Characteristic Erosional Processes in Granitic Drainage Basins as Found in Tanakami Mountain Range, Shiga Prefecture, Japan

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Abstract

The erosional processes in the stream channels and on the hillslopes are analyzed quantitatively in Tanakami mountain range on the basis of geology, geomorphology, hydrology and pedology of this region.

As the dynamic balance of sediment does not hold on the stream bed, the rate of downward erosion of the channel is assumed to be a power function of the bottom shear stress due to the running water. Applying a Manning's type law of mean velocity to the hydraulics of the stream, the rate of the channel erosion and that of the channel retreat are expressed as some power functions of the stream discharge, the channel gradient, the channel width, and a coefficient representing the effect of such factors as geology and climate. The contemporary distribution of the knick points of varied "age" is related to the rate of their retreat. A statistical analysis leads to a concrete form of the relationship between the rate of the channel erosion and the above hydrogeomorphological factors.

The hillslope processes are described as the processes conditioned by the channel erosion. The time series of developing profile of a hillslope is reconstructed from a sequence of hillslope profiles along the reach of a stream. It is shown that the hillslopes recede with the slope angle gradually decreasing when the rate of the channel erosion is small, and contrarily increasing when the latter is great, and that a parallel recession takes place as a long term average because the above processes take place in turn. It is also shown that three different weathering zones have respectively different fashions of denudation.

The average and the maximum rates of denudation over this region under the natural conditions are estimated and compared with the actual rate under the bare-land conditions due to human activities. It is shown that the bare-land conditions in this region have accelerated the rate of denudation by a factor of more than ten.

The above results are interpreted as being characteristic of granitic rocks being lifted under a lateral geomechanical pressure with fracturing, and being exposed to physical weathering.

1. Introduction

Tanakami mountain range is only a tiny part of Shigaraki mountain range located to the south-east of the Lake Biwa (see Figs. 1 and 2). Particularities in mineralogy and topography, and the barren landscape distinguish it from the other parts[1]. It is well known as the origin of heavy discharge of sand to the surrounding lowlands[2,3], as a mine of rock crystal and jewels[1], and also as a picnic place.

Different theories have been proposed so far concerning the characteristic landscape

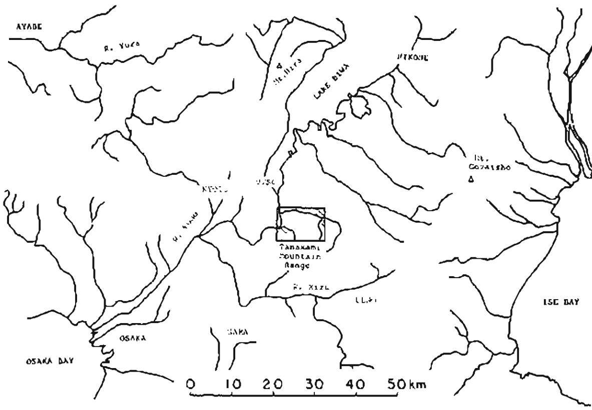

Fig. 1 A map of Kinki district.

of the bare lands in this region. It has been realized that the essential cause is destructive human activities such as overfelling in the past as much as in the other bare lands in southwest Japan[2,5]. However, natural conditions are also important because the rate of sediment production and the difficulty of the recovery of the vegetative cover differ according to the physical factors if the degree of overfelling seems to have been the same[5]. These natural conditions would be summarized as particularities in the erosional processes.

Geological properties of Tanakami granite predominant in this region have been described in many literatures (e.g. by Matsushita[1], Hirose[6], Yoshizawa et al[7], and Tachikawa[8]). The mineralogy of the weathering product of biotite has been studied by Shigezawa[9].

Concerning the geomorphological property, it has once been believed that this region is in the fully matured stage in geomorphological cycle on the basis of the hypsometric curve. Ikeda[10] has explained the particular features of this region as the result of the disintegration of the geomorphological surface of the older cycle due to rejuvenation. Thus he is the first to have given a convincing explanation to the distribution of the barren parts in this region. Matsuda and Okunishi[4] have pointed out that the erosional surfaces of different heights have been formed in this region through repeated rejuvenation in the Pleistocene (see Fig. 2), and have explained thereby the distribution of the bare lands in detail (bare soil lands on the ridges and the naked rock lands on the steep slopes near the rivers). However, it is needed to establish a physical ground for the above theories on the physiographical basis. The recent investigations of hydrologic balance[11,12] and of sediment production[13] in this region have prepared what is necessary for a physical description of the erosional processes.

It is therefore possible to give a quantitative description of the erosional processes of this region, to say, during the last 1,000,000 years, through the comparison of the geomorphological features among the different erosional surfaces.

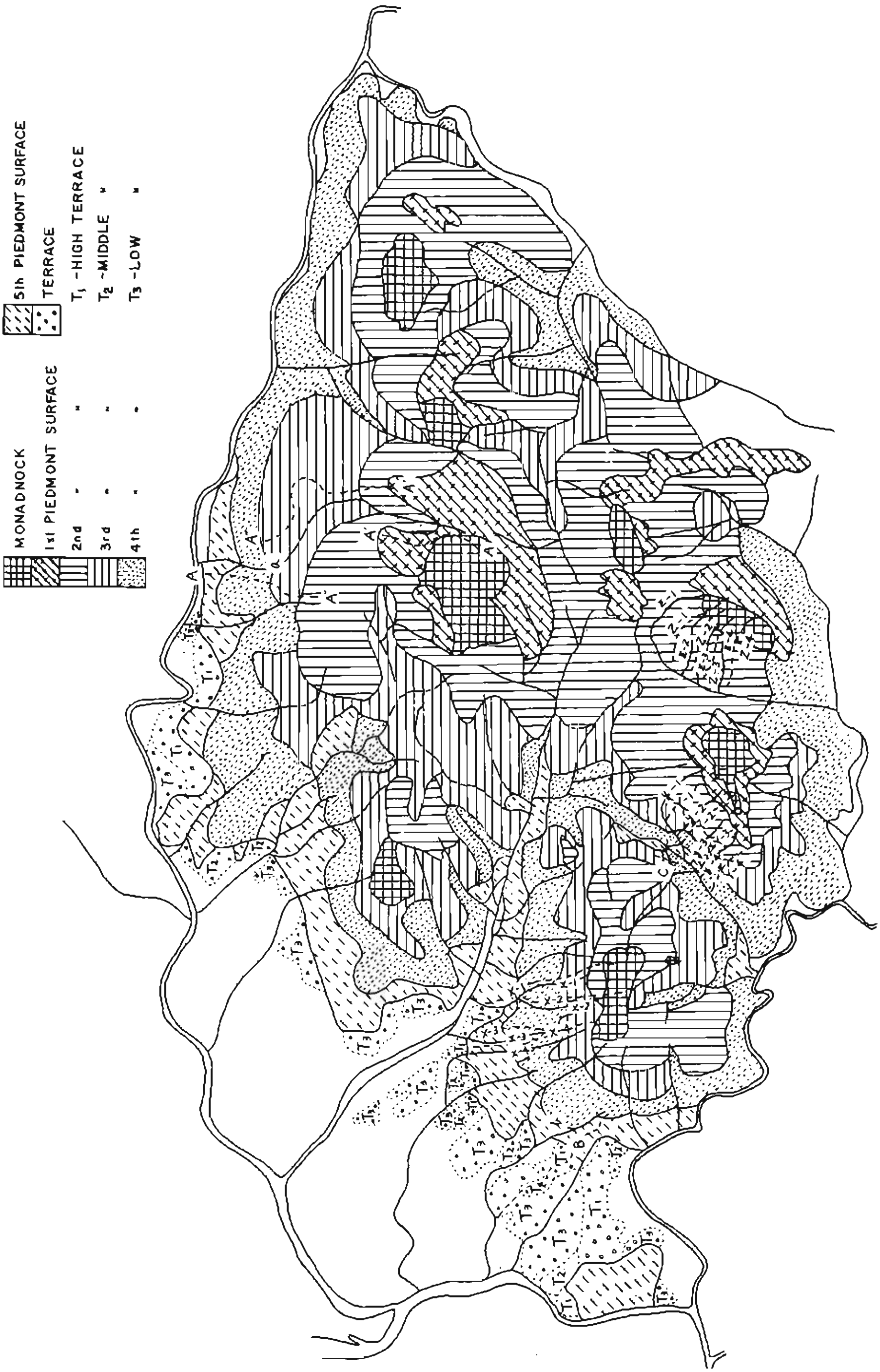

Fig. 2 Distribution of different geomorphological surfaces in Tanakami mountain range. After Matsuda et al[4].

2. The patterns of the erosional processes

These entirely waste barelands are located on the gentle slopes near the ridges of the hills with low relief on each of the five erosional surfaces pointed out by Matsuda and Okunishi[4]. At such a place the granite is intensively weathered and has become coarse sand of dense packing. The result of the seismic prospecting[14] indicates that the residual soil of weathered granite (Masa-soil) exists in the top layer of the thickness of 5–6 meters, and that in the underlying layer up to the depth of 12–20 meters the entirely disintegrated granite is mixed with slightly weathered one changing their mixture ratio with depth. The material which corresponds to the second layer by the seismic prospecting appears at the lower part of the hillslopes and presents the naked rock land. The channel bed is scoured into the fresh but densely jointed granite which corresponds to the third layer in the seismic prospecting. According to the mineralogical and hydrochemical investigations[9,15,16], chemical weathering is negligibly slow, and the existing weathering product is thought to be brought about as a result of physical weathering.

The Masa-soil is loosened by the cycle of freezing and thawing, and is transported downhill by creeping mechanism[17] or by the surface flow[13]. Until it is loosened, it is comparatively stable for any erosive agents because of low porosity and large angle of internal friction. The failure of hillslope can occur only when the slope is covered with vegetation and the slope exceeds 45 degrees. The rate of the surface erosion is large in the land with naked Masa-soil (several milimeters in each year) and small in the forested lands[13]. The surface erosion takes the form of creep or sheet erosion at the upper part of the hillslope. At the lower part, the rill erosion and gully erosion take place because the surface flow increases downhill, unless the layer of Masa-soil has not yet entirely been stripped off by the erosion. Where the layer of Masa-soil is already lost, the surface is now covered by the naked rocks partly containing the Masa-soil along the joints, and the rate of the surface erosion is much decreased. Sandy soil accumulated in the hollows among the naked rocks bears some diminutive shrubs. Near the base of the hillslopes, the slope angle is commonly great because of the downcutting action of stream accompanying the repeated rejuventation. In such a place, the erosion seems to take place either as shallow slide or as rockfall.

At the bottom of the valley there is a perennial stream wherever the drainage area is larger than one hectare. The bed of the stream channel consists commonly of the bedrock, sometimes covered by a thin layer of screes where the gradient of the channel is very small. Exceptionally thick deposit is seen where the rate of erosion at the bank is great due to the passage of the knick points, or where the sediment transport is obstructed by an erosion control dam. They are, however, either ephemeral or recent events, so that it can be said that the erosion has exclusively taken place throughout the course of the geomorphological development.

According to the observation of the sediment transport at the stream[13], a great quantity of sediment is brought from the hillslopes to the stream channel when there are intense rain storms. It is, however, much less than the transporting capacity of the stream at that time[11]. This fact means that the erosion at the channel is not affected by the erosional processes on the hillslopes. The latter is, however, dependent on the former, because the lowering of the channel makes the neighboring hillslope unstable and thus stimulates erosion on the hillslopes.

Therefore, in order to describe the erosional processes of this region on a physical basis, it is proper to describe first the channel processes, and then the hillslope processes.

3. The retreat of knick points of the stream channels

The rejuvenation as has caused the formation of the different erosional surfaces in this region is attributable to the uplift of the earth's crust relative to the base level of erosion. The horizontal tectonic compression of E-W trend has been predominant in southwest Japan since the Plio-pleistocene[18]. It caused a set of conjugate fractures (faults and joints) in the crust and thus has divided it into many blocks. These blocks have then moved vertically in an individual manner according to the stress on them. This event is called Rokko movement. Tanakami mountain range is one of these blocks, and therefore presents a rhombic shape bordered by faults and joints. The fractures developing densely in its interior present no apparent evidence of differential movement between each side of them. Yokota[19] has computed the quantity of the deformation of the block involving Tanakami mountain range, on the geodynamic basis. Accordingly, the height of the uplift is greater at the central parts (warping). The local difference of the uplift is, however, not significant compared with the uplift of this mountain range relative to surrounding lowlands, so that the uplift can be assumed approximately uniform within Tanakami mountain range. Though nothing has been known about the detailed history of the uplift, it is suggested from the sedimentary facies of Kobiwako group sediments depositing in the Plio-pleistocene[20] that the uplift could be intermittent. It must be also noted that there is no evidence denying the occurrence of crustal submergence in the intervals of the repeated uplift.

The erosional surfaces are bordered from each other by the knick points at the bottom of the valleys and by the lines of the abrupt slope change on the hillslopes. The latter can be traced across the valleys and ridges. Other types of knick points in the channels are found at the sites where a small stream joins with a much larger one, and where the geological property of the bedrock is different from that at neighboring sites. They are distinguished from the above knick points in that they are not connected to the lines of abrupt slope change on the hillslopes. The knick points that border the different erosional surfaces are located more upstream than the corresponding lines of abrupt slopechange on the hillslopes. Sometimes they intrude into several steps upper erosional surface, which means that the downward erosion and the accompanying retreat of the channels precede those of the hillslopes. There is seen a tendency that the distance of retreat of knick points is greater where the drainage area is greater (see Figs. 2 and 3). It suggests that the channel erosion is governed primarily by the hydraulic condition, and therefore that the correlation

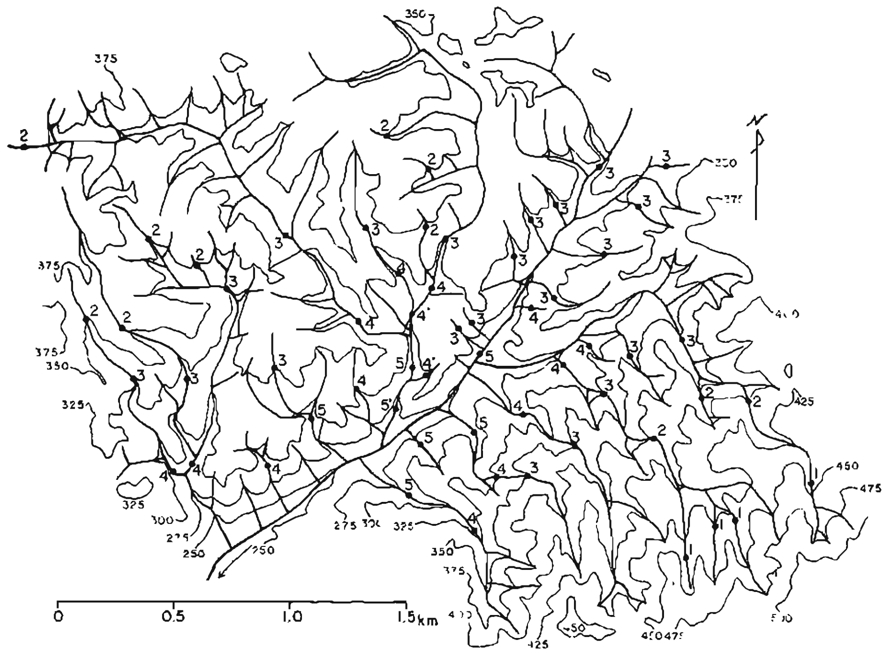

Fig. 3 Spatial distribution of the knick points. The numerals indicate the identity of the time of their occurrence. The numerals with ' mean that the time of the occurrence can not be distinctively identified. Partly reproduced after Matsuda[24]

between the retreat of knick points and some hydraulic and geomorphological factors will lead inductively to the law of the channel erosion for this region.

The retreat of knick points due to the channel erosion takes place as shown in Fig. 4. When the profile of the channel ANPB changes to A'N'P'B' due to the erosion in a short time, the edge of the knick point moves from N to N'. This distance represents the distance of retreat of the knick point. The depth of erosion at the knick point is defined as the length of the normal line NN". Furtheremore, drawing the line PP" normal to ANPB and the line PP' parallel to NN', the depth of erosion and the distance of retreat of the arbitrary point P can be analogously defined. The reach immediately upstream the knick point commonly presents a very small gradient so that the rate of erosion is negligible here. It is reasonable that this gradient represents that of the graded channel under the same geological and hydrological conditions, because the erosional processes characteristic of the old age in the geomorphological cycle takes place there.

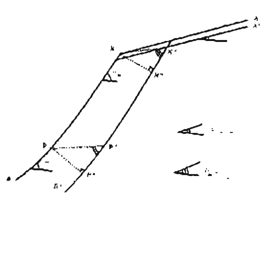

Fig. 4 Geometry of the channel recession.

Therefore, the point N' moves virtually along the line AN, i.e. the knick point retreats along the line AN. Thus a geometrical observation of Fig. 4 leads to the expression,

$$\overline{NN'}=\overline{NN''}\ \mathrm{cosec}(\theta_n-\theta_c),$$

$$\overline{PP'}=\overline{PP''}\ \mathrm{cosec}(\theta-\theta_c),$$

where θ is the slope angle of the channel, θ_n the value at the knick points, and θ_c the value for the graded channel which would be realized at the upstream reach AN of the knick point. Denoting the horizontal component of the rate of the retreat of any point as v (that of the knickpoint as v_n) and the rate of erosion as E (E_n at the knick point), one has,

$$v=E\ \mathrm{cosec}(\theta-\theta_c)\cos\theta_c, \tag{1}$$

$$v_n=E_n\ \mathrm{cosec}(\theta_n-\theta_c)\cos\theta_c. \tag{2}$$

The physical description of the rate of the erosion has been usually done through writing the equation of the mass conservation of the sediment, assuming that the flux of the sediment is equal to the transporting capacity of the stream[22]. However the dynamic balance of sediment is not attained in this region because the sediment transporting capacity of the stream is much larger than the quantity of sediment brought to the channel as stated above. Thus it is reasonable to express the rate of channel erosion as a power function of the tractive force of the stream, as Mizutani[21] has done. Assuming the critical tractive force, one has,

$$E=k(\tau-\tau_c)^n, \tag{3}$$

where τ is the tractive force of the stream for unit area of the channel bed, τ_c the critical value of τ, k the erodibility of the channel bed, and n a constant.

Though the direct evaluation of τ is difficult for each location, the latter can be expressed as a function of discharge using an appropriate formula for mean velocity. Yamaguchi et al[23] have developed a Manning's type formula,

$$U=ch^{3/4}(\sin\theta)^{1/2}, \tag{4}$$

for small and steep streams, where U is the mean velocity, and h is the depth of the stream, c being a constant. Combining this formula with the additional well known formulae,

$$Q=UhW$$

$$\tau=\rho gh\sin\theta,$$

for steady flow in shallow rectangular channel, one has,

$$\tau=\rho g(Q/cW)^{4/7}(\sin\theta)^{5/7}, \tag{5}$$

where Q is the discharge, W the width of the channel, g the acceleration of the gravity, and ρ the density of water. Considering that E is virtually zero at the reaches immediately upstream the knick points where $\theta=\theta_c$, and that the erosion is still active near the source point of the stream where the discharge is very small but θ is appreciably large, it is reasonable to express $\tau-\tau_c$ as,

$$\tau-\tau_c=\rho g(Q/cW)^{4/7}\{\sin(\theta-\theta_c)\}^{5/7}, \tag{6}$$

where θ_c may be a function of the discharge.

Next, one has to devise a method for evaluating the horizontal velocity of the retreating knick points. This evaluation is possible through relating this value to the distance between two knick points formed in different geological time. As the channels present an obvious evidence of antecedence in this region, the direction of which being determined by the joint system, it can be assumed that the drainage pattern is fixed on the plan throughout the course of the geomorphological development. Therefore, the location of a point on a channel can be identified by the horizontal distance x along the channel from a certain fixed point. For a knick point which was formed at the time t_0 at the point x_0 and now has retreated to the point x,

$$x=x(t, t_0), \tag{7}$$

$$x_0=x(t_0, t_0), \tag{8}$$

hold. Eqs. (1), (3) and (6) suggest that the horizontal velocity of the retreating knick point v_n is approximated as the product of a function of the location (the effect of the topography and geology) with a function of time (the effect of the long term variation of discharge and the other climatological factors). Then one can write formally,

$$v_n=\partial x/\partial t=u(t)w(x). \tag{9}$$

Defining a quantity v_n' as,

$$v_n'=-\partial x/\partial t_0, \tag{10}$$

and putting Eqs. (9) and (10) into

$$\mathrm{d}x=\frac{\partial x}{\partial t}\mathrm{d}t+\frac{\partial x}{\partial t_0}\mathrm{d}t_0, \tag{11}$$

which yields from Eq. (7), one has,

$$\frac{\mathrm{d}x}{w(x)}-u(t)\mathrm{d}t=-\frac{v_n'}{w(x)}\mathrm{d}t_0. \tag{12}$$

As the left side of Eq. (12) represents the total derivative of a certain function of x and t, the right side must be also the total derivative of some function of t_0, whereby v_n' must take the form,

$$v_n'=u'(t_0)w(x). \tag{13}$$

Differentiating now Eq. (8), one has,

$$\mathrm{d}x_0=u(t_0)w(x_0)\mathrm{d}t_0-u'(t_0)w(x_0)\mathrm{d}t_0=0,$$

as x_0 is constant. It leads to,

$$u'(t_0)=u(t_0), \tag{14}$$

and therefore, Eq. (13) becomes,

$$v_n'=u(t_0)w(x)=v_n(t_0, x). \tag{15}$$

Eq. (15) means that v_n' represents a past (when $t=t_0$) rate of retreat of a hypothetical knick point which might exist at x at the time t_0. Therefore, the dependence of v_n' on t_0 involves the influence of the past (at the time of t_0) climatological conditions on the rate of erosion, and it is possible to determine the present rate of the erosion as a limit of the (descrete) time series of the past rate thus obtained.

4. The laws of the channel erosion derived from the contemporary distribution of the knick points

Matsuda and Okunishi[4] have recognized five kinds of knick points in this region according to the time of their occurrence. Matsuda[24] has plotted them on the map of the scale of 1:5,000 prepared by the Biwako Construction Office of the Ministry of Construction. A part of it is reproduced in Fig. 3 where the numerals from 1 to 5 are assigned to the knick points to identify the "age" of them. Only the knick points whose "age" can be definitely identified have been plotted in this figure. The identification has been based on the reason that the knick points formed at the same time are mutually connected through the line of abrupt slope change on the hillslopes. It is difficult to find the above connection between the knick points of a small scale. The knick points formed due to the local geological and/or the hydraulic conditions are not mutually connected in the above manner.

Thus it has become possible to process the data by Matsuda[24] using Eq. (15). It is, however, difficult to relate the location of the knick points to the pertinent factors directly through multivariate statistical analysis, because it is hardly possible to evaluate all of these factors at a place. As these factors are closely related to the drainage area, which is always measurable, it can be expected that one has a more reliable result by establishing at first the statistical dependence of these factors on the drainage area. From Eqs. (2), (3), (6) and (15), one has,

$$v_n'=k\left[\frac{Q}{cw}\right]^{\frac{4}{7}n}\{\sin(\theta_n-\theta_c)\}^{\frac{5}{7}n-1}\cos\theta_c. \tag{16}$$

Assuming that Q, W, $\sin(\theta_n-\theta_c)$ and $\cos\theta_c$ can be approximated as some power functions of the drainage area, $A(x)$, one can formally write as,

$$v_n'=k_A(t_0)\{A(x)\}^m, \tag{17}$$

where k_A is a function of t_0 and m a constant. Next, combining Eq. (17) with Eq. (10) expressed in the finite difference, one has,

$$\begin{aligned}\Delta x&=x(t, t_{0,i})-x(t, t_{0,i+1})=v_n'\Delta t_0\\&=k_A\{A(x)\}^m(t_{0,i+1}-t_{0,i}),\end{aligned}$$

where $x(t, t_{0,i})$ and $x(t, t_{0,i+1})$ indicate the present location of the i-th and $(i+1)$-th knick points formed at the time $t_{0,i}$ and $t_{0,i+1}$, respectively, and the bars upon k_A and A^m mean the averaging over the interval $t_{0,i} \sim t_{0,i+1}$ and $x(t, t_{0,i+1}) \sim x(t, t_{0,i})$, respectively. The operation of the averaging can not be immediately executed as the value of m is unknown. However, $A(x)$ changes abruptly at the junctions of the channels and moderately elsewhere. Therefore defining A_j as the average drainage area at the j-th of the fractions of the reach Δx bordered at the junctions and other points, the following equation holds with satisfactory accuracy;

$$\sum_j \frac{l_j}{A_j^m} = \overline{k_A(t_0)}(t_{0,i+1} - t_{0,i}), \tag{18}$$

because $(l_j/A_j^m)/\overline{k_A(t_0)}$ is the time necessary for a knick point to pass through the distance l_j along the channel. As the right side of this equation does not depend on A, the left side becomes a constant if the proper value of m is given. Otherwise the left side contains the variation depending on A_j. Thus the proper value of m can be found through the condition that it minimizes the relative variance of the left side (Fig. 5). Unless the relative variance is treated, this procedure would lead to an improper value of m, because the dimension of the left side of Eq. (18) varies with the value of m. The values obtained in the way of the above procedure is shown in Table 1, which indicates that about a half of the variation in Δx is a function of A (i.e. a function of the hydrogeomorphological condition), and that the remainder is due to other conditions, e.g. the geological conditions and numerical error. It is also indicated that the value of m is larger as the identifying numeral of the knick points is smaller, which correspond to the smaller value of t_0. However, only the average value (0.304) is considered here, because no reasonable explanation is available for this fact.

Next, one has to establish the relationships between the factors in Eq. (16) and the drainage area, A, to find the value of n. When one expresses these factors as the power functions of A, the effect of their time change on v_n is involved implicitly in the coefficient

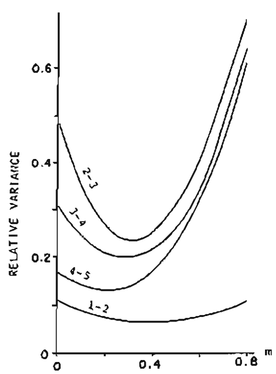

Fig. 5 The relative variance of the value of the left side of Eq. (18) as a funtcion of m for different combination of the knick points.

Table 1 The result of a statistical analysis according to Eq. (18).

Identifying numerals of knick points	Sample size	The value of n	Relative variance	Relative variance ($m=0$)	Average value of $\overline{k_A(t_0)}\,(t_{0,i+1}-t_{0,i})$	Average value of $\overline{k_B(t_0)}\,(t_{0,i+1}-t_{0,i})$
5 and 4	34	0.220	0.130	0.169	154	87.3
4 and 3	42	0.285	0.196	0.311	142	80.2
3 and 2	41	0.310	0.235	0.498	218	123.2
2 and 1	11	0.400	0.063	0.111	183	103.7
	average	0.304			total	394.4

The above values are based on the measured values of the length in meters and on those of the area in hectares.

of proportionality. A direct evaluation of the discharge of the stream, Q, is difficult because it shows great time variation over a wide range of the frequency spectrum. One can, however, assume that it is proportional to A at any point and at any time because it has been found that the base flow coponent is predominant in the discharge from Tanakami mountain range[11,12,25] and that the concentration time of this component is almost independent of the drainage area. The quantity θ_c was estimated as the slope angle of the channel at the reach where the profile of the graded channel seemed to be attained, using the topographical map of the scale of 1:1,000 prepared by the Biwako Construction Office. This procedure has a slight tendency to overestimate the values of θ_c, because some of its values might have been obtained at the reaches where the graded profile is not fully attained. The values of θ_n were measured by field survey. The reaches (usually of a length from 10 meters to 30 meters, but shorter lengths in particular cases) whose average gradient is greater than that of neighboring reaches were chosen as the representatives of the knick points. The choice of the shorter reaches would have led to an extreme value reflecting some local geological conditions. In connection with W, two quantities were measured at the field survey. The one is the interval W' between the lines of abrupt slope change bordering the valley bottom and the steep bank slope. The other is the width of running water W at the time of the field survey and it is far narrower than W'. The quantity W involves a large variation due to the variation of the stream discharge, which appears, however, to be a random variation in correlation with the drainage area. It was observed in the field that channel erosion usually proceeds through the mechanism in which the running water wahses out the disintegrated part of the bedrock along the joints, then isolates the individual rock pieces, and finally makes them come off the channel bed. It was supposed that the erosion takes place within the interval W at individual time through the above mechanism, and that this interval wanders randomly in the valley bottom of a width W', if averaged over a long time. Therefore Eq. (16) should be rewritten for this region as,

$$v_n'=kQ^{\frac{4}{7}n}(cW)^{-\frac{4}{7}n}\left[\frac{W}{W'}\right]\{\sin(\theta_n-\theta_c)\}^{\frac{5}{7}n-1}\cos\theta_c. \tag{19}$$

When a great local variation of these factors or an effect of the erosion control works on them was observed, the measured values were not used in the analysis.

The correlations between these factors and the drainage area are shown in Figs. 6 and 7 on a logarithmic scale, whence,

$$\left.\begin{array}{l} W\propto A^{0.360\pm0.030}, \\ W\propto A^{0.206\pm0.030}, \\ \sin(\theta_n-\theta_c)\propto A^{0.040\pm0.043}, \\ \cos\theta_c\propto A^{0.003\pm0.001}, \end{array}\right\} \tag{20}$$

where the numeral values succeeding to the symbol $\pm$ mean the standard deviation. Except that $\sin(\theta_n-\theta_c)$ is rather independent of A, the other factors are the function of A. It is possible that they are also the function of a quantity independent of A (probably reflecting the geological conditions). Putting this result into Eq. (19) and comparing it with Eq. (17), one finds that n is equal to 0.474.

The independence of $\sin(\theta_n-\theta_c)$ of A suggests that in Eq. (17) k_A may be a function of it. The value K_R, the relative value of k_A to their average value, has been correlated to $\sin(\theta_n-\theta_c)$ on a logarithmic scale (Fig. 8). There are some plots showing particularily small value of K_R. These plots are based on the data at the place where the density of joints in the bed rock is exceptionally small. At such a place the channel seems to be gradually worn down by the running water without the removal of rock pieces from the channel bed, and therefore the erodibility is by far smaller than at neighboring places. The other plots gather around a straight line, whence Eq. (18) becomes,

$$\Sigma(l_j/A_j^m)=\bar{k}_B(t_0)(t_{0,i+1}-t_{0,i})\{\sin(\theta_n-\theta_c)\}^{-0.434\pm0.109}, \tag{21}$$

and Eq. (17) becomes,

$$v_n'=k_B(t_0)\{A(x)\}^{0.304}\{\sin(\theta_n-\theta_c)\}^{-0.434\pm0.109}, \tag{22}$$

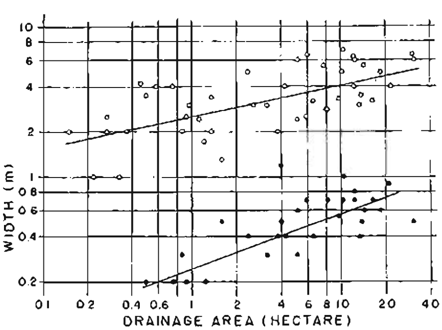

Fig. 6 Statistical dependence of W (bottom) and W' (top) on the drainage area on a logarithmic scale.

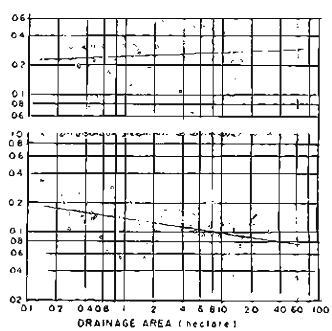

Fig. 7 Statistical dependence of $\sin(\theta_n-\theta_c)$ (top), $\cos\theta_c$(middle), and $\tan\theta_c$(bottom) on the drainage area on a logarithmic scale.

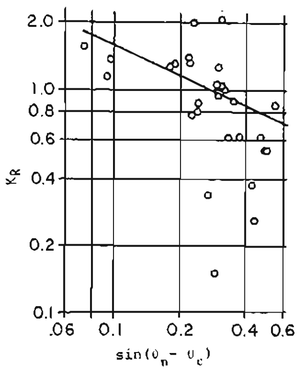

Fig. 8 Statistical dependence of K_R on $\sin(\theta_n - \theta_c)$ on a logarithmic scale.

where $k_B(t_0)$ is a new coefficient. A comparison of Eq. (22) with Eq. (19) leads to another value of n which is 0.792. The difference between the two values of n estimated by the different procedures is thought to be due to measurement error, sampling error at the statistical treatment, etc. Evaluating the error in n from the standard deviation of the factors which is available, one has $n=0.474\pm0.117$ and $n=0.792\pm0.153$. Therefore it would be concluded that the value of n lies between 1/2 and 2/3 if a narrow range of estimation is taken.

The above result is applicable to any point on the channel, not only to the knick points. One can, then, remove the subscript n from the above formulae. Though E increases as Q increases, the rate of the increase of the former is similar to that of $Q^{1/3}$ as E is proportional to $Q^{\frac{4}{7}n} \simeq Q^{1/3}$. Therefore, the smaller the time variation in Q, the more is the erosion in a certain period, if the total discharge in this period is the same (see Appendix I). It yields, along with the fact that the baseflow is predominant in the total runoff, a property of the channel erosion of this region that the base flow component of the stream discharge is much more significant in the channel erosion than the direct runoff. It also turns out that an increase of θ brings about an increase of E but a decrease of v. This nature leads to a tendency of steepening of the channel system (see Apepndix II). If the value of n exceeded 7/5, the subduing of the steepeness would occur.

In Eq. (22), k_B is a function of t_0. The values of $\overline{k_B(t_0)(t_{0,i+1}-t_{0,i})}$ averaged for the same combination of the knick points are shown in Table 1. The effect of local conditions on k_B has been smoothed out in these values, so that $\overline{k_B(t_0)}$ represents only the effect of the climatic change (e.g. the long term variations of rainfall and the coefficient of runoff). Though the sample size is not sufficiently large, the fact that the values of $\overline{k_B(t_0)}(t_{0,i+1}-t_{0,i})$ in Table 1 are rather constant (the value of the ratio of the maximum to the minimum being about 1.5) for varying "age" of knick points suggests that both $\overline{k_B(t_0)}$ and $(t_{0,i+1}-t_{0,i})$ have been constant throughout the geomorphological development in this region, because they are statistically independent of each other. It might seem unreasonable that $k_B(t_0)$ which involves the effect of the climatic change throughout the Pleistocene, is constant, as it was the age of repeated glaciation[26]. It is, however, probable that the effect of the climatic change has been smoothed out as the values of $k_B(t_0)$ are the average over the time interval from $t_{0,i}$ to $t_{0,i+1}$ whose length is supposed to be of an order of magnitude of 100,000 years (cf. next chapter) and somewhat longer than the recurrence interval of the glacial ages[26]. Though an explanation is needed for the constancy of $(t_{0,i+1}-t_{0,i})$, this is the problem of geodynamics and shall not be discussed here.

The deviation of the values of $k_B(t_0)$ for individual pair of the knick points from the average values is expected to involve the dependence of $k_B(t_0)$ on the locality of the knick points. It would be appropriate to calculate the relative value of $\overline{k_B(t_0)}$ through dividing the value of $\overline{k_B(t_0)}(t_{0,i+1}-t_{0,i})$ for each pair of the knick points by the average value for the same combination of i and $i+1$ shown in Table 1. The distribuction of this relative value on a map has shown no simple correlation with the systematic geological structure of this region. It is, therefore, concluded that they depend on the local geological conditions.

5. Simulation of the development of channel profiles

In order to ascertain the property of the downward erosion of the channel as derived above, and for the quantitative evaluation of its rate in the natural state, simulation of the development of the channel profile has been tried. According to the above results, the retreat of the channel toward the direction upstream with an angle of incidence of θ_c is expressed as,

$$\mathrm{d}x = v\,\mathrm{d}t, \tag{23}$$

$$\mathrm{d}z = v \tan\theta_c \mathrm{d}t + G(t)\mathrm{d}t, \tag{24}$$

if $\theta > \theta_c$, where $G(t)$ is the rate of uplift of the earth crust. Assuming that v, θ_c, and G are the functions of t and/or x, the trajectory of any point on a channel is given by solving Eqs. (23) and (24) simultaneously, whose schematic representation is given in Fig. 9. In this diagram the point which started at x_0 retreats along the profile of graded river A_1A when no crustal movement takes place. During the crustal uplift it takes a course such as A_2B_1, and again retreats along B_1B when the uplift has stopped, and so on. Fig. 10 shows the present profile of a channel in this region and the trajectories of the knick points on it when $G=0$ is assumed. The differences among their height represent the height of uplift which caused the occurrence of each knick point.

The time change of the channel profile can be estimated by calculating the profile after a short time Δt using Eqs. (23) and (24), and repeating it. The quantity v should,

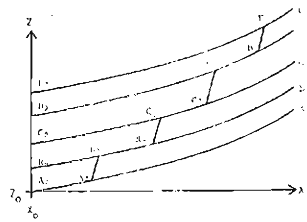

Fig. 9 A schematic representation of the trajectory of a retreating knick point on a profile of a channel.

then, be substituted beforehand with the function of x and t using Eqs. (15) and (22). The quantity G was assumed to be zero, which, however, does not lead to an error in the shape of the channel profile in the interval from the location of the most downstream knickpoint to the source point of the stream, as the effect of the crustal uplift does not spread beyond the knick points formed by it. Eqs. (23) and (24) are now rewritten in a nondimensional form as,

$$\frac{dx'}{dt'}=k'(t')\{A'(x')\}^{0.3}\{\sin(\theta-\theta_c)\}^{-0.4}, \tag{25}$$

$$\frac{dz'}{dt'}=\frac{dx'}{dt'}\tan\theta_c, \tag{26}$$

where,

$x'=x/L$,
$z'=z/L$,
$t'=t/T$,
$A'=A$ (in hectare),
$k'=k_BT/L$.

The quantity L and T denotes the distance between the knick points No. 1 and No. 5, and the difference of the time of occurrence between them, respectively. The coefficient k' was assumed to be constant, and was evaluated as a sum of the values of $\overline{k_B(t_0)}(t_{0,i+1}-t_{0,i})$ in Table 1 divided by L (the numeral value being 394 meters in the time T). It can be easily shown that a knick point retreats through the distance between the knick points No. 1 and No. 5 theoretically in the time T.

The result of the simulation in the above manner starting with the contemporary channel profile is shown in Fig. 11 for the channel named T–10. Almost parallel recession of the channel profile is seen there, which coincides with what has been stated above concerning the development of the channel profiles. A tendency of steepening of the gradient of the channel is also seen. It is due to the effect of the drainage area decreasing upstream and thus making the rate of erosion decrease upstream, as well

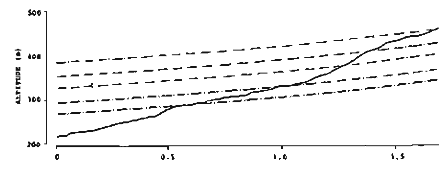

Fig. 10 A profile of a channel named T–10 (solid line) and the the trajectories of different knick points (chained lines).

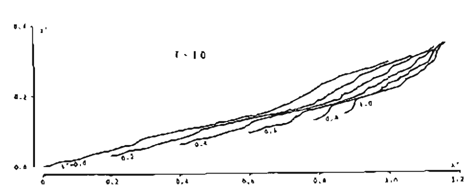

Fig. 11 The result of a simulation of the development of a channel profile according to Eqs. (25) and (26) starting with the contemporary profile shown in Fig. 10.

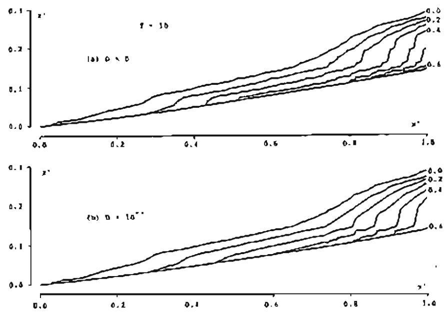

Fig. 12 The effect of the linear diffusion term introduced in Eq. (28) on the development of channel profile. The numeral beside each curve represents the relevant value of t'.

as the effect of the value of n being less than 7/5. The steepening of the channel profile in the way of its retreat leads to the result that the channel profile is steeper at an upstream knick point than at a downstream one because the channel is "older" at the upstream knick point. The actual channel profile, however, shows no such tendency (see Fig. 7). It is probable that another factor than those expressed in Eqs. (25) and (26) is active in maintaining the gradient of the channels beneath a limiting value.

It is commonly accepted that geomorphological evolution is usually more or less of a diffusive nature. Introducing the mathematical expression as proposed by Scheidegger[27] and adding the linear diffusion term proposed by Hirano[28], Eqs. (25) and (26) can be rewritten in the form of a partial differential equation as,

$$\frac{\partial z'}{\partial t'}=-k'(t')\{A'(x')\}^{0.3}\{\sin(\theta-\theta_c)\}^{0.6}\sec\theta+D\frac{\partial^2 z'}{\partial x'^2}, \tag{27}$$

where D is the nondimensional diffusivity. In order to express such a frontal features as knick points correctly, it is recommended[29] to solve this equation with a computer after rewriting it as,

$$\frac{\partial x'}{\partial t'}=k'(t')\{A'(x')\}^{0.3}\{\sin(\theta-\theta_c)\}^{0.6}\operatorname{cosec}\theta-D\frac{\partial}{\partial z'}\left[1\Big/\frac{\partial x'}{\partial z'}\right], \tag{28}$$

using the relations,

$$\frac{\partial z'}{\partial t'}=-\left[\frac{\partial x'}{\partial t'}\right]\Big/\left[\frac{\partial x'}{\partial z'}\right],$$

$$\frac{\partial z'}{\partial x'}=1\Big/\left[\frac{\partial x'}{\partial z'}\right].$$

The solution of Eq. (28) for the channel T–10 is shown in Fig. 12 choosing the values of D as zero and 10^{-4}, respectively. The features presented in these diagrams are more different from those of the actual channels than in Fig. 11. A part of the channel profile is buried in the profile of graded channel as time lapses, because the finite difference of Eq. (28) leads to a horizontal retreat of the knick points, if a simple method of numerical differentiation is adopted. However, it can be found from this result that the introduction of a linear diffusion term was not successful in this case, because it has not been effective in cancelling the tendency of the steepening of the knick points but has brought a disadvantageous result of diffusing out the knick points. Therefore, another explanation is needed. A further discussion shall be given later.

The contemporary distribution of the value of E along the channel and the time change in E at a fixed point on the channel have been calculated when solving Eqs. (25) and (26) as shown in Figs. 13 and 14, respectively. The quantity $\partial z/\partial t$ is plotted in Fig. 13 according to the assumption that T is 1,000,000 years, a half of the duration of the Pleistocene. This assumption is based on the consideration that the monadnocks in Tanakami mountain range belong to the erosional surface at the height of about 500 meters which was formed in the Plio-pleistocene.[4] It is seen in this diagram that the rate of the channel erosion is particularly large at the reaches of a length of 100 meters or so downstream the knick points. There are some local knick points other than what is classified according to the time of their occurrence and marked with the symbol * in this diagram. It can be seen in this diagram that a uniform wearing down is proceeding in this region as an average, because the pattern in Fig. 13 moves upstream. Fig. 14 also indicates the same property. It is observed that the maximum value of $\partial z/\partial t$ is of an order of magnitude of 1 mm/year in these diagrams.

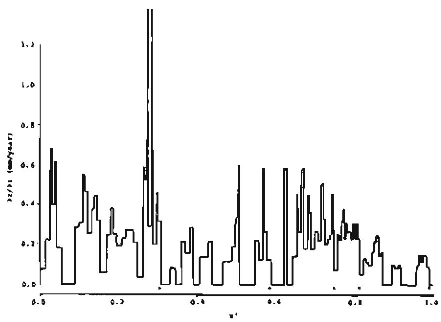

Fig. 13 An example of the distribution of the rate of the drawdown of the channel bed. The mark * represents the location of such knick points as shown in Fig. 3.

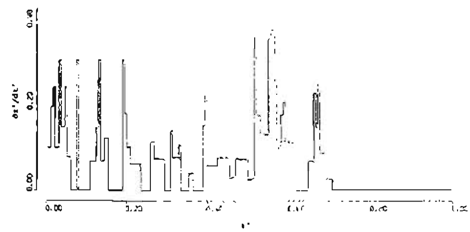

Fig. 14 An example of the time change of the nondimensional rate of the drawdown of the channel bed at a fixed point on the channel.

6. Hillslope profiles and hillslope processes

As the hillslope erosion is commonly accompanied by the transport of sediment along the direction of the maximum gradient, a hillslope can be treated as a set of its profiles along this direction. Transversal cross sections of a small ridge between two streams are illustrated in Fig. 16 with the plan in Fig. 15. The internal structure

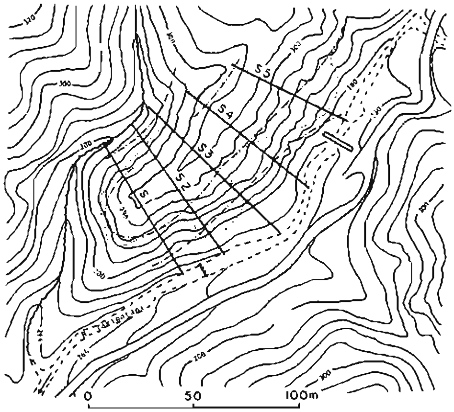

Fig. 15 A map of a small ridge indicating the locations of its transversal cross section illustrated in Fig. 16. The dotted line and the chained lines represent the border between different vegetative cover and the lines of abrupt slope change, respectively.

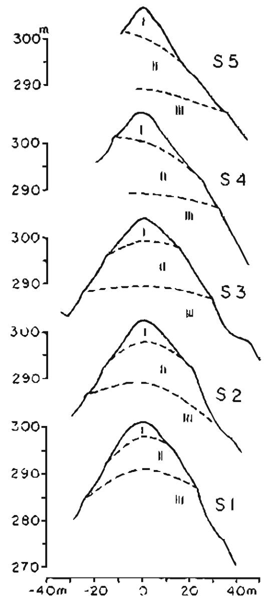

Fig. 16 The transversal cross sections of the ridge shown in Fig. 15 at different location. The Roman numerals identify the weathering zones.

of the ridge is also illustrated in Fig. 16 according to the field observation of surface geology[4] and the result of a seismic prospecting by Nakagawa[14]. The ridge involves the three zones of weathering as stated in Chapter 2. Each of them has a characteristic slope angle, suggesting the different erosional processes on them. The lines of abrupt slope change frequently occur at the borders among these zones. Fig. 16 shows a typical example thereof.

The profiles of hillslopes are commonly divided into some elementary slopes by the points of abrupt slope change which manifest themselves as a line of abrupt slope change on a plan. It is noted that these elementary slopes are concave except near the ridge point, whereas the slopes are, as a whole, convex. Such a feature seems to reflect the particular physical processes predominant on the hillslopes.

The result of the analysis in the above chapters make it possible to reconstruct the history of the evolution of the channel profile. The change in the profiles of the hillslopes is conditioned by the history of the channel drawdown. The other conditions of the hillslopes do not seem to show an extreme change with time or with space. Therefore, it stands to reason to consider that the hillslopes change in their profiles with time as if they move upstream along with the retreating channel. Thus it is possible to rearrange the profiles of the present hillslopes along a channel as a time series of their developing profiles. The practical procedure of it is as follows; The relative time, t' required for a knick point to retreat from the present location of the knick point No. 5 (the newest) to the location of any point on the channel is calculated using Eq. (25). This is the "age" of the channel at the location. Next, a graded profile passing a knick point on the actual profile is superimposed to the latter. As the graded profile coincides with the trajectory of this knick point, the level of the channel at any point relative to that of the graded profile represents the depth of the channel erosion since the passage of the knick point. Finally the hillslope profiles in different location are drawn on the same paper putting the above level as the datum level, with the "age" of the channel at each location written asides. The example of this for the channel named T-18 is illustrated in Figs. 17, 18, and 19. Fig. 19 indicates that the hillslopes became gentler during their denudation when slow or no channel erosion took place, and that a rapid channel erosion brought about a steepening of the hillslopes near their feet. The combined effect of these processes seems to lead to a parallel recession of the hillslopes as a whole in this region.

It has been observed that the dynamic balance of sediment does not hold also on the hillslopes. Therefore, the rate of erosion on the hillslopes can be expressed by the formula analogous to Eq. (22) in which n is equal to the unity (see Appendix II), and one has,

$$E=K\sin(\phi-\phi_c), \qquad (29)$$

where E is again the rate of erosion (normal to the slope), ϕ the slope angle, ϕ_c its critical value, and K a constant. Eq. (29) ignores the variety of the denudational processes active in different parts of the hillslopes. It is, however, possible to evaluate an approximate value of the rate of denudation of the hillslopes through a simulation using Eq. (29) putting adequate values of K and ϕ_c. The value of ϕ_c can be estimated from the trajectories of the points of abrupt slope change, and Fig. 19

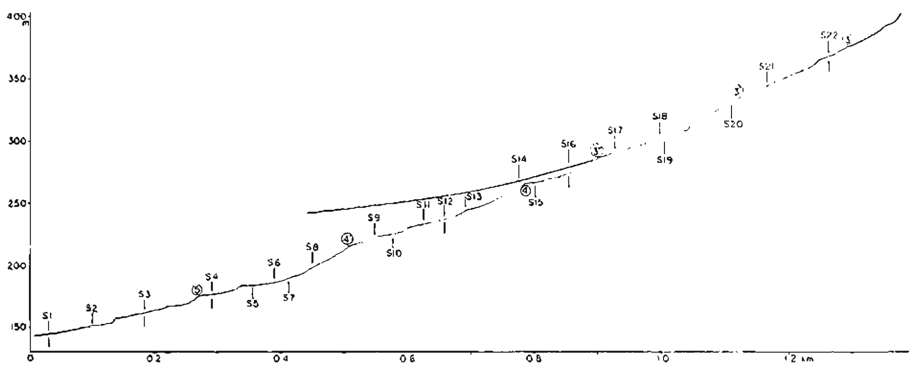

Fig. 17 A profile of a channel (T-18) indicating the locations of the cross section illustrated in Fig. 18. A profile of the corresponding graded channel is superimposed to illustrate the depth of the channel erosion after the passage of the knickpoint 3".

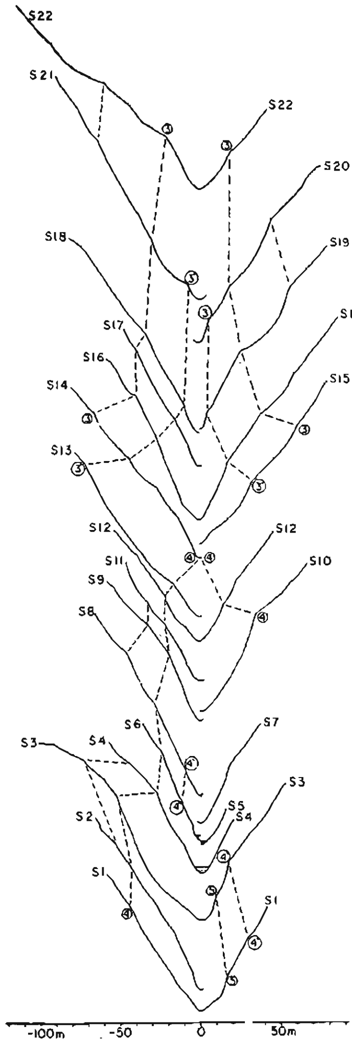

Fig. 18 The profiles of hillslopes along the cross section of the channel T-18 shown in Fig. 17. The lines of abrupt slope change corresponding to the knick points on the channel profile are indicated by the same numerals with that of the latter shown in Fig. 17. The veritcal scale is enlarged two times. Each profilea is on a respectively arbitrary datum level.

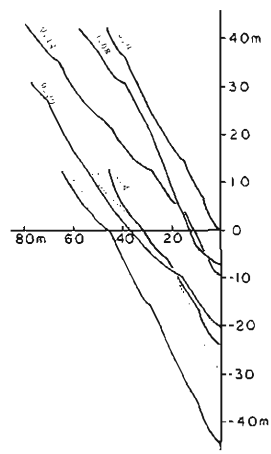

Fig. 19 The time series of developing profiles of a hillslope as constructed from the profiles in Fig. 18. The numeral values indicate the values of the nondimensional time t' after the passage of the knick point 3" at the foot of the hillslope.

suggests that it is 11.7 degrees. The result of the simulation starting with the profile S17 in Fig. 18 is shown in Fig. 21, where the time change in the channel level was assumed as shown in Fig. 20, and the value of K was decided as,

$$KT = 200 \text{ meters},$$

from the condition that the hillslope must be of similar profile as shown in Fig. 19 when t' is 0.35. Thus Eq. (29) is written in a concrete form as,

$$E = 200 \sin(\phi - 11.7 \text{ deg.}) \text{ meters in the time } T. \tag{30}$$

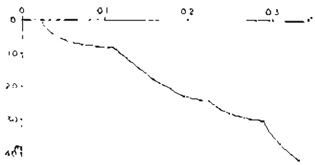

Fig. 20 The history of the drawdown of the channel T-18 at the location of S8 in Fig. 17 estimat ed through the procedure described in the text.

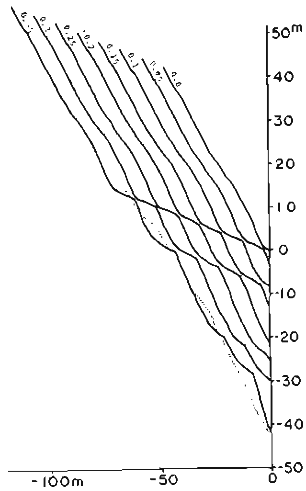

Fig. 21 The result of the simulation of the development of the hillslope according to Eq. (29) starting with the profile S17 in Fig. 19. The numeral values indicate the values of t'. The dotte line represents the profile in Fig. 19 when $t'=0.35$.

7. Discussion

The channel profiles and the hillslope profiles have been analyzed on a hydro-geomorphological basis in the preceding chapters.

The analyses in Chapter 4 and 5 have led to the conclusions that channel erosion is mainly caused by the base flow component of the stream discharge, and that the channel profile becomes steeper during its retreat. The former property leads to the asynchronism of the sediment transport between on the hillslopes and in the channels, because the sediment transport on the hillslopes takes place only when there are heavy rain storms[13]. Therefore, the deposit of sand and the abrupt slope change in the longitudinal profile of the valley bottom are commonly seen at the source points of the streams.

The latter property is contradictory to the observational fact that the channel gradient at a knick point is almost independent of whether the knick point is at a downstream reach or at an upstream reach as seen in Fig. 7 and in Eq. (20). Therefore, some discussion is needed here. A limit of the gradient of the channel might exist beyond which the channel becomes unstable with the rate of erosion exceeding what is expected from the above analysis. It is also probable that the channel erosion at a usual reach is slower than what is predicted from Eq. (22) based on the retreat of knick points. In this connection, the systematic error in the evaluation of θ_c and the deviation of Eq. (4) from the real hydraulics of the knick points may have led to an underestimation of n. A larger number of n than has been given above will produce a channel recession nearer to the parallel recession.

The component of the variation in the rate of the channel retreat which can not be explained on the hydrogeomorphological basis is attributable to the effect of local geological conditions because it shows no regularity in its spatial distribution. Though the real picture of the geological condition in the sense taken above is not obvious, the comparison of the geomorphological properties of this region with those of the other granitic regions suggests that the size of mineral grains of the granite and the direction and the density of joints in the bedrock are the major factors of the "geological conditions".

As the density of joints in the bedrock is not uniform, the effect of rock control can be expected on the channel profiles. There are knick points with a large discontinuity of the channel level. Some of them are located at the sites where the bedrock is sparsely jointed. Such an effect of rock control may disturb the upstream retreat of the channel and make the rate of retreat of the knick points deviate from what is predicted from Eq. (22). The geological investigation sufficient for a quantitative discussion about the "geological conditions" in the erosional processes in this region has not been available.

The morphology and the denudational processes of hillslopes has been treated in Chapter 6. It has been revealed that they consist of concave elementary slopes. The borders between the neighboring elementary slopes represent the lines of abrupt slope change which cross the valleys and the ridges at the knick points. They are eminent when they occur at the borders between different weathering zones. The latter seem to make the former to stay there for a time in the course of their retreat.

Hillslopes involve different weathering zones in their interior. These zones seem to be subject to their respective fashion of the erosional processes; creep and sheet erosion at Masa-soil zone, water erosion varying from sheet erosion to gully erosion at mixture zone and rockfall at fresh rock zone in the bare lands, mass movement in the shallow layers being predominant in the forested lands. Though the law of the slope recession is different in various weathering zones, it is reasonable to postulate that the erodibility is larger at upslope part than at downslope part reflecting the degree of weathering. It is also reasonable to postulate the direct erosion of a rocky slope because no significant deposition of sediment is seen on the hillslopes except for the creeping Masa-soil on the ridges and the thin layer of screes on the bank of the graded reaches of the channels. It has turned out that Eq. (30) could explain the quantity of the recession of the hillslope picked up as an example rather well, though this equation can not describe the different erosional processes on the individual elementary slopes.

Whereas the rate of the channel erosion varies extremely with time and space, it has been revealed that it is rather constant if averaged either over the time or over the space, and that the maximum rate of the channel erosion probable at a point under the "natural" conditions (without the bare-land conditions due to the human activities) is of an order of magnitude of 1 mm/year if the difference in the time of occurrence between the knick points No. 1 and No. 5 is assumed to be 1,000,000 years. The rate of hillslope denudation averaged over a slope can be estimated from Eq. (30) to be of an order of magnitude of 0.1 mm/year. Concerning the average picture of denudation in this region, it can be assumed that the hillslope processes represent a parallel recession as a result of combined effect of subduing and stimulation of the steepness. Therefore, the average rate of the channel erosion is available as an estimate of the average rate of the hillslope denudation. The former is written as,

$$\partial \bar{z}/\partial t=\int (\partial z/\partial t)\mathrm{d}A/A_t, \tag{31}$$

where $\mathrm{d}A$ denotes an infinitesimal area of the hillslope the foot of which is being downcut at the rate $\partial z/\partial t$. The integration is carried out over the whole area A_t. As $\partial z/\partial t$ is defined along the channel, the above equation can be rewritten as,

$$\partial z/\partial t=\int_0^L (\partial z/\partial t)\{\mathrm{d}A(x)/\mathrm{d}x\}\,\mathrm{d}x/A_t, \tag{32}$$

where $A(x)$ is defined as in the above chapters. Concerning the catchment area of the channel T-10, the value of $\partial z/\partial t$ thus calculated is 0.18 mm/year. In this connection, the average rate of the crustal uplift in this region is evaluated in Fig. 10 as about 0.12 mm/year.

The bare-land conditions of this region due to the human activities occurred either in the Nara era or in the Edo era according to different literatures,[2,5] and the afforestation work has been carried out intensively since the Meiji era. At any rate, the history of the bare-land conditions due to the human activities is a momentary event compared with the history of the development of the erosional surfaces. Therefore, such a bare-land conditions can not have brought about a significant effect on the contemporary topography of this region except for the micromorphological features. However, the contemporary rate of hillslope denudation must be much different from the average value as estimated above, because it is very sensitive to the vegetative cover. Takei and Fukushima[13] have observed the rate of denudation of 13–15 mm/year at a naked hillslope with the gully erosion of Masa-soil and a sediment production of 4,400 m^3/km^2/year (equivalent to the rate of denudation of 4.4 mm/year if no volume change is assumed) from a naked hillslope without gully erosion, whereas eventually no sediment production has observed on a forested slope by them. It is, therefore, suggested that the present rate of hillslope denudation is by far larger than that in the natural conditions, and that it can be decreased into a level of an order of magnitude of 1 mm/year or less through the adequate treatment for the problem of afforestation.

The characteristics of the erosional processes in Tanakami mountain range discussed above is thought to be due to the geological conditions of the bedrock and to the properties of the external agents on it. As the knick points of the channels and the ridges are frequently seen in the regions of granite or of similar rocks in Japan, it stands to reason to consider that such an erosional features are due to the common characteristics of granitic rocks. A different fashion of the erosional processes is seen in some region of granite where pediments are developing. By an elaborating work of Akagi[30] it has turned out that the feature of pediment develops under the specific lithological and climatological conditions. The climatological effect on the geomorphological processes of the granitic regions seems to involve the determination of the form of weathering[31]. Arid and semiarid climate is combined with physical weathering mainly due to temperature change, and is apt to lead to the occurrence of the inselberges and the pediments.

Other features are seen in the regions where the chemical weathering of granite is active. It is carried out in Japan mainly in the form of the degradation of feldspar into clay minerals, and is recognized through the chemical analysis of the land waters.[16] In such a region, mass movement seems to be the major form of denudation, because a thick layer of clayey weathering product commonly develops on the hillslopes[33]. Typical cases thereof are seen in some parts of Rokko mountain area, in the granitic region to the south of the Lake Shinji, etc.

Intensively fractured granite under the physical weathering agents seems to manifest such a feature as seen in Tanakami mountain range. Similar features are frequently found in the regions around the Inland Sea and have been described in the literatures[32]. The piedmont surfaces in Chugoku district and in the Abukuma mountain range are famous and have been studied for a long years[32]. They are, however, of a large scale, and it is difficult to decide whether they are due to the geological conditions similar to those of Tanakami mountain range.

Oyagi[33] has pointed out that the different fashions of weathering of the granitic rocks lead to the different aspects of natural hazard in the denudational process. Tanaka[34] has pointed out that the transitional zone between the parts belonging the different erosional cycles is also the transitional zone of the denudational processes both in the qualitative and quantitative senses. Fukushima et al[35] have found that the Kawamukai experimental drainage basin in Tanakami mountain range is of different hydrological properties from those in the Kiryu experimental drainage basin in the neighboring mountain range.

The major external conditions which have led to the present features of Tanakami mountain range are thought to be the crustal uplift and the erosional action of running water. As the final base level of erosion is the sea level, a very long term average of the rate of denudation is nearly equal to the rate of uplift. Therefore, whether the rate of uplift is larger or smaller than that of weathering is critical though the latter is dependent on the former. In Tanakami mountain range, the direct erosion of rocky hillslopes is commonly observed. This indicates that the rate of weathering is not larger than that of erosion. If the rate of weathering were greater than the rate of uplift, denudation would take place mainly in the form of mass movement. Similar condition is expected to occur where the chemical weathering action of the groundwater is effective, because its activity does not depend on the exposure to the atomosphere. Among the physical weathering actions, fracturing can take place at any depth. It enables the everlasting downcutting of the channels in Tanakami mountain range. Other physical weathering actions can take place essentially only near the ground surface.

In Tanakami mountain range, the crustal uplift has brought about the rapid downcutting of the channel. The foot of a hillslope becomes a rock wall when affected by the passage of a knickpoints, and in another time, is covered with thin layer of screes. Here, erosion can be stimulated by a great slope angle without significant weathering. The influence of channel drawdown propagates to the middle part of a hillslope in somewhat indirect fashion. There the ground water infiltrating into the ground along the joints can disintegrate the rock nearby into mineral grains. Thus the rocks have become a mixture of materials with varied degrees of weathering. This form of weathering may attain great depths as far as the ground water flow is available. At the top of a hillslope is the perfectly disintegrated granite (Masa-soil), probably because sufficient time for weathering is available there.

Thus it has been revealed that different forms of erosion are active at different parts of hillslopes in contrast to the fact that the channel erosion is subject to the same process everywhere. Quantitative description of each physical process on the hillslope is left for future researches.

8. Conclusions

The rate of retreat of the channel along the direction of the retreat of the knick points was related to the rate of erosion, and the latter was written as a power function of the hydrogeomorphological quantities of the channel taking account of the direct erosion of the channel bed. Next, the distance between two knick points on the same channel which had occurred at different times was related to the rate of the channel retreat. A statistical analysis of the contemporary distribution of the knick points led to the following equations,

The rate of erosion: $E=k(\tau-\tau_c)^n \qquad (1/2<n<2/3)$,

The rate of retreat: $v=k_B(t)\{A(x)\}^{0.3}\{\sin(\theta-\theta_c)\}^{-0.4}$,

where,

$v=E\,\mathrm{cosec}(\theta-\theta_c)\cos\theta_c$.

The other equations (Eqs. 20) relating the geometrical property of the channels to the drainage area were also established. These equations indicate that the channel erosion is carried out mainly by the base flow component of the stream, and that the knick points do not diffuse out during the retreat, and that a steepening of the knick points occurs in the same time. These characteristics coincide with what are actually observed in this region except for that no evidence of steepening can be found at the knick points. Some mechanism cancelling the steepening is needed. It was also revealed that $k_B(t)$ does not contain a significant time change with long periods (say,the periods greater than 100,000 years), and that the repeated crustal uplift causing the development of geomorphological surfaces has occurred periodically with almost the same magnitude everytime.

It was found that hillslopes are divided into some elementary slopes by the lines of abrupt slope change which run almost parallel to the contour lines and cross the channels at the knickpoints. The elementary slopes are usually concave ecxept at the ridge. A sequence of the hillslope profiles along the course of a stream was rearranged to construct a time series on the basis of the history of channel erosion given by the result of the analysis of the present channel profile. This time series revealed that the upper part of the hillslope recedes with decreasing slope angle when the channel erosion is slow, and that a heavy drawdown of the channel induces a rejuvenation of the bank slope by steepening it. The combined effect of the above two processes seems to lead to a parallel recession of the hillslope, thereby one finds similar hillslopes both at the upstream and the downstream parts of a drainage basin. It was suggested that the three weathering zones (the Masa-soil zone, the zone of mixture of Masa-soil and slightly weathered rocks, and the zone of fresh but fractured rocks) have different processes of denudation on them, the erosive agents being different. A simple relationship for the rate of denudation,

$$E = k\sin(\phi - \phi_c),$$

was assumed ignoring the variety in the denudational processes. The result of the simulation of the hillslope development according to this equation has revealed that the value of K is about 0.2 mm/year. The average rate of denudation over this region expected under the natural conditions was estimated to be of an order of magnitude of 0.1–0.2 mm/year. This value is smaller by a factor of more than ten than what has been actually observed under the bare-land conditions due to the past human activities.

The properties of the erosional processes in Tanakami mountain range as revealed above have been interpreted as characteristic of granitic bedrock which is being lifted periodically under a lateral geodynamical pressure common in southwest Japan in the Quarternary, and exposed for a long time to physical weathering agents. The particular form of the erosional law such as Eq. (3) in this paper seems to be due to a common nature of granitic rocks under direct erosion. This nature can lead to the occurrence of different erosional surfaces when repeated uplift of the crust with adequate magnitude takes place. The particularity in the channel processes in Tanakami mountain range seems to be also due to the rate of the crustal uplift exceeding that of the weathering and to the dense fracture system. The hillslopes in Tanakami mountain range can take every form of the erosional processes expected for physically weathered granite according to variable external conditions. They are rockfall, gully erosion, rill erosion, sheet erosion, shallow slides, and creep.

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Appendix I The Depedence of the Channel Erosion on the Time Change in the Stream Discharge

In order to consider the effect of the relative variation in the stream discharge Q on the rate of channel erosion E when the latter is proportional to the m-th power of the former, the equations,

$$Q=Q_0(1+x), \tag{33}$$

$$\bar{E}=\frac{1}{T_0}\int_0^{T_0} E\,dt, \tag{34}$$

are introduced, where Q_0 and $\bar{E}$ are the mean values of Q and E in a sufficiently long time T_0, respectively. From these equations one has,

$$\bar{E}=\frac{Q_0{}^m}{T_0}\int_0^{T_0}(1+x)^m dt. \tag{35}$$

The Taylor expansion of the integrand leads to,

$$\bar{E}=Q_0{}^m\int_0^{T_0}\left\{1+mI_1+\frac{(m-1)}{2!}I_2+\frac{m(m-1)(m-2)}{3!}I_3+\dots\right\} \quad (36)$$

where,

$$I_n=\frac{1}{T_0}\int_0^{T_0}x^n\,\mathrm{d}t,$$

is the n-th moment of x. In this case,

$$I_1=\bar{x}=0,$$

and thereby,

$$I_2=\text{variance}=\sigma^2,$$

$$I_3=\text{skewness, etc.,}$$

have certain values according to the stochastic property of the discharge Q. It is sufficient here to consider the dependence of E on I_2, because the latter represents the magnitude of the relative variation of Q. It is obvious from Eq. (36) that if $m>1$ E increases with I_2, and that if $0<m<1$ the reverse is the case. If $m=1$, E is independent of I_2.

Appendix II The Dependence of the Slope Recession on the Slope Angle of the Channels and the Hillslopes

An erosional law,

$$E=K\{\sin(\theta-\theta_c)\}^m, \quad (37)$$

is applied to the channels or to the hillslopes with arbitrary profiles, where E is the rate of denudation in the direction normal to the slope, θ the slope angle, θ_c the critical value of it, and K and n the constants. At an arbitrary point P (see Fig. 4), the depth of the erosion during an infinitesimal time $\mathrm{d}t$ is,

$$\mathrm{PP}''=E\,\mathrm{d}t=K\{\sin(\theta-\theta_c)\}^m, \quad (38)$$

The distance of retreat of the point P along the direction upslope with the angle of incidence θ_c during the time $\mathrm{d}t$ is, then, given by,

$$\mathrm{PP}'=\mathrm{PP}''/\sin(\theta-\theta_c)=K\{\sin(\theta-\theta_c)\}^{m-1}\,\mathrm{d}t. \quad (39)$$

It is, therefore, obvious that the rate of retreat along this direction increases monotonically with θ when $m>1$. It means that the steeper part of a slope retreats faster. If $m<1$ and the slope angle decreases monotonically downslope, as is the case in Chapter 4, the downslope part retreats faster and causes the steepening of the slope during the recession until every part has the same slope angle equal to the maximum of the initial values. If $m=1$, the rate of retreat along this direction is equal to K notwithstanding the value of θ. It means the parallel recession in the strict sense along this direction.