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ScienceDirect
Geomorphology 82 (2006) 16–38
GEOMORPHOLOGY
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Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River, North Island, New Zealand

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Received 13 July 2004; received in revised form 14 January 2005; accepted 3 June 2005
Available online 9 August 2006

Abstract

If knickpoints transmit signals of base level fall in river networks, then improvements in our understanding of their retreat rate and basin wide distribution helps constrain the transient response following perturbation. Many studies of knickpoint retreat focus on the response of trunk streams to base level fall. Here we examine the response of an entire fluvial network, as recorded by 236 active knickpoints distributed within the Waipaoa River on the North Island of New Zealand. Base level fall within the Waipaoa catchment initiated 18,000 years ago in response to a climatically triggered and tectonically exacerbated pulse of incision. Using observations from field work, aerial photo analysis and a digital elevation model (DEM), we study the knickpoint positions within the network. We find that ~70% of the knickpoints are located at drainage areas between 1×10^5 m^2 and 1×10^6 m^2 and more than half are <1 km upstream of a large change in drainage area. For the knickpoints <1 km upstream of large tributary junctions, we find that the retreat distances were well correlated with the tributaries' drainage areas. In order to determine how a pulse of incision distributes itself throughout a fluvial network, we develop two simple, end-member models and compare their behavior to the observed knickpoint distribution in the Waipaoa. In the first model, we propose that a knickpoint initiated at the basin outlet retreats upstream and distributes the signal throughout the network at a rate that is a power law function of drainage area. In the second model, we propose that knickpoints form near a threshold drainage area, below which channels cannot incise with the same efficiency as possible in downstream reaches. Though neither model addresses the along-stream variability in substrate or knickpoint form, the misfit between the modeled and the observed knickpoints' along-stream positions are surprisingly low (<1 km; ~1.25% of the total stream length) for knickpoints with drainage areas $<1\times10^6$ m^2. Large misfits (up to 3.5 km) are observed for knickpoints with present-day drainage areas greater than 1×10^6 m^2. The large, single step in channel elevation that characterizes knickpoints presently observed in tributaries of the Waipaoa River may not characterize the base level fall signal that propagated through the trunk streams. Evidence for progressive (rather than instantaneous) incision in the trunk streams, the knickpoints' vicinities to tributary junctions and the equivalent success of the two-end member models lead us to conclude that the present positions of the 236 observed knickpoints are largely a consequence of thresholds in channel incision at low drainage areas.

Keywords: Knickpoint; Waipaoa River; Bedrock incision; Fluvial network; Transient phenomena; Waterfall

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doi:10.1016/j.geomorph.2005.08.023

1. Introduction

1.1. Transient adjustment in fluvial networks

River longitudinal profiles of both alluvial and bedrock channels tend toward a form which best facilitates transport of the sediment load and erosion of the bed (Mackin, 1948; Hack, 1957; Howard et al., 1994; Whipple and Tucker, 1999). Following a change in boundary conditions, the efficiency of erosion or the efficiency of sediment transport, the channel adjusts to a different form appropriate for the new conditions. In studies of bedrock rivers using field, experimental and modeling techniques, most workers have examined the adjustment of the trunk stream to new conditions (Brush and Wolman, 1960; Holland and Pickup, 1976; Gardner, 1983; Seidl and Dietrich, 1992; Seidl et al., 1994; Sklar and Dietrich, 1998; Stock and Montgomery, 1999; Whipple and Tucker, 2002). Though modeling studies have made significant progress toward understanding how this transient adjustment extends throughout an entire fluvial network (e.g. Howard, 1994; Moglen and Bras, 1995a,b; e.g. Tucker and Slingerland, 1997; Crosby, 2006, Ch. 2), few have examined this aspect of the problem using laboratory or field techniques (Weissel and Seidl, 1998; Hasbargen and Paola, 2000; Bishop et

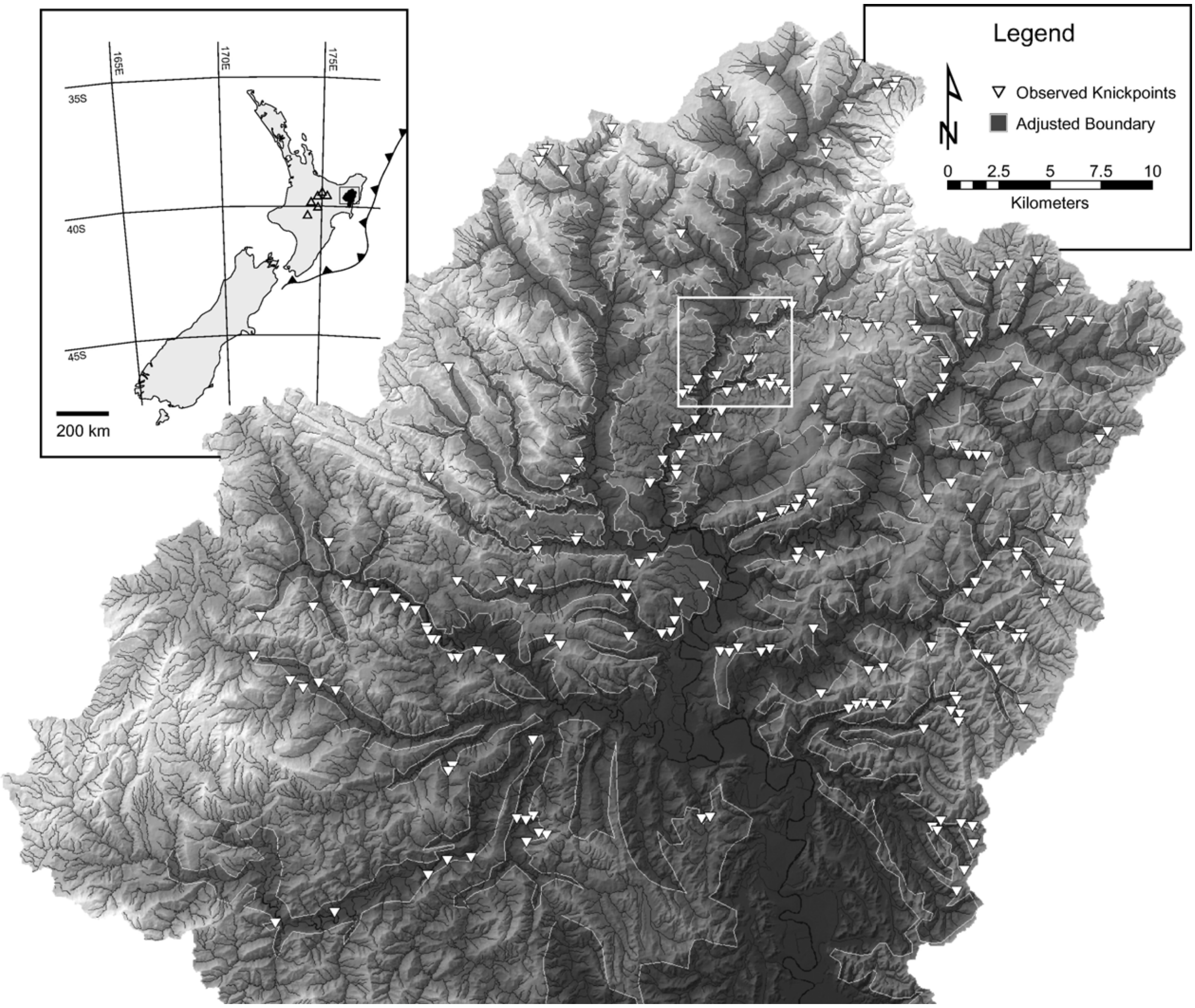


Fig. 1. Location map for the northern two thirds of the Waipaoa drainage basin. On the inset regional map (upper-left), the Waipaoa catchment is located on the northeastern coast of the North Island of New Zealand, ~150 km east of the central North Island volcanic centers (triangles) and ~100 km west of the Hikurangi subduction trench. In the catchment view (central image), 236 knickpoints (inverted triangles) are identified along a mobile boundary that distinguishes which portions of the landscape have adjusted to a pulse of incision initiated 18,000 years ago (dark overlay with thin white outline) and which portions retain their relict, pre-disturbance form. The white square locates Fig. 3.

al., 2005). The rate of this basin-wide transient response determines the landscape response time to external forcing, the history of sediment delivery to offshore depositional centers and ultimately mediates the dynamic coupling between tectonics, climate, and erosion — a coupling that is hypothesized not only to affect landscape form but to strongly influence orogen evolution (e.g. Beaumont et al., 1992; Koons, 1995; Willett, 1999). To better understand how bedrock river networks respond to a change in the conditions that govern their form, we study the actively adjusting, transient landscape of the Waipaoa River drainage basin on the North Island of New Zealand Fig. 1).

As adjustment following perturbation is not contemporaneous throughout the basin but rather migrates upstream (Howard, 1994; Tucker and Slingerland, 1994), a mobile boundary develops, that separates portions of the landscape that are adjusting to the new conditions from those that retain their relict, pre-disturbance form. Although many analyses have purposefully considered the idealized and useful concept of topographic steady state (in which erosion balances rock uplift) (Adams, 1985; Willgoose et al., 1991; Howard et al., 1994), it is likely that most landscapes through geologic time have existed in a state of constant perturbation away from steady state conditions. One of the difficulties in understanding the transient response of fluvial systems arises from the diversity of perturbations capable of initiating similar responses. Some perturbations are regional, such as where a long term change in bedrock uplift rate or climate requires the landscape to assume a new form. Other perturbations are local, such as base level fall and do not require the landscape to assume a new form, but rather to just adjust the present form to a new elevation. A rapid change in base level can occur due to surface rupture on faults, changes in sea level, stream capture or incision rate contrasts at the junctions of tributary streams. Whether the perturbation is regional or local, during the transient response the network of upstream channels can change their elevation, slope, width, or bed state in order that the final form is adjusted to the new conditions. We use the term ‘bed state’ to encompass bed morphology, bed roughness, grain size distribution and the thickness and percent of alluvium covering the channel bed (Whipple, 2004).

1.2. Knickpoints as transient features

We will define the fluvial portion of the transient boundary between adjusting and relict topography as a knickpoint (Fig. 2). These enigmatic features provided early examples of the dynamic response of bedrock rivers (Gilbert, 1896; Penck, 1924; Davis, 1932) and continue to offer compelling evidence for disequilibrium conditions in field, experimental and theoretical studies. Despite the frequency with which knickpoints are discussed in the literature, fundamental questions regarding their origin, mobility and form remain unanswered. Some of this difficulty results from the diversity of landforms and processes implied by the term. The term knickpoint can be used morphologically to describe an abrupt change in river gradient (Whipple and Tucker, 1999), but in this work we will use the ‘classic’ definition where a knickpoint describes a discrete, steep reach

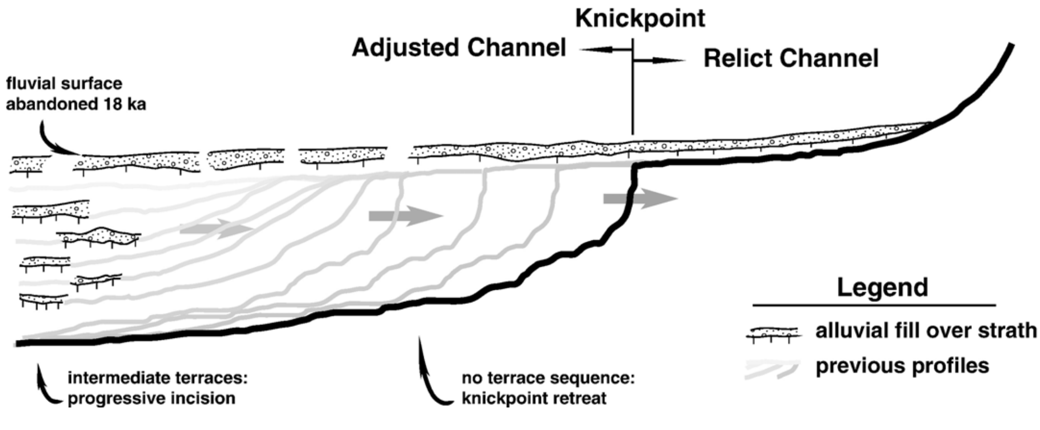


Fig. 2. Schematic illustration of a typical knickpoint on a long profile of a tributary of the Waipaoa River. The knickpoint defines the mobile boundary between the adjusting and relict portion of the channel. The 18 ka discontinuous strath terrace surface is shown, as well as strath terraces formed during progressive vertical incision. In reaches where base level lowering is achieved through knickpoint propagation, no intermediate terraces are created. Grey sequential channel profiles show two potential ways that incision may occur along stream. The grey profiles also demonstrate how these different styles of adjustment may influence the channel’s ability (or inability) to generate terrace surfaces. Arrows denote the direction of knickpoint retreat.

which creates a local convexity in the generally concave-up equilibrium channel profile (Fig. 2). These landforms can range from high gradient rapids to waterfalls.

In many field studies, the upstream retreat of knickpoints has been suggested as the dominant mode of channel adjustment in response to either regional or local perturbation (Gilbert, 1896; Holland, 1974; Wolman, 1987; Seidl and Dietrich, 1992; Wohl, 1993; Seidl et al., 1994; Weissel and Seidl, 1998; Stock and Montgomery, 1999; Zaprowski et al., 2001; Haviv et al., 2003; Hayakawa and Matsukura, 2003; Bishop et al., 2005). Multiple mechanisms have been suggested for knickpoint retreat. In regions where the substrate is horizontally stratified or a resistant cap-rock prevents erosion of the knickpoint lip, circulation of water and sediment in a plunge pool at the base of the drop undercut the lip and the step retreats upstream (Gilbert, 1896). In other settings, groundwater seepage along a permeability contrast is suggested to accelerate weathering and facilitate erosion by undercutting the knickpoint lip (Laity and Malin, 1985; Dunne, 1990). Others have suggested that the impact of water and sediment against the bedrock base and steep face of the knickpoint drive retreat (Miller, 1991; Hayakawa and Matsukura, 2003). The stream power erosion model (Howard and Kerby, 1983) has also been applied to describe knickpoint retreat and provides the most popular, quantitative tool for comparing the form and position of modeled and observed knickpoints (Rosenbloom and Anderson, 1994; Seidl et al., 1994; Weissel and Seidl, 1998; Stock and Montgomery, 1999).

Experimental studies of knickpoints demonstrate that the mechanical properties of the substrate (homogeneous, stratified, jointed, cohesive vs. noncohesive) influence whether the knickpoint face progressively decreases gradient (typically noncohesive) (Brush and Wolman, 1960; Begin et al., 1981; Gardner, 1983), or whether the knickpoint migrates upstream with varying degrees of incision upstream of the lip and/or gradient reduction on the face (typically cohesive) (Holland and Pickup, 1976; Gardner, 1983). Retreat without substantial modification of the knickpoint form has only been observed under the special circumstance where either pervasive and extensive bedrock jointing exists or a strongly cohesive cap-rock prevents erosion of the knickpoint lip (Holland and Pickup, 1976; Stein and LaTray, 2002). Gardner (1983), recognized that under certain conditions, as the flow approaches the free overflow, it accelerated and enhanced erosion of the knickpoint lip. The region over which this enhanced erosion occurred was referred to as the draw-down reach. Another experimental study using a non-cohesive, homogeneous substrate observed autogenic knickpoint-like waves of base level fall migrating throughout a channel network (Hasbargen and Paola, 2000). Another flume-scale experimental study examined knickpoint retreat across vertically oriented beds of variably cohesive substrate (Frankel et al., 2001). They found that the knickpoint diminished in height when translating across the weakly cohesive sections, then reformed, migrated and diminished again as it passed through highly cohesive sections. Though experimental studies offer workers the opportunity to observe the time-evolution of a transient form, there are numerous scaling concerns that indicate that the rate-limiting erosion process at the flume-scale may be very different from those occurring in the field.

Theoretical or modeling studies of knickpoints provide workers with both the capacity to observe the time-evolution of the transient response and to effectively test the influence of different variables on the result. Studies of knickpoint behavior in systems where erosion is limited by the channel's capacity to transport the imposed sediment load (transport limited) are typically analogous to experimental studies in noncohesive substrates where the knickpoint face progressively decreased gradient (Brush and Wolman, 1960; Begin, 1988). If these knickpoints migrate upstream, the initial step in elevation could be described as diffusing, decaying, degrading or rotating as it migrates upstream. Studies of knickpoint behavior in systems where erosion is limited by the channel's capacity to incise into bedrock (detachment limited) are typically analogous to experimental studies in cohesive substrates where the knickpoint migrated upstream with varying degrees of reduction in height and/or gradient. Detachment limited channels are often described by the stream power incision model (Howard and Kerby, 1983), where incision rate along the channel is a power function of both upstream drainage area and local slope. Using this model, others have derived the celerity, or wave speed of a knickpoint (Rosenbloom and Anderson, 1994; Weissel and Seidl, 1998; Whipple and Tucker, 1999). Knickpoint celerity is a power law function of both upstream drainage area and local slope. The propagating knickpoint's form is invariant if the celerity is not dependent on slope (e.g., the slope exponent is zero).

Generalizing the field, experimental and theoretical findings above, we find that if the steep slope of the knickpoint face enhances erosion, then the local convexity migrates upstream (Fig. 2). The expectation that a migrating step persists from the point of initiation throughout the fluvial network is complicated by two concerns. First, the conditions that set the rate of retreat and form of the migrating knickpoint change as the knickpoint retreats upstream. For example, water and sediment discharge decrease stepwise at tributary junctions and substrate erodability often varies within a drainage basin. The second concern is that steps in channel elevation are unstable and are rapidly modified. If knickpoints are susceptible to modification as they translate upstream, then caution must be used when associating steps in fluvial profiles with basin-wide, upstream migrating transients. In addition, non-transient, static knickpoints can be fixed in space by local decreases in bed erodability such as an erosion-resistant intrusive body or coarse sediment armoring downstream of a tributary junction. These static knickpoints must be distinguished before the distribution of transient knickpoints is analyzed. Provided the controls on knickpoint form and retreat rate can be determined, the distribution of transient knickpoints may provide insight into how pulses of incision are communicated throughout fluvial networks.

1.3. Our approach

The landscape in the Waipaoa River catchment (Fig. 1), records the transient response following a large magnitude episode of rapid incision (Berryman et al., 2000; Eden et al., 2001). Incision began ca 18 ka and initiated a pulse of incision that extended into all large tributaries of the Waipaoa. The present position of this headward advancing wave of incision is marked in many tributaries by a knickpoint, often in the form of a waterfall (Fig. 1). Field observation and historical aerial photo analysis offers clear evidence for headward migration of these knickpoints, at least over short distances (~1 km). This leads us to first test a simple model of knickpoint propagation that assumes knickpoint retreat rate is a power law function of drainage area. This simple model assumes that a knickpoint initiated at the basin outlet swept upstream and branched into tributaries, without substantially changing form or incision process. However, there is reason to expect more complex behavior. For instance, if mixed bedrock–alluvial channels are increasingly alluvial in character at large drainage areas as suggested by some models and data (see review by Whipple, 2004), one might anticipate diffusive attenuation of knickpoints in downstream channel segments, and an increasing tendency to form coherent, detachment-limited bedrock knickpoints as the wave of incision reaches upstream channel segments. Moreover, one might anticipate changes in the dominant processes of incision and knickpoint retreat as drainage area decreases upstream. Indeed, abrupt changes in drainage area, water discharge, and sediment flux at tributary junctions might trigger knickpoint initiation. This behavior has been suggested by theoretical river incision models that include a dual sediment flux dependence (Gasparini, 2003; Crosby, 2006, Ch 2; Gasparini et al., 2006), such as the saltation–abrasion model of Sklar and Dietrich (1998, 2001, 2004). In these models, the efficiency of bedrock incision increases with additional sediment flux up until the point that the increasing sediment no longer functions as tools to abrade the bed, but rather covers and armors the bed from further incision. In addition, there is some direct evidence (discussed below) against a simple basin-wide propagation of knickpoints in the Waipaoa. In order to test the possibility that knickpoints develop high in the network (at small drainage areas or at tributary junctions), we also evaluated a second, alternative model that simply predicts knickpoint formation at a threshold drainage area. We compare the results of these two, simple, end-member models against the present distribution of 236 knickpoints observed within the Waipaoa fluvial network.

2. Field area

2.1. Geologic setting

The 2150 km^2 Waipaoa drainage basin is etched into forearc sediments accreted along the east coast of New Zealand's North Island (Fig. 1). Along this subduction margin, the thinned, leading edge of the Australian plate obliquely overrides the west-dipping and overthickened portion of the Pacific Plate called the Hikurangi Plateau (Davy, 1992). As the two plates converge at a rate of ~45 mm/year (DeMets et al., 1994), seamounts entering the trench deform and destabilize the trench slope suggesting that the oceanic plate topography and thickness strongly influence the time evolution of wedge deformation (Lewis and Pettinga, 1993; Collot et al., 2001; Eberhart-Phillips and Chadwick, 2002). In the Waipaoa drainage basin, the exposed forearc is composed of latest Cretaceous to Pliocene shelf and slope sediments. These are dominated by clay-rich siltstone and mudstone units, interbedded with sandstone and limestone lenses (Black, 1980; Mazengarb and Speden, 2000). Due to different structural histories (sheared argillite to undeformed sandstone) and different chemical compositions (clay rich mudstones to calcite cemented sandstones) the bedrock of the Waipaoa drainage basin exhibits significant variability in strength.

Faulting and folding of the exposed forearc sediments is of late-Miocene to recent age (Mazengarb et al., 1991; Mazengarb and Speden, 2000). Active structures in the region have a dominantly normal sense, but low preservation potential for fault scarps in this rapidly eroding landscape suggests that available field observations likely sample only a small fraction of the recently active faults (Berryman et al., 2000). Rock uplift rates in the region are reported between 0.5 and 4 mm/yr using the near-shore record (Ota et al., 1992; Brown, 1995), river terrace sequences (Berryman et al., 2000) and summit accordance along the crest of the Raukumara Range (Yoshikawa, 1988). In the Waipaoa itself, analysis of strath river terrace sequences suggested that the rock uplift rate ranged between 0.5 and 1.1 mm/yr (Berryman et al., 2000). Located 100–200 km east and downwind of the central North Island volcanic centers (Fig. 1), the Waipaoa drainage basin has received frequent deposits of airfall tephra throughout the Quaternary (Eden et al., 2001). As will be discussed in the proceeding section, tephra deposits of known age are found on terraces or other stable landforms and provide valuable stratigraphic markers (Berryman et al., 2000).

2.2. Present landscape morphology

At present, the Waipaoa drainage basin is actively adjusting its form following a large magnitude pulse of incision initiated 18,000 years ago (Berryman et al., 2000; Eden et al., 2001; Berryman et al., in preparation). The prevalence of retreating knickpoints, incised gorges, unstable hillslopes and fill and strath terraces associated with this pulse of incision provides dramatic evidence for the dynamic response of this landscape (Fig. 3). Because the pulse of incision is so large (50 to 120 m), it is straightforward to distinguish the mobile boundary that separates portions of the landscape that are adjusting to the new base level from those that still retain their relict, pre-disturbance form. An initial investigation using ~1:25,000 stereo aerial photographs revealed that >50% of the areal extent of the Waipaoa drainage basin retains this relict topography (Fig. 1). This relict topography is found upstream of the knickpoints and on the hillslopes left hanging above the incised gorges downstream of the knickpoints (Fig. 3). Today, the headward retreat of knickpoints and failure of over-steepened hillslopes continues to adjust the relict surface to the lower base level. Downstream of the knickpoints, terrace remnants of the relict surface either trace continuously to or are graded to the relict surface upstream of the knickpoint (Fig. 2). If knickpoint retreat was the dominant mechanism for propagating base level fall, then most of the incision would occur abruptly as the knickpoints pass; there would be no record of progressive incision (Fig. 2). However, in some large Waipaoa tributaries ($\sim > 5 \times 10^7$ m^2), geomorphic features indicative of progressive fluvial incision exist between the 18 ka relict surface and the present river elevation. These features include flights of strath surfaces and abandoned meander cutoffs (Fig. 2), and have been documented in some detail in the Waihuka tributary. In other reaches of this tributary, there is no evidence preserved indicating progressive incision. In these locations, narrow, incised gorges that terminate at waterfalls suggest that as the knickpoint retreated, base level was lowered step-wise. This record leads us to suggest that a pulse of incision can assume multiple forms as it translates upstream and encounters variations in substrate erodability or decreases in sediment and water flux at locations such as tributary junctions (Fig. 2).

Preservation of the relict surface throughout the basin is sufficient enough to reconstruct the paleotopography prior to incision ~18 ka (Fig. 1). Though the Waipaoa drainage basin was never glaciated, the colder temperatures during the last glacial maximum had a profound effect on the local landscape; vegetation changed from forest to shrub, sediment production increased and precipitation decreased (Pillans et al., 1993; Newnham et al., 1999; Berryman et al., 2000). These conditions are suggested to have produced the thick strath terrace cover-beds and the subdued, sediment mantled topography that we see today in relict portions of the landscape (Fig. 3). Within this relict landscape there exists evidence for multiple older generations of transient adjustment such as terraces and knickpoints that predate the 18 ka surface (Berryman et al., 2000). This strongly indicates that in this drainage basin, fluctuations in climatic or tectonic conditions outpace the landscape's response time for readjusting to the new conditions (Whipple, 2001).

Berryman et al. (2000) suggest that incision was initiated by two consequences of the transition to postglacial climatic conditions ~18 ka. First, as climate became warmer and wetter, more substantial vegetation provided greater soil cohesion and reduced both sediment supplied from the hillslopes and physical weathering. Second, the warmer and wetter conditions increased stream discharge and raised the transport capacity and the erosive potential of the channels. We also note that at the time climate began to change, sea level was >100 m below its present elevation (Shackelton, 1987; Chappell, 2001) and thus a pulse of incision could have initiated as sea level dropped below the shelf-slope break. This could have generated an unstable step in the channel profile that would have propagated toward the headwaters.

On active fluvial surfaces, airfall tephra deposits are only preserved once river incision adjacent to that surface is significant enough to prevent overbank flows from reworking the tephra. The first tephra deposit preserved on the terraces created by the pulse of incision that we study in this work was the Rerewhakaaitu (Eden et al., 2001), which erupted from the Okataina Volcanic Center ∼17,700 years before present (Lowe et al., 1999). The previous tephra-producing event, (the Okareka tephra, ∼21,000 years before present), is not preserved on the relict fluvial surface, suggesting that the river was actively reworking the surface ∼21 ka.

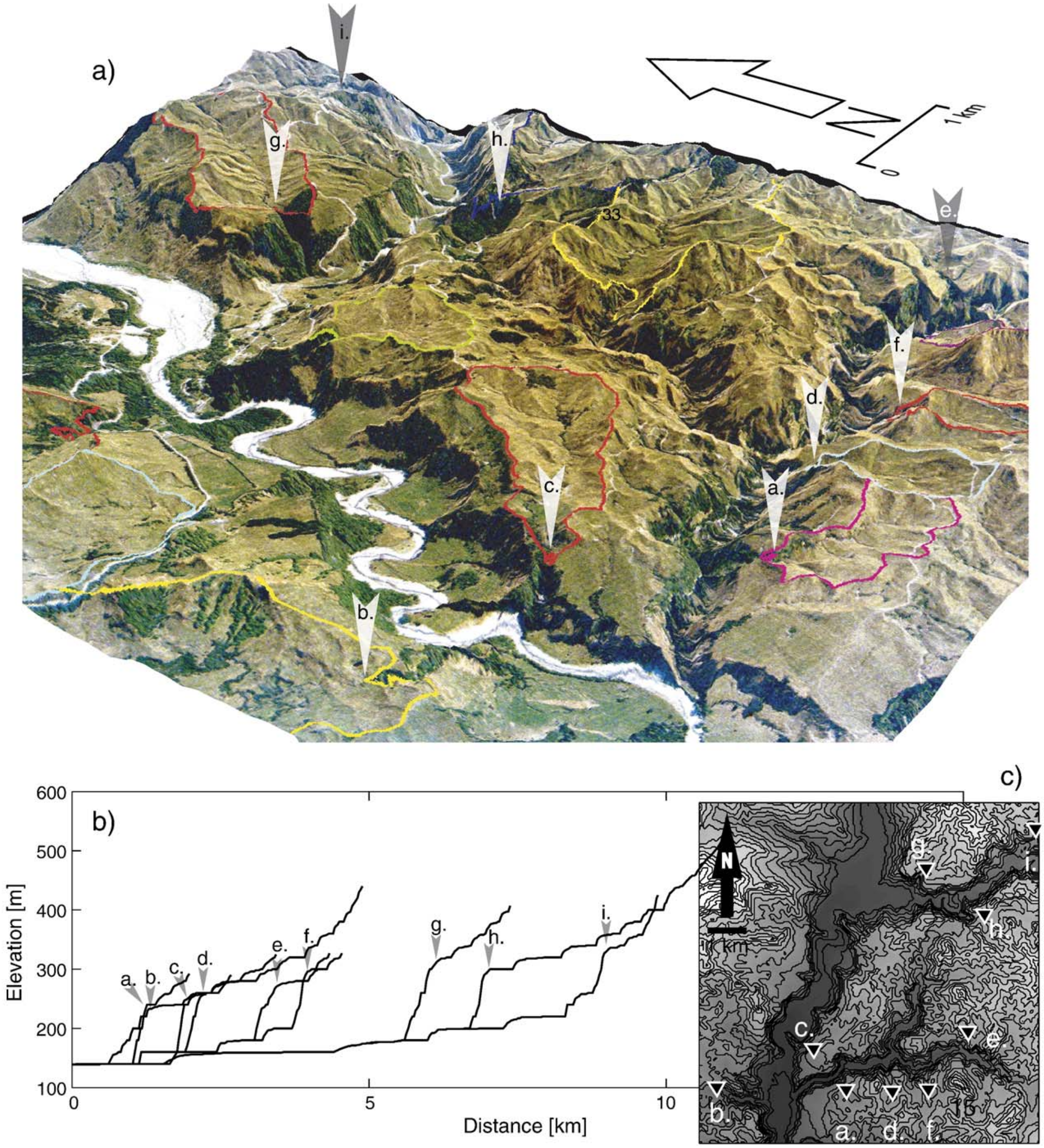


Fig. 3. The topography of the Waipaoa catchment is visualized in a color aerial photograph, (3a), draped over a 25 m digital elevation model (DEM) from the upper catchment (for location see Fig. 1). The mainstem Waipaoa flows downstream, left to right. Note that the two large tributaries entering from the east are adjusted to the elevation of the mainstem, while smaller tributaries are elevated above and separated from the mainstem by knickpoints (located by lettered arrows). The same knickpoints are shown, (3b), along their channel profiles as extracted from the 25 m DEM. Besides the large knickpoints, also note the 20 m convex step-like artifacts in the DEM. A contour map, (3c), of the same region locates the knickpoints in map view (contour interval: 10 m).

This brackets the initiation of incision between ~21 ka and ~18 ka.

2.3. Knickpoint morphology

Despite broad variations in lithology, structure, position within the basin, upstream drainage area and bed state, our observations (collected over five field seasons) indicate that knickpoint morphologies are strikingly similar throughout the Waipaoa drainage basin (Figs. 2 and 3b) (Crosby, 2006, Ch 2). Most trunk streams are low gradient (between 0.003 and 0.01) and alluviated at drainage areas greater than $\sim 5 \times 10^7$ m^2. Farther upstream, bare bedrock reaches become more common as channels' slopes increase to values between 0.02 and 0.1. These bedrock reaches are punctuated by discrete alluvial patches often associated with temporary storage of sediment shed from nearby over-steepened banks. In the first kilometer downstream of knickpoints, most of the elevation gain is achieved over 1–2 m bedrock steps. Less than 500 m downstream of knickpoints, coarse debris begins to litter the channel beds as mass failures become frequent in the narrow, steep-walled gorges (Fig. 3). The knickpoint faces are 15–50 m tall and are most often composed of one or two near-vertical drops. Though not undercut, the faces are so steep that at high flows, water may not make direct contact with the knickpoint face. There are no plunge pools or cap-rocks observed that would maintain the knickpoint lips. We hand-surveyed water surface elevation and noted bed elevation of ~27 channels (Crosby, 2006) and found that knickpoints in the Waipaoa lack drawdown reaches (Gardner, 1983), as introduced earlier. Upstream the knickpoint lip there is no enhanced erosion near the free overflow. Instead, upstream of the knickpoint, the channels are low gradient, sediment poor and have only incised through the alluvial fill of the relict surface and 1–2 m into the underlying bedrock (Fig. 2). Contrary to the expectation for a drawdown reach, this incised morphology is not localized to the region near the knickpoint lip but rather continues for more than a kilometer upstream of many knickpoints. This observation suggests that the initial stripping of sediment was localized within channels and did not extend across the broad valley floors or to the hillslopes. This has implications for the history of sediment delivery during the incisional event. At present, the channel beds above the knickpoints contain very little sediment and their slopes range between 0.008 and 0.02. The morphology of the knickpoint and the relict reach is relatively consistent throughout the basin and suggests that these channels are presently behaving in a systematic fashion following incision in the the trunk streams.

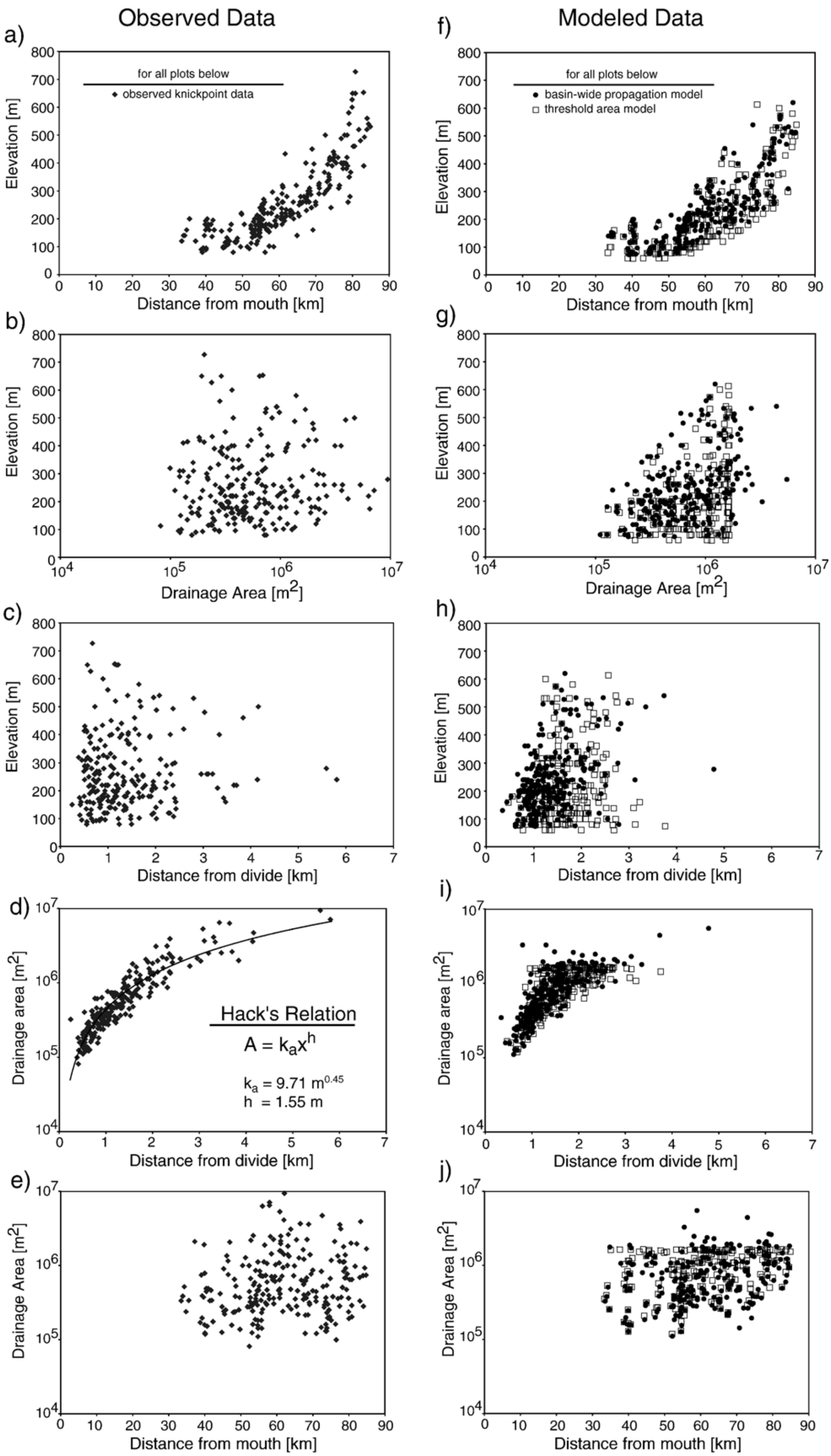
3. Observed knickpoint distribution

3.1. Methods

Multiple observational tools were used to identify and confirm the location and form of knickpoints within the Waipaoa drainage basin (Fig. 1). Though a 25 m digital elevation model (DEM) proved extremely valuable to other aspects of this project, the channel profiles extracted from this dataset could not be used reliably to identify knickpoint form or location because of the artificial 20 m steps inherited from the original contour data (Fig. 3b). Therefore, an accurate mapping of knickpoint location and form was accomplished using aerial photo analysis and field verification. We used color stereo aerial photography flown at a scale of ~1:25,000 between 1997 and 1999 by Air-Maps New Zealand. We analyzed only the northern 3/4 of the basin due to limitations in the aerial photo coverage available to us at the time of the study. This was not a concern because aggradation during sea level rise had buried most of the relict landscape in the southern 1/4 of the Waipaoa basin. Only knickpoints with discrete steps in channel elevation were selected for analysis as it was too difficult to identify the upstream extent of adjustment in diffuse knickpoints. Controls on the variability of knickpoint form and the distribution of these forms will be addressed in future work (Crosby, 2006).

Of the ~350 potential knickpoint locations identified using the aerial photos, ~55 were visited, characterized and located with GPS. This exercise confirmed the accuracy of our air photo technique for locating knickpoints and revealed the striking consistency in knickpoint form as discussed in the previous section. After observed knickpoint locations were transferred onto digitized 1:50,000 topographic maps and incorporated into a GIS database, their spatial distribution could be examined relative to topographic, lithologic and structural parameters. For every channel containing a knickpoint, we extracted its longitudinal channel profile from the 25 m DEM and measured for each pixel along the profile the along-stream distance from outlet, the along-stream distance from divide, the elevation, the upstream contributing area and the underlying lithology. For a subset of 161 channels we also measured the knickpoint's distance upstream from the closest significant tributary junction.

Approximately 350 potential knickpoints were then filtered to remove those whose form or location appeared to be a consequence of special circumstances. This was necessary in order to study how a single incisional event is distributed throughout the many


Observed Data
Modeled Data
a)
b)
c)
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e)
f)
g)
h)
i)
j)
for all plots below
observed knickpoint data
basin-wide propagation model
threshold area model
Elevation [m]
Distance from mouth [km]
Drainage Area [m2]
Distance from divide [km]
Drainage area [m2]
Hack's Relation
A = k_a x^h
k_a = 9.71 m^0.45
h = 1.55 m

channels of a fluvial network. First, we separated out the 33 knickpoints that predate the pulse of incision initiated 18,000 years ago and were found within the relict surface. Second, we separated out 76 knickpoints whose locations or morphologies were attributable to their proximity to a lithologic or structural contact. The third population removed from the dataset was 5 composite knickpoints that consisted of multiple, broadly spaced knickpoints. In this population, the farthest downstream knickpoint was often anchored by a resistant lithology, leaving the upper basin to adjust to a base level fall of lesser magnitude. The remaining 236 knickpoints that we examined were: (1) attributed only to the pulse of incision initiated ~18 ka, (2) not lithologically or structurally constrained and (3) composed of a single major knickpoint.

3.2. Results and discussion

The topographic and hydrologic characteristics of the 236 selected knickpoints were examined to determine if their distribution within the basin exhibited systematic behavior (Fig. 4a–e). Knickpoints in the Waipaoa drainage basin were predominantly located in the uppermost regions of the network and were thus found primarily in first or second order blue-line channels. For channels that are roughly 80 km long, the mean distance from the divide was 1369.09 m (Fig. 4c). Normalizing for the different channel lengths in the basin, we calculated that the population of 236 knickpoints was 97.79±1.33% (1σ) of the way from the present outlet to their headwaters. As a consequence of being so far up within the network, knickpoints are found within a narrow range of characteristically low drainage areas. 75% of the knickpoints (176 of the 236) were found to have upstream drainage areas between 1×10^5 m^2 and 1×10^6 m^2 (Fig. 4b). This observation that channel adjustment extends almost to their headwaters seems in conflict with our earlier observation that >50% of topography still retains its relict form (Fig. 1). This apparent conflict arises from the large percentage of the landscape that is composed of unadjusted hillslopes above gorges and in low-order tributary basins. Many channels in the Waipaoa have incised deep, narrow gorges, leaving most of the hillslopes hanging, still graded to the elevation of the 18,000 year old terrace surface (Fig. 3a).

Knickpoint elevations are distributed between 100 and 750 m above sea level (asl) with ~55% of the knickpoints found at elevations between 150 and 300 m asl (Fig. 4a). Theoretical studies of detachment limited channels responding to an increase in uplift rate predict that knickpoints communicating this adjustment should remain at like elevations throughout their passage through the basin (Whipple and Tucker, 1999; Niemann et al., 2001). Instead, in the Waipaoa river we find that the elevations of the knickpoints appear to be a function of where low drainage area reaches are encountered along the individual stream profiles (Fig. 4b).

The upstream drainage area, distance from divide, distance from outlet and elevation of each knickpoint were compared to evaluate whether some systematic relation exists between these parameters (Fig. 4a–e). The correlation between distance from the mouth and elevation only demonstrates where the knickpoints are located on the longitudinal profiles of the channels (Fig. 4a). The correlation between knickpoint drainage area and distance from divide (Fig. 4d) is a consequence of Hack's relation (Hack, 1957) which states that the distance from the divide is a power law function of drainage area. All other comparisons between the measured knickpoint parameters showed no statistically significant correlation (Fig. 4b,c,e).

Though we filtered the knickpoints to remove those retained on lithologic contacts, we wanted to determine whether particular lithologies favored the formation or preservation of knickpoints. To do this, we compared knickpoint location with the mapped geologic units in the basin (Mazengarb and Speden, 2000). First, we measured how often a knickpoint occurs within a particular lithology (ex. 23% of the knickpoints are in the early-Miocene, Tolaga group mudstones, (eMt)). Second, we measured how often a particular lithology occurs within the study area (ex. 22% of the study area is underlain by the eMt). These measurements were used to normalize the frequency of knickpoint occurrence in a particular lithology relative to the areal distribution of that lithology. Some erosion-resistant geologic units were moderately 'over-populated,' having a disproportionately large number of knickpoints relative to their areal extent. Conversely, erosion-prone lithologies (as evidenced by lower slopes, less relict surface preservation and greater structural deformation) were found to be 'under-populated.' This demonstrates that lithology

Fig. 4. Plots comparing channel parameters (elevation, distance from outlet, distance from divide and drainage area) at observed (4a–e) and modeled (4f–j) knickpoints. The presence or lack of a correlation between the parameters is discussed in the text. Note that the both the basin-wide retreat and the threshold area models give similar results and match the observed knickpoint parameters well. In both observed and modeled environments, the lack of correlation between the parameters (except for in the long profile (4a,f) and in Hack's relation (4d,i)), demonstrates how each channel's unique course across the landscape influences knickpoint position.

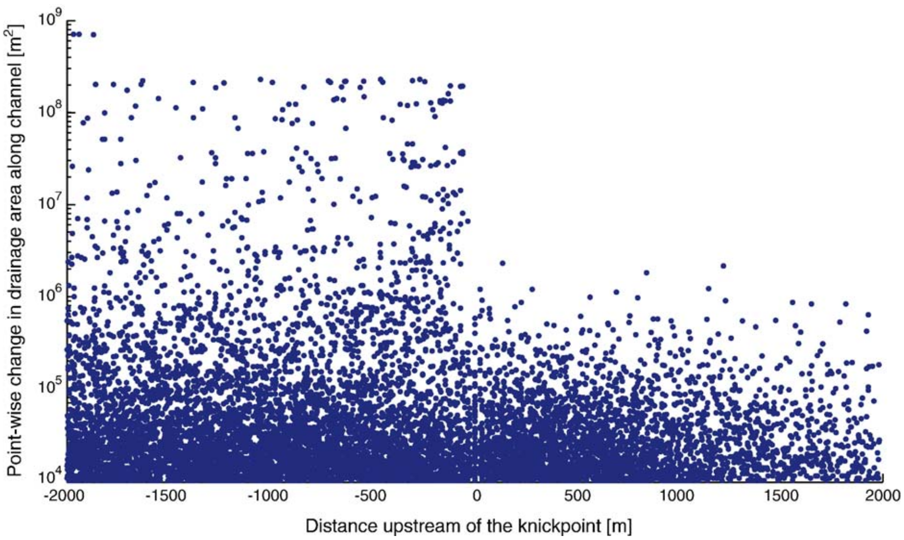


Fig. 5. For each of the 236 knickpoint-containing channels, we examined the point-wise change in drainage area 2 km downstream and upstream of the knickpoint. Each point above the *x*-axis notes the location of a step-wise increase in drainage area at a tributary junction. The larger the point-wise change in drainage area, the larger the tributary. The most striking aspect of the plot is the abrupt decrease at the knickpoint of the magnitude of the maximum drainage area changes. Upstream of the knickpoint, the maximum drainage area changes decrease by 2 orders of magnitude. Also note the moderately dense cluster of large magnitude drainage area changes 0–500 m downstream of the knickpoints.

influences but does not determine the distribution and preservation of knickpoints in the Waipaoa.

A large subset ($n=161$) of the 236 knickpoints were further examined to determine if their position in the network was related to their proximity to tributary junctions. We found that ~78% of the knickpoints examined were less than 1 km upstream of large tributary junctions. At these large tributary junctions, drainage areas dropped on average from $\sim 5\times10^7$ m^2 in the trunks to $\sim 1.5\times10^6$ m^2 in the tributaries. This drop was most evident when we plotted the point-wise change in drainage area for each of the 236 knickpoint-containing channels against the distance upstream of the knickpoint (Fig. 5). Looking at the data for reaches 2 km downstream of knickpoints, there are often large changes in drainage area, but in the upstream direction, changes in drainage area are significantly smaller. We then compared the drainage area at the knickpoint to its distance upstream from the tributary junction but found no statistically significant correlation. However, a good correlation was observed between the tributary's drainage area at the junction and the distance the knickpoint had traveled upstream of that junction (Fig. 6). Though this is consistent with the expectation that knickpoints in larger tributaries would have retreated greater distances upstream, such a correlation is also expected if knickpoints simply form at some small threshold drainage area, as a consequence of Hack's law (dashed line on Fig. 6). We will explore this point at greater depth in Section 5.2. In order to explore controls on knickpoint position and gain insight into the processes responsible for their retreat or initiation, we evaluate two simple end-member models

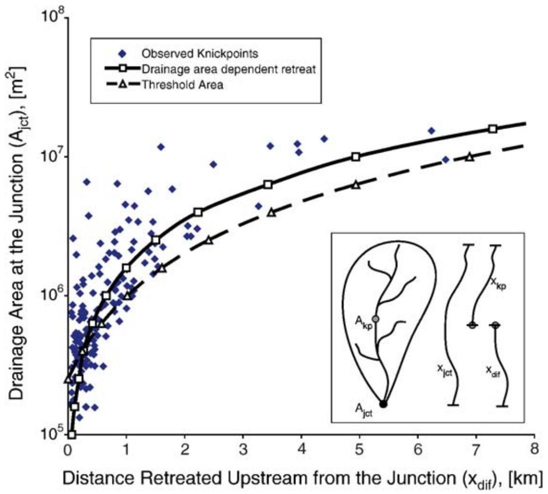


Fig. 6. We observe that knickpoints have retreated farther upstream in tributaries with large drainage areas. As explained further in Section 5.2, this observation could result from two different behaviors. The data suggest that knickpoints could retreat at a rate that is a function of drainage area (solid line with squares) but a similar relation could result from knickpoints forming at a threshold drainage area in basins with a Hack's relation-type geometry (dashed line with triangles). This observation limits our ability to say whether or not knickpoint retreat rate is function of drainage area. The inset figure defines variables used in the discussion section.

motivated by the above discussion of the characteristics and spatial distribution of the observed knickpoints.

4. Modeled knickpoint distributions

Consistencies in the location and form of knickpoints in the Waipaoa drainage basin suggest that their present distribution may reflect some systematic behavior. There is evidence for rapid incision and adjustment to a lower base level throughout larger drainage area portions of the network (Fig. 1), but at present, most knickpoints are found at relatively small drainage areas (Fig. 4b) and provide some evidence for area-dependent migration (Fig. 6). In accordance with these observations, we developed and tested two plausible, end-member models of knickpoint behavior. In the first, we use a forward model to predict how knickpoint positions evolve through time. In this model, a knickpoint initiated at the basin outlet retreats upstream and distributes itself throughout the channel network at a rate that is a function of the local upstream drainage area. In the second model, we do not model knickpoint migration, but instead examine if knickpoints initiate at some threshold drainage area. The second model does not evolve through time or provide information about the rate of response to the perturbation. It instead tests for some stable equilibrium condition where knickpoints would form at low drainage areas and then retreat by a different set of processes that may be independent of drainage area (Weissel and Seidl, 1997; Weissel and Seidl, 1998).

The models treat upstream drainage area as a proxy for both sediment and water discharge, each of which strongly influences the channel's erosional efficiency (Sklar and Dietrich, 1998, 2004). Because both models use drainage area to determine knickpoint positions, their predicted distribution depends strongly on the irregular, step-wise manner that drainage area decreases in the upstream direction in each individual channel. The pattern and frequency with which these abrupt changes in drainage area (Fig. 5) at tributary junctions are encountered ultimately depends on the network geometry and ridge spacing of the basin. For each model, we will discuss the basis for their formulation, explain the mechanics of the model and discuss model results.

4.1. Basin-wide knickpoint propagation

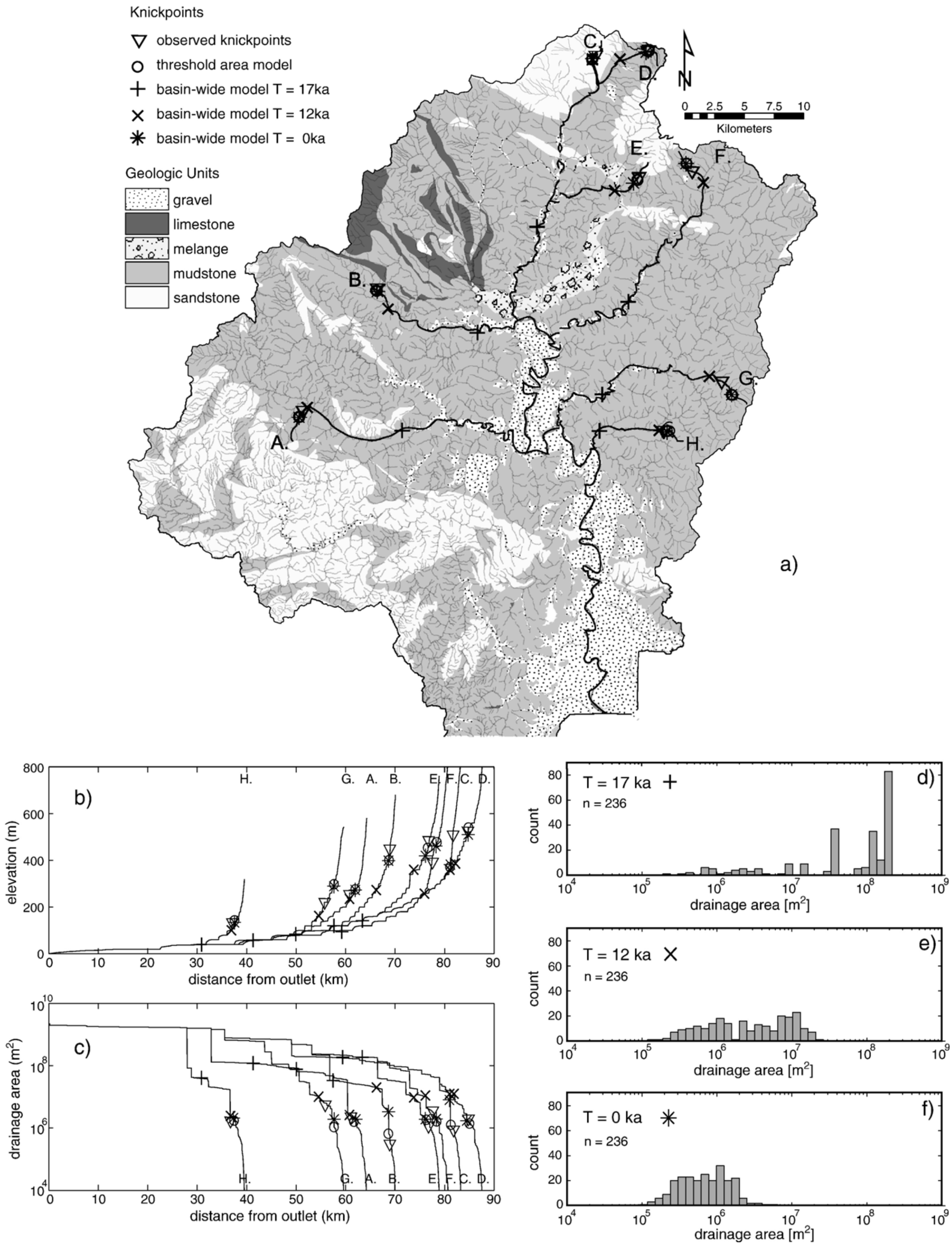
4.1.1. Model concept and mechanics

Since the late-nineteenth century, the upstream retreat of knickpoints has remained a popular mechanism for fluvial readjustment following base level fall. Though others have examined the conditions under which knickpoints are initiated and retreat, few have examined how this adjustment distributes through a fluvial network. Understanding how a pulse of incision is distributed within a fluvial network may prepare us to better approximate basin response times and sediment flux histories following base level fall. Our first model proposes that following the initiation of an incisional pulse at a downstream location, knickpoints propagate upstream throughout a fluvial network at a rate that is a power law function of the upstream drainage area. Modeled knickpoints thus migrate quickly along the large drainage area trunk streams and slow significantly upon entering tributaries of lesser drainage area.

The relationship we chose between retreat rate and drainage area bears a similar form to knickpoint celerity (Rosenbloom and Anderson, 1994; Weissel and Seidl, 1998; Whipple and Tucker, 1999). As discussed earlier, knickpoint celerity treats the rate of knickpoint propagation as analogous to speed of a kinematic wave (Whitham, 1974) and is derived from the well-known detachment-limited stream power incision model (Howard and Kerby, 1983). In the celerity derivation, the stream power incision model is combined with a statement of mass balance and rearranged to resemble the wave equation. In this form, the change in elevation with time (incision rate) is directly proportional to the change in elevation with distance (slope). The terms in the proportionality "constant" vary along the channel and define the wave speed. These terms include bed erodability, drainage area raised to an exponent and slope raised to another exponent.

Our approach recognizes the utility of this formulation, but also recognizes that the assumptions inherent in the formulation of the stream power model are violated at very steep reaches and at waterfalls in particular. The stream power model explicitly assumes that fluid flow is uniform (spatially invariant), steady (time invariant) and over a low slope. The slope must be low enough that the shear stresses of the fluid and sediment acting on the bed can drive incision, and in the case of knickpoints, drive retreat. For knickpoints at both large and small drainage areas, we found that waterfall faces were too steep to interact much with the falling water and sediment. Moreover, the assumption of uniform flow is violated as the fluid accelerates as it approaches and flows over the knickpoint lip. Because of these concerns, we do not associate our preliminary model with the stream power model and instead simply posit that the rate of knickpoint propagation is a power law function of drainage area:

$$\text{velocity} = \frac{\mathrm{d}x}{\mathrm{d}t} = CA^p \tag{1}$$


Knickpoints
observed knickpoints
threshold area model
basin-wide model T = 17ka
basin-wide model T = 12ka
basin-wide model T = 0ka
Geologic Units
gravel
limestone
melange
mudstone
sandstone
0 2.5 5 7.5 10
Kilometers
N
A.
B.
C.
D.
E.
F.
G.
H.
a)
b)
H. G. A. B. E. F. C. D.
elevation (m)
distance from outlet (km)
c)
drainage area (m^2)
distance from outlet (km)
d)
T = 17 ka
n = 236
count
drainage area [m^2]
e)
T = 12 ka
n = 236
count
drainage area [m^2]
f)
T = 0 ka
n = 236
count
drainage area [m^2]

where dx/dt is the upstream knickpoint velocity, C is an unknown constant dimensional coefficient representing the efficiency of retreat [meters^{1-2p}/years], A is the upstream drainage area [m^2], and p is an unknown constant describing the power law dependence on drainage area [non-dimensional]. Though we acknowledge that the efficiency of retreat may vary throughout the basin as a function of local lithology or climate, we assume in this simple model that these factors are not dominating the basin wide behavior and thus treat C as a constant (see Section 5.1 for a discussion of possible influences of lithologic heterogeneity). Some factors that ought to affect the rate of retreat, such as water discharge, sediment supply and sediment character, are known to vary throughout the basin as a function of drainage area. In restricting our analysis to a constant value of the exponent, p, we are effectively assuming that these factors vary with drainage area in a consistent way within the basin. The data do not justify a more complex analysis in this regard. We also examined a variation on this formulation that includes a critical drainage area (A_{crit}) below which the knickpoint cannot propagate. This variation addresses some of the observations made earlier regarding the potential formation of knickpoints at tributary junctions and the upstream decrease in sediment flux. Requiring that A must be greater than A_{crit}, this variation takes the form:

$$\text{velocity} = \frac{\mathrm{d}x}{\mathrm{d}t} = C(A - A_{\mathrm{crit}})^p \tag{2}$$

These two models for area-dependent knickpoint retreat were then tested in the Waipaoa drainage basin. We used the 25 m DEM to extract the 236 knickpoint-containing longitudinal profiles. Each channel profile starts at the basin outlet at the Pacific Ocean, extends upstream and past the knickpoint and stops at the drainage divide (Fig. 7a,b). For each pixel along each longitudinal profile, the upstream drainage area was calculated so that changes in drainage area were known along the entire path from the outlet to the divide (Fig. 7c). Using these data, modeled knickpoints initiated at the basin outlet traveled together up the mainstem, progressively slowing and branching off into smaller and smaller sub-basins, finally entering the unique portion of their path that contains the observed knickpoint (Fig. 7). This model thus mimics the way a single pulse of incision propagates up a trunk stream, and progressively distributes itself into lesser and lesser tributaries.

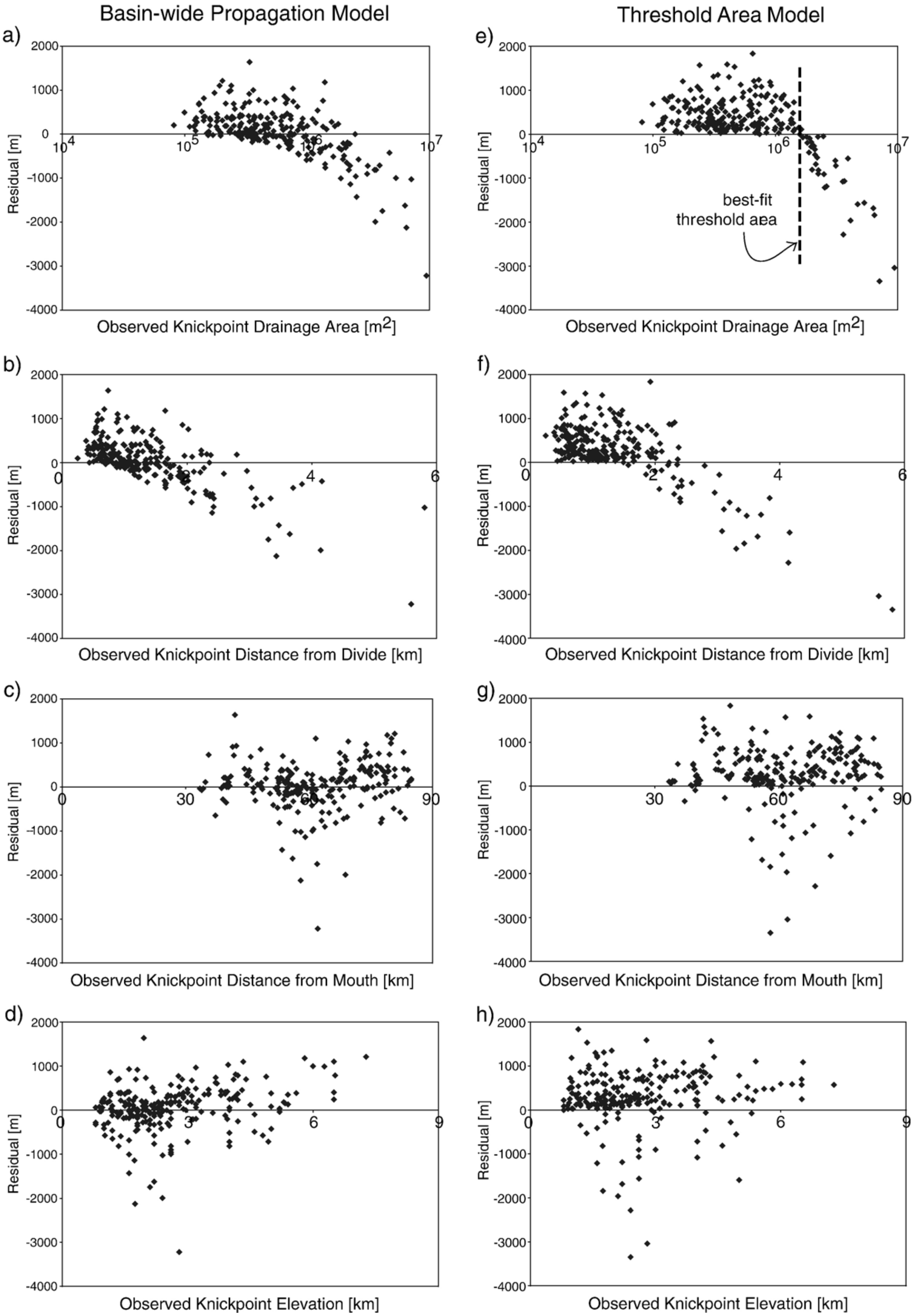
Each model run starts with particular values for C and p and then calculates the time required to translate across each pixel along the channel's path,

$$\mathrm{d}t = \mathrm{d}x(CA^p)^{-1} \tag{3}$$

where dt is the time necessary to translate across each pixel and dx is the diagonal or straight line distance across the pixel. These pixel travel times are then cumulatively summed from the outlet upstream. The predicted position of the knickpoint is where the cumulative travel-time equals or first exceeds 18,000 years. We calculated the misfit for each model by comparing the predicted and the observed knickpoints' along-stream distances from the divide. Because we have two unknowns and only one equation, an infinite number of pairs of C and p values provide a perfect fit for any individual channel. To find a single pair of C and p values that minimize the sum of the squares of these misfits for all 236 channels, we perform a brute-force search of C and p parameter space in each channel. The final C and p combination that results in the lowest sum of squares of the misfits in all the channels is the regional best fit (method similar to Stock and Montgomery, 1999).

We could have chosen to define the misfit by comparing the modeled and the observed knickpoint's drainage area or elevation but we found that when compared to the 'distance from divide' result, these best-fit model parameters were indistinguishable within uncertainty. In addition, the measurement of misfit using elevation is complicated by artificial 20 m steps observed within the DEM-derived stream profiles and the discreet jumps in elevation at waterfalls (Figs. 3b and 7b). Therefore, we present only the more intuitive stream-wise, linear measure of the misfit. The magnitude and structure of residuals to the best-fit models are then used to evaluate the relative successes and failures of the model (Fig. 8a–d). By definition, a positive residual indicates that the modeled knickpoint is downstream of the observed knickpoint.

Fig. 7. Comparison between 8 selected knickpoint positions according to field observation, the basin-wide propagation model and the threshold area model. Plots compare knickpoint locations relative to basin geology (7a), channel profiles (7b) and drainage area structure (7c). Histograms also show the distribution of drainage areas of the 236 modeled knickpoints at three time steps during the 18,000 year long basin-wide propagation model run (7d–f). Note that some knickpoints in the basin-wide propagation model have already traveled from the outlet and into sub-tributaries within 1000 years. Also note that in the last 12,000 years of the model run, the knickpoints travel only a very short distance as decreasing drainage area dramatically decreases knickpoint velocities. In many of the channels, the final modeled positions (stars and circles) do a good job of matching the observed knickpoint positions (triangles).


Basin-wide Propagation Model
Threshold Area Model
a)
e)
b)
f)
c)
g)
d)
h)
Residual [m]
Observed Knickpoint Drainage Area [m^2]
best-fit
threshold aea
Observed Knickpoint Distance from Divide [km]
Observed Knickpoint Distance from Mouth [km]
Observed Knickpoint Elevation [km]

4.1.2. Basin-wide model result

The C and p combination that minimized the misfit between the observed and predicted knickpoint positions in the Waipaoa drainage basin was 7.9×10^{-9} $(\mathrm{m}^{1.25}\ \mathrm{yr})^{-1}$ and 1.125 respectively. The difference between this power law dependence and a linear dependence on area is not statistically significant or within the error of the analysis. Using these values of C and p, the mean residual was $\sim 40 \pm 560$ m (1σ) downstream of the observed knickpoint (Fig. 8a–d). In the case where a critical area was included in the model (Eq. (2)), there was no improvement in the fit; i.e. the lowest residuals were for a critical area of zero with the same best-fit C and p values as the standard model (Eq. (1)). The basin-wide model residuals were uncorrelated at smaller drainage areas, but for knickpoints with upstream drainage areas greater than 1×10^6 m^2, the residuals were well correlated with area (Fig. 8a). Because drainage area and the distance from the divide can be related through Hack's relation, this same correlation exists between the distance from the divide and the residual (Fig. 8b). No correlations were observed between the residuals and the knickpoint elevations or the distances from the mouth (Fig. 8c–d). For all measured parameters, the residuals were well distributed around zero.

4.1.3. Basin-wide model discussion

The basin-wide propagation model provides valuable insight into how a drainage area dependent signal distributes itself within a fluvial network. The model makes its greatest contribution by demonstrating how each channel's unique, step-wise drainage area structure (Fig. 7c) ultimately sets the knickpoint distribution. Given the complexity of drainage networks, it is not surprising that no simple correlations (besides the long profile form (Fig. 4f) and Hack's law (Fig. 4i)) exist among drainage area, distance from divide, distance from outlet or elevation (Fig. 4g,h,j).

In order to evaluate how the modeled knickpoint positions varied through time, we tracked the distribution of knickpoint drainage areas at 1000 year time steps using the best-fit parameters of the basin-wide propagation model. We found that just after model initiation (17 ka), knickpoints demonstrate a narrow distribution strongly weighted toward high drainage areas (Fig. 7d). As the signal propagates upstream (12 ka), the distribution of drainage areas broadens (Fig. 7e). This broadening of the distribution is attributed knickpoints leaving the mainstem and branching into tributaries of varying drainage area. As the model reached the present time (0 ka), we found that the knickpoints in small, low drainage area tributaries near the outlet had retreated very little during the lifetime of the model. In the upper basin, the knickpoints that had once traveled so quickly in the mainstem have since slowed upon reaching drainage areas similar to the knickpoints near the outlet. As knickpoints throughout the basin all slow in low drainage area regions, the distribution of knickpoint drainage areas begins to narrow (Fig. 7f). If the basin-wide model was allowed to run beyond the present, we found that the distribution narrowed even further. We also used the model to track knickpoint velocities through time. One startling result is that in channels with drainage areas $> 1 \times 10^9$ m^2 (the first 35 km of the mainstem), knickpoints were found to travel at rates greater than 100 m/yr. By the time they reach their present positions, the mean modeled velocity has dropped to ~ 4 cm/yr. Though the modeled retreat rate at present is reasonable given the observed frequency with which knickpoint faces collapse, the retreat rates at large drainage areas may be unrealistically fast.

Though the sequential terrace elevations observed between the 18,000 year old terrace and the active channel argue against the likelihood of a single, headward-propagating knickpoint lowering base level 50 to 100 m, we suggest two alternative scenarios to explain this circumstance. First, multiple mid-size knickpoints could have progressively swept through the system, generating sequential terrace elevations but culminating into a single step at tributary junctions where a large decrease in drainage area limits their retreat. Alternatively, if along-stream variations in substrate erodability can temporarily slow the pulse of incision, an episodic base level fall signal could culminate into a single step in harder lithologies. As this harder substrate reach is passed, the large, single-step knickpoint may become unstable and degrade progressively into multiple pulses of lowering, thus generating flights of terraces upstream of the resistant unit. Under these conditions, some reaches of the channel may experience knickpoint retreat, incising in a step-like manner and producing no intermediate terraces, while in others the base level lowering would be more gradual, producing sequential terraces (Fig. 2). In the second scenario, even if the knickpoint forms and degrades, the mean retreat rate of the pulse of incision may also still depend on upstream drainage area. Though we

Fig. 8. Residuals for the best-fit basin-wide propagation model (8a–d) and best-fit threshold area model (8e–h). By definition, a positive residual indicates that the modeled knickpoint is downstream of the observed knickpoint. For drainage areas $> 1 \times 10^6$ m^2, model residuals are strongly correlated with drainage areas of observed knickpoints. Because of the Hack relation, the same relationship is evident in comparisons between residuals and observed knickpoint distance from divide. Otherwise, residuals are uncorrelated and quite similar for the two models.

acknowledge that terrace preservation plays a large role in how we interpret the incision history, we presently favor the second model because the evidence for progressive incision is only observed within short, local reaches. In this model, the success with which the prediction matches the observed knickpoint distribution may be attributed to the tendency for most erosional responses, whether transport or detachment limited, to migrate upstream as some function of drainage area (Whipple and Tucker, 2002). Another positive attribute of this model is that the propagation of base level fall continues slowly into the upper-most reaches of the basin and could eventually reach drainage divides.

4.2. Knickpoint initiation at a threshold drainage area

4.2.1. Model concept and mechanics

Although the basin-wide knickpoint retreat model matches the Waipaoa knickpoint locations relatively well, there are reasons to believe, as briefly discussed above, that the present knickpoint distribution is not the end-result of a basin-wide process of knickpoint retreat. Instead the present distribution may be simply a consequence of a threshold in the channel's capacity to communicate large magnitude incision signals. As discussed earlier, previous workers only observe retreat without modification for knickpoints that have plunge pools, strong seepage erosion or horizontally stratified substrates with a resistant cap-rock. In the Waipaoa these conditions generally are not met. More importantly, as previously discussed, some trunk streams in the Waipaoa contain flights of terraces that suggest that the channel's elevation lowered progressively, not step-wise as would occur during the passage of a single knickpoint. These concerns lead us to develop an alternative model for the present distribution of knickpoints in the Waipaoa. This model does not address how the pulse of incision may have translated upstream, but rather suggests that stable knickpoints are only generated once the processes responsible for their retreat are no longer dominantly fluvial. First we will discuss the reasoning for why knickpoints might be initiated at a threshold drainage area and then we will discuss which processes might be responsible for the subsequent evolution of the knickpoint.

Some models for bedrock channel incision suggest that sediment flux plays a fundamental role in setting the rate and style of channel response to a pulse of incision (Sklar and Dietrich, 1998, 2001; Whipple and Tucker, 2002; Sklar and Dietrich, 2004). These models predict that as the base level fall signal reaches farther into the basin, the upstream drainage area can drop below a threshold where sediment discharge is not sufficient to continue rapid incision (Gasparini, 2003; Gasparini et al., 2006). Whether base level fall is progressive or step-wise, erosion continues downstream of the threshold drainage area as sediment shed from the over-steepened banks provides the tools necessary to erode the channel downstream of the knickpoint. Upstream of the threshold drainage area, low water and sediment flux suppress fluvial incision and knickpoint retreat becomes a function of other, non-fluvial processes.

Following Weissel and Seidl (1997), we hypothesize that once the knickpoint reaches the threshold drainage area, the primary mechanisms responsible for knick-point retreat switch from dominantly fluvial processes to processes such as rock-mass failure and weathering. Our field observations suggest that the retreat rates of many of the 236 knickpoints are determined by the frequency of large block failures on the steep faces of the knick-points. Because much of the substrate in the basin is clay-rich, these failures are most active on the knick-point faces where the seasonally wetting and drying rocks experience significant shrinking and swelling. This accelerated physical weathering prepares the planes of weakness along which most failures occur. As the knickpoints slowly retreat upstream from the critical drainage area, they continue to define the boundary between the adjusting and relict portions of the basin. This theory of a threshold drainage area is also consistent with our earlier observation that many knickpoints are found at drainage areas between 1×10^5 m^2–1×10^6 m^2 (Fig. 4b) and just upstream of tributary junctions where the channel experiences a large rapid change in drainage area (Fig. 6).

We tested the behavior of the threshold drainage area model in the Waipaoa drainage basin and compared the model's predicted distribution with the observed knickpoint distribution (Fig. 8e–h) and with the predictions of the basin-wide retreat model (Fig. 4f–j). Like the basin-wide knickpoint propagation model discussed above, this model also used the 236 unique knickpoint-containing longitudinal profiles that run from outlet to divide. Because the upstream drainage area is known at every pixel along each channel profile, we could rapidly locate the point along each channel where the drainage area first decreases below the threshold drainage area (circles in Fig. 7a–c). Due to the efficiency of the model, we were able to test over 300 different threshold drainage areas between 1×10^4 m^2 and 1×10^8 m^2. For each model run we calculated the misfit in each channel by comparing the predicted and the observed knickpoints' distances from the divide. The best-fit threshold drainage area provided the lowest sum of squares of these misfits.

4.2.2. Threshold area model result

Though a threshold drainage area of 1.65×10^6 m^2 minimizes the sum of the squares of the 236 residuals (Fig. 8e), values between 1.1×10^6 m^2 and 2.0×10^6 m^2 all provided low residuals that were not statistically separable. For the best-fit threshold area, the mean modeled knickpoint position was $\sim 270 \pm 670$ m (1σ) downstream of present day observed knickpoint position (Fig. 8e–h). When minimizing the sum of squares for the residuals, the result was strongly influenced by a small population of large drainage area knickpoints. The threshold area model residuals were uncorrelated at smaller drainage areas, but knickpoints that occur at relatively large drainage areas ($>1 \times 10^6$ m^2) demonstrate a strong correlation between the residuals and drainage area (Fig. 8e). Because drainage area and the distance from the divide can be related through Hack's law, this same correlation exists between the distance from the divide and the residual (Fig. 8f). There is no correlation, however, between the residual and the distance from the mouth or the knickpoint elevation (Fig. 8g,h). For all measured parameters, the residuals were not well distributed around zero, but were skewed downstream; the best-fit threshold drainage area (1.65×10^6 m^2) is larger than the mean drainage area at the observed knickpoints ($\sim 9 \times 10^5$ m^2).

4.2.3. Threshold area model discussion

Though the model locates knickpoints where the drainage area first falls below the threshold area, the model predicted knickpoints positions over a broad range of sub-threshold drainage areas ranging between $\sim 1 \times 10^5$ m^2 and 1.65×10^6 m^2 (Fig. 4g,i,j). We found that this broad range of predicted drainage areas was due to the model locating knickpoints just upstream of tributary junctions. At junctions, the drainage area decreases sharply to sub-threshold values which vary with tributary size (Fig. 7c). This modeled behavior is consistent with the fact that the observed knickpoints are also distributed over a similar range of drainage areas and that they are also located close to tributary junctions. This result suggests that if knickpoints do form at threshold drainage areas, then the dimensions of landscape parameters such as network density or ridge spacing (which determine the drainage area of the first order tributary basins) may play an important role in determining where threshold knickpoints are initiated.

It is interesting that for bedrock channels around the world, the transition between fluvial to arguably debris-flow dominated erosion processes occurs at drainage areas similar to our best-fit threshold area, $\sim 1 \times 10^6$ m^2 (Montgomery and Foufoula-Georgiou, 1993; Snyder et al., 2000; Stock and Dietrich, 2003; Whipple, 2004; Wobus et al., 2006). In the Waipaoa, the reaches upstream of knickpoints are at low gradients (<0.020), receive a very small amount of coarse sediment from hillslopes and debris flows are not observed to be an important process. This suggests that though the drainage areas are similar, debris-flow dominated erosion is not likely determining knickpoint position or form. Also, knickpoints in the Waipaoa are not located at positions along the channel where the slope increases rapidly (Figs. 2 and 3b), as was suggested by Seidl and Dietrich (1992) and Schumm and Hadley (1957). However, the transition to debris-flow dominated conditions in other landscapes and the apparent stability of knickpoints in the Waipaoa both speak to a marked decrease in the efficiency of fluvial erosion processes at drainage areas less than $\sim 1 \times 10^6$ m^2.

One important and unique attribute of this model is that it does not require a rapid change in base level to create a knickpoint. Though steady channel incision can create knickpoints at threshold areas just as readily as a rapid pulse of incision, it is important to note that the theoretical models find that the rate of base level fall dictates the magnitude of the threshold drainage area (Gasparini, 2003; Gasparini et al., 2006). The quality of the model fit is not likely influenced by knickpoint retreat beyond the threshold area since, for the subset of tributary junctions studied, 78% are less than 1 km upstream of the large tributary junction where they may have initiated. It would be valuable for future models to allow the threshold area to vary as some function of substrate properties, water discharge or sediment flux and character. In addition, models for non-fluvial retreat processes are necessary to propagate the knickpoint upstream once the threshold area is reached.

5. Discussion

5.1. Lithologic influence on knickpoint formation and retreat

Although it seems intuitive to expect that the variability of the substrate strength in the Waipaoa should play a role in setting knickpoint location and retreat rate, we observed no relation between the residuals to either best-fit model and any particular lithology. However, this is largely a consequence of the fact that we filtered out knickpoints that are directly influenced by local lithologic contacts or conditions. The subset of knickpoints we fit our models to are found in relatively comparable substrates (Fig. 7a) and thus exhibit a similar form. If the models were run for all the channels in the Waipaoa, not just the 236 with well-defined knickpoints associated with the 18,000 year old incision event, the quality of the fit would decrease dramatically and a strong lithologic influence would become apparent. In soft or strongly deformed substrates we observed very few knickpoints, but in harder, more coherent units, most tributaries with sub-threshold drainage areas contained knickpoints. We surmise that knickpoints in the softer units either degraded in a diffusive manner as seen in Gardner's (1983) experiments, or never formed in the first place.

5.2. Comparison between models: knickpoint propagation vs. threshold area

For end-member models whose underlying mechanics are fundamentally different, both predict a surprisingly similar knickpoint distribution and match the observed knickpoint distribution quite well (Figs. 4 and 7). Both models do a good job of fitting observed knickpoints at small drainage areas near tributary junctions, but both models have a poor fit to the large drainage area knickpoints (Fig. 8a,e). These similarities in model performance are likely a consequence of the mature stage of the fluvial component of the transient response in the Waipaoa. Because of this maturity, most knickpoints are at similar, small drainage areas. In the basin-wide propagation model, it may be the re-narrowing of the knickpoint drainage area distribution (Fig. 7f) that gives the model such striking similarity to the observed and threshold model distribution of knickpoints. Unfortunately, while the fluvial adjustment is so nearly complete, it is not possible to unequivocally differentiate between the basin-wide and the threshold models. To successfully compare the performance of the models, observations of the transient response need to be made at some earlier time when the relative differences in the performance of the two models would be more apparent.

A striking example of this inherent difficulty in tests of knickpoint formation and propagation models is found in our data for the distance between major tributary junctions and knickpoints (x_{dif}) as a function of drainage area at the tributary junction (A_{jct}). As shown in Fig. 6, there is a strong correlation between these variables. This correlation is of course expected for the scenario in which knickpoint retreat is driven by fluvial processes, as such processes are drainage-area dependent. This is illustrated on Fig. 6 by plotting a solid line of knickpoint positions predicted by the basin-wide propagation model (using our best-fit model parameters [$C=7.9\times10^{-9}$ $(\mathrm{m}^{1.25}\ \mathrm{yr})^{-1}$, $p=1.125$]) in different sized tributary drainage basins. This calculation assumes (1) knickpoints initiate simultaneously at tributary junctions, and (2) each drainage basin is characterized by the same Hack's relation parameters [typical values for the Waipaoa; $k_{\mathrm{a}}=9.71$, $h=1.55$ (Fig. 4d)]. It is tempting to take this as strong confirmation of knickpoint retreat as a function of drainage area (at least upstream of tributary junctions where a knickpoint may actually initiate). However, a simple analysis reveals that a correlation between x_{dif} and A_{jct} is in fact also predicted using the simple threshold area model for knickpoint formation in basins following a Hack's relation-type geometry.

Using Hack's relation we can write distance from divide to the junction, x_{jct}, as a function of A_{jct}:

$$x_{\mathrm{jct}} = k_{\mathrm{a}}^{-1/h} A_{\mathrm{jct}}^{1/h} \tag{4}$$

The distance from divide to the junction, x_{jct}, is by definition (Fig. 6) also equal to the sum of the upstream distance from the junction to the knickpoint, x_{dif}, and the distance from the divide to the knickpoint, x_{kp}.

$$x_{\mathrm{jct}} = x_{\mathrm{dif}} + x_{\mathrm{kp}} \tag{5}$$

The value of x_{kp} is determined according to Hack's relation and the threshold drainage area A_{kp}. Solving Eq. (5) for x_{dif}, we can plug Eq. (4) in for x_{jct} and rewrite an analogous expression for x_{kp}. Thus we find a simple, direct relation is expected between tributary drainage area and the distance between the tributary junction and the knickpoint, even in the case where no fluvially-driven knickpoint retreat has occurred:

$$x_{\mathrm{dif}} = [k_{\mathrm{a}}^{-1/h} A_{\mathrm{jct}}^{1/h}] - [k_{\mathrm{a}}^{-1/h} A_{\mathrm{kp}}^{1/h}] \tag{6}$$

This predicted relation using a threshold drainage area is plotted in Fig. 6 as a dashed line. This result suggests that for a set of basins with drainage areas and drainage network structures similar to those in the Waipaoa, we would find similar relations between A_{jct} and x_{dif} whether knickpoints were formed at some threshold drainage area, A_{kp}, or whether their locations in the basin were a function of drainage-area-dependent knickpoint retreat (Fig. 6).

5.3. Basin-wide knickpoint retreat: toward a general theoretical model

Our field observations from the Waipaoa drainage basin and the preliminary models presented above offer some insight into which factors may influence the distribution of knickpoints in a fluvial network. Actively retreating knickpoints may play an important, sometimes dominant role in fluvial adjustment following perturbation, yet there is little field evidence as to whether they retain their form while translating upstream throughout entire drainage basins. To account for the complications outlined above we propose a much more dynamic response to perturbation. If rapid base level fall generates a step in the channel that propagates upstream, this form may be unstable during retreat and degrade and re-form multiple times as it encounters regions of higher and lower erodability (Frankel et al., 2001). This behavior would allow knickpoints to temporarily exist in reaches where sediment and water discharge are large. In addition, a knickpoint that forms and degrades multiple times may generate a complicated terrace record. In locations where base level fall is distributed over time, incision may be recorded by sequential terrace levels (Fig. 2). In other reaches where the knickpoint retreats as a single step, no record of progressive incision would be recorded (Fig. 2). One might anticipate that at any given time, even migrating knickpoints would most likely appear to be “hung up” on hard bedrock ribs or at tributary junctions where there is a step decrease in sediment and water discharge. As a consequence, the very idea of knickpoint migration has been challenged and debated episodically for over 100 years (Gilbert, 1896; Penck, 1925; von Engeln, 1942; Leopold et al., 1964; Gardner, 1983; Higgins and Gardner, 1984; Wohl et al., 1994). Because this conceptual model allows knickpoints to form and degrade multiple times during their translation through the downstream reaches, it is likely that multiple small pulses of incision or even steady base level fall would be held up at a resistant substrate and collect into a single step. Moreover, if knickpoint formation occurs at locations where the erosive capacity cannot keep pace with downstream rates (such as at the junction of a small tributary and a large trunk stream), it does not require rapid base level fall to generate knickpoints. These two concerns suggest that our interpretation of knickpoints as responding to pulses of incision must be made with caution as they could result from either gradual base level fall or a pulse of incision.

As the pulse of incision extends into the upper reaches of the network or encounters a lesser tributary, the erosive capacity of that channel may not be capable of keeping pace with downstream incision rates. The reduced erosive capacity may be due to an insufficient upstream sediment supply or water discharge to move the available sediment load. Lower sediment supply would limit the erosive potential of the accelerating flow upstream of the knickpoint lip, thus explaining the lack of incised drawdown reaches in the Waipaoa. In this case, the knickpoint would not lip degrade as there would be too few tools to develop a drawdown zone. With a diminished supply of erosive tools, the rate-limiting process for knickpoint retreat is no longer fluvial, but instead relies on rock-mass stability, weathering and hillslope erosion processes (Weissel and Seidl, 1997). As the knickpoint face collapses and retreats upstream, the downstream incised gorge is supplied with sediment eroded from the knickpoint face and over-steepened banks. This material provides tools to continue incision in the over-steepened reach downstream of the knickpoint.

It must be emphasized that though much of the Waipaoa river and its tributaries has responded to the base level lowering, much of the aerial extent of the basin remains disconnected from the base level fall signal. If channel form depends on sediment supply, channels will remain in disequilibrium until the relict surface has been removed and hillslope–channel connectivity is reestablished.

5.4. Research needs

A model describing the multi-process, transient response of a fluvial network to a pulse of incision would greatly contribute to our understanding of landscape evolution. One of the greatest challenges in developing this model would be providing the flexibility for detachment and transport limited erosional processes to trade-off as local substrate, sediment and flow conditions change along the channel. As well, in the upper reaches of the channels, the transition between fluvial bedrock incision and rock-mass wasting at waterfalls must be better explored. If we desire to use a knickpoint retreat model to approximate the sediment flux history following an incisional pulse, we must also better understand the response times of hillslopes following base level fall. Though the Waipaoa provides a great resource to study knickpoint behavior in the upper reaches of a basin, it would also be valuable to examine a suite of younger transient systems where the incisional pulse has not extended as far into the network. If the issues concerning the scaling of basin-wide processes can be better constrained, it would be most valuable to use laboratory experiments to examine how bedrock incision in a trunk stream is propagated into tributaries whose discharge is some fraction of the trunks.

6. Conclusions

The present distribution of 236 knickpoints within the Waipaoa drainage basin can be well approximated using models that either allow knickpoints to propagate upstream at a rate that is an approximately linear power law function of drainage area or initiate knickpoints at a threshold drainage area. These models may succeed at matching observed knickpoint locations because they link the basin’s response to incision to the network’s drainage area structure. Alternatively, the consistency of our low residuals between the two models could be a consequence of the maturity of the pulse of incision and the knickpoints' consistent upper-network, lower-drainage area position.

Combining observation from field analysis and model behavior, we propose that the response to a pulse of incision may consist of three stages. First, large drainage area channels incise as knickpoints form and degrade multiple times as the pulse of incision propagates upstream. Second, as this incisional wave sweeps up the network, lower order, small drainage area channels are unable to keep pace with the lowering and thus develop steep knickpoints. Third, these knickpoints slowly migrate upstream and decay as a consequence of primarily weathering and mass-wasting driven erosion processes.

Further developments to modeling the transient response of landscapes to a pulse of incision will need to acknowledge (1) the variability in erodability along each channel's path and the dynamic response of knickpoints to this variability, (2) the erosional processes active at low drainage areas and (3) the lag-time between channel incision and hillslope response. With these improvements, future landscape evolution models may be capable of determining more accurate fluvial response times and sediment fluxes following a pulse of incision.

Acknowledgements

The authors would like to thank those who provided great assistance in the field: especially Mike Marden (Landcare Research), The Meban Family (Te Hau Farmstay), Simone Hood Hills, Cana Crosby and Ben Gross. Early discussions with and reviews by Jeremy Boyce, Doug Jerolmack, Joel Johnson, Blair Schoene and Cameron Wobus helped sharpen the focus of this work. Later versions of the manuscript we considerably improved following reviews by Nicole Gasparini, Simon Mudd and an anonymous reviewer. The authors also extend thanks to Landcare Research, the Institute of Geological and Nuclear Sciences, Air Maps New Zealand Ltd. and Eagle Technology Ltd. for kindly sharing their mapping resources. This work was supported through an NSF grant, EAR-0208312 (to KXW) and an NSF Graduate Research Fellowship (to BTC).

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