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Autocyclic perturbations of orbitally forced signals in the sedimentary record

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ABSTRACT

Small-scale cyclicity in stratigraphic sequences (1 mm–10 m) is often attributed to regular orbital signals. Commonly, however, these signals are overprinted by other signals. A dynamic forward model for clastic sedimentation in foreland basins suggests that this overprint can be caused by slope instability, stress variations in the lithosphere, and autocyclic fluctuations induced by climate change. Spectral analyses of predicted sedimentation rates with various external controls demonstrate the occurrence of autocyclic fluctuations in sediment flux on time scales smaller than the time scale of the variation of the original, triggering, external control. This feature probably represents the response of the sedimentary system to external variations, depending on the eigenfrequencies of this system. Because the eigenfrequencies are determined by the basin geometry, changing through time, a chaotic frequency distribution of sedimentation rates is expected. This hypothesis explains the commonly observed absence of a significant number of frequencies of the orbital spectrum in a large number of sediment sequences.

INTRODUCTION

The stratigraphic record in many sedimentary basins is characterized by a hierarchy of small-scale (1 mm–10 m) variations in sediment composition (e.g., Clemmensen et al., 1994; Goodwin and Anderson, 1985; De Boer and Smith, 1994). Regular patterns in these variations have been explained as the impact of orbital processes with various periodicities, e.g., eccentricity ($1/400 \text{ ka}^{-1}$ and $1/100 \text{ ka}^{-1}$), obliquity ($1/41 \text{ ka}^{-1}$), and precession ($1/23 \text{ ka}^{-1}$ and $1/19 \text{ ka}^{-1}$), on the basis of results of astronomical analyses (Berger, 1988).

Orbital processes thus seem to override the generally chaotic sedimentary processes. However, studies of carbonate and clastic sequences in different settings show that the orbital signals can be obscured by other signals (e.g., Ten Kate and Sprenger, 1992; De Boer and Smith, 1994; Schwarzscher, 1993; Reijmer et al., 1994). In such cases, specific orbital frequencies appear not to occur, or frequencies are observed that do not correspond to an orbital frequency.

Speculations on the causes for these aberrations include autocyclic variations of sedimentation rates and tectonics (e.g., Lukyanov, 1987; Cloetingh, 1988; De Boer and Smith, 1994; Peper et al., 1992). Autocyclic, a process that is not very well un-

derstood, is caused by (self-induced) perturbations of topographic relief and can occur on different time scales. Examples of autocyclic controls are the high-frequency shifting of deltaic lobes and slope instability, which leads to the collapse of submarine slopes when they reach a critical angle (Stanley and Moore, 1983; Lukyanov, 1987). Slope instability is controlled by orbital and nonorbital processes, the latter of which are, for example, erosion and tectonic changes in topography and basin geometry. Short-term tectonic events (10 yr–100 ka), caused by stick-slip and aseismic faulting, may also affect sedimentation processes (Peper et al., 1992). The intensity and frequency of these motions depend on the rheological properties of rocks. Tectonically induced cyclic motions on a 10–100 yr time scale have been observed in the sedimentary record of swamp marshes in the western United States (Darienzo and Peterson, 1990) and in carbonate platforms in the Indian Ocean (Taylor et al., 1990).

In this paper, we examine the possible effect of variations in climate, slope instability, and intraplate stress on the sedimentary record in foreland basins. The following four models are presented: a standard model, a model of slope instability (with a low-angle critical slope and a high-angle critical slope), a model of intraplate stress variations (with and without slope instability), and a model of climate change. In each model, sedimentation rates at different sites in the basin are calculated. Variations in

sedimentation rates correspond to variations in layer thickness and probably to variations in sediment composition. Fourier analyses are used to investigate the impact of various processes on the sedimentary signal. Calculation of coherence of the frequency spectra allows a discrimination of processes that affect the stratigraphy, when external controls vary. It appears that a simple variation of external controls causes a complex response of sedimentation rates, with a large number of different frequencies, obscuring the frequency of the original variation.

MODELING

Forward Modeling

The sedimentation model is based on an elastic model of the lithosphere, flexurally loaded by evolving, and eroding, orogenic and sedimentary wedges (Fig. 1; Peper, 1993; Peper et al., 1994). Erosion and sedimentation are calculated from a diffusion equation (see also Kenyon and Turcotte, 1985; Flemings and Jordan, 1989):

$$\frac{\partial h}{\partial t} = \frac{\partial}{\partial x} K(x) \frac{\partial h}{\partial x}, \quad (1)$$

where h = height, t = time, x = distance, and K = transportation coefficient. The model adopts three different domains of fluid energy, each with a specific value for K : a fluvial and coastal-plain domain (K_f), a shelf domain (K_{sh}), and a slope domain (K_{sl}), with $K_f \gg K_{sh} > K_{sl}$ (e.g., Hanks et al., 1984; Stanley and Moore, 1983; see also

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Figure 1. Summary of forward model and definition of modeling parameters and environments. K refers to transportation coefficient in fluvial (fl), shelf (sh), and slope (sl) domains. Dot patterns in sediments reflect depositional fluid-energy domain of sediments.

Fig. 1). The values adopted for K are taken from Hanks et al. (1984) and Peper and De Boer (1995) and yield sedimentation rates varying between 2×10^{-5} and 9 mm/yr, with a mean of 1 mm/yr. Climatic variations are simulated by time-dependent changes of K_{fl} (200 ka half-sinusoidal fluctuation). For simplicity, no distinction between types of sediments has been made. However, it is likely that changes in the intensity of erosion are reflected in the sediment properties.

The initial modeling configuration adopts a 3000-m-high mountain belt and a 450–1000-m-deep basin about 100 km wide. The maximum dip of the sediment slope is 3° in the model with critical slope buildup, which is within reasonable limits of observations (e.g., Stanley and Moore, 1983). We adopt an effective elastic thickness (EET) of 20 km and a stress change of 20 MPa. The latter value is in the lower range of estimates inferred from seismicity studies and modeling (Govers et al., 1992; Peper et al., 1992).

Fourier Analyses

Sedimentation rates are calculated at the near-shelf edge of the basin and in the deeper marine realm for a period of 300 ka. Temporal variations in these rates have been converted to a frequency domain by means of fast Fourier transform methods using MATLAB (1988) programs. Smoothing and filtering have been performed with linear detrend and Hanning window filters. Because a 5000 yr time step is adopted in the forward models, frequencies higher than 10^{-4} /yr are ignored. Implicitly, any temporal effects of lateral node switching, caused by digitization of the model at each time step, are excluded from the analysis. Here we in-

vestigate whether significant changes in a reference spectrum occur when the external controls change. Such reference spectrum changes are determined by using coherence diagrams, reflecting the correspondence of the spectra of “observed” signals (model with external controls) and a reference signal (standard model), with values between 0 and 1 (e.g., Jenkins and Watts, 1968). If coherence for a specific frequency has a value V_{crit} , a $V_{crit} \times 100\%$ chance exists that the signal is the same as in the reference model, where this specific frequency is concerned. Otherwise, coherences smaller than a critical value mark potentially significant differences from the reference model in the frequency spectrum of the sedimentation rate. Here we define the critical value to be 0.3, which is a conservative estimate (see also Jenkins and Watts, 1968).

RESULTS

Lateral Variations

A significant difference is observed between the spectra at the shelf and at the slope (Fig. 2A). Low coherencies are predicted both in the low-frequency and high-frequency domains: more high-frequency signals are predicted at the shelf, largely as a consequence of larger transportation coefficients at the shelf. Higher values for transportation coefficients imply that topographic variations are modified at higher rates. Successive modifications of topography, therefore, also follow each other up more rapidly.

Slope Instability

Slope instabilities may cause significant perturbations of the standard signal

(Fig. 2B). In cases of slope instabilities, the relief of the shelf is minimized for a significant time, during the buildup of a slope to a critical angle. This minimization leads to a temporal modification of the rate of sedimentation, a modification that does not occur in the standard model (see also Lukyanov, 1987). Subsequent collapse of the slope introduces a disturbed topographic equilibrium, tending to restore itself as soon as possible. Consequently, a quasi-periodic process is introduced into the sedimentary system with a frequency previously absent in this system. Variations of sedimentation rates characterized by other frequencies may be impeded by this process. The impact of slope buildup and subsequent collapse is not identical at different sites in the basin and depends on the value of the critical angle of the slope (Fig. 2B). Because the critical angle depends on time-varying sediment properties, temporal variations in the character of frequency perturbation can be expected.

Stress

The effect of a 20 MPa change in horizontal stress appears minimal when slope instability is absent (Fig. 2C). When high-angle slope instability is introduced, i.e., the slope builds up to a critical angle, effects of stress do become significant, because of the change of the slope angle resulting from stress variations. Increase of compression causes laterally varying subsidence, temporarily reducing or increasing the slope angle. This change in slope angle can lead to delay or acceleration of slope collapse, imposing another type of cyclicity on the sedimentary signal.

Climate

The model predicts that a 200 ka climate fluctuation causes a large perturbation in the high-frequency domain of the reference model; i.e., a long-wavelength process (200 ka) also has effects in the short-wavelength (10–40 ka) domain (Fig. 2D). This perturbation can be explained as follows. The response of sedimentation rates at a location x to changes in the entire basin can be described by an operation Ox :

$$O \propto O\left(\frac{\partial A(t)}{A(t)}\right), \quad (2)$$

with $\partial A(t) \propto \Delta b + \Delta S$, where $A(t)$ reflects the initial accumulation space and $\partial A(t)$ the change in it (see also Peper, 1993); Δb represents vertical motions of the basement due to, for example, intraplate stress variations, loading, and unloading of the lithosphere by sedimentation in the basin and erosion of the accretionary wedge; and ΔS reflects rel-

active sea-level changes by eustatic processes or basin floor rise as a result of sediment filling.

Operator O has a number of eigenvectors and eigenvalues that basically reflect eigenfrequencies of the sedimentary system and powers of them. The eigenfrequencies may partly represent the autocyclic response of the system, which implies that sedimentary sequences incorporate system-generated, cyclic patterns (see also Griffiths and Smith, 1993). Because $O \propto 1/A(t)$, and $A(t)$ is determined by the basin geometry (Peper, 1993), it follows that continuous modifications of autocyclic changes of sedimentation rates occur as a result of the continuous changes in basin geometry.

This theorem applies to any other quantitative model for sedimentation in the sedimentary basin (e.g., Beaumont et al., 1990). If geologic systems obey physical laws, represented by an operation Ox , signals with temporally varying, and thus chaotically distributed, eigenfrequencies will appear in the sedimentary record.

DISCUSSION AND CONCLUSIONS

Numerical models demonstrate that the character of stratigraphic sequences in sedimentary basins is at least partly determined by the eigenfrequencies of the sedimentary system. These frequencies can be regarded as frequencies of the autocyclic response of the sedimentary system and are strongly dependent on the basin geometry and the character of the sedimentary environment (e.g., shelf domain or slope domain). Because any variation of the external controls produces a new perturbation of the sedimentation rates, a chaotic frequency distribution seems likely when one compares different sedimentary systems (see also Griffiths and Smith, 1993). Orbital frequencies are commonly reconstructed on the basis of thickness distributions, i.e., adopting assumed sedimentation rates, whereas the modeling presented here shows that care should be taken when inferring orbital controls on a sedimentary sequence based on such assumptions. The theory of eigenfrequencies could well explain the notion that in almost any study of repetitive sequences, only a few of the complete spectrum of orbital frequencies are observed (see also Schwarzacher, 1993; Weltje and De Boer, 1993). For example, a number of external Milankovitch cycles can be superimposed on the response of the sedimentary system. Which of the cycles are obscured depends on the evolving shape of the accommodation space. Consequently, different cyclic patterns are expected in different basins and in different superimposed sequences in the

Figure 2. Coherence and power spectra of sedimentation rates on shelf and on slope in (A) standard model, in which coherence was calculated between slope and shelf, (B) model with slope buildup and slope instabilities, (C) model with intraplate stress variations, and (D) model with 200 ka climate variation. In B-D, coherence calculated between standard model and models with external controls. Confidence intervals have not been marked because the signals are computer generated and therefore identical for each experiment. Horizontal lines in upper panels mark critical coherence with value 0.3.

same basin. This result may explain observations of the above features in the Mediterranean basins (Weltje and De Boer, 1993; Hilgen, 1994) and on Greenland (e.g., Clemmensen et al., 1994). Therefore, this study does not point to absolute values of eigenfrequencies in sedimentary basins. More detailed studies and accurate dating of stratigraphic cycles are required to do so.

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