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GEOMETRY OF FACETED SPURS ON AN ACTIVE NORMAL FAULT: CASE STUDY OF THE CENTRAL WASATCH FAULT, UTAH, U.S.A.

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Abstract: Faceted spurs preserved along the Central Wasatch Fault, north-central Utah, display different geometry and state of development. Geometric parametres of the largest faceted spurs that have been shaped since the Pliocene or early Quaternary appear to reflect lithological, structural and seismotectonic differentiation among the four fault segments studied (Brigham City, Weber, Salt Lake City, and Spanish Fork). The size of a faceted spur is a function of the distance between major canyons incised into mountain front and of the spur's height. Most of the canyons that truncate the western side of the Wasatch Mts. follow zones of weakness. Some of geometric parametres reflect the size of triangular facets (the numer and length of 1st-order interfluves), whereas dimensionless ratios (bifurcation and length ratios) are usually size-independent and are controlled by the rate of both seismotectonic uplift and erosional downcutting. The height of a faceted spur is a function of uplift whereas average slope may be affected by a variety of factors. On homogeneous bedrock the youngest facets are usually the steepest. Along the Wasatch fault such a relationship is, however, seldom observed due to either highly differentiated lithology of underlying rocks or the presence of subsidiary, high-angle normal faults that run parallel to the main fault zone, and dip towards the base of mountain front. The latter case resembles that of the Aegean-type fault scarps. The geometry of faceted spurs developed on differentiated bedrock, although controlled by seismotectonic uplift, is also strongly modified by rock resistance to erosion and by bedrock structure.

Abstrakt: Artykuł charakteryzuje wpływ czynników tektonicznych oraz litologiczno-odpornościowych na morfologię lic progów uskokowych (*triangular facets*) w obrębie czterech segmentów uskoku Wasatch w północno-wschodniej części prowincji Basin and Range w stanie Utah. Dla charakterystyki topologicznej lic progów uskokowych zastosowaliśmy zmodyfikowaną klasyfikację Hortona-Strahlera. Lica progów uskokowych wykazują zróżnicowaną geometrię i stopień zachowania. Parametry geometryczne największych zespołów lic, kształtowanych od pliocenu lub wczesnego plejstocenu, odzwierciedlają różnice litologiczne i strukturalne oraz odmienne tempo ruchów sejsmotektonicznych pomiędzy czterema analizowanymi segmentami uskoku. Niektóre parametry (liczba i długość odcinków 1 rzędu, suma długości działów wodnych) odzwierciedlają rozmiary lica progu, podczas gdy wskaźniki bezwymiarowe (wskaźniki bifurkacji i długości) nie zależą od wielkości danej formy i są uwarunkowane tempem ruchów tektonicznych oraz prędkością rozcięcia erozyjnego. Wysokość poszczególnych lic jest funkcją wypiętrzenia tektonicznego, natomiast ich nachylenie może być efektem zarówno tektoniki, jak też zróżnicowania litologicznego i strukturalnego. Przeprowadzona analiza wykazuje, że geometria lic progów uskokowych w równym stopniu odzwierciedla tempo ruchów sejsmotektonicznych, jak też odporność i strukturę skał podłoża.

Key words: active normal fault, faceted spurs, Wasatch Fault, Utah, U.S.A.

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INTRODUCTION

The aim of this paper is to describe the state of preservation of faceted spurs of different age, developed along an active normal fault which shows variable offset and rates of slip. The principal objective of this study is to decide whether the morphology of a triangular facet is a function of uplift rate and climate, as generally accepted (*cf.* Bull, 1984, 1987), or is it rather controlled by the lithology and structure of the bedrock.

The shaping of faceted spurs is thought to result mostly from fluvial erosion concurrent with uplift of the mountain

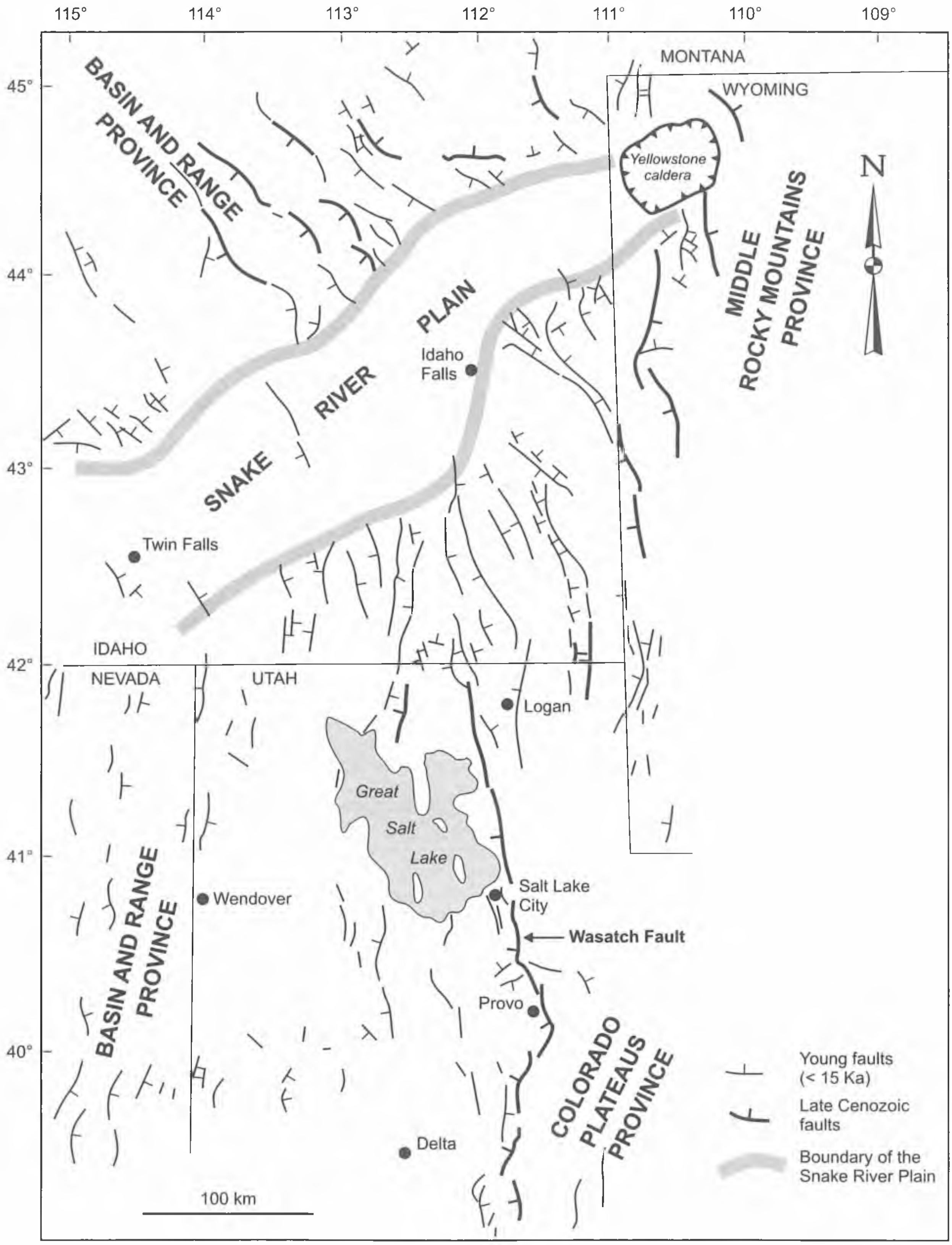


Fig. 1. Simplified tectonic sketch showing location of major late Cenozoic faults in the NE part of the Basin and Range Province (based on Machette *et al.*, 1989; modified)

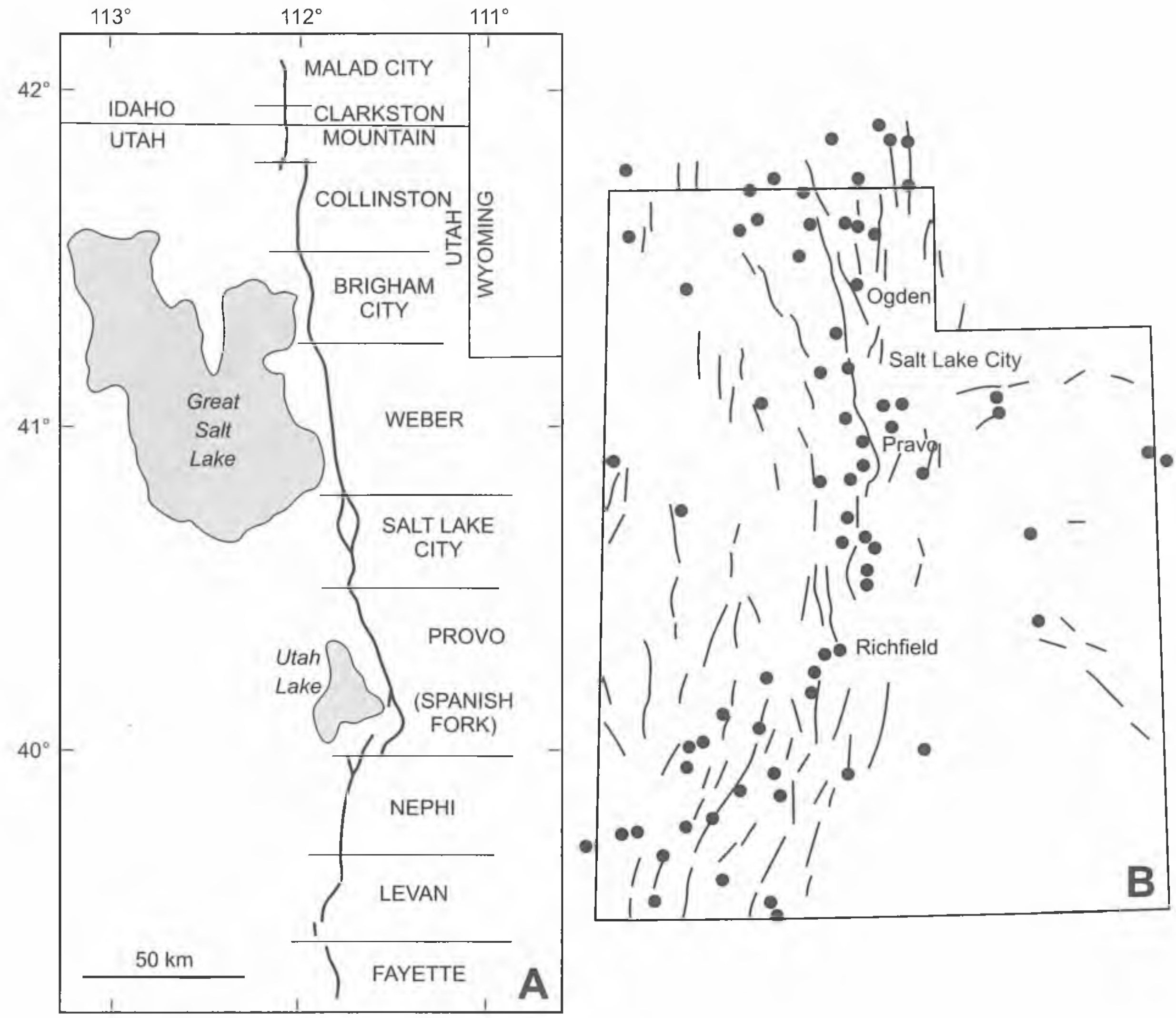


Fig. 2. Location sketch of the Wasatch fault segments and recent seismicity of the study area: **A** – Wasatch fault segments (based on Schwartz & Coppersmith, 1984; Machette *et al.*, 1989; and Gori & Hays, 1992); **B** – earthquakes of magnitude >4 in Utah in 1850-1986 (modified from Arabasz *et al.*, 1987)

front (Hamblin, 1976; Wallace, 1978) or from gradual backwearing, aided by gravitational mass movements (*cf.* Anderson, 1977 and discussion therein). Some authors point to the importance of subsidiary faults and fracture zones that run parallel to the main range front fault in modelling fault scarps (*cf.* Stewart & Hancock, 1988, 1990). Faceted spurs of the longest active normal fault in the United States, the Wasatch fault (Fig. 1), north-central Utah, showing differentiated morphology and state of development, provide excellent opportunity for testing an hypothesis of the principal role exerted by lithology and structure upon morphology of triangular facets.

AREA

The area studied is located on the western side of the Wasatch Mountains, north-central Utah, between Brigham City and Spanish Fork (112° W, 40°–41.5° N; Figs. 1–3). Five, best developed faceted spurs representing each of the four segments of the Central Wasatch fault (Brigham, Weber, Salt Lake City, Spanish Fork), have been chosen for detailed studies. The spurs differ both in size and elevation, extending between 1716 and 2805 m a.s.l. The base of each spur is covered by the Upper Pleistocene Bonneville sediments (Crittenden, 1983; Curray *et al.*, 1983), whereas triangular facets themselves are developed on bedrock rocks showing contrasting lithology and structure (Stokes, 1986).

STATE OF RESEARCH

Quaternary tectonic activity of the Wasatch fault was noted by Gilbert (1890, 1928) who described numerous scarps in the Upper Pleistocene Bonneville sediments. Triangular facets along the Wasatch fault were defined by Davis (1903, 1909) as representing primary fault surfaces. Pack (1926), however, was the first to recognize that these

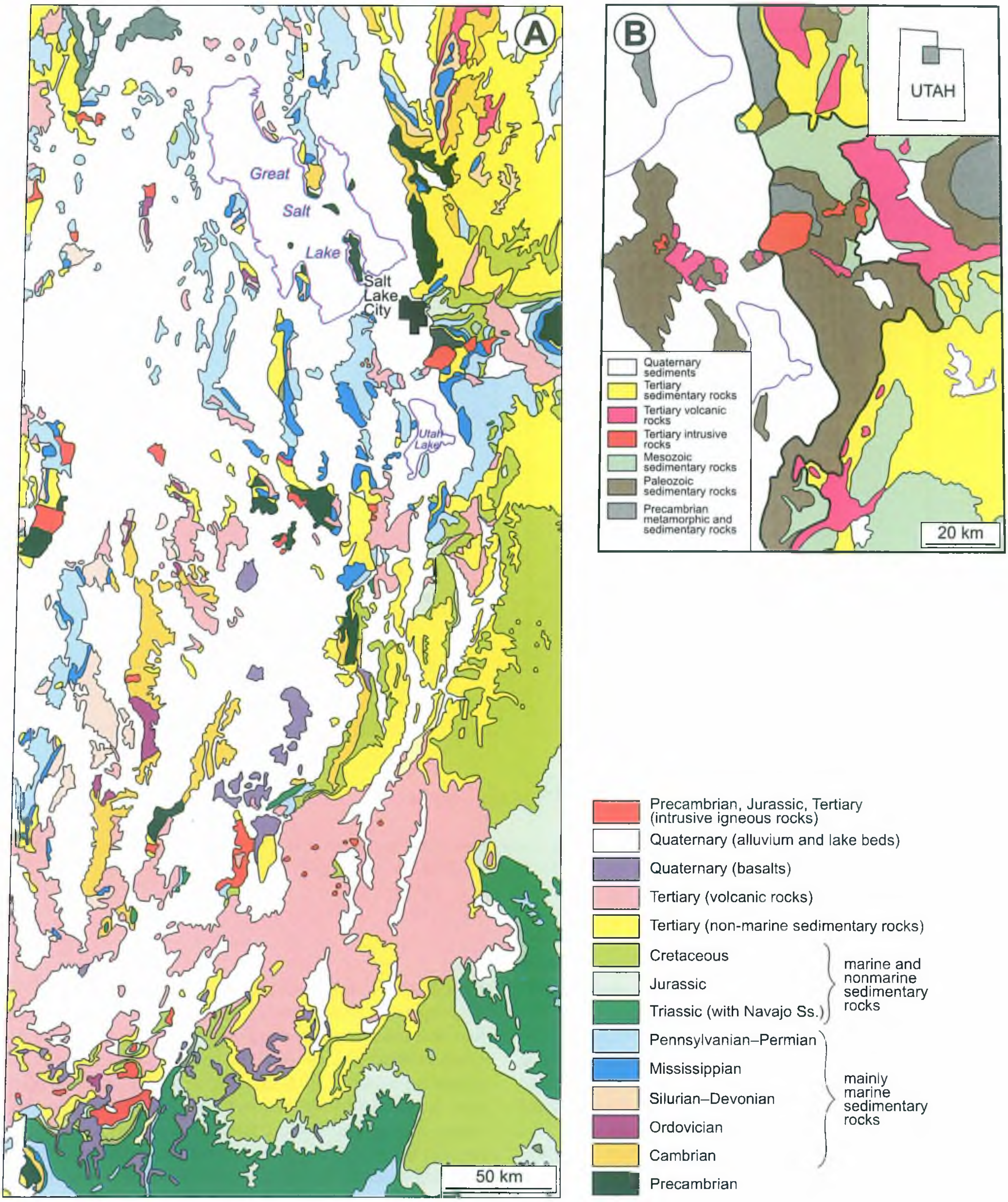
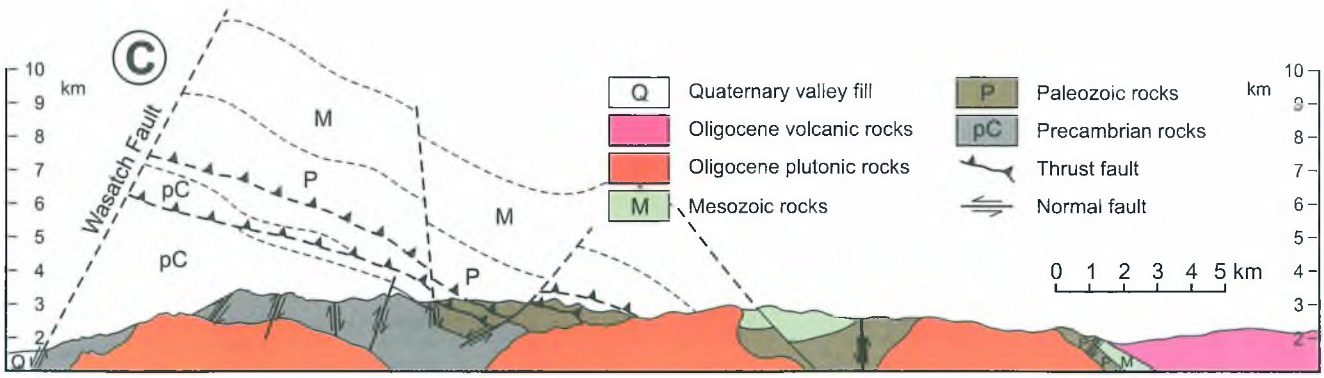


Fig. 3. Simplified geological maps of the study area: **A** – Wasatch fault zone in Utah (adopted from Stokes, 1986), **B** – Wasatch Mts. near Salt Lake City (modified from Parry & Bruhn, 1987), **C** – generalized cross-section of the Wasatch Mts. south of Salt Lake City (based on Crittenden, 1964; adopted from Parry & Bruhn, 1987)



facets are not remnants of the fault surface proper, but represent erosional surfaces preserved along the fault zone. Gilluly (1928) described several examples of steep bedrock fault planes at the base of much more gently dipping triangular facets in the Great Basin. A comprehensive study of compound faceted spurs along the Wasatch fault at Spanish Fork, east of Utah Valley, was presented by Anderson (1977), who distinguished 11 more or less continuous pediment surfaces occurring at the apices of triangular facets. In this model, pediments represent periods of tectonic quiescence whereas the intervening areas result from repeated cycles of active uplift (Figs. 4, 5). The equilibrium tendencies

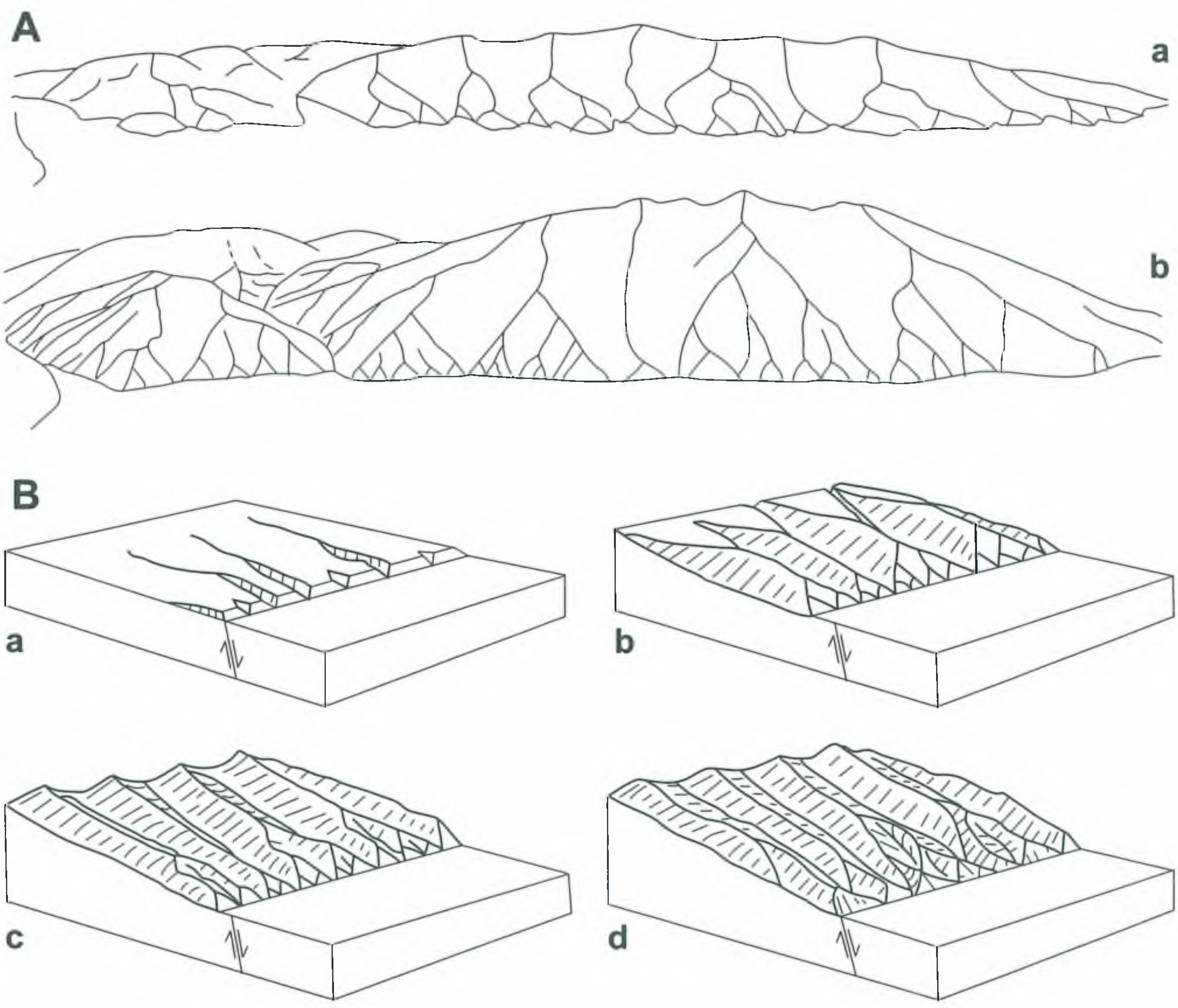


Fig. 4. Triangular facets in Spanish Fork segment of the Wasatch fault (taken from Anderson, 1977; modified and simplified): **A** – oblique perspective sketch showing possible development of faceted spurs from the beginning of Tertiary planation (a) to present (b); **B** – concept of compound faceted spur development

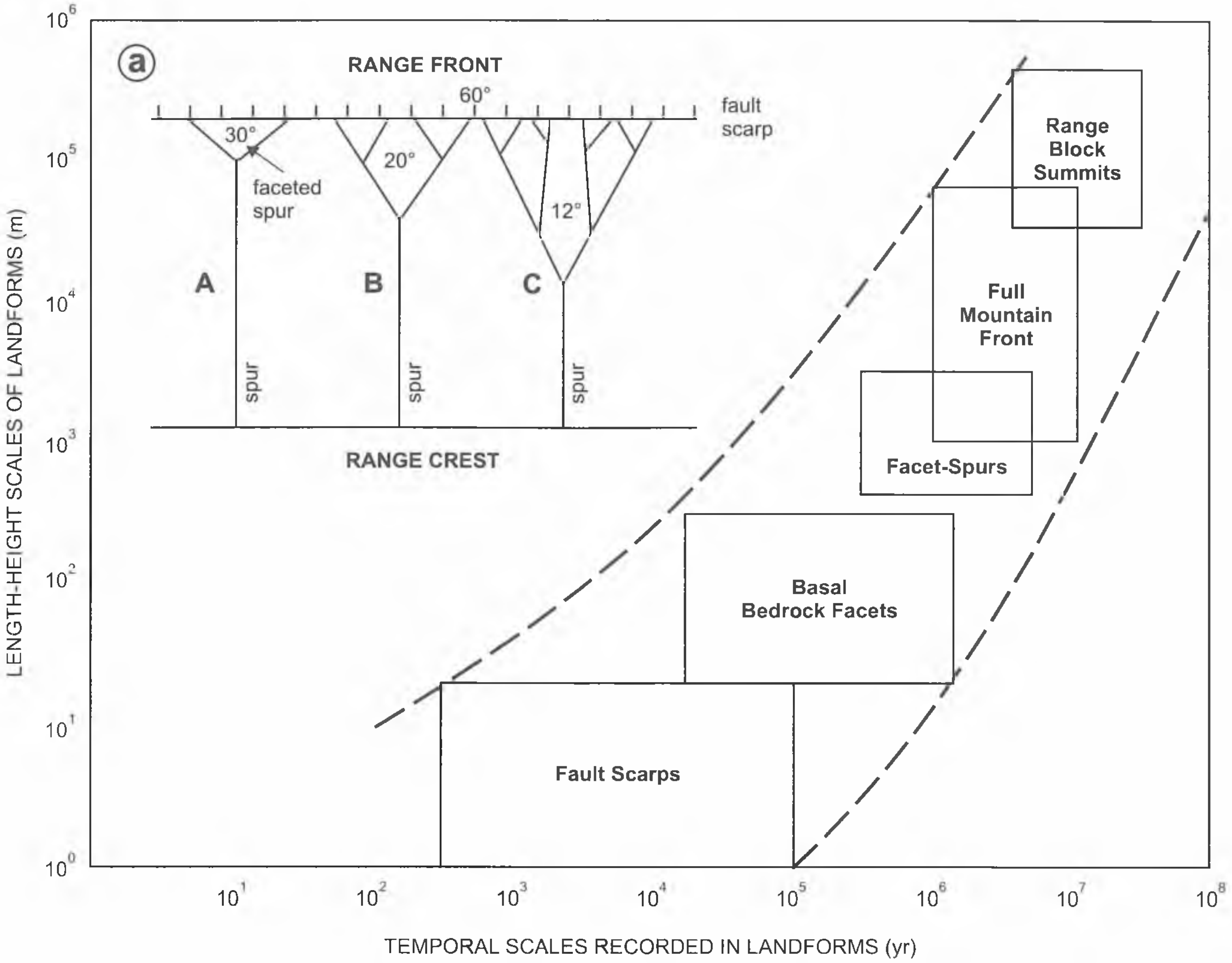


Fig. 5. Concept of time-space scales of hillslope landforms of fault-generated mountain front, exemplified by Sangre de Cristo Mts., New Mexico, of relative uplift rates 0.1–0.2 mm/yr and Holocene continental, semiarid climate (modified from Menges, 1988); a – cartoon showing temporal development (A through C) of drainage divides along mountain front and decreasing slope of triangular facets with age (taken from Wallace, 1978)

in denudation of piedmont scarps along the Wasatch fault have been dealt with by Petersen (1985), who describes relationships among different slope attributes of the fault scarps and the Bonneville shoreline cliffs. Piedmont scarps are found to develop convex-straight-concave profiles, irrespective of the number of seismotectonic events. A subsequent phase of development includes gradual slope decline. The two most strongly correlated variables are the midslope angle and the height/slope length ratio, the latter diminishing with the increasing age of the scarp.

GEOLOGIC SETTING

The northern and southern segments of the Central Wasatch fault are composed of Palaeozoic sedimentary rocks that dip moderately (Brigham; 35–40°) or gently (Spanish Fork; 10–20°) to the mountain front (Fig. 3). The medial segments, in turn, are built up of either Precambrian gneisses and schists (Weber) or Cretaceous through Tertiary quartz monzonites piercing through Precambrian quartzites and siltstones (Salt Lake City; *cf.* Stokes, 1986; Parry & Bruhn, 1987).

Estimates of displacement on the Wasatch fault, based on topographic, geomorphic and stratigraphic projection evidence, vary from 1.5–1.8 km (Marsell, 1932, Eardley, 1939) to 3.0–4.6 km (Gilbert, 1928; Crittenden, 1964; Hintze, 1971; Zoback, 1983), and even 11 km (Parry & Bruhn, 1987). Stokes (1986) provides evidence for at least 5 km of Quaternary displacement. Apatite ages of uplift vary from 8.5±1 Ma in the Salt Lake City segment (Crittenden *et al.*, 1973) to 4.9 Ma in the Weber segment close to the Wasatch fault, and 94.4 Ma on the crest of the Wasatch Range (Naeser *et al.*, 1986). Rates of uplift calculated by Naeser *et al.* (1986) for the past 5 Ma and 10 Ma (0.8 mm/yr and 0.4 mm/yr, respectively) are concordant with the recent rates of 1.0 and 1.8 mm/yr, reported by Swan *et al.* (1980) for the past 12 ka and 6 ka, respectively.

SEISMOTECTONIC SETTING

The active medial segments of the Wasatch fault, between Brigham City and Nephi (Table 1), appear to have Holocene slip rates of 1–2 mm/yr, strong earthquake recurrence intervals of 2–4 ka, and average lengths of about 50 km (Machette *et al.*, 1991). Seismotectonic slip rates estimated for the Late Quaternary are between 0.1 and 0.2 mm/yr (Machette *et al.*, 1986).

The Holocene scarps associated with individual surface-faulting events are 2–4.5 m tall, those formed in Upper Pleistocene sediments attaining 15–20 m in height (Machette *et al.*, 1991). Magnitudes of Holocene earthquakes are Mw 7.1–7.4 and Ms 7.5–7.7. Average displacement per event changes from 1.6 m in the north to 3.0 m in the south (Schwartz *et al.*, 1983).

The major surface-rupturing earthquakes on the Central Wasatch fault have occurred every 395±60 yrs during he past 6 ka, and every 220 yrs between 1500 and 400 yrs BP (Machette *et al.*, 1991). No large earthquake has occurred during the past 400 yrs. The Brigham segment appears to be the least active one, since it has not ruptured during the past 3600 yrs. The average recurrence interval for Holocene seismic events has been estimated at 1980±310 yrs (Machette *et al.*, 1991).

The present-day seismicity is seldom related directly to the trace of the Wasatch fault (Arabasz *et al.*, 1979), being concentrated 20–30 km away from it (*cf.* Fig. 2B). All the available pieces of evidence indicate an E–W or WSW–ENE orientation of the least principal stress (Zoback, 1983). Geodetic survey in Ogden and Salt Lake City areas, however, reveal compressional deformation oriented nearly perpendicular the the fault (Prescott *et al.*, 1979; Zoback, 1983).

CLIMATE

The present-day climatic conditions along the entire Central Wasatch fault zone are uniform. Average annual temperatures range between 3.8–4°C and 17.5°C, averaging at 10–11°C, and the total annual precipitation is from 380 to 402 mm (Wahlquist, 1981). Winters are fairly cold, with temperatures averaging below O°C, whereas summers are hot, with mean July temperaures about 25°C. Crests of the highest-situated faceted spurs (2500–2825 m a.s.l.) are exposed to more severe climatic conditions, characterized by lower annual temperatures and high snowfall during winter times. All the faceted spurs display similar, western or WSW aspect, except those of the Spanish Fork segment which face NW. We suppose, therefore, that the share of climate in shaping triangular facets along all the studied segments of the Wasatch fault was similar.

METHODS

To characterize the geometry of faceted spurs of the four segments studied, we have chosen a modified Horton-Strahler's classification scheme, originally applied to the drainage networks (Horton, 1945; Strahler, 1952, 1958), and used sometimes to describe length frequencies of fault systems (*cf.* Gartner & Shaw, 1983). All single interfluves of a given faceted spur which reach the foot of the mountain front are considered as 1st-order links. Two 1st-order links merge higher upslope into a 2-nd order link. Two 2nd-order links join, in turn, to form a 3rd-order link, etc. Such an "interfluve network" makes it possible to apply Horton-Strahler's power laws, concerning the number and length of links of different orders (*cf.* Fig. 6). We have used 1:24,000 topographic maps to delimit triangular facets dealt with in this study.

The following descriptive parameters have been calculated for each large faceted spur:

(1) the lengths of links of the 1st, 2nd, 3rd and 4th order (R); L_1, L_2, L_3, L_4;

(2) the total length of all links within a given faceted spur; L_{TOTAL};

(3) the number of 1st-order links; N-1;

Table 1

Basic characteristics of the Central Wasatch fault segments (based on Schwartz *et al.*, 1983; Zoback, 1983; Machette, 1988; Nelson, 1988; Personius, 1988; Forman *et al.*, 1989; Machette *et al.*, 1991)

parameter	BRIGHAM	WEBER	SALT LAKE CITY	SPANISH FORK
length, km	40	61	46	69.5
curvature	1.127	1.089	1.179	1.178
minimum vertical offset, km	3.4	3.7	3.15 - 11*	4.0
Holocene seismic events	2 between 4700±500 & 3600±500	4 between 3750±250 & 500±300	5250±250 1500±300	5300±300 2600±300 500±200
total Holocene net displacement, m	8-9**	8	9 (?)	15-23***

* – post-Oligocene; ** – after 13.5 ka; *** – post-Bonneville

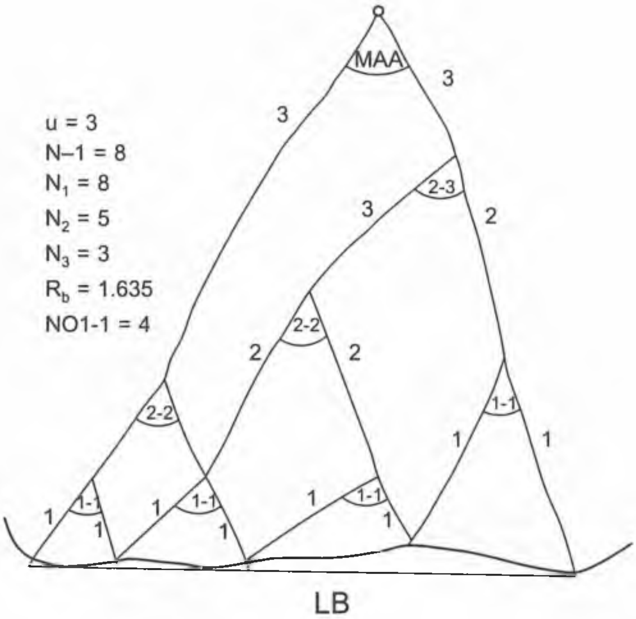


Fig. 6. Example of a compound faceted spur; u = 1, 2, 3 – link orders; 1-1, 2-2, 2-3 – angles comprised between links of different orders; see text for other explanation

(4) the bifurcation ratio R_b, defined as arithmetic mean of ratios N_u/N_{u+1}, where N = number of links, u = order;

(5) the length ratio R_L, equal to arithmetic mean of ratios L_u/L_{u+1}; where L = link length, u = order;

(6) the length of spur base LB, measured along straight line;

(7) the length of spur base LR, measured along the Bonneville shoreline;

(8) angles between neighbour links; A1-1, A2-2, A3-3, A1-2, A1-3, A2-3, A3-4;

(9) the number of angles comprised between 1st-order links NO 1-1, representing the number of 1st-order spurs at the base of the mountain front; and

(10) the main apical angle MAA, defined as the highest-situated main angle of the triangle, whose sides contour a large faceted spur.

L_{TOTAL} together with LB may serve as estimates of the spur's size, whereas N-1 describes the intensity of erosional dissection of the mountain front. The average length of 1st-order links is a function of size of the youngest, 1st-order spurs, and may be indicative of the latest seismotectonic event. High values of the bifurcation ratio indicate the increased number of 1st-order links, resulting from stronger erosional dissection of a faceted spur. R_b appears to be strongly dependent upon bedrock lithology and structure. The length ratio appears to reflect directly the role of tectonic slip in the preservation and shaping of faceted spurs. Low R_L values imply progressively increasing lengths of links of higher orders; high values of R_L denote very long 1st-order links and considerably shorter and diminishing lengths of higher-order links. Angles comprised between links of the same order describe the shape of individual facets. It can be assumed that in active tectonic mountain fronts the youngest, *i.e.* lowest-situated faceted spurs would display higher angular values, whereas higher-order links would tend to join at gradually diminishing (more acute) angles. Departures from this theoretical trend can be interpreted as being controlled by differentiated resistance of bedrock rocks to erosion, different attitude of beds, fracture density, the presence of subsidiary fault-related zones of weakness, etc.

RESULTS

The largest faceted spurs along the Central Wasatch fault range in order between 2 and 4. The Brigham segment spurs are entirely of the 3rd order, whereas the only one, large 2nd-order facet, occurs in Salt Lake City segment (Table 2, Figs. 7–9, 11, 13). Most of the canyons that truncate the western side of the Wasatch Mts. follow zones of weakness (Marsell, 1932; Eardley, 1939; Personius, 1988).

The highest values of L_1 characterize Weber segment (3.9 km; Figs. 8, 12), the lowest ones are typical of Brigham spurs (2.5 km). Both Salt Lake City and Spanish Fork segments display high scatter of data (Figs. 7–10, 13, 14, 16). The total length of segment links usually decreases with increasing order, except isolated single spurs. Weber segment displays the largest spurs, characterized by the highest L_{TOTAL} values (9.5 km), whereas the lowest figures are confined to Brigham segment (4.75 km).

The highest number of 1st-order links (N-1) is observed in Weber (15), the lowest one in Salt Lake City (10) segments. The northern and southern segments appear to display the same intensity of erosional dissection of young facets (N-1 = 12).

The bifurcation ratio decreases from the north to the south, irrespectively of the changeable N-1, L_1 or L_{TOTAL} values (Figs. 7–10). Both Spanish Fork and Salt Lake City segments show similar R_b, although they differ in the range of scatter.

The highest length ratios are observed in Weber segment, the lowest ones have been detected in Salt Lake City segment. The Brigham and Spanish Fork spurs show comparable figures (Figs. 7–10).

The lengths of the largest faceted spurs, measured along a straight line (LB), range from 0.432 to 2.520. The longest mean LB occurs in Weber, the shortest one characterizes Brigham segment. The lengths of spur bases measured along the Bonneville shoreline, in turn, are longer than LB, and vary from 0.504 to 3.348 km. The highest average values describe Weber segment, the lowest ones are confined to Spanish Fork.

The angles comprised between spur links show considerable scatter throughout the four segments studied (21°–121°). In Salt Lake City segment, apical angles tend to increase with increasing order of the spur-forming links (from 45° to 88°); the other segments do not reval such a regularity, although the angles comprised between 3rd-order links are always wider than those between 1st-order links.

The number of angles between 1st-order links (NO 1-1) defines the number of the youngest spurs in each segment, ranging from 2 to 10.

Table 2

Parameters of faceted spurs on selected Wasatch fault segments

parameter	R_b	R_L	N-1	L-1	L_{TOTAL}	LB
BRIGHAM SEGMENT (spurs 1, 2, 3, 4, 5)						
range	2.65-3.33	1.41-3.77	8-17	2.004-3.264	2.568-5.640	0.552-1.344
mean	3.04	2.16	12	2.520	4.747	1.042
st. dev.	0.27	0.96	3.5	0.463	1.284	
WEBER SEGMENT (spurs 5, 6, 7, 8, 9)						
range	2.72-3.50	1.82-3.35	9-24	2.112-6.588	4.224-16.09	0.996-2.520
mean	3.14	2.34	15	3.924	9.454	1.740
st. dev.	0.31	0.60	6.5	1.972	4.826	
SALT LAKE CITY SEGMENT (spurs 2A, 4, 5, 6, 7)						
range	2.00-3.25	0.52-2.31	4-15	0.828-4.704	1.536-10.56	0.852-1.560
mean	2.63	1.48	10	2.880	6.518	1.253
st. dev.	0.46	0.71	4.3	1.681	3.705	
SPANISH FORK SEGMENT (spurs 1, 2, 3, 4, 5)						
range	2.25-2.75	1.54-2.57	5-16	1.056-5.100	1.800-11.46	0.432-1.848
mean	2.47	1.97	12	2.873	6.732	1.207
st dev.	0.22	0.38	4.8	1.701	4.010	

R_b – bifurcation ratio; R_L – length ratio; N-1 – number of 1st-order links; L-1 – length of 1st-order links, km; L_{TOTAL} – total length of all links, km; LB – length of the spur's base, measured along the straight line, km

The main apical angle (MAA) is usually comprised between links of orders 2-3 or 3-3 (Brigham, Salt Lake City) and 3-3 or 3-4 (Spanish Fork). MAA is always greater than 50°; the highest values occurring in Weber (121°) and Spanish Fork (117°) segments.

The southward increasing R_b values are indicative of the diminishing intensity of erosional remodelling of facets what, in turn, may reflect the southward-increasing intensity of coseismic uplift. The curvature of spur base (LR/LB) also gradually diminishes from the north to the south, pointing to the southward-increasing "freshness" of tectonic landforms (*cf.* Figs. 15, 16).

A comparison among the above parameters suggests that the two most similar segments of the Central Wasatch fault are Brigham and Spanish Fork (Figs. 11, 16). Both reveal similar values of N-1 and R_L, show the most acute main apical angles and very wide angles comprised between 1st-order links. This similarity can reflect comparable geologic settings of both segments, i.e. the presence of layered sedimentary rocks dipping into the mountain front. The least similar pairs of segments are Brigham–Weber (Figs. 11, 12) and Weber–Salt Lake City (Figs. 12–14). The Spanish Fork segment, however, appears to be the most tectonically active one, as suggested by the shape and "freshness" of its faceted spurs (Figs. 15, 16). The latter display the lowest bifurcation ratios and nearly straight-line bases. Very high values of LB, L_{TOTAL}, L_1, N-1, R_b, NO 1-1 and MAA, typical for Weber segment, seem to result primarily from intensive denudational remodelling of faceted spurs, controlled by highly erodible and nearly homogeneous bedrock.

Correlation analysis

Correlation coefficients among descriptive geometric parameters have been calculated for individual fault segments and the entire Central Wasatch fault (Fig. 17).

The pairs N-1/L_1, N-1/L_{TOTAL} and L_1/L_{TOTAL} reveal strong positive correlation (>0.70), both for individual segments, and all faceted spurs taken together. Such a trend is not surprising, since all the three parametres are interrelated by definition. One would expect strong linear relationship between R_b and N-1. This holds true only for the Spanish Fork segment (0.33). Both the Brigham and Weber segments show negative values of all correlation coefficients considered, whereas Salt Lake City and Spanish Fork segments reveal only positive values. Mutual relationships between R_b and other parameters are the strongest in Spanish Fork segment, whereas those between R_L and other parameters are stronger in Salt Lake City segment.

The Spanish Fork segment shows the strongest positive relationships between R_b and the number and length of 1st-order links, as well as the total length of spur links. It is, therefore, the only segment wherein the above relationships are close to those which should be expected.

Positive correlation between the R_b and the main apical angle of 1st-order facets implies that with increasing

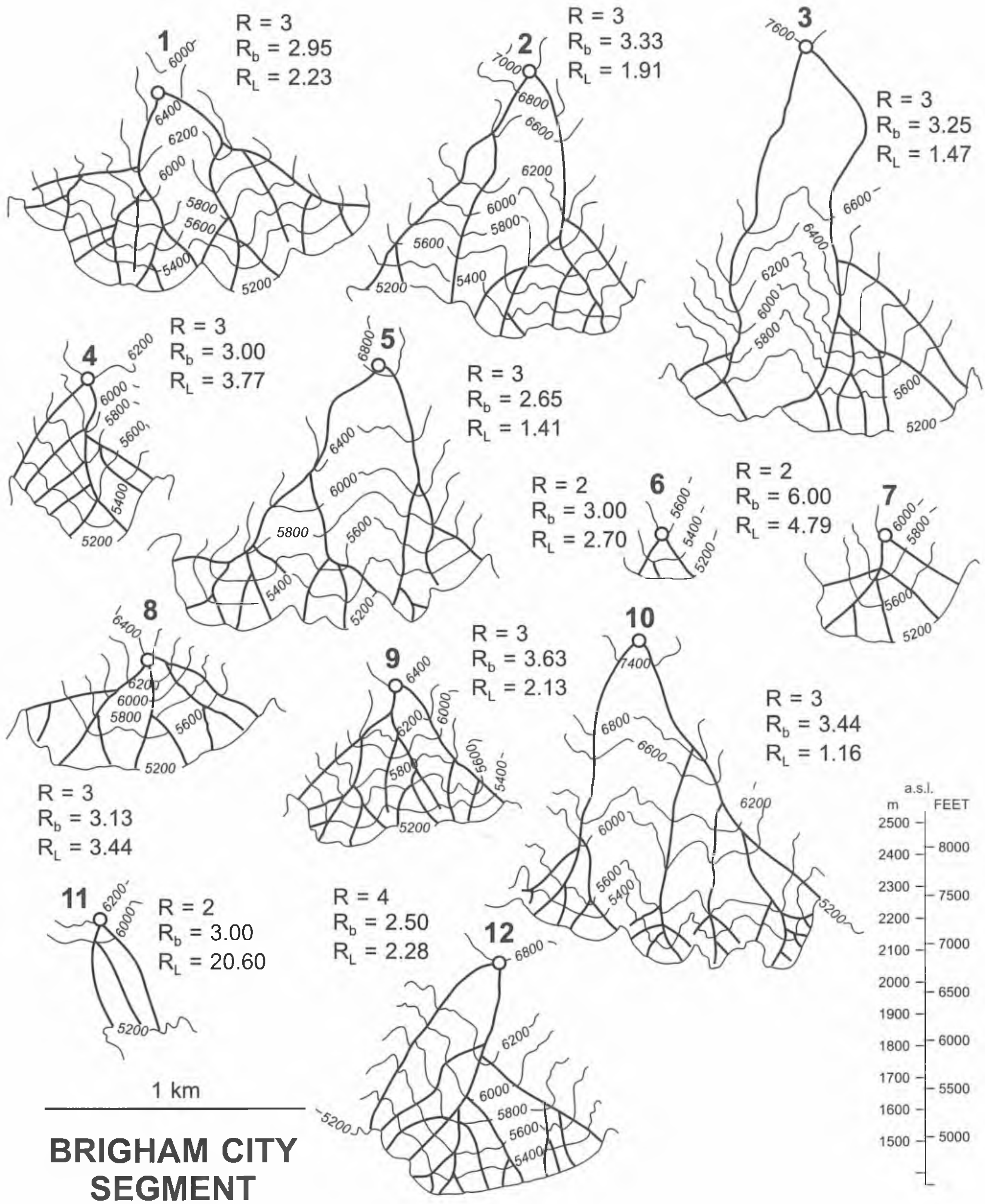


Fig. 7. Plots of faceted spurs on the Brigham City segment. See text for explanation

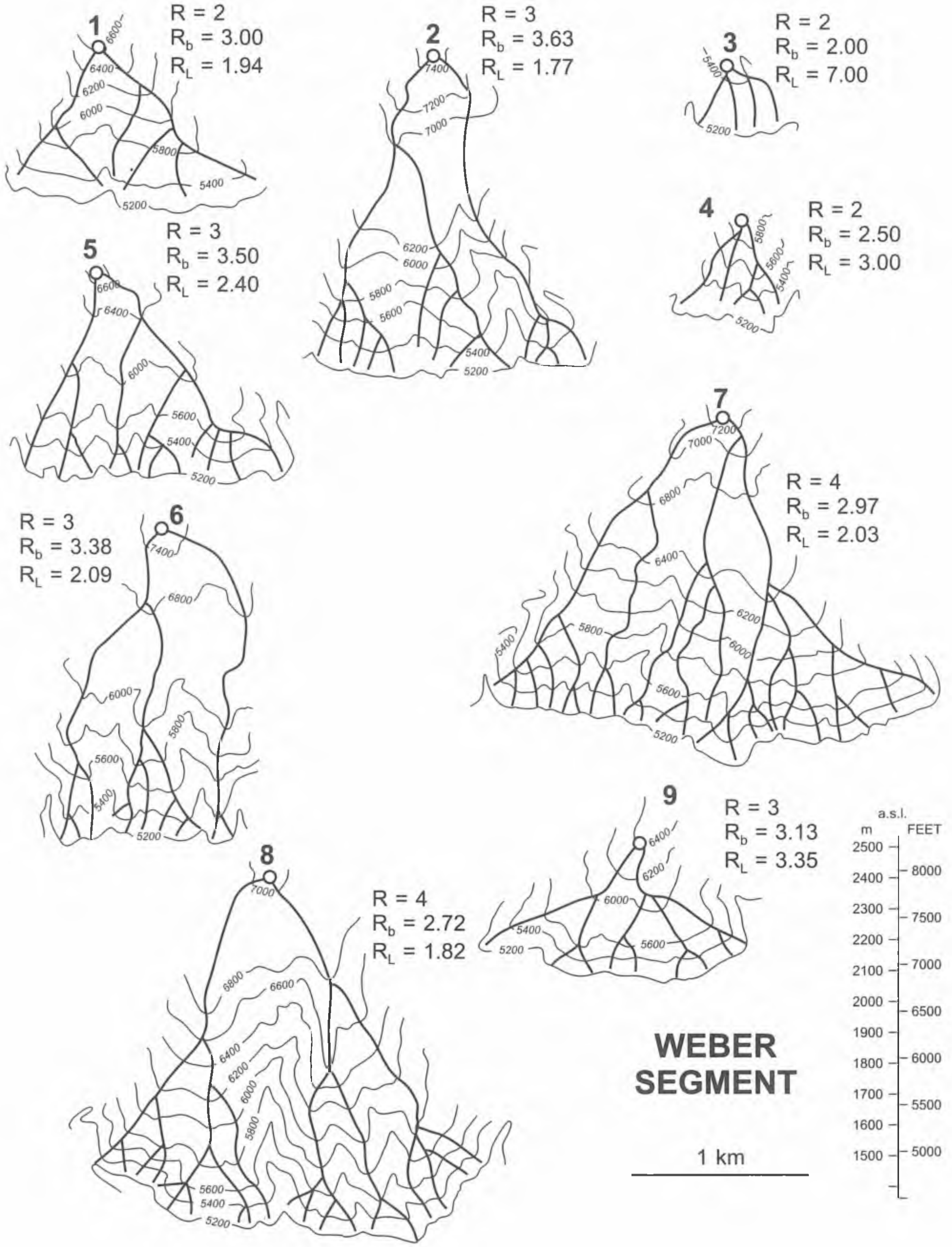


Fig. 8. Plots of faceted spurs on the Weber segment. See text for explanation

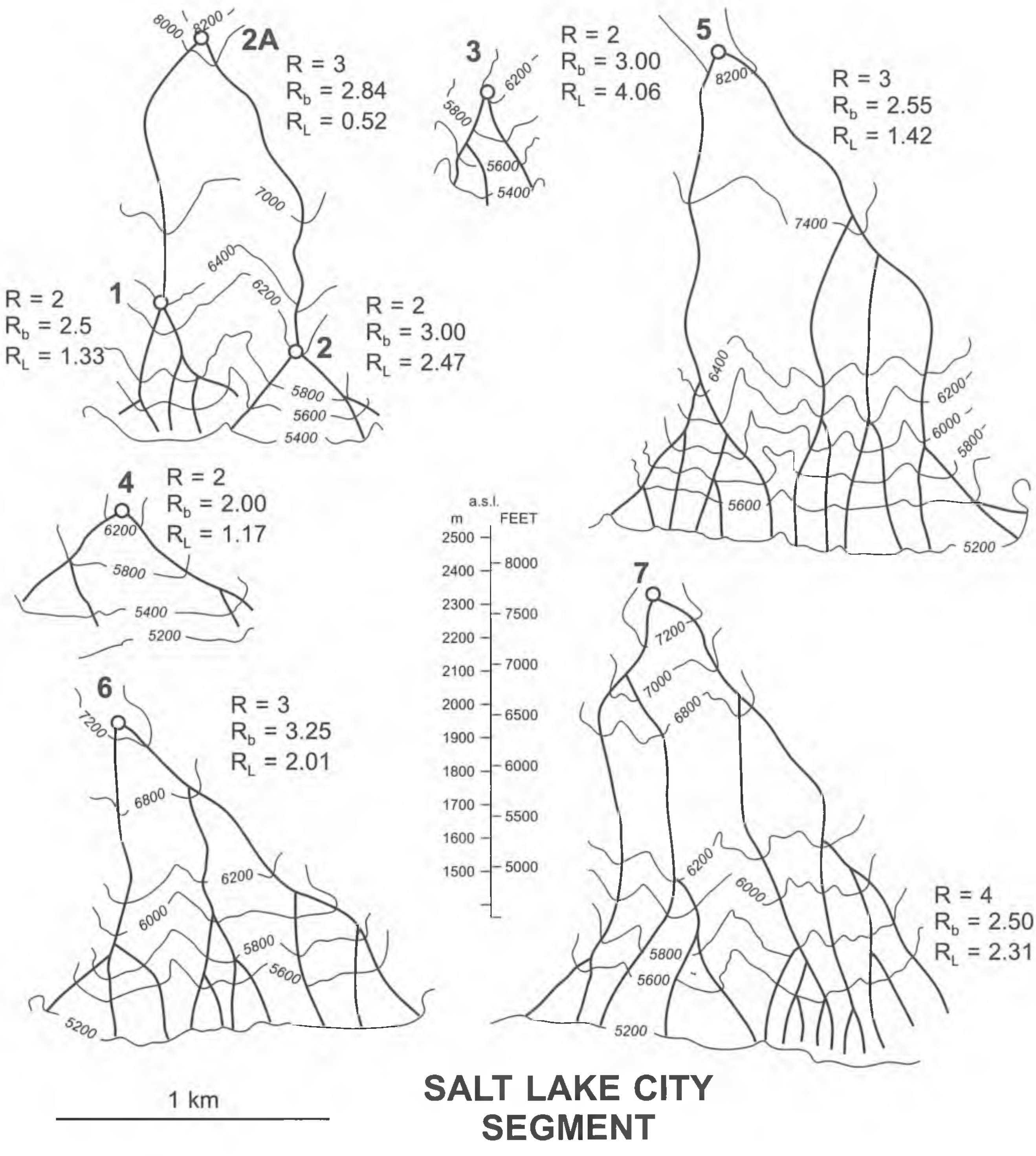


Fig. 9. Plots of faceted spurs on the Salt Lake City segment. See text for explanation

number of 1st-order links, apical angles of the youngest facets should increase. Negative correlation suggests the reverse, more understandable, relationship. Moderately to strongly positive correlation characterizes Brigham and Weber segments; weakly to strongly negative correlation is typical for Salt Lake City (–0.26) and Spanish Fork (–0.82) spurs. Positive correlation may also be expected to occur between R_b and the number of 1st-order facets (NO 1-1). This is true again for Salt Lake City and Spanish Fork segments; the other segments display negative correlation coefficients. Strong positive correlation between R_b and MAA has only been observed in Spanish Fork segment (0.80).

The most similar pairs of segments, as far as the number of comparable correlation links is concerned, are Salt Lake City–Spanish Fork and Brigham–Weber; the least similar appear to be Brigham–Salt Lake City and Brigham–Spanish Fork (Fig. 17). This suggests a stronger influence of the intensity of seismotectonic uplift upon angular parameters of faceted spurs, as compared to that of lithological differentiation.

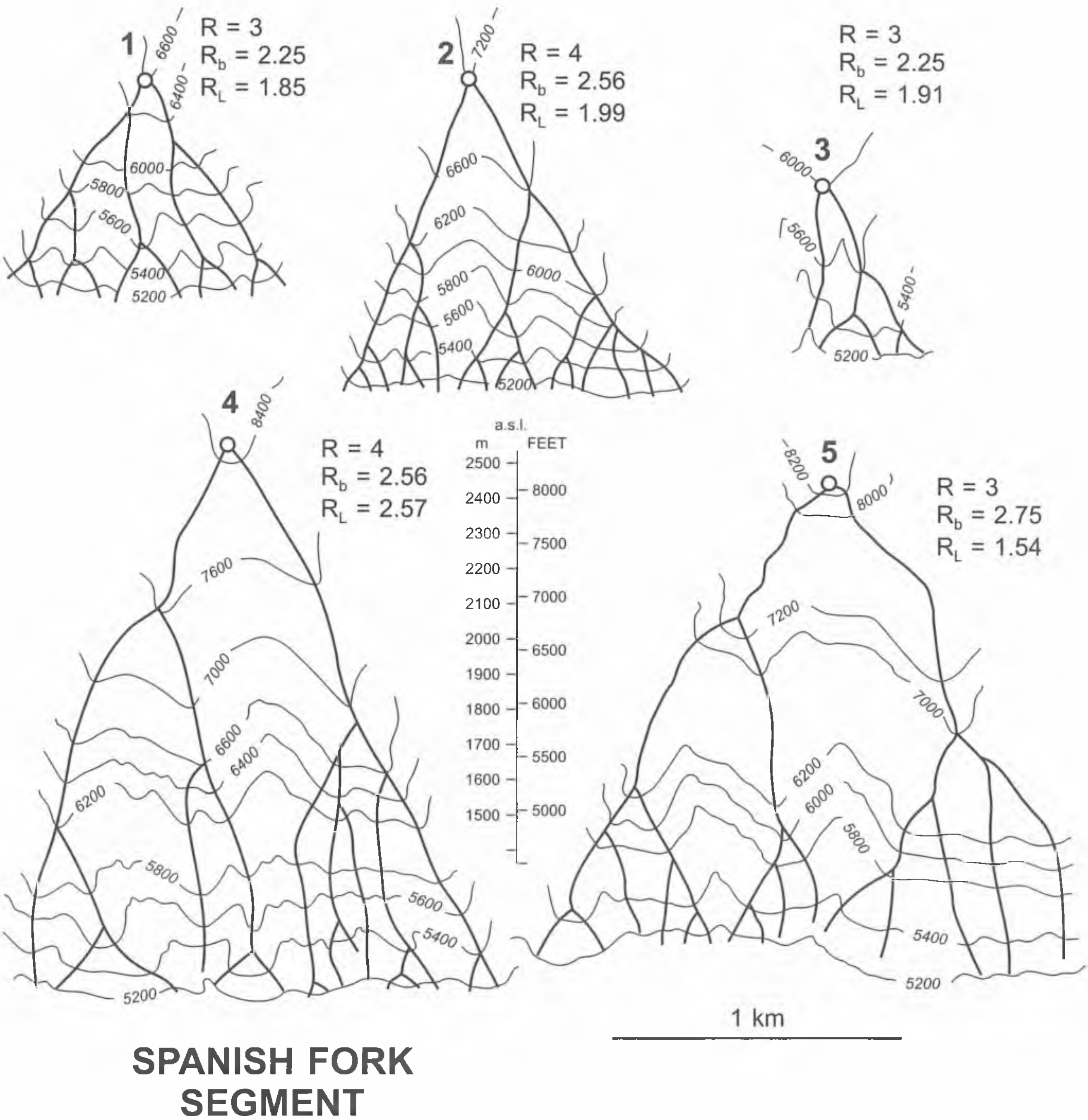


Fig. 10. Plots of faceted spurs on the Spanish Fork segment. See text for explanation

Discussion

The analysis of geometry of faceted spurs preserved along the Central Wasatch fault does not allow for drawing unequivocal conclusions as to predominant effects of tectonic and/or other factors upon the development of triangular facets. Geometric parameters point to a close similarity between Brigham and Spanish Fork segments; both showing comparable lithological and structural settings. Mutual relationships among geometric parameters, however, appear to imply that the intensity and size and seismotectonic fault slip are the dominant factors. The two contrasting pairs of fault segments include Brigham–Weber and Salt-Lake City–Spanish Fork. These pairs occupy, respectively, the less and more active parts of the Central Wasatch fault. We should not forget, however, that this subdivision is based on geometric characteristics of the largest faceted spurs (5 per segment), which have been formed during different time spans, and witnessed different number of seismic events.

RELATIVE AGE OF FACETED SPURS

Twenty age levels, A through T (from the youngest to the oldest), and representing pediment surfaces occurring at the apices of triangular facets, have been distingusihed

Fig. 11. Brigham City segment. The Provo level delta (14.5–13.5 ka; *cf.* Curray *et al.*, 1983) at the foot of faceted mountain front

Fig. 12. Weber segment. Outlet of the Ogden Canyon

Fig. 13. Salt Lake City segment. Faceted spurs at the base of Wasatch front. Note the Bonneville shoreline (16–14.5 ka; *cf.* Curray *et al.*, 1983) underlying the lowermost facets

Fig. 14. Salt Lake City segment. Sediments of the Bonneville delta (16–14.5 ka) at the base of faceted mountain front

Fig. 15. Provo segment. Highly elevated Wasatch mountain front cut by triangular and trapezoidal facets

Fig. 16. Spanish Fork segment. Well-developed triangular facets sloping down to the Bonneville shoreline

within the four fault segments studied, basing on their elevation above the sea level and relative height above the Bonneville shoreline (Table 3). The second criterion is even more important, since the elevation of the top of Bonneville sediments varies throughout the entire length of the Wasatch fault due to post-Bonneville isostatic rebound. Isostatic uplift along the fault is found to have changed from 26–33 m in Brigham, through 26 m in Weber and Salt Lake City, to 20 m in Provo segments (Crittenden, 1963). The elevation of the Bonneville shoreline rises from Brigham to

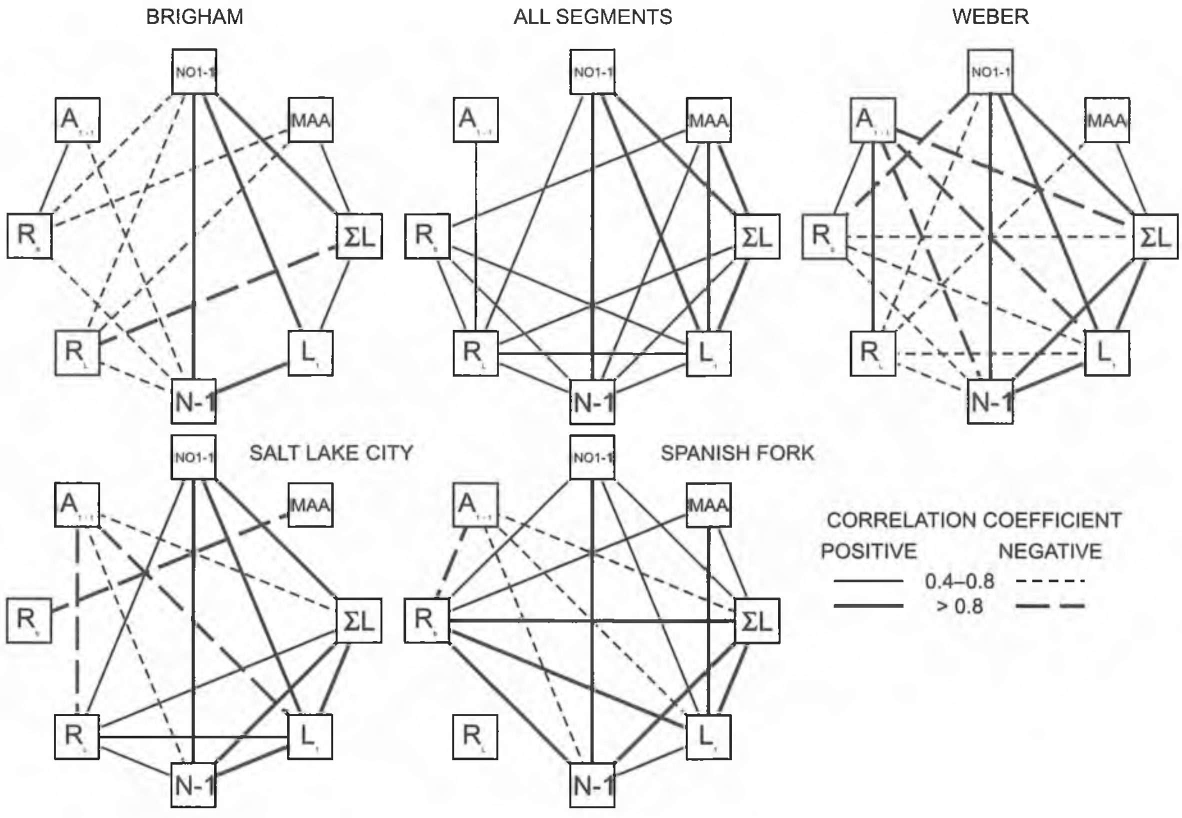


Fig. 17. Mutual correlation among basic characteristics of the Wasatch fault triangular facets

Salt Lake City by about 79 m, then drops farther southwards by 39–26 m at Spanish Fork (Figs. 11, 13, 16).

Individual segments do not display all the age levels distinguished; three levels are most common, one occurs less frequently, and the remaining ones appear sporadically within one or two spurs per segment. Out of the total 20, Brigham, Weber and Spanish Fork segments display 15 age levels, whereas the Salt Lake City segment shows only 12 facets of different age. The youngest age level (A) has been distinguished at 1742–1756 m a.s.l. (39–40 m above the base) in Brigham and Spanish Fork segments; the oldest level (T), occurring at 2825 m a.s.l. (1122 m above the base), is characteristic for the Spanish Fork segment only (Fig. 15; Table 3).

Average elevations of the main spur apices rise from Brigham (2265 m a.s.l.) to Salt Lake City (2481 m a.s.l.), then plunge to 2416 m a.s.l. at Spanish Fork. The same holds true for relative heights. Such a trend, resembling that of the Bonneville shoreline position, as well as the inferred Late Pleistocene–Holocene coseismic uplift rates along the Wasatch Front (Machette *et al.*, 1991; Hecker, 1991), may be indicative of a long-term, increased tectonic activity of the medial segments of the fault.

Height differences among individual age levels vary from 13–105 m in Brigham, 7–119 m in Weber, 27–132 m in Salt Lake City, and 27–106 m in Spanish Fork segments; the average figures being 45 m, 53 m, 74 m, and 62 m, respectively.

The faceted spurs dealt with in this study rise above the Bonneville shoreline, hence, they are older than 13–16 ka. Assuming a constant rate of seismotectonic slip along the Central Wasatch fault, equal to 0.1 to 0.2 mm/yr, a figure suggested by Machette *et al.* (1986) for the Late Quaternary, we receive the following time intervals for the four segments studied (Table 4).

On the other hand, taking into account the results of apatite fission-track dating of basement rocks in the Wasatch Mts. (Naeser *et al.*, 1986), indicative of an average uplift rate of 0.4 mm/yr for the last 10 Ma, we may estimate the age of the oldest faceted spurs at: 1.98 Ma (Brigham), 2 Ma (Weber), 2.6 Ma (Salt Lake City), and 2.8 Ma (Spanish Fork). All these figures are highly speculative, since there are no data that would support the concept of constant rates of uplift. On the contrary, one can expect highly changeable rates, illustrated, *e.g.*, by a comparison between Late Pleistocene (0.1–0.2 mm/yr; Machette *et al.*, 1986) and Holocene (1–2 mm/yr; Machette *et al.*, 1991) rates of slip on the Central Wasatch fault.

FINAL REMARKS

Faceted spurs preserved along the Central Wasatch fault display differentiated geometry and state of development (Figs. 7–10, Table 1). Geometric parameters of the largest faceted spurs, that have been shaped since the Pliocene or Early Pleistocene, appear to reflect lithological, structural and seismotectonic variability among the four segments studied. The two most similar segments are Brigham and Spanish Fork, both showing comparable val-

Table 3

Faceted spurs along the Wasatch fault: age levels of the norther and median fault segment

LEVEL	NORTHERN FAULT SEGMENTS				MEDIAN FAULT SEGMENTS			
	BRIGHAM		WEBER		SALT LAKE CITY		SPANISH FORK	
	m a.s.l.	m above base	m a.s.l.	m above base	m a.s.l.	m above base	m a.s.l.	m above base
A	1756 (2)	40					1742 (1)	39
B	1769 (1)	53	1782 (2)	53				
C	1795-1808 (3)	79-92	1789-1822 (4)	60-93	1861 (1)	66	1756-1795 (5)	66-92
D	1848-1861 (5)	132-145	1822-1865 (5)	93-136	1822-1901 (4)	93-132	1795-1822 (5)	105-119
E	1874-1888 (3)	158-172	1874-1894 (5)	145-165	1861-1914 (5)	145-172	1835-1848 (4)	132-158
F	1914-1927 (5)	198-211	1904-1934 (3)	175-205	1914-1980 (4)	185-211	1888-1914 (4)	185-224
G	1980-2006 (3)	264-290	1947-2013 (5)	218-284	1967-2046 (4)	251-277	1954-2006 (3)	251-303
H	2020-2033 (2)	304-317	2020-2033 (3)	291-304	2020-2112 (5)	317-347		
I	2046-2059 (4)	330-343						
J	2086-2125 (2)	370-383	2086-2125 (4)	357-396			2046-2072 (4)	343-369
K	2138 (1)	422	2138 (1)	409			2112 (2)	409-422
L	2165-2178 (2)	449-462	2178-2204 (2)	449-475	2152 (1)	436	2178 (3)	475-488
M	2270 (1)	554	2244-2284 (3)	515-555	2257-2270 (2)	541	2231-2257 (2)	528-554
N	2323 (1)	607	2363 (1)	634	2350-2389 (2)	621-673	2284-2310 (2)	581-607
O			2429 (1)	700	2435-2468 (3)	713-752	2376-2402 (2)	689-699
P	2508 (1)	792	2495 (1)	766				
Q			2534 (1)	805			2521 (1)	818
R					2693 (1)	898		
S					2746 (1)	1030	2719 (1)	1016
T							2825 (1)	1122

(1) – number of spurs that display given age level

ues of N-1 and R_L, most acute main apical angle, and very wide angles comprised between 1st-order links (Fig. 17, Table 2). These segments are composed of Palaeozoic sedimentary rocks that dip moderately or gently into mountain front. The Brigham segment shows a sequence of alternating layers of different resistance to erosion; the Spanish Fork segment displays a more uniform sequence which is, however, cut by a series of subsidiary, high-angle normal faults striking parallel to the Wasatch fault and coinciding with apices of some of faceted spurs.

The least similar pairs of segments, as far as facet topology is concerned, are Brigham–Weber and Weber–Salt Lake City (Fig. 17, Table 2). The Weber segment is characterized by very high values of LR/LB, L_{TOTAL}, L_1, N-1, R_b, NO 1-1 and MAA; all of them indicating strong dissection of highly erodible bedrock (*cf.* Stokes, 1986). Faceted spurs of the Spanish Fork segment, in turn, appear to be the most fresh tectonic landforms, as shown by their shape, lowest bifurcation ratios, and nearly rectilinear spur bases. That part of the Central Wasatch fault is thought to be the most tectonically active one (Schwartz *et al.*, 1983; Zoback, 1983; Machette *et al.*, 1989, 1991).

Mutual relationships among geometric parameters appear to reflect both tectonic and seismotectonic differentiation of the fault. The most similar pairs of segments are Salt Lake City–Spanish Fork and Brigham–Weber. The first pair shows only positive correlation coefficients among the parameters studied, as well as the strongest relationships between R_b or R_L and the other characteristics (Fig. 17). The Spanish Fork segment is the only one which reveals strong linear relationships between R_b and N-1, L_1, and L_{TOTAL}. The least similar segments are Brigham–Salt Lake City and Brigham–Spanish Fork, suggesting strong influence of the rate of tectonic uplift upon angular parameters of faceted spurs, as compared to that exerted by lithology and structure.

Average values of selected parameters of those faceted spurs which belong to different age levels do also indicate strong tectonic, lithological and structural control. The curvature of the spur's base diminishes southward, from

Table 4

Age estimation of faceted spurs on the Central Wasatch fault

age level	Brigham	Weber	Salt Lake City	Spanish Fork
youngest	A	B	C	A
ka:	200-400	265-530	330-660	195-390
oldest	P	Q	S	T
Ma:	3.96-7.92	4.0-8.1	5.2-10.3	5.6-11.2

Brigham to Spanish Fork; whereas R_b, R_L, L_{TOTAL} and N-1 attain highest values in the northern, less active segments. The highest figures are confined to the Weber facets which are composed of less resistant, sheared metamorphic rocks. Main apical angles increase with facet's age in Brigham and Weber segments, whereas the more tectonically active Salt Lake City and Spanish Fork segments display the opposite trend. The length ratios diminish with age throughout the segments, pointing to gradual shortening of higher-order links. Bifurcation ratios generally increase with the age of faceted spurs in Brigham and Spanish Fork segments, but they tend to decrease both in Weber and Salt Lake City segments.

The size of a faceted spur is a function of the distance between major canyons incised into the mountain front and of the spur's height. Most of the canyons that truncate the western side of the Wasatch Mts. follow the zones of weakness associated with either transversal high-angle normal faults or fractures (*cf.* Fig. 12). The steepness of canyon walls exerts control upon main apical angles of faceted spurs. One would expect that on relatively homogeneous bedrock these angles would tend to decrease with facet's age. Departures from this trend imply lithological control. Some of geomorphic parameters dealt with in this study reflect the size of the facet (N-1, L_1 or L_{TOTAL}), whereas dimensionless ratios (R_b, R_L) are usually size-independent and seem to be controlled by the rate of both seismotectonic uplift and erosional dissection. The height of faceted spurs, in turn, is a function of uplift, whereas average inclination may be controlled by a variety of factors. One of them is the age of the spur: on homogeneous bedrock (*cf.* Wallace, 1977, 1978) the younger facets are steepest (see also Fig. 5). Along the Central Wasatch fault such a relationship is, however, seldom observed due to either highly differentiated lithology of underlying rocks (Brigham) or the presence of subsidiary, high-angle normal faults that are parallel to the Wasatch fault and dip to the west, i.e. towards the base of the mountain front (Spanish Fork). The latter case resembles that of the Aegean-type fault scarps (Stewart & Hancock, 1988, 1990).

The above review leads to a conclusion that the geometry of faceted spurs developed on differentiated bedrock, although controlled primarily by the rate of seismotectonic uplift, is frequently modified by resistance to erosion and structure of the bedrock.

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Streszczenie

GEOMETRIA LIC PROGÓW USKOKOWYCH AKTYWNEGO USKOKU NORMALNEGO NA PRZYKŁADZIE ŚRODKOWEGO SEGMENTU USKOKU WASATCH W STANIE UTAH (U.S.A)

Witold A. Zuchiewicz & James P. McCalpin

Celem pracy jest ocena wpływu czynników tektonicznych oraz litologiczno-odpornościowych na morfologię lic progów uskokowych (*triangular facets*) w obrębie czterech segmentów uskoku Wasatch (Fig. 1–5, 11–16) w północno-wschodniej części prowincji Basin and Range w stanie Utah (od północy: Brigham City, Weber, Salt Lake City, Spanish Fork). Dla każdego segmentu wybrano 5 najlepiej wykształconych lic progów uskokowych. Spąg najmłodszych form przykrywają górnoplejstoceńskie osady jeziora Bonneville (Fig. 11, 14), podczas gdy lica progów są wykształcone w obrębie skał podłoża o zróżnicowanej litologii i strukturze. Poszczególne piętra hipsometryczne (fragmenty pedymentów) kolejnych lic zaklasyfikowaliśmy do odpowiednich poziomów wiekowych (od najmłodszego do najstarszego: A – T), a następnie porównaliśmy ich parametry geometryczne.

Segmenty północny i południowy są zbudowane z paleozoicznych skał osadowych zapadających 35–40° (Brigham City) i 10–20° (Spanish Fork) w stronę czoła masywu Gór Wasatch, tj. ku wschodowi. Segmenty centralne są zbudowane z prekambryjskich gnejsów i łupków krystalicznych (Weber), względnie kredowych i trzeciorzędowych monzonitów kwarcowych, indrudujących w prekambryjskie kwarcyty i metaargility (Salt Lake City).

Dla charakterystyki topologicznej lic progów uskokowych zastosowaliśmy zmodyfikowaną klasyfikację Hortona-Strahlera (Fig. 6). Działy wodne usytuowane najbliżej podnóża skarpy uskokowej uznaliśmy za odcinki 1 rzędu. Ostrogi 1 rzędu łączące się w górę stoku tworzą dział rzędu 2, itd. Tak skonstruowana "sieć" działów wodnych obramowujących lica progów uskokowych umożliwia zastosowanie analizy hortonowskiej w odniesieniu do liczby, długości, spadków oraz kątów wierzchołkowych poszczególnych ostróg (*faceted spurs*).

Przeciętna długość odcinków 1 rzędu jest funkcją rozmiarów najmłodszych ostróg, będących efektem najmłodszego epizodu sejsmicznego. Wysokie wartości wskaźnika bifurkacji wskazują z kolei na wzrastającą liczbę odcinków 1 rzędu, wynikającą z silnego rozcięcia erozyjnego ostrogi. Wskaźnik bifurkacji zależy w głównej mierze od litologii i struktury podłoża, natomiast wskaźnik długości bezpośrednio odzwierciedla wpływ przemieszczenia uskokowego na zachowanie lica progu. Kąty zawarte między odcinkami tego samego rzędu opisują kształt poszczególnych lic. W obrębie aktywnych skarp uskokowych można oczekiwać stopniowo malejących wartości kątów wierzchołkowych wraz ze wzrastającym rzędem działów wodnych. Odchylenia od tej tendencji wynikają głównie ze zróżnicowanej odporności skał budujących skarpę, ich ułożenia, gęstości spękań oraz obecności podrzędnych uskoków równoległych do czoła masywu górskiego.

Lica progów uskokowych (Fig. 6–10) zachowanych w centralnej części uskoku Wasatch wykazują zróżnicowaną geometrię i stopień zachowania. Parametry geometryczne największych zespołów lic, kształtowanych od pliocenu lub wczesnego plejstocenu, odzwierciedlają różnice litologiczne i strukturalne oraz odmienne tempo ruchów sejsmotektonicznych pomiędzy czterema analizowanymi segmentami uskoku (Tab. 1–4). Największym podobieństwem odznaczają się segmenty Brigham City i Spanish Fork (Fig. 11, 16), zbudowane z osadowych skał paleozoicznych. Segment Brigham City wykazuje naprzemianległe ułożenie skał o zróżnicowanej odporności; segment Spanish Fork ujawnia sekwencję o mniejszych kontrastach odpornościowych, przeciętą jednakże przez serię podrzędnych wysokokątowych uskoków normalnych, o upadach zgodnych z nachyleniem skarpy głównej. Najmniej cech wspólnych wykazują pary segmentów (Fig. 17): Brigham City–Weber oraz Weber–Salt Lake City. Analiza współczynników korelacji między parametrami geometrycznymi dotyczącymi kątów wierzchołkowych lic progów dla poszczególnych odcinków uskoku pozwala, z kolei, na wydzielenie par segmentów o zbliżonych własnościach sejsmotektonicznych: Salt Lake City–Spanish Fork (Fig. 13–16) oraz Brigham City–Weber (Fig. 11, 12). Dwa pierwsze segmenty ujawniają największe tempo przemiesz- czeń uskokowych (Tab. 1).

Niektóre parametry geometryczne (liczba i długość odcinków 1 rzędu, suma długości działów wodnych) odzwierciedlają rozmiary lica progu, podczas gdy wskaźniki bezwymiarowe (głównie wskaźniki bifurkacji i długości) nie zależą od wielkości danej formy i są uwarunkowane tempem ruchów tektonicznych oraz prędkością rozcięcia erozyjnego. Wysokość poszczególnych lic jest funkcją wypiętrzenia tektonicznego, natomiast ich nachylenie może być efektem zarówno mobilności tektonicznej, jak też zróżnicowania litologicznego (Brigham) i strukturalnego (seria uskoków schodowych w segmencie Spanish Fork).

Powyższy przegląd wykazuje, że geometria lic progów uskokowych jest w równym stopniu uwarunkowana tempem ruchów sejsmotektonicznych, jak też odpornością i strukturą skał podłoża.