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THE TIDE-DOMINATED HAN RIVER DELTA, KOREA

Geomorphology, Sedimentology, and Stratigraphic Architecture

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CHAPTER 1

Introduction

Chapter Points

- Tide-dominated deltas are the most common type of large delta in the world today
- Few have been studied
- Within them, proximal–distal trends in hydraulic energy, facies, and architecture are complex
- A well-accepted facies model does not exist
- The Han River delta was studied to help fill this knowledge gap
- It has the largest tidal range of any delta studied to date

River deltas are some of the most beautiful, complex features on Earth. Viewed from space, they almost look alive, their channels branching across the land surface like air passages in a lung or the limbs of a tree. In addition to looking alive, deltas help sustain life. Hundreds of millions of people live on them, commonly within meters of sea level (Goodbred and Saito, 2012). To the farmer, the delta is the field; to the engineer, the substrate of the city; to the geologist, the reservoir for drinking water and petroleum. To the ocean, the delta is like a security gate, a macroscopic physical, biological, and chemical filter through which most sediment, nutrients, and water-borne pollutants from the continent must pass. Deltas were one of the first sedimentary environments to be studied in detail (Gilbert, 1885; Fisk, 1944) and they remain the focus of intense study today (Bhattacharya, 2010).

All deltas share two fundamental traits. First, they consist primarily of fluvial sediment: deltas owe their existence to deposition from decelerating, expanding river flow issuing into a body of water. The sediment may be reworked by non-fluvial processes following initial deposition (Wright and Nittrouer, 1995), but ultimately the delta exists because a river supplied it with sediment. Second, deltas are progradational: they build outward into the body of water. The outbuilding typically occurs by accretion of sediment onto the distal (i.e., seaward) face of the delta, which in mature systems takes the form of a sloping depositional surface known as a clinoform. The term progradational is used somewhat loosely here. Deltaic outbuilding typically involves shoreline progradation, but for many of the larger and more strongly tidally influenced deltas, most of the outbuilding takes place far from shore, beneath the water surface (Figure 1.1). In these systems, the top ("topset") of the delta, across which most sediment is bypassed, is largely subaqueous, the prograding *clinoform** displaced 40–120 km offshore and submerged in 10–50 m of water (Friedrichs and Wright, 2004; Walsh et al., 2004).

* Words that are italicized are defined more fully in the Glossary at the end of the book.

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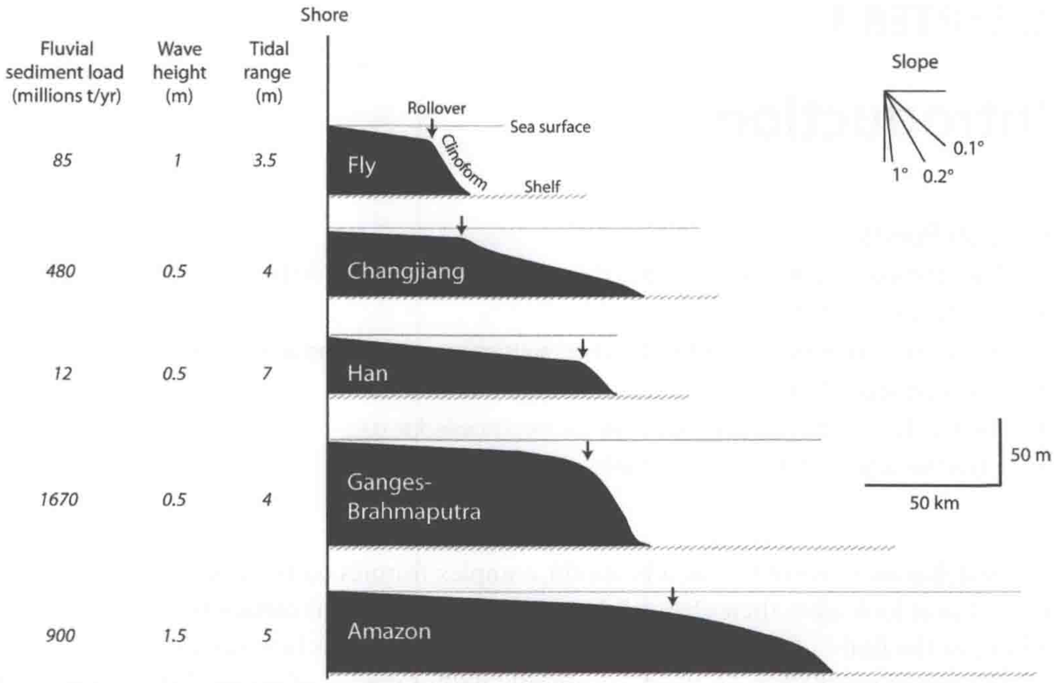

Figure 1.1 The Han River subaqueous delta platform compared to that of other tide-dominated and strongly tide-influenced deltas. Basinward is to the right. The sediment load, tidal range, and wave height values quoted should be thought of as average and approximate because they are inherently spatially and temporally variable. *Data from Milliman and Meade (1983), Hong et al. (2002), and Hori et al. (2002).*

Beyond these two common traits, variability is the norm. Grain size, basin physiography, tectonic setting, climate, and physical oceanography all play a role in determining delta physiography (Coleman and Wright, 1975), leading to a conceivably infinite number of possible outcomes. However, for large marine deltas, which tend to be fine grained because of inland trapping of coarse sediment, variability is often primarily a function of the physical oceanography of the receiving basin, and in particular the degree to which waves versus tidal currents rework the fluvial sediment in the coastal zone. Recognizing this, Galloway (1975) proposed a geomorphological classification of deltas with three end-member types: (1) river-dominated deltas, whose *mouth bars*—the fundamental deposit of river outflow (Bates, 1953)—experience little reworking by waves or tides; (2) wave-dominated deltas, within which waves and wave-generated currents perform most geomorphic work, reworking the mouth-bar sediment alongshore into beaches; and (3) tide-dominated deltas, within which tidal currents perform most geomorphic work, reworking mouth bars into shore-normal tidal bars. Significant advances in understanding have been made since Galloway's publication, thanks in part to numerical modeling (Pirmez et al., 1998; Swenson et al., 2005), flume experiments (Southard, 1991; Dumas et al., 2005), integration of ichnology (MacEachern et al., 2005) and hydrodynamic data (Kineke and Steinberg, 1995;

Geyer et al., 2004), and, perhaps most importantly, the study of deltas themselves (Wright and Nittrouer, 1995; Goodbred and Saito, 2012). However, Galloway's simple yet elegant scheme remains the *de facto* starting point for discussion.

Of Galloway's three end-member delta types, tide-dominated deltas remain the least well understood, despite the fact that five of the 10 largest rivers in the world today have tide-dominated or strongly tide-influenced deltas (Middleton, 1991; Goodbred and Saito, 2012). There are several reasons for this. At the time of Galloway's publication, several of the tide-dominated deltas he listed had not been studied in detail. Subsequent work has shown that some of these may actually be drowned river mouths still undergoing transgression (i.e., they are "*estuaries*" *sensu* Dalrymple et al. (1992)), not progradational sediment bodies that are actively outbuilding onto the shelf (i.e., *deltas*). The presence of very broad shallow water areas on the subaqueous delta plain (Figure 1.1), coupled with the presence of strong tidal currents, makes access difficult and dangerous. Thus, to this day, few modern examples of tide-dominated deltas have been studied in detail (for a summary, see Goodbred and Saito (2012)). Furthermore, within tide-dominated deltaic environments, proximal–distal variations in hydraulic energy, and thus facies, tend to be more complex and less well understood than in their river- and wave-dominated counterparts (Dalrymple and Choi, 2007). The morphologic complexity of tide-dominated deltas with their multitude of channels and bars further compounds the problem of characterizing such deltas. Consequently, a comprehensive tide-dominated delta facies model has not taken root in the geological community. This may explain why so few ancient examples have been identified despite their abundance in modern settings (Willis, 2005; Bhattacharya, 2010).

To help fill this knowledge gap, the Han River delta, a tide-dominated delta along Korea's west coast, was studied using a large integrated dataset of short cores, long drill cores, and seismic data (Figure 1.2). The study represents the most comprehensive investigation of a tide-dominated delta to date. Straddling the border between North and South Korea, the Han is the Korean peninsula's largest river. It debouches into Gyeonggi Bay (alternative spelling: *Kyunggi Bay*), a shallow (~40 m depth), rocky, wide-mouthed embayment fringed by tidal flats, dotted by bedrock islands, and characterized by an extreme tidal range (Figure 1.3), which exceeds 9 m at the very head of the bay during spring tides. The river mouth lacks a distinct shoreline protruberance, which has led some to refer to it as an estuary (Lee et al., 2013). However, as is common to all tide-dominated deltas studied to date (Figure 1.1), most of the action has taken place out of sight, beneath the water surface: previous data show that an aerially extensive, heterolithic package of sediment has aggraded and then prograded offshore of the river mouth, with upward of 60 m of sediment having accumulated since the last glacial maximum lowstand (Jin, 2001). The Han's subaqueous delta platform is not flat-topped like those of other deltas. Rather, it consists of several broad, shore-attached, finger-like protrusions. The protrusions are larger—and especially wider—than "typical" tidal bars observed in previously studied deltas. We therefore refer to them as large tidal bars. In the

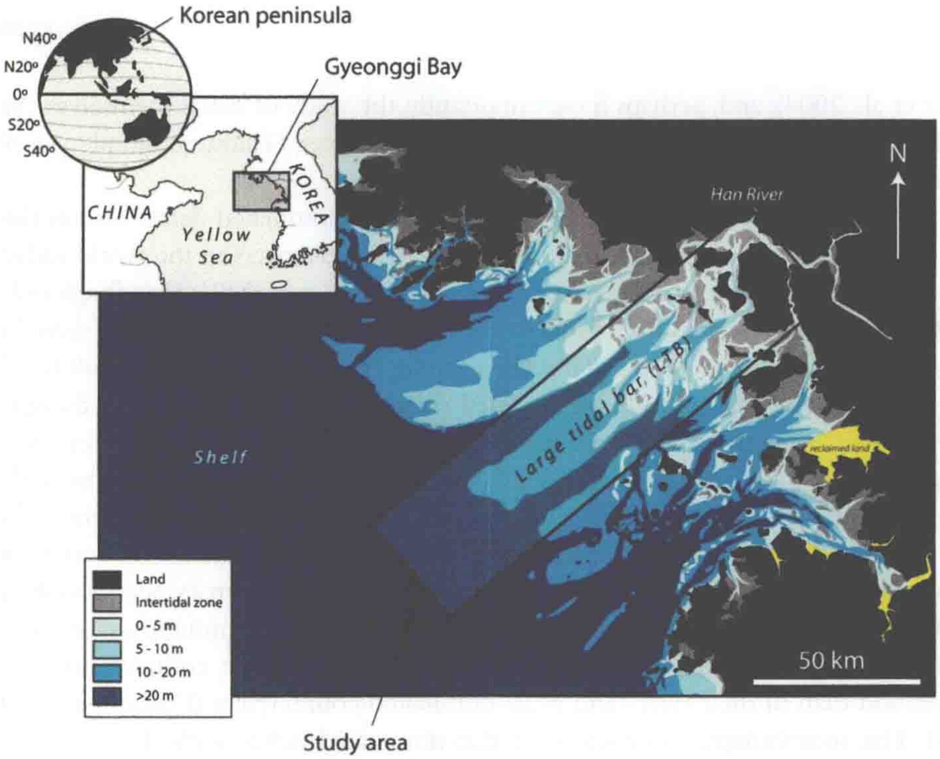

Figure 1.2 Location of the study area, Han River delta, Gyeonggi Bay, Korea. The Han River at this location demarcates the boundary between North and South Korea.

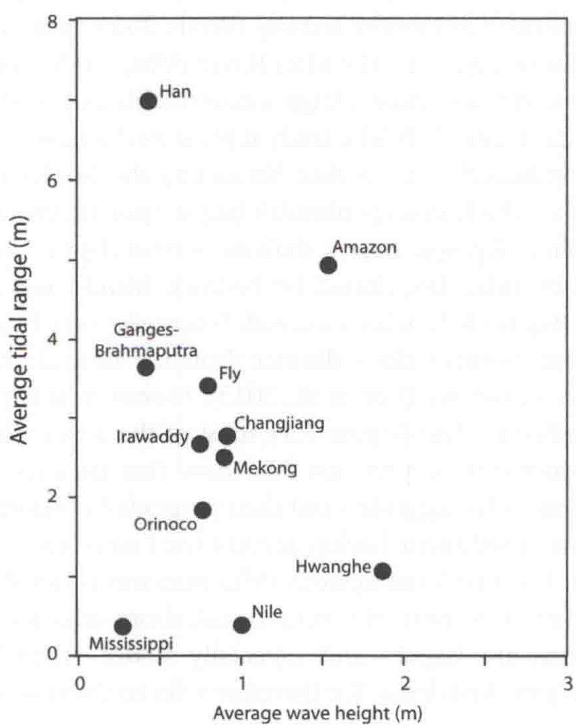

Figure 1.3 The Han River delta's depositional setting, as characterized by tidal range and wave height, relative to that of other major deltas *(in part from Hori et al. (2002))*. The Han River delta has by far the largest tidal range of any delta studied to date.

mid-2000s, an extensive dataset was collected from the centermost large tidal bar by a government–industry–academic consortium. These data, along with older, unpublished data from the inner large tidal bar (Jin, 2001), form the focus of this book. In later chapters, data from other subenvironments, such as *distributary channels* and *tidal flats* will be folded into the analysis, the overarching objective being to provide the reader with a holistic view of the geomorphology, sedimentology, and stratigraphic architecture of the delta. Specifically, readers will be provided with an outline of the "rules" governing the geomorphology of such systems; a comprehensive description of sediment facies, from the landward limit of the tidal flats along the shoreline seaward to the *prodelta* and shelf; information on the architecture of the deltaic deposits; and the sequence stratigraphic organization of the thick wedge of sediment that underlies the seafloor.

CHAPTER 2

Depositional Setting

Contents

Chapter Points

- Korean climate is monsoonal: summers are warm and wet; winters are cold, dry, and windy
- Precipitation events are intense and are associated with summer storms
- The Han River catchment is small and steep, with limited floodplains
- Fluvial discharge is seasonal and flashy; sediment yield is moderately high
- Extreme tides characterize the receiving basin
- Wave energy is low except during winter storms; the dominant wave energy flux is southward

The depositional setting imposes a set of conditions on a sedimentary system that, assuming similar internal (autocyclic) behavior, will lead to a repeatable (predictable) stratigraphic response in other locations under similar conditions. For the Han River delta, the key conditions are as follows (Figure 2.1).

- Han River water discharge is 23 km^3/year, 70% of which is delivered in summer. Maximum discharge is 30,000 m^3/s.
- Han River sediment discharge is 12.4 million tons/year, 10% of which is sand, and 90% of which is silt and clay. Sediment yield is 475 tons/km^2/year.
- The catchment is small, steep, commonly bedrock-confined, with limited floodplains.
- The receiving basin is a shallow epicontinental sea with a low-gradient seafloor, flanked by steep, bedrock-cored hills on the Korean peninsula.
- The tidal range is extreme (maximum 9 m). Tidal currents are almost rectilinear in Gyeonggi Bay. Current speeds exceed 2 m/s locally.
- Winds are weak and northward in summer, except during typhoons, and they are strong and southeastward in winter.
- Waves are small in summer, and bigger in winter but not huge (i.e., the bay is fetch limited). Waves decrease in size landward.

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- The water column is well mixed due to strong tidal currents, except possibly during river floods.
- The *Coriolis effect** is substantial, potentially leading to mud advection to the north.
- The precipitation is high in summer (intense rainfalls) and very low in winter.
- Climate is temperate and monsoonal. Climate may have become increasingly arid since the start of the Holocene.
- Sediment provenance is mixed (fluvial and shelf), but is fluvially dominant now. Comparatively more sediment may have been derived from the shelf during the early–mid-Holocene transgression.
- Bedrock consists of granite and metamorphic rocks that form small, steep mountains and coastal islands.
- The area is tectonically stable; a few meters of subsidence may possibly have occurred over the last 100 ka.
- In terms of sea-level history, the floor of the Yellow Sea was exposed during the last glacial maximum (LGM) lowstand, followed by a rapid rise (14 mm/year) from 17 to 8 ka BP, then a slow rise (1 mm/year) from 8 ka BP to present.

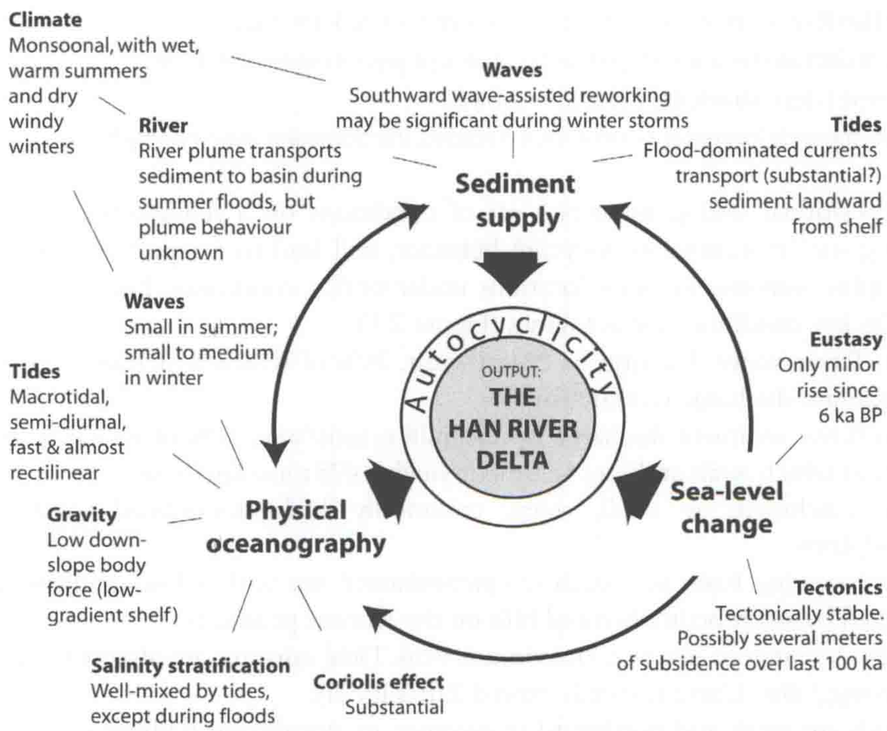

Figure 2.1 Controls on the physical character of the Han River delta (highly simplified). Note that three major controls exist: sea-level change (independent variable), physical oceanography (dependent variable), and sediment supply (dependent variable).

* Expanded definitions of italicized words appear in the Glossary.

- Sequence stratigraphically, the system is in the early highstand systems tract.
- Anthropogenic influences before Japanese occupation (i.e., pre-1910) include deforestation, dyking, and tidal-flat reclamation. Post-1910 influences include extensive dyking and an increased rate of tidal flat reclamation, construction of dams and concrete levees, deforestation, urbanization of floodplains, and extensive mining of sand bars in the lower Han River for concrete production.

2.1 PLATE TECTONIC SETTING

The tectonic framework of the Korean peninsula, and of East Asia in general, is characterized by two major factors: northwestward-directed subduction of oceanic crust beneath Japan (Schellart and Lister, 2005) and eastward expulsion of continental crust by the collision of India and Eurasia (Molnar and Trapponier, 1975) (Figure 2.2). Although the Korean peninsula now sits in a tectonically quiescent zone in the middle of stable, eastward-moving continental crust (Chiu and Kim, 2004), it has a complex tectonic history. Korea was assembled in the Mesozoic when three Precambrian terrains collided and sutured (Chough et al.,

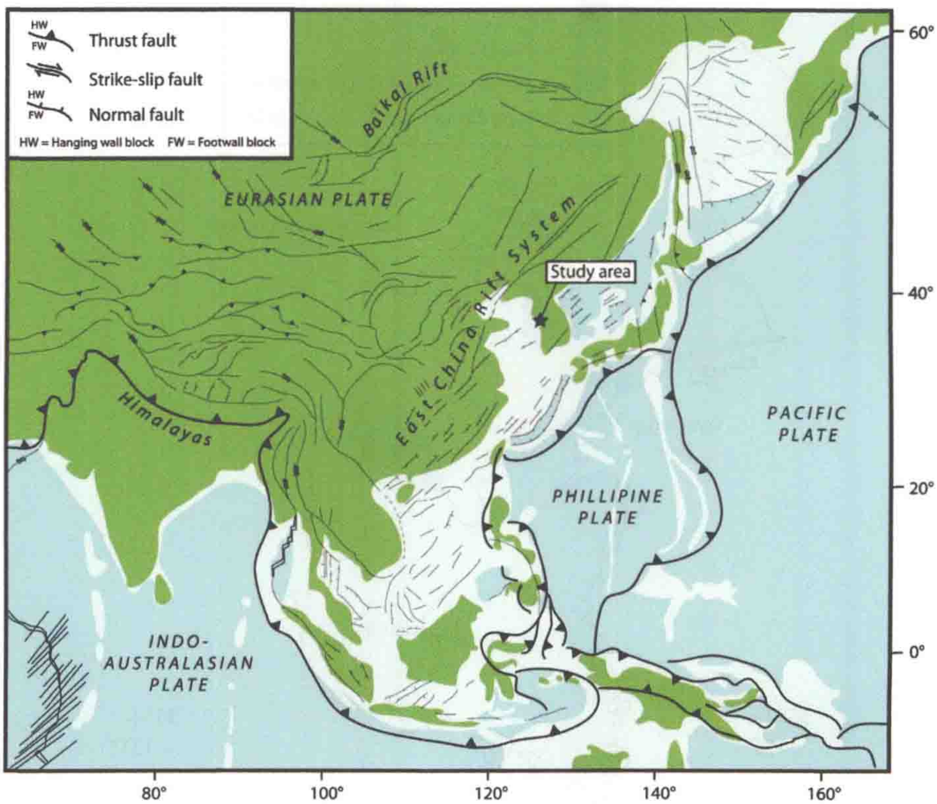

Figure 2.2 Tectonic map of East Asia. *Modified from Schellart and Lister (2005).*

2000). Since then, sedimentary, plutonic, and volcanic rocks have been deposited and emplaced as a result of westerly directed subduction (Figure 2.3), and the Japan/East Sea and Yellow Sea depressions have formed on either side of the Korean peninsula, likely as a result of backarc extension associated with slab-rollback (Schellart and Lister, 2005). Yellow Sea rifting and subsidence occurred first, between 65 and 30 Ma (Ren et al., 2002), whereas rifting in the Japan/East Sea started later, at 30 Ma, and proceeded to a seafloor-spreading stage before extension stopped at 10 Ma (Jolivet et al., 1994). The orientation of Gyeonggi Bay corresponds to the NE–SW structural grain of the Korean peninsula and Yellow Sea (e.g., Chough et al., 2000), suggesting its location may be structurally controlled.

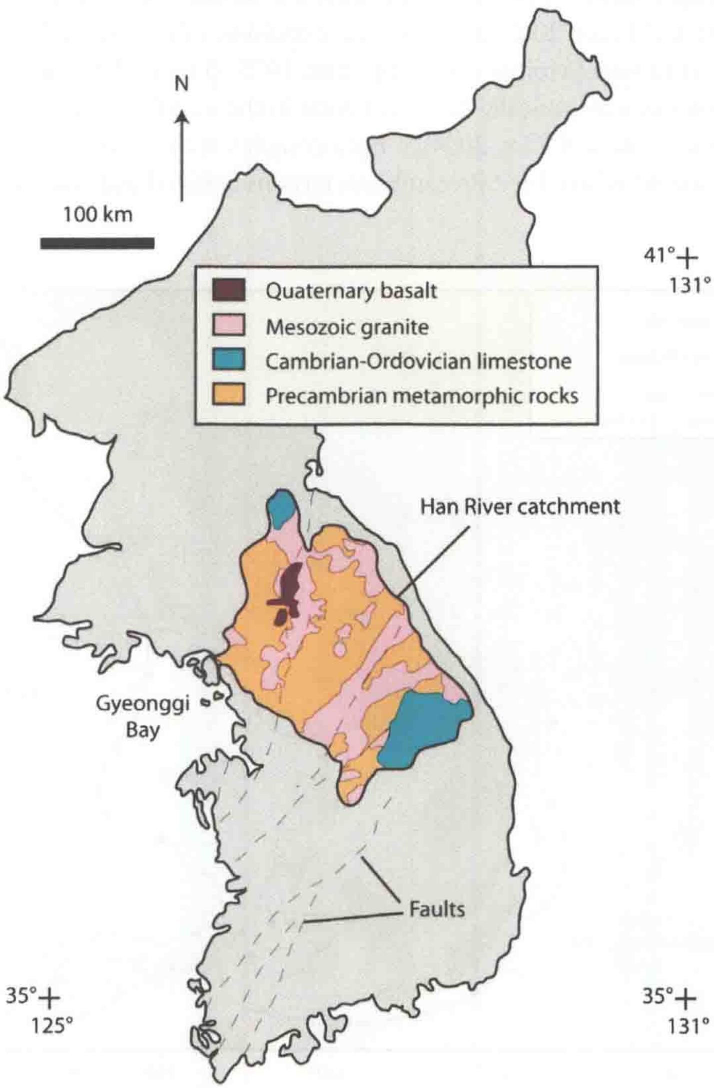

Figure 2.3 Bedrock geology in the Han River catchment. *Modified from Chough et al. (2000).*