Tectonophysics 677–678 (2016) 241–247

Contents lists available at ScienceDirect

Tectonophysics

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

Estimation of maximum burial depth of Neogene–Quaternary fore-arc basin formation based on laboratory porosity measurements under pressure

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ARTICLE INFO

Article history:
Received 26 November 2015
Received in revised form 1 April 2016
Accepted 2 April 2016
Available online 9 April 2016

Keywords:
A fore-arc basin
The Kazusa Group
Laboratory experiment
Porosity measurement
Over pressurization
The maximum burial depth

ABSTRACT

Estimating the maximum effective stress that rocks have experienced, $P_{e,max}$, or the maximum burial depth for sedimentary rocks, D_{max}, is important for many types of research, ranging from engineering applications to estimation of tectonic evolution. We estimated $P_{e,max}$ and D_{max} for the Kazusa fore-arc basin formations (the Kazusa Group) in the Boso Peninsula of Japan using a laboratory-based method. We carried out measurements of porosity n with siltstone specimens from the Kazusa Group formations (the Umegase, Otadai, Kiwada, Ohara, and Katsuura formations) under various effective pressure P_e conditions and estimated $P_{e,max}$ from the inflection points of the log P_e-log n curve on the P_e increasing path. Except for the specimens from the Ohara Formation, estimated values of $P_{e,max}$ ranged from approximately 13–24 MPa. This range corresponded to approximately 1.3–3.2 km of D_{max}. Differences in D_{max} among the specimens were at least four times smaller than distances normal to bedding planes among the sampling locations. This suggests that the formations were not deposited horizontally, but that deposition proceeded as the subsidence center of the fore-arc basin moved in a northwestward (NW) direction, and that formations were then uplifted almost horizontally. The $P_{e,max}$ of the specimens from the Ohara Formation were 6–10 MPa smaller than the others. Thus, it is possible that pore pressure at the sampling location was more than 6 MPa larger than the hydrostatic condition when the sediments were deposited and lithified. Previous studies reported the center of a high-porosity zone at the Ohara Formation, and this high-porosity zone probably developed due to P_p over-pressurization. These results support the applicability of this method to estimation of tectonic evolution of sedimentary basins and magnitude of over-pressurization.

1. Introduction

Estimating the maximum effective stress that sedimentary rocks have experienced, $P_{e,max}$, is important for many types of research, ranging from estimation of tectonic evolution to engineering applications. For instance, stress history, especially $P_{e,max}$, significantly influences the hydraulic properties of sedimentary rocks or faults, as well as fractures in the rocks (Ingram and Urai, 1999; Zhang and Cox, 2000; Uehara et al., 2012). $P_{e,max}$ for sedimentary rocks is also directly related to rocks' maximum burial depth, D_{max}. Estimating D_{max} for sedimentary rocks is key to understanding the amount and rate of uplift, erosion, and exhumation of sedimentary basins.

Our goal is to estimate $P_{e,max}$ and D_{max} for the Kazusa Neogene–Quaternary fore-arc basin formations (the Kazusa Group) in the Boso Peninsula of Japan (Fig. 1). The Kazusa fore-arc basin is close to the Triple Trench Junction. Such junctions cannot be stationary with respect to the overriding plate (McKenzie and Morgan, 1969), and therefore the fore-arc regions experience time-dependent topography. Tectonic evolutions of the Kazusa fore-arc basin have been studied on a regional scale by many researchers (e.g., Mitsunashi et al., 1959; Mitsunashi, 1973; Kitazato, 1986, 1997; Kaizuka, 1987; Mitsunashi and Yamauchi, 1988; Tokuhashi, 1992; Yamaji, 2000), and the regional-scale movement of the Kazusa basin is well understood. Kitazato (1986, 1997) estimated the paleodepth of the Cenozoic strata on the Pacific side of central Japan based on benthic foraminiferal assemblage. Based on the data, Kaizuka (1987) roughly estimated that the amount of uplift at the south part of the Boso was approximately 2 km. However, a detailed evaluation of the local-scale variability of the maximum overburden (or $P_{e,max}$) has not been conducted for the Kazusa Group formations.

A variety of methods have been proposed for estimating the maximum overburden or magnitude of uplift of sedimentary basins (Anell et al., 2009). Conventional and practical methods to reveal $P_{e,max}$ and D_{max} for local-scale areas include (a) analysis of thermal history (Gleadow and Fitzgerald, 1987; Burnham and Sweeney, 1989; Bray et al., 1992; Laughland and Underwood, 1993; Jolivet et al., 2001; Japsen et al., 2007) and (b) methods based on mechanical compaction of sedimentary rocks (Bulat and Stoker, 1987; Japsen, 1998; Lin et al.,

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http://dx.doi.org/10.1016/j.tecto.2016.04.004
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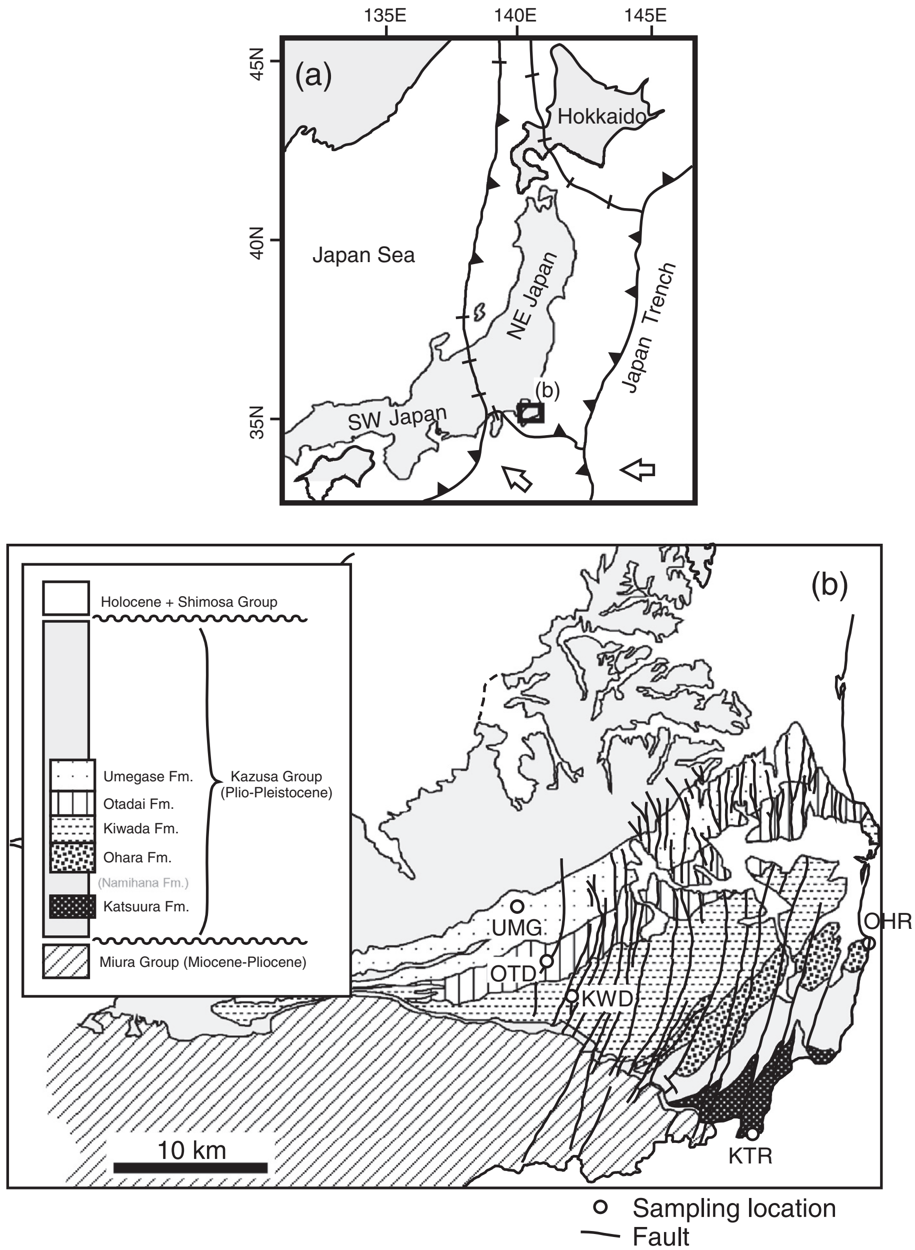

Fig. 1. (a) Location and (b) simplified geological map of the study area (after Ishiwada et al., 1971; Mitsunashi, 1973; Mitsunashi and Yamauchi, 1988). The sampling locations for the siltstone samples are also indicated. Most faults in the Miura Group are omitted in this figure for simplicity.

2003). The (a) methods estimate the thermal history of rock samples from vitrinite reflectance (Burnham and Sweeney, 1989; Bray et al., 1992; Laughland and Underwood, 1993; Hirono, 2005; Yamamoto et al., 2005; Japsen et al., 2007) or apatite fission track (Gleadow and Fitzgerald, 1987; Bray et al., 1992; Jolivet et al., 2001; Japsen et al., 2007) and reveal D_{max} based on estimated thermal history and geothermal gradient. With these methods, uncertainty of geothermal gradient directly affects the estimation of D_{max}. During the sedimentation and exhumation processes, geothermal gradients are time dependent, and therefore the estimation of D_{max} for a tectonically active basin based on these methods can be complicated.

Meanwhile, the (b) methods estimate D_{max} from observed depth-porosity or depth-elastic velocity relationships, based on the reference relationships of normal sedimentation-compaction processes (Japsen, 1998). The reference relationships are influenced by factors other than burial process, such as mineralogical composition, burial history, and environmental conditions such as temperature. It is therefore necessary that the reference relationships be established for each area studied. It is hard to establish the reference relationships for the Kazusa Group in the Boso Peninsula, because D_{max} is basically unknown at and around the area. In addition, mechanical compaction associating with porosity reduction might also be influenced by several time-dependent factors such as creeping, fluid drainage and pressure solution. Therefore, both (a) and (b) methods appear to be unsuitable for the Kazusa Group in the Boso Peninsula.

Wu and Dong (2012) proposed a laboratory-based method to determine $P_{e,max}$. In this method, a sediment/sedimentary rock specimen is compacted under confining pressure. As confining pressure is increased, porosity of the specimen is generally decreased, and the slope of the confining pressure-porosity curve plotted on a logarithmic or semilogarithmic basis may dramatically change at some confining pressure condition. In the case of soil, the confining pressure condition at the inflection of the curve is supposed to be the maximum effective overburden the soil has experienced, and stress conditions under and over the