Sedimentary Geology 363 (2018) 69–82

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Quantitative reconstruction of cross-sectional dimensions and hydrological parameters of gravelly fluvial channels developed in a forearc basin setting under a temperate climatic condition, central Japan

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ARTICLE INFO

Article history:
Received 14 September 2017
Received in revised form 25 October 2017
Accepted 26 October 2017
Available online 5 November 2017

Editor: B. Jones

Keywords:
Fluvial system
Bankfull channel depth
Bankfull channel width
Regression analysis
Japan
Iwaki Formation

ABSTRACT

Reconstructions of the dimensions and hydrological features of ancient fluvial channels, such as bankfull depth, bankfull width, and water discharges, have used empirical equations developed from compiled data-sets, mainly from modern meandering rivers, in various tectonic and climatic settings. However, the application of the proposed empirical equations to an ancient fluvial succession should be carefully examined with respect to the tectonic and climatic settings of the objective deposits. In this study, we developed empirical relationships among the mean bankfull channel depth, bankfull channel depth, drainage area, bankfull channel width, mean discharge, and bankfull discharge using data from 24 observation sites of modern gravelly rivers in the Kanto region, central Japan. Some of the equations among these parameters are different from those proposed by previous studies. The discrepancies are considered to reflect tectonic and climatic settings of the present river systems, which are characterized by relatively steeper valley slope, active supply of volcaniclastic sediments, and seasonal precipitation in the Kanto region. The empirical relationships derived from the present study can be applied to modern and ancient gravelly fluvial channels with multiple and alternate bars, developed in convergent margin settings under a temperate climatic condition. The developed empirical equations were applied to a transgressive gravelly fluvial succession of the Paleogene Iwaki Formation, Northeast Japan as a case study. Stratigraphic thicknesses of bar deposits were used for estimation of the bankfull channel depth. In addition, some other geomorphological and hydrological parameters were calculated using the empirical equations developed by the present study. The results indicate that the Iwaki Formation fluvial deposits were formed by a fluvial system that was represented by the dimensions and discharges of channels similar to those of the middle to lower reaches of the modern Kuji River, northern Kanto region. In addition, no distinct temporal changes in paleochannel dimensions and discharges were observed in an overall transgressive Iwaki Formation fluvial system. This implies that a rise in relative sea level did not affect the paleochannel dimensions within a sequence stratigraphic framework.

1. Introduction

Empirical relationships between geomorphic attributes of modern fluvial systems and the water conveyed through them, including the relationships among bankfull channel depth, mean bankfull channel depth, bankfull channel width, annual mean and bankfull water discharge, drainage area, and between variations in paleocurrent directions and sinuosity, have been used to estimate the geomorphological and hydrological features of ancient fluvial systems (Lorenz et al., 1985; Khan et al., 1997; Bridge and Tye, 2000; Bridge et al., 2000; Adams and Bhattacharya, 2005; McLaurin and Steel, 2007; Hampson et al., 2013; Xu et al., 2017). These studies used empirical equations that were derived from datasets obtained mainly from meandering rivers in passive continental margin and continental interior settings (Leopold and Maddock, 1953; Leeder, 1973; Ethridge and Schumm, 1978; Williams, 1984a, 1986; Blum et al., 2013). On the other hand, geomorphological and hydrological features of modern fluvial systems in various tectonic and climatic settings have also been studied in terms of regional hydraulic geometry (Jowett, 1998; Castro and Jackson, 2001; Montgomery and Gran, 2001; Moody et al., 2003; Lawlor, 2004; Chaplin, 2005; Modrick and Georgakakos, 2014). Hydrological features of fluvial systems are considered to be sensitive to allogenic controls, such as tectonic and climatic fluctuations (Kuenzi et al., 1979; Knox,

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https://doi.org/10.1016/j.sedgeo.2017.10.014
0037-0738/

1983; Leeder and Gawthorpe, 1987; Miall, 1996, 2014; Blum et al., 2000; Blum and Törnqvist, 2000; Straffin et al., 2000; Gawthorpe and Leeder, 2000). For instance, precipitation, valley slope, and rate of uplift control spatial and temporal variations in hydrological features in fluvial systems, such as water and sediment discharge, and denudation rates (Ohmori, 1983a, b; Blum and Törnqvist, 2000). These hydrological features also affect bed material size, proportion of bedload relative to suspended load, and channel form (Leopold et al., 1964; Carson, 1984; Schumm, 1985; Orton and Reading, 1993). Furthermore, each fluvial system has longitudinal variations in slope, grain size, bed configuration, and channel pattern (Ikeda, 1975). Thus, geomorphological and hydrological features of ancient fluvial systems should be reconstructed on the basis of empirical equations derived from modern fluvial systems, which have similar channel form and are developed under equivalent tectonic and climatic setting, as pointed out by Williams (1984b).

The relationships among the bankfull channel depth, mean bankfull channel depth, and bankfull channel width have been considered to be crucial for the quantitative reconstruction of channel dimensions and hydrological features of ancient fluvial systems (Leeder, 1973; Bridge and Mackey, 1993), because the bankfull channel depth has been reconstructed from outcrops, cores, and wireline-logs using the maximum thickness of bar deposits (Allen, 1965; Bridge and Diemer, 1983), and that of cross bedding (i.e., cross-set thickness: Bridge and Tye, 2000; Leclair and Bridge, 2001; Bridge, 2003) with some correction for diagenetic compaction (Ethridge and Schumm, 1978; Lorenz et al., 1985; Bridge and Mackey, 1993). Therefore, the empirical equations describing the relationships among the bankfull channel depth, mean bankfull channel depth, and bankfull channel width in modern fluvial systems in convergent margin settings is crucial to widen the applicability of geomorphological parameters for the reconstruction of paleohydrological features of ancient fluvial systems, particularly for fluvial channels formed in an ancient convergent margin setting. These relationships can also be used to provide an improved understanding of spatial and temporal variations in paleogeomorphological and paleohydrological features in response to global environmental changes, and spatial and temporal variations in tectonic regimes in a sedimentary basin.

In this study, we determined the empirical relationships among geomorphological and hydrological parameters, including bankfull channel depth, mean bankfull channel depth, bankfull channel width, drainage area, and mean and bankfull water discharges of modern gravelly rivers in the Kanto region of central Japan, which was developed in a forearc basin setting under temperate climatic condition (Fig. 1). The region consists of the Kanto Plain, which is the broadest alluvial plain in Japan and has some densely-populated cities, such as Tokyo and Yokohama (Fig. 1). The Kanto Plain is drained by several large river systems, such as the Tone, Naka, and Ara rivers, which flow from the western and northern mountains. These fluvial systems are characterized by relatively gentle valley slopes, moderate erosion rates, and supply of coarse-grained sediments compared to other fluvial systems in the Japanese islands (Yatsu, 1951; Takahashi and Sakaguchi, 1976; Ohmori, 1983a, b; Sakaguchi et al., 1986). Information on the hydrological features of modern rivers in the Kanto region is useful in the mitigation of flood-related disasters, as local heavy rainfall events in and around the Tokyo metropolitan area, located within the Kanto region, have increased in frequency in the recent years (Sato and Takahashi, 2000). Therefore, the purposes of this paper are to (1) construct empirical equations that describe the relationships among bankfull channel depth, mean bankfull channel depth, bankfull channel width, drainage area, and mean and bankfull discharges, based on the geomorphological and hydrological datasets of the modern fluvial channels of the Kanto region, (2) compare the empirical equations derived from the present study with those from modern fluvial systems in continental areas and those developed from datasets that are derived from fluvial systems in different tectonic settings, and (3) apply the empirical equations to an ancient fluvial system, developed in a convergent margin setting under a temperate climatic condition, for the reconstruction of paleogeomorphological and paleohydrological features of the Paleogene Iwaki Formation, Northeast Japan.

2. Relationships among geomorphic attributes of modern rivers in the Kanto region

2.1. Tectonic and climatic settings

The Kanto Plain is located in a forearc region of the Honshu Arc in the central part of the Japanese islands, and has been formed in response to the subduction of the Pacific and Philippine Sea plates beneath the North American (or Okhotsk) plate (Taira et al. 2016) (Fig. 1A). In addition to plate subduction, the collision of the Izu–Ogasawara (Bonin) Arc with the Honshu Arc has caused uplift of the mountains around the Kanto Plain in association with the development of active volcanoes in these mountains (Fig. 1B).

The temperate climatic condition in the Japanese islands is characterized by four distinct seasons and humid conditions with plentiful precipitation of about 900 mm to 3800 mm per year in average recorded from 1981 to 2010 (National Astronomical Observatory of Japan, 2016). The Kanto region experiences heavy rainfall in summer and early autumn in association with seasonal rain fronts and typhoons, although sunny weather is common even during the winter season. In addition, the mountain areas in the northern Kanto region also experience thunderstorm-related sudden showers in summer seasons (Nakamura et al., 1986). The annual mean precipitation and annual mean temperature of Maebashi, Gunma Prefecture, located in the upstream area of the Tone River (Fig. 1B), are 1248.5 mm and 14.6 °C (both average from 1981 to 2010), respectively (National Astronomical Observatory of Japan, 2016).

2.2. Modern fluvial channels and human impacts on them

In general, fluvial lowlands in the Japanese islands are divided into alluvial fan, natural levee and back marsh, and delta regions in the downstream directions (Yoshikawa et al., 1973). Ikeda (1975) classified the configuration of alluvial channels in the four regions into four types in the downstream direction as follows: (1) sandy and gravelly multiple bars, (2) sandy and gravelly alternate bars with sharp crest lines, (3) sandy alternate bars with obscure crest lines, and (4) absence of bars. The present study examined gravelly fluvial channels in the Kanto region (Fig. 1B), which have developed mainly in a levee and back marsh region and also partly in a distal part of alluvial fan region. The gravelly fluvial channels are commonly characterized by multiple-thread channels that are associated with point bars, mid-channel bars, and braid bars, and are equivalent to "sandy and gravelly multiple bars", and "sandy and gravelly alternate bars with sharp crest line" types of Ikeda (1975), although these two types of bed configurations gradually change in the downstream directions in each river. The studied gravelly fluvial channels are also considered to be classified as "braided, point bar" type as defined by Ethridge (2011). The slope and hydrological parameters, such as the mean annual specific discharge and denudation rate of the Tone River, which is the longest river in the Kanto region, are larger than those of continental area rivers, although these values are relatively small in rivers of the Japanese islands (Ohmori, 1983a, b; Sakaguchi et al., 1986). In addition, the Tone and some other rivers in the Kanto region have also received regular inputs of volcaniclastic material from active volcanoes in their hinterlands (Sakaguchi et al., 1986; Nakayama, 1997).

Most modern river channels in the Japanese islands have been subjected to engineering work, so they have not necessarily retained their natural geomorphological and hydrological features. The human impacts on the geomorphological and hydrological features of modern river channels were reviewed by Takahashi (1971, 1990) and Yamamoto (2004). For example, banks have been constructed on the natural levees on both sides of river channels to prevent floodwater