been active for an extremely long time and would have been spatially more extensive in its earlier stages than in its more recent stages; (4) there may be a gap in time, on the basis of crater density, between heavily cratered terrain and the mapped volcanic units in the Tharsis province. We do not regard these arguments as valid objections to the model for Tharsis evolution proposed here.

Soderblom et al. [1978] noted distinctive color variations in the southern equatorial cratered terrain which they attributed to local lithologic variations. The color differences between heavily and lightly cratered units within Tharsis may result from differences in volcanic composition or may simply reflect differing degrees of impact breccia formation, regolith formation, or chemical weathering rather than substantive differences in the mode of origin of the units. A volcanic origin for all heavily cratered terrain on Mars, in fact, is not precluded by these data.

The lack of physiographic features diagnostic of a volcanic origin presumably refers only to the hilly and cratered material in Figure 1, since the cratered plateau materials do retain such volcanic features as flow fronts and constructs [*Wilhelms*, 1974; *Scott and Carr*, 1978; *Greeley and Spudis*, 1978, 1981; *Scott and Tanaka*, 1981*b*]. As sufficiently heavy cratering would be expected to obliterate such features, their lack on the oldest surfaces on Mars does not permit the conclusion that volcanic features were never present.

The conclusion that Tharsis volcanic activity, by our scenario, lasted over the exceedingly long time interval from before the end of heavy bombardment 3.8 b.y. ago to as recently as a few hundred million years ago [*Schaber et al.*, 1978; *Plescia and Saunders*, 1979*b*] is valid. We do not regard this conclusion as an objection to our model, however, and we have outlined a sequence of events that can account for such an extended history. The inference that Tharsis volcanic activity in its early stages occurred over an area much broader than that of more recent volcanic plains emplacement is also correct. Rather than an objection to the model, this result is a natural consequence of the waning of the Tharsis volcanic flux and the general thickening of the Martian lithosphere with time following the earliest widespread activity.

The final objection of *Plescia and Saunders* [1980] is based on an apparent gap in the relative surface ages of Tharsis units as measured by crater density. Even if an age gap (i.e., between cratered plateau material and ridged plains material) is real, the length of time represented by such a gap may be short by geological standards. The rate of crater formation decreased very sharply at the end of heavy bombardment [e.g., *Neukum and Wise*, 1976; *Soderblom*, 1977; *Hartmann*, 1977; *Wise et al.*, 1979*a*], so that the density of preserved craters on surfaces formed just before and just after that time would differ substantially. Expressed in terms of the 'crater number,' or the total number of craters of diameter 1 km and greater per 10^6 km^2, *Wise et al.* [1979*a*] give 50,000 and greater for the time of establishment of the hemispherical asymmetry of Mars and 20,000 and less for the emplacement of ridged plains volcanic units. This apparent gap, however, represents a time interval of only 100–150 m.y. according to the various curves of crater density versus age given by *Wise et al.* [1979*a*], and a few surfaces with intermediate values for the crater number are shown in map view by Wise and co-workers for units indicated as cratered plateau material by *Scott and Carr* [1978]. An age difference of 100–150 m.y. is comparable to that between major eruptions in lunar maria [e.g., *Solomon and Head*, 1980*a*] and need not signify a fundamental change in the nature of operative volcanic processes. Similarly, any gap in time between heavily cratered material (much of it volcanic) and the next oldest volcanic units in the Tharsis province may not have been any longer than other subsequent time intervals between major volcanic eruptive episodes.

Advantages of the model. The model for the evolution of the Tharsis province proposed in this paper has several advantages not shared by many or all of the models previously proposed. Because the topographic high associated with the region is primarily constructional and is presently supported by lithospheric strength, the topographic rise and the associated positive gravity anomaly are permanent features, in contrast to models in which uplift is caused by thermal or dynamical anomalies in the Martian mantle. This statement would also apply to the Elysium province if the evolution of that region followed the model proposed here for Tharsis. The concept of stress concentration in an elastic lithosphere locally thinned by elevated near-surface thermal gradients provides a natural explanation for the association and localization of lithospheric fracturing and volcanic activity in distinct provinces. The response of the lithosphere to volcanic loads dominates the stress field and gives rise to the systems of prominent fractures, in agreement with recent calculations [*Willemann and Turcotte*, this issue; *Banerdt et al.*, this issue].

A major distinction between the explanation for the Tharsis province offered here and all earlier explanations [e.g., *Carr et al.*, 1973; *Phillips et al.*, 1973; *Hartmann*, 1973; *Carr*, 1974; *Wise et al.*, 1979*a*, *b*; *Sleep and Phillips*, 1979; *Finnerty and Phillips*, 1981] is that no special or anomalous properties need to be ascribed to the mantle beneath major Martian volcanic provinces for extended periods of time. The location of volcanism on Mars is governed primarily by the sites of easiest access of magma to the surface. In this respect, Tharsis and Elysium may be similar to midocean ridges on the earth. The Mid-Atlantic Ridge and the East Pacific Rise are major planetary volcanic centers and are nearly stationary in a hot spot reference frame [*Morgan*, 1972; *Minster et al.*, 1974; *Solomon et al.*, 1975], yet no anomalous characteristic is attributed to the mantle beneath them. The mantle beneath terrestrial midocean ridges plays a passive rather than an active role [cf. *Sengör and Burke*, 1978]; volcanism occurs at ridges more readily than elsewhere because the lithosphere is locally thin and is subjected to continuing fracture and extension. According to the scenario presented in this paper, the Martian mantle similarly plays a passive role beneath Tharsis. Continued volcanism is a consequence of a locally thin lithosphere subjected to extensional fracturing and not to a chemical or dynamical anomaly sustained for billions of years beneath the Tharsis province.

CONCLUDING DISCUSSION

We have proposed a physical model for the history of the Tharsis province of Mars incorporating zones of locally thin lithosphere capable of concentrating stress and lithospheric failure, closely associated volcanism and fracturing that maintained the lithosphere locally thin by positive feedback, and an evolving topographic construct built by the successive addition of volcanic units and presently sup-