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# Residual Heat Flow and Crustal Properties

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ABSTRACT: The seemingly scattered plot of heat flow versus crustal thickness is explained by geodynamic processes and simple thermal relaxation in two contrasting tectonic elements. Elevated heat flow is characteristic of rift provinces where the crust is attenuated by stretching but also of orogenic belts where thrust tectonics thickens the crust and significantly enhances crustal heat production. With the progression of time, isostatic processes thin the thickened crust through uplift and erosion and thicken the rifted crust through subsidence and sedimentation. Heat flow relaxes to a value in equilibrium with background mantle heat flow.

## INTRODUCTION

With the rapid increase of heat flow data during the last decade, attempts have been made to refine relationships between heat flow and other geophysical parameters such as crustal thickness and P wave velocity in the uppermost mantle, and to establish relations for the continents. From an earlier analysis, Herrin (1972) suggested that there is a relation between crustal structure and heat flow in the Canadian Shield and the Basin and Range provinces. Roy et al. (1972) also concluded that heat flow seems to be related to crustal thickness. Gilluly (1972), Negi and Pandey (1976), and Cermak (1977b) have arrived at the similar conclusion. Veliciu and Demetrescu (1979), Bodri and Bodri (1985), Wdowinski and Bock (1994) have presented results indicating that heat flow shows a tendency to increase in areas with thin crust and to decrease with thick crust. Several authors have demonstrated that there is positive correlation between geologic and Moho depth. This trend holds in Ausralia (Finlayson, 1993), in the European region (Meissner, 1970), in India (Negi and Pandey, 1976), and in North America (Woollard, 1972; Clowes, 1993; Kanasewich et al., 1994).

The work that has preceded our consideration of $V_{Pn}$ and heat flow began with Pakiser (1963), who first noted the relationship between $V_{Pn}$ and crustal thickness. Horai and Simmons (1968) then found a correlation between heat flow and travel time anomalies in the upper mantle. The next addition to our understanding was the work by Warren and Healy (1973) and Chung (1977) which related $V_{Pn}$ to density variations. An alternative interpretation was offered by Wu et al. (1993) who attributed variations in $V_{Pn}$ to compositional differences.

The most recent study of seismic velocity and the thermal state of the continents was reported by Black and Braile (1982) and Clowes (1993) who employed North America data to show an inverse relationship between heat flow and $V_{Pn}$. They also developed a temperatue/pressure derivatives correction and began sophisticated statistical analysis of heat flow and $V_{Pn}$ data.

In this study, an analysis of continental heat flow for 36 geological provinces on a global basis is presented. In particular, We explore the relationships between surface heat flow ($q_0$), geological age, heat flow originating from crustal radioactivity ($q_{CR}$), crustal thickness (M), and Pn velocity. Because of the large number of seismic profiles and locations of seismic observations, the data and analyses have been sorted into two groups: (1) orogenic fold belts and uplift regions; and (2) rifted and stable regions. Pn velocities and Moho depths are tabulated from seismic profiles of 36 locations on the globe. The locations are selected according to physiographic provinces (Fenneman,1946) for the United States and geologic provinces for other locations. Mean Pn velocity is calculated for each geologic province. In Table 1, geological age and surface heat flow are listed. Pn velocity ($V_{Pn}$), Moho depth, and heat flow by crustal radioactivity are listed in Table 2. References for each geologic province are presented in the bibliography. This interpretation and analysis will discuss residual heat flow, radiogenic heat flow, crustal thickness, and analysis of Pn velocity.

## RESIDUAL HEAT FLOW

In order to emphasize local heat flow anomalies, residual heat flow which is left after regional heat flow has been removed can be defined as the difference between observed heat flow and heat flow calculated from

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a base curve for the age of the tectonic provinces. Residual surface heat flow ($q_{0\,resid}$) is the difference between observed surface heat flow and heat flow calculated by the best fitting curve. Surface heat flow residuals vary between $-32$ and $+32\,mWm^{-2}$, with a root mean square of $15\,mWm^{-2}$. Residual reduced heat flow ($q_{r\,resid}$) can be defined as the difference between reduced heat flow and heat flow calculated by the base curve. With the exeption of the Sierra Nevada, reduced heat flow residuals vary only from $-6$ to $+13\,mWm^{-2}$.

Further explanations for residual heat flow variations may be sought by examining their correlations with other physical crustal properties including geologic age, crustal thickness, Pn velocity, and estimates of the crustal radiogenic heat contribution.

We applied a detailed seismic profile to each of the 36 provinces. In this study we combined geological and geophysical information in a self-correcting approach which took into account the complexity of the processes under study. Table 1 lists surface heat flow values and geologic ages for the 36 geologic provinces. Fig. 1 indicates the decrease of continental heat flow with age in geologic provinces. Open circles in Fig. 1 represent geologic provinces which contain orogenic fold belt and uplift regions. Closed circles indicate stable and rifted geologic provinces. As shown in Fig. 1, heat flow values for geologic provinces decay more or less with the increase in geological ages over 35 of the 36 provinces(Sierra Nevada being excluded). This seems to be in agreement with earlier observations.

Shield provinces (age>600My) are characterized by low mean heat flow, and the scatter of mean heat flow is not broad. This kind of scatter of heat flow values in shield or stable provinces can be explained by shallow thermal processes and local geologic considerations. Heat flow values in younger provinces show generally high mean heat flow, and the scatter of mean heat flow is large. However, heat flow ranges from low to high values.

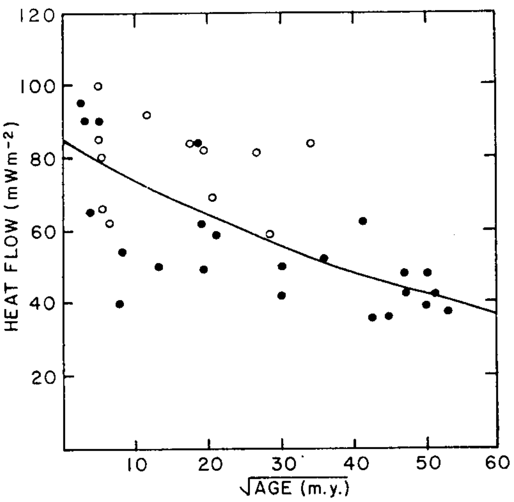

Fig. 1. Decrease of continental heat flow with age. Open circles represent origenic fold and uplift regions, closed circles indicate stable or rifted geologic provinces.

## RADIOGENIC HEAT FLOW

Vitorello and Pollack (1980) have proposed a threefold partition of surface heat flow into (1) a background su blithospheric contribution from the mantle; (2) an orogenic contribution from cooling of the lithosphere following orogeny; and (3) an amount that arises from radiogenic heat prodution in the crust. This latter contribution in their model is simply considered to be equal to $A_0b$, the product of the surface heat production and the characteristic depth b found from the linear heat flow-heat production relationship. The quantity $A_0b$ properly represents the radiogenic heat from the enriched upper crust. An equally fundamental parameter would be the radiogenic heat from the entire crust $q_{CR}$ which can be estimated from seismic velocity crustal profiles and a relationship between seismic velocity and heat production.

Values for crustal radiogenic heat flow $q_{CR}$ are estimated as follows:

$$q_{CR} = \int_0^M A(z)\,dz \qquad (1)$$

where M is Moho depth, A(z) is the heat production value of each layer, and dz is the thickness of each layer. The calculation of A (z) uses the experimental results reported by Rybach and Buntebarth(1982), based upon the relationship between heat production (A) and P wave velocity ($V_P$). The relationships are as follows:

$$\ln A = 16.5 - 2.74\,V_P^* \text{ at } P = 50\,MPa \qquad (2)$$

$$\ln A = 13.7 - 2.17\,V_P^* \text{ at } P = 100\,MPa \qquad (3)$$

$$\ln A = 12.4 - 1.93\,V_P^* \text{ at } P = 200\,MPa \qquad (4)$$

where A is given in $\mu Wm^{-3}$ and $V_P^*$ in km/s.

It is difficult to judge the better values to use because the velocity data reported by Kern and Richter (1981) and Rybach and Buntebarth (1982) show significant velocity anisotropy and the dependence of elastic parameters on constituent minerals.

The use of higher velocity at 200 MPa will produce heat production distributions A(z) on the high side,

Table 1. Age and Heat Flow ($q_0$) for Geologic Provinces.

| Geologic province | Age (My) | N | $q_0$ (mWm$^{-2}$) | Reference |
|---|---|---|---|---|
| 1. Ukraine | 2500-1100 (1800) | 12 | 21-50 (38) | 13, 21, 30 |
| 2. Carpathians (outer) | 60-11 (30) | 15 | 39-94 (66) | 6, 7, 9, 10, 11, 13, 21, 25, 29, 38, 40 |
| 3. Pannonian Basin | 20-1 (10) | 5 | 70-135 (90) | 4, 5, 6, 13, 18, 32, 39 |
| 4, Baltic Shield | 3000-1000 (2000) | 4 | 20-51 (40) | 13, 15, 16 |
| 5. Norwegian Caledonide | 415-345 (380) | 5 | 20-54 (41) | 20, 30, 36 |
| 6. Thuringian | 350-280 (315) | 26 | 77-86 (74) | 6, 7, 8, 9, 10, 11, 12, 13, 28, 29 |
| 7. Moldanubian | 1570-280 (350) | 5 | 50-54 (52) | 6, 7, 8, 9, 10, 11, 12, 13, 28, 29 |
| 8. Alps | 40-11(25) | 12 | 70-110 (85) | 1, 2, 13, 19, 24, 26, 33, 34, 35 |
| 9. Tuscany | 10-0.4 (8) | 6 | 83-107 (95) | 3, 14, 17, 27, 37 |
| 10. Apennine | 135-11 (40) | 5 | 31-43 (38) | 22, 23 |
| 11. England and Wales | 1100-270 (600) | 10 | 37-129 (59) | 31 |
| 12. Canadian Shield | 3550-1460 (2500) | 14 | 20-54 (36) | 204, 215, 223, 224, 227, 231, 239, 502 |
| 13, Coastal California | 180-40 (70) | 23 | 31-67 (54) | 210, 214, 217, 221, 222, 237, 243 |
| 14. Sierra Nevada | 135-1 (65) | 25 | 19-58 (40) | 210, 214, 216, 217, 219, 220, 236, 241, 243 |
| 15. Basin and Range | 65-1 (25) | 292 | 42-130 (91) | 202,. 203, 205, 207, 209, 210, 214, 222, 233, 505 |
| 16. Colorado Plateau (exterior) | 135-11 (30) | 33 | 54-126 (89) | 203, 209, 210, 216, 218, 222, 226, 232, 233, 234, 235 |
| Colorado Plateau (interior) | 225-11 (45) | 57 | 43-116 (61) | 203, 209, 210, 216, 218, 222, 226, 232, 233, 234, 235 |
| 17. Southern Rocky Mountains | 270-11 (135) | 23 | 67-120 (92) | 208, 209, 210, 211, 216, 217, 230, 232, 236, 244 |
| 18. Great Plains | 1200-700 (900) | 38 | 33-62 (50) | 205, 207, 209, 210, 213, 216, 217, 236, 238 |
| 19. Coastal Plain (eastern) | 350-135 (175) | 17 | 21-67 (50) | 206, 210, 229, 240, 242, 243 |
| 20. Columbia Plateau | 25-11 (15) | 4 | 59-71 (65) | 201, 210, 217, 222, 505 |
| 21. Maritime, Canada | 395-345 (370) | 10 | 41-82 (62) | 212, 225, 238, 245 |
| 22. Pilbara Craton | 2000- (2500) | 5 | 46-50 (45) | 310, 312, 316, 320, 321, 322 |
| 23. Yilgarn Craton | 3000-2500 (2800) | 19 | 29-56 (39) | 301, 302, 304, 305, 309, 311, 312, 316, 320, 321, 322, 323 |
| 24. Central Australia | 1400-900 (1150) | 29 | 42-136 (74) | 303, 312, 316, 319, 321, 322 |
| 25. Georgina Basin | (1700) | 11 | 44-102 (56) | 307, 319, 321 |
| 26. Adelaide Fold Belt | 900-260 (340) | 9 | 49-126 (90) | 307, 308, 319 |
| 27. Bowen Basin | 400-350 (375) | 5 | 32-60 (49) | 303, 307, 312, 313, 314, 315, 321, 325 |
| 28. Murray Basin | 400-350 (375) | 4 | 61-102 (82) | 303, 307, 312, 314, 315, 316, 321, 325 |
| 29. Lachlan Fold Belt | 440-135 (225) | 5 | 42-102 (69) | 303, 306, 307, 312, 313, 314, 315, 316, 317, 318, 321, 322, 324, 325, 326, 503 |
| 30. Sydney Basin | 400-135 (225) | 5 | 50-102 (82) | 303, 307, 308, 312, 314, 315, 316, 321, 325 |
| 31. Andes Altiplano | 70-3 (25) | 13 | 54-183 (100) | 413, 426, 427, 506 |
| 32. Brazilian Shield | 2600-1800 (2200) | 13 | 23-77 (42) | 408, 414, 423, 424, 427 |
| 33. Kalahari Craton | 2500-600 (2200) | 18 | 36-57 (48) | 403, 404, 405, 406, 410, 419, 501, 504 |
| 34. Southern Indian Shield | 3200-900 (2600) | 15 | 26-75 (42) | 401, 402, 407, 409, 411, 412, 418, 419, 420, 421 |
| 35. Eastern Siberia Platform | 1200-600 (900) | 32 | 29-71 (42) | 415, 416, 417, 422 |
| 36. Hopei Shantung | 1100-500 (800) | 10 | 30-77 (59) | 425 |

N is number of heat flow sites, $q_0$ is surface heat flow, values in parentheses are mean geologic age and surface heat flow values.

while using lower velocity at 50 MPa may produce an A(z) profile on the low side. Kern and Richter (1981) claim that 100 MPa is required for each 100℃ because this will close grain boundary cracks. The physical conditions which exist in the natural environment must be transferred to the $V_P$* measured at 100 MPa and 20℃. The

Table 1. continued.

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correction $dV_P$ from measured $V_P$ is $dV_P=(\partial V_P/\partial P)dP+(\partial VP/\partial T)\,dT$.

The $\partial V_P/\partial P$ values reported in the literature are as follows (Black and Braile, 1982; Clowes, 1993) : $2\times10^{-4}$ (gabbro), $2.9\times10^{-4}$ (amphibolite), $3.0\times10^{-4}$ (granulite), $3.5\times10^{-4}$ (gneiss), and $4.0\times10^{-4}$ km s$^{-1}$ MPa$^{-1}$ (granite). The pressure gradient ($dP=\rho gdz$) is about 30 MPa km$^{-1}$. However, equation (2) is inappropriate to apply in continental geologic provinces because at the pressure 50 MPa, the rate of increase of $V_P$ is too large. However, although equation (4) is appropriate to apply to such provinces, this relationship between heat production and P wave velocity is not firmly established because of insufficient rock samples.

For acidic rocks, the rate of change of $V_P$ at 100 MPa is quite small while for basic rocks at 100 MPa, the change becomes minimal. These results, obtained primarily on samples of igneous rock, can be applied to metamorphic rock as well. To obtain $\dot{q}_{CR}$, a mapping from equation (3) can be used to calculate heat production values in continental layers using well-known seismic velocity studies. The experimental works and rock samples for equation (3) are sufficient. Table 2 lists $q_{CR}$, Moho depth (M), and Pn velocity for the 36 geologic provinces.

A generalized relationship between seismic velocity and heat production, incorporating the continuum of pressure and temperature effects for normal conditions in the crust is tabulated in Table 3. This table has been used to compute $q_{CR}$ in this study. For the calculation of heat production values, Prodehl's Table 2.1 (Prodehl, 1984) of seismic velocities has been employed. Heat

Table 2. P-Wave Velocity ($V_{Pn}$), Moho Depth (M), and $q_{CR}$ Summaries for Geologic Provinces.

| Geologic Province | N | $q_{CR}$ ($mWm^{-2}$) | M (km) | $V_{Pn}$ (km/s) | Reference |
|---|---|---|---|---|---|
| 1. Ukraine | 3 | 30-37 (33) | 35-50 (38) | 8.1-8.3 (8.2) | 73P1, 73S3, 77S1, 80Z1 |
| 2. Carpathians (outer) | 2 | (41) | 32-57 (49) | 8.0-8.1 (8.05) | 80Z1 |
| 3. Pannonian Basin | 3 | 17-40 (30) | 22-30 (26) | 8.0-8.5 (8.16) | 72B2, 72B3, 77P1, 80Z1 |
| 4. Baltic Shield | 10 | 20-40 (30) | 34-52 (41) | 8.0-8.3 (8.2) | 71A1, 71P2, 71V1, 79L1 |
| 5. Norwegian Caledonide | 3 | 29-53 (34) | 25-43 (36) | 8.1-8.2 (8.12) | 71K2, 71S2, 71V2 |
| 6. Thuringian | 3 | (29) | 27-32 (29) | 8.0-8.1 (8.02) | 71K3, 78M3 |
| 7. Moldanubian | 8 | 25-44 (38) | 24-42 (36) | 8.0-8.2 (8.07) | 72B2, 72B3, 71E1, 75E1 |
| 8. Alps | 14 | 38-64 (47) | 35-57 (54) | 8.1-8.2 (8.16) | 78M2, 79A1, 80M6 |
| 9. Tuscany | 2 | 26-43 (35) | 21-35 (30) | 7.5-8.1 (7.8) | 77M6, 81G2 |
| 10. Apennine | 2 | 28-48 (38) | 33-47 (45) | 8.0-8.1 (8.03) | 69C1, 73C1, 73G1, 78S1 |
| 11. England and Wales | 3 | (39) | 27-37 (35) | 8.0-8.1 (8.05) | 71H1, 78B1 |
| 12. Canadian Shield | 2 | 36-36 (36) | 36-50 (44) | 8.0-8.5 (8.2) | 71M1, 73B2, 73B3 |
| 13. Coastal California | 4 | 24-35 (31) | 24-36 (30) | 8.0-8.2 (8.03) | 79P1, 83B1 |
| 14. Sierra Nevada | 3 | 36-43 (40) | 49-51 (45) | 7.8-7.9 (7.87) | 79P1, 80P1, 81S2 |
| 15. Basin and Range | 3 | 27-46 (37) | 20-36 (30) | 7.6-8.1 (7.8) | 79P1 |
| 16. Colorado Plateau (exterior) | 1 | (40) | (43) | (7,6) | 79P1 |
| Colorado Plateau (interior) | 1 | (32) | (40) | (7.8) | 69W1 |
| 17. Southern Rocky Mountains | 1 | (40) | 37-52 (48) | (7.9) | 80P2 |
| 18. Great Plains | 5 | 30-45 (37) | 38-51 (44) | 8.0-8.2 (8.13) | 66M1, 68S1, 70M1, 77P1, 79K1 |
| 19. Coastal Plains (eastern) | 2 | (40) | (35) | (8.1) | 69H1 |
| 20. Columbia Plateau | 1 | (35) | 20-34 (28) | (7.9) | 72H1 |
| 21. Maritime, Canada | 2 | 34-40 (37) | 18-43 (30) | 7.9-8.5 (8.2) | 66D1, 81K1 |
| 22. Pilbara Craton | 1 | 38-42 (40) | 28-52 (40) | (8.3) | 79D2, 81D1 |
| 23. Yilgarn Craton | 3 | 17-51 (35) | 34-52 (44) | 8.1-8.25 (8.2) | 74M1, 79D2, 81D1 |
| 24. Central Australia | 4 | 25-44 (35) | 34-60 (42) | 8.2-8.3 (8.23) | 74F1, 78H1 |
| 25. Georgina Basin | 1 | (36) | 34-52 (43) | (8.1) | 79F1 |
| 26. Adelaide Fold Belt | 1 | (46) | (34) | (8.0) | 79F2 |
| 27. Bowen Basin | 1 | (36) | 32-36 (34) | 7.9-8.1 (8.0) | 78C1 |
| 28. Murray Basin | 1 | (38) | 31-37 (34) | (8.0) | 76B1, 77M2, 79F2 |
| 29. Lachlan Fold Belt | 1 | (31) | 41-60 (47) | (8.0) | 79F2, 81F1 |
| 30. Sydney Basin | 1 | (36) | (42) | 8.0-8.01 (8.05) | 81F1 |
| 31. Andes Altiplano | 1 | (48) | 71-76 (73) | (8.0) | 71O1, 72O1 |
| 32. Brazilian Shield | 1 | (38) | (42) | (8.2) | 80G5 |
| 33. Kalahari Craton | 1 | (38) | (38) | (8.2) | 52W1 |
| 34. Southern Indian Shield | 1 | (32) | (40) | (8.1) | 79K1, 79K2 |
| 35. Eastern Siberia Platform | 2 | 32-34 (33) | 32-42 (38) | 8.2-8.4 (8.3) | 80Z1 |
| 36. Hopei Shantung | 1 | (25) | 35-40 (38) | 8.0-8.5 (8.25) | 79Z1 |

N is number of location, $q_{CR}=\int_{O}^{M} A\,(z)\,dz$, M indicates Moho depth, 52 W1 to 81S2 indicate reference numbers of seismic data by Prodehl (1984), values in parentheses are mean $q_{CR}$ and M values.

production (A) is assumed to be 1.0 $\mu Wm^{-3}$ for nearsurface (sedimentary) layers. In case where $V_P$ is larger than 5.7 km/s, heat production values (A) are calculated by using the relationship between A and $V_P$ (equation 3). Once again Prodehl's Table 2.1 (1984) was used to calculate heat production in the crustal layer for each geologic province.

Because there is a degree of uncertainty about the cause of seismic velocity distribution with depth in such regions, we used a constant or gradual incrase of the seismic velocity through low velocity zones. If equations (2) through (4) are used for crustal low velocity zone, unreasonable heat production values are predicted. An example of applying Table 3 to a given province is shown in Fig. 2. This seismic velocity profile $V_P(z)$ appears in (I) of Fig. 2 while the heat generation profile A(z) appears in (II).

The relationships between surface heat flow ($q_0$), residual heat flow ($q_{0\ resid}$), residual reduced heat flow ($q_{r\ resid}$), and radiogenic heat flow ($q_{CR}$) are shown in Fig. 3. In the upper diagram, some geologic provinces, including orogenic fold belt and uplift regions, show a hi-

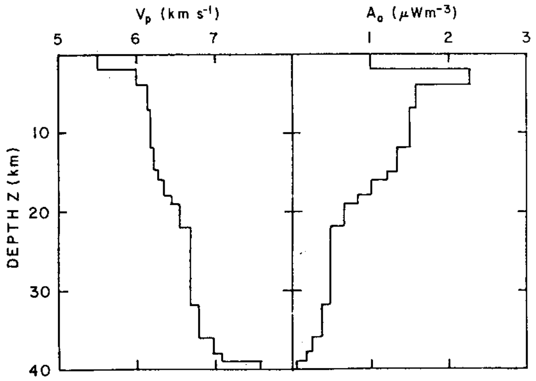

Fig. 2. Profiles for the crustal structure. (I); seismic velocity model $V_p(z)$, (II); heat generation model $A(z)$.

Table 3. Table for Making Corrections for Radioactivity from Seismic Velocity.

| $V_p$ (km/s) | A ($\mu$Wm$^{-3}$) | $V_p$ (km/s) | A ($\mu$Wm$^{-3}$) |
|---|---|---|---|
| 5.7 | 3.78 | 7.3 | 0.12 |
| 5.8 | 3.04 | 7.3 | 0.095 |
| 5.9 | 2.45 | 7.5 | 0.076 |
| 6.0 | 1.97 | 7.6 | 0.061 |
| 6.1 | 1.59 | 7.7 | 0.049 |
| 6.2 | 1.28 | 7.8 | 0.040 |
| 6.3 | 1.03 | 7.9 | 0.032 |
| 6.4 | 0.83 | 8.0 | 0.026 |
| 6.5 | 0.67 | 8.1 | 0.021 |
| 6.6 | 0.54 | 8.2 | 0.017 |
| 6.7 | 0.43 | 8.3 | 0.013 |
| 6.8 | 0.35 | 8.4 | 0.010 |
| 6.9 | 0.28 | 8.5 | 0.009 |
| 7.0 | 0.22 | | |
| 7.1 | 0.18 | | |
| 7.2 | 0.15 | | |

ghly variable and scattered distribution. The middle diagram in Fig. 3 shows that $q_{0\ \mathrm{resid}}$ for orogenic fold belts are scattered variably and clustered in high $q_{CR}$ and $q_{0\ \mathrm{resid}}$ sides. However, $q_{0\ \mathrm{resid}}$ for stable regions are clustered around 0 $q_{0\ \mathrm{resid}}$ with a $q_{CR}$ range of 30~40 mWm$^{-2}$. The rifted regions show a variation of $q_{0\ \mathrm{resid}}$.

A factor that can cause abnormal distribution of $q_{CR}$ and $q_{0\ \mathrm{resid}}$ is the large dispersal of an observed heat flow due to both the hydrothermal/magmatic and the crustal thinning/thickening processes in younger provinces. The bottom diagram shows a cluster of $q_{r\ \mathrm{resid}}$ around 0 $q_{r\ \mathrm{resid}}$ except in the Southern Indian Shield. The middle diagram gives the most important relationship. Fig. 4 confirms that no clear relationship exists between $q_0$ and $q_{CR}$.

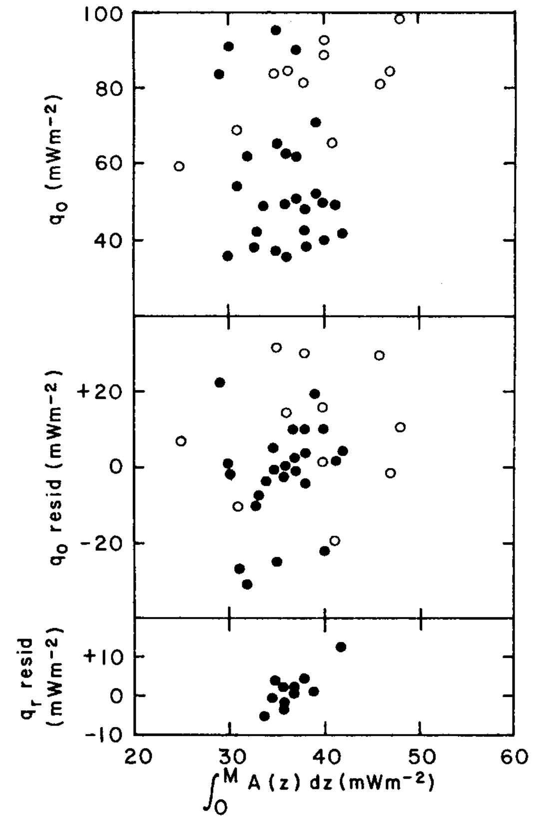

Fig. 3. Relationship between surface heat flow ($q_0$), residual heat flow ($q_{0\ \mathrm{resid}}$), residual reduced heat flow ($q_{r\ \mathrm{resid}}$), and radiogenic heat flow. Open circles represent uplife or fold belt regions, closed circles indicate rifted or stable regions.

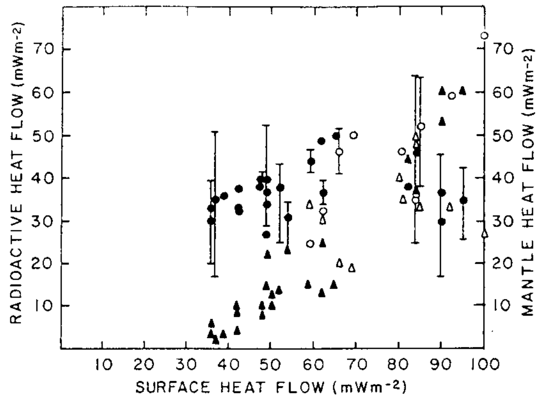

Fig. 4. Plot of heat flow ($q_0$) versus $q_{CR}$ for geologic provinces. Vertical bars indicate mean values and range. Geologic provinces are coded as follows : open circle; $q_{CR}$ in uplift or fold belt, closed circle; $q_{CR}$ in rifted or stable province.

## CRUSTAL THICKNESS

In order to achieve a global perspective on heat flow and seismic data, we selected crustal thickness data from Table 2.1 of Prodehl's worldwide seismic refraction co-

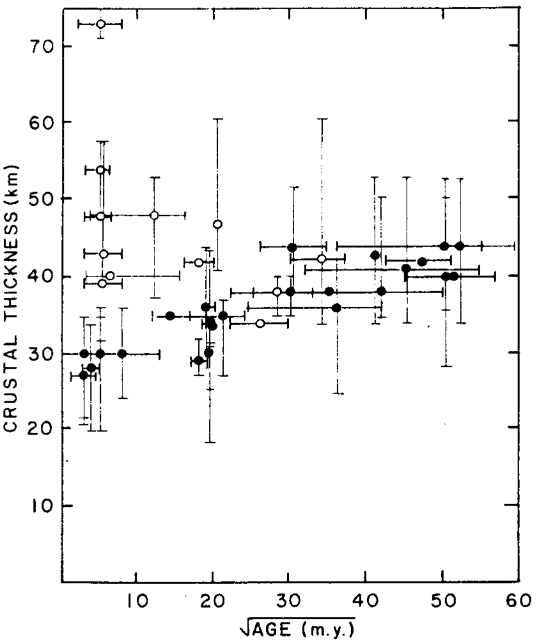

Fig. 5. Crustal thickness versus geologic age for geologic provinces. Horizontal bars indicate geologic age range. Vertical bars represent Moho depth range. Geologic provinces are coded as follows : open circles; uplift or orogenic fold belt, closed circles; rifted or stable provinces.

mpilation (Prodehl, 1984). Crustal thicknesses were chosen from 36 geologic provinces and represent a range of thickness from 18 km to 76 km.

Crustal thickness is plotted against the age of geologic province in Fig. 5. Horizontal bars indicate the age range while the vertical bars represent the Moho depth range. Open circles show folded mountain belts while the closed circles indicate rifted or stable regions.

The large crustal thickness variability in provinces of young age results from two distinct populations: folded mountain belts and rifted regions. This large variability in crustal thickness decreases with increasing age of geologic province. In folded mountain belts, the thickened crust thins as time progresses through uplift and erosion, while in thin rifted crust, thickening can occur through subsequent subsidence with sedimentation, and with magmatic underplating. Provinces older than 500 My show a crustal thickness range of 35~40 km indicating an equilibrium envelope with increasing age.

The relationship between surface heat flow and crustal thickness is shown in Fig. 6. Surface heat flow is variable in the case of fold belts and uplift regions, reflecting the important role that tectonic activity can play. In rifted or stable provinces, high surface heat flow tends to be found in provinces of thin crust while low surface heat flow usually indicates a province with a thick crust.

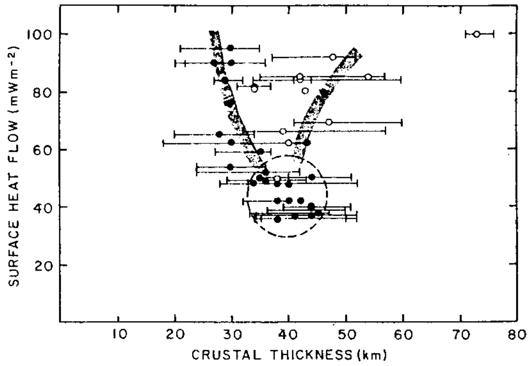

Fig. 6. Heat flow ($q_0$) versus crustal thickness (M) for geologic provinces. Horizonal bars show the range of crustal thickness.

In contrast to Cermak's (1982) analysis which has proposed a simple and causal relationship between heat flow and crustal thickness, this analysis (Fig. 6) provides an explanation for observed correlations where both crustal thickness and heat flow respond to dynamic geologic processes accompanying and following rifting and orogeny. One can demonstrate that the maximum variability in crustal thickness coincides with the youngest geological provinces such as the Alps and Andes Altiplano. Crustal thickening occurs during collision orogeny or in Andean type arc complexes; crustal thinning occurs predominantly by rifting.

The thermal state of all these types of young provinces is generally characterized by high heat flow, up to about 90 mWm$^{-2}$. With the progression of time, isostatic processes operate to thin the thickened crust through uplift and erosion and thicken the rifted crust through subsidence and sedimentation. This crustal thickness for old geologic terrains varies only between 35 and 45 km. Thermal processes accompanying the dynamic crustal processes return the perturbed thermal state to an equilibrium thermal state (characterized by heat flow of 35 ~50 mWm$^{-2}$) along characteristic paths which provide one explanation for the pattern of heat flow-crustal thickness data.

## Pn VELOCITY

A second measurable parameter used to characterize continental crust and upper mantle is the uppermost mantle compression wave velocity $V_{Pn}$. For this analysis, we have used the $V_{Pn}$ and crustal thickness data tabulated by Prodehl (1984), and added our compilation of heat

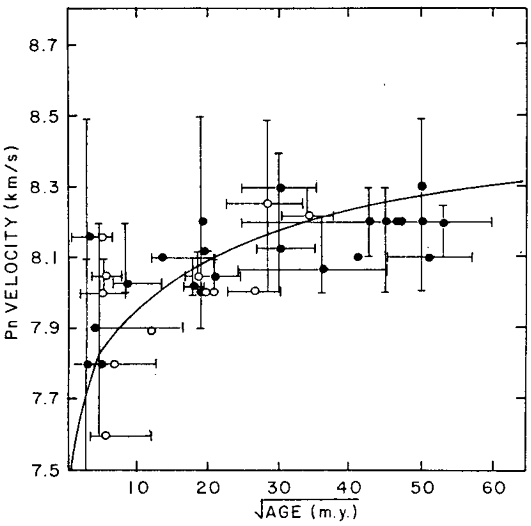

Fig. 7. Relation between Pn velocity ($V_{Pn}$) and age. Vertical bars show mean $V_{Pn}$ and $V_{Pn}$ range. Horizontal bars indicate representative age and age range.

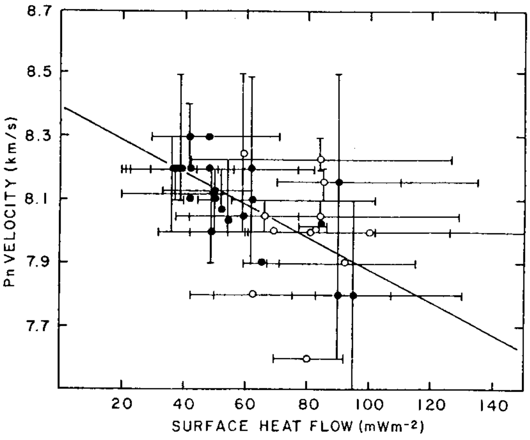

Fig. 8. Relation between Pn velocity ($V_{Pn}$) and heat flow ($q_0$). Horizontal bars indicate mean $V_{Pn}$ and $V_{Pn}$ range. Vertical bars show mean heat flow and heat flow range. Geologic provinces are coded as follows : open circle; uplift or fold belt, closed circle; rifted or stable province.

flow and age for selected geologic provinces.

Upper mantle Pn velocities are plotted against crustal age in Fig. 7. Pn velocities depends on crustal thickness and vary from 7.6 km $s^{-1}$ to 8.3 km $s^{-1}$. The average crustal thickness for the geologic province is calculated from the seismic data. Minimum values of Pn velocity, about 7.6 km $s^{-1}$, occur in young rift provinces. Velocity increases steadily with increasing age back to Early Paleozoic provinces (Fig. 7) consistent with the time scale of heat flow variations noted earlier.

The relation of surface heat flow to Pn velocity is shown in Fig. 8. The data points from orogenic fold belts or uplift regions are scattered because of tectonic activity. The relationship of surface heat flow ($q_0$) to Pn velocity is evaluated by the least-squares linear regression. When we exclude the orogenic fold belt or uplift regions and Sierra Nevada, the relationship of surface heat flow ($q_0$) to Pn velocity for 23 locations is as follows :

$$V_{Pn}=8.39-0.0052\,q_0 \qquad (5)$$

with a correlation coefficient of $\gamma=-0.70$.

This study confirms and extends the results of Black and Braile (1982), showing that Pn velocities are negatively correlated with surface heat flow. If this relationship is caused by thermal effects alone, then the Pn velocity variations can be used to evaluate thermal evolution of the continental lithosphere, there few or no heat flow measurements exist.

The inverse relationship between Pn velocity and surface heat flow shown in Fig. 8 is consistent with laboratory results whereby seismic velocities are decreased by increasing the temperature of the sample. A field test under in situ Moho conditions is possible with an extension of $V_{Pn}$, heat flow, and crustal thickness data. By using geotherms constrained primarily by surface heat flow values (Pollack and Chapman, 1977) to estimate Moho temperature, and adjusting $V_{Pn}$ to compensate for pressure effects of variable thickness crusts, $V_{Pn}$ can be compared directly with temperature. Such a comparison made by Black and Braile (1982) yield a velocity derivative with temperature of :

$$\frac{\partial V_{Pn}}{\partial T}=(-4.4\sim-8.1)\times10^{-4}\,\mathrm{km\ s^{-1}\ K^{-1}} \qquad (6)$$

The similarity between this result and laboratory experiments confirms that the trends seen in Figs. 7 and 8 have a thermal origin.

## DISCUSSION

There is bound to be a certain amount of subjectivity involved in the process both of age assignment and of calculation of mean heat flow due to the decisions by the investigators about how many samples will be studied or how broad an age range should be assigned to given provinces. This study has been hampered by limited and geographically uneven data, gathered in only several tectonic provinces.

Extension regions such as the Basin and Range, Tuscany, and the Pannonian Basin show crustal extension due to lithospheric thinning above asthenospheric diapirism (Morgan and Baker, 1983). In general, an elevated temperature can be expected to result from crustal thinning in the extension region. As shown in Tables 2 and 3, high heat flow occurs usually in thin crust.

Continental collisions indicate generally high heat flow and a gradational trend of seismic P-wave velocity due to both the complex dips of layers and a well-developed LVZ. Our analysis of Prodehl's seismic profile (1984) is the basis of our opinion. Cermak and Hurtig (1977) and Cermak (1979) conclude that the high heat flow in the Alps is due to the effects of erosion. However, this use of erosional effects to explain heat flow and heat flow provinces should be reconsidered, even though England and Richardson (1977, 1980) have espoused its validity. Uplift regions such as the periphery of the Colorado Plateau, the Southern Rocky Mountains, the Alps, and Hopei-Shantung respond to surface heat flow and extensional features. A variety of geologic and tectonic influences are at work. Heat flow in any uplift region or orogenic fold belt is both geologic/tectonic process dependent and time dependent.

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# 잔여 지열류량과 대륙지각의 특성

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**요 약**: 지각의 두께에 따른 지열류량을 표시한 그림에서 나타나는 산만성은 다른 두개의 구조구를 전제하고 지구 동력학적 과정과 열적 감쇠현상을 적용하면 설명이 분명하게 된다. 높은 지열류량은 지각이 가늘게 확장되어 얇아진 열곡지역뿐만 아니라 트러스트 구조작용으로 지각이 두껍게 되고 지각의 열생산이 많은 조산대 지역의 특징이다. 지질학적 시간이 경과함에 따라서 지각평형작용에 의해 두꺼운 지각은 융기와 침식작용으로 얇게 되며 얇은 지각은 침강과 퇴적작용으로 두껍게 된다. 지열류량은 배경의 맨틀 지열류량과 평형을 이루는 값까지 감소하게 된다.