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Evolution of Polygonal Fracture Patterns in Lava Flows

ATILLA AYDIN AND JAMES M. DEGRAFF

Cooling-induced fractures, also known as columnar joints, divide basaltic lava flows into prismatic columns with polygonal cross sections. The regularity and symmetry of the fracture patterns have long fascinated naturalists. In view of the recent selection of two candidate nuclear waste sites in areas where polygonally fractured volcanic rocks are located, a better understanding of the fracture patterns is required. Field data indicate that the tetragonal networks at flow surfaces evolve systematically to hexagonal networks as the joints grow inward during solidification of lava. This evolution occurs by the gradual change of most orthogonal intersections to nonorthogonal intersections of about 120 degrees. The surface features and intersection geometries of columnar joints show that joint segments at any given level form sequentially yet harmoniously.

MANY VOLCANIC ROCKS, ESPECIALLY BASALTIC LAVA flows, are divided by fractures into slender prismatic columns (Fig. 1a). In plan view, these column-bounding fractures, also called columnar joints, form remarkable polygonal patterns that vary from being tetragonal (Fig. 1b) to nearly hexagonal (Fig. 1c). The regular and distinctive geometry of columnar joints has long impressed scientists and laymen, who have observed this phenomenon in remote areas such as the Devils Postpile in California, the Devils Tower in Wyoming, and the Giant's Causeway in Northern Ireland. These sites have recently been designated national parks. In addition to the aesthetic qualities of columnar joints, however, recent efforts in the planning of a national repository for high-level nuclear waste necessitate a detailed understanding of factors that control the length, spacing, and pattern of these

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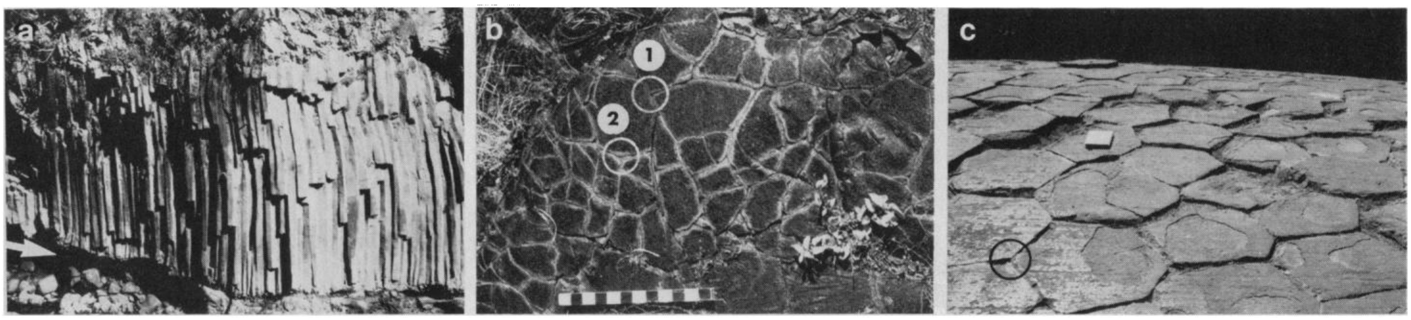


Fig. 1. Columnar joint arrangement in basaltic lava flows. (**a**) Profile view of the base (arrow) of a lava flow with vertical joint-bounded columns at the Boiling Pots site near Hilo, Hawaii. (**b**) Plan view of mostly tetragonal columns on the surface of a recent lava flow along the east rift of Kilauea volcano, Hawaii. The joints are marked by a white sublimate. Circles mark T(1) and curved T(2) intersections. Scale is 30.5 cm long. (**c**) Plan view of mostly hexagonal columns on an erosional surface through the interior of a lava flow at Devils Postpile National Monument, California. Circle shows a Y intersection. Field book (upper left) is 12 cm wide.

Fig. 2. Hypotheses concerning the formation of Y-type triple junctions of joints. Dots and arrows show the origins and propagation directions, respectively, of the joints. (**a**) Simultaneous arrival and intersection of three joints at each Y junction after the joints start midway between their eventual junctions. (**b**) Simultaneous beginning of three joints at each Y junction. (**c**) Repeated joint bifurcation to produce fork-shaped Y junctions. (**d**) Sequential joint formation to produce six basic types of pseudo Y junctions, defined by the number of segments involved and the lateral propagation directions of the segments.

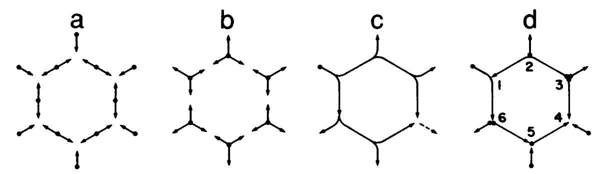
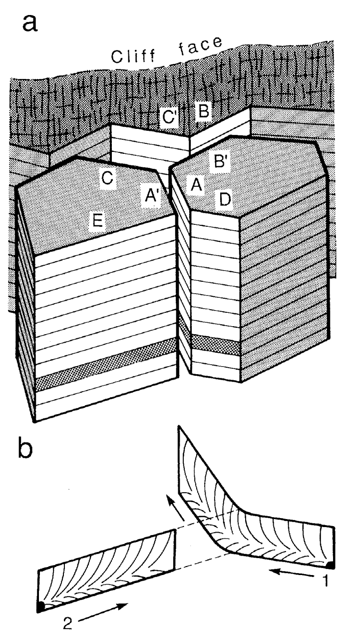


Fig. 3. Characteristics of column triple junctions. (**a**) Schematic representation of an exposure near the base of a Snake River basalt flow near Boise, Idaho. Letters indicate the eight joint surfaces examined in detail. (**b**) Schematic surface morphology and intersection of joint segments at one level of the triple junction. Dots show origins; thin curved lines show hackles that define plumose structure; arrows give local propagation directions of the segments; and numbers give the formation sequence of the segments.



joints. Two candidate sites for a nuclear waste repository are in volcanic rocks with columnar joints (*1*), whose characterization has important engineering and hydrologic applications.

Early legends attributed the formation of columnar joints to supernatural beings, as reflected by the names of the sites. Educated ideas about the origin of columnar joints began in the late 17th century with the publication of the first letters concerning the Giant's Causeway (*2*). Although these early ideas were more scientific than previous folk explanations, they were still largely speculative and often were influenced by moral and religious considerations (*3*). Nearly two centuries passed before the development of the modern concept that columnar joints form as the result of contraction during cooling and solidification of lava (*4, 5*). The idea that joints initiate at the surfaces of a cooling lava flow and grow inward as cooling proceeds was proved only recently (*6–9*). It has been established that the joint growth occurs incrementally and produces joint segments (*7*), whose surface markings and intersections indicate the vertical sequence of segment formation and the local and overall directions of joint growth (*9*). We used joint-surface morphology and joint-intersection geometry to investigate the initial formation and the subsequent evolution of columnar joint patterns. We found that columnar joints form individually and sequentially at any level of a lava flow and that joint patterns change systematically from the surface to the interior by means of interaction and selective termination of joints.

Hypotheses on Joint Intersections

Joint intersection geometry at the corners of columns permits one to determine the processes that are responsible for the observed joint patterns. The three most common types of joint intersections are T, curved T, and Y (Fig. 1, b and c). The first two are orthogonal intersections that result from sequential joint formation whereby the truncated joint forms after the through joint (*10*). These intersection types are common at the surfaces of lava lakes where early joints form sequentially (*6*). The polygons so formed are typically tetragonal (Fig. 1b), but other geometries are also observed. In contrast, joint patterns in a flow interior mostly consist of hexagonal polygons and Y-type intersections with angles of about 120° (Fig. 1c). This suggests that columnar joint patterns evolve from mostly tetragonal ones to mostly hexagonal ones as the joints grow inward from the flow surfaces (*11*).

The formation mechanism of Y-type intersections is not well understood, but there are four competing hypotheses. According to two hypotheses, equidistantly distributed stress centers develop with a regular arrangement on the surfaces of cooling lava (*12, 13*). In one scenario, joints begin simultaneously at the midpoints of lines connecting the so-called stress centers, and grow toward Y-type intersections to form a hexagonal joint network (Fig. 2a) (*12*). In another scenario, three joints begin simultaneously at each Y-type intersection and grow toward approaching joints from neighboring intersections (Fig. 2b) (*13*). These cases imply that all joints either grow toward or away from the intersections. A third hypothesis invokes the repeated bifurcation of an accelerating joint into two arms at 120° to each other, which implies that one joint always grows toward a junction and two joints grow away from it (Fig. 2c) (*10, 14, 15*). The latest hypothesis supposes sequential formation of joints at intersections and allows for any combination of growth directions and formation sequence of the joints (Fig. 2d) (*16*). These four hypotheses can be tested by determining the local horizontal growth direction and the formation sequence of collateral joint segments (Fig. 3b) at a statistically significant number of column triple junctions. By making these determinations at several adjacent levels along a single triple junction, changes of joint intersections during overall vertical growth of joints can be investigated (Fig. 3a).

Method of Study

The propagation direction of a joint segment is determined by analyzing its surface morphology (*9*). Each segment surface contains a set of curvilinear hackles (Fig. 3b), or lines at which the surface level changes abruptly, known collectively as plumose structure. Hackles radiate from the segment origin and fan away from a plume axis, indicating the lateral propagation direction of a segment. The sequence or simultaneity of segment formation is determined by carefully examining segment intersections at triple junctions. A consistent termination of segments against others (Fig. 3b) would support a purely sequential model of triple junction formation (Fig. 2d). Fork-shaped intersections (Fig. 2c) (*17*) or single-line intersections where three segments meet simultaneously (Fig. 2, a and b) would support, respectively, a bifurcation model or one of the stress-center models.

Order of Joint Formation

We have studied joints in several lava flows in the western United States and Hawaii (*9*); two outcrops are described here. One outcrop near Boise, Idaho, is at the base of a Snake River basalt flow, where the rock columns have well-preserved surface features and are slightly separated from each other (Fig. 3a). The joint segments resulting from incremental growth of each column face are defined by geometric discontinuities, changes of surface relief, and plumose structure. At triple junction ABC, we observed all three pairs of adjacent column faces, designated as AB′, BC′, and CA′ (Fig. 3a). The two pairs of column faces in Fig. 4a (AB′) and Fig. 4b (CA′) are at the same scale and show an equal vertical extent of the triple junction, so that the segments and their intersections can be correlated easily by eye. All three pairs of column faces were correlated by identifying corresponding points on matching faces AA′, BB′, and CC′.

Examination of surface features and intersections of the joint segments that make up triple junctions ABC and ADE leads to the following key observations and interpretations.

1) All segment intersections identified with confidence are T or curved T types, indicating sequential formation of collateral segments (Fig. 5). Triple junctions that may appear to be Y type are either sharply curved T or double T intersections (Fig. 5, c and d). We have never observed a fork-shaped column triple junction or one at which three segments intersect along a single line.

2) All six basic types of column triple junctions portrayed in Fig. 2d are observed at the Boise site. These types differ in the number of segments involved (two or three) and in the directions of segment propagation relative to the junction.

3) The upper and lower edges of collateral segments at triple junctions are generally not aligned (Figs. 4 and 5). Obvious examples of misaligned segments are 11 of face A and 10 and 13 of face B′ (Fig. 4a) and also 25 of face A′ and 26 of face C (Fig. 4b). This segment misalignment indicates that at times one column face extended slightly beyond the leading edges of the other faces at a triple junction, whereas at other times another face extended farther inward.

4) The absolute sequence of segment formation (numbers in Fig. 4) at both triple junctions is determined by combining the upward vertical sequence of segment formation of each column face (*9*) with the horizontal sequence of collateral segment formation at many levels. Having thus determined the propagation directions and absolute formation sequence of joint segments, we have specified precisely the kinematic development of sizable portions of two column triple junctions.

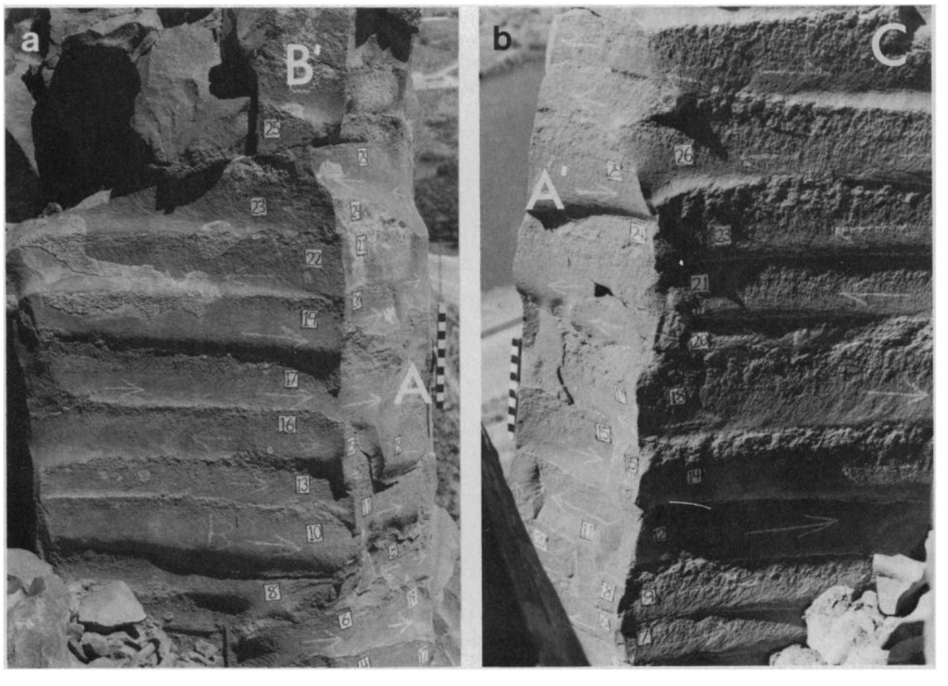


Fig. 4. Triple junction ABC of Fig. 3a with interpretation shown on pairs AB′ (**a**) and CA′ (**b**) of column faces. White dots show segment origins, and white arrows show local lateral propagation directions of segments. Numbered white squares with black outlines indicate the absolute formation sequence of segments along triple junction ABC. A few numbered squares without black outlines correspond to triple junction ADE, on which the scale is positioned. The scale is 30.5 cm long.

Evolution of Joint Patterns

We are able to infer the evolution of mostly tetragonal joint networks at flow surfaces to mostly hexagonal joint networks in flow interiors. This evolution requires that column triple junctions shift laterally in a flow from level to level, that side lengths of polygons (face widths of columns) lengthen and shorten, and that the horizontal directions of segments change relative to those of previous segments on the same column face. Examination of Fig. 4 reveals that the lateral positions of triple junctions ABC and ADE change significantly from level to level, as does the width of column face A (or A′). Also, the segments of a column face are generally rotated about vertical axes relative to preceding segments (for example, segments 24 and 25 of face A′, 17 and 19 of face B′, and 23 and 26 of face C in Fig. 4). We have identified two processes that are associated with these changes from level to level. First, a new segment may approach a triple junction at a level slightly higher than that of the older segments at the junction, such that its lower portion truncates against the older segments, while its upper portion propagates over the top of the junction (Fig. 5a). The overshooting segment does not propagate far on the other side of the triple junction. This process tends to shift the triple junction at the next level in the overshoot direction, to widen the column face containing the overshooting segment, and to narrow the other column faces that intersect at the triple junction. Second, a new segment that more or less follows the leading edge of a previous segment may approach a triple junction obliquely such that it cuts the corner of the triple junction without stopping and propagates away from the junction along another segment (for example, segment 17 relative to the triple junction defined by segments 15 and 16 in Fig. 4a). The next formed segment on the third column face (for example, segment 18 in Fig. 4b) intersects the corner-cutting segment at a position that is shifted laterally relative to the former position of the triple junction. This process narrows the two column faces that contain the corner-cutting segment and widens the third column face.

The Boise site clearly shows processes that would permit the evolution of columnar joint patterns, but it does not afford views of the flow base where the initial stage of the inferred evolution takes place. The base of a basalt lava flow at the Boiling Pots site near Hilo, Hawaii, is well exposed (Figs. 1a and 6a). Tabulation of the percentages of triple junction types at three levels near the flow base shows that T and curved T junctions are predominant at the base (Fig. 6b). At 2 m above the base, most triple junctions are pseudo Y type with angles mostly between 100° and 140°. By tracing triple junctions from the flow base to the flow interior, we found that they evolve in a variety of ways, two of which are basic. A T junction gradually evolves upward into a pseudo Y junction as the through segments on two column faces become increasingly curved (Figs. 6a and 7a). A triple junction thus eventually changes to one composed of three segments instead of two. In a second case, a flat T junction does not evolve upward (Figs. 6a and 7b). It disappears instead at a short distance above the base when the laterally truncated column face terminates vertically and two columns merge into a larger one.

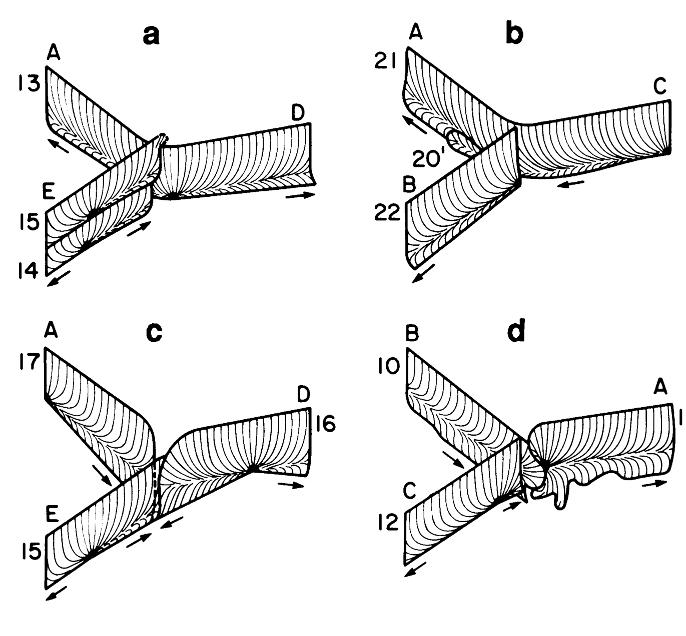


Fig. 5. Sketched examples of joint-segment intersections isolated from triple junctions ABC and ADE. Explanation of symbols is the same as that in the legend to Fig. 3b. Letters corresponding to Fig. 3a indicate column faces on which the segments lie. Numbers give the formation sequence of the segments and correspond to Fig. 4 for junction ABC. (**a**) Curved T intersections of type 1 (Fig. 2d). Segments 14 and 15 propagated toward the triple junction and terminated against the through segment 13. The upper portion of segment 15 propagated over the top of segment 13 and for a short distance beyond. (**b**) Curved T intersection of type 2 (Fig. 2d). Segment 22 started at the triple junction and propagated away, while also terminating against the through segment 21. (**c**) Pseudo Y intersection of type 4 (Fig. 2d). Segments 16 and 17 propagated toward the triple junction, like segment 15, and terminated against segment 15 at two distinct T intersections of type 1. The intersection of segments 15 and 17 is shown by a dashed line. (**d**) Pseudo Y intersection of type 5, consisting of types 1 and 2 T intersections (Fig. 2d). Segment 10 propagated toward the triple junction, and its upper portion terminated blindly in the lava at the junction. Segment 11 started on the edge of segment 10 and propagated away from the triple junction. Segment 12 started near the triple junction and terminated against segment 10.

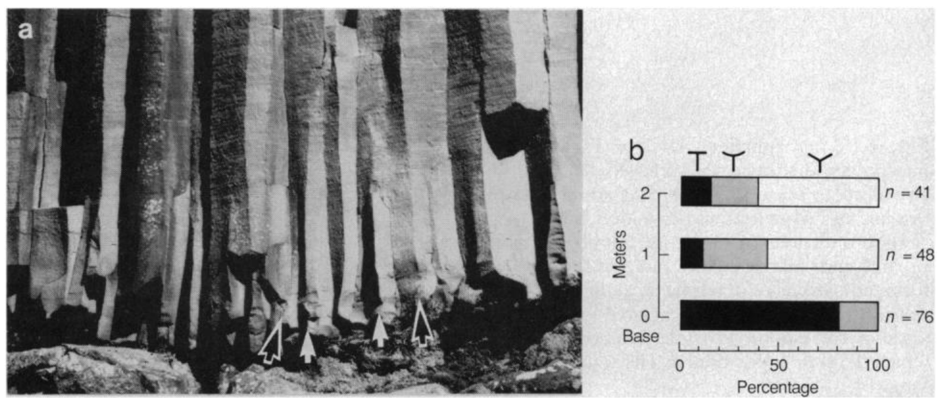


Fig. 6. Evolution of joint patterns at the Boiling Pots site near Hilo, Hawaii. (**a**) Detailed view of the flow base showing the upward evolution of T to pseudo Y intersections (black arrows) and the upward elimination of some T intersections (white arrows) as a result of termination of joints. (**b**) Tabulated percentages of T, curved T, and pseudo Y triple junctions for traverses at three levels near the flow base. Every intersection encountered on each level is measured. Number of measurements is given on the right of each bar.

Therefore, the initial T junctions at the flow base either evolve to pseudo Y junctions or disappear as the joints grow toward the flow interior. The net effect is that a mostly tetragonal joint network evolves into a mostly hexagonal one. Preferential termination of some joints results in an increasing joint spacing or column diameter upward from the flow base.

Conclusions

The overall continuity of many column faces implies that a joint pattern at one level in a flow strongly controls the pattern at the next level. Stress concentrations at the leading edges of column faces induce new joint segments and guide these segments mostly along the existing joint network (*9*). However, gradual changes of the joint pattern are permitted from level to level because most joint segments do diverge somewhat from the leading edges of previous segments. Joints propagate normal to the direction of local maximum tensile stress, σ_y, and are very responsive to changes of this direction (*18*). Therefore, if the new direction of σ_y is rotated by a small angle, α, relative to the direction when the previous segment formed (Fig. 8), the new segment will propagate at an angle α relative to the previous segment. We have described in detail the kinematics of this process of segment rotation about vertical axes (*9*). The incorporation of this process in a predictive model of joint-pattern evolution would require a three-dimensional mechanical analysis of the interactions among the many nonplanar joint segments at a triple junction and neighboring ones. At this time we can only note that tetragonal joint networks occur at flow surfaces where the thermal stress field parallel to the surfaces is strongly anisotropic and where the lava is highly heterogeneous. Hexagonal joint networks occur in flow interiors where the absence of surface effects and the homogeneity of lava produce a relatively isotropic thermal stress field perturbed only by the advancing joint fronts. Some workers have argued that hexagonal joint networks are favored because, for a fixed number of columns, they minimize the fracture surface energy (*4*) or the strain energy of the system (*10, 19*). In fact, concepts in fracture mechanics require that the sum of both energies be minimized simultaneously. These energy factors, together with the relative isotropy of the stress field and the change of material homogeneity, perhaps dictate the transition from a tetragonal to a hexagonal joint system.

The evolution of columnar joint patterns documented here may be the cause of a correlation between the side length, *L*, of a polygon and the opposing angle, θ (Fig. 9, inset). Weaire and O'Carroll (*20*) noticed at the Giant's Causeway that as the angle between two joints at a triple junction increases, so does the length of the third joint, but they did not document the supposed evolutionary process. Our data from Devils Postpile is in agreement with this conclusion (Fig. 9). The correlation between *L* and θ is related to the evolution of joint patterns, as suggested by the systematic changes of these parameters illustrated schematically in Fig. 7a.

Columnar joint segments form sequentially at triple junctions with a determinable order. The nature of a triple junction, defined by the propagation directions and formation sequence of collateral joint segments, usually changes abruptly from one level to the next. The angles between joint segments at triple junctions change gradually. As the joints grow toward the flow interior, termination of some joints causes a systematic increase of joint spacing and column diameter. The final product of these harmonious evolutionary changes is a joint system that bounds small tetragonal columns at flow surfaces and larger hexagonal columns in flow interiors.

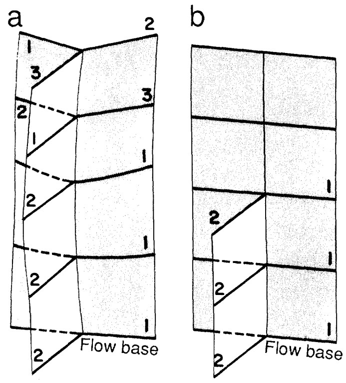


Fig. 7. Schematic representation of triple junctions showing observed processes involved in joint-pattern evolution as joints grow upward from the flow base. Numbers give the formation sequence of segments (marked by thick lines) at each level. (**a**) Evolution of an early-formed T junction to a pseudo Y junction. (**b**) Elimination of an early-formed T junction by the upward termination of a column face.

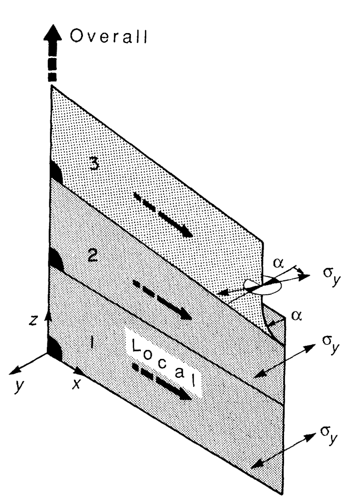


Fig. 8. Mechanism of rotation of a column face about a vertical axis. Numbers indicate the formation sequence of the joint segments. Each segment starts at a point (black dots) on the edge of a previous segment and propagates mostly horizontally (thin broken arrows) within the *xz* plane and normal to the direction of local maximum tensile stress, σ_y. Bold broken arrow shows overall direction of joint growth. If σ_y remains unchanged in direction during the formation of two consecutive segments (1 and 2), they will be coplanar. If σ_y changes horizontal direction by an angle, α, between the formation of two consecutive segments (2 and 3), the later segment propagates at the same angle relative to the earlier segment [modified from (*9*)].

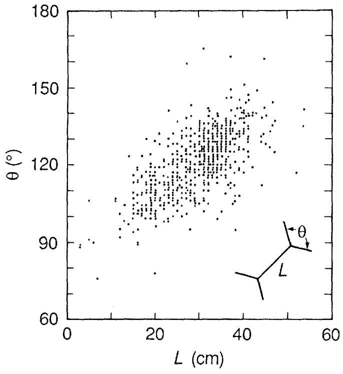


Fig. 9. Relation between polygon-side length (width of column face), *L*, and opposing angle, θ, of triple junctions at the Devils Postpile in California. Inset shows the definition of the plotted parameters. The 654 data points represent measurements of *L* and θ at the corners of 116 polygons exposed in an area of about 40 m^2. There is a positive correlation between *L* and θ.

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Pathogenesis of Dengue: Challenges to Molecular Biology

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Dengue viruses occur as four antigenically related but distinct serotypes transmitted to humans by *Aedes aegypti* mosquitoes. These viruses generally cause a benign syndrome, dengue fever, in the American and African tropics, and a severe syndrome, dengue hemorrhagic fever/dengue shock syndrome (DHF/DSS), in Southeast Asian children. This severe syndrome, which recently has also been identified in children infected with the virus in Puerto Rico, is characterized by increased vascular permeability and abnormal hemostasis. It occurs in infants less than 1 year of age born to dengue-immune mothers and in children 1 year and older who are immune to one serotype of dengue virus and are experiencing infection with a second serotype. Dengue viruses replicate in cells of mononuclear phagocyte lineage, and subneutralizing concentrations of dengue antibody enhance dengue virus infection in these cells. This antibody-dependent enhancement of infection regulates dengue disease in human beings, although disease severity may also be controlled genetically, possibly by permitting and restricting the growth of virus in monocytes. Monoclonal antibodies show heterogeneous distribution of antigenic epitopes on dengue viruses. These epitopes serve to regulate disease: when antibodies to shared antigens partially neutralize heterotypic virus, infection and disease are dampened; enhancing antibodies alone result in heightened disease response. Further knowledge of the structure of dengue genomes should permit rapid advances in understanding the pathogenetic mechanisms of dengue.

DENGUE VIRUSES, MEMBERS OF THE FLAVIVIRIDAE FAMily, occur as four distinct serotypes that are biologically transmitted from infected to susceptible human beings principally by *Aedes aegypti* mosquitoes, the yellow fever vector. This species, which bites during the day and breeds in freshwater collections in and around human habitations, now is almost universally distributed around the globe between 30°N and 20°S (*1*). In these tropical and subtropical regions live more than one half of the world's human population. The ecological disturbances of World War II, the rapid postwar growth of population and urbanization, the deterioration in urban living environments, and global economic downturns have contributed collectively to the spread of *Aedes aegypti* and to the epidemic and endemic dispersal of the different dengue serotypes (*2*).

Dengue is a human disease of global significance. Up to 100 million cases of dengue infection per year worldwide can be estimated from available data if one assumes there is an average annual infection rate of 10% for endemic areas, with most susceptible hosts being children (*3*). Although dengue infections in children usually result in mild disease, a 1962 study in Bangkok suggested that more than half of the cases were of sufficient severity to require medical attention (see *4*). When *Aedes aegypti* extends its range into areas previously free of this species, outbreaks of dengue fever may also involve a large portion of the adult population. Recent epidemics of dengue fever in Africa, Australia, Brazil, and Central America have caused medical and economic burdens, but few deaths (*5*).

In tropical Asia, the region of highest dengue endemicity, the disease is more severe. In that area, dengue viruses cause a serious, often rapidly fatal disease of children known as dengue hemorrhagic fever (DHF) or, in its most severe form, dengue shock syndrome (DSS). In DHF, hemostatic disorders and increased vascular permeability are accompanied frequently by internal bleeding and shock. These disturbances follow a minor febrile illness that lasts 3 to 5 days. At least 1.5 million children are reported to have been hospitalized and 33,000 have died with this syndrome since it was recognized in the 1950s (*6, 7*). Mortality rates vary from 2 to 10%. In 1981, the first recent outbreak of DHF/DSS outside Southeast Asia occurred in Cuba and resulted in 116,000 hospitalizations (1% of the total population) within a 3-month period (*8*).

Evidence for Immunological Modification of Dengue Illness

When it was discovered in Southeast Asia that dengue fever without complications occurred in nonindigenous foreigners while DHF/DSS occurred in indigenous children, explanations were sought (*9*). Studies of the pathogenic mechanisms of dengue virus

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