Part I

Background

1 Introduction

Tectonics enters into every aspect of the earth sciences. Although it is possible to study erosional and depositional processes without concern for tectonics, the relief that permits these processes to continue is always in some way related to uplift or subsidence. For example, the erosional evolution of a landscape, as proposed by W.M. Davis, requires a tectonic boost to start the process (Davis, 1899; King and Schumm, 1980), and in an attempt to link tectonics to landforms, Walter Penck (1953) estimated relative rates of uplift and denudation from the shape of valley-side profiles.

Obviously, tectonics has had a role in earth history since the origin of the planet, and the interpretation of this history has been the traditional role of the structural geologist. More recently much attention has been paid to the role of tectonics in human affairs, and active tectonics has become a major concern with much emphasis on earthquake studies (McCalpin, 1996). Active tectonics is the ongoing deformation of the earth's surface (Wallace, 1985). More broadly, active tectonics is defined as "those tectonic processes that produce deformation of the earth's crust on a time scale of significance to human society" (Keller and Pinter, 1996, p. 2). As noted above, the major concern is with earthquake prediction. In order to predict and to understand active tectonics it must be studied within the context of the tectonic framework that probably developed during millions of years, which is the time span (post-Miocene) during which deformation is referred to as neotectonics. However, without measurements it is not possible to determine if one is dealing with ongoing active tectonics or geologically recent neotectonics. For us, the important factor is that the deformation is impacting a river, and it is the syntectonic response of the river that is of concern. Syntectonics refers to contemporaneous or coeval deformation and river response, which permits discussion of both active tectonic and neotectonic impacts on rivers. This is a largely ignored aspect of tectonic geomorphology, the study of landforms that result from tectonic processes (Yeats *et al.*, 1997, p. 139), which has been involved primarily with earthquake effects and prediction. Emphasis has been on the morphology and evolution of fault scarps, deformed river and marine terraces, and the morphology of mountain fronts (Bull, 1984; Morisawa and Hack, 1985; Merrits *et al.*, 1994; Keller and Printer, 1996; Keller *et al.*, 1998). We, on the other hand, are concerned with the effect of tectonics on the most susceptible of landforms, alluvial rivers and their deposits. The purpose is threefold as follows: to explain the variability of alluvial rivers, as affected by active deformation, to relate syntectonic river response to fluvial sedimentary deposits, flood hydrology, and hydraulics, and finally to consider briefly the practical significance of these findings for structural geologists, geomorphologists, sedimentologists, stratigraphers, economic geologists (petroleum), and river engineers.

Three books have been published that deal with structural landforms (Twidale, 1971; Tricart, 1974; Ollier, 1981), but the discussion of syntectonic effects on rivers is limited. In Tricart's (1974) book, the discussion centers on long-term effects of faulting and warping, the offsetting of river courses, the formation of lakes by faulting, and the effect of faulting on meanders, which may become very angular in plan.

Twidale (1971, pp. 133–6) recognizes the effect of faulting on drainage lines. He states that the rise of a fault block across a stream causes either the formation of a lake or swamp, or avulsion and the development of an irregular or abnormal drainage pattern. Twidale refers to the Murray River near Echuca in Victoria, Australia as a classic example of tectonic diversion caused by the rise of the Cadell Fault block (Figure 1.1), which has converted the Murray River from a single channel to two channels that flow around the obstruction (Bowler and Harford, 1966). The abandoned segment of the Murray River channel is preserved on the dipslope of the fault block.

Ollier (1981) devotes a chapter to drainage patterns, rivers and tectonics, and he discusses the effects of warping and faulting on drainage systems, but nothing on river morphology. However, recently Keller and Pinter (1996) have published a book on active tectonics, and they devote a chapter to rivers and drainage network response to deformation. More recently, Miall (1996) in his comprehensive work on fluvial deposits discussed the syndepositional effects of faults and folds.

Drainage patterns

Tectonic effects can be readily recognized in consolidated rocks, where stream channels and drainage networks have incised into and have

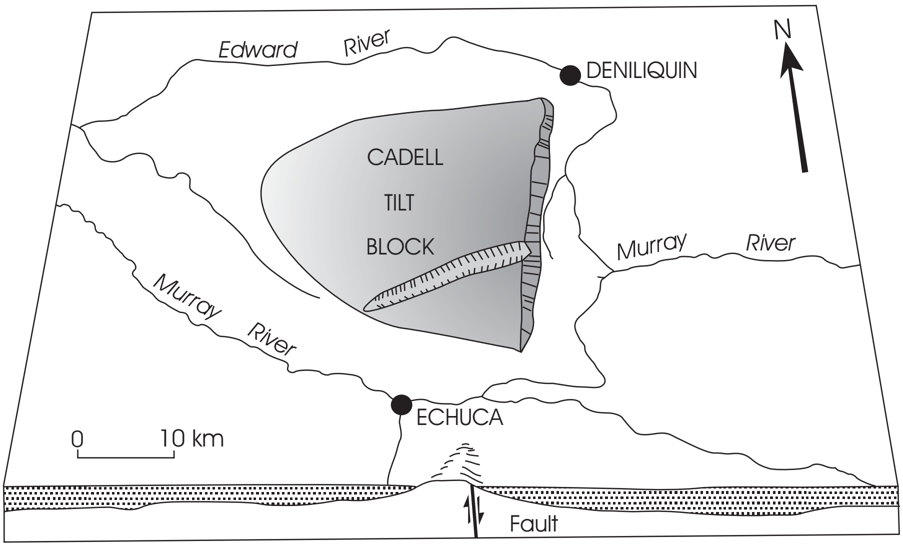

Figure 1.1 Disruption of Murray River, New South Wales, Australia, by Cadell Fault (modified after Bowler and Harford, 1966).

adjusted themselves to the varying resistance of rocks which compose the earth's surface. The best examples are the various types of drainage networks; for example, a rectangular drainage network forms as the result of intersecting joint sets or faults, and a trellis drainage network develops on folded strata (Figure 1.2, Table 1.1). In most cases, the effect of structure and tectonics is an accomplished fact. Nevertheless, there must have been a long period of adjustment, as the channels in the drainage networks responded to tectonic influences. If deformation was too rapid, undoubtedly there was a disruption of the existing river system. If deformation was slow, the existing river system could persist in its location. Deformation may not be continuous; it will probably be episodic, and it can cause earthquakes or it can be aseismic. An example of drainage network adjustment to tectonics is provided by Gupta (1997), who recognized the merging of several networks to form a gridiron or pitchfork pattern (Figure 1.3) in Nepal, as adjacent anticlines expanded laterally.

The landscape evolves as tectonically produced slopes are modified by erosion and deposition as well as by the continued growth of active structures (Figure 1.3). Drainage systems adapt to the changes of surface slope, and they have the potential to record information about the evolution of faults and folds (Ollier, 1981; Leeder and Jackson, 1993). For example, the drainage system on an anticline can mirror its structure and asymmetry (Figure 1.4A). In this case, there is a drainage divide situated close to the steeper flank. The

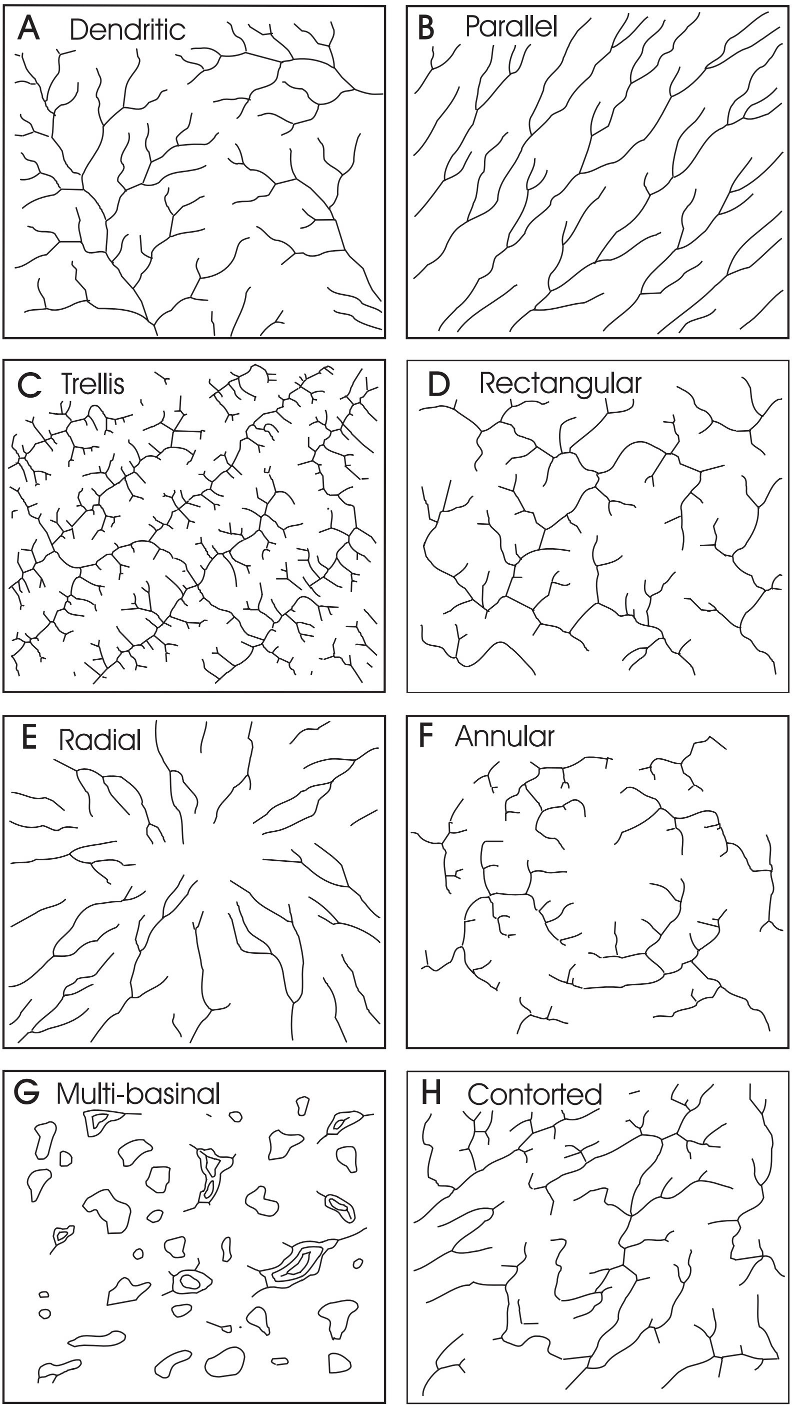

Figure 1.2 Drainage networks, for an explanation see Table 1.1 (modified after Howard, 1967).

Table 1.1. *Basic drainage patterns and their geologic significance. (see Figure 1.2)*

	Basic	Significance
A	Dendritic	Horizontal sediments or beveled, uniformly resistant, crystalline rocks. Gentle regional slope at present or at time of drainage inception. Type pattern resembles spreading oak or chestnut tree
B	Parallel	Generally indicates moderate to steep slopes but also found in areas of parallel, elongate landforms. All transitions possible between this pattern and type dendritic and trellis
C	Trellis	Dipping or folded sedimentary, volcanic, or low-grade metasedimentary rocks; areas of parallel fractures; exposed lake or sea floors ribbed by beach ridges. All transitions to parallel pattern. Type pattern is regarded here as one in which small tributaries are essentially same size on opposite sides of long parallel subsequent streams
D	Rectangular	Joints and/or faults at right angles. Lacks orderly repetitive quality of trellis pattern; streams and divides lack regional continuity
E	Radial	Volcanoes, domes, and erosion residuals. A complex of radial patterns in a volcanic field might be called multi-radial
F	Annular	Structural domes and basins, diatremes, and possibly stocks
G	Multi-basinal	Hummocky surficial deposits; differentially scoured or detailed bedrock; areas of recent volcanism, limestone solution, and permafrost. This descriptive term is suggested for all multiple-depression patterns whose exact origins are unknown
H	Contorted	Contorted, coarsely layered metamorphic rocks. Dikes, veins, and magmatized bands provide the resistant layers in some areas

Note:
From Howard (1967).

streams flow perpendicular to both the drainage divide and the structural contours on the uplifted surface. Although the structure of the Rock and Pillar range appears roughly symmetric (Figure 1.4B), its drainage system is very asymmetric. The drainage divide is located close to the front margin (southeast), across which there is a system of closely spaced streams flowing perpendicular to the divide and to the structural contours. The drainage pattern indicates that the symmetric box fold grew from an originally asymmetric fold related to movement of fault 1 (Figure 1.4B), which established the drainage divide along the southeast flank. The northwest flank was later elevated and steepened (fault 2), requiring the streams draining northwest to incise.

An important point to consider is that mountain ranges can be formed by

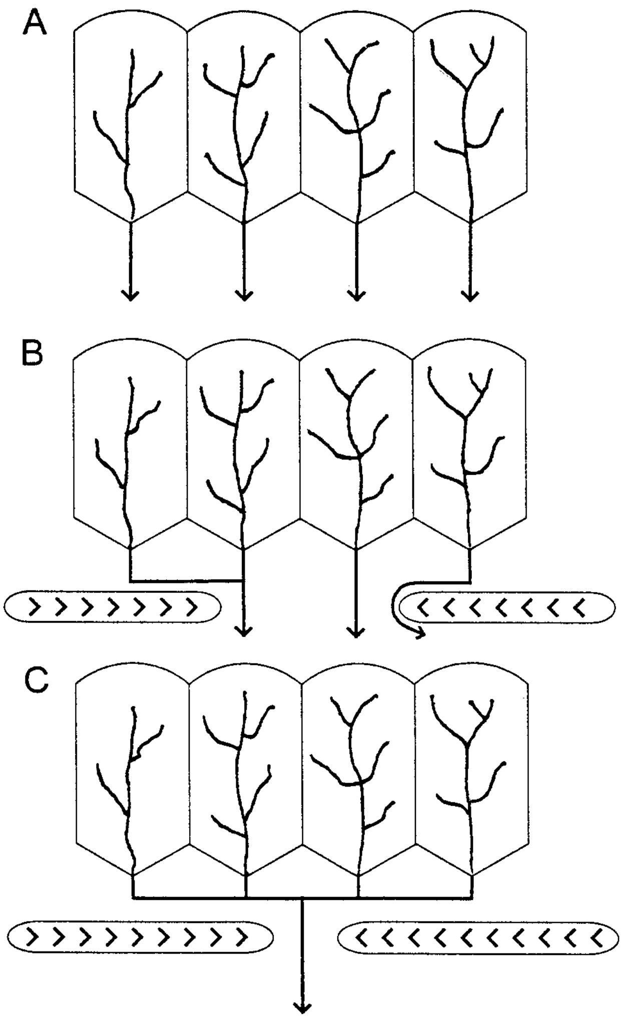

Figure 1.3 Cartoon showing disruption of several river networks by laterally growing anticlines to form a single network with a gridiron or pitchfork pattern (modified after Gupta, 1997).

the progressive longitudinal juxtaposition of discrete segments of the range. Jackson *et al.* (1996) analyzed longitudinal segment growth of the Blackstone and Raggedy Range and the Rough Ridge and South Rough Ridge, in the Alpine Range of New Zealand. The Blackstone and Raggedy Ranges constitute a continuous folded range schematically illustrated in Figure 1.5. The identification of the successive positions of the uplift is based on the occurrence of wind gaps on the drainage divide. Wind gaps on the Raggedy Range indicate that streams previously crossed the ridge south of the Ida Burn gorge (stage 1). This position has been progressively pushed northeast by the rising

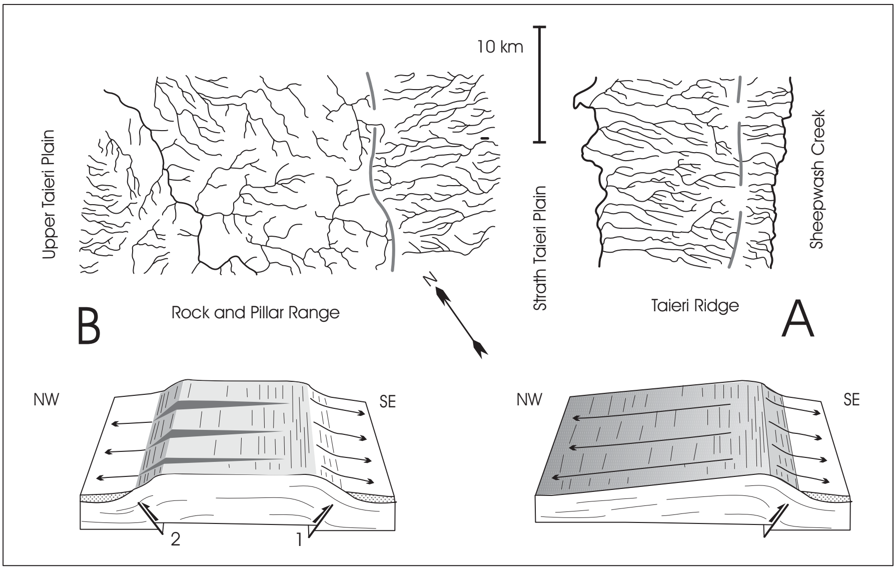

Figure 1.4 Maps and block diagrams of (A) Taieri Ridge and (B) Rock and Pillar Range, New Zealand (modified from Jackson *et al.*, 1996). Taieri Ridge has an asymmetric drainage pattern related to an asymmetric fold. The apparently symmetrical uplift of the Rock and Pillar Range has anomalous drainage and incised channels on one side, which indicates that the front thrust fault (1) occurred before the back thrust fault (2).

ridge of the Raggedy Range (stages 2 and 3). Increased width of the Raggedy Range uplift led to incision of Lauder Gorge.

Lateral growth of a folded range is also illustrated by the case of the Rough Ridge and South Rough Ridge near Oliverburn in Otago, New Zealand (Figure 1.6). Note the wind gaps on South Rough Ridge. They were formed by the drainage issuing from the front slope of Rough Ridge, prior to the uplift of the South Rough Ridge. The asymmetric pattern of the two major streams that cross South Rough Ridge suggests that the fault underlying it (2 in Figure 1.6) is later than the one forming Rough Ridge (1), and it has propagated to the north.

Jackson *et al.* (1996) propose an interesting check-list for the evaluation of drainage pattern development in segmented mountain ranges:

1. If the drainage divide (or fold axis) is perpendicular to the main streams on the flanks of the uplift (Figure 1.4), then the stream system is likely to be consequent with ridge development. If not, the stream system may be antecedent, predating the growth of the ridge.
2. If the asymmetry of the drainage is not mirrored in the asymmetry of

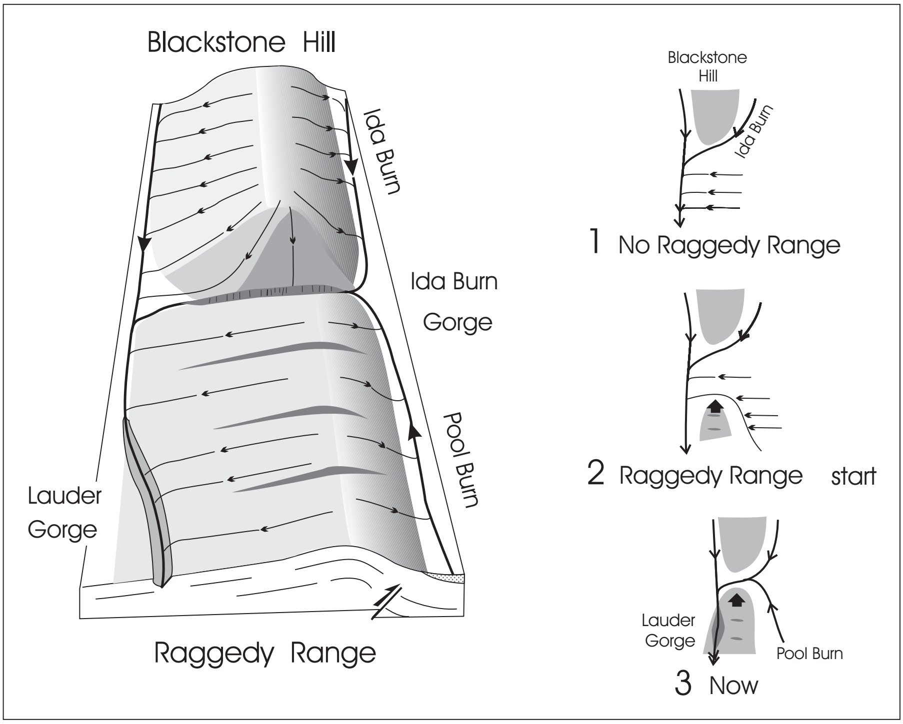

Figure 1.5 Schematic block diagram (left) illustrating the effect on drainage of propagation and joining of range segments, and interpretation of the evolution (right) (from Jackson *et al.*, 1996). Wind gaps were cut by previous drainage across the Raggedy Range (stage 1). As Raggedy Range was uplifted and extended to the north, the drainage was progressively directed toward the Ida Burn Gorge (stage 2). Water gaps are abandoned and Lauder Gorge was excavated as Raggedy Range uplift increased and the range expanded laterally (stage 3).

the topography (Figure 1.4), there may be other structural explanations.

3. The position of wind gaps on drainage divides may be significant for asserting both the relative ages (or activity) of structures and their directions of propagation (Figure 1.5).
4. Where antecedent streams cross ridges in gorges, the asymmetry of their catchment areas upstream may indicate the direction of propagation of the ridge (Figure 1.6).
5. Longitudinal stream courses may also contain clues to fault growth and interaction, particularly if they flow against the regional drainage trend, or incise through other structures (Figure 1.5).

The most interesting and challenging point of the Jackson *et al.* (1996) approach is the attempt to determine the age of deformation in relation to

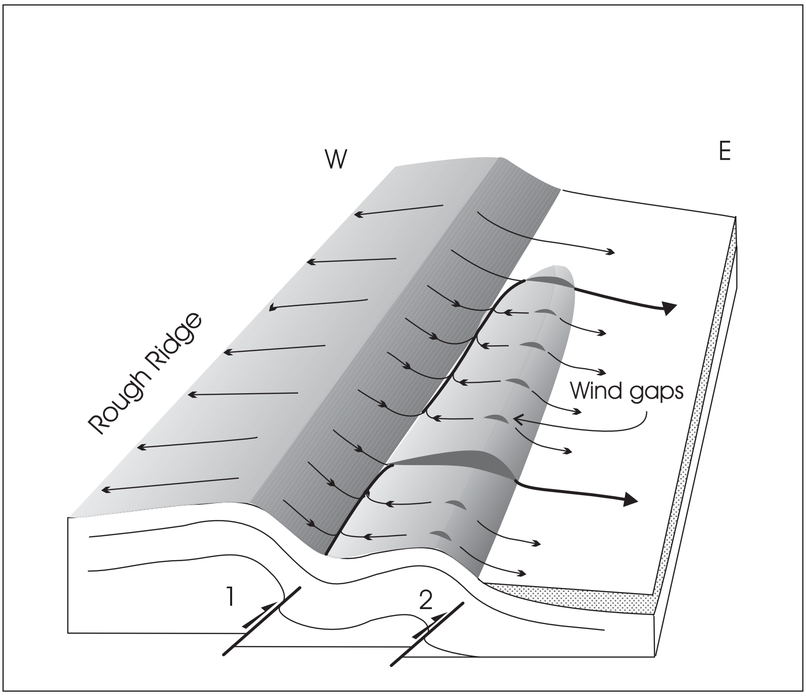

Figure 1.6 Schematic block diagram illustrating the structure of the drainage in a stepped range front (from Jackson *et al*., 1996). The gathering of major streams into asymmetric catchments that cross the low front ridge suggest that fault 2 is later than fault 1. Water gaps formed as drainage from the front slope of Rough Ridge was superimposed during the early stage of uplift. They are preserved as wind gaps due to the increase of the uplift and the formation of a two-directional drainage on the flanks of the low front ridge

fault movement and seismic activity. Leeder and Jackson (1993) also examined the effects of surface deformation due to normal faulting on stream channel behavior. Seismotectonic considerations led them to conclude that drainage patterns can help to analyze the structure and evolution of fault segments. The vertical movements and tilting associated with normal faults can establish a drainage pattern that is strongly influenced by the continuity of the faults.

Alluvial rivers

Alluvial rivers flow through sediments that have been eroded and deposited by the river. That is, they are not significantly affected or constrained by bedrock or old terrace alluvium. Their morphology reflects a balance between the erosive power of the stream flow and the erosional