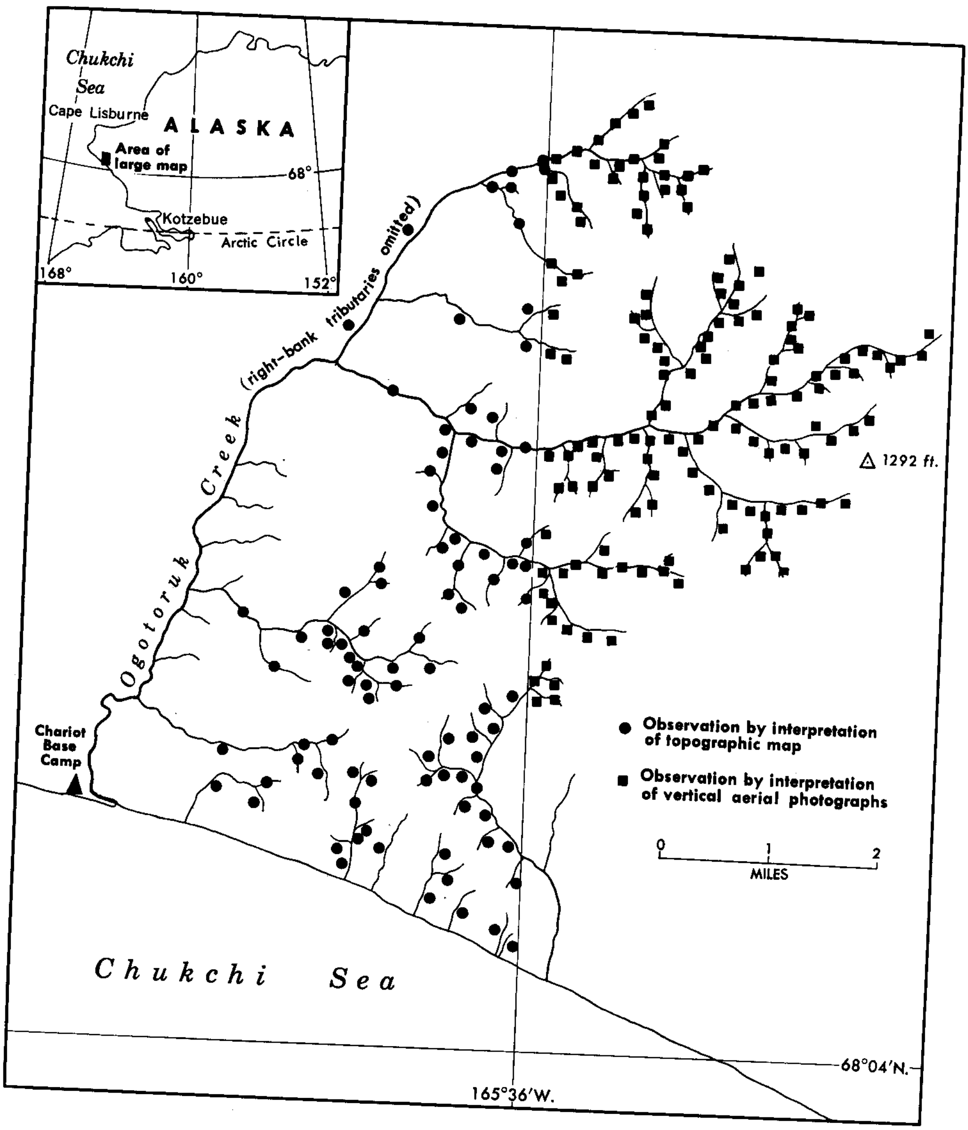

Fig. 1. Map of the Ogotoruk Creek area showing eastern part of the Ogotoruk drainage, several adjacent streams, and locations of symmetry observations. Observation symbol astride drainage line denotes little or no observable asymmetry; symbol to side of drainage line denotes steeper valley side. Map interpretation observations pertain to entire stream segments; aerial photograph interpretation observations are of transverse profiles at intervals of 0.2 mile.

A PRELIMINARY STUDY OF VALLEY ASYMMETRY IN THE OGOTORUK CREEK AREA, NORTHWESTERN ALASKA*

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MANY stream valleys in northwestern Alaska, between Kotzebue and Cape Lisburne, appear in reconnaissance view to be asymmetric in transverse profile. That is, opposing sides of many of the valleys appear to have quite dissimilar slope angles. Most striking is the apparent frequency with which the steeper slope angles are assumed by north-facing valley sides. The writer was, therefore, pleased to avail himself of the opportunity to examine in some detail the valley asymmetry in, and adjacent to the watershed of Ogotoruk Creek (Fig. 1), an area readily accessible from a base camp at the site of the proposed Project Chariot nuclear excavation. This paper seeks to give an indication of the degree to which valley asymmetry in the Ogotoruk Creek area is preferentially oriented and to discuss the asymmetry in terms of processes that may be responsible. Field observations on which this paper is based were made during the summers of 1959 and 1960 in conjunction with geologic mapping programs of the U.S. Geological Survey in support of Project Chariot of the Atomic Energy Commission.

Setting

Ogotoruk Creek is about 115 miles north of the Arctic Circle, about 120 miles northwest of Kotzebue, and about 60 miles south of Cape Lisburne. The creek, which is approximately 12 miles long with a drainage basin of about 40 square miles, flows generally south-southwest into the Chukchi Sea. The pattern of Ogotoruk drainage is essentially dendritic. Along the coast several short, steep, relatively straight resequent streams flow directly into the sea. Relief in the area is slightly less than 1,300 feet, defined by a high point 5.5 miles from the sea. The land rises abruptly to altitudes of more than 800 feet at several points within 1 mile of the coast. That part of the Ogotoruk watershed and the adjacent area considered in this study are underlain by interbedded mudstones, siltstones, and sandstones of Jurassic and Cretaceous age that have been highly deformed (Kachadoorian *et al.* 1960, p. 6). The multitude of small but intricate structural complexities that characterize the bedrock minimize whatever morphogenic influence

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may be exerted by the gross structural grain, a grain which trends north-northeast.

The region is treeless, generally covered by tundra on lower slopes and rubble-strewn on upper slopes, and lies entirely in the zone of continuous permafrost. Mean annual temperature at Kotzebue (based on 19 years of record) is 20.7°F. and that at Cape Lisburne (based on 9 years of record) is 17.4°F. (U.S. Weather Bureau 1962). Mean monthly temperatures at the Chariot base camp were below freezing from October 1959 to April 1960; from late October to early April daily maximum temperatures were rarely above freezing (Committee on Environmental Studies for Project Chariot 1960, p. 45). The surface of the ground at the Chariot base camp was frozen from November 1959 to April 1960 and was partly or entirely frozen from September to May (*ibid.*, p. 47); depth of seasonal thaw ranges from a few inches to a few feet. As a rule there is little or no flow in Ogotoruk Creek from late October to early May (*ibid.*, p. 13).

Methods of study

In this preliminary study three methods were employed to collect basic data regarding valley symmetry.

(1) Sixty-seven transverse profiles regularly spaced along several streams in the Ogotoruk area were briefly sketched in the field by pace- and Abney-level traverses. Because the information gathered by field traverses areally overlaps that collected by the other two methods, it has not been tabulated; it has, however, provided a check on the accuracy of the other methods and a basis for the consideration of processes possibly operating in the area.

(2) Symmetry relations of valleys associated with each of 90 stream segments were interpreted from the Point Hope A-2, Alaska, Quadrangle sheet (edition of 1952) of the U.S. Geological Survey 1:63,360 Topographic Series. This topographic map, which has a contour interval of 50 feet, was found to give a good representation of the local drainage net and a reasonably satisfactory impression of the landforms associated with the drainage. Stream segments were taken as starting at the source of first-order streams, or at an upstream confluence and terminating at a downstream confluence or at the sea. (First-order streams are the smallest unbranched tributaries; second-order streams are initiated by the confluence of two first-order streams; etc.) Symmetry was categorized, with reference to an observer facing downstream, as (a) left-bank valley side steeper, (b) little or no asymmetry, or (c) right-bank valley side steeper, on the basis of the relative spacing of contours on either side of the axial drainage. A stream segment was classed as (a) or (c) only if one or the other of the corresponding valley sides was clearly steeper over the major part or the full length of the segment. A stream segment was classed as (b) if neither side was clearly steeper or if along the length of the segment the steeper side alternated about equally between the right and left banks. Average azimuth of stream flow, estimated

to the nearest degree, and stream order were also noted for each segment. The part of the area studied by interpretation of the topographic map includes tributaries in the eastern part of the Ogotoruk watershed as far east as 165°36′ W., the eastern limit of the quadrangle, as well as eight small streams that flow directly into the Chukchi Sea (Fig. 1). An area of about 15 square miles and an aggregate of about 40 linear miles of stream segments were studied in this manner.

(3) Symmetry relations of valleys in the eastern part of the Ogotoruk watershed, east of 165°36′ W. (Fig. 1), were interpreted from vertical aerial photographs taken at a scale of 1:12,000 by Mendenhall Aerial Surveys in 1959. Stereoscopic observations were made at an arbitrary ground-distance interval of 0.2 miles along all well-defined drainage lines appearing in the photographs. Symmetry at each point of observation was categorized as under method (2) except that only the relative steepness of valley sides adjacent to observation points was considered. As under method (2), azimuth of stream flow to the nearest degree and stream order were also noted in each observation. An area of about 14 square miles and about 30 linear miles of drainage lines are represented by 142 observations.

Table 1. Summary of observations by symmetry class and azimuth of stream flow.

Azimuth of stream flow	*Left-bank valley side steeper*		*Little or no asymmetry*		*Right-bank valley side steeper*		*Total number of obser-vations*
	Number observed	*Percentage of total no.*	*Number observed*	*Percentage of total no.*	*Number observed*	*Percentage of total no.*	
1°-180°	8*	17.0	15	31.9	24†	51.1	47
181°-360°	104†	56.2	66	35.7	15*	8.1	185
Total	112	48.3	81	34.9	39	16.8	232

*Face south; †Face north. In this study the sides of a stream valley are considered to face in opposite directions, 90° from the azimuth of the corresponding axial stream. North-facing valley sides face generally north, between due west and due east; south-facing valley sides face generally south, between due east and due west.

Quantitative results of study

For this preliminary study the 90 observations based on interpretation of the topographic map and the 142 observations based on photographic interpretation have been combined into a single tabulation (briefly summarized in Table 1) containing 232 observations. Little or no asymmetry was noted in 81 of the observations; one or the other of the opposing valley sides was clearly steeper in 151 of the observations. All observations are plotted in a bar graph (Fig. 2) by symmetry class and sector of stream-flow azimuth. Bar length of each symmetry class is proportional to the percentage of observations in that class of the total observations in the azimuth sector. The unequal distribution of observations with respect to azimuth sectors is caused by a predominance of regional drainage southwestward, toward the sea, and because by design the study does not include stream valleys in the western part of the Ogotoruk watershed.

The 151 observations in which asymmetry was noted show a striking pattern in Fig. 2. Along stream-flow azimuths that trend about due north and about due south the number of observations of steeper left-bank valley sides approximately balances the number of observations of steeper right-bank valley sides. However, along all stream-flow azimuths that depart appreciably from due north and south (disregarding the azimuth sector with only one observation) valley asymmetry is clearly unbalanced, i.e., either steeper left-bank valley sides or steeper right-bank valley sides predominate. This imbalance is consistently skewed toward a preponderance of steeper north-facing valley sides.

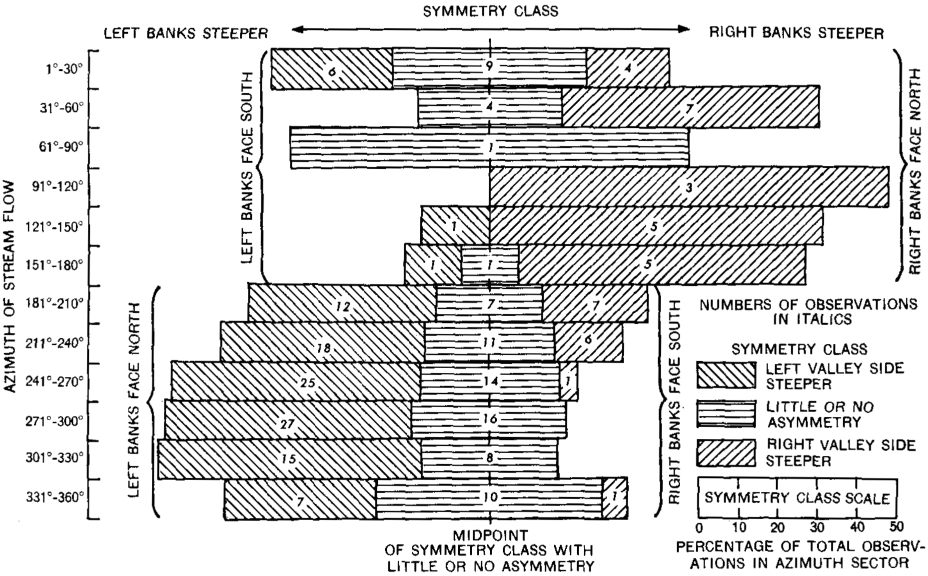

Fig. 2. Bar graph showing percentage of observations by symmetry class for 30°-sectors of stream-flow azimuth; 232 observations.

Observed frequencies, N_0, of steeper north-facing valley sides and observed frequencies, S_0, of steeper south-facing valley sides are entered in Table 2 with respect to departures, δ, of corresponding stream-flow azimuths from due north or south. Values of δ are measured from the nearer polar direction and range from 1° to 90°; as values of δ approach 90° stream-flow azimuths approach due east or west and corresponding valley sides face more and more squarely north and south. Although steeper north-facing valley sides are more frequent for all values of δ than steeper south-facing valley sides, it is clear by inspection of Table 2 that steeper north-facing valley sides are relatively much more frequent, and steeper south-facing valley sides much less frequent, as the valley sides face more and more squarely north and south. That this relationship among the data in Table 2 is statistically significant is confirmed by chi-square test (appended to Table 2).

A more concise expression of the relationship seen among the data in Table 2 is accomplished if the observed frequencies, N_0, are reduced to observed proportions, $(N/N+S)_0$, of the totals, $N_0 + S_0$, for appropriate values of δ. The observed proportions, $(N/N+S)_0$, for 10° intervals of

Table 2. Observed frequencies of steeper north-facing and south-facing valley sides by departure of corresponding stream-flow azimuths from due north or south.

Departure of stream-flow azimuths from north or south δ	*Observed frequencies*				
	Steeper north-facing valley sides N_0		*Steeper south-facing valley sides* S_0		$N_0 + S_0$	
1° — 10°	5		4		9	
11° — 20°	11	28 (36.4)*	5	15 (6.6)*	16	43
21° — 30°	12		6		18	
31° — 40°	17		3		20	
41° — 50°	14	45 (44.1)*	2	7 (7.9)*	16	52
51° — 60°	14		2		16	
61° — 70°	9		0		9	
71° — 80°	24	55 (47.5)*	0	1 (8.5)*	24	56
81° — 90°	22		1		23	
Total	128		23		151	

*Frequencies are pooled so that differences between N_0 and S_0 with respect to δ can be tested by chi-square. Frequencies in parentheses are predicted by the null hypothesis that there are no differences between N_0 and S_0 with respect to δ. The null hypothesis can be confidently rejected, at the 0.001 level of significance, because χ^2_0 (= 20.83, 2 d.f.) substantially exceeds $\chi^2_{0.001(2)}$ (= 13.82). Although in Fig. 2 the asymmetry would appear to be exactly balanced a little east of north and a little west of south, chi-square trials having the same design as Table 2 but predicated on azimuth departures from NNE, etc., and SSW, etc., show χ^2_0 <20.83

δ are entered in Table 3. Furthermore, a truly general description of the pattern of valley asymmetry in the Ogotoruk area can be formulated on the basis of the relationship seen among the data in Table 2. Such a description is the function,

$$(N/N+S)_c = 0.5 + 0.5 \sin \delta.$$

In the form above and evaluated for a given value of δ, the function expresses steeper north-facing valley sides, N, as a computed proportion, $(N/N+S)_c$, of the sum, N + S, of steeper north-facing and south-facing valley sides. The computed proportions, $(N/N+S)_c$, for midpoints of 10° intervals of δ are also entered in Table 3. $(N/N+S)_c = 0.5 + 0.5 \sin \delta$, continuous from $\delta = 1°$ to $\delta = 90°$, is fitted to point values of $(N/N+S)_0$ in Fig. 3. That the general description closely fits the observed pattern of Ogotoruk asymmetry is evident by inspection of Table 3 and Fig. 3. The coefficient of determination, ρ^2, indicated by curvilinear correlation analysis (Fig. 3) confirms that 93 per cent of the variation of $(N/N+S)_0$ is described by $(N/N+S)_c = 0.5 + 0.5 \sin \delta$.

Percentages of observations with respect to exposure of steeper valley side, method of interpretation, symmetry class, and stream order appear in Tables 4 and 5. From Table 4 it appears, as might be expected, that photographic interpretation is more sensitive in discerning the prevalent pattern of asymmetry than map interpretation. The high incidence, evident in

Table 5, of little or no asymmetry associated with first-order streams arises from the incipient, unentrenched condition of many of the first-order streams.

Table 3. Steeper north-facing valley sides as observed and computed proportions of the sums of steeper north-facing and south-facing valley sides corresponding to given values of δ.

δ		*Observed proportions**	*Proportions computed†*
Interval	*Midpoint*	$(N/N+S)_0$	*according to* $(N/N+S)_c = 0.5+0.5 \sin \delta$
1° - 10°	5.5°	0.56	0.55
11° - 20°	15.5°	0.69	0.63
21° - 30°	25.5°	0.67	0.72
31° - 40°	35.5°	0.85	0.79
41° - 50°	45.5°	0.88	0.86
51° - 60°	55.5°	0.88	0.91
61° - 70°	65.5°	1.00	0.96
71° - 80°	75.5°	1.00	0.98
81° - 90°	85.5°	0.96	0.99

*Using values of N_0 and $N_0 + S_0$ from Table 2. †Using midpoint values of δ.

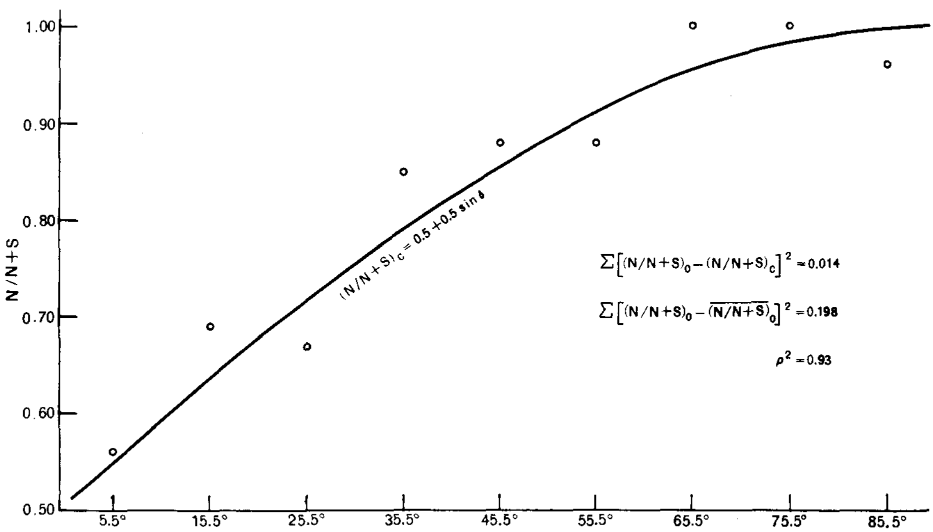

Fig. 3. $(N/N+S)_c = 0.5 + 0.5 \sin \delta$ fitted to point values $(N/N+S)_0$; based on data in Table 3. Function not defined at $\delta = 0°$ because valley sides face neither north nor south at $\delta = 0°$.

Characteristics of asymmetric valleys

Slope characteristics repeatedly observed in field traverses across asymmetric stream valleys in the Ogotoruk area are shown in Fig. 4. The lower parts of south-facing valley sides are characteristically mantled by a mat consisting of tundra vegetation and what may be loosely termed tundra soil; angles of about 5° are typical of these slopes. The tundra mat, as revealed in cuts along axial streams and tributary gullies, generally overlies an apron of colluvium. Composed principally of subangular, locally-derived cobbles in a matrix of silt, the colluvium is frozen except where seasonal thaw

Table 4. Observations of steeper north-facing and south-facing valley sides by method of interpretation.

Method of interpretation	*Steeper north-facing valley sides*		*Little or no asymmetry*		*Steeper south-facing valley sides*		*Total number of observations*
	Number observed	*Percentage of total no.*	*Number observed*	*Percentage of total no.*	*Number observed*	*Percentage of total no.*	
Map	47	52.2	28	31.1	15	16.7	90
Photos	81	57.0	53	37.3	8	5.7	142

Table 5. Observations by symmetry class and stream order.

Stream order	*Left-bank valley side steeper*		*Little or no asymmetry*		*Right-bank valley side steeper*		*Total number of observations*
	Number observed	*Percentage of total no.*	*Number observed*	*Percentage of total no.*	*Number observed*	*Percentage of total no.*	
1	52	38.8	56	41.8	26	19.4	134
2	41	61.2	17	25.4	9	13.4	67
3	13	54.2	7	29.1	4	16.7	24
4	6	85.7	1	14.3	0	0.0	7

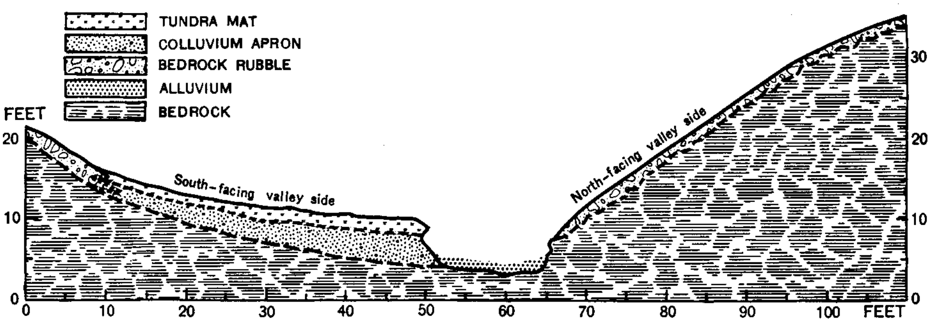

Fig. 4. Schematic cross section along hypothetical north-south line showing characteristics of an idealized asymmetric valley in the Ogotoruk Creek area.

penetrates to a depth slightly below the tundra-colluvium interface. Upslope the tundra-colluvium component steepens and grades into a mantle of frost-riven bedrock rubble with little vegetation cover and comparatively little interstitial matrix.

North-facing valley sides, in contrast, are mantled over much of their area by relatively unstable frost-shattered bedrock rubble; angles averaging about 30° are typical of these slopes. Intact bedrock is frequently exposed on the lower parts of north-facing valley sides and such exposures are sometimes vertical or even overhanging. Alluvium in stream channels has its source in both the colluvium from the south-facing valley sides and the rubble from the north-facing valley sides. Average gradients of stream channels vary from about 500 feet per mile for first-order streams to about 40 feet per mile for fourth-order streams; these gradients appear to be such that near-equilibrium is maintained between summer stream flow and the addition of colluvium and rubble load.

Explanations of development of asymmetry

A number of explanations of the development of asymmetric stream valleys under the influence of high-latitude or periglacial environment have been advanced in the geologic and geographic literature (cf., e.g., Weber 1958, Wright 1961). Eight are briefly summarized and, in turn, evaluated in terms of applicability to relationships observed in the Ogotoruk Creek area.

(1) The assertion is sometimes made (e.g., by Cressey 1962, p. 108) that steep right-hand banks are characteristic of all rivers in high latitudes, North America included. In the northern hemisphere such asymmetry should in theory result from stream deflection by the Coriolis force.

(2, 3, and 4) As a result of processes operating under cold climates in the northern hemisphere, south-facing slopes may be steeper than opposing north-facing slopes. At least three explanations have been advanced to account for such asymmetry. (2) South-facing slopes, which receive more heat by insolation than north-facing slopes, are more susceptible to steepening because they thaw more completely and therefore offer less resistance to lateral corrasion by streams than corresponding north-facing slopes (Smith 1949, p. 1503). (3) During spring melting north-facing slopes, in which infiltration is retarded by ground frost, shed more debris into stream channels than corresponding south-facing slopes, thereby deflecting drainage against, and hence steepening, the toes of adjacent south-facing slopes (Büdel 1953, p. 255). (4) South-facing slopes, which receive more insolation and therefore undergo more freezing and thawing than more permanently frozen north-facing slopes, are subject to strong physical weathering, solifluction, and erosion by creep, causing them to attain the steeper gradients (Ollier and Thomasson 1957, p. 79).

(5 and 6) Valleys with generally steeper windward slopes may develop under the influence of snow drifted by prevailing winter winds. At least two versions of this explanation have been advanced. (5) Snow drifted on leeward slopes would, it is frequently stated (cf., e.g., Derruau 1958, pp. 169, 170), favour active solifluction of colluvium down the lee slopes during the season of thaw, thereby deflecting local drainage against, and hence steepening, adjacent windward slopes. (6) Kachadoorian (1962) has observed that runoff from snow on lee slopes, flowing down the gradient of the drifted snow, particularly on ice layers near the base of the snow, may impinge against and oversteepen the lower parts of windward slopes.

(7 and 8) As a result of processes operating under cold climates in the northern hemisphere, north-facing slopes may be steeper than opposing south-facing slopes. At least two explanations for such asymmetry have been advanced. (7) Protracted snow cover tends to protect north-facing slopes from denudation, whereas the comparative brevity of snow cover on south-facing slopes permits their relatively rapid reduction (Russell 1931, p. 484). (8) North-facing slopes, which undergo fewer days of freeze and thaw cycles and which have a thinner mantle of thawed soil, experience less morphologic activity and retain more of their initial steepness than the morphologically more active, and hence flatter, south-facing slopes (Malaurie

1952). In this context, morphologic activity is the action of an assemblage of degradational processes, including frost-riving, frost-heaving, and creep, that is promoted by frequent freeze and thaw cycles and by periodic availability of unfrozen water in a mantle of weathering rock.

For the sake of completeness, the possibility that valley asymmetry in the Ogotoruk Creek area is best explained by structural or stratigraphic factors should also be entertained. An examination of the bedrock and surficial geology of the area does not sustain this explanation. Moreover, reconnaissance traverses indicate that the pattern of valley asymmetry dominant in the Ogotoruk area is also prominent over a broad area to the north, despite important variations in lithology and structure.

Evaluation of explanations

Explanation (1) is not consistent with the obvious pattern of valley asymmetry in the Ogotoruk Creek area. Rather than having a prevalence of steeper right-bank valley sides as the explanation would predict, the area has a prevalence of steeper left-bank sides. It is apparent from Tables 5 and 6 that, irrespective of stream order and departure of stream-flow azimuths from north or south, observations of steeper left-bank valley sides consistently outnumber observations of steeper right-bank valley sides. However, Table 6 also indicates that steeper right-bank valley sides are proportionately more frequent for low values, and less frequent for high values, of δ; that this not-so-obvious pattern is statistically significant is confirmed by chi-square test (appended to Table 6). This suggests that stream deflection by the Coriolis force does have a residual effect on asymmetry in the Ogotoruk area. Nevertheless, it is clear that as an asymmetry-producing mechanism the Coriolis force, which is constant for all azimuths at a given latitude, is for the most part cancelled by overriding processes, processes

Table 6. Observed frequencies of steeper left-bank and right-bank valley sides by departure of corresponding stream-flow azimuths from due north and south.

Departure of stream-flow azimuths from north or south δ	*Observed frequencies* — *Steeper left-bank valley sides* L_0		*Steeper right-bank valley sides* R_0		$L_0 + R_0$	
1° — 10°	7		2		9	
11° — 20°	9	26 (31.9)*	7	17 (11.1)*	16	43
21° — 30°	10		8		18	
31° — 40°	11		9		20	
41° — 50°	10	34 (38.6)*	6	18 (13.4)*	16	52
51° — 60°	13		3		16	
61° — 70°	9		0		9	
71° — 80°	22	52 (41.5)*	2	4 (14.5)*	24	56
81° — 90°	21		2		23	
Total	112		39		151	

*Frequencies are pooled so that differences between L_0 and R_0 with respect to δ can be tested by chi-square. Frequencies in parentheses are predicted by the null hypothesis that there are no differences between L_0 and R_0 with respect to δ. The null hypothesis can be rejected at the 0.001 level of significance because χ_0^2 (= 16.61, 2 d.f.) exceeds $\chi^2_{0.001(2)}$ (= 13.82).

that seem to intensify as opposing valley sides face more and more squarely north and south.

Explanations (2), (3), and (4) also are inconsistent with the pattern of asymmetry observed in the Ogotoruk area. Rather than having a prevalence of steeper south-facing valley sides, as those explanations would predict, the area has a prevalence of steeper north-facing valley sides. From Table 4 it is evident that, regardless of method of interpretation, the incidence of steeper north-facing valley sides far exceeds that of steeper south-facing valley sides.

Warranting closer scrutiny than the foregoing are explanations (5) and (6), which, in predicting a windward orientation of the steeper valley sides, are consistent with patterns actually observed in the Ogotoruk area. At the Chariot base camp winds during the winter of 1959-60, from October to April, blew from the north or north-northwest during 70.7 per cent of the time (Com. on Env. Stud. Proj. Chariot 1960, p. 47); Ogotoruk winds have been described as exceptional in their intensities, the most prominent feature of the wind pattern being the strong northerlies (*ibid.*, p. 45). Snowfall at the Chariot base camp during the winter from October 1959 to May 1960 totalled about 23 inches (*ibid.*); considerable drifting of snow in the Ogotoruk watershed has been reported by Eskimos, as well as by scientific personnel who have visited the area in winter.

Further judgment in favour of explanations (5) and (6) must, however, be based on more information on the effects of snowbanks on mobility of colluvium and on basal corrasion of the steeper valley sides by meltwater. Preliminary evidence regarding disposition of snowbanks in the area is not conclusive. Numerous remnants of snowbanks, many of them associated with asymmetric valleys and gullies, appear in the aerial photographs taken on July 20, 1959. These snowbanks occur on valley sides, both steep and gentle, oriented toward all points of the compass; in many instances the snowbanks occur on both sides of a single asymmetric valley. There is even some justification, in a preliminary assessment of the role played by snowbanks, for suspecting that late-lying snow might actually impede solifluction by insulating subjacent frozen colluvium and retarding its seasonal thawing. An investigation by Williams (1959, p. 485) of solifluction movements near a late-lying snow patch in Norway largely discounts direct effects of the snow in causing movement. Although runoff flowing directly down favorably disposed south-facing snowbanks is undoubtedly capable of locally eroding, and thereby steepening, the lower parts of opposing north-facing valley sides, the importance of this process, considered for the whole Ogotoruk area, is difficult to evaluate.

Also warranting close scrutiny are explanations (7) and (8), which, in predicting steeper north-facing valley sides, are geometrically consistent with the asymmetry observed in the Ogotoruk area. Other considerations, however, make the value of explanation (7) doubtful. Many of the south-facing, hypothetically less protected valley sides, particularly those mantled with tundra, are not disproportionately eroded. Moreover, the south-facing valley sides seem to have about as much late-lying, hypothetically protective snow cover as the north-facing valley sides. On the other hand, explanation (8) helps, as will be seen below, to account for much, perhaps even for most, of the preferentially oriented transverse asymmetry manifested by stream valleys in the area.

Origin of the Ogotoruk asymmetry

A sequence of several processes seems to explain best the origin and the apparently continuing development of valley asymmetry in the Ogotoruk area. The sequence begins with, and consistently has the pattern of asymmetry established by the unequal morphologic activity discussed above under explanation (8). The sequence is given in Table 7 in order of apparent causality.

Table 7. Causally ordered sequence of asymmetry-producing processes.

Asymmetric morphologic activity	→	*Asymmetric development of colluvium*	→	*Asymmetric positioning of axial drainage*	→	*Asymmetric lateral corrasion by axial drainage*	→	*Asymmetric valley of Ogotoruk type*

Under a climate like that prevailing in the Ogotoruk area, morphologic activity must in large measure be directly related to surface heating. Thermal asymmetry is inevitably translated into asymmetric morphologic activity; because morphologic activity is likely to be more intense on slopes that face generally south, toward peak incoming solar radiation, a deeper mantle of more comminuted rubble usually develops on those slopes than on slopes that face generally north, away from peak insolation. The rubble of the south-facing valley sides appears to evolve comparatively readily into colluvium subject to movement by solifluction, whereas the rubble of north-facing valley sides tends to remain a scree-like veneer. Establishment of more abundant vegetation on the relatively hospitable south-facing valley sides increases moisture retention and undoubtedly contributes to the mobility of south-facing colluvium. Colluvium moving into stream channels by solifluction from south-facing valley sides appears (Fig. 4) to exceed substantially, in terms of volume, the rubble shed from north-facing valley sides.

Even if axial drainage were not a factor, it is probable that a semblance of valley asymmetry would result merely from the opposition of the lower equilibrium angles of south-facing colluvium and the steeper repose angles of north-facing rubble. However, as it is inexorably displaced to the south by the asymmetric development and deployment of colluvium, axial drainage becomes a major factor. Asymmetric positioning of drainage near or against the toes of north-facing valley sides and away from the toes of south-facing valley sides creates an erosional environment favouring asymmetric lateral corrasion. As this progresses, the north-facing rubble slopes tend to be increasingly shortened and steepened and the south-facing colluvium slopes tend to become longer and more gentle. The upper part of a north-facing slope may in time become graded to the angle of repose of its rubble; if lateral corrasion is sufficiently vigorous, the lower part of the same slope may temporarily exceed that angle. On the other hand, a south-facing slope may approach a gradient so low that solifluction is barely capable of moving colluvium toward the axial drainage at a rate sufficient to maintain the drainage in an asymmetric position. The rubble slope appearing in Fig. 5 is

Fig. 5. Narrow, rubble-choked channel of intermittent stream asymmetrically positioned in valley consisting of steep, in part oversteepened, rubble slope in background and gently-inclined colluvium slope in foreground. Line delineates toe of rubble slope.

at its angle of repose except where temporary oversteepening has resulted from especially vigorous lateral corrasion; asymmetric deployment of gently sloping colluvium in the foreground maintains the stream in its asymmetric position. Much as it is the ultimate cause of valley asymmetry in temperate regions (Melton 1960, p. 133), asymmetric lateral corrasion by streams that have been displaced through asymmetric deployment of slope materials appears to be the process by which most asymmetric valleys in the Ogotoruk area are ultimately shaped. Elsewhere in Alaska asymmetric valleys with steeper north-facing sides are similarly reported (Hopkins and Taber 1962, p. 116) to have resulted, ultimately, from persistent lateral migration of streams.

The sequence of processes postulated above is not only consistent with the high proportion of steeper north-facing valley sides that characterizes asymmetric valleys in the Ogotoruk area generally, it is also consistent with the variation of that proportion with respect to δ (Table 3 and Fig. 3). Opposing valley sides corresponding to axial streams that depart little from north-south are over a period of time exposed to comparable amounts of insolation per unit area and are likely to have comparable thermal regimes and comparable intensities of morphologic activity. In the absence of the sequence of processes that would stem from asymmetric morphologic activity, lateral corrasion related to ordinary stream sinuosity, due particularly to meanders and entering tributaries, tends to produce steeper left-bank and right-bank valley sides alternately and in approximately equal proportions.

Table 8. Observed frequencies of little or no asymmetry and observed frequencies of asymmetry by departure of stream-flow azimuths from due north and south.

Departure of stream-flow azimuths from north or south δ	*Observed frequencies* — *Little or no asymmetry* X_0	*Observed frequencies* — *Asymmetry* $L_0 + R_0$† $= N_0 + S_0$‡	*Total*
1° – 10°	12 (7.3)*	9 (13.7)*	21
11° – 20°	8 (8.4)*	16 (15.6)*	24
21° – 30°	7 (8.8)*	18 (16.2)*	25
31° – 40°	9 (10.1)*	20 (18.9)*	29
41° – 50°	8 (8.4)*	16 (15.6)*	24
51° – 60°	6 (7.7)*	16 (14.3)*	22
61° – 70°	8 (5.9)*	9 (11.1)*	17
71° – 80°	9 (11.5)*	24 (21.5)*	33
81° – 90°	14 (12.9)*	23 (24.1)*	37
Total	81	151	232

† From Table 6.
‡ From Table 2.
* Frequencies in parentheses are predicted by the null hypothesis that there are no differences between X_0 and $L_0 + R_0 = N_0 + S_0$ with respect to δ. Tested by chi-square the null hypothesis cannot with assurance be rejected because χ_0^2 (= 7.89, 8 d.f.) is less than $\chi^2_{0.30(8)}$ (= 9.52).

Although no explanation can be offered, it is interesting to note (Table 8) in this regard that observations in the little-or-no-asymmetry class appear to be proportionately no more frequent for low values of δ than for higher values.

Conclusion

Data collected thus far strongly indicate that the Ogotoruk Creek area is characterized by a pattern of valley asymmetry in which steeper north-facing valley sides are consistently dominant. Available information points to the processes postulated in Table 7 as the probable cause of much, if not most, of the asymmetry. In northwestern Alaska, as in other regions of polar and microthermal climates, continued investigation is needed to insure the correctness of generalizations regarding the existence and nature of valley asymmetry. Additional data by which to evaluate possible causes of valley asymmetry are also needed. For example, the correlation between streams of all orders and evidence for deflection by the Coriolis force, and the disposition of snowbanks relative to clearly established asymmetry need to be more fully examined.

Many questions remain that can be answered only as more information becomes available regarding the thermal and mechanical properties of variously exposed and variously composed slopes in regions of perennially frozen ground. Why, for instance, does seasonal thaw in surficial deposits seldom seem to penetrate more deeply than 2 or 3 feet in an area such as the Ogotoruk watershed (Kachadoorian *et al.* 1960, p. 34), yet many of the south-facing solifluction aprons, where exposed by dissection, are several or even tens of feet thick? Possibly the deep, perennially frozen colluvium observable today is largely in a fossil state, having originally been generated during a period of warmer climate, perhaps during the post-Wisconsin thermal optimum, that permitted deeper seasonal thaw and has since become stabilized and preserved as a result of climatic deterioration; or possibly the deep, perennially frozen colluvium, in spite of its frozen state, is to some extent subject to gradual movement under the present climatic regime; or possibly colluvium aprons accrue more rubble along their headward margins than can be moved by near-surface solifluction into the nearest stream channels, a disequilibrium that would result in the downslope thickening and self-burial of the aprons.

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References

Büdel, J. 1953. Die "periglazial"-morphologischen Wirkungen des Eiszeitklimas auf der ganzen Erde. Erdkunde 7:249-266.

Committee on Environmental Studies for Project Chariot. 1960. Bioenvironmental features of the Ogotoruk Creek area, Cape Thompson, Alaska. U. S. Atomic Energy Comm.: TID-12439, 69 pp.

Cressey, G. B. 1962. Soviet potentials, a geographic appraisal. Syracuse: Syracuse Univ. Press, 232 pp.

Derruau, M. 1958. Précis de géomorphologie, 2d ed. Paris: Masson et Cie, 395 pp.

Hopkins, D. M., and Bond Taber. 1962. Asymmetrical valleys in central Alaska. *In* Abstracts for 1961. Geol. Soc. Am. Spec. Pap. 68, p. 116.

Kachadoorian, R., *et al.* 1960. Geologic investigations in support of Project Chariot in the vicinity of Cape Thompson, northwestern Alaska — preliminary report. U. S. Geol. Survey: Trace Elements Invest. Rept. 753, 94 pp.

Kachadoorian, R. 1962. In letter.

Malaurie, J. N. 1952. Sur l'asymétrie des versants dans l'île de Disko, Groenland. Académie des Sciences, Paris, Comptes Rendus 234:1461-1462.

Melton, M. A. 1960. Intravalley variation in slope angles related to microclimate and erosional environment. Geol. Soc. Am. Bull. 71:133-144.

Ollier, C. D., and A. J. Thomasson. 1957. Asymmetrical valleys of the Chiltern Hills. Geog. Jour. 123:71-80.

Russell, R. J. 1931. Geomorphological evidence of a climatic boundary. Science 74:484-485.

Smith, H. T. U. 1949. Physical effects of Pleistocene climatic changes in nonglaciated areas: eolian phenomena, frost action, and stream terracing. Geol. Soc. Am. Bull. 60:1485-1515.

U. S. Weather Bureau, Climatological Section, Anchorage, Alaska. 1962. Written communication.

Weber, H. 1958. Die Oberflächenformen des festen Landes. Leipzig: B. G. Teubner Verlag, 350 pp.

Williams, P. J. 1959. An investigation into processes occurring in solifluction. Am. Jour. Sci. 257:481-490.

Wright, Jr., H. E. 1961. Late Pleistocene climate of Europe: a review. Geol. Soc. Am. Bull. 72:933-84.