The feedback between joint-zone development and downward erosion of regularly spaced canyons in the Navajo Sandstone, Zion National Park, Utah

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Abstract – Large NNW-trending slot canyons cut into, but generally not entirely through, the approximately 600 m-thick Jurassic Navajo Sandstone at Zion National Park (ZNP). These canyons sit immediately above, and parallel to, joint zones and exhibit a regular spacing (*c*. 450 m). The joint zones, in particular, consist of vertical and steeply dipping joints that tend to dip towards the axis of the canyon. These regularly spaced, joint-localized canyons are confined to the Navajo, suggesting a stress-shadow origin for their configuration; however, this explanation does not predict closely spaced joints in joint zones at each canyon. To explain the development of the joint zones, we treat the canyons themselves as cracks. Early, widely-spaced, NNW-trending joints propagated into the top of the Navajo, and later preferential erosion along these joints initiated the pattern of canyons with a cross-sectional profile consistent with blunt edge cracks spaced at about 450 m. Analogous to edge cracks, the canyons subsequently concentrated tensile stress at their tips while subjected to regional extension. Concentration of canyon-tip tensile stress was sufficient to drive steeply dipping secondary joints, reflecting principal stress rotation in a process zone ahead of the canyon tip. Joint density in each joint zone increases as a consequence of a gravity-induced shear traction that drives vertical wing cracks from the tips of steeply dipping secondary joints. Exfoliation jointing along canyon walls also contributes to the widening of canyons. The preferential erosion of slot canyons follows the joint zones, and thus, a feedback loop is set up between the growth of secondary jointing in the canyon-tip stress concentration and the downward erosion of the canyon.

NNW-tending joint zones have preferentially eroded into regularly spaced slot-shaped canyons yielding Zion National Park's (ZNP) dramatic landscape (Gregory 1950; Eardley 1965). From the air, these linear, regularly spaced slot canyons take on the appearance of a joint set where canyon spacing is approximately equal to the *c*. 600 m-thickness of the flat-lying Navajo Sandstone (Fig. 1). This canyon fabric is analogous to bedding-confined joint sets possessing a spacing proportional to bedding thickness (Price 1966; Gross *et al.*, 1995). The analogy is appropriate because the slot canyons follow joint zones that cut through the Navajo Sandstone, a stratigraphic unit that appears to have acted as an extraordinarily thick mechanical unit (Gross 1995). A stress-reduction-shadow theory is often proposed as the mechanism explaining this one-to-one relationship between joint spacing and bed thickness (Pollard & Segall 1987; Narr & Suppe 1991). The question is how did canyon-related joint zones in the Navajo come to posses this same spacing–thickness relationship, particularly when the close spacing of joints in each zone is not consistent with a stress-shadow mechanism?

Groupings of closely spaced joints are known as *joint swarms* (e.g. Laubach *et al.* 1995; Hennings & Olson 1997), *joint clusters* (e.g. Olson 1993; Cooke *et al.*, 2000) and *joint zones* (Engelder 1987; Dyer 1988). Dyer (1988) describes joint zones at Arches National Park as 'individual, subparallel en echelon joints confined to a narrow zone, separated from adjacent zones by a characteristic distance . . . confined to a single lithologic interval' and 'generally perpendicular to bedding'. Although the NNW-trending joint zones at Zion are also narrow, defined by a characteristic distance and confined to the thick Navajo Sandstone, they are not predominantly composed of en echelon joints. In addition, there is a considerable population of steeply dipping joints included in the canyon-tip joint zones that are not perpendicular to bedding. The explanation for the joint-zone development at ZNP must take these characteristics into consideration.

Mechanisms proposed for closely spaced joint propagation include the propagation of en echelon arrays prior to shearing/faulting followed by oblique secondary fractures (Myers & Aydin 1998), fold-hinge joint localization (Fischer & Jackson 1999), formation of fold-limb splay cracks due to bedding-plane slip (Cooke *et al.* 2000), subcritical crack growth (Olson 1993), joint propagation in response to elevated stress in crack-tip process zones (Dyer 1988) and process-zone development associated with

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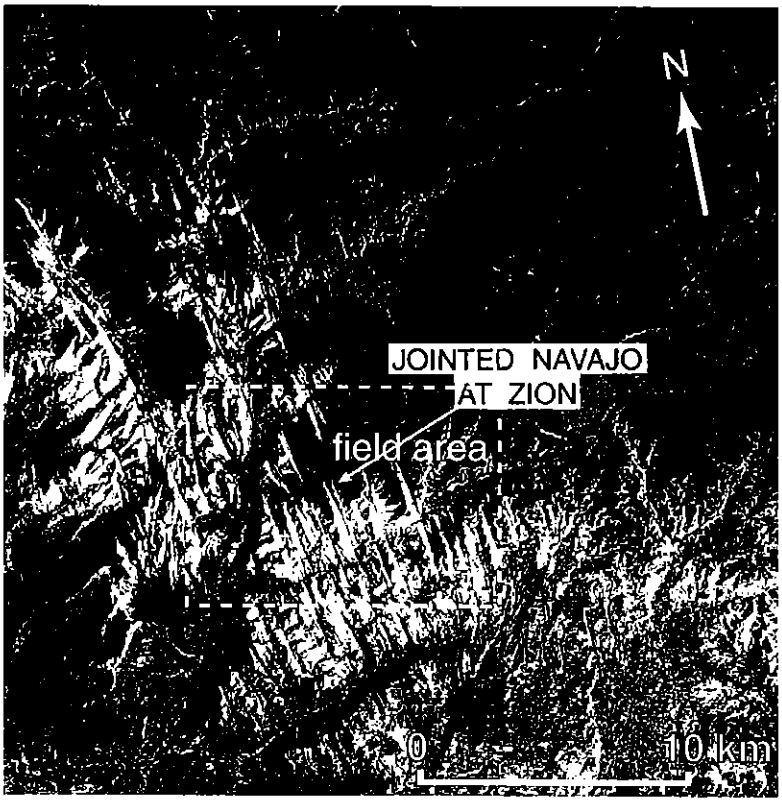

Fig. 1. Satellite image taken over Zion National Park. Slot canyons, which have eroded form NNW-trending joint zones, are readily apparent (note the white coloration) (modified from Davis 1999; source Chevron).

dyke emplacement (e.g. Delaney *et al.* 1986). Of the mechanisms described above, joint zones at ZNP are best explained in terms of a process zone. The process zone consists of additional cracks, which develop within a zone of elevated tensile stress, concentrated about the tip of the original crack. Above a threshold, tensile stress can drive new cracks independent of, but in close proximity to, the original crack.

The objectives of this chapter are to document joint-zone development within the Navajo Sandstone at ZNP and to examine the potential mechanisms by which such joint zones can form. Ultimately, our analysis leads to a detailed mechanical explanation for the growth of ZNP's regularly spaced slot canyons as a feedback between joint-zone growth and differential erosion following in the wake of the joint zones.

Geology of ZNP

ZNP is located in SW Utah at the western edge of the Colorado Plateau, adjacent to the central Basin and Range subprovince (Fig. 2). The Navajo Sandstone within ZNP exhibits prominent, regularly-spaced canyons associated with joint zones in a relatively undeformed block of the Colorado Plateau between the Basin and Range-style Hurricane and Sevier normal fault systems (Fig. 3). The ZNP canyon network is an attribute of the Jurassic Navajo Sandstone (Fig. 4). The Navajo is a cliff-forming, eolian sandstone ranging in thickness from 550 to 670 m at ZNP (Biek *et al.* 2000). The Mesozoic sediments underlying the Navajo Sandstone, including the Moenkopi, Chinle, Moenave and Kayenta formations, are predominantly clastic continental deposits, varying in composition between mudstone and fine-grained sandstone (Fig. 5).

Colorado Plateau uplift and extensional unroofing (i.e. Biek *et al.* 2000) accounts for the overburden removal and subsequent headward erosion that uncovered the jointed Navajo and initiated the downward erosion of slot canyons along pre-existing NNW-trending joints. Based on the stratigraphic section of the Zion region (Hintze 1988), the average overburden above the Navajo is estimated at approximately 1400 m at the time of initiation of Miocene WSW regional extension in the neighbouring central

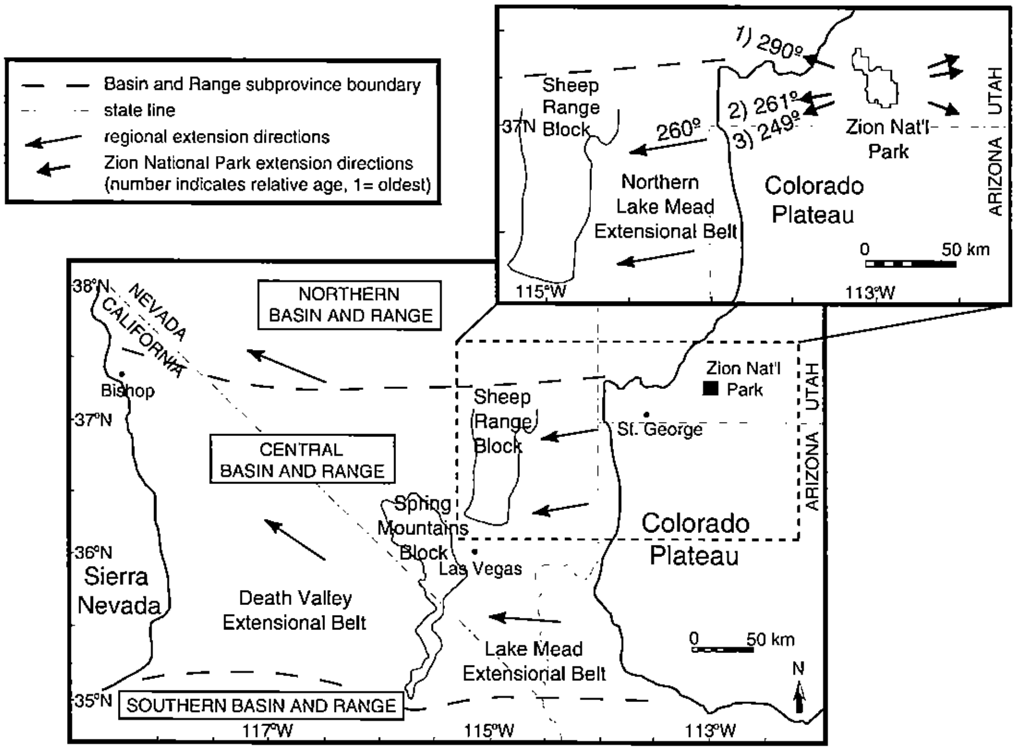

Fig. 2. The central Basin and Range subprovince with the relatively undeformed Colorado Plateau and Sierra Nevada to the east and west, respectively. Within the central Basin and Range, two highly extended regions, the Lake Mead and Death Valley extensional belts, differ in extension direction and are separated by the Sheep Range and Spring Mountains Blocks. Zion National Park is located at the western margin of the Colorado Plateau just east of the northern Lake Mead extensional belt (modified from Snow & Wernicke 2000).

Basin and Range subprovince. Aerial photographs and field checks indicate that the NNW-trending slot canyons and associated joint zones are typical for the Navajo Sandstone but not for the underlying Kayenta or the overlying Temple Cap formations. The orientation of the linear slot canyons suggests that regional jointing was critical to their origin during WSW Basin and Range extension imparted on the Colorado Plateau (Rogers *et al.* 2004). A 261°-trending extension apparently produced bed-confined, regularly spaced joints, and subsequent differential erosion following these early joints produced the NNW-trending slot canyons. This trend closely parallels the average extension direction of 260° identified for the northern Lake Mead Belt of the central Basin and Range subprovince (Snow & Wernicke 2000).

Field observations

Field observations were made in the southern half of ZNP where the canyon network is best exposed due to the headward erosion of the north and east forks of the Virgin River. Horizontal exposures of joint zones were observed in the eastern half of the Park along Highway 9 (Fig. 4). Thirty-eight joint-perpendicular scanlines were taken in the Navajo Sandstone across these joint zones. Photographs of joint dip distributions across the joint zones were evaluated for trends in joint dip direction relative to position at slot-canyon tips in order to compare field observations with finite-element models (see the Appendix for the methodology used to sort out the distribution of joint dips). In addition, orientations/geometries reflective of wing-crack growth and exfoliation fracturing were identified in an effort to gain a further understanding of the evolution of the joint zones.

Overview

Slot canyons have two trends at ZNP, and they correlate with the strikes of joints in joint zones cutting the Navajo Sandstone. The NNW, *c.* 350°, set of canyons, spaced at approximately 450 m, provides the dominant topographic fabric within ZNP (Fig. 4).

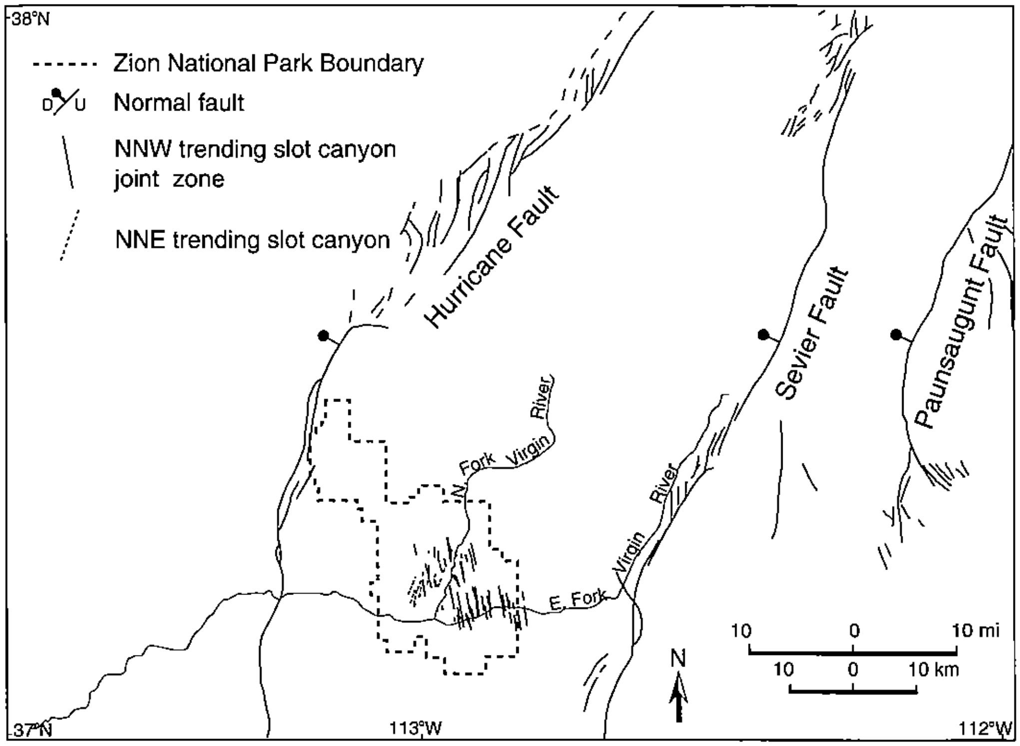

Fig. 3. Zion National Park is located in a relatively undeformed crustal block of the Colorado Plateau. This block is bounded by the Sevier and Hurricane high-angle, down to the west, Basin and Range style normal faults, to the east and west, respectively (modified from Davis 1999). Slot canyons located in the field area (Fig. 4) are represented.

NE-trending canyons located to the west of (and including) Zion Canyon, the widest and deepest (606 m) canyon in the field area, form a second set. In addition to the slot canyons, a third joint set, trending *c*. 340°, is found between slot canyons. These joints exhibit an average spacing of 22 m and do not preferentially erode into slot canyons. Joint-abutting relationships indicate that the 350°-trending canyons have eroded from joints that post-date those of the NE-trending canyons and predate those of the 340° orientation (Rogers *et al.* 2004). This sequence of jointing indicates that a counterclockwise rotation of the regional stress field has affected the Colorado Plateau in the vicinity of ZNP. This rotation may reflect gravity collapse of the Cordilleran thrust front that culminated in the WSW–ENE extension of the northern Lake Mead belt of the central Basin and Range about 10 Ma ago (Rogers *et al.* 2004).

The relationship between NNW-trending slot canyons and joint zones

The NNW-trending slot canyons are situated directly above one or more joint zones composed of closely spaced (sub)vertical joints. At many locations, the average joint orientation parallels the associated slot canyon. Cumulatively, the vector mean pole of data from all scanlines defines a joint trend of 171° (right-hand rule) (Fig. 6). In terms of distribution, these 351° (171°) joints are found exclusively in the vicinity of the slot canyons. Between slot canyons, the 351° joints are absent and the younger 320–340° joint set predominates.

Vertical outcrops reveal no stratigraphic offset on fractures within the zones. Although joint zones cut to the base of the Navajo Sandstone, individual joints do not. Local wing-crack growth associated with subvertical joints indicates a component of vertical propagation within joint zones. In addition, exfoliation joints occurring in canyon walls contribute to the jointing within the zones (Bahat *et al.* 1995) (Fig. 7).

Slot-canyon morphology is a function of the character of the associated joint zones. Single joint zones are associated with V-shaped, sharp-tipped, slot canyons (e.g. R slot, Fig. 7) while pairs of joint zones are associated with 'box' canyons (e.g. M slot, Fig. 8). These box canyons are V-shaped with a squared tip. Where the Navajo–Kayenta contact is

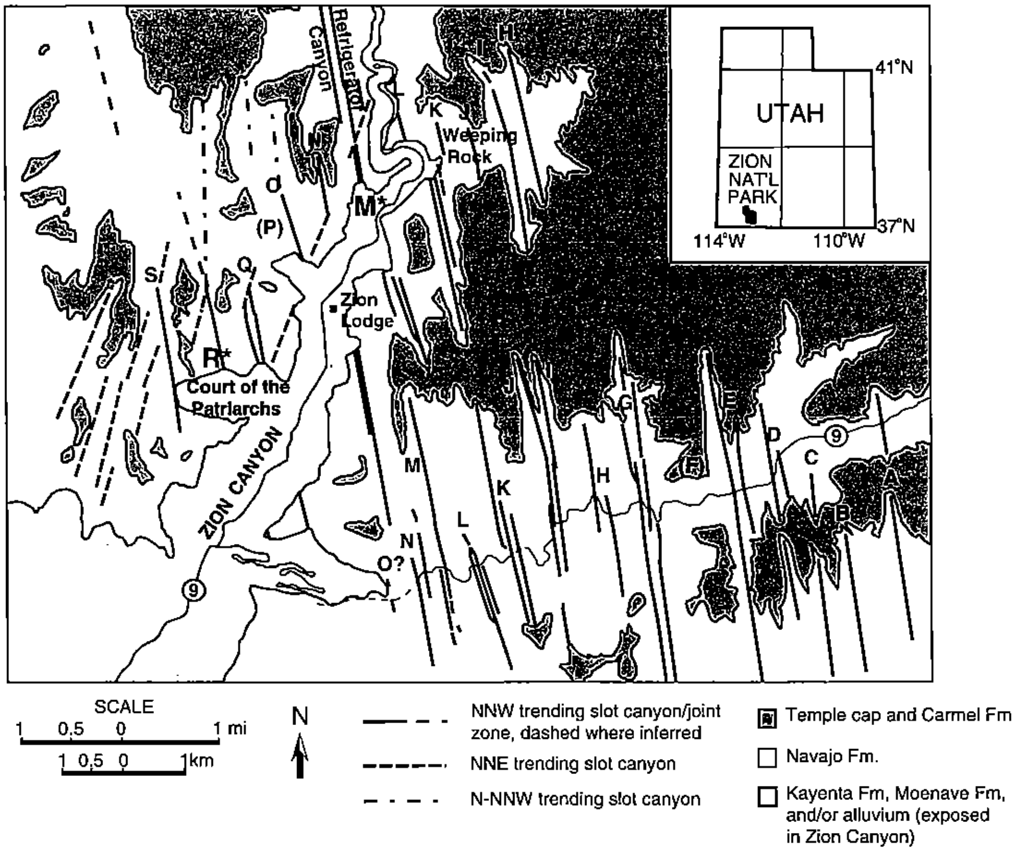

Fig. 4. Field area at Zion National Park. The NNW-trending slot canyons, confined to the Navajo Sandstone and labelled A–S, represent the locations of large-scale joint zone lineaments of particular interest to this investigation. The average orientation of joints that compose these joint zones indicates a 261° regional extension direction, an extension direction exhibited in the central Basin and Range subprovince immediately west of the Colorado Plateau at the latitude of ZNP (Fig. 2).

exposed the joint zones extend to, but not beyond, the base of the Navajo.

Joint zone dip distribution

Our hypothesis is that the erosional geometry of the slot canyons generates a local tensile stress concentration in the Navajo Sandstone below, but restricted to, the tip of the canyon. Furthermore, this stress concentration promotes joint propagation in the form of joint zones analogous to crack-tip process zones in the Navajo Sandstone of ZNP. As joints propagate normal to the local least principal stress, they serve as (palaeo)stress indicators. In the case of the slot canyons at ZNP, joint location and dip-angle distribution at slot-canyon tips should be indicative of the stress concentration that developed there, and by recognizing patterns, the stress conditions that created these joints can be reconstructed.

Exfoliation jointing adds to the population of joints next to the walls of slot canyons (Fig. 7). In order to avoid the influence of exfoliation fractures in the joint dip distributions, the following observations concern jointing below the level of slot-canyon tips. The digitized joint population was split, east v. west, based on their respective position to the axis of the slot canyon. For our analysis of dip trends, K slot (Weeping Rock), M slot (Refrigerator Canyon) and R slot (Court of the Patriarchs) (Fig. 4) were chosen based on the quality of outcrop exposure below the level of their respective slot-canyon tips. The joint distributions were compared to a typical normal distribution for statistical skewness. A skewed distribution departs from a normal distribution in a particular direction, right or left, and in this case, east or west, indicating that one tail (side) of the distribution

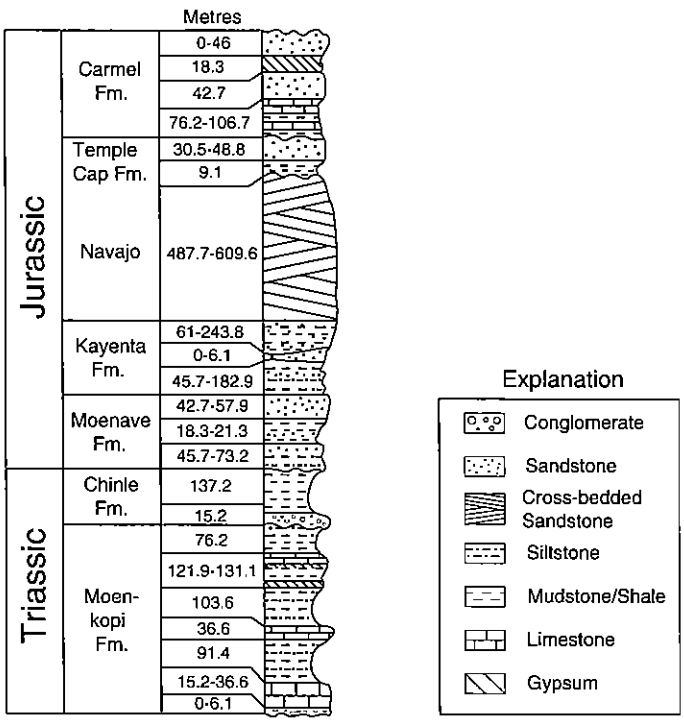

Fig. 5. Stratigraphic column of the Zion National Park area, Utah (Peterson & Pipiringos 1979; Marzolf 1983; Hamilton 1984; Hintze 1988).

exhibits a greater amount/range of data v. the other. This analysis assumes that a skewed distribution represents a measurable trend in dip direction for the population of individual joints within the zone. Each joint zone is briefly described below and followed by the statistical analysis that characterizes joint dip trends resulting from two sampling methods (described in the Appendix): (1) a collection of single joints measured tip to tip; and (2) a collection of 5 m-joint segments expected to account for dip deviations along a single joint due to a temporally changing stress field. This statistical information is summarized in Table 1.

Dip trends: K slot. A single joint zone characterizes K slot at the head of the ZNP's Weeping Rock trail (Figs 4 and 9). Jointing at K slot includes en echelon arrays expressed in V-shaped patterns, a characteristic that is less common at M or R slots. Approximately 120 m of Navajo Sandstone remains below the downward-eroding canyon, and, although the joint zone extends to the base of the Navajo, no *single* joint appears to cut through the remaining 120 m of sandstone.

Statistics derived from the single-joint sampling method suggests that the east half of the zone is skewed/biased toward W-dipping joints, and the west half is skewed toward E-dipping joints. In comparison, the 5 m-segment sampling method suggests that both the east and west halves of the zone are skewed/biased toward W-dipping joints (Table 1).

Dip trends: M slot. Two joint zones define M slot, ZNP's Refrigerator Canyon, where it meets Zion Canyon (Figs 4 and 8). The associated slot canyon exhibits a 'box' morphology with approximately 120 m of Navajo Sandstone remaining below its base. Fractures within this pair of zones exist symmetrically below and define the box-canyon edges at the base of the canyon. Each zone extends to the base of the Navajo Sandstone. Although no *single* joint appears to cut the remaining Navajo below the zone to the west, a single joint does cut the Navajo below the zone to the east.

Both sampling methods reveal the same result. The eastern zone has a dip distribution biased toward W-dipping joints, and the western zone, has a dip distribution biased toward E-dipping joints.

Dip trends: R slot. A single joint zone controls the erosion of R slot in the Court of the Patriarchs (Figs 4 & 10). This slot canyon exhibits a tilted 'V' shape in cross-section and cuts 90% of the thickness of the

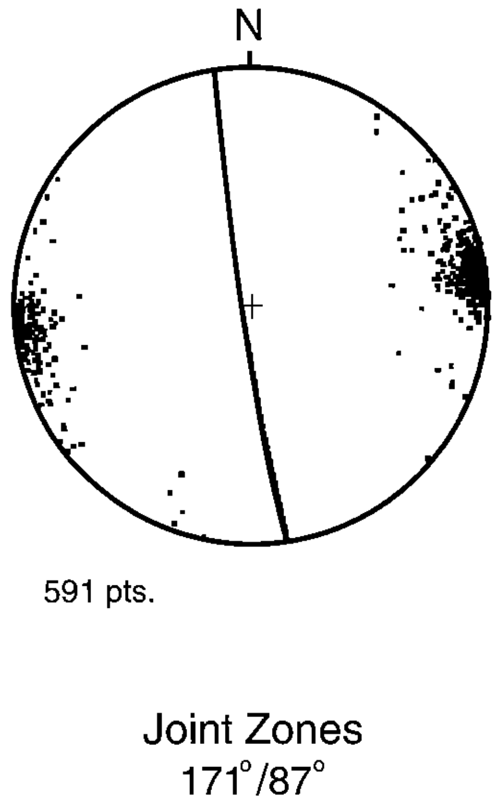

Fig. 6. Lower-hemisphere stereonet plot displaying poles to joints measured in joint-perpendicular scan-lines across slot-canyon joint zones. The average strike and dip of the joints that compose the NNW-trending joint zones is displayed at 171°/87° (right-hand rule).

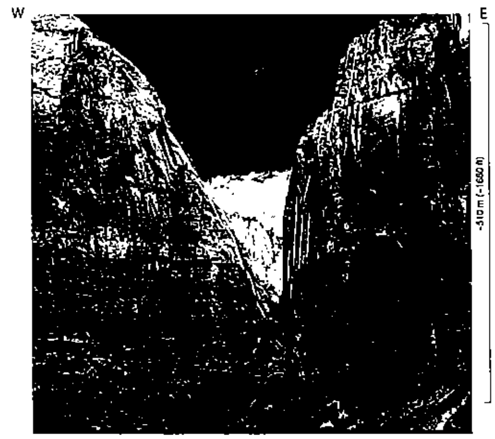

Fig. 7. View of the Navajo Sandstone at R slot looking north from the Court of the Patriarchs (Fig. 4). R slot is characterized by a single fracture zone and a 'V'-shaped slot-canyon morphology: examples of exfoliation jointing along canyon walls at R slot are highlighted. Exfoliation jointing acts to widen existing canyons (Bahat *et al.* 1995) and occurs in the final stage of joint-zone development at ZNP.

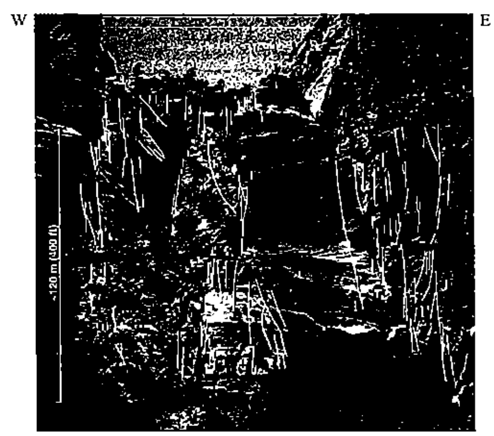

Fig. 8. Oblique view of the Navajo Sandstone at M slot, Refrigerator Canyon, looking north from Zion Canyon (Fig. 4). Two joint zones, evident from the intervening unfractured volume of rock, and a 'box canyon' ('V'-shaped canyon with squared tip) characterize M slot.

Navajo Sandstone where joints have been bypassed by the downward-eroding canyon. At the canyon tip a prominent joint cuts to the base of the remaining Navajo Sandstone.

Below the canyon tip, statistics derived from both sampling methods indicate that R slot joints are biased toward E-dipping joints on both sides of the canyon (Table 1). However, weaker confidence levels (<90%) for skewness are represented on the west side of the canyon by the single-joint sampling method and the east side of the canyon by the 5 m-segment sampling method.

Summary of dip-trend analysis. At each slot canyon, the following are true: (1) joints dip to the east and west regardless of which side of the canyon they are observed; (2) although these are skewed populations, the mode of each of these distributions is representative of vertical joints; and (3) positive kurtosis exhibited by each distribution indicates that the 'tails' of distribution cover a greater range of values than that of a normal distribution. Although the mode of these distributions indicates an abundance of vertical joints, the skew and kurtosis values indicate that a considerable population of steeply dipping joints exists.

The whole-joint sampling method resulted in five out of six skewed distributions that show that joints below the level of slot-canyon tips, east v. west, have a tendency to dip towards each other/the axis of the

Table 1. *Summary of descriptive statistics for joint-dip distributions observed below canyon tips at K, M and R slots (Figs 9, 8 and 7, respectively). Joint populations were defined by position, east v. west, relative to the slot canyon. Two sampling methods were analysed for each population: (A) statistics for the distributions composed of whole joints; (B) statistics for the distributions composed of 5 m-joint segments. Normal distributions are described by skewness and kurtosis values of zero. Here, positive skewness denotes E-dipping measurements while negative values denote W-dipping measurements. In five or six cases of the whole-joint sampling method and four of six cases of the 5 m-segment sampling method, the skewness indicates that joints dip toward the slot-canyon axis. Positive kurtosis indicates that the 'tails' of the distribution cover a greater range of values v. a normal distribution and lends validity to the interpretation of a population of steeply dipping joints in addition to vertical joints.*

Joint zone		Number of observations	Mean	Standard deviation	Median	Skewness (Kurtosis)	Confidence level – skew
(A) Descriptive statistics – whole joint sampling							
K slot	east	29	−88.7	9.64	88.5	−1.52 (2.65)	98% – West
	west	101	−89.4	5.50	90.0	0.39 (1.80)	90% – East
M slot	east	51	89.8	7.51	88.7	−0.59 (1.40)	90% – West
	west	97	86.1	10.97	89.4	2.37 (5.97)	98% – East
R slot	east	53	89.8	6.30	−89.6	1.19 (2.02)	98% – East
	west	34	88.1	8.59	89.4	0.54 (0.04)	[<90% – East]
(B) Descriptive statistics – 5 m-joint segment sampling							
K slot	east	64	90.0	8.25	89.4	−0.5 (0.79)	90% – West
	west	188	−89.1	5.94	−89.9	−0.48 (1.68)	98% – West
M slot	east	208	84.5	12.6	−88.2	1.74 (1.31)	98% – West
	west	140	88.9	7.95	88.2	−0.59 (2.76)	98% – East
R slot	east	167	89.5	9.05	90.0	0.24 (2.66)	[<90% – East]
	west	283	−88.4	6.22	−87.9	0.49 (1.14)	98% – East

canyon. Furthermore, the comparisons of skewness and mean values complement each other. In the whole-joint sampling, not only does the skewness indicate a propensity for joints to dip toward the slot-canyon axis, but the values of the mean at each canyon also support this conclusion in a relative sense. The mean values for each analysed canyon reveal that the joints, east v. west of the canyon tip, have a tendency to dip towards each other. For example, at M slot, the east and west halves of the zone have means that are represented by E-dipping values (Table 1). However, the mean dip value of the west half of the zone dips less steeply (departs more from the vertical) than that of the east half of the zone, indicating the same *relative* dip relationship between the two halves of the canyon as expressed by the skewness. Both the mean dip and skewness values indicate a relationship among joints below the canyon tip: joints from opposite sides of the canyon tend to dip toward each other. This relationship is true at K and R slots as well. We suspect that the sampling of vertical wing cracks has promoted this relative result and masked the absolute sense of dip relative to the canyon that is recognized by the skewness values.

In comparison, the 5 m-segment sampling method yields the same skewness result in four out of the six joint distributions, where only the result at K slot (west) differs between the two methods. This analysis, however, does not consistently reproduce the relative relationship between mean values observed in the whole-joint analysis. Understanding that the 5 m-segment data are flooded with vertical wing-crack measurements, we expect the dip trends in the distributions to weaken and so recognize that this method is more likely to measure the growth of wing cracks.

Models for slot-canyon development at ZNP

To explain the development of the joint zones, we presume that early, widely-spaced, NNW-trending joints propagated into the top of the Navajo and that later, preferential erosion downward along these joints initiated the pattern of canyons, which exhibits a cross-sectional profile consistent with blunt edge cracks spaced at about 450 m. Regarding the early NNW-trending joint set, the model considers two possibilities for the depth of penetration of individual joints into the Navajo: (1) the initial regional joints, produced by Miocene Basin and Range extension, cut the entire thickness of the Navajo Sandstone. Such through-cutting joints may be present at M and R slots. If true, the Navajo, as a mechanical layer, had no tensile strength during erosion of the slot canyons, and a gravity (body) load, alone, is the only possibility for a joint-driving stress ahead of (i.e. below) the slot-canyon tips where joint zones develop; (2) early regional joints only partially cut the Navajo, and the sandstone, as a mechanical layer, maintained tensile strength below the downward-eroding slot canyons. This appears to have been the case for K slot. Here, a slot-tip tension could have arisen from regional

Fig. 9. View of K slot joint zone in cross-section looking north from ZNP's Weeping Rock trail head (Fig. 4). A single joint zone characterizes K slot at this location. In addition, en echelon ('V'-shaped) joint patterns are evident here, yet not well developed at other slot canyons (e.g. M slot (Fig. 8) and R slot (Fig. 10)). No single joint is observed to cut the entire remaining section of Navajo Sandstone below the slot canyon.

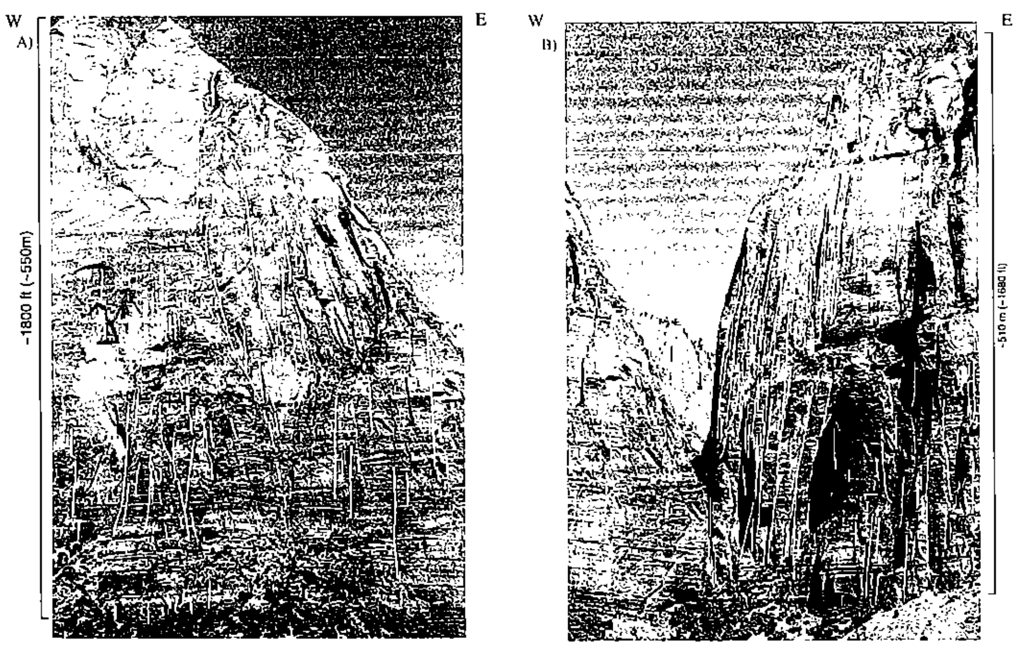

Fig. 10. Detail of the joint zone at R slot looking north from the Court of the Patriarchs (Figs 4 and 7). (A) West half of R slot and (B) east half of R slot.

Table 2. *Range of material properties values assigned to the Navajo Sandstone during FRANC (finite-element) modelling. Values based on sandstone values reported by Birch (1966) and Fischer (1994)*

	Young's modulus (E)	Poisson ratio (ν)	Density (ρ)	Loading
Model values	15–45 GPa	0.10–0.20	2.3 g cm^{-3}	Gravity body load and/or regional tension

extension and superimposed on the stress arising from gravity loading.

Finite-element models were constructed in order to provide insight into the development of the joint zones below the canyon tips at ZNP. Three slot-canyon geomorphologies were considered in the modelling process. Our initial working model incorporates a symmetric 'V'-shaped notch. Additional models include a symmetric 'V'-shaped notch with a squared tip (e.g. M slot; Fig. 8) and an asymmetric 'V'-shaped notch with a sharp tip (e.g. R slot; Fig. 7). These models were studied with and without the benefit of a tensile strength below the canyon tips.

The finite-element program FRANC (Wawrzynek & Ingraffea 1987) was used to generate a deformed mesh and calculate the resulting stresses at each node. As the 350°-trending joint zones are exclusively linked to the slot canyons that have developed at Zion, each model was scaled to represent the configuration of a slot-canyon as observed in the field. Material properties, loading conditions and slot canyon geomorphologies were varied in order to understand how stress could be concentrated in the notch of the slot canyons.

Plane-strain simulations were constructed using a finite-element mesh scaled to represent the 600 m-thick Navajo Sandstone. The underlying Kayenta Formation is assumed to be in frictional contact with the Navajo and is included in the slot-canyon models. The loading conditions assigned to the models were designed to fit the tectonic environment that has affected the western edge of the Colorado Plateau in the vicinity of ZNP. Local tension and/or extensional displacements were set as boundary conditions in our models.

Material properties assigned to the Navajo Sandstone were derived from average sandstone properties (dry rock) reported by Birch (1966) and Fischer (1994) (Table 2). Variation in Poisson ratio (ν) between 0.10 and 0.20 (Table 2) does little to change the stress during loading by extension, and, therefore, an arbitrary value of 0.15 was assigned to approximate the Navajo Sandstone. In contrast, variation in Young's modulus (E) from 15 to 45 GPa strongly influences the tensile stress at the canyon tip. A Young's modulus value of 15 GPa was found to offer the most realistic radius of stress in excess of the pre-

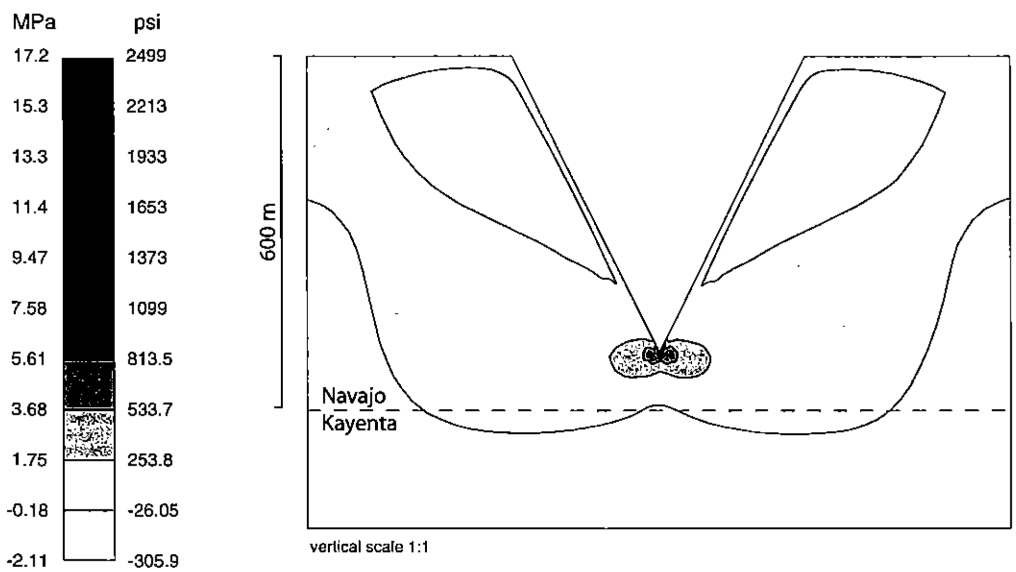

Fig. 11. FRANC (finite-element) model of an unconfined 500 m-deep Navajo Sandstone slot canyon subjected to a gravity body load (vertical scale = horizontal scale). Although highly restricted in lateral extent, the tensile stress concentrated at the very tip of the canyon exceeds the presumed tensile strength (5 MPa) of the Navajo. However, this tensile stress concentration does not account for the width of the observed joint-zone development at ZNP.

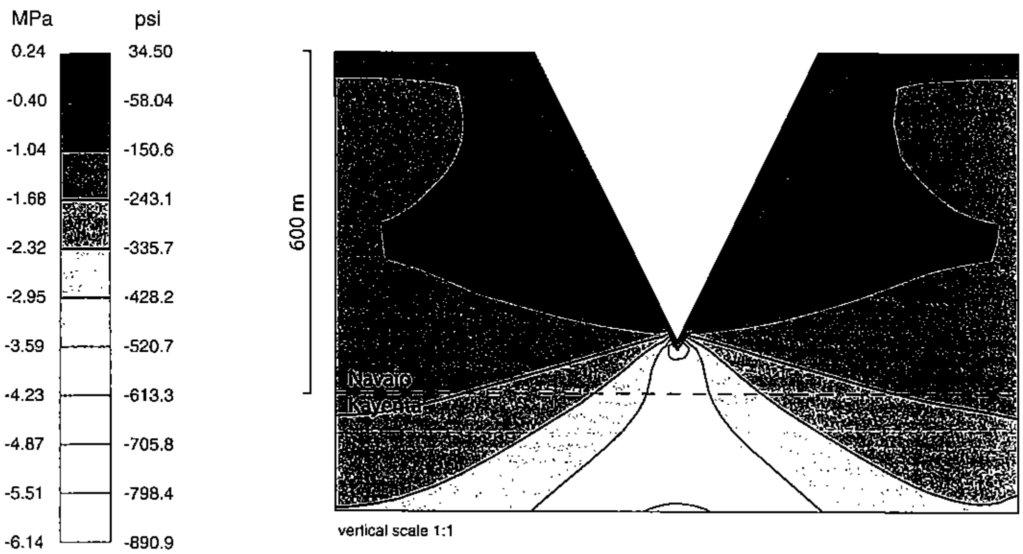

Fig. 12. FRANC (finite-element) model of confined 500 m-deep Navajo Sandstone slot canyon subjected to a gravity load (vertical scale = horizontal scale). The canyon tip is in a state of compression, while only minor tension develops just above the tip along the canyon walls. This tension is not predicted to exceed the tensile strength of the sandstone at any canyon depth in the Navajo.

sumed tensile strength of the rock, 5 MPa (tension is positive), available to joint-zone development. The Kayenta Formation was assigned constant values for thickness of 200 m (Hintze 1988), E=12 GPa, ν= 0.10 and, ρ, of 2.6 gcm^{-3}.

State of stress below slot-canyon notches

Our initial model represents a single slot canyon at ZNP with a simple symmetric V-shaped configuration (Fig. 11). Gravity body loads and horizontal tractions (i.e. regional extension) were simulated independently to understand the contribution of each to the state of stress at slot-canyon tips. In particular, the two loading conditions were simulated using combinations of four boundary conditions: an unconfined gravity load (no lateral boundaries) confined gravity load (zero displacement lateral boundaries), remote tension (displacement/ extension of lateral boundaries) and the mechanical interaction with the underlying Kayenta (welded bottom boundary). All have particular effects on the concentration of stress at the slot-canyon tip.

Each model was fixed at the mid-point of its base in the vertical direction. When a gravity body load was simulated independently, the base of the model was also fixed in the horizontal direction. In contrast, when remote tension was applied to a model, either alone or superimposed with gravity, the model was fixed on one side in the horizontal direction while the rest of the model was allowed to slide horizontally (including the base) as the opposite side was 'pulled' to simulate the regional extension.

The gravity body load with no lateral constraints concentrates tensile stress at the canyon tip as long as the sandstone has a tensile strength; however, the width of the predicted zone of joint development at the canyon tip is too narrow to simulate the joint-zone widths observed at ZNP (Fig. 11). If, instead, a joint of zero strength below the slot tip cuts this model, then it does not support a tension under a gravity load. In these scenarios, joint zones at ZNP would be the result of exfoliation jointing at canyon walls, which does not account for the extent of (sub)vertical jointing in the zone *below* the tip of the downward-cutting canyon.

If a gravity body load is applied with zero-displacement lateral constraints, the canyon tip is in a state of compression even when the tip is cut by a vertical joint. Only after the simulated slot canyon has 'eroded' half way through the sandstone (approximately 300 m canyon depth) does minor tension appear in the vicinity of the canyon tip just *upward* along the canyon walls (Fig. 12). This is the only location of tension in the model, and although tensile stress at this location increases as canyon depth increases, it is not predicted to exceed the tensile strength of the sandstone. Again, joint-zone development would be a function of exfoliation jointing in the canyon walls, while no jointing is predicted below the canyon tip.

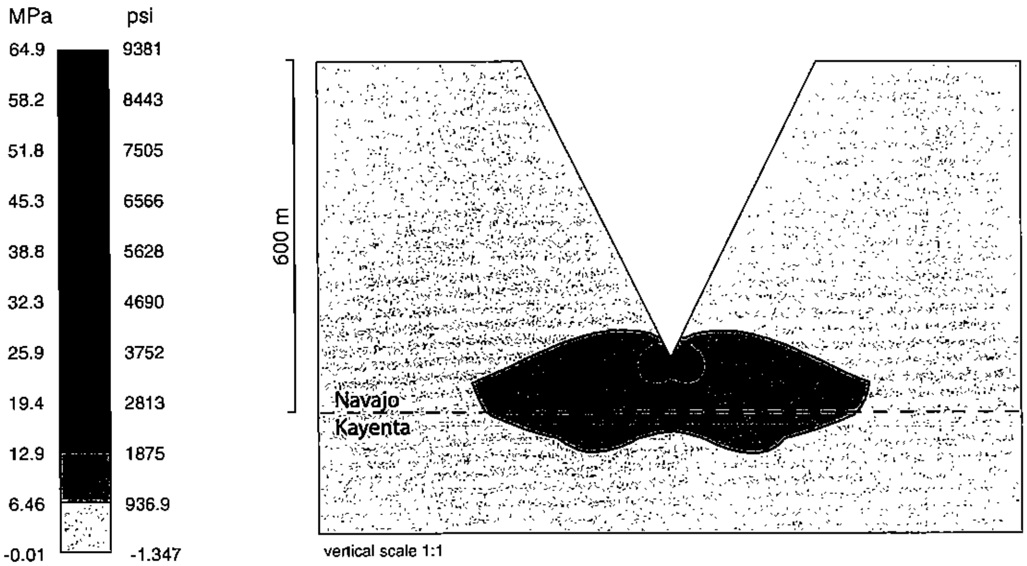

Fig. 13. FRANC (finite-element) model of a 500 m-deep Navajo Sandstone slot canyon subjected to tension equivalent to a 5×10^{-4} strain (vertical scale = horizontal scale). The tensile stress concentration at the canyon tip exceeds the presumed tensile strength (5 MPa) of the Navajo hundreds of metres from the tip of the slot canyon.

Remote tension results in a tensile stress concentration at the canyon tip as long as the Navajo Sandstone there is not cut by a joint and, thus, has a tensile strength. Tension is generated in the model by applying a displacement to one side of the model while fixing the other. Under strains of approximately 10^{-4}, the tensile stress concentration exceeds the tensile strength of the sandstone at a radius comparable to the widths of joint zones observed at ZNP (Fig. 13).

Finally, the underlying Kayenta Formation is assumed to be in frictional contact with the Navajo and, therefore, is included in these models. The influence of the Kayenta, as illustrated in the gravity, unconfined model, is such that an absence of Kayenta in the model results in a stress reduction within the Navajo at the canyon tip (Fig. 14A). Although a frictional contact with the Kayenta increases the tensile stress concentration at the canyon tip in the Navajo (Fig. 14B), slot canyons at ZNP do not penetrate into the Kayenta. This is observed in air photographs and in the field, and is also suggested by the gravity, unconfined model. As a Navajo slot canyon deepens, tensile stress concentrated at the tip is predicted to increase and then decrease in the final 100 m above the Kayenta contact (Fig. 14).

In each of the above models, where a net canyon-tip tensile stress concentration develops, stress trajectories indicate that joints on opposite sides of the canyon are predicted to dip toward each other and toward the axis of the slot canyon below the level of the canyon tip (Fig. 15). Because this same trend in dip is observed in the joints below the tips of the slot canyons in the field at Zion, we are encouraged that our models do approximate the state of stress ahead of the downward-eroding slot canyons at ZNP. In this manner, the pattern of stress trajectories modelled at the tips of slot canyons is analogous to that of a crack-tip stress field (Lawn 1993), and the joint zone below the slot canyons is analogous to new cracks propagating in a crack-tip process zone.

Regional tension plus gravity on a 'V'-shaped slot canyon

Our finite-element models suggest that gravity, alone (either unconfined or confined scenarios), generates a canyon-tip tensile stress concentration that is too local to account for the width of the joint zones at ZNP. However, as canyon walls at ZNP maintain steep cliffs (hundreds of metres of Navajo Sandstone), an overburden load is an important component in each model. Consequently, we superimpose a regional extension in order to generate a local tensile stress concentration that reaches outward from the canyon tip at the scale of ZNP joint zones. This necessitates that tensile strength is maintained below slot canyons and that initial regional joints cut only part way through the Navajo. Therefore, any hypothesis for early through-going joints in the Navajo is rejected implying that the taller joints that appear below the R and M slot canyons are not a remnant of

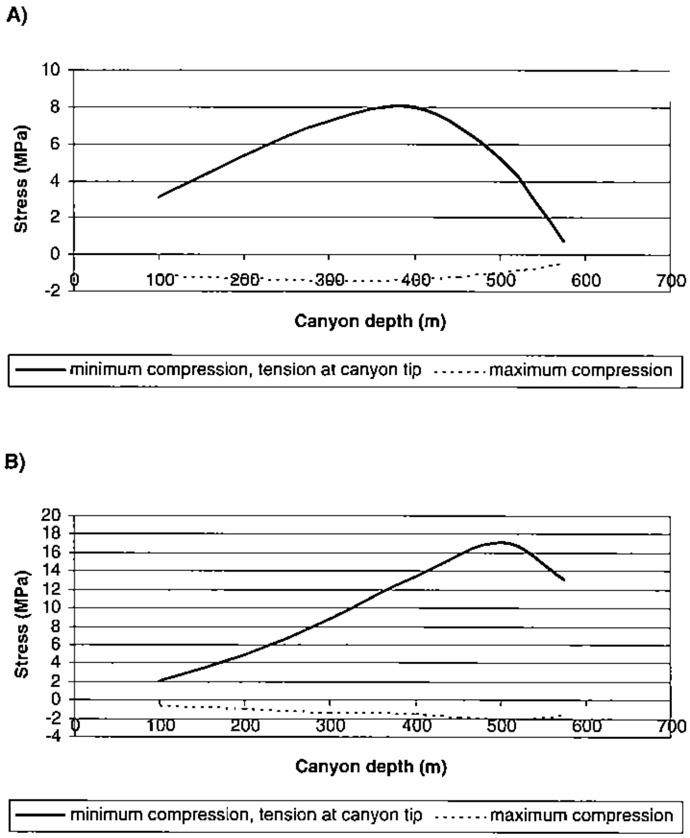

Fig. 14. Graphs of FRANC (finite-element) model results from unconfined Navajo Sandstone slot canyon subjected to a gravity load: (**A**) the model without the underlying Kayenta Formation, i.e. no frictional contact; and (**B**) the model including a frictional contact with the Kayenta. Note that the tensile stress concentration at the canyon tip is predicted to increase when the Navajo is in frictional contact with the underlying Kayenta and, in both cases, peaks and then decreases as the Kayenta contact is approached by the deepening canyon.

a through-cutting joint dating from the Miocene time.

Simulating a regional extension at ZNP was accomplished by applying a uniform displacement to one side of the FRANC model. This displacement was increased until the 5 MPa (tension is positive) contour extended out a lateral distance from the slot-canyon tip that is comparable to the width of the joint zones at ZNP. With an extensional strain of 5×10^{-4}, our model (i.e. Fig. 16) simulates stress magnitudes and trajectories associated with a 575 m-deep canyon, approximating the depth of the slot canyons in the Court of the Patriarchs (Fig. 4). In this model everything under the depth of the slot-canyon tips is in tension, and an extensional strain of 5×10^{-4} generates a tensile stress in excess of the presumed tensile strength of the sandstone out to a radius of about 225 m (Fig. 17). Symmetric lobes of tension characterize the pattern of tension about the symmetric V-shaped slot-canyon tip. In effect, the canyons are analogous to large-scale blunt edge cracks cutting downward into the Navajo Sandstone; therefore, the tensile stress pattern in our model is akin to a crack-tip stress field (Fig. 16).

Effect of canyon morphology

The same boundary conditions were applied to models for two additional slot-canyon geometries. The first geometry approximates the asymmetric V-shaped slot canyon at R slot (i.e. Figs 4 and 7) and the second geometry approximates the box canyon at M slot, the V-shaped canyon with squared base (i.e. Figs 4 and 8). Although a joint below the tip of R slot and the east zone of M slot appears to cut from the canyon tip to the base of the Navajo, there is no direct evidence that these joints once cut the entire Navajo

A)

B)

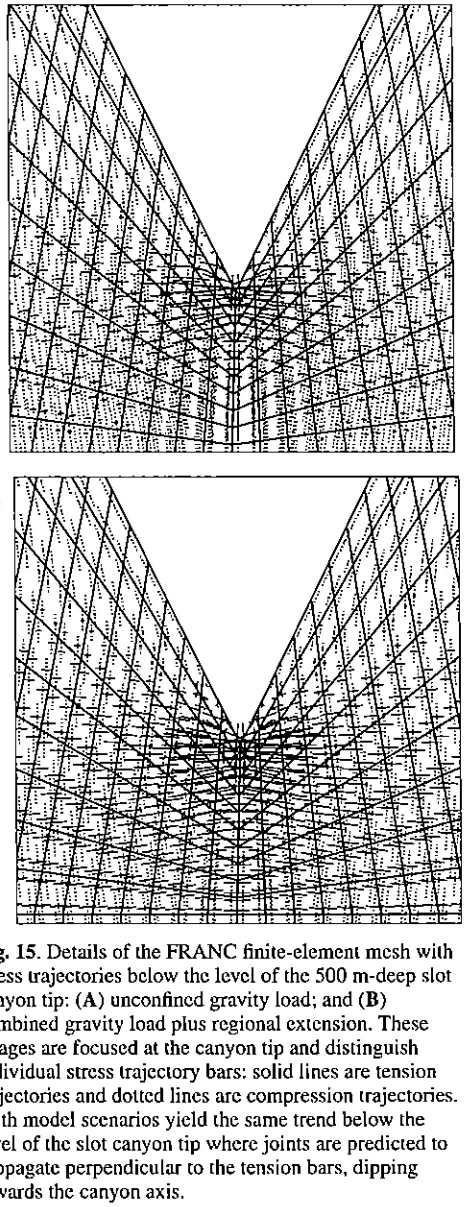

Fig. 15. Details of the FRANC finite-element mesh with stress trajectories below the level of the 500 m-deep slot canyon tip: (**A**) unconfined gravity load; and (**B**) combined gravity load plus regional extension. These images are focused at the canyon tip and distinguish individual stress trajectory bars: solid lines are tension trajectories and dotted lines are compression trajectories. Both model scenarios yield the same trend below the level of the slot canyon tip where joints are predicted to propagate perpendicular to the tension bars, dipping towards the canyon axis.

Sandstone prior to canyon development. Experiments with these two geometries included boundary conditions of gravity loading alone and regional extension superimposed on a gravity loading condition assuming a tensile strength below the slot canyons.

The asymmetric V-shaped canyon at R slot was simulated under the same boundary conditions as the symmetric V-shaped canyon (i.e. gravity loading plus regional extension of 5×10^{-4} strain). An asymmetric distribution of tension is predicted where the maximum predicted tension, located at the canyon tip, is approximately 22 MPa (Fig. 18). The predicted zone of tensile failure (5 MPa contour) extends to a width of about 210 m underneath the more steeply dipping east wall. The 5 MPa contour under the less steeply dipping west canyon wall exhibits a radius of about 250 m. This result is consistent with the asymmetry in joint-zone width beneath the R slot canyon tip where the east half of the zone is about 250 m and the west zone is about 380 m in width (Fig. 7). The 5 MPa contour is predicted to extend to the base of the Navajo, as is observed in the field.

Although an asymmetric joint distribution is predicted when a superimposed gravity and regional extension are applied to the R slot model, the unconfined gravity model (i.e. no regional extension) better predicts the joint free 'shielded zone' observed just west of the R slot canyon tip (Figs 7 and 19). However, despite the better overall location of tensile stress concentration, a gravity body load, alone, does not result in a sufficient magnitude of tension to create the joint-zone width observed at R slot.

Under the same boundary conditions that predict a 225-m wide joint zone laterally away from the symmetric V-shaped canyon (i.e. gravity loading plus regional extension of 5×10^{-4} strain), the predicted zone of tensile failure (5 MPa contour) in the M slot model extends at least 380 m from the axis of the canyon (Fig. 20) with a maximum tension of approximately 32 MPa generated at the M slot canyon tip. This 5 MPa contour in the M slot model greatly exceeds the width, *c.* 75 m, of the joint zones observed in the field at M slot (Fig. 8), and the same contour appears to penetrate the Kayenta Formation, which does not contain the M slot joint zone in the field. In addition, the same M slot model does not predict the 'shielded' zone (i.e. no joint-zone development) under the centre of the canyon. The central shielded zone separates the two joint zones under the corners of the 'box' canyon at M slot. In an effort to match the 5 MPa contour with the field observations at M slot, we find that the unconfined gravity model offers a better solution for an M slot joint-zone radius, predicting joint development in the immediate vicinity of the canyon tip. However, the pattern of predicted tensile failure does not extend to the base of the Navajo nor indicate that a double joint zone at M slot would exist (Figs 8 and 21), indicating that additional complexities are inherent to the development of the double joint-zone lineaments at M slot.

Discussion

Closely spaced joint propagation is enigmatic in that it is not predicted by joint normal tractions; however,

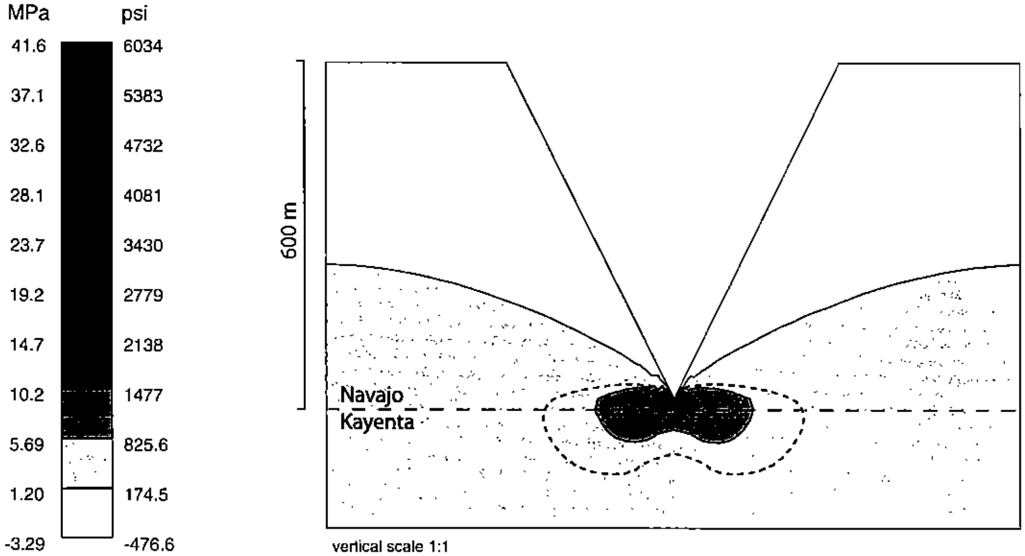

Fig. 16. Working slot-canyon FRANC model simulating the extent of joint-zone development associated with a canyon-tip tensile stress concentration at ZNP. Model parameters: 600 m of Navajo Sandstone (E=15 GPa, ν=0.15, ρ=2.3 g cm^{-3}) in frictional contact with the underlying 200 m of Kayenta (E=12 GPa, ν=0.10, ρ=2.6 g cm^{-3}) (vertical scale = horizontal scale) containing a symmetric, 'V'-shaped, sharp-tipped, 575 m-deep canyon with a superimposed gravity and regional extension (5×10^{-4} strain) loading condition. The dashed line represents the 5 MPa contour line, the extent to which joints are predicted to propagate in the Navajo due to the canyon-tip tensile stress concentration. This radius of joint propagation is comparable to the widths of joints zones observed at ZNP.

the dramatic NNW-trending, regularly spaced slot canyons of ZNP erode from distinct joint zones. The vertical and steeply dipping joints that compose the joint zones parallel the slot canyons and are spatially linked with them. To explain this observation we propose that there is a feedback between the downward erosion of the slot canyons at ZNP and the development of joint zones ahead of the downward-advancing tip of the canyons. This feedback has to generate joint zones below the canyon tip while leading to a regular spacing for the slot canyons that is roughly equivalent to the thickness of the Navajo.

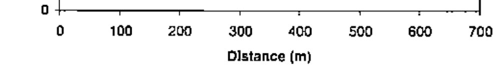

Fig. 17. Radius of tensile stress magnitudes extrapolated from σ_1 contours of the 575 m-deep canyon FRANC model (Fig. 16) subjected to a superimposed gravity load and remote tension (5×10^{-4} strain). The horizontal line represents the presumed tensile strength of the sandstone.

Evolution of slot-canyon joint zones

We presume that the history of the NNW-trending slot canyons of ZNP goes back to the propagation of individual joints in intact Navajo Sandstone some time during the Miocene. At that time, the western edge of the Colorado Plateau stretched in response to extension in the northern Lake Mead Extensional Belt of the central Basin and Range subprovince. This extension was directed just south of west, an extension direction shared by the NNW-trending slot canyons of ZNP in the adjacent Colorado Plateau (Rogers *et al.* 2004) (Fig. 2). Later, erosion downward into these regional joints initiated ZNP's prominent NNW-trending slot-canyon network. Once initiated, these slot canyons acted as notches, concentrating tensile stress at their tips under a combination of gravity loading and minor regional extension.

This canyon-tip tensile stress concentration was responsible for closely spaced jointing in joint zones below canyon tips. The closely spaced jointing at

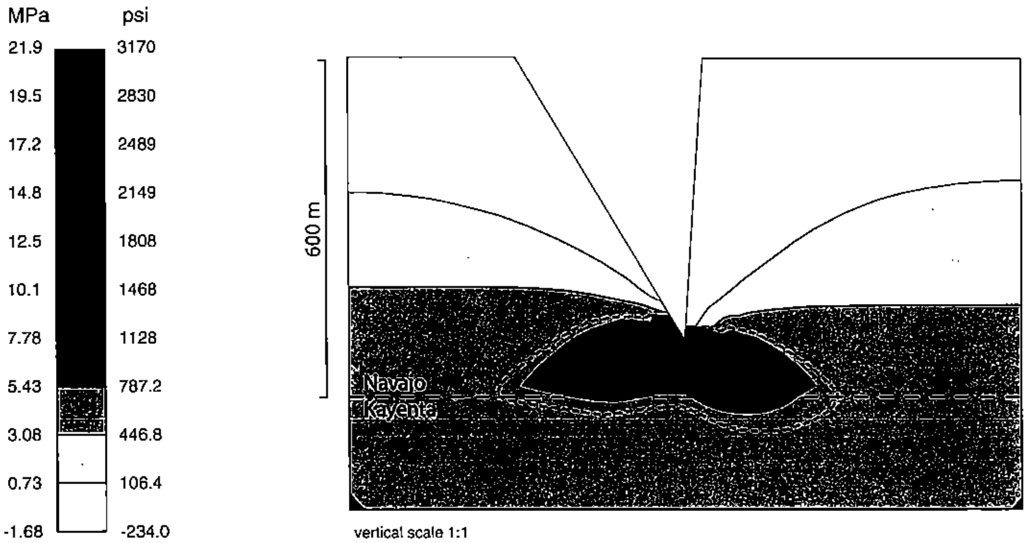

Fig. 18. Boundary conditions from the working model (Fig. 16) applied to an asymmetric 'V'-shaped, sharp-tipped canyon geomorphology simulating R slot at the Court of the Patriarchs (Fig. 7). The dashed line represents the 5 MPa contour line, the extent to which joints are predicted to propagate in the Navajo due to the canyon-tip tensile stress concentration.

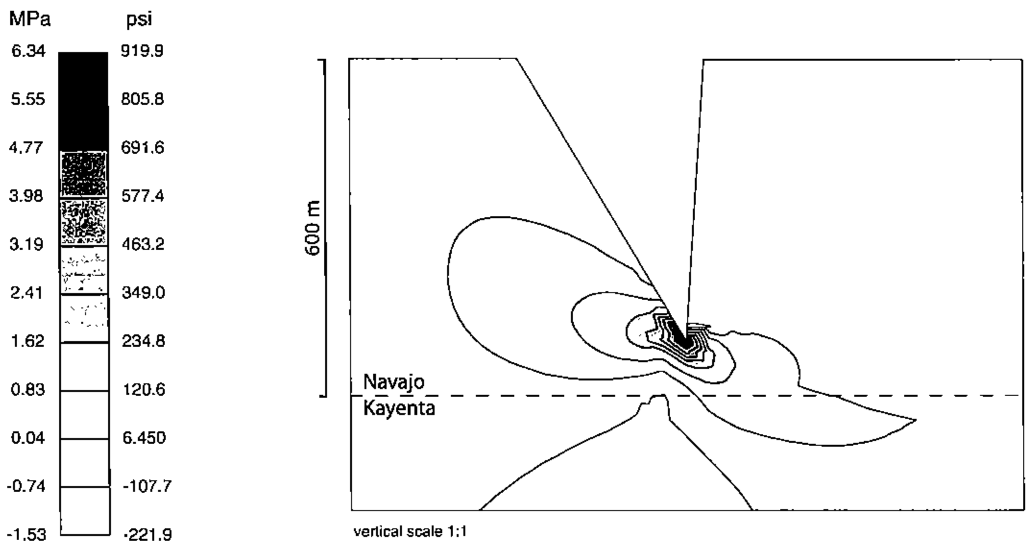

Fig. 19. Gravity body load applied to an unconfined FRANC model of R slot at the Court of the Patriarchs. Although, when compared to field observations, this model better predicts the pattern of tensile stress concentration below the canyon tip including the 'shielded' joint free zone offset toward the west, less steeply dipping cayon wall, it does not predict tensile failure at the observed joint zone width observed at R slot (Fig. 7).

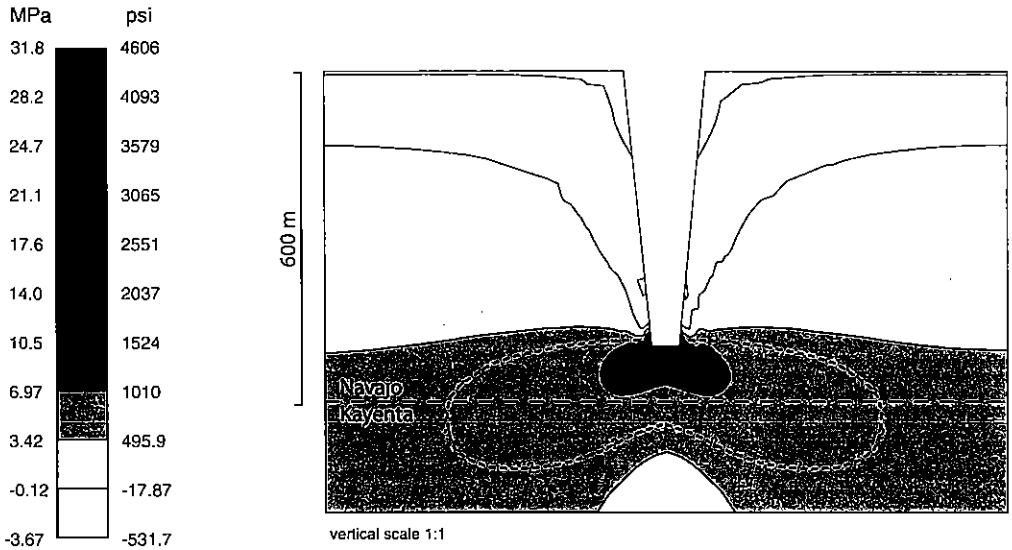

Fig. 20. Boundary conditions from the working model (Fig. 16) applied to a symmetric 'V'-shaped, squared-tip canyon geomorphology simulating M slot, Refrigerator Canyon. The dashed line represents the 5 MPa contour line, extrapolated into the Kayenta, indicating the extent to which joints are predicted to propagate in the Navajo and Kayenta due to the canyon-tip tensile stress concentration.

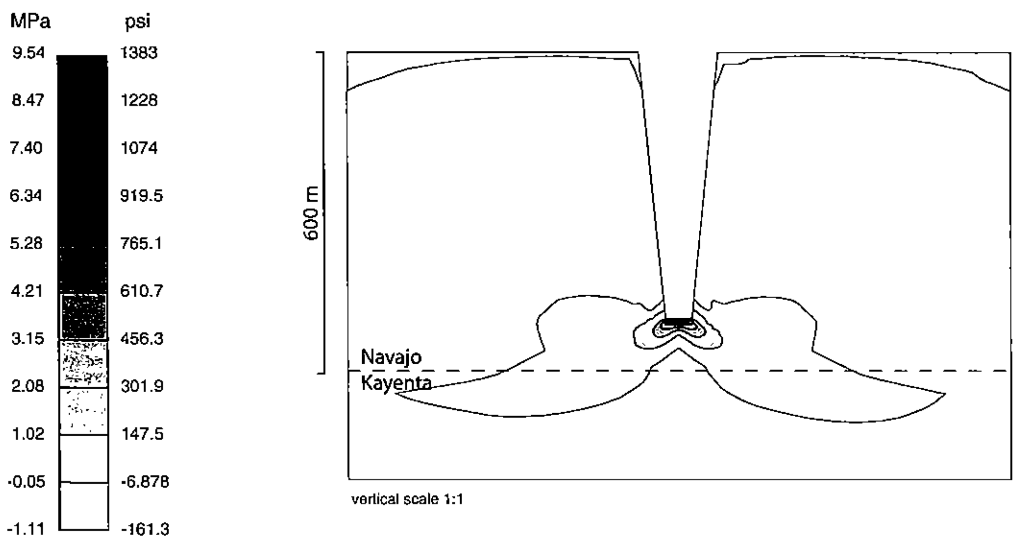

Fig. 21. Gravity body load applied to an unconfined FRANC model of M slot, Refrigerator Canyon. Although, when compared to field observations, this model better predicts a width of tensile failure in the Navajo comparable to the overall joint zone width observed at M slot (Fig. 8), it does not predict tensile failure to the base of the Navajo nor indicate that a double joint zone would exist.

slot-canyons tips is analogous to a crack-tip process zone where joints form in response to elevated tensile stress beyond the crack tip (Delaney *et al.* 1986). The slot-canyon 'notch' concentrates stress in a similar pattern to that generated by an edge crack in an elastic medium (Lawn 1993). A regional extension was necessary to generate a tensile stress concentration of sufficient magnitude and lateral extent to produce the observed joint zones. As the Navajo is assumed to be a confined system, this remote tension compensates for compression induced by the gravity load (weight) of the overlying Navajo Sandstone.

Joint-dip analysis performed from field photographs indicates that joints below the canyon tip have a tendency to dip toward the slot-canyon axis (Table 1). However, joints dip both east and west regardless of their position relative to the associated slot canyon. The models presented here represent stresses arising in a continuous medium where all trajectories dip toward the slot canyon. A jointed medium would not be expected to produce such a simple result, as the local stress field would continue to become more complex with the propagation of additional joints.

Following the relief of tensile stress at the canyon tip, the gravity load (overburden) then drives vertical wing cracks from the tips of the steeply dipping joints, therefore augmenting the canyon-tip joint zone. Joint-dip analysis reveals that the mode of each population of joints observed at slot canyons is vertical, the orientation of wing cracks propagating in response to gravity. In addition, the 5m-joint sampling statistics, which are biased towards measuring wing cracks, are weaker in the identification of a preferential joint dip direction within a particular canyon-tip joint population.

These wing cracks can exhibit a very close spacing as a response to a vertical, crack-parallel gravity load acting on inclined parent joints. This crack-parallel loading is distinct from the crack-perpendicular loading ((sub)horizontal tension) of original parent cracks (secondary joints) that propagated in response to elevated tensile stress in the canyon-tip process zone. This early crack-normal tension is already relieved by the propagation of the parent joints where spacing is expected to be governed by stress shadows. Subsequent wing-crack growth is required to infill and achieve a close joint spacing.

Ultimately, exfoliation jointing at canyon walls completes the sequence of jointing in the zones at ZNP slot canyons (Bahat *et al.* 1995). However, the development of a process zone under the canyon tip is an independent source of jointing from the exfoliation mechanism. Therefore, closely spaced joints found below the canyon tip are to be distinguished from exfoliation fracturing that occurs at canyon walls in direct response to lateral unloading while an overburden stress is still present.

Slot-canyon spacing

Our modelling of the slot canyons at Zion suggests several things about both the width of the joint zones and the spacing of the canyons. First, we conclude that the width of each canyon-tip joint zone(s) can be reproduced only when the 600 m bed of Navajo Sandstone maintains its tensile strength below slot canyons. A gravity-driven stress concentration at the tip of the slot canyons produces a zone of tensile stress concentration that is too narrow, in a laterally unconfined model, and of insufficient magnitude to cause tensile failure in a laterally confined model, to reproduce the joint zones at ZNP. Therefore, in order to generate a sufficiently far-reaching tensile stress contour, a superimposed regional extension is a necessary boundary condition in our models. This means that we must reject the hypothesis that the even spacing of the slot canyons at Zion is a consequence of a direct relationship with the initial propagation of through-going joints confined to the Navajo Sandstone in a manner similar to joints cutting the full thickness of stiff beds contained within shale layers. We reject the through-cutting joint hypothesis, because through-cutting joints would cause a local loss of tensile strength in the Navajo at the location of each eroding canyon. Such a lack of tensile strength pre-empts the possibility that a sufficient tensile stress concentration can develop at the leading edge of a downward-eroding slot canyon under a gravity load alone. Consequently, we cannot appeal to the classic stress-shadow theory as discussed by Gross *et al.* (1995) and many other authors to explain the relatively even spacing of the slot canyons at ZNP.

The density of joint-zone lineaments increases from west to east across the field area, while the depth of erosion of the slot canyons decreases, west to east, over the same area. If we measure the density of slot canyons cutting to the base of the Navajo Sandstone along the west side of the valley of Zion Canyon, we see that seven slots cut to within 100 m of the basal contact between slots M and S (Fig. 4) where Q slot counts for two data, P is missing and M is counted once. These slots project onto a profile of 4 km to give a density of $1.75\ km^{-1}$. If the stress-shadow model is used to explain the spacing of slot canyons, we predict a slot-canyon density of one per 600 m (average 600 m Navajo thickness), or $1.66\ km^{-1}$.

If we measure the density of slot canyons cutting through Highway 9 from D slot to N slot, we find that 18 joint zones/slots touch the road in Figure 4 in a profile distance of 6.5 km. This gives us a density of $2.76\ km^{-1}$ or almost double the density found near the base of the Navajo Sandstone. In this distance there are several slot canyons that are composed of double joint-zone lineaments (i.e. D, E, G, H, K, L, M and N). In this same profile I and J have

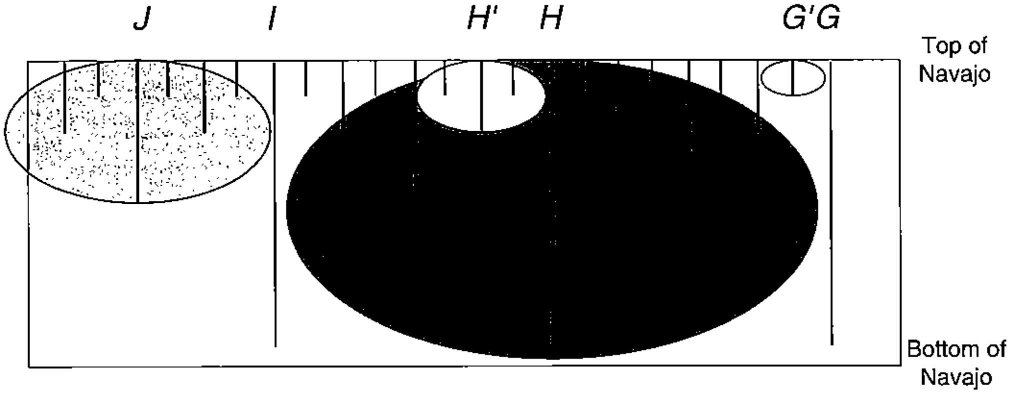

Fig. 22. Hypothetical cross-section along Highway 9 from G slot to J slot (Fig. 4). Schematic of edge cracks (canyons) in the Navajo Sandstone analogous to Lachenbruch's thermally induced edge cracks in permafrost. The horizontal extent of stress shadows is comparable to edge-crack (canyon) depth and, as particular cracks propagate, they suppress the growth of neighbours due to their expanding stress shadow.

merged to form a canyon with a double lineament as well. Only F slot is missing. We believe that the presence of multiple canyons composed of double lineaments in the upper half of the Navajo Sandstone is a key pointing to the mechanism controlling the spacing of the slot canyons.

Lachenbruch (1961) presented an analysis of the development of thermally induced cooling cracks in permafrost. He pointed out that as the cracks grow into the permafrost, they may start as relatively close-spaced discontinuities. As they grow downward into the permafrost, their spacing increases. Lachenbruch (1961) believed that this growth pattern was a manifestation of the relief of tensile stress near the wall of cracks. The extent of the relief of tensile stress scales with the depth of the crack. This stress relief model of Lachenbruch (1961) is an early version of the stress-shadow model later quantified by Geyer & Nemat-Nassar (1982) in a series of experiments on the propagation of cracks from the edge of a glass plate as a consequence of a thermal shock. Pollard & Segall (1987) applied this model to joints that cut completely across a bed and Gross *et al.* (1995) provided greater detail for this model, which became known as the stress-shadow model. The distinction between the permafrost model and the later stress-shadow model is that the former model represents the growth of edge cracks from an unconfined boundary, whereas the latter involves the growth of internal flaws within a confined bed. In the edge-crack model (i.e. permafrost model of Lachenbruch), the faster growing cracks suppress the growth of adjacent cracks by the expansion of their stress shadow, a process referred to as crack-tip shielding (e.g. Olson 1993).

We can apply the edge-crack model to the development of the slot canyons at ZNP. Although slot canyons are localized along pre-existing joints in the upper Navajo, they are themselves analogous to large cracks in the Navajo Sandstone and must be recognized as such in this explanation. Once slot-canyon 'cracks' begin to erode in the Navajo, they 'grow' downward due to a feedback loop between erosion and jointing arising from progression analogous to a process zone. The joint zones are more easily eroded, thus focusing erosion into a series of slot canyons. The slot-canyon 'cracks' concentrate a tensile stress downward from their tips, thus driving joint-zone development ahead of the downward-eroding slot canyons. Because the canyon walls become free surfaces, slot-canyon 'cracks' project stress shadows into the adjacent Navajo Sandstone at ZNP. This stress shadow will act to suppress the downward growth of closely spaced slot canyons, leaving only more widely spaced canyons to work further down into the Navajo.

Consider a hypothetical cross-section along Highway 9 from G slot to J slot (Fig. 22). In this profile we have demonstrated that the upper half of the Navajo Sandstone has many more joint zones than it should based on stress shadows developed about joint zones cutting the entire thickness of the Navajo. We denote G, H and I slots by joint zones that cut the entire thickness of the Navajo. In this hypothetical profile view we also add joint zones that are half the thickness of the Navajo, 25% of its thickness and 12.5% of its thickness. We also assign a spacing that is proportional to the depth of penetration for each size joint zone. Stress shadows are drawn about each size joint zone. This gives a profile for joint-zone penetration that is the same as that realized by Geyer & Nemat-Nassar (1982)

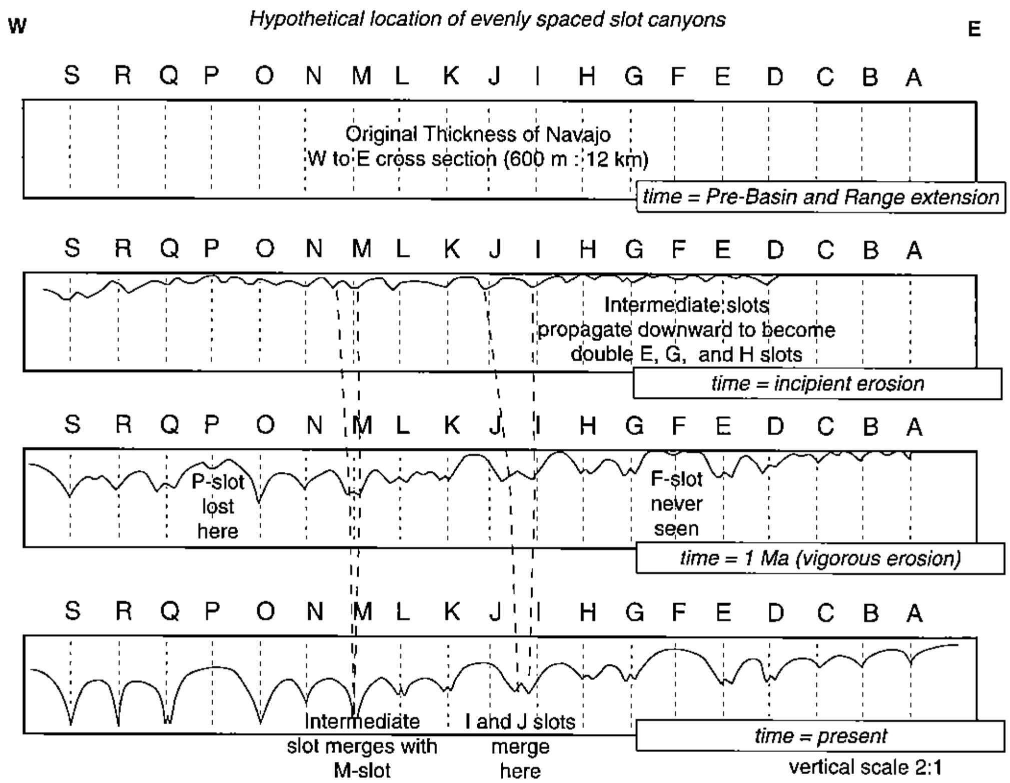

Fig. 23. Hypothetical set of cross-sections in a time sequence for the development of the topography at ZNP. We see the initial erosion gives a topography with many more slot canyons toward the top of the Navajo Sandstone. Canyons deepen due to the feedback loop between erosion and jointing in response to minor regional extension. These slot canyons either merge, form double joint zone lineaments or are suppressed in the present topography as stress shadows associated with canyon erosion develop.

experimentally and by Lachenbruch (1961) theoretically for the edge-crack model of stress-shadow development. On the Highway 9 profile we note that G slot has two joint-zone lineaments with G′ spaced about 72 m from G, and we note that H slot has a double lineament with H′ spaced about 140 m from H (Fig. 4). Along Highway 9, we note that and I and J approach each other. Finally, the 600 m spacing between slot canyons is denoted by an appropriately large stress shadow (Fig. 22). By this same model we predict that some double joint-zone lineaments (i.e. M slot) eventually merge to become one slot canyon.

Conclusions

Our thesis is that the eroding slot canyons within the Navajo Sandstone of ZNP are analogous to large, blunt-tipped 'edge cracks' and behave in the same fashion as cracks in permafrost (i.e. Lachenbruch 1961) and thermal-shock cracks (i.e. Geyer & Nemat-Nassar 1982) where crack growth results in regular spacing that increases with depth due to stress-shadow shielding effects that suppress the growth of neighbouring cracks. This is seen in the pattern of canyons and joint-zone density in the Navajo Sandstone across ZNP. From this model, we can then construct a hypothetical set of cross sections in a time sequence for the development of the topography at ZNP. We see the initial erosion gives a topography with many more slot canyons toward the top of the Navajo Sandstone (Fig. 23). These slot canyons either merge, show double joint-zone lineaments or are suppressed in the present topography, depending on the depth of canyon erosion.

In summary, we find that stress-shadow theory does apply to Zion and that it is responsible for the even spacing of the slot canyons. However, our stress-shadow interpretation is based on the propagation of edge cracks (i.e. the eroding slot canyons) downward from the top of the Navajo Sandstone. We reject the hypothesis that early jointing extended the entire thickness of the Navajo Sandstone. Rejection of this hypothesis is consistent with the fact that we see little evidence for initial joints that propagated the full thickness of the Navajo Sandstone. In addition, rejection is also consistent with the observation that there are more double joint-zone lineaments within individual slot canyons near the top of the Navajo Sandstone than near the bottom. We see indications of slot-canyon development during a period of continued extension of the western edge of the Colorado Plateau. This extension was enough to place the tips of the slot canyons of ZNP into tension in a stress concentration zone, directly analogous to a crack-tip stress concentration, that may have extended more than 100 m into the adjacent rock ahead of the tip of the canyons.

This tensile stress concentration zone is responsible for initiating a 'process zone' of secondary jointing resulting in the joint zones observed at the base and ahead of each slot canyon. Following the slot-canyon-induced jointing, wing cracks develop from the tips of the secondary joints below the canyon under a gravity load, leaving exfoliation jointing to occur in a zone very near the canyon wall of the slot canyons. This exfoliation jointing is driven by a gravity load and is independent of the regional extension, which causes the joint zones ahead of the tip of the slot canyons. Cumulatively, these events result in the closely spaced jointing observed at slot canyons in ZNP.

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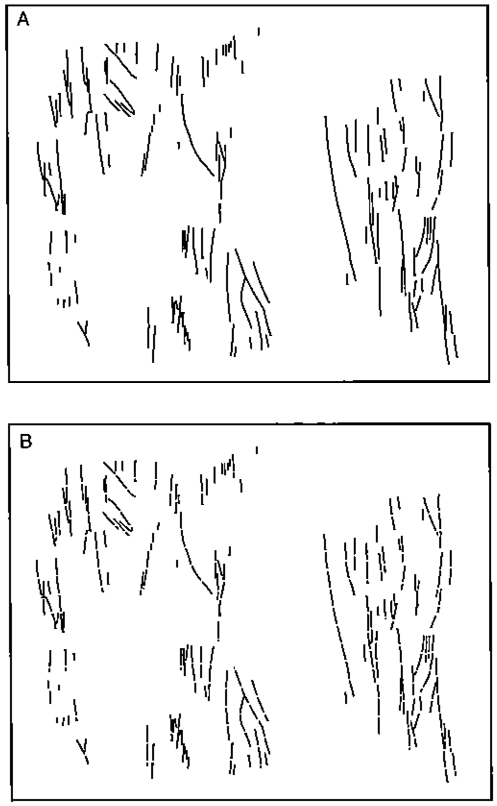

Fig. A1. Joint sampling methods used for joint dip analysis by Scion Image software: (**A**) example of the whole joint (measured tip to tip) sampling; and (**B**) 5 m-joint segment sampling applied to M slot, Refrigerator Canyon.

Appendix: Photograph interpretation

Individual joints were digitized from field photographs of joint zones in cross-section, paying close attention to dip angle. Photographic interpretation was performed repeatedly. Multiple tracings (three–four) of the same photograph were compared and, in an effort to include only reproducible results, only those joints that appeared in each tracing were included in the final interpretation. Secondly, if a joint was recognized or suspected of trending in a direction other than that of the slot canyon, it was not included in the final tracing.

Scion Image computer software, developed at the Research Services Branch (RSB) of the National Institute of Mental Health (NIMH) (part of the National Institutes of Health (NIH)), was used to measure joint dip values directly from the cross-section photograph tracings. Scion Image is a public domain image processing and analysis program used here to fit ellipses to line segments (joints). The program measures the angle of the long axis of the ellipse, which, in this case, is parallel to the joint (segment) length, thus providing the dip angle of digitized joints. Based on the average joint trend derived from scanline data (Fig. 6), all Scion Image data were corrected for the effects of apparent dip expressed in canyon walls prior to statistical analysis.

Two different joint sampling methods were analysed. Ellipses were first fit to the whole length of each digitized joint, measured from tip to tip (Fig. A1A). These data represent dip values of individual joints treating each as a planar feature without regard to fracture length. Secondly, all digitized joints were converted to 5 m-dashed line segments with minimal interdash intervals in order to approximate the full joint length (Fig. A1B). These data were expected to account for potential deviations in joint dip along a single joint, which may be attributed to a temporally varying stress field. In histograms these data were binned according to dip value, independent of joint identity and joint length.

Ultimately, the statistics and observations presented here are an accurate representation of trends in dip direction only, not the measured dip value. It was not possible to remove additional photographic distortions that affect these photographs (Wolf 1974) and, therefore, the accuracy of our measure of the absolute dip angles is unknown.

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