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The Paradox of Equivalence of the Davisian End-Peneplain and Penckian Primary Peneplain

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Abstract. The Davisian model elucidates landscape development through an orogeny by denudation processes, postulating prolonged still-stand of a landmass following rapid tectonic uplift, ultimately resulting in a peneplain. The Penckian model emphasizes that landscape is shaped by concurrent tectonics and denudation, and includes the primary peneplain as an antithesis against the Davisian end-peneplain by assuming a steady state between tectonic uplift and denudation from the beginning of orogenesis. Every ordinary landscape development through an orogeny has been expected to follow a course located between the two distinctive courses of landscape development. On the basis of the relationships between mountain altitude, local relief and denudation rate observed in Japan, denudation rate increases with local relief and the local relief increases with mountain altitude. A mountain range is considerably denuded even during the uplift phase. As denudation rate approaches tectonic uplift rate with an increase in mountain altitude by tectonic uplift, a steady state between denudation and uplift appears, and the mountain range attains a critical altitude that remains constant, in spite of continuous tectonic uplift. If tectonic uplift ceases, the mountain range is lowered by denudation, resulting in a subdued low relief landscape, ultimately a peneplain. The primary peneplain requires a low uplift rate to keep a balance with the low denudation rate due to its low altitude. Based on the observed data in Japan whose denudation rates are among the highest class in the world, the tectonic uplift rate must be 0.05 mm/yr or lower for a mountain range with an altitude of 100 m above sea level to maintain its low altitude. This low uplift rate should be classified not as an orogenic crustal movement but as crustal stability. Thus, the Penckian primary peneplain must be an irrelevance. A low relief landscape recognized as a primary peneplain must be formed originally as a Davisian end-peneplain. The sequence of ordinary landscape development is outside the two courses of the Davisian and Penckian models.

Keywords: Uplift, Denudation, Orogeny, Peneplain, Davisian Model, Penckian Model

INTRODUCTION

Two basic, classic and famous models of landscape development have greatly influenced and promoted modern macroscale geomorphology. One is the Davisian model (Davis, 1899) and the other is the Penckian model (Penck, 1924). One of the most important results of the models is the illustration of sequential changes in landscape during an orogeny, as expressed by Davis (1899); initial form, youth, maturity, old age, and peneplain. The sequential changes in landscape are extremely different between the two, resulting from remarkably different geomorphic processes associated with tectonic uplift and denudation. Each of them, however, produced the most basic sequence. It was necessary, therefore, for most of the textbooks of geomorphology to make reference to the two models for describing macroscale landscape development, including many arguments about the geomorphic processes in the models, and proposing many models modifying, rectifying and extending them (e.g. Geikie, 1913; Tsujimura, 1922; Cotton, 1922, 1942; Lobeck, 1939; Worcester, 1939, 1949; Inoue *et al.*, 1940: Thornbury, 1954; Maull, 1958; Sheidegger, 1961; King, 1962; Chorley *et al.*, 1964; Tricart, 1965; Chorley, 1965; Chorley *et al.*, 1973; Twidale, 1976; Büdel, 1977; Bloom, 1978, 1991; Louis and Fischer, 1979; Chorley *et al.*, 1984; Summerfield, 1991, 2000; Beaumont *et al.*, 2000; Hovius, 2000).

One of the most significant differences between the two models is the position of a peneplain in the sequence of landscape development, that is, the end-peneplain of the Davisian model and the primary peneplain of the Penckian model. The two peneplains are located at opposite ends of the sequence. Is the difference, however, a true difference? Textbooks of geomorphology have consumed many pages to argue the problems included in the "Geographical Cycle", especially the rapid uplift without serious denudation postulated in the Davisian model, or to examine practical applications of the "Morphological Analysis", especially the steady state of the Penckian model. The difference seems to have been accepted as a natural result coming from the different models. The question; "Is the difference physically true or not true?", however, must be a basic and conceptual problem in the geomorphology of macroscale landscape development (Ohmori, 2001a).

This paper first introduces some problems of the Davisian and Penckian models, and then provides estimates of denudation rates observed in Japan. The relationship between denudation rate and local relief is then assessed, and the change in mountain altitude resulting from concurrent tectonics and denudation is modelled. Finally the paper discusses the relationship between the Davisian end-peneplain and the Penckian primary peneplain on the basis of the concurrent tectonics and denudation model.

THE DAVISIAN AND PENCKIAN MODELS

Landscape changes at any time with changes in physical condition of the forces working on and in an area. The activities of the forces, in turn, are controlled under dynamic relationships between tectonics, denudation process and the landscape itself. An essential problem of present-day geomorphology must be to deduce the temporal changes in landscape; not only the temporary changes during a relatively short time but also the sequential changes during an orogeny. In particular, it is desirable for a conceptual model of landscape development to illustrate a general sequence of landscape changes during an orogeny as a basis for understanding the landscape and its nature. It seems as if we want to know not about the histories of individual persons, but about the

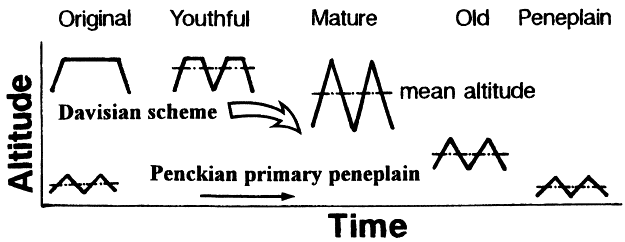

Fig. 1. Two courses of landscape development in orogenesis inferred from the Davisian scheme and Penckian model. Stages are referred to the Davisian scheme (Ohmori, 2001b).

generalized sequential changes in the life of a human being without interruptions by accidental events, as a basis for understanding the human being and our lives.

There have been many arguments against the Davisian model and Davis himself made additional explanations of his model (Davis, 1901, 1905, 1909, 1912, 1922, 1923, 1926, 1932, etc.). When a model, however, has once been proposed, it becomes relatively independent of the person who proposed it, even if the person has other ideas about it. The "interruption", "episode" and "event" may be caused by temporary actions of tectonics and denudation and must occur more or less in most mountain ranges. These are, however, side issues for the essential sequence of landscape development. The elementary framework of a model must represent the most basic concept and should be a target for discussing and examining the problems included in the model.

In terms of summarizing the landscape changes in drainage basins by the denudation processes discussed by Powell (1875), Gilbert (1877), Davis (1889, 1890) and others, the Geographical Cycle (or the Cycle of Erosion) model was proposed by Davis (1899) in a scientific journal. It was the first systematic introduction of a genetic model of landscape development into geomorphology. In the basic scheme of the Davisian model of the Ideal Geographical Cycle, the original surface is rapidly uplifted without serious denudation (Fig. 1; Ohmori, 1993, 2001b). The mountain range is therefore uplifted to the highest position at first. Then the mountain range continuously decreases in altitude by the ensuing denudation. Local relief, however, is significantly low at first. In particular, when the uplifted initial landform is assumed to be a peneplain or a flat surface emerged from the sea, the local relief is the lowest of any in the sequence of landscape development. Local relief increases with progressive dissection during the youthful and mature stages. It is not until the mountain range has passed full maturity that local relief starts decreasing. After full maturity, local relief decreases together with altitude. The mountain range is lowered by prolonged denudation, it approaches base level, and finally results in a low relief landscape. This low relief denudational landscape is a peneplain (Fig. 1). The peneplain as a technical term was proposed by Davis (1889) for the first time, and was later called the "end-peneplain (Endrumpf)" by Penck (1924).

The Penckian model emphasizes that change in surface altitude is controlled under the relationship between tectonic uplift rate and denudation rate. The difference between the two rates determines the direction (up or down) and rate of change in altitude. On the basis of the Penckian model, when denudation rate is equal to tectonic uplift rate, altitude does not change. This is a steady state between tectonic uplift and denudation. When the steady state appears and continues from the beginning of orogenesis, a region which is expected to be a mountain range can not increase in altitude, and a low relief landscape should be maintainable through the orogenic period. This low relief denudational landscape is the primary peneplain (Primärrumpf) (Fig. 1). The sequence of landscape development resulting from the steady-state process was proposed by Penck (1924) as an extreme case against the other extreme case of the Davisian scheme. The primary peneplain, therefore, is an antithetic landscape to the end-peneplain.

As introduced above, the two models have deduced two different sequences of macroscale landscape development following the first set of initial landforms. The changes in landscape were described in terms of altitude and local relief. The end-peneplain and primary peneplain are both a low altitude and low relief landscape, resulting from denudation processes, but with different relations to tectonic uplift. Their courses in the sequence of landscape development are poles apart; an up at first and slowly down curve in the Davisian model and a low horizontal line in the Penckian model (Fig. 1). Every ordinary landscape development resulting from concurrent tectonics and denudation has been expected to follow a course between the two. A mountain range is uplifted to some altitude through a course between the two, then decreases in altitude, and is finally reduced to peneplain. How does the local relief, however, change with change in altitude through this course? What relationship is observed between altitude and local relief through a mountain building? Do all sequences of landscape development resulting from concurrent tectonics and denudation truly follow a course between the two?

Now, the Penckian model is mathematically expressed by the following equation:

$$\frac{\partial H}{\partial t} = -\varepsilon\left(\frac{\partial H}{\partial x}\right) \tag{1}$$

where H is the altitude, x is the horizontal distance, t is the time and ε is a constant. The term $\partial H/\partial x$ indicates surface gradient, and therefore, Eq. (1) means that denudation rate is proportional to surface gradient. It implies that denudation rate is zero when the surface is flat. On the basis of Eq. (1), therefore, the denudation rate working on the primary peneplain must be low throughout an orogeny. Nevertheless, the primary peneplain requires a denudation rate equal to the tectonic uplift rate in the orogenesis to keep it at low altitude.

Here, a question is raised. Is it physically possible that a low relief landscape such as peneplain has a denudation rate to keep a balance with the tectonic uplift rate expected for orogenesis? What relationship can be induced between local relief and denudation rate in macroscale landscapes on the earth? Is the primary peneplain actually able to exist on the earth? This question was suggested by Ohmori (1978) and clearly emphasized by Yoshikawa (1985b, p. 102–103) on the basis of the quantitative relationships between tectonics, denudation, and morphometric attributes in Japan. Two questions will be examined on the basis of the data observed in Japan; what relationships are there between denudation rate, local relief, and altitude, and how does local relief change through an orogeny?

DENUDATION RATES IN RELATION TO LOCAL RELIEF IN JAPAN

Present-day denudation rates for macroscale landscape in Japan have been estimated mainly based on the sediment delivery rates to reservoirs (Tanaka and Ishigai, 1951; Tanaka, 1955; Namba and Kawaguchi, 1965; Ishigai, 1966; Yoshikawa, 1974; Ohmori, 1978, 1983b, 1983c; Mizutani, 1981; Tanaka, 1982; Fujiwara *et al.*, 1999, 2001). In contrast to variations in temporary denudation rate due to individual landslides and floods, denudation rates calculated from total sediment supply for reasonably long periods show stable values for individual drainage basins of reservoirs (Yoshikawa, 1974; Ohmori, 1978, 1983b, 1983c, 2000; Fujiwara *et al.*, 1999, 2001). In Japan, there are 116 reservoirs each of which has a drainage basin area larger than 20 km^2 together with a data set of annual sedimentation rate. For estimating the denudation rates in drainage basins, 82 reservoirs were selected among the 116 reservoirs (Fujiwara *et al.*, 1999, 2001; Ohmori, 2001a). Each satisfies the criteria of sedimentation such as sediment volume over 50,000 m^3, water storage capacity over 2,000,000 m^3, sedimentation ratio to water storage capacity less than 25%, and observation duration longer than 10 years. Trap efficiency of sediment in the reservoir satisfying the criteria is estimated to be more than 90% (Ezaki, 1966; Ashida, 1971). Most of them are the upper-most ones in a sequence of reservoirs through individual rivers. The mean observation duration is about 30 years, with a longest duration of 66 years, including many typhoons and a number of heavy rainfall events.

The denudation rate E in the drainage basin of reservoir is given by:

$$E = \frac{1}{S}\left(\frac{V}{T}\right)\left(\frac{\rho}{\sigma}\right) \tag{2}$$

where V is the total sediment volume in each reservoir, T is the observation duration, ρ is the mean sediment density, σ is the crustal density, and S is the drainage basin area. The values of ρ and σ are assumed to be 1,750 kg/m^3 and 2,500 kg/m^3, respectively. Denudation rates in drainage basins of the 82 reservoirs are shown in Fig. 2 (Ohmori, 2001a). They show values ranging from 0.06 to 7.04 mm/yr (Fujiwara *et al.*, 1999, 2001; Ohmori, 2001a).

A conspicuous characteristic of the distribution of denudation rates is a marked difference between drainage basins even in the same district. For some

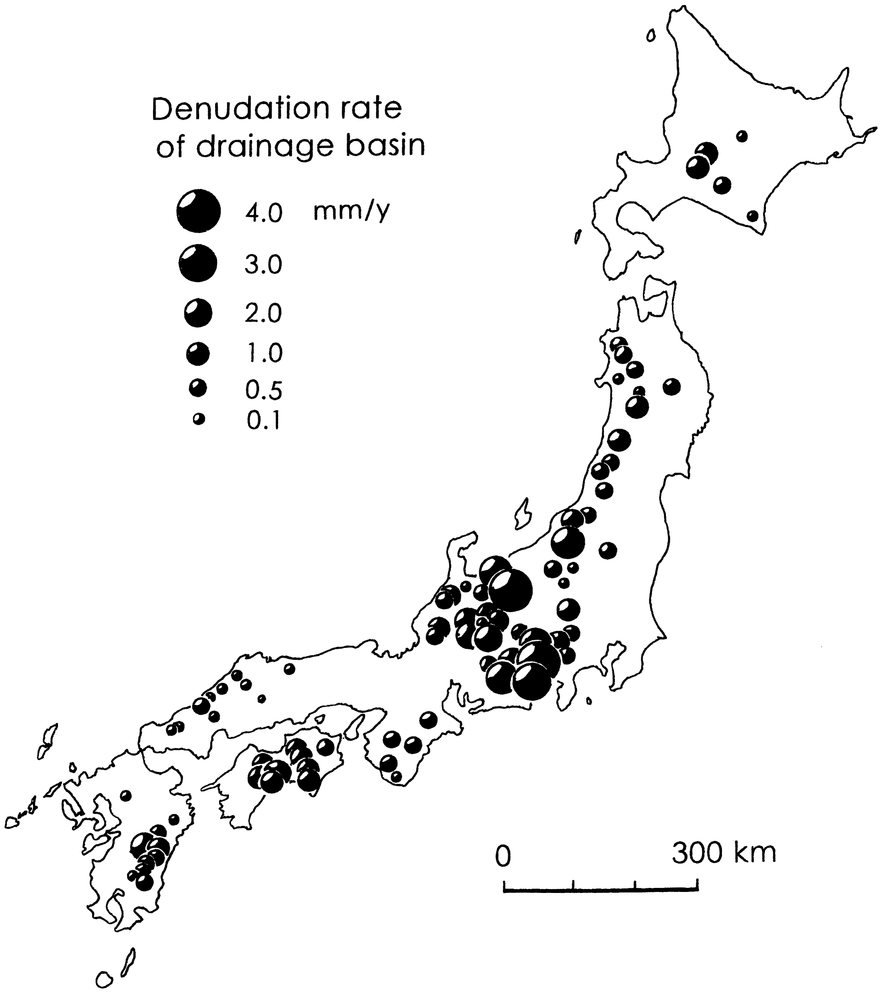

Fig. 2. Denudation rates in drainage basins of reservoirs in Japan. The rate indicates the value calculated by dividing the total sediment volume accumulated in a reservoir by the area of drainage basin of the reservoir and by the observation duration (Ohmori, 2001a).

mountain ranges, the highest rate is ten times or higher than the lowest one. Such local variations in denudation rate depend predominantly not on local differences in precipitation and rock type but on local differences in local relief as examined below.

The dispersion of altitude (altitude dispersion) D is defined as the standard deviation of the frequency distribution of surface altitude in a unit area of specific size (Ohmori, 1978):

$$D = \left[\frac{\sum_{i=1}^{n} (h_i - H)^2}{n-1} \right]^{1/2} \tag{3}$$

where h_i is the altitude of point i, n is the number of points in a unit area, and H is the mean altitude given by:

$$H = \frac{\sum_{i=1}^{n} h_i}{n} \tag{4}$$

The altitude dispersion is a measure of local relief (Evans, 1972; Ohmori, 1978; Ohmori and Hirano, 1984; Ohmori and Sugai, 1995). It is directly proportional to mean surface gradient (Ohmori, 1978; Ohmori and Sohma, 1983; Ohmori and Hirano, 1984) and indicates the dispersion of potential energy of the surface materials with a high relation to landslide occurrence (Ohmori and Sugai, 1995). In Japan, altitude dispersion in a certain unit area varies regionally, and in each region throughout Japan it increases with size of unit area at approximately the same rate (Ohmori, 1978). This indicates that the altitude dispersion in a unit area with any specific size can be used to describe regional characteristics of local relief in Japan. The altitude dispersion of a unit square with an area of 1 km^2 is called the "basic dispersion of altitude (basic altitude dispersion)".

The relationship between altitude dispersion and denudation rate has been expressed empirically by a power function for drainage basins larger than some tens of km^2 in Japan (Ohmori, 1978, 1982, 2001a; Fujiwara *et al.*, 1999, 2001). The "50 m DEM" published by Geographical Survey Institute of Japan is a data set of surface altitudes of lattice points in a grid system with horizontal intervals of about 50 m, 1.5″ (ca. 46 m) in latitude and 2.25″ (ca. 49–63 m) in longitude: it covered all of Japan by 2000. Using the 50 m DEM which has about 450 lattice points in each unit area of 1 km^2, basic altitude dispersion was calculated. The relationship between denudation rate E (mm/yr) and mean basic altitude dispersion D (m) of drainage basins of the 82 reservoirs is given by:

$$E = \alpha D^{\beta} \tag{5}$$

where α and β are constants. The correlation coefficient is 0.94, and $\alpha = 4.4 \times 10^{-5}$ and $\beta = 2.2$ for the best-fit function (Fig. 3; Fujiwara *et al.*, 1999, 2001; Ohmori, 2001a).

The relationships between denudation rate and rainfall condition in individual drainage basins of the 82 reservoirs are shown in Fig. 4 (Fujiwara *et al.*, 1999,

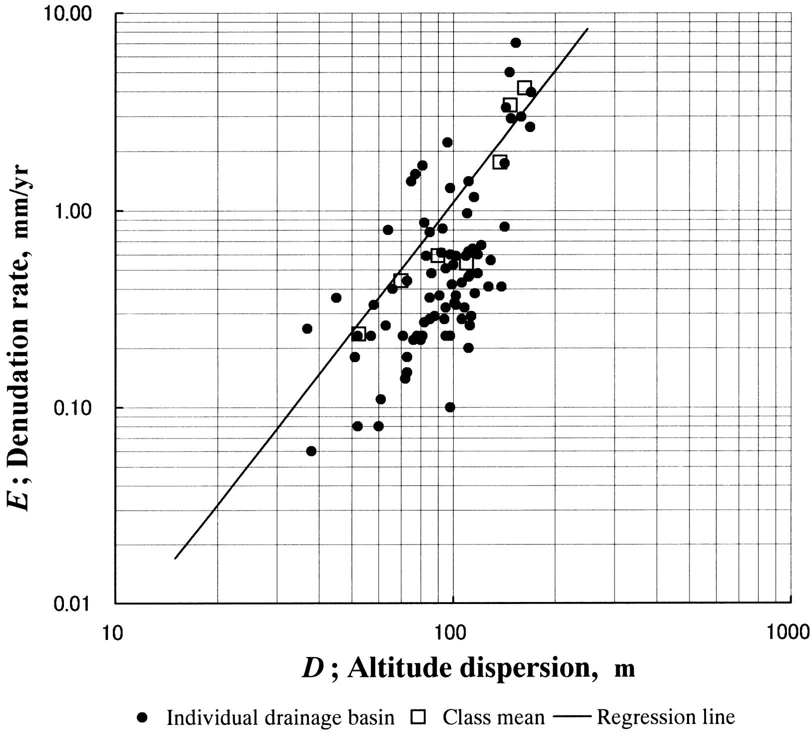

Fig. 3. Relationship between altitude dispersion and denudation rate for 82 selected reservoirs in Japan (Fujiwara *et al.*, 1999, 2001; Ohmori, 2001a). Closed circles are denudation rates for individual reservoirs, open squares show mean denudation rates for individual classes of altitude dispersion, and solid line indicates a non-biased regression line.

2001; Ohmori 2001a). In Fig. 4, open squares indicate the relationship between denudation rate and mean annual rainfall, and closed circles indicate the relationship between denudation rate and intense rainfall which is represented by the mean yearly total volume of individual rainfalls over 100 mm a day. Neither relationship shows any clear trend. Thus, concerning not the temporary denudation rate but the mean short-term denudation rate for some tens years, denudation rate does not have any strong relationships to rainfall conditions in Japan.

On the other hand, among the 82 drainage basins, 59 drainage basins, each of which has a dominant rock type occupying over 70% of the area of drainage basin, were selected for examining the effect of rock type on denudation. Rock types were classified into Cenozoic volcanic rocks, Neogene sedimentary rocks, Granitic rocks, Mesozoic-Palaeozoic sedimentary rocks, and Metamorphic rocks. Figure 5 shows the relationship between mean basic altitude dispersion and denudation rate by each rock type for the 59 drainage basins (Fujiwara *et al.*, 1999, 2001; Ohmori 2001a). Metamorphic rocks show a denudation rate a little

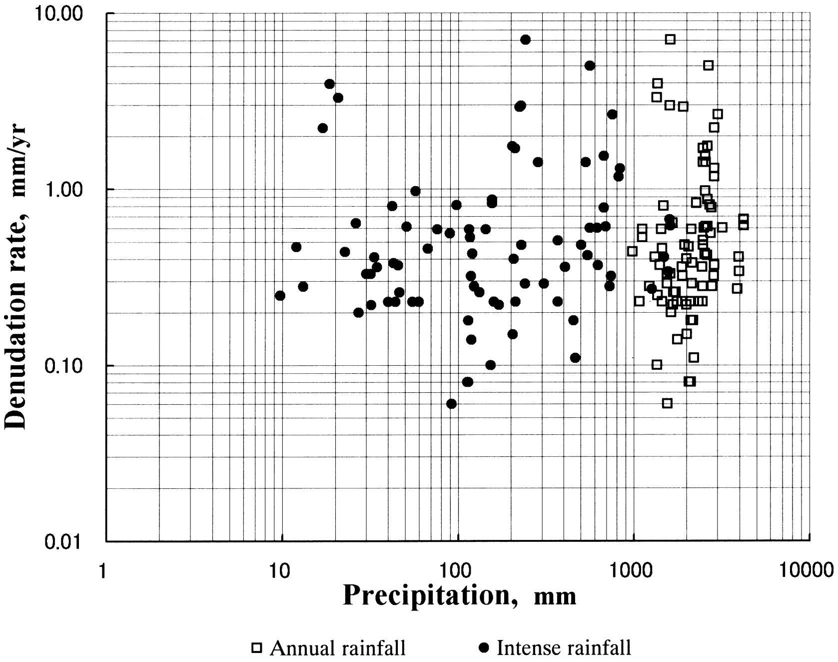

Fig. 4. Relationship between denudation rate and rainfall (Fujiwara *et al.*, 1999; Ohmori 2001a). Open squares indicate mean annual rainfall in drainage basins, and closed circles indicate the amount of intense rainfall (mean yearly total volume of individual rainfall over 100 mm a day).

higher than that of Granitic rocks for the same altitude dispersion. Remarkable differences in denudation rate, however, are not recognized among the rock types, and denudation rate increases with altitude dispersion at similar rates for all the rock types. The principal factor, therefore, causing local variations in denudation rate is judged to be the altitude dispersion, that is, the local relief (Ohmori, 1978, 1983a, 2001a; Tokunaga and Ohmori, 1989; Fujiwara *et al.*, 1999, 2001).

Using mean basic altitude dispersion over a whole mountain range, mean denudation rates of individual mountain ranges in Japan have been calculated from Eq. (5) (Fig. 6; Fujiwara *et al.*, 1999, 2001; Ohmori, 2001a). Numerals in Fig. 6 indicate the long-term denudation rates in drainage basins for ten thousands years or longer. They were estimated from the morphometric analysis of mountain slopes and/or volume of alluvial fans formed since the late Pleistocene including the Last Glacial Age (Iso *et al.*, 1980; Akojima, 1983; Nakano, 1989; Yoshinaga *et al.*, 1989; Oguchi, 1991; Yoshiyama and Yanagida, 1995). The mean short-term denudation rates estimated for mountain ranges correspond well with these, although it has been sometimes presumed that climatic changes might cause remarkable changes in denudation rate (e.g. Yoshikawa *et al.*, 1981; Yoshikawa, 1985a). Water flow, glacial and periglacial processes, rock weathering and vegetation coverage might be changed by climatic change. Some of them,

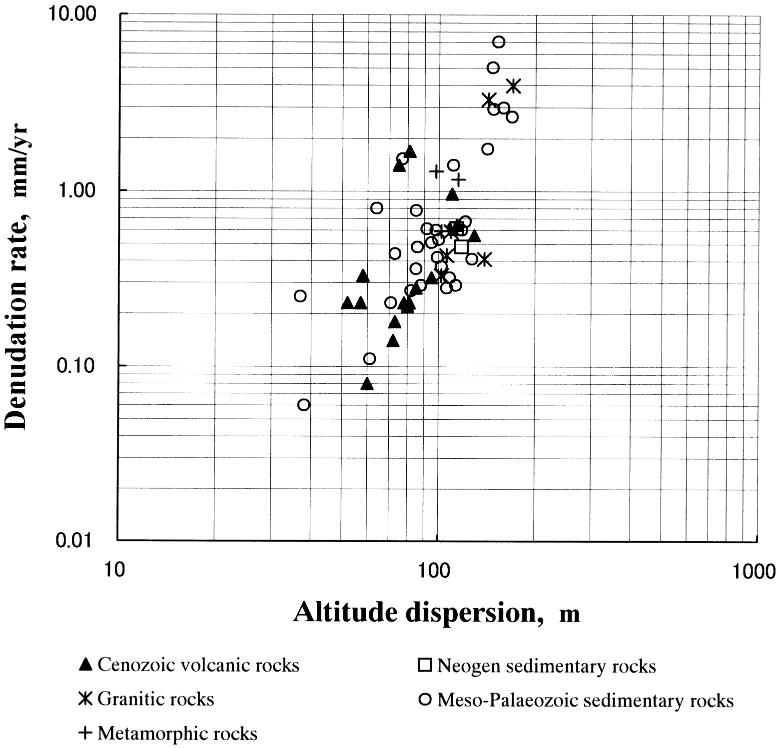

Fig. 5. Relationship between altitude dispersion and denudation rate for each rock type (Fujiwara *et al*., 1999; Ohmori 2001a). Drainage basins are categorized on the basis of a dominant rock type occupying over 70% of each drainage basin.

however, have positive responses to a climatic change, while others show negative responses. Thus, it is not easy to estimate how denudation rate changes with climatic change. The change in denudation rate with climatic change might be small due to complex responses of the agencies, and denudation rate might be maintained on an average in proportion to the magnitude of local relief in Japan.

The resulting variations in estimated denudation rate for individual mountain ranges show contrasts between morphotectonic terrains with different Quaternary vertical displacements (Fig. 7; Research Group for Quaternary Tectonic Map, 1968, 1969, 1973; Ohmori, 1978, 1995, 2000). The denudation rates are high in Central Japan, the outer belt of Southwest Japan and the inner belt of Northeast Japan, and low in the inner belt of Southwest Japan, the outer belt of Northeast Japan and the mainland of Hokkaido. In particular, values greater than 1.0 mm/yr are indicated for the central Japanese mountain ranges whose mean altitudes are about 1000 m above sea level with peaks of about 3000 m. These rates are almost equal to the mean Quaternary uplift rates of individual mountain ranges

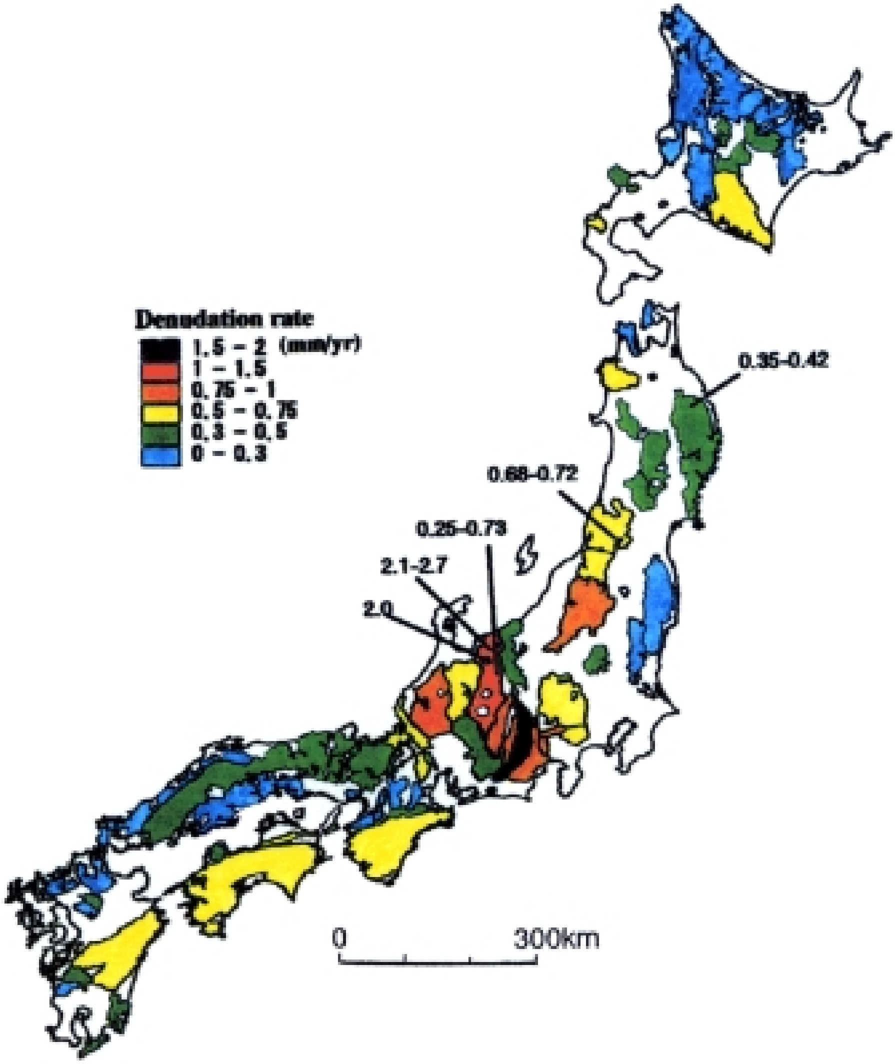

Fig. 6. Denudation rates in individual mountain ranges in Japan estimated from Eq. (5) (Fujiwara *et al*., 1999, 2001; Ohmori, 2001a). Numerals are the long-term denudation rates which were estimated from the morphometric analysis of mountain slopes and volume of alluvial fans formed since the late Pleistocene.

inferred from the Quaternary vertical displacements (Yoshikawa, 1974, 1985a, 1985b; Ohmori, 1978, 1987).

In detail, using the mean basic altitude dispersion, denudation rates were calculated from Eq. (5) for individual squares with an area of 36 km^2; 6 km (ca. 3′15″) in latitude by 6 km (ca. 3′35″–4′35″) in longitude, in Japan (Fig. 8,

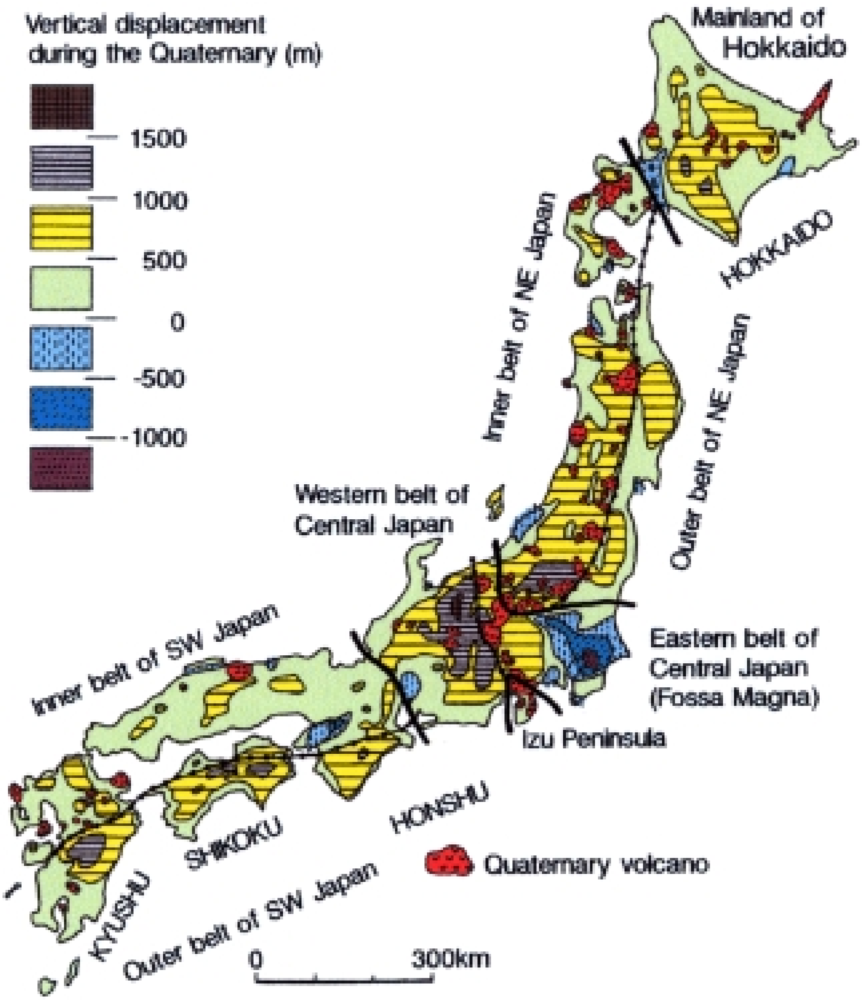

Fig. 7. Morphotectonic divisions of Japan and vertical displacement during the Quaternary (Ohmori, 2000, compiled from Okayama, 1953; Research Group for Quaternary Tectonic Map, 1968, 1969, 1973; Research Group for Active Faults, 1980; Yoshikawa *et al.*, 1981; Ohmori, 1995).

Fujiwara *et al.*, 1999, 2001). The estimated denudation rates are high in the central part with high peaks, and decrease outward with decreasing altitude in individual mountain ranges. The denudation rates are around 5.0 mm/yr for squares with peaks of about 3000 m above sea level, around 3.0 mm/yr for squares with peaks of about 2000 m, and around 1.0 mm/yr or less for squares with peaks of about 1000 m. These facts suggest that there are strong relationships between altitude, altitude dispersion, and denudation rate.

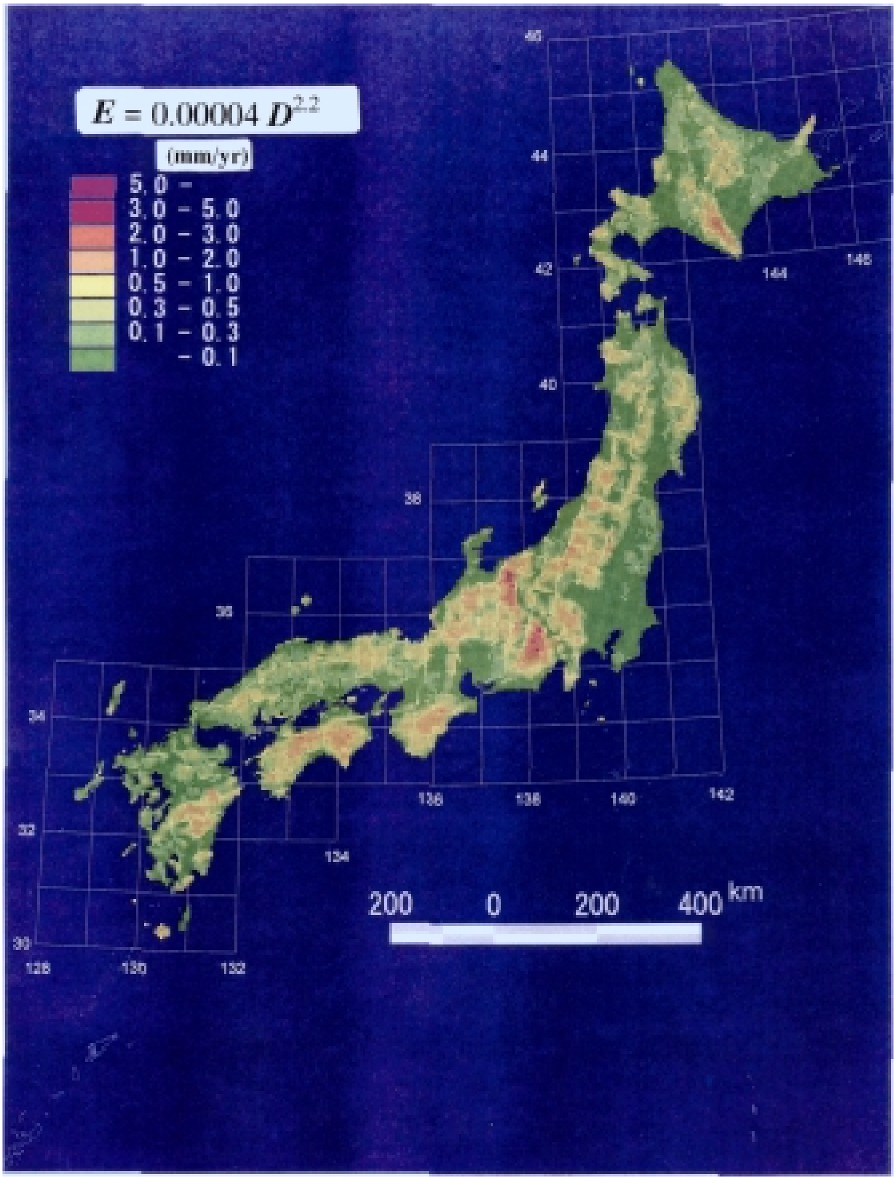

Fig. 8. Denudation rates in individual squares of 36 km^2 in Japan estimated from Eq. (4). Each square is 6 km (ca. 3′15″) in latitude by 6 km (ca. 3′35″–4′35″) in longitude (Ohmori *et al*., 1999).

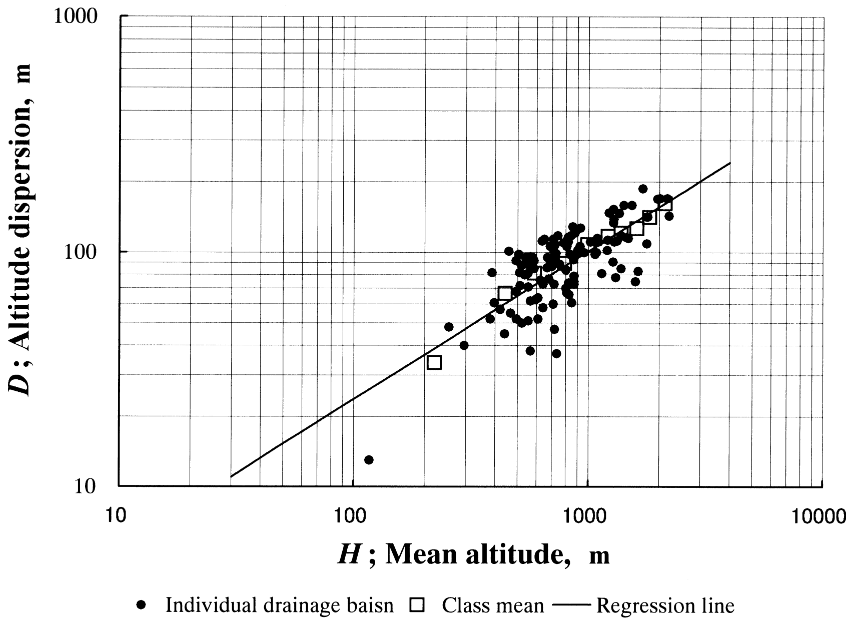

Fig. 9. Relationship between mean altitude and mean altitude dispersion for drainage basins of 116 reservoirs with an area larger than 20 km^2 (Ohmori, 2001a).

LANDSCAPE DEVELOPMENT RESULTING FROM CONCURRENT TECTONICS AND DENUDATION

1. Relationships between altitude, altitude dispersion, and denudation rate

For the Japanese mountain ranges, the relationship between altitude H (m) and altitude dispersion D (m) is expressed by a power function with high correlation:

$$D = aH^b \tag{6a}$$

where a and b are constants (Ohmori, 1978, 1982, 1983b; Ohmori and Hirano, 1984; Tokunaga and Ohmori, 1989; Oguchi, 1991; Sugai *et al.*, 1994; Ohmori and Sugai, 1995; Fujiwara *et al.*, 1999, 2001). Using mean altitude and mean basic altitude dispersion in drainage basins of the 116 reservoirs in Japan with precise geomorphometric data sets, Eq. (6a) has shown $a = 1.300$ and $b = 0.63$ for the best-fit function with a correlation coefficient of 0.89 (Fig. 9; Ohmori, 2001a).

Here, by differentiating Eq. (6a) by H, we have:

$$\frac{\partial D}{\partial H} = baH^{b-1} \tag{6b}$$

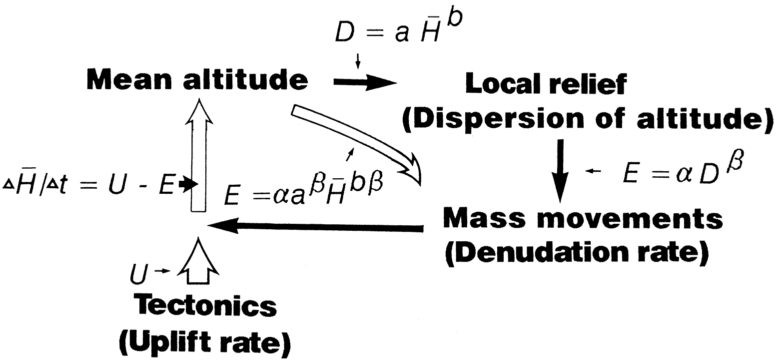

Fig. 10. Schematic relations between uplift rate, morphometry (altitude and local relief) and denudation (Ohmori, 2000)

Equation (6b) can be transformed by transposing after dividing both sides by *D*:

$$\frac{\partial D}{D} - b\left(\frac{\partial H}{H}\right) = 0 \tag{6c}$$

Equation (6c) is an expression showing a quasistatic process, implying that when *H* is changed by tectonics and denudation, *D* changes with *H* satisfying a dynamic equilibrium state between *H* and *D* (Ohmori, 1984, 1985; Ohmori and Hirano, 1984). It indicates mathematically that the ratio of change in altitude dispersion is proportional to about 63% of that in mean altitude. For example, when a mountain range increases in mean altitude from 500 m to 550 m above sea level, basic altitude dispersion increases from about 65 m to 69 m. The increment ratio in altitude dispersion is 6%. It corresponds to 63% of the increment ratio in mean altitude, that is, 10%. It indicates that for intensely denuded regions, local relief changes functionally in relation to the change in altitude.

Now, by coupling Eqs. (5) with (6a), denudation rate is also expressed by a power function of altitude. Substituting Eq. (6a) into Eq. (5) yields the equation:

$$E = \alpha\left(aH^{b}\right)^{\beta} = \gamma H^{\delta} \tag{7}$$

where $\gamma\,(=\alpha a^{\beta})$ is 7.8×10^{-5} and $\delta\,(=b\beta)$ is 1.39 when *E* and *H* are expressed in mm/yr and m, respectively. Regression analysis between denudation rate and altitude directly calculated from the observed data for the 82 reservoirs has shown $\gamma = 9.7 \times 10^{-5}$ and $\delta = 1.32$ with a correlation coefficient of 0.83, indicating that Eq. (7) is a reasonable result (Ohmori, 2001a). On the basis of Eq. (7), the denudation rate is only 0.047 mm/yr for a mean altitude of 100 m, 1.15 mm/yr for a mean altitude of 1000 m, and 5.31 mm/yr for a mean altitude of 3000 m. Indeed, landslides which are the dominant denudation process in the Japanese mountain ranges are very rare at lower altitudes and increase in volume with altitude dispersion which, in turn, is functionally related to altitude (Sugai *et al.*, 1994; Ohmori and Sugai, 1995).

The relationships between tectonic uplift rate, denudation rate, altitude and local relief (altitude dispersion) expressed by Eqs. (5), (6a) and (7) are illustrated in Fig. 10. Rate of increase in altitude is determined by subtracting denudation rate E from tectonic uplift rate U. Denudation rate is controlled by local relief, and local relief is controlled by mountain altitude. The mountain altitude, in turn, is determined by the difference between tectonic uplift rate and denudation rate. A feedback system is therefore recognized between tectonics, denudation and morphometric attributes (altitude and local relief), although the tectonic movements associated with plate motion may be relatively independent of the other factors in Japan (Ohmori, 2000).

2. Changes in altitude and local relief resulting from concurrent tectonics and denudation

Sequential changes in altitude resulting from concurrent tectonic uplift and denudation have been discussed on the basis of Eq. (7) (Ohmori, 1978, 1983a, 1984, 1985, 1993, 2000; Yoshikawa, 1984, 1985a, 1985b). Values of coefficients of Eqs. (5), (6a) and (7) presented in this paper differ from those of Ohmori (1978). The function types and results of simulation, however, are not seriously different. Using the new values of the coefficients of Eq. (7), landscape development is discussed in this paper.

Temporal change in altitude is controlled by the difference between tectonic uplift rate and denudation rate. It is expressed by:

$$\frac{\partial H}{\partial t} = U - E \tag{8}$$

From Eq. (8), the time necessary for mean altitude to increase from h_1 to h_2 is given by:

$$t = \int_{h_1}^{h_2} \frac{1}{U - E} dH \tag{9}$$

By substituting Eq. (7) into Eq. (9):

$$t = \int_{h_1}^{h_2} \frac{1}{U - \gamma H^{\delta}} dH \tag{10}$$

where the measurement units of U, H and t are mm/yr, m, and year, respectively.

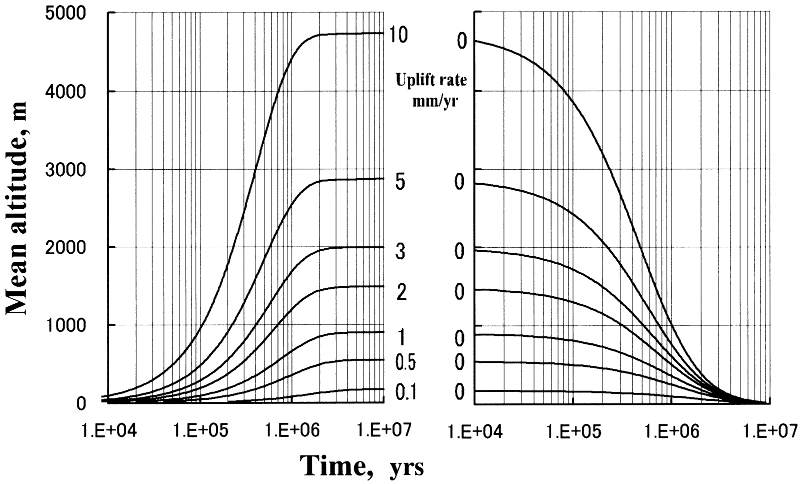

Fig. 11. Changes in mean altitude resulting from concurrent tectonics and denudation from an initial altitude at sea level.

Though the model does not require a constant uplift rate, assuming that the tectonic uplift rate is constant, and that the presently observed relationship between denudation rate and altitude dispersion is valid over time, the change in mean altitude can be simulated as a simplest case (Fig. 11). Using Eq. (6a), local relief can also be estimated for any mean altitude. The resulting landscape development can be divided into developing, culminating and declining stages (Ohmori, 1978, 1985, 1993, 2000; Yoshikawa *et al.*, 1981; Yoshikawa, 1984, 1985a, 1985b).

In the developing stage, the mean altitude of a mountain range increases due to the tectonic uplift rate exceeding the denudation rate. Denudation rate increases with mean altitude, as altitude dispersion becomes greater. As it approaches the tectonic uplift rate, rate of increase in mean altitude is progressively slower. When the denudation rate catches up with the tectonic uplift rate, a steady state appears, and the mountain range enters the culminating stage. The culminating stage indicates that a time-independent landscape is maintained in dynamic equilibrium between tectonic uplift and denudation. Mean altitude attains a critical altitude and then remains constant, in spite of continuous tectonic uplift. Altitude dispersion also reaches a maximum and keeps a constant sediment yield. Parallel retreat of slope is a dominant process maintaining the landscape (Ohmori, 1983a, 1984), resulting in accordance of summit level, which may correspond to the "oberes Denudationsniveau" of Penck (1894, 1919) (Ohmori, 1978, 1985, 2000; Yoshikawa *et al.*, 1981; Yoshikawa, 1984, 1985a, 1985b). The critical altitude H_c (m) is uniquely determined by tectonic uplift rate, and given by:

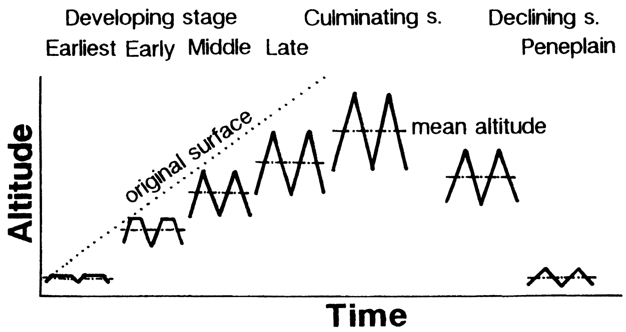

Fig. 12. Landscape development in orogenesis resulting from concurrent tectonics and denudation (Ohmori, 1985, 2001b).

$$H_c = \left(\frac{U}{\gamma}\right)^{1/\delta} \quad (11)$$

For example, when the tectonic uplift rate is 1 mm/yr, a complete steady state appears at the critical altitude of about 900 m above sea level in about 3 million years. The basic altitude dispersion is estimated to be about 95 m. When the tectonic uplift rate is 3 mm/yr, the critical altitude of about 2000 m above sea level, with a basic altitude dispersion of about 150 m, is attained in about 2 million years. The critical altitude becomes greater with a higher uplift rate, and the higher the uplift rate, the earlier the mountain ranges attain their critical altitudes.

During the declining stage, when the uplift rate declines, mean altitude falls and there is a decrease in altitude dispersion and sediment yield. The higher areas with high altitude dispersions are lowered more rapidly than the lower areas characterized by lower altitude dispersions. A decline in slope plays a significant part in the decrease in altitude in comparison with the parallel retreat of slopes (Ohmori, 1983a, 1984), resulting in a subdued landscape. The mean altitude is lowered to 100 m above sea level, with a basic altitude dispersion of about 25 m, in about 10 million years, regardless of its initial altitude. This low relief denudational landscape should be in the latest old stage, an end-peneplain. The landscape development discussed above is illustrated in Fig. 12 (Ohmori, 1985, 2001b).

On the basis of the model represented by Eq. (10), it is possible to assess the impact of changes in tectonic uplift rate on the sequence of landscape development. This produces a sequential change in mean altitude composed of several phases with different uplift rates. In such a case, there is not significant difference between a mean altitude calculated by the integrated uplift of individual uplift rates for 1 million years or longer, and a mean altitude calculated using the mean uplift rate, u (the mean weighted uplift rate):

$$u = \frac{\left(\sum_{i=0}^{n} u_i t_i\right)}{T} \tag{12a}$$

where t_i is the duration of each uplift rate of u_i, n is the number of the changes in uplift rate, and T is the total duration of simulation; $\sum t_i$ (Ohmori, 1987, 1990a, 1990b). When the uplift rate is constant throughout the total duration, n is 0. The mean uplift rate is practically estimated by:

$$u = \frac{H_n}{T} \tag{12b}$$

where H_n is the cumulative vertical displacement of land surface without denudation during the total duration of T. The cumulative vertical displacement must be estimated on the basis of the altitude of a reference surface such as an uplifted depositional surface or uplifted peneplain remnant, geologically and chronologically confirmed.

As the same way, it is also possible to assess the impact of changes in denudation rate with climatic change on the sequence of landscape development. Values of the coefficients γ and δ may be peculiar to each climatic phase. As examined in the previous section, however, denudation rate might be maintained on an average in proportion to the magnitude of local relief, in spite of climatic changes, in Japan. For avoiding the “simulation game”, therefore, the change in denudation rate seems better to be ignored in the simulation until reliable denudation rate in each climatic phase is revealed.

The changes in altitude and local relief in the developing stage have been discussed on the basis of morphometric analyses and chronological data for the mountain ranges in central Japan (Sugai and Ohmori, 1999). Having formed during the late Pliocene and early Pleistocene, the original low-relief surfaces have been progressively dissected by valley deepening from the increase in altitude by tectonic uplift. The original surface on an interfluve disappears due to intersection of the valleys that eroded both flanks, when the original surface attains about 1600–2000 m above sea level. The shape of cross-section of an interfluve changes from trapezoidal to triangular, indicating that the mountain range enters into the full mature stage in the Davisian sense. At this time, the local relief expressed by the altitudinal difference between ridge top and foot reaches about 1000 m. Even after the original surface disappears, ridge top altitude and local relief still increase as a result of tectonic uplift. When the mountain range ultimately attains its own critical altitude, the shape of an interfluve approaches a steady state, and remains the same until relative rates of tectonic uplift and denudation change. These results agree well with the model discussed above.

The relationship between sediment yield and stage of landscape development has been discussed on the basis of the relationship between stage of mountain range and alluvial fan development at the mountain foot (Saito, 1988, 1989a, 1989b) as follows. In Japan, 586 alluvial fans with an area larger than 2 km^2 formed since the late Pleistocene are counted. Regional variations in distribution of alluvial fans show contrasts between morphotectonic terrains. On the basis of multiple discriminant analysis, the principal factor controlling regional variations is the relief ratio of the drainage basin. The relief ratio is a measure of local relief and functionally related to altitude dispersion (Oguchi and Ohmori, 1994). It is also related to the stage of landscape development of a mountain range (Saito, 1989a, b). Using the stages of individual mountain ranges evaluated by Ohmori (1978), mountain ranges in the advanced stages with high mean altitudes and high altitude dispersions have extensive and well-developed alluvial fans with thick deposits at their foot. Mountain ranges in the early stages with low mean altitudes and low altitude dispersions have small alluvial fans with thin deposits or no conspicuous alluvial fan at their foot. The proportion of drainage basins having alluvial fans in individual mountain ranges increases with advance in stage of mountain landscape: Mountain ranges in the more advanced stage have a higher proportion of drainage basins with alluvial fans. Depositional landforms in the lowlands, therefore, have been developed in connection with the dissection processes in mountain ranges controlled by altitude and altitude dispersion, both of which change with advance in stage (Saito, 1988, 1989a, 1989b).

3. *Differences in the course of landscape development between the three models*

The model discussed above is now called the RAD model (the Relief-Altitude-Denudation model). The Penckian model is also a model for landscape development resulting from concurrent tectonics and denudation, although it was originally developed for describing hill-slope development. What difference is there between these two models? For the RAD model, we can assume arbitrarily any possible values only for tectonic uplift rate. Denudation rate is determined by mean altitude that is, in turn, functionally related both to rates of tectonic uplift and denudation. On the basis of the empirical relationships between denudation rate, local relief and mean altitude, the course of landscape development can have only one course for a value of tectonic uplift, although the values of $\gamma(=\alpha a^{\beta})$ and δ $(=b\beta)$ may be different between tectonic or climatic regions. The tectonic movements associated with plate motion may be relatively independent of the other factors during the developing and culminating stages, while those associated with isostasy during the declining stage may be related to denudational unloading (Ohmori, 2000).

For the Penckian model, however, there is no functional relationship between denudation rate and altitude, although denudation rate is assumed to be proportional to surface gradient which may be a measure of local relief. We can, therefore, assume arbitrarily and independently any values for both rates of tectonic uplift and denudation. On the basis of the Penckian model, we can deduce any courses of landscape development in terms of using the tectonic uplift rate and denudation rate assumed, at our own convenience. From this kind of simulation, we can not

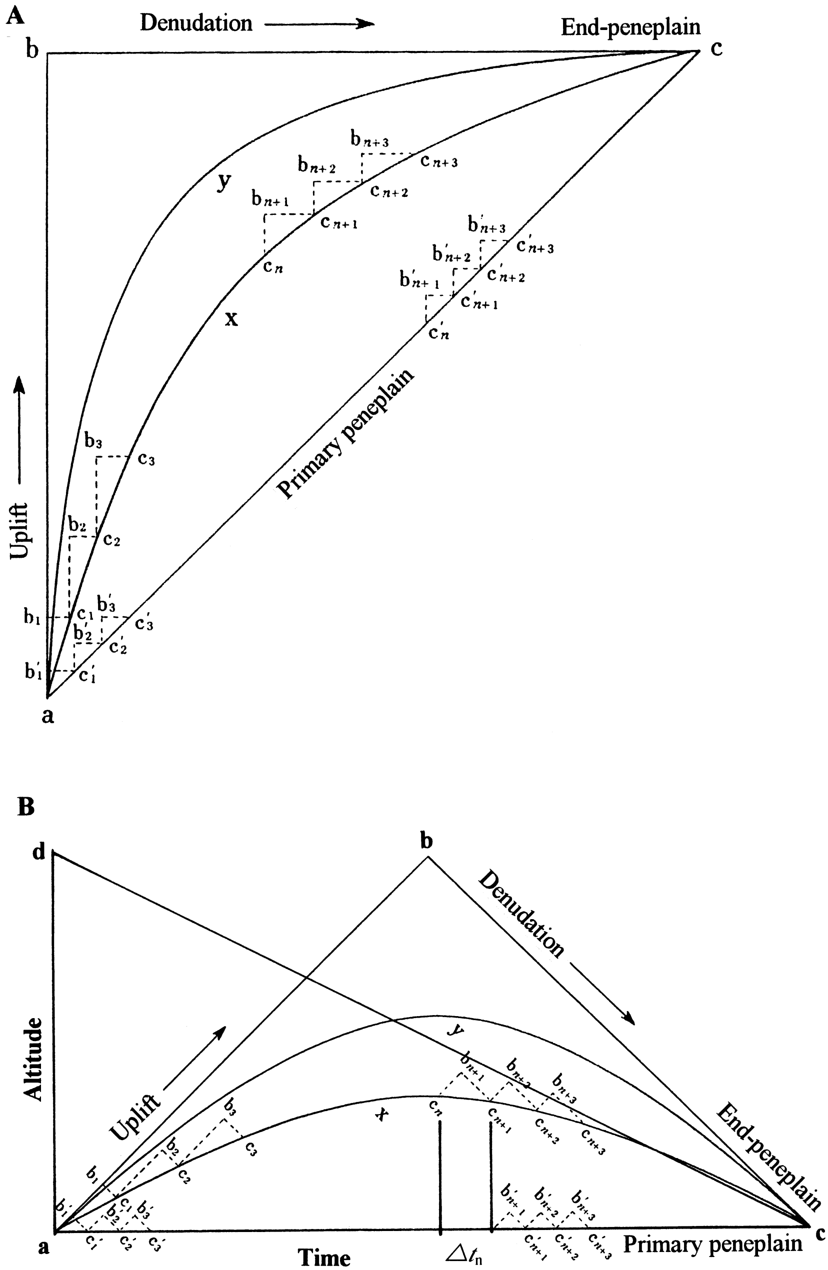

Fig. 13. Change in altitude for cases of different relationship between tectonic uplift and denudation. **A**: Penckian diagram (Penck, 1924, p. 11; transformed by Yoshikawa (1985b) to express tectonic uplift and denudation by the same measurement scale). The lengths of $c_n b_{n+1}$ and $b_{n+1} c_{n+1}$ are the uplift and denudation in a short time span, respectively. **B**: Rotated diagram of **A** for expressing the course in terms of the time-altitude relationship. The lengths of $(c_n b_{n+1})\sin(\pi/4)/\Delta t_n$ and $(b_{n+1} c_{n+1})\sin(\pi/4)/\Delta t_n$ are respectively the uplift rate and denudation rate in Δt_n.

confirm which course among a number of simulated courses is adequate as a basis for understanding landscape and its nature. A model with a high degree of freedom for determining values of its constituent elements is not always a superior model. The freedom sometimes implies that we can not determine actually any possible values of the elements. With imaginary and arbitrary values, the model may sometimes deduce meaningless results.

Figure 13-**A** is a diagram which was transformed by Yoshikawa (1985b, figure 2.3, p. 37) from the diagram of Penck (1924, figure 1, p. 11) to express tectonic uplift and denudation on the same scale. In the diagram, W. Penck intended to express the Davisian model by the lines **ab** and **bc**, and the primary peneplain by the line **ac**. The two curves ***x*** and ***y*** are example courses of the sequence resulting from concurrent tectonics and denudation. Total amount of tectonic uplift is the same as that of denudation for each course, and they are also the same for all the courses. It means that each curve ***x*** and ***y*** expresses a sequence of landscape development throughout an orogeny. Every course of the sequence resulting from concurrent tectonics and denudation has been considered to be necessarily in the triangle **abc** (Penck, 1924). This may be an origin of the idea that every ordinary landscape development is expected to follow a course between the Davisian sequence **a–b–c** and the Penckian primary peneplain sequence **a–c**.

The Penckian diagram can be rotated into Fig. 13-**B** for expressing the courses in terms of the time-altitude relationship. Figure 13-**B** is not mathematically accurate expression, but is convenient for explanation. In Fig. 13-**B**, Δt_n, the time span, varies with course and changes with time except for the line **ac**. The lengths of $c_n b_{n+1}$ and $b_{n+1} c_{n+1}$ indicate not time length but relative rates of tectonic uplift and denudation in Δt_n. To be exact, $(c_n b_{n+1})\sin(\pi/4)/\Delta t_n$ and $(b_{n+1} c_{n+1})\sin(\pi/4)/\Delta t_n$ indicate tectonic uplift rate and denudation rate, respectively. It is clear that the **a–b–c** course does not show the correct course of the Davisian model with respect to time. This is from lack of the adequate concept of time in the Penckian diagram. For this kind of comparison, the course of the Davisian model must be expressed by the course **a–d–c**, because the Davisian model starts from the highest position in the sequence.

In Fig. 13-**B**, each central part of the curves ***x*** and ***y*** shows a steady state keeping a balance between uplift rate and denudation rate for a short time span. In the RAD model, the culminating stage appears when both the mean altitude and the local relief remain constant due to dynamic equilibrium between tectonic uplift and denudation, while in the Davisian model the mountain altitude continuously decreases. It is sure that the dynamic equilibrium state is outside the Davisian model (Hack, 1960; Ahnert, 1970; Ohmori, 1978, 1985; Yoshikawa, 1984, 1985a, 1985b).

For examining the differences in sequence between the RAD model and the Davisian model, it is difficult to compare altitude between the models, because altitude was not quantitatively expressed in relation to time in the Davisian model. If denudation rate changes with time, the Davisian model could show many courses of the sequence of landscape development. Figure 13-**B**, however, suggests that many mountain ranges among those following the sequence resulting from concurrent tectonics and denudation may exceed in altitude the mountain

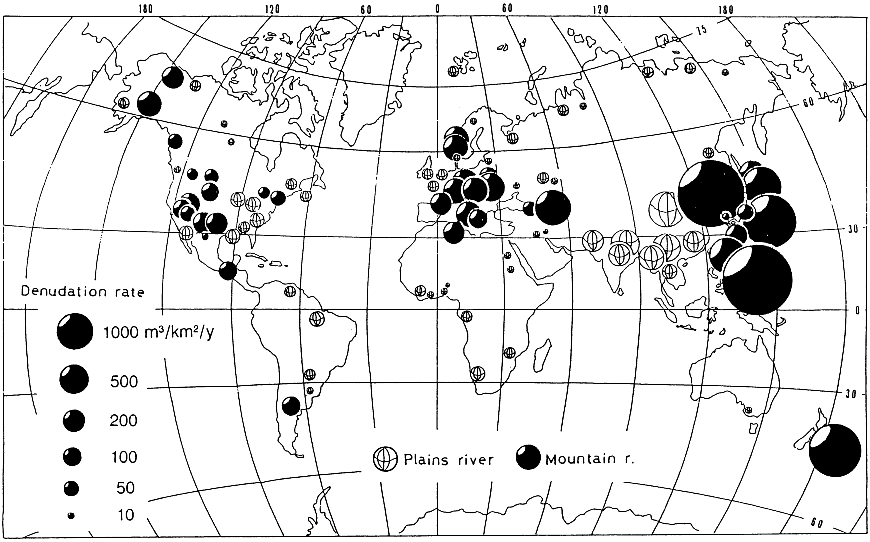

Fig. 14. Distribution of denudation rates in drainage basins of rivers in the world (Ohmori, 1983c).

range following the Davisian model in the later stage of orogeny, for the same condition of total tectonic uplift and total denudation. It is also difficult to compare the local relief between the models, because in the Davisian model local relief was not quantitatively expressed in relation to altitude. For a mountain range in the full maturity of the Davisian model, local relief is at its maximum but mean altitude is significantly lower than the initial altitude. Local relief of the RAD model, however, continues increasing with an increase in altitude by tectonic uplift even after the mountain range has entered the full maturity until it reaches the critical altitude. Even if the mean altitude in the full maturity is equal to the critical altitude, local relief must be maintained by continuous tectonic uplift and exceeds that of the Davisian model sooner or later, because local relief in the Davisian model decreases continuously after the full maturity. This is also another case of the RAD model coming out of the Davisian model. These indicate that the Davisian model draws not an extension of the sequence of landscape development but just a special case. Much of the sequence of landscape development resulting from concurrent tectonics and denudation must lie outside the sequence of the Davisian model.

RELATIONSHIP BETWEEN THE END-PENEPLAIN AND PRIMARY PENEPLAIN

The distribution of denudation rates in drainage basins of rivers in the world is shown in Fig. 14 (Ohmori, 1983c). It shows that denudation rates in Japan are among the highest class in the world. It indicates that the denudation rates estimated from Eqs. (5) and (7) must also be among the highest class in the world. Even in the areas of high denudation rates such as Japan, when mean altitude is 100 m above sea level, with a basic altitude dispersion of about 25 m, the denudation rate is calculated to be about 0.05 mm/yr from Eqs. (5) and (7). The tectonic uplift rate, therefore, must be about 0.05 mm/yr or less to keep a balance with the denudation rate working on a peneplain for maintaining it at low altitude. A tectonic uplift rate of 0.05 mm/yr means that the land surface is tectonically uplifted only 5 mm in a hundred years, 5 m in a hundred thousand years, and 50 m in a million years. If the mean altitude of an imaged primary peneplain is considerably lower than 100 m above sea level, the tectonic uplift rate for maintaining the primary peneplain needs to be much lower than 0.05 mm/yr in any regions in the world. Such a low uplift rate could not be measured by our surveying techniques, and in practice must be recognized as a stable stand as noted by Yoshikawa (1985b, p. 102–103). Essentially it cannot create a mountain range, even though there is little denudation, and it should be out of orogenic processes. It hardly needs saying that an initially low relief landscape maintained at low altitude not by denudation but by a vertically stable stand, by a lack of crustal movement, is not a Penckian primary peneplain. The origin of the initially low relief landscape itself is the very problem with respect to a peneplain.

On the basis of the changes in altitude and local relief for the mountain ranges in Japan, interfluve cross-section shape transforms from trapezoidal to triangular in the late developing stage and remains the same during a steady state of culminating stage (Ohmori, 1990a, b; Sugai and Ohmori, 1999). If the stages occur at a low altitude, the landscape may show a low relief landscape similar to a peneplain. Maintaining the culminating stage at a low altitude for a considerably long term needs also an extremely low tectonic uplift rate. It necessarily accompanies a considerably long-term youthful stage in the Davisian sense. The sequence of landscape development with the long-term youthful stage due to a low tectonic uplift rate is also quite different from the concept of the primary peneplain.

On the contrary, the tectonic uplift rate in orogenesis should easily exceed such a low denudation rate, and altitude and local relief must become high. The observed lowest denudation rate among the 82 reservoirs in Japan is 0.06 mm/yr. The mean altitude of the drainage basin with the lowest denudation rate is 565 m above sea level, and the mean basic altitude dispersion is 38 m. The mean altitude and altitude dispersion are relatively higher than those expected from the observed denudation rate. The basic altitude dispersion of 38 m, however, is considerably lower than the 70 m expected from the mean altitude. The drainage basin is located in the Chugoku Mountains famous for “uplifted peneplain remnants” in the inner belt of Southwest Japan. Extensive low relief denudational surfaces formed during the late Tertiary and early Quaternary are widely distributed on ridge tops in and around the drainage basin (Okazaki, 1967; Yoshikawa *et al.*, 1981; Ohmori, 1984). They have been dissected by deep but narrow valleys. The Quaternary vertical displacement of the Chugoku Mountains is about 400–800 m (Research Group for Quaternary Tectonic Map, 1968, 1969, 1973; Fig. 7), indicating that the mean Quaternary tectonic uplift rate is about 0.2–0.4 mm/yr (Ohmori, 1978). Though the absolute value of the tectonic uplift rate is among the lowest class in Japan, the uplift rate has overcome the denudation rate, causing the high mean altitude. As dissection processes could not follow the tectonic uplift, extensive peneplain surfaces remain on ridge tops, resulting in the relatively low altitude dispersion. This is an exceptional case in Japan. The case, however, indicates that the denudation rate working on a peneplain must be significantly low, being easily exceeded by the tectonic uplift rate in orogenesis.

The primary peneplain must be formed under a condition with some high uplift rate expected for orogenesis and also with some high denudation rate equivalent to the uplift rate for maintaining it at low altitude. As examined above, however, such a place can not be found in the world, especially in the orogenic zones even with significantly high denudation rates like Japan. The primary peneplain imaged by W. Penck, therefore, cannot actually exist on the earth.

If a low relief denudational landscape has been kept at low altitude for a considerably long term, it should have been formed originally not as a primary peneplain under the steady state of the Penckian model, but as an end-peneplain of the Davisian model. It must have been maintained at low altitude due to a vertically stable stand of the crust. Therefore, it can be practically, physically and conceptually said that the Penckian primary peneplain must be the same as the Davisian end-peneplain.

CONCLUSIONS

On the basis of the relationships between denudation rates, mountain altitude and local relief observed in Japan, the landscape development resulting from concurrent tectonics and denudation can be divided into developing, culminating and declining stages. In the developing stage, mean altitude increases together with local relief due to the tectonic uplift exceeding the denudation. During the culminating stage in a steady state between tectonic uplift and denudation, mean altitude attains a critical altitude and remains constant, in spite of continuous tectonic uplift. Local relief reaches a maximum and maintains a constant sediment yield. In the declining stage, mean altitude, local relief and sediment yield decrease. As higher areas with high local relief lowered more rapidly than lower areas with lower local relief, a peneplain of a subdued and rolling landscape finally appears.

The culminating stage does not exist in the Davisian model. It must be sure also that many mountain ranges among those following the sequence resulting from concurrent tectonics and denudation exceed in altitude a mountain range following the Davisian model. On the other hand, the relationships between denudation rate, altitude, and local relief observed in Japan indicate that the tectonic uplift rate for keeping a balance with the denudation rate working on a peneplain must be much lower than 0.05 mm/yr. Such a low uplift rate cannot create a mountain range and should be outside orogenic processes. A low relief denudational landscape maintained at low altitude should have been formed originally not as a primary peneplain under the steady state of the Penckian model, but as an end-peneplain of the Davisian model. It can be conclusively said that the primary peneplain imaged by W. Penck cannot actually exist on the earth and that it must be the same as the Davisian end-peneplain. The sequence of landscape development resulting from concurrent tectonics and denudation, therefore, can not always stay within the framework bounded by the Davisian model and the Penckian primary peneplain.

For a physical mode of landscape formation process constructed on the basis of the dynamic relationships between tectonics, denudation process and landscape, it sometimes appears that no assumptions are necessary for the simulation. Even such a physical model, however, can not estimate any landscape changes in the future, even for the past, without any assumptions of the changes in tectonics or denudation process, or in the landscape itself. When an assumption is conceptually recognized to be typical of cases, for example, an abrupt uplift, a constant uplift, a gradual uplift or a stable stand, the assumption itself must not be criticized. The model may show an imaginable case. It is important to examine whether or not the model and assumption give us a comprehensive, realistic and basic sequence of landscape development for understanding landscape and its nature. “How do we use it” depends on the level of our geomorphology.

We should remember, however, that a model deductively given on the basis of a mathematical or physical assumption indicates the result at the same time as it is proposed, if the equation has been mathematically solved already. For one of the simplest examples, when a model that denudation rate (dH/dt) is assumed to be proportional to altitude (H) is proposed, the model is mathematically expressed by $dH/dt = -\lambda H$, and at once the solution is given by $H = H_0 e^{-\lambda t}$, where H_0 is the initial altitude, t is the time, and λ is a constant. The locus drawn by the equation indicates the sequence of changes in altitude, and the characteristics of the locus have been mathematically established already, too. For such a model, the assumption itself needs to be examined whether or not it is adequate for understanding geomorphic processes going on the actual field, because the assumption includes both geomorphic processes and results themselves. Examining the results from such a model can not explore a new horizon further than the mathematical meanings that have been discovered already. If a model, even if it appears to have a physical basis, is not tested on the basis of the data actually observed on the earth, further discussion including simulation sometimes induces not better understandings but awful misunderstandings about landscape development.

The Davisian and Penckian models seemed to have indicated the fundamental courses of landscape development through an orogeny. They provided a new world of geomorphology. The actual sequence of landscape development in orogenesis, however, lies outside these two models.

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