value in the solution 5 of this study.

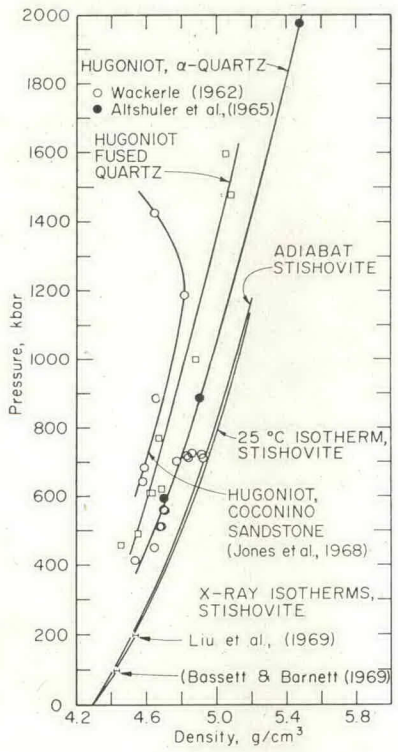

Fig. 1. Pressure-density Hugoniot curves for solid and porous (sandstone) α quartz and fused quartz in the stishovite regime. Calculated adiabat centered at standard conditions and 25°C isotherm for stishovite are calculated from solid α quartz data. Isothermal X-ray data for stishovite compares closely with calculated 25°C isotherm.

TABLE 3. Comparison of Elastic and Thermodynamic Data for Stishovite and Rutile

	SiO_2 (Stishovite)	TiO_2 (Rutile)
ρ_0, g/cm³	4.287	4.250[a] 4.260[b]
C_p, ergs/g	0.715×10^7[c]	0.7125×10^7
α, °K⁻¹	$15.0 \pm 2.0 \times 10^{-6}$[d]	22.75×10^{-6}
K_{0a}, kb	3000[e] 3370[f]	2155[g] 2158[b]
$(dK_{0a}/dP)_T$	7[e] 5[f]	6.4[h] 6.76[b]
$(dK_{0a}/dT)_P$, kb/°K	−0.5	−0.41[b]
γ_0	1.58[h] ± 0.35	1.62

[a] Single-crystal value.
[b] Crystal measured by *Manghnani* [1969].
[c] *Holm et al.* [1967].
[d] Determined by Weaver (1969, private communication) by means of the X-ray diffraction method in a temperature range of 8°C to 800°C using synthetic stishovite.
[e] Analysis of shock data, α quartz.
[f] Birch-Murnaghan fit of the X-ray data of *Liu et al.* [1969].
[g] Polycrystalline value, *Chung and Simmons* [1969].
[h] Preferred value, see Table 1. The uncertainty is based on the uncertainty in α and that in K_{0a}, 3 ± 0.3 Mb, which includes the values obtained by *Bassett and Barnett* [1969] and *Liu et al.* [1969].

The use of equation 4, with appropriate parameters for γ_0 and A to describe the volume or temperature dependence of the Grüneisen ratio along the Hugoniot, rather than the Dugdale-MacDonald relation, has the effect of reducing the zero-pressure bulk modulus from 3.6 Mb given by *Ahrens et al.* [1969] to ~3.0 Mb and increasing $(\partial K_a/\partial P)_s$ from ~3 to ~7. We note also that the new values for both the Grüneisen ratio and the zero-pressure density of stishovite results in the lowering of the calculated zero-pressure bulk sound speed from the 10 km/sec value of *McQueen et al.* [1963] to 8.4 ± 0.2 km/sec for the shock data or 8.4 ± 0.6 km/sec from high pressure X-ray data.

Gruneisen's Ratio at High Pressure

With the availability of high-pressure Hugoniot data in the stishovite regime for porous aggregates of quartz (actually Coconino sandstone) obtained by *Jones et al.* [1968], it is possible to apply the thermodynamic definition

TABLE 4. Grüneisen's Ratio for Stishovite from Porous Quartz and Fused Quartz Data

1. Sandstone[a] and α Quartz Data		2. Fused Quartz[b] and α Quartz Data		3. Fused Quartz[c] and Sandstone	
ρ, g/cm^3	γ	ρ, g/cm^3	γ	ρ, g/cm^3	γ
4.583	0.96	4.637	0.87	4.583	1.01
4.594	0.97	4.671	1.08	4.594	1.03
4.659	0.99	4.881	0.66	4.659	1.03
4.818	0.86	4.969	0.98	4.818	0.69
4.648[d]	1.23	4.68[f]	0.88[f]	4.648	1.32
4.65[e]	1.49				
4.82[e]	1.40				

[a] Initial density, 1.98 g/cm^3 [*Jones et al.*, 1968].
[b] Initial density, 2.195 g/cm^3 (H. Shipman, private communication, 1969).
[c] Data of Shipman and *Wackerle* [1962] are combined.
[d] Hugoniot point in region where pressure is double-valued function of density.
[e] Limiting values obtained for point at which Hugoniot curve achieves maximum density.
[f] Average of 24 points calculated from data of *McQueen* [1968].

of Grüneisen's ratio (equation 3) to obtain an independent determination of γ at high pressure. The Hugoniot data for Coconino sandstone, which has an initial density of 1.98 g/cm^3, are also shown in Figure 1. For a given density these data indicate a higher pressure than the data for stishovite obtained by shocking α quartz. This results because of the greater thermal pressure accompanying compression for the distended (26% porosity) state. In order to calculate Grüneisen's ratio, the internal energies and pressures at a given density are differenced to form the ratio

$$\gamma = v(p_{hss} - p_{hq})/(e_{ss} - e_q) \qquad (8)$$

where the subscripts ss and q denote sandstone and quartz. The assumptions implied by equation 8 are:

1. The standstone is pure quartz. The analysis of *Jones et al.* [1968] indicates 97% quartz and 3% feldspar, with a trace of heavy minerals. Because of the similarity of quartz and feldspar in density and Si-O coordination in both the low- and high-pressure phase (hollandite structure in the case of feldspar, [*Ringwood et al.*, 1967], the effect of the feldspar impurities should be small.

2. The energy required to reduce the porosity of sandstone to zero upon shock compression, plus the surface energy of the quartz grains, is negligible as compared with the shock energy. The compaction energy can be roughly estimated by assuming it to be comparable to the energy required to isothermally collapse the pore structure of sandstone. Assuming a pressure of the order of 50 to 100 kb is required [*Stephens and Lilley*, 1968], a compaction energy of $\sim 6 \times 10^9$ ergs/g is obtained. The surface energy for quartz grains of $\sim$0.5-mm diameter, is $\sim 10^4$ ergs/g [*Brace and Walsh*, 1962]. The energies are both small compared with the shock energies associated with the densities given in Table 4.

3. For the high-temperature states lying between the quartz and sandstone Hugoniots, Grüneisen's ratio is only a function of volume (or density). This implies that the finite difference of equation 8 is mathematically equivalent to the derivative in equation 3. A critical test of this assumption would be to compare the apparent Grüneisen's ratios obtained from Hugoniot data for the same compound with different initial densities. As shown in Table 4, the values of γ calculated from the Hugoniot data for solid and fused quartz and sandstone (excluding the region of double-valued density versus pressure) are essentially in agreement with each other. This observation supports the assumption above.

The values of Grüneisen's ratio obtained from each of the high-pressure data points for sandstone are given in Figure 2 and Table 4. The first four data points give Grüneisen ratios in the density range 4.6 to 4.8 g/cm^3 as 0.94 $\pm$