PROCESSES OF KNICKPOINT PROPAGATION
AND BEDROCK INCISION IN THE OREGON
COAST RANGE

By:
JACOB SELANDER

Presented to the
Department of Geological Sciences
University of Oregon

JUNE 2004
Advising Committee:

Joshua Roering, Head advisor
Department of Geological Sciences

Other members: Martin Miller
Department of Geological Sciences

W. Andrew Marcus
Department of Geography

Department of Geological Sciences
1272 University of Oregon
Eugene, OR 97403
CONTENTS

Abstract

1. Introduction

2. Bedrock Channel Study

3. Slope Area Analysis and Topographic Signatures

4. Discussion

5. Conclusions

Bibliography

Figure Captions

Table Captions

Figures 1. – 22.

Tables 1. – 5.
ABSTRACT

Rivers dictate landscape evolution, exerting controls on erosional processes, setting boundary conditions for hillslope processes and governing height limits of mountain ranges. The mechanics by which alluvial streams transport sediment are well known. However, erosional processes that shape bedrock channels are poorly understood. A debated but undocumented process of bedrock incision is the propagation of knickpoints. To improve our understanding of incisional processes and the controls bedrock channels exert on the landscape, I document their signature at three different spatial scales. At individual knickpoints I quantified small scale structural controls and documented erosional processes. At the reach scale, I identify bedrock stratigraphic and structural controls on knickpoint and channel morphology and provide evidence for the headward migration of knickpoints. On a basin scale, I quantified the morphology of 5-10 km² basins using estimates of basin area and slope to identify a topographic signature for channels at various orientations relative to bedrock structure. Results from these studies create a data set that describes bedrock channel evolution and its controls on landscape evolution.
1. INTRODUCTION

1.1 MOTIVATION

Tectonic geomorphology explores the balance of erosion and uplift. Much attention has been paid to the debate as to whether uplift is the driving force behind erosion, or if erosion is driving uplift via isostatic compensation in mountainous regions (Molnar and England, 1990). The effects of uplift have tremendous implications for global climate change; it has been proposed that uplift of large regions of the crust is responsible for global cooling over the Cenozoic (Molnar and England, 1990; Raymo and Ruddiman, 1992). Regions tectonically uplifted can perturb local and global scale atmospheric circulation patterns. Increases in chemical weathering due to tectonic forcing have been proposed to remove carbon dioxide from the atmosphere leading to global cooling (Raymo and Ruddiman, 1992). This juxtaposition of different processes and effects provides the motivation to study the mechanics of landscape evolution.

Bedrock channels play a major role in landscape evolution, transmitting signals of climatic or tectonic change across the landscape, controlling the timescale of response of the landscape to these changes, setting the boundary conditions for hillslope processes and eventually governing the height limits of mountain ranges (Seidl and Dietrich, 1992; Seidl, 1993; Howard et al., 1994; Sklar and Dietrich, 1998; Whipple and Tucker, 1999; Whipple et al., 2000). Many attempts have been made to quantify rates of bedrock channel lowering based on the stream power incision model (Howard and Kerby, 1983; Seidl and Dietrich, 1992; Seidl, 1993; Howard, 1994, Howard et al., 1994; Seidl et al., 1994; Sklar and Dietrich, 1998; Stock and Montgomery, 1999; Whipple and Tucker,
Despite the recent interest in the theoretical models of bedrock channels there is a paucity of knowledge on field scale incision processes (Whipple and Tucker, 1999; Whipple et al., 2000). Qualitative documentation of these processes is needed to constrain the various parameters in the theoretical models (Whipple et al., 2000).

A widely recognized means of bedrock channel incision is the propagation of knickpoints (Miller, 1991; Seidl and Dietrich, 1992; Seidl, 1993; Howard et al., 1994; Zaprowski et al., 2001). A knickpoint is defined as steep local reach between lower gradient sections (Howard et al., 1994), and can be produced in a variety of ways, e.g. sudden base level change, tectonic deformation or main stem incision which sends an incisional pulse upstream into its tributaries. Knickpoint migration can provide a link between main stem and tributary incision which illustrates basin scale responses to base level or tectonic change (Seidl and Dietrich, 1992; Seidl, 1993). It has been proposed that knickpoint propagation continues upstream until the channel is too steep to support the knickpoint, at which point debris flow scour will control channel incision (Seidl, 1993).

Although numerous studies identify the propagation of knickpoints as a method of incision, few have expanded on this hypothesis (Seidl and Dietrich, 1992; Seidl, 1993; Howard et al., 1994). Knickpoint migration has been overlooked in terms of its ability to remove material from the landscape. Here, bedrock channels are studied to determine how processes such as abrasion, plucking and spallation control the morphology of individual knickpoints, how the knickpoints affect the channel morphology and how these knickpoints propagate upstream. Recently, fluvial unroofing of landscapes has
been thought to influence tectonic processes at depth in the crust (Zaprowski et al., 2001; Zeitler et al., 2001), directing knickpoint propagation into the spotlight.

1.2 STUDY AREA

The Oregon Coast Range is a belt of uplifted, deeply dissected topography between the Pacific Ocean to the west and the Willamette Valley inland. Bedrock structures are characterized by gentle, long wavelength anticlines and synclines trending northeast-southwest (Baldwin 1956; 1961; 1973). The tectonic setting of the OCR is east of the Cascadia Subduction Zone, continued motion between the subducting Juan de Fuca plate and over-riding North American plate has caused uplift of the OCR since the Miocene (McNeill et al., 2000).

The majority of the Coast Range is underlain by the Eocene Tyee formation, a sequence of rhythmically bedded deltaic sediments and turbidites (Snively et al., 1964; Heller and Dickinson, 1985). In the regions studied here, the bedrock is mainly interbedded sandstone and siltstone. Towards the northern region of the study area the sandstone becomes split in places by intrusive basaltic volcanics (Baldwin, 1956; 1961; 1973), but the majority of the study area (~90%) is underlain by rocks of the Tyee formation. Figure 1 depicts a digital elevation model of the Tyee formation within the study area.

The Oregon Coast Range is an ideal geomorphic laboratory, with homogeneous bedrock lithology, uniform annual precipitation rates and remaining unglaciated during the Pleistocene (Kobor and Roering, 2004). Personius (1995) and Reneau and Dietrich (1991) documented uplift and sediment yield rates in the OCR, other studies of erosion
and bedrock lowering (Heimsath et al., 2001) show erosion to be approximately uniform in space (Reneau and Dietrich, 1991; Heimsath et al., 2001). Parameters widely used in current bedrock incision models depend greatly on climate, rock uplift rate and lithology (Whipple et al., 2000(A)). Because constraints on variables such as precipitation, tectonic setting and lithology are well understood in the OCR, bedrock channels can be studied in great detail for the processes taking place.

1.3 PROJECT SECTIONS

In order to gain a greater understanding behind the processes of bedrock incision, I study three different spatial scales. First, I studied individual knickpoints and local incision processes that occur on centimeter to meter scales. Second, to determine larger controls on channel morphology I surveyed bedrock channel profiles with different orientations to underlying bedrock structure. Third, I look at how bedrock structure controls overall basin morphology.

Processes of knickpoint evolution

Similar to the work of Miller (1991), I documented local scale processes controlling bedrock channels. Little work has been done to document how processes such as abrasion, fluting and plucking affect individual knickpoints. This is not a quantitative study, rather a qualitative look at the processes and where they are taking place. Detailed feature maps of knickpoints are made to locate the various processes and features controlling knickpoint morphology. I also observed how bedrock strike and dip locally affect knickpoints. Cases can be made for the upstream propagation of
knickpoints, field measurements and observations are made to provide evidence in support of these arguments.

**Channel profile analysis**

To determine how bedrock structure affects channel morphology, I surveyed bedrock channel reaches at a meter scale, looking at how bedrock structure affects overall channel morphology in these regions. Detailed longitudinal profiles were measured on channels at different orientations relative to bedrock strike and dip, revealing different morphologies at different channel orientations.

**Basin-wide analysis**

Using a steady-state variation of the stream power incision model first proposed by Howard and Kerby (1983), I apply the slope-area power law (e.g., as applied by Stock and Dietrich, 2003 and Kobor and Roering, 2004) to various basins in the Oregon Coast Range. My goal is to identify the topographic signature of bedrock channels at various orientations to large scale bedrock structures. This will establish quantitative linkages between bedrock structure and basin morphology.
2. BEDROCK CHANNEL STUDY

2.1 INTRODUCTION

Knickpoints are defined to be steep gradient sections of channel between reaches with lower gradient (abrupt topographic breaks) and are considered non-equilibrium landforms (Schumm et al., 1987; Miller, 1991; Howard et al., 1994). Figure 2 is a photograph of a knickpoint on Spencer Creek in the Oregon Coast Range, nomenclature of the knickpoint is labeled.

The upstream propagation of knickpoints has been identified as an important means of bedrock channel lowering, but little is known about the mechanisms that control the shapes and migrations of knickpoints (Miller, 1991; Seidl and Dietrich, 1992; Seidl, 1993; Whipple et al., 2000(A,B); Zaprowski et al., 2001). Previous studies identify bedrock structures at different scales that exert controls on knickpoints (e.g. Miller, 1991; Whipple et al., 2000(A,B)). Processes of bedrock channel incision were studied in detail by Whipple et al. (2000)(A), indicating that fractures and bedding planes exert the most control but do not discuss how these processes effect the morphology of individual knickpoints. Miller (1991) studied knickpoints in homogeneous strata and determined that knickpoints are influenced by jointing, lithologic layering and relations between dipping strata and stream flow direction.

Seidl (1993) identified a number of modes of bedrock channel incision, among which are vertical wearing of the channel due to stream flow by processes such as abrasion and dissolution, and the propagation of knickpoints. The net effect of physical processes such as abrasion and plucking is knickpoint propagation; however the style of
propagation is debated. Two modes of knickpoint propagation were proposed by Seidl and Dietrich (1992) and Seidl (1993) (Figure 3A). The first calls for upstream propagation of the knickpoint with the face remaining at a constant height, the other holds the knickpoint location constant while material downstream of the face is removed, causing the face height to increase over time due to differential vertical erosion rates. Flume studies of knickpoint propagation (Holland and Pickup, 1976; Gardner, 1983) have shown that knickpoints in cohesive materials either rotate (i.e., the face decreases in slope until the knickpoint diffuses into the channel bed) or maintain a constant face height while propagating upstream (Figure 3B).

In this study I identify various erosional processes and local structural features that control knickpoint morphology and constrain the mode of upstream migration. In addition to individual reach scale processes, I study large scale bedrock structural controls on overall channel morphology.

2.2 LOCATIONS

In choosing individual channels to survey I used a series of criteria. First, the entire study area is underlain by the Eocene Tyee formation, removing bedrock lithologic changes as a knickpoint controlling variable. Second, I limited the channels to first or second order streams whose slope is greater than 0.02, below this threshold bedrock channels no longer dominate and alluvial reaches are prevalent (Montgomery et al., 1996; Montgomery and Buffington, 1997). The focus on first and second order streams is to concentrate on where the majority of basin relief is felt. Low gradient bedrock channels are also present in the Oregon Coast Range, but in these locations stream power is
competent enough to remove alluvial materials from the channel. Third, I choose streams at different orientations to bedrock structure. Channels are divided into three categories: dip-slope, strike-parallel and opposite-dip channels (Figure 4). Strike and dip data were taken from published geologic maps (Baldwin, 1956; 1961; 1973) as well as measured in the field to define the channel orientation. Channels are classified as bedrock if the majority of the bed is exposed bedrock with little to no alluvium present.

Figure 1 shows the locations of the channels surveyed. The Spencer Creek (Smith River drainage) location consisted of two separate sites. A detailed profile of the East Fork of Spencer Creek (a first order stream flowing opposite to bedrock dip) was measured, and processes controlling knickpoints were studied at a single knickpoint on the main stem. The Big Creek site (lower Umpqua drainage) had channels at all three orientations to bedrock at the confluence of the North Fork and the main stem of Big Creek. Three profiles were measured and two individual knickpoints were mapped in detail. Sullivan Creek in the Millacoma drainage system is a dip-slope channel where I surveyed detailed long profiles.

2.3 METHODS

In the field, I define a knickpoint as a short horizontal reach consisting of a vertical face and, where present, a steep gradient section upstream and/or downstream of the face. Both upstream and downstream of the knickpoint region are lower gradient bedrock or short alluvial reaches.

Long profiles of channels were measured using a laser range finder with a digital clinometer. Fracture orientation, flute size and orientation, exfoliation sheeting regions,
bedrock orientation and bedding thickness were measured with a compass, ruler and tape measure. Individual knickpoints were surveyed using a laser range finder. Channel features, their locations, orientations and sizes within the surveyed area, and were mapped by hand. The survey data was used to create maps of individual knickpoints detailing where the various features occur in the channel location around the knickpoint.

2.4 OBSERVATIONS AND RESULTS

Controls on knickpoint morphology and migration

Detailed mapping of knickpoints and their features leads to insight as to the distribution of processes controlling their morphology. Exfoliation sheeting is the most widespread feature throughout all areas studied. Stock and Dietrich (2003) identify surface parallel fractures in the Tyee bedrock that enables the removal of thin sheets ~0.5 – 3 cm thick in debris flow scoured areas. The removal of thin sheets of rock has been termed exfoliation, and it is present on the majority of exposed Tyee bedrock (both stream channel and outcrop, e.g. roadcuts). Typically, sheets 0.5 – 3 cm thick and 2 – 400 cm² and larger in area will flake off, leaving visible scarps in the exposed bedrock (Figure 5). The mechanics of exfoliation sheeting in the Tyee sandstone is not well understood, making it difficult to quantify in a field setting. Due to this lack of understanding, I am limited to observing where exfoliation occurs and postulating its role. In stream channels, exfoliation is most prevalent at the knickpoint face and proximal regions upstream. At the face, exfoliation rounds the lip (Figure 2 for knickpoint nomenclature) creating a convex profile (Figure 6). In locations upstream of the lip, exfoliation serves as a means of bedrock lowering.
Figures 7 and 8 are maps of two knickpoints on Big Creek, depicting locations and orientations of fractures, fluting and exfoliation. These vertical fractures/joints are present in sub-parallel groupings and their orientations show no preference to channel orientation or underlying bedrock strike and dip. Fracturing/jointing of the bedrock perpendicular to bedding planes exert controls on knickpoint shape. These fractures are planes of weakness in the otherwise highly coherent bedrock, creating areas of preferential erosion. Field measurements and observations show that there is a direct correlation between the orientations of the knickpoint face(s) and the orientations of the fractures in the bedrock. Figure 9 is a photograph of a fracture that coincides directly with the knickpoint face. These weak planes in the rock create areas where spallation is likely to occur and where the knickpoint faces are located.

In addition to controlling the locations and orientations of the knickpoint faces, fractures also control the orientation of fluting. Flutes (also referred to as potholes) are rounded, oblate, hollow features that have been fluvially carved into the bedrock. Present in the bottom of these features are sediments of sand to small cobble size, which presumably serve as the tools used to carve these flutes. Each flute has a long and short horizontal axis; orientations of the long axes were measured in the field. Figure 9 details two flutes and their orientation relative to a large fracture in the bedrock. For each field site, flute and fracture orientations were compared with rose plots (Figure 10 A-E). Flute long axis orientations were found to be generally coincident with fracture orientations. Flute sizes represent the amount of material removed during the formation of the flute, Figure 11 shows a rough correlation between the long axis length and depth of the flute.
In all locations studied, the Tyee sandstone consists of interbedded sandstone and siltstone. The siltstone layers are weaker than the massive sandstones and therefore more susceptible to erosion. This leads to faster erosion rates of the siltstone relative to the sandstones and undercutting of the sandstone layers (Figure 6). This undercutting can lead to failure of the overlying sandstones and spallation of large, cohesive blocks. These failures occur along horizontal bedding planes and vertical fracture planes in the bedrock.

Bedding thickness of the sandstone units was measured at the two knickpoints mapped on Big Creek. Measurements were taken on well exposed bed(s) at locations ~15 and 5 meters downstream of the knickpoint face and at the face itself. Bed thickness remained at a constant height from downstream up to the face at both locations in all beds measured, consistent with the stratigraphy measured by Heller (1985). Sandstone layers also influence the location of beveled surfaces upstream and downstream of the knickpoint face. Present at each knickpoint were multiple flat, bedding plane surfaces (Figures 7 and 8) in the massive sandstone layers at equal elevations on either side of the channel. These surfaces are downstream of the knickpoint face, semi-“V” shaped in plan form opening downstream. Surface erosional features such as exfoliation sheeting, abrasion, and cavitation (Whipple et al., 2000(A); Knighton, 1998) are absent downstream of the knickpoint face. The majorities of erosional features (fluting, spallation of blocks along fracture planes) are associated with the individual knickpoint faces and well exposed fractures.

**Channel morphology**

Detailed long profile surveys of bedrock channels were made to investigate the controls bedrock strike and dip exert on channel morphology. Knickpoints, bedding
plane surfaces and short alluvial reaches on the channels comprise different portions of channel relief dependent on the orientation of the channel to bedrock. Data from surveyed channels is summarized in Table 1. Local slope is also greatly influenced by bedrock structure and lateral spacing of knickpoints.

strike parallel channels (Figure 13) consist of long bedding plane surfaces separated by short steep reaches where knickpoints occur. At the downstream end of the bedding plane surfaces, generally above knickpoints, short alluvial reaches exist. Knickpoints constitute a greater portion of relief than bedding plane surfaces or short alluvial regions. Field observations show that sandstone layers exert controls on the heights of the knickpoints, which are approximately equal to bedding thickness. Larger knickpoints can consist of multiple beds. In the surveyed reach on Big Creek, the knickpoints commonly occur in pairs, with two distinct breaks comprising the majority of local relief (Figure 13).

Channels that flow opposite bedrock dip display a different morphology (Figure 14). Knickpoint density (i.e. horizontal spacing along the channel reach) is greater than strike parallel or dip- slope channels. Although heights of individual knickpoints are less than strike- parallel reaches knickpoints constitute a higher portion of vertical relief because of their higher density. Channel reaches consisting primarily of bedrock are less numerous and shorter due to the closer spacing of knickpoints. Alluvial regions are more common in opposite- dip reaches, but their length is short and they generally remain fairly steep.

Dip- slope channels are dominated by long bedding plane surface that are roughly consistent with bedrock dip (Figure 15 A and B). Knickpoints are widely spaced; relief is
contained mostly in bedding plane surfaces rather than individual knickpoints. The exception to this is Upper Sullivan Creek, which has a large (~15 meter) knickpoint at the top of the surveyed reach. Bedding plane thickness in the sandstone layers controls the heights of the larger knickpoints; smaller knickpoints are present when the local channel slope is greater than bedrock dip. Alluvial regions are few; those that do exist are short and steep. Small plunge pools exist below some of the larger knickpoints where sediments can accumulate, but overall the bedding plane surfaces remain free of loose alluvial materials.

Knickpoints in each of the surveyed channels exhibit the erosional features discussed above, but in varying abundance. All orientations contain numerous sub-parallel fractures and fluting, although flutes are most prevalent in strike-parallel channels. In dip-slope channels, fluting is not always associated with knickpoint faces; they can be present in steep bedding plane channel surfaces as well. Exfoliation sheeting and rounded knickpoint faces were found at all surveyed channel knickpoints. Along steeper dip-slope channel surfaces, exfoliation often persists. Knickpoint faces tend to be coincident with fracture orientations and locations.

2.5 DISCUSSION

Erosional processes

Although different physical processes of channel incision (abrasion or corrasion, plucking) into bedrock have been identified in a qualitative sense (Howard et al., 1994; Hancock et al., 1998; Knighton, 1998; Whipple et al., 2000(A)), it has not been shown how these shape knickpoints. Abrasion of the channel surface is the least consequential
of these processes at the locations studied; however abrasion along fracture planes producing flutes removes large quantities of material from the channel. In the base of active flutes (flutes present in the low water regime of the channel bed), coarser sediments are found. During high flow events these flutes would be inundated, helical flow inside the flutes would cause the sediments to act as tools shaping and eroding the bed.

Orientation and growth of flutes is highly governed by local fracture orientation. Figure 10 A – E plots reach fracture orientations with flute orientations, local channel azimuth is averaged. Long axis flute orientations correlate with fracture orientations along each surveyed reach; both are independent of channel azimuth. The numbers of fractures along each reach greatly outweighs the number of flutes and dictate the local planes of weakness in the bedrock.

Spallation, plucking of blocks and exfoliation sheeting are the dominant processes outside of fluting, as fluting is not present at every knickpoint. Development of flutes along fracture planes, impact from saltating grains during high flow events can also produce fracture growth (Whipple et. al., 2000(A)), weakening the rock and increasing the likelihood of entrainment of loosened blocks. Exfoliation produces thin sheets that are consequently plucked away from the channel bed. This appears to be the dominant process of removal of material from the surface of the knickpoint face.

**Proposed mechanics of exfoliation sheeting**

Exfoliation sheets are found on all exposed surfaces of the Tyee bedrock, be it stream channels or cliff faces. The thickness of these sheets is consistently between 1 and 3 cm, which implies processes acting to create planes of weakness in the very upper
regions of the bedrock. Observations of exfoliation scarps hand samples taken from these scarps reveals the presence of a weak plane, roughly parallel with the channel surface approximately 1-3 cm below the surface. Samples from the exfoliation scarp itself are easily broken off with a rock hammer; these consistently break along this same plane. Weathering of minerals to produce clays at very shallow depths in the bedrock could potentially create these weak planes. Impacts from saltating particles could pluck these sheets or pressure differences between the water in the stream and the bed could produce cavitation causing these pieces to flake off. The chemical weathering of the upper portions of the bedrock could also impact the rock strength. This could create weaker regions on the order of 1-3 cm thick that would be more susceptible to removal than less altered regions. This set could explain the presence of exfoliation in stream channels; however it precludes processes of exfoliation sheeting on exposed bedrock not part of the channel. It also does not account for the lack of exfoliation away from the knickpoint face in some exposed bedrock channels.

**Controls on knickpoint morphology**

Miller (1991) concluded that knickpoints form when channel orientation changes relative to bedrock dip, and knickpoints are limited to jointed strata that dip upstream or downstream at an angle less than the local channel gradient. This is contrary to findings here in the Oregon Coast Range. Knickpoints are found on all bedrock channels, regardless of channel orientation to strata structure. Occurrence of knickpoints and their lateral density is related to, not restricted by bedrock structures. A detailed study of knickpoints and bedrock channel morphology revealed numerous controls on knickpoint morphology. Fractures or planes of weakness in the bedrock determine locations and
orientations of knickpoint faces, and the orientations of flutes that develop. Because the fractures in the bedrock occur in conjugate sets, knickpoint faces are not limited to one orientation. Often knickpoints will have multiple faces whose orientations are determined by local fracturing. Planes of weakness in the bedrock are an integral part of knickpoint dynamics. Without this influence knickpoints would not have a predictable structure and it is questionable whether or not fluting would be present. The faces of individual knickpoints are shaped by the locations of flutes and the presence of exfoliation sheeting above the face. Although poorly understood, exfoliation sheeting is an important means of removing large amounts of material from the channel surface and the knickpoint face. This removal of material from the face creates a rounded, convex profile of the knickpoint lip. Heights of the knickpoints are determined by the local bedding thickness of the sandstone layers. However, because faces can consist of multiple couplings of sandstone and siltstone sets, individual bed thickness cannot be used as a proxy for face height.

**Knickpoint propagation**

Previous experiments in stratified sediments have suggested that less cohesive layers act as knickpoint forming planes and knickpoint steps propagate upstream along these planes (Holland and Pickup, 1976; Gardner, 1983). This model is viable in the Oregon Coast Range, where the Tyee bedrock is composed of alternating sandstone and less cohesive siltstone layers. Field observations of knickpoint height water depth also support a model proposed by Leopold et al. (1964), where knickpoint propagation would occur when the ratio between the height of the knickpoint face and flow depth is significantly greater than one:
and stream power is competent enough to remove material from the base of the knickpoint. The majority of knickpoints present on the first and second order channels surveyed were much greater in height than the high water mark (highest deposits of debris from winter high flow events) along the channel banks. Seidl (1993) also proposes that knickpoints migrate when the channel bed gradient is low compared to the local gradient of the knickpoint.

Field measurements and evidence can be used to determine the validity of the two knickpoint erosion modes proposed by Seidl and Dietrich (1992) and Seidl (1993) (Figure 3A). The lack of erosional features on beveled bedrock surfaces downstream of knickpoints provides evidence for the headward migration of knickpoints rather than downstream surface lowering. Bedding thickness remains constant downstream of a knickpoint, indicating the knickpoint face has remained at a constant height while moving upstream. Rounding of the knickpoint face and short reaches upstream of the knickpoint indicate slight rotation of the knickpoint, as proposed by Holland and Pickup, (1976) and Gardner (1983) (Figure 3B).

Vertical fracture planes, development of flutes and undercutting of layers can be used to constrain a model for upstream propagation of knickpoints (Figure 16). Fluting develops along fracture planes in the sandstone layers while the weaker siltstone layers erode at a faster rate, undercutting the sandstone. Exfoliation and abrasion at the lip of the knickpoint creates a rounded profile, rotating the upper portion of the face. These processes will continue until the sandstone layer can no longer support itself, and blocks will spall off along fracture planes, creating a new knickpoint face. The newly created
knickpoint face will approximate the same height as the previous face. Rotation decreases the height of the vertical portion of the knickpoint, but the overall knickpoint region (face and over steepened region upstream) remains at a constant height. As this process continues, the knickpoint migrates upstream at a constant height and creating beveled bedding plane surfaces downstream of the knickpoint. This undercutting process of knickpoint erosion was identified by Miller (1991), but little attention was paid to the role of fluting in the erosional process.

Large, map-scale bedrock structures influence channel morphology. As rivers incise into the bedrock of the OCR, the presence of anticlines and synclines causes these rivers to flow at different orientations to bedrock strike and dip. Detailed longitudinal profiles of bedrock reaches shows differing distributions and sizes of knickpoints for different channel orientations. Knickpoints constitute different fractions of total relief as do beveled bedding plane surfaces. Dip-slope channels are comprised mainly of bedding plane surfaces that coincide with bedrock dip, knickpoints are widely spaced and account for a small fraction of relief. Knickpoints in strike parallel channels account for a higher fraction of relief than bedding plane surfaces. These flat, beveled surfaces are present below knickpoints and terminate in short alluvial regions. Channels opposite bedrock dip lack long bedding plane surfaces and have the highest density of knickpoints. Alluvial regions are few throughout all channel orientations, and appear to have little influence on the dynamics of knickpoint occurrence in bedrock dominated channels.

Channel orientation to bedrock strike and dip also influences the amount that bedding planes will effect knickpoint migration. A model proposed by Holland and Pickup (1976) and Gardner (1983) involves less cohesive layers acting as knickpoint
propagation planes would have different consequences for different channel orientations. Channels oriented parallel to strike or down-dip may exhibit faster knickpoint migration rates, as the bedding planes have a higher influence over channel morphology. In order for knickpoints to propagate on opposite dip channels by this proposed method, the stream would have to erode in a direction opposite channel slope. Propagation of knickpoint would slow because the bedding planes dip into the slope, lending more material to be eroded through.
3. SLOPE – AREA ANALYSIS AND TOPOGRAPHIC SIGNATURES

3.1 THE SLOPE – AREA POWER LAW

The slope – area analysis which I applied here has roots in the stream power incision model. This model is a power function that relates bedrock channel incision and basal shear stress or stream power. Numerous other studies (Howard, 1994; Howard et al., 1994; Montgomery and Buffington, 1997; Sklar and Dietrich, 1998; Stock and Montgomery, 1999, Whipple and Tucker, 1999; Kirby and Whipple, 2001; Montgomery, 2001; Dietrich et al., 2003; Stock and Dietrich, 2003; Kobor and Roering, 2004) have used this simple detachment limited stream power model of bedrock incision to study different bedrock incision mechanisms. In this study I attempt to determine a signature of bedrock channels.

Early work on attempting to quantify erosion of bedrock channels using the stream power incision model (e.g. Howard and Kerby, 1983) yielded a relationship between the rate of channel lowering ($\frac{\delta z}{\delta t}$), also referred to as erosion rate $E$, and a set of measurable parameters such that

$$\frac{\delta z}{\delta t} = KA^m(\delta z/\delta x)^n \quad (2a)$$

where $A$ is the upstream drainage area and $(\delta z/\delta x)$ is the local channel slope, $K$ is the erosion coefficient which depends on rock erodibility, and $m$ and $n$ are empirically
derived constants. Simplifying the notation so that local channel slope is $S$ and the rate of channel lowering (erosion rate) is $E$ yields

\[ E = K A^m S^n \]  \hspace{1cm} (2b)

For landscapes experiencing tectonic uplift, Howard (1994) recognized that the net land surface change in time ($\delta z/\delta t$) would be a function of the uplift rate $U$ and erosion rate $E$, which can be expressed as

\[ (\delta z/\delta t) = U - E \]  \hspace{1cm} (3a)

or

\[ (\delta z/\delta t) = U - K A^m S^n \]  \hspace{1cm} (3b)

Under topographic steady state conditions, uplift can be assumed equal to erosion such that ($\delta z/\delta t$) = 0. The Oregon Coast Range has been observed to be at spatial wide scale equilibrium (Personius, 1995; Reneau and Dietrich, 1991), and therefore $U$ and $E$ can be assumed constant throughout the study area. At steady state, the channel profile is at equilibrium with changes in uplift and subsequent downcutting. Solving equation 3b for channel slope at equilibrium given upstream area $A$ generates the expression

\[ S_e = (U/K)^{1/n} A^{-m/n} \]  \hspace{1cm} (4)
which leads to a power law relationship between slope and drainage area

$$S_e = k_s A^{-m/n} \quad (5)$$

where $S_e$ is the equilibrium channel slope and $k_s$ is the steepness index and $k_s = (U/K)^{1/n}$. The overall steepness of a channel is governed by $k_s$, and the channel concavity by the $m/n$ ratio (referred to as the concavity index). Using these principles, my goal is to look for a topographic slope – area signature (separate $k_s$ and $m/n$ populations) for basins whose channels flow at different orientations relative to the underlying bedrock structure.

### 3.2 LOCATIONS AND RATIONALE

For slope-area analysis I chose 34 different basins in the Siuslaw, Smith, lower Umpqua and Millacoma drainages (Figure 18) that have mapped structural data (Baldwin, 1956; 1961; 1973). These basins all lie within Tyee bedrock with little or no influence from igneous intrusions. Of these basins, 11 of the channels are oriented parallel with bedrock strike, 13 opposite bedrock dip and 10 are dip-slope channels. Here, I define a channel orientation if the mean channel azimuth lies within 20 to 30 degrees of bedrock strike or dip in that location. The channels plotted are first through third order streams, the areas are small (generally < 10 km$^2$) but contain the majority of topographic relief of the basin. Channel slopes remain above 0.02, a region in which bedrock channel process are dominant (Montgomery et al., 1996; Montgomery and Buffington, 1997).
3.3 METHODS

Using published United States Geological Survey 1:24,000 maps and a computer digitizing program (Didger 3, Golden Software) I created slope-area plots for the 34 basins listed in Table 2. Each contour line along the valley axis represents one data point in the slope-area plots. For each data point upstream drainage area was calculated digitally by tracing and digitizing the drainage boundary. Slope was measured by averaging gradient above and below the reference point along the valley floor, using the nearest adjacent contour lines. Values for slope (percentage, m/m) and area (km²) were plotted and regression equations yielded estimates of $k_s$ and $m/n$ for each basin.

3.4 RESULTS

$k_s$ and $m/n$ values for different channel to bedrock orientations

I calculated slope-area data for 34 basins in the Oregon Coast Range, all with uniform bedrock lithology. This set is divided into three categories, strike-parallel basins, opposite dip basins and dip-slope basins. Locations of these basins are shown in Figure 17, cumulative slope-area plots of all three basin orientations are displayed in Figure 18. Plots of area versus channel slope revealed a scaling break at 0.01 km², regressions were performed using this threshold as the lower bound. (See Figure 19 for an example of a slope-area plot and the presence of a scaling break) This scaling break will be discussed in detail later in this section. Regression generated values for $k_s$, $m/n$ and $R^2$ are listed in Table 2.
Using 0.01 km\(^2\) as the lower bound for regressions, \(R^2\) values were between 0.69 and 0.98, averaging 0.90. Dip-slope basins had the highest correlation with \(R^2\) values averaging 0.91. Strike-parallel and opposite dip channels were also well represented with \(R^2\) values of 0.89 and 0.90, respectively.

Values of \(k_s\) approximate the average steepness of the channel. For strike-parallel basins, these values ranged between 0.045 and 0.077 with a mean of 0.067. Opposite dip basin \(k_s\) values fell between 0.035 and 0.108 with a mean at 0.074. Analysis of dip-slope basins revealed \(k_s\) values between 0.042 and 0.091, averaging 0.056. The mean values of \(k_s\) are listed in Table 3, Figure 20 is a set of box plots for \(k_s\) and \(m/n\) values for the three orientations.

The \(m/n\) ratio determines the slope of the slope-area plot in log-log space, reflecting the overall concavity of the basin. Higher \(m/n\) values indicate higher concavities and vice versa. Strike parallel values of \(m/n\) averaged 0.491 with a range between 0.372 and 0.668. Basins that are opposite dip have a mean \(m/n\) value of 0.471 and a range from 0.366 to 0.637. Dip slope \(m/n\) values average 0.499 and range between 0.3585 and 0.5967. Mean \(m/n\) values for each channel orientation are displayed in Table 3.

**Statistical analysis of \(k_s\) and \(m/n\)**

**Methods**

In order to determine the statistical significance of a topographic signature of bedrock channels at different orientations, I apply a two-sample t-test using 90% significance first to the set of \(k_s\) values and second to the \(m/n\) values. I break the three different channel orientations into three different comparisons for each test. First I
compare strike-parallel basins to opposite dip basins, second, opposite dip to dip-slope basins and third, dip-slope basins to strike-parallel basins. Distributions of $k_s$ and $m/n$ values are displayed in Figure 20, and summaries of values used in the statistical analyses are present in Table 4.

**Results**

Statistical values calculated for these analyses are given in Table 5 A and B. Overall throughout all the comparison tests, variances of the data sets were found to be similar, indicating the appropriate use of the t-statistic tests to determine differences or similarities amongst the data. In the comparison of $k_s$ values, no difference was determined between strike-parallel and opposite dip basins, or between strike-parallel and dip-slope basins. Comparing opposite dip basins and dip-slope basins, I determined significant difference between the two sets of $k_s$ values, providing evidence for a topographic signature.

Comparing the $m/n$ values, I determined that the variances of all sets are similar. However, the data sets have a great deal of overlap and no statistical difference could be found between the three. In all cases, $t_{\text{calculated}} < t_{\text{critical}}$, indicating a lack of a separation between the data sets, $m/n$ values have no correlation with $k_s$ values (Figure 21), and therefore no evidence for a topographic signature.

### 3.5 DISCUSSION

**$k_s$ and $m/n$ values at different channel orientations**

Table 3 summarizes the different $k_s$ and $m/n$ values for the three channel orientations to bedrock studied here. As discussed earlier, $k_s$ represents the steepness of
the channel and m/n is a proxy for the overall concavity of the basin. For basins that
drain an area of equal change in elevation, two end-member scenarios are possible. A
high k_s value indicates a steeper channel but less concavity (lower m/n value) to agree
with the slope-area power law relationship (Equation 5). Low k_s values indicate a
gentler slope of the basin but require higher concavity (m/n). These two scenarios are
apparent in the slope-area analysis of the Oregon Coast Range. Basins that are oriented
opposite to bedrock dip display the highest k_s values, indicating the highest overall
channel slope. Dip-slope basins contain the lowest k_s values, k_s of strike-parallel
channels lies in between the two. The analysis on m/n values for the three orientations
did not determine any difference between the sets so no definitive statements can be
made.

Dip-slope channels are controlled largely by bedrock structure. In the OCR, bedrock structure is composed of numerous long wavelength, gentle folds; steeply
dipping strata is rarely found. Therefore the overall slope of dip-slope channels is
controlled by bedrock dip and is lower than the other basin orientations. One potential
explanation for the high concavity is the stacking of knickpoints towards the basin head.
This stacking could create short, local steep reaches at the channel head that could
account for the greater concavity of these basins. As discussed earlier, opposite-dip
channels contain a greater portion of their relief as individual knickpoints (Table 1). This
close lateral spacing of knickpoints could also generate steep channels.

**Evidence of a topographic signature?**

I used statistical testing to explore the apparent separation of the k_s and m/n sets
gained from power-law regressions of slope-area trends. Values for m/n for different
channel orientations do not vary enough to define a topographic signature for the concavities of different orientations. Values $k_s$ of were analyzed to find statistical difference. The raw data show a steepening of the channel from dip-slope to strike-parallel to opposite dip basins. By performing t-statistic tests on the data sets, it was found that dip-slope basins and strike parallel basins do not have a statistically significant difference between the $k_s$ values. This holds constant for the comparison between strike-parallel and opposite dip basins. Comparing the dip-slope and the opposite dip basins found statistical differences in their mean $k_s$ values, meaning the two data sets come from different populations. This provides evidence for a topographic signature of dip-slope basins and opposite dip basins in comparison with each other. At a large map scale, this signature suggests a distinguishable variation between dip-slope basins and opposite dip basins based on its shape and steepness in slope-area space. This signature also implies how bedrock structure controls overall basin morphology in addition to local channel morphology.

**Bedrock channel signature vs. differential uplift**

Kobor and Roering (2004) studied slope-area analyses of basins in the Smith and Siuslaw River drainages in the Oregon Coast Range observing variations of $k_s$ values on a broad range scale. Regions of differing $k_s$ values are attributed to regions of differential uplift rates, with a broad swath of high $k_s$ values trending northeast-southwest roughly coincident with the anticlines (See Figure 1 for geology). This correlation may suggest the distribution of $k_s$ is related to differential uplift, regions with higher $k_s$ may be experiencing greater uplift rates due to the growth of local folds (Kobor and Roering, 2004). Although individual basins were observed, $k_s$ in relation to local bedrock
structure was not observed. In this study, \( k_s \) values are being analyzed on a finer, local scale to determine a signature of bedrock channels at varying orientation to bedrock.

Using data presented in Kobor and Roering (2004) and published geologic maps (Baldwin 1956; 1961; 1973), I determined the orientation of basins (where possible) whose \( k_s \) values were found to be greater than 0.060 (mean \( k_s - S_x \) for opposite- dip basins). The majority of these basins are opposite bedrock dip, consistent with the topographic signature of opposite dip basins described in this study. In addition basins with the lowest \( k_s \) values (less than 0.040) were found to contain channels coincident with bedrock dip, again consistent with the signature of dip- slope basins.

Differences in interpretation can be attributed to differing scales of study. The Kobor and Roering (2004) differential uplift zone has a much greater wavelength than the individual fold structures present in the Oregon Coast Range. Studying large, range scale processes has potential to smooth over smaller spatial scale variations such as \( k_s \) values for different channel orientations to bedrock. Methods of extracting slope- area data are similar and provided similar results. To extract slope- area data, I used published U.S.G.S. topographic maps in order to gain high resolution data. This method can be more precise than using digital elevation models to extract slope- area data, dependent on the resolution of the DEM. Kobor and Roering (2004) used 10m DEMs, providing a high level of detail. Basins that were analyzed in both studies have similar values for \( k_s \) and \( m/n \).

**Presence of a scaling break at \( A = 0.01 \text{ km}^2 \)**

Numerous other studies have identified the presence of a scaling break in slope-area space for basins in relatively uniform bedrock lithology (Montgomery and
Buffington, 1997; Whipple and Tucker, 1999; Stock and Dietrich, 2003; Kobor and Roering, 2004). These scaling breaks were identified at a number of different area and slope locations throughout the basin and attributed to varying processes. Some studies (Montgomery and Buffington, 1997; Whipple and Tucker, 1999; Montgomery, 2001?) attribute this break to the colluvial to alluvial transition zone where landslides and debris flow processes transition to fluvial bedrock channels, and the approximate location is at $10^5 - 10^6$ m$^2$ ($0.1 – 1.0$ km$^2$). At areas below this scaling break, slope remains approximately constant and areas larger than the break decrease in slope approximating a power-law relationship (Equation 5). Stock and Dietrich (2003) attribute their scaling break at S ~ 0.1 to a potential debris flow topographic signature.

In this study, I find the scaling break to occur at areas of approximately 0.01 km$^2$, which are relatively small areas and are generally the steepest portions of the study basins (S > 0.3 – 0.4). The “kink” appears to be the transition zone from hillslope to channel processes (similar to Montgomery and Buffington, 1997 and Whipple and Tucker, 1999). Much of the steeper topography of the Oregon Coast Range is composed of divergent noses and convergent hollows. Hollows act as areas of collection of sediment and debris (Reneau and Dietrich, 1991), potential sites for debris flow initiation (Schmidt et al., 2001) or regions where overland flow converges and contains enough kinetic energy to entrain material and begin channel initiation (Knighton, 1998; Selby, 2000). These hollows are typically steep (S > 0.3 – 0.4) and small (A < 0.01 km$^2$), consistent with the values and trend of the plots in slope-area space. Further work is needed to determine this feedback and illuminate other potential reasons behind the scaling break.
Shape of slope- area plots

Examining the shape of individual basin slope- area trends reveals not only the scaling break at 0.01 km$^2$, but the presence of large knickpoints and local steep reaches. Many plots exhibit stepped patterns as areas increase above 0.01 km$^2$. These patterns can be attributed to anomalously high slope relative to area over localized reaches, in some cases large knickpoints that are not related to changes in bedrock lithology (e.g. Sullivan Creek, see Figure 22 for the slope- area plot and Figure 15 B for the presence of this knickpoint along the surveyed reach). These systematic changes in slope were recognized by Stock and Dietrich (2003) on Sullivan and Marlow creeks, and attributed to these large knickpoints. This pattern is not characteristic of channels at a particular orientation to bedrock; rather it is present throughout all orientations. Channels without this pattern are better constrained in log-log space; representative of a systematic decrease in slope consistent with Equation 5.
4. DISCUSSION

4.1 MODES OF BEDROCK CHANNEL LOWERING

Physical processes

Field observations of bedrock streams in the Oregon Coast Range reveal a diverse collection of physical processes that remove material from the channel. Processes described by Whipple et al. (2000(A)) and Knighton (1998) such as abrasion and plucking act to shape the channel bed and control the morphologies of individual knickpoints. Abrasion of the channel bed along fracture planes creates flutes. The presence of numerous coarse tools in the base of many flutes indicates the fluvial sculpting of these features. The movement of particles during high flow events impacting the bed can produce weakening of fracture planes (Whipple et al., 2000(A)). This weakening, combined with undercutting of sandstone layers leads to plucking or spallation of large blocks from the knickpoint face. Flute growth behind the knickpoint face further weakens the rock adding to this process of spallation. Whipple et al. (2000(A)) describe this interaction of plucking and abrasional processes as one agent responsible for the formation of bedrock strath terraces. This combination of processes results in strath formation and the upstream propagation of knickpoints. Beveled bedrock surfaces downstream of knickpoints in the Oregon Coast Range are small strath terraces produced by the passing of the knickpoint and subsequent removal of material. Plucking of exfoliation sheets also removes material from the channel, although the mechanics behind the exfoliation sheeting remains unknown. This local scale suite of interactions
between processes can be responsible for short term lowering of the channel via knickpoint propagation. By quantifying centimeter to meter scale processes, their interactions and the controls exerted on channel morphology evolutions of bedrock channels can be better understood.

The combination of these physical processes leads to the upstream propagation of knickpoints. Each surveyed knickpoint displayed evidence of active erosion, indicating that individual knickpoints are transitory features on long temporal scales. The absence of erosional features on beveled bedrock surfaces downstream of knickpoint faces indicates that knickpoints move upstream over time. If the knickpoint face were to remain stationary over time (i.e. Figure 3B), erosional features would be prevalent downstream of the knickpoint face, as this is where material would be removed from the channel.

**Chemical weathering of the Tyee sandstone**

The Tyee Formation bedrock of the Oregon Coast Range consists primarily of deltaic sediments and turbidites (Snavely et al., 1964; Heller and Dickinson, 1985) derived from the Idaho Batholith (Heller et al., 1985). This rock is composed of lithics and arkosic fragments with large amounts of feldspar (Snavely et al., 1964; Heller et al., 1985). Thin section observations of the Tyee Formation show the rock to contain large amounts of potassic feldspar, numerous lithic fragments, quartz and some amount of biotite micas. Pettijohn (1963) defines this composition as a lithic sandstone or subgreywacke. Due to the moist climate of the Oregon Coast Range, chemical weathering of the Tyee formation may be relevant to removal of bedrock material in channels.
The high concentration of potassium feldspars in the bedrock warrants an examination of the hydrolysis of these minerals. Microcline (K-feldspar) will weather to muscovite, silica and dissolved ions in solution via the reaction:

\[
3\text{KAl}_3\text{Si}_3\text{O}_8 + 2\text{H}^+ + 12\text{H}_2\text{O} \rightarrow \text{KA}l_3\text{Si}_3\text{O}_{10} \text{(OH)}_2 + \text{H}_4\text{SiO}_4 + 2\text{K}^+ \quad (6)
\]

Muscovite is an unstable phase in temperate, humid conditions such as those present in the Oregon Coast Range, and readily weathers to the clay mineral kaolinite:

\[
2\text{KAl}_3\text{Si}_3\text{O}_{10} \text{(OH)}_2 + 2\text{H}^+ + 3\text{H}_2\text{O} \rightarrow 3\text{Al}_2\text{Si}_2\text{O}_5 \text{(OH)}_4 + 2\text{K}^+ \quad (7)
\]

(Weathering reactions after Blatt et al., 1980; Yatsu, 1988; Halsey, 2000) In addition to this process transforming microcline to kaolinite via muscovite, microcline can also weather directly to kaolinite (Blatt et al., 1980). Biotites, although not as abundant as the feldspars in the Tyee, can also weather to kaolinite (Yatsu, 1988), leading to large amounts of clay minerals in exposed channel bedrock.

Two samples of Tyee bedrock were examined as hand samples and thin section to observe chemical weathering processes taking place. The first sample is fresh and unaltered enabling me to determine the bulk composition of the Tyee formation. The second sample is from the stream channel, presumably actively undergoing chemical alteration. A noticeable difference between the hand samples is the color. The unaltered sample is gray in color and does not appear to have large quantities of secondary alteration minerals. The sample from the stream channel reddish-brown in color,
indicating the presence of alteration products. Thin section optical observations show the unaltered sample contains < 1% secondary minerals and is composed mainly of feldspars, quartz, biotite and lithics. The sample from the channel also contains quartz, but smaller amounts of lithics and feldspars. Approximately 15 – 20% of the channel sample compositions are secondary alteration products produced by chemical weathering.

Chemical weathering of the Tyee formation in stream channels has implications for rock strength at the channel surface and potentially the mechanics underlying exfoliation. Accumulation of clay minerals at the channel surface could weaken the rock and increase the amount of material removed by abrasion from impact of saltating grains or plucking. Certain clay minerals swell greatly when hydrated, this swelling of clays near the channel surface could further weaken the rock and serve as surface-parallel planes of weakness.

4.2 IMPLICATIONS FOR OTHER REGIONS

These controls on knickpoint and channel morphology can be applied to bedrock channels in regions with uniform jointed lithology. Joints and fractures exert the highest order controls on knickpoint morphology; lack of these could result in a less predictable knickpoint form. Abrupt changes in lithology can result in differential erosion rates and the formation of large, stationary knickpoints. These knickpoints will follow the second model proposed by Seidl and Dietrich (1992) and Seidl (1993), increasing in height over time. These processes and modes of propagation presented in this study are meant for regions underlain by homogeneous bedrock. The mode of knickpoint propagation may differ in varying lithologies, but propagation will occur. Knickpoints in homogeneous
strata, with or without jointing, will remain transient features so long as there is sufficient stream power to abrade the surface and pluck loosened blocks.
5. CONCLUSIONS

5.1 SUMMARY OF FIELD AND THEORETICAL STUDIES

Detailed observations from both field (physical) and model (theoretical) perspectives at a wide range of scales explains processes that are shaping bedrock channels and eventually basins in the Oregon Coast Range.

The bedrock and its structures in the Oregon Coast Range have a large impact on the morphology of drainage basins on all different scales. Influences are noted at individual knickpoints at the centimeter to meter scale and overall basin morphology at a scale of many square kilometers. At individual knickpoints, their morphology is controlled first by bedding thickness and orientation. The presence of interbedded sandstones and less cohesive siltstones leads to the undercutting of the sandstone layers and consequent spallation and removal of material from the knickpoint face. Bed orientation determines the height of knickpoints, their lateral spacing and presence of beveled surfaces above and below the knickpoint faces. Shaping the individual faces and exerting controls on their locations and orientations are a number of processes. Exfoliation sheeting removes material from the channel bed and rounds the face of a knickpoint. Fractures and planes of weakness in the bedrock control where the knickpoint face will be oriented and the locations and orientations of flutes that develop in the area proximal to the knickpoint face. These processes can be used to determine a mode of knickpoint propagation.
Field measurements and observations of knickpoints, bedding plane thickness and the presence of beveled strath surfaces downstream of knickpoints presents evidence for the upstream propagation of knickpoints. During the migration of the knickpoint, the overall height of the knickpoint remains constant while the face can rotate slightly. This process is controlled by bedding thickness and the orientations of fractures and planes of weakness in the bedrock.

Channel orientation relative to bedrock orientation and bedding in the bedrock exert controls on knickpoint height and lateral spacing. Bedrock reach morphology is also highly influenced by underlying structures. Detailed longitudinal profiles of channels that are strike-parallel, opposite dip and dip-slope display three distinct morphologies with different characteristics. Strike-parallel channels consist of knickpoints that are often stepped pairs followed by beveled, low gradient bedding plane surfaces. Channels opposite to bedrock dip have a high lateral density of knickpoints; these knickpoints comprise a high percentage of relief for a particular reach. Dip-slope channels are mostly bedding plane surfaces that are consistent with bedrock dip. Knickpoints are smaller in height and less dense laterally, comprising a smaller portion of relief of the channel. The majority of relief in dip-slope channels is felt via bedding plane surfaces.

The structure of the bedrock in the Oregon Cost Range also influences large-scale basin morphology. Slope-area analysis of different basins at various orientations to bedrock strike and dip reveals a topographic signature of dip-slope and opposite-dip basins and how their morphologies differ. The morphologies of entire basins reflect individual channel morphology which can be characterized with field based analyses.
Dip-slope and opposite dip channels were determined to have distinct slope values from each other, despite the fact that their concavity ratios are similar. These data sets combined with field surveys indicate that knickpoints may control basin morphology as well as local channel patterns.

5.2 FUTURE RESEARCH NEEDS

Further research beyond the scope of this project is needed to better understand the evolution of the topography of the Oregon Coast Range. Long term detailed observations of knickpoints and channels studied in this project could present opportunities to monitor the morphologies of knickpoints over time and how this affects the channel morphology. Field studies of basins present the opportunity to interpret the scaling break at 0.01 km$^2$ present in slope-area power law plots of basins in the OCR. Exfoliation sheeting is a poorly understood process, answers could be found through detailed studies of weathering in the Tyee sandstone. Ultimately, processes of bedrock incision can be used to predict the topography of bedrock-dominated mountain systems and the response of these landscapes to tectonic or climatic perturbations.
ACKNOWLEDGEMENTS

Thanks to Josh Roering for the project ideas, discussion and advising; T.C. Hales, Craig Stephens, Suzanne Walther and Russ Harrel for their field assistance.
References


FIGURE CAPTIONS

Figure 1. 30-meter DEM of the Eocene Tyee formation in the Oregon Coast Range study area and locations of the three field sites where channel survey data was taken and knickpoint maps were made. Geology and structures mapped by Baldwin (1956, 1961, 1973).

Figure 2. Photograph of a knickpoint on Spencer Creek, Smith River drainage. Idealized knickpoint nomenclature (after Holland and Pickup, 1976 and Gardner, 1983)

Figure 3. Three scenarios for erosion at knickpoints (after Holland and Pickup, 1976; Gardner, 1983; Seidl and Dietrich, 1992; Siedl, 1993). A: Top: Knickpoint face remains at constant height while propagating upstream. Bottom: Knickpoint face remains stationary while downstream material is removed, increasing the knickpoint height over time. B: Rotation of the knickpoint face over time.

Figure 4. Generic landscape depicting channels at three different orientations to bedrock structure. Anticline is representative of structures present in the OCR. Channel (1) is dip-slope, (2) is strike-parallel and (3) is opposite dip. No set scale.

Figure 5. Close up of exfoliation sheeting. Select exfoliation scarps have been highlighted, typical scarp height is between 1 and 2 cm for scale. Photo taken at Big Creek, April 2004.

Figure 6. Close up of a knickpoint face on Spencer Creek. Top sandstone layer is approximately 50 cm thick for scale. Dashed lines indicate locations of fractures in the upper sandstone layer. Select exfoliation sheets have been highlighted. Exfoliation sheeting has rounded the knickpoint face. Bedding is indicated, note the thin, recessive siltstone layer between the two sandstone layers.
Figure 7. Plan view of a knickpoint on Big Creek, a second order stream in the Lower Umpqua drainage system. Features were mapped by hand. Stream flow is from right to left, total knickpoint relief is approximately 1.5 meters.

Figure 8. Plan view of a second knickpoint on Big Creek. Stream flow is from right to left, total knickpoint relief is approximately 2 meters.

Figure 9. Fluting, fracture and knickpoint face on Big Creek. Fracture (dotted yellow line) and flutes (solid red line) have been highlighted. Note the knickpoint face lies along the fracture plane. Each flute has one axis sub-parallel to the fracture plane. The block in the center of the top flute is not in-situ, it has been carved and spalled off. Picture is 130 cm wide for scale.

Figure 10. Rose plots of fracture and joint orientations (left) and flute long axis orientations (right). Note the rough sub-parallel correlation between the fracture and flute orientations consistent throughout all areas studied. Mean channel azimuth is noted on each plot. A. Lower Sullivan Creek  B. Upper Sullivan Creek  C. Main stem Big Creek  D. North Fork Big Creek  E. East Fork Spencer Creek.

Figure 11. Plot showing relationship between flute long axis length (cm) and flute depth (cm).

Figure 12. Surveyed profile of Big Creek along its strike-parallel reach. Individual knickpoints and short alluvial regions are labeled. Dashed lines approximate bedding planes.

Figure 13. Photo of a stepped pair of knickpoints on Big Creek. Total relief comprised by the knickpoints is approximately 2 meters.
Figure 14. Surveyed profiles of opposite-dip channel reaches. Top is East Fork Spencer Creek, bottom is the opposite-dip reach of Big Creek. Individual knickpoints and short alluvial regions are labeled. Dashed lines approximate bedding planes.

Figure 15. Surveyed profiles of dip-slope channels. Individual knickpoints and short alluvial regions are labeled. Dashed lines approximate bedding planes. A. Top channel is Lower Sullivan Creek, bottom channel North Fork Big Creek. B. Upper Sullivan Creek. Note the large knickpoint at the top of the surveyed reach (photo is of this knickpoint, field bitch in the foreground is ~1.9 meters tall)

Figure 16. Schematic of headward knickpoint propagation.

1. Cross section view of a knickpoint consisting of two thick-bedded, massive sandstone layers with a weaker siltstone layer between. Dashed lines denoted (A) represent planes of weakness (fractures) in the sandstone.

2. Erosion of the knickpoint has begun. Fluting develops along fracture planes, removal of exfoliation sheets (B) rounds the knickpoint face. Preferential erosion of the less cohesive siltstone (C) undercuts the more endurated sandstone.

3. Development of mature flutes along fracture planes, continued removal of exfoliation sheets, rotation of the knickpoint lip, further undercutting of the siltstone layer.

4. Undercutting and fluting continue until the sandstone layer cannot support itself, block (D) spalls away causing upstream migration of the knickpoint face (E). The blue line represents the original knickpoint shape, note the knickpoint region remains at a constant height through propagation while the lip rotates.
Figure 17. Locations of basins used to produce the slope-area data set. Numbers correspond to basins listed in Table 2. Strike-parallel basins are red, opposite-dip basins black and dip-slope basins blue.

Figure 18. Cumulative slope-area plots for basins at three different orientations to bedrock. Data from all basins at a particular orientation was compiled and is displayed in these plots. A. strike-parallel basins B. opposite-dip basins C. dip-slope basins

Figure 19. Slope-area plot for Tap Creek, channel orientation is opposite bedrock dip. Shown are the scaling break at 0.01 km$^2$ and the regression generated power law data. Also indicated are areas where hillslope and channel processes dominate, and where channel initiation is believed to begin.

Figure 20. Box plots for $k_s$ and $m/n$ data sets. A. $k_s$ B. $m/n$

Figure 21. Plot of $k_s$ vs. $m/n$. Red triangles are dip-slope data points, purple boxes opposite-dip and blue diamonds strike-parallel basins.

Figure 22. Slope-area plot for Sullivan Creek. Scaling break at 0.01 km$^2$ is marked, dashed line indicates the zigzag pattern found for many basins regardless of channel orientation to bedrock. The large knickpoint highlighted in Figure 16 B is visible in slope-area space and is located on the plot.
TABLE CAPTIONS

**Table 1.** Summary of data collected from surveyed profiles. Shown is local reach slope (S), length of the reach (L), horizontal length felt via knickpoints (L_{kp}), percentage of lateral distance that the knickpoints compose (kp\_L), total vertical relief of the reach (Z), knickpoint relief (Z_{kp}) and percentage of vertical relief composed by knickpoints (kp\_Z).

* - The presence of a large, ~15m knickpoint on Upper Sullivan Creek greatly influences these values.

**Table 2.** Slope-area power law derived data for each of the basins studied.

**Table 3.** Mean values of k_s and m/n for each channel orientation.

**Table 4.** Values used for statistical analysis of sets of k_s and m/n values.

**Table 5.** Statistical comparison test values used.
Figure 1.
Figure 2.
Figure 3.
Figure 6.
Figure 7.

- **S3**: Beveled bedrock surface (0.1m)
- **BEDROCK - COLLUVIUM CONTACT (APPROXIMATE)**
- **Fracture location (azimuth)**
- **dashes indicate extrapolation**
- **Flute location (long axis azimuth)**
- **Long and short axis drawn to scale**
- **Shaded region represents densest exfoliation sheeting**
- **Stream flow**
Figure 8.

- Bedrock elevation
- Fracture location (azimuth)
- Dashes indicate extrapolation
- Flute location (long axis azimuth)
- Long and short axis drawn to scale
- Shaded region represents densest exfoliation sheeting

Legend:
- Beveled bedrock surface
- Bedrock elevation
- Fracture location (azimuth)
- Dashes indicate extrapolation
- Flute location (long axis azimuth)
- Long and short axis drawn to scale
- Shaded region represents densest exfoliation sheeting

Stream flow direction:
Figure 9.
Figure 10. (A and B)
Figure 10. (C and D)

Main stem Big Cr. (azm = 084)

North Fork Big Cr. (azm = 007)
East Fork Spencer Cr. (azm = 089)

Figure 10. (E)

Figure 11.
Figure 12.

Figure 13.
Figure 14.
Figure 15. (A)
Figure 15. (B)
Figure 16.
Figure 17.

Strike-parallel (1-11)
Opposite-dip (12-24)
Dip-slope (25-34)
Figure 18.
Hillslope processes
Channel initiation
Fluvial/Debris Flow Processes

Drainage Area (km²)
Channel Slope (m/m)

Tap Creek
\[ y = 0.0777x^{-0.4742} \]
\[ R^2 = 0.9103 \]

Figure 19.
Figure 20.
Figure 21.

Figure 22.
<table>
<thead>
<tr>
<th></th>
<th>S (m/m)</th>
<th>L (m)</th>
<th>L_{kp} (m)</th>
<th>k_{P_{L}} (m/m)</th>
<th>Z (m)</th>
<th>Z_{kp} (m)</th>
<th>k_{P_{Z}} (m/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Opposite- dip channels</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Big Cr</td>
<td>0.057</td>
<td>182.05</td>
<td>16.75</td>
<td>0.092</td>
<td>10.35</td>
<td>5.37</td>
<td>0.519</td>
</tr>
<tr>
<td>EF Spencer Cr</td>
<td>0.074</td>
<td>171.5</td>
<td>9.81</td>
<td>0.057</td>
<td>12.63</td>
<td>5.26</td>
<td>0.417</td>
</tr>
<tr>
<td><strong>Strike- parallel channels</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Big Cr (main stem)</td>
<td>0.048</td>
<td>233.32</td>
<td>12.36</td>
<td>0.0529</td>
<td>11.28</td>
<td>5.09</td>
<td>0.451</td>
</tr>
<tr>
<td><strong>Dip- slope channels</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NF Big Cr</td>
<td>0.096</td>
<td>226.14</td>
<td>11.44</td>
<td>0.0504</td>
<td>21.77</td>
<td>8.19</td>
<td>0.376</td>
</tr>
<tr>
<td>Sullivan Cr (lower)</td>
<td>0.069</td>
<td>217.4</td>
<td>16.54</td>
<td>0.0761</td>
<td>15.01</td>
<td>3.48</td>
<td>0.231</td>
</tr>
<tr>
<td>Sullivan Cr (upper)*</td>
<td>0.178</td>
<td>271.26</td>
<td>52.84</td>
<td>0.1947</td>
<td>48.29</td>
<td>23</td>
<td>0.476</td>
</tr>
</tbody>
</table>

Table 1.
<table>
<thead>
<tr>
<th>Basin Number</th>
<th>Drainage Name</th>
<th>Quadrangle</th>
<th>k_s</th>
<th>m/n</th>
<th>R²</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Buck</td>
<td>Smith River Falls</td>
<td>0.069</td>
<td>0.439</td>
<td>0.80</td>
<td>strike-parallel</td>
</tr>
<tr>
<td>2</td>
<td>Buck</td>
<td>Windy Peak</td>
<td>0.069</td>
<td>0.440</td>
<td>0.82</td>
<td>strike-parallel</td>
</tr>
<tr>
<td>3</td>
<td>Cedar</td>
<td>Goodwin Peak</td>
<td>0.075</td>
<td>0.522</td>
<td>0.95</td>
<td>strike-parallel</td>
</tr>
<tr>
<td>4</td>
<td>EF Green</td>
<td>Herman Creek</td>
<td>0.050</td>
<td>0.668</td>
<td>0.90</td>
<td>strike-parallel</td>
</tr>
<tr>
<td>5</td>
<td>Footlog</td>
<td>Elk Peak</td>
<td>0.096</td>
<td>0.436</td>
<td>0.92</td>
<td>strike-parallel</td>
</tr>
<tr>
<td>6</td>
<td>Jeff</td>
<td>Gunter</td>
<td>0.064</td>
<td>0.546</td>
<td>0.95</td>
<td>strike-parallel</td>
</tr>
<tr>
<td>7</td>
<td>NF Harvey</td>
<td>Deer Head Point</td>
<td>0.073</td>
<td>0.372</td>
<td>0.82</td>
<td>strike-parallel</td>
</tr>
<tr>
<td>8</td>
<td>Pataha</td>
<td>Clay Creek</td>
<td>0.045</td>
<td>0.522</td>
<td>0.92</td>
<td>strike-parallel</td>
</tr>
<tr>
<td>9</td>
<td>Un-named</td>
<td>Clay Creek</td>
<td>0.054</td>
<td>0.468</td>
<td>0.87</td>
<td>strike-parallel</td>
</tr>
<tr>
<td>10</td>
<td>SF Johnson</td>
<td>Trail Butte</td>
<td>0.077</td>
<td>0.565</td>
<td>0.91</td>
<td>strike-parallel</td>
</tr>
<tr>
<td>11</td>
<td>WF Spencer</td>
<td>Smith River Falls</td>
<td>0.060</td>
<td>0.428</td>
<td>0.89</td>
<td>strike-parallel</td>
</tr>
<tr>
<td>12</td>
<td>Franklin</td>
<td>Deer Head Point</td>
<td>0.086</td>
<td>0.414</td>
<td>0.81</td>
<td>opposite dip</td>
</tr>
<tr>
<td>13</td>
<td>Big</td>
<td>Elk Peak</td>
<td>0.080</td>
<td>0.424</td>
<td>0.96</td>
<td>opposite dip</td>
</tr>
<tr>
<td>14</td>
<td>Charlotte</td>
<td>Deer Head Point</td>
<td>0.108</td>
<td>0.415</td>
<td>0.86</td>
<td>opposite dip</td>
</tr>
<tr>
<td>15</td>
<td>Dean</td>
<td>Deer Head Point</td>
<td>0.089</td>
<td>0.463</td>
<td>0.96</td>
<td>opposite dip</td>
</tr>
<tr>
<td>16</td>
<td>EF Spencer</td>
<td>Smith River Falls</td>
<td>0.076</td>
<td>0.366</td>
<td>0.71</td>
<td>opposite dip</td>
</tr>
<tr>
<td>17</td>
<td>Hollo</td>
<td>Greenleaf</td>
<td>0.067</td>
<td>0.504</td>
<td>0.89</td>
<td>opposite dip</td>
</tr>
<tr>
<td>18</td>
<td>Marlow</td>
<td>Golden Falls</td>
<td>0.079</td>
<td>0.513</td>
<td>0.93</td>
<td>opposite dip</td>
</tr>
<tr>
<td>19</td>
<td>Oxbow</td>
<td>Gunter</td>
<td>0.060</td>
<td>0.637</td>
<td>0.91</td>
<td>opposite dip</td>
</tr>
<tr>
<td>20</td>
<td>Panther</td>
<td>Elk Peak</td>
<td>0.052</td>
<td>0.421</td>
<td>0.92</td>
<td>opposite dip</td>
</tr>
<tr>
<td>21</td>
<td>Tap</td>
<td>Scottsburg</td>
<td>0.078</td>
<td>0.474</td>
<td>0.91</td>
<td>opposite dip</td>
</tr>
<tr>
<td>22</td>
<td>WF Millacoma</td>
<td>Elk Peak</td>
<td>0.035</td>
<td>0.495</td>
<td>0.97</td>
<td>opposite dip</td>
</tr>
<tr>
<td>23</td>
<td>WF SF Johnson</td>
<td>Trail Butte</td>
<td>0.078</td>
<td>0.453</td>
<td>0.87</td>
<td>opposite dip</td>
</tr>
<tr>
<td>24</td>
<td>Woodruff</td>
<td>Golden Falls</td>
<td>0.068</td>
<td>0.538</td>
<td>0.96</td>
<td>opposite dip</td>
</tr>
<tr>
<td>25</td>
<td>Coon</td>
<td>Smith River Falls</td>
<td>0.050</td>
<td>0.506</td>
<td>0.94</td>
<td>dip-slope</td>
</tr>
<tr>
<td>26</td>
<td>Hadsall</td>
<td>Baldy Mountain</td>
<td>0.072</td>
<td>0.476</td>
<td>0.91</td>
<td>dip-slope</td>
</tr>
<tr>
<td>27</td>
<td>Herb</td>
<td>Twin Sisters</td>
<td>0.041</td>
<td>0.589</td>
<td>0.98</td>
<td>dip-slope</td>
</tr>
<tr>
<td>28</td>
<td>Johnson</td>
<td>Smith River Falls</td>
<td>0.046</td>
<td>0.597</td>
<td>0.97</td>
<td>dip-slope</td>
</tr>
<tr>
<td>29</td>
<td>Knife</td>
<td>Elk Peak</td>
<td>0.042</td>
<td>0.482</td>
<td>0.92</td>
<td>dip-slope</td>
</tr>
<tr>
<td>30</td>
<td>Otter</td>
<td>Elk Peak</td>
<td>0.046</td>
<td>0.437</td>
<td>0.90</td>
<td>dip-slope</td>
</tr>
<tr>
<td>31</td>
<td>Roberts</td>
<td>Elk Peak</td>
<td>0.075</td>
<td>0.423</td>
<td>0.95</td>
<td>dip-slope</td>
</tr>
<tr>
<td>32</td>
<td>Sullivan</td>
<td>Allegeny</td>
<td>0.091</td>
<td>0.359</td>
<td>0.70</td>
<td>dip-slope</td>
</tr>
<tr>
<td>33</td>
<td>Sweden</td>
<td>Twin Sisters</td>
<td>0.053</td>
<td>0.538</td>
<td>0.93</td>
<td>dip-slope</td>
</tr>
<tr>
<td>34</td>
<td>WF Deadwood</td>
<td>Herman Creek</td>
<td>0.049</td>
<td>0.587</td>
<td>0.93</td>
<td>dip-slope</td>
</tr>
<tr>
<td>Orientation</td>
<td>k_s</td>
<td>m/n</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>------</td>
<td>-----</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strike-parallel</td>
<td>0.067</td>
<td>0.491</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opposite dip</td>
<td>0.074</td>
<td>0.471</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dip-slope</td>
<td>0.056</td>
<td>0.499</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>n</th>
<th>k_s</th>
<th>S_k</th>
<th>m/n</th>
<th>S_x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strike-parallel</td>
<td>11</td>
<td>0.067</td>
<td>0.014</td>
<td>0.491</td>
<td>0.083</td>
</tr>
<tr>
<td>Opposite dip</td>
<td>13</td>
<td>0.074</td>
<td>0.018</td>
<td>0.471</td>
<td>0.070</td>
</tr>
<tr>
<td>Dip-slope</td>
<td>10</td>
<td>0.056</td>
<td>0.017</td>
<td>0.499</td>
<td>0.080</td>
</tr>
</tbody>
</table>

Table 4.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>k_s</th>
<th>( 2 = 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>F_c</td>
</tr>
<tr>
<td>St-p vs. Op-d</td>
<td>1.58</td>
<td>3.62</td>
</tr>
<tr>
<td>Op-d vs. D-s</td>
<td>1.13</td>
<td>3.87</td>
</tr>
<tr>
<td>St-p vs. D-s</td>
<td>1.39</td>
<td>3.78</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Comparison</th>
<th>m/n</th>
<th>( 2 = 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>F_c</td>
</tr>
<tr>
<td>St-p vs. Op-d</td>
<td>1.75</td>
<td>3.37</td>
</tr>
<tr>
<td>Op-d vs. D-s</td>
<td>1.31</td>
<td>3.44</td>
</tr>
<tr>
<td>St-p vs. D-s</td>
<td>1.08</td>
<td>3.96</td>
</tr>
</tbody>
</table>

Table 5.