Effects of in-phase and out-of-phase sediment supply responses to tectonic movement on the sequence development in the late Tertiary Southern Ulleung Basin, East (Japan) Sea

Wonsuck Kim\textsuperscript{a,b,*}, Daekyo Cheong\textsuperscript{b}, Christopher G. St. C. Kendall\textsuperscript{c}

\textsuperscript{a}Department of Geology and Geophysics and St. Anthony Falls Laboratory, University of Minnesota, Minneapolis, MN 55414, USA
\textsuperscript{b}Department of Geology, Kangwon National University, Chuncheon, Kangwon-do 200-701, Korea
\textsuperscript{c}Department of Geological Sciences, University of South Carolina, Columbia, SC 29208, USA

Received 21 July 2005; received in revised form 9 May 2006; accepted 1 August 2006

Abstract

Stratigraphic inverse modeling using the SEDPAK stratigraphic simulator established the size of the physical parameters that together controlled the development of the stratigraphic patterns in the late Tertiary Ulleung Basin, East (Japan) Sea. The modeling results provided a quantitative history of the basin. This included the dimension of variations in rates of tectonic subsidence (or uplift) and sediment supply. Input variables were based on the ages and geometries of strata determined from well and seismic interpretations and the given base-level control of the Haq et al. eustatic curve. The simulation results indicate that changes in the rate of sediment supply clearly correlate with local back-arc tectonic events that occurred both with (out-of-phase) and without (in-phase) a time lag associated with the local tectonic movements. The initial package of the basin stratigraphy was generated by an in-phase response of sediment supply to back-arc spreading in the Early and Middle Miocene, during which a high rate of sediment supply caused a series of downlap surfaces onto which strata prograding northward. In contrast, the basin experienced an out-of-phase response to the sediment supply during the second stage of basin growth, a back-arc closure characterized by rapid uplift, thrusts, and folds during the Late Miocene. In the latter case, the time lag in sediment supply response, caused by sediment trapping behind the thrust zone, produced transgressive surfaces and halted basin growth, and then gradually forced the shelf front to migrate basinward as the sediment supply slowly increased in response to the further tectonic uplift.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: Back-arc; Eustatic sea level; Stratigraphic modeling; Tectonic subsidence; Ulleung Basin

1. Introduction

Over the last two decades conventional sequence stratigraphic analyses have developed conceptual models in which sediment-stacking patterns are interpreted as signatures to allocyclic changes in basin forcing, particularly eustasy (Vail et al., 1977; Pitman, 1978; Jervey, 1988; Posamentier and Vail, 1988; Posamentier et al., 1988; Wilgus et al., 1988;
The application of the conceptual models to systems dominated by tectonic movement, however, has not been as widely accepted. This is because a combination of tectonic movement and tectonic driven sediment supply often is a dominant influence on the development of geometric configuration of the stratigraphic section, and suppresses the effects of the eustatic control on regression and transgression.

The Ulleung Basin is a late Tertiary back-arc rift basin in the East (Japan) Sea off the Korean coast. It has experienced marked basin-wide tectonic signatures across the whole basin that has controlled the effects of both tectonic movement and sediment supply on stratigraphic development. The sequence stratigraphic simulator (SEDPAK) was used to reconstruct a depositional history of the Ulleung Basin. It was used to investigate how changes in rates of regional tectonic movement acted as a driver of sediment yield in the sediment source area, and enabled sediment to be trapped in the basin depocenter. The results of the SEDPAK model runs demonstrate that there were at least two kinds of sediment supply response to basin tectonism. These are designated as in-phase and out-of-phase (Fig. 1); for the in-phase response, the sediment supply responds immediately to the tectonic event and changes in rates of the tectonic movement and sediment supply coincide with each other, with no time lag. In contrast the out-of-phase response includes a time lag that is either the product of a rate of sediment supply that remains low when tectonics is already active and then slowly increases or alternatively the rate of sediment supply is still high when tectonic event ends and then slowly decreases. The objective in this paper is to reconstruct the Ulleung Basin’s geohistory and stratigraphy and provide a fundamental understanding of the connection between these in-phase and out-of-phase responses and stratigraphic development. In the course of modeling, it is shown how to optimize basin analysis and observed data so they can be used as process parameters.

2. Geologic setting of Late Tertiary Ulleung Basin

The Ulleung Basin lies between the Precambrian and Paleozoic craton of the Korean Peninsula to the west and the Cenozoic Japanese Island Arc to the east (Fig. 2(A)). The basin is on the eastern margin of the Amurian Plate where it overrides the Pacific and Philippine plates, and is associated with the convergent zones of the Japan trenches and the Nankai Trough (Minami, 1979; Uyeda and Kanamori, 1979; Chough and Barg, 1987). The Ulleung Basin has experienced three major tectonic events related to the migration of the convergent zones. These are referred to as Stages I, II, and III. The basin was initially formed by back-arc spreading related to the process of subduction (Stage I) (Isezaki and Uyeda, 1973; Uyeda and Miyashiro, 1974; Uyeda and Kanamori, 1979). This initial subsidence of the Ulleung Basin began sometime prior to 25 Ma (Chough and Barg, 1987). In response to the back-arc spreading, the SW Japanese Islands detached from the eastern Asian continent and then migrated southeastward over 250 km (Yoon et al., 2002) while the lithosphere under the Sea of Japan appears to have stretched and thinned to less than 50 km (Utsu, 1971; Yoshii, 1973). In the Late Miocene, the collision zone of the Bonin Arc with the Amurian Plate met the central
axis of Honshu Island (the main island of Japan) and caused the subduction hinge to retreat landward at the Ryukyu Trench (Nankai Trough) (Chough and Barg, 1987). This landward-retreating subduction zone caused back-arc closure of the Ulleung Basin (Stage II) (Matsuda, 1979). This compressional tectonic event forced the southern margin of the basin to rise, while NE–SW trending thrust faults and wrench structures formed (Inoue, 1982; Chough et al., 1997) (Fig. 2(B)). A regional unconformity near the Dalgorae-I well site was detected between the Miocene sequence and the undisturbed younger sequences. In the Pliocene to Pleistocene, the continental margin progressively subsided as local normal faults developed (Stage III). The tectonic subsidence rate for this period was less than that of the previous events (Chough and Barg, 1987; Chough et al., 1997).

3. Reproducing basin fill history

3.1. SEDPAK

SEDPAK is a forward stratigraphic modeling program that provides a conceptual framework for the sedimentary fill of basins. It recreates stratal geometries that match those seen in the sequences of seismic cross sections (Strobel et al., 1989; Kendall et al., 1991). SEDPAK displays the stratigraphic sedimentary geometries of a basin in two dimensions as these evolve in response to rates of (1) tectonic subsidence (and/or uplift) and/or faulting, (2) sea-level change, (3) changes in the sediment discharge and sediment transport distance, and (4) compaction. It also considers (5) alluvial and submarine depositional angles, bypass angle, and repose angle of submerged sediment (Fig. 3). The program models sedimentation by providing a given sediment supply expressed as predetermined wedge-shaped depositional layer. This thins from the sediment source and slopes with given depositional angles for specific depositional conditions (e.g., alluvial, shallow and deep marine settings). If tectonic deformation causes either the sediment surface angle to be higher than the alluvial angle of repose for subaerial sedimentation and/or the submarine angle of repose for subaqueous sedimentation, then the supplied sediment bypasses that slope and local erosion occurs, reducing the slope. For details describing the internal mechanics of SEDPAK the reader should visit http://sedpak.geol.sc.edu/index.html.

The SEDPAK forward modeling routine allows the user the change the size of the geological controls (i.e., rates of change of sea-level, tectonic movement, and sediment supply) responsible for observed stratigraphic geometries. The eventual size of the parameters input to the program is determined by an iterative scheme of a trial-and-error that Cross and Lessenger (1999) refer to as stratigraphic inversion. As described by these authors a stratigraphic inversion model may achieve a fair match to the real geohistory of a basin. This occurs if the varying types, quality, and quantity of stratigraphic
data contain sufficient information to describe the process parameters that produced the observed stratal geometries. In the modeling described below the data are limited by the ages and lithology of the strata penetrated by a well (Lee, 1994) and the descriptive interpretations of seismic studies (Chough and Barg, 1987; Park, 1998; Yoon et al., 2002). The SEDPAK simulation is used to test hypotheses of how tectonic activity has effected the sediment response time expressed by the sedimentary record. However, it does not attempt to create the fine-scale stratigraphic architecture that an automated, stratigraphic inversion model (e.g., Cross and Lessenger, 1999) might produce if it were tied to complete data for the process parameters.

The inversion process used in SEDPAK begins by making an initial estimate of the rates of change in the geological controls expressed in the input parameters, and then changes these by reasonable magnitudes when the results of the iterative forward modeling runs are analyzed (Fig. 3). In this way the input parameters are iteratively and systematically corrected until there was agreement between the modeling results and the observed geometry. The SEDPAK output can be superimposed on the cross sections of the local geology, allowing comparisons of the modeling results and the observed strata while guiding the editing of the input parameters in a logical flow.

For the present stratigraphic inversion, the SEDPAK simulator was applied to a 100-km-long dip section across a southern part of the Ulleung Basin (Fig. 4(A)). It modeled the last 17 Ma of this basin at a time resolution of 0.2 Ma and a spatial resolution of 1 km. The seismic interpretation of Park (1998) and age dates of the Dolgorae-I well (Lee, 1994) were used to constrain the timing and depths of deposition and aid in resolving the stratigraphic inversion of the Ulleung Basin evolution. The basin fill thins northward with an overall wedge-like geometry. This suggests that the main sediment source was located on the southern margin of the basin (Lee and Kim, 2002). The simulation matched this by introducing sediment at the southern margin of the modeled cross section.

### 3.2. Given input parameters

In the present inversion process, the eustatic sea-level history, angles of repose and deposition, and paleobathymetry were assumed to be known so that the problem in extracting rates of tectonic movement and sediment supply could be isolated from these given parameters (Table 1).

The eustatic curve of Haq et al. (1987) was selected as an approximation for the sea-level history of the Ulleung Basin (Chough and Brag, 1987; Yoon et al., 1997; Choi, 1998; Cheong et al., 1999). Mean slopes of the current depositional
surface of the basin floor were measured for use as the deep-water depositional angle $\delta_d$ (Fig. 4(B)), shelf front for shallow-water depositional angle $\delta_s$ (Fig. 4(B)), and maximum slope of the current marine deposit as the submarine angle of repose ($\delta_t$). This water depth was set to be the transition between the shallow-water and deep-water depositional regimes. Space and time variations in depositional angles were neglected, and thus the depositional surfaces for each regime were simplified as assigned prescribed geometries with user-defined slopes. The resulting depositional surface is a simplified realization and does not capture all the local details in observed stratal geometries and bathymetries. This is because for the relatively long timescale involved with this study and the coarse resolution of the seismic data means that only the major character of overall stratal geometries formed by the simulation were needed. This matches similar assumptions that have been applied in many other geometric sedimentary models and simulations (Paola, 2000).

Table 1
Input parameters used in the SEDPAK forward modeling

<table>
<thead>
<tr>
<th>Input parameters effecting on evolution of basin</th>
<th>Given input parameters</th>
<th>Derived input parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial basin surface</td>
<td>1500 m depth at 17 Ma</td>
<td></td>
</tr>
<tr>
<td>Eustatic sea level</td>
<td>Haq et al. (1987) curve</td>
<td></td>
</tr>
<tr>
<td>Angle of repose, alluvial</td>
<td>0.1$^\circ$</td>
<td></td>
</tr>
<tr>
<td>Angle of repose, submarine</td>
<td>7.97$^\circ$</td>
<td></td>
</tr>
<tr>
<td>Depositional angle, shallow water</td>
<td>7.41$^\circ$</td>
<td></td>
</tr>
<tr>
<td>Depositional angle, deep water</td>
<td>0.02$^\circ$</td>
<td></td>
</tr>
</tbody>
</table>

| Input parameters of modeling run             |                          |                          |
| Simulation time                              | 17 Ma                   |                          |
| Time interval                                | 0.2 Ma                  |                          |
| Number of layers (Simulation time step)      | 85 layers               |                          |
| Simulation area length                       | 100 km                  |                          |
| Number of grid                               | 100                     |                          |
| Pseudo well                                  | 85 km from north end    |                          |
The Paleobathymetry of the model at the Dolgorae-I well site was 1500 m during 17–12 Ma, 100–200 m at 10 Ma, and 200–300 m during 6 Ma to present (KIER, 1982; Chough and Barg, 1987; Yoon, 1994; Park, 1998). These bathymetries were based on the study of foraminiferal biostratigraphy (Lee, 1994). This paleobathymetric data constrained the timing and the depths of depositional surfaces during the simulated reconstruction of the basin stratigraphy. The initial basin profile of the model was also determined from the paleobathymetry at 17 Ma. Never the less the water depth from the Dolgorae-I well site alone was not sufficient to determine the submarine topography over the complete cross section of the modeled area. The initial profile was extrapolated from a modeling run between 28 and 17 Ma using the depositional angles listed in Table 1. This initial basin profile was slightly inclined to the middle of the basin with a 1500-m-water depth at the Dolgorae-I well site.

The spatial distribution and geometrical patterns of the basin strata were mapped (Fig. 4(B)) based on the sequence stratigraphic analyses of Park (1998). The sediment-stacking patterns exhibited in the seismic intervals between 17 and 12.5 Ma consist of progradational units which downlap onto volcanic flows and sills in the northern half of the study area. The stacking patterns of the sequences bounded by the 12.5 and 6.5 Ma horizons comprise oblique progradational units that first down-step onto the pre-existing shelf slope sequence beyond the anticlinal fold, and these are then overlain by sigmoid progradational to aggradational units. The stratal units bounded by the 6.5 Ma sequence boundary and the present depositional surface are characterized by a set of lower retrogradational patterns and upper sigmoid progradational patterns. The dates for the specific stratal packages were categorized as given parameters. Sequences and intra-sequential patterns record a signal from a specific set of rates of tectonic movement, sediment supply, and sea-level change. An understanding of the stratal architecture was used in the interpreted seismic profile and applied to solve the stratigraphic inversion.

3.3. Derived input parameters

The sediment supply and subsidence (or uplift) rates were determined by iterative applications of the forward model by varying the magnitudes of these input parameters and examining their products. The set of final derived input parameters for the tectonic movement and sediment supply was, therefore, a final SEDPAK solution for the stratigraphic inversion.

The model initially set the “first pass” preliminary parameters for sediment thickness that accumulated between the mapped horizons. Thicknesses of each sedimentary body were simply taken from the real-depth section created by the velocity profile (KIER, 1982) at the Dolgorae-I well. The thickness from the real-depth section was de-compacted to match the thickness expected for that burial depth and duration of the time from its deposition (Baldwin and Butler, 1985). The greater thickness and the longer the emplacement of the overburden took, the greater the porosity reduction of the sediment and the greater its effect on the subsidence. Thus, the rates of vertical tectonic movement for each sequence were investigated to accommodate the pre-compacted thick deposit under the given paleobathymetry. Burial depth and depositional duration for a given sequence were very sensitive to the rates and geometries of both tectonic movement and sedimentation across the basin. Therefore the thickness of a pre-compacted deposit could be determined only after the iterative processes of editing the rates of both tectonic movement and sediment supply were completed as the inversion was solved. To reach the solution of the stratigraphic inversion the two controlling parameters were systematically corrected, one at a time. Inputs successively converged on the solution, and the results exhibited the patterns of the stratigraphy that had been observed.

Table 2 and Fig. 5 present a final version of the input parameters that were derived for the rates of tectonic movement and sediment supply. Keys to determining the size of processes associated with stratigraphic inversion are described below for each tectonic stage. Table 2 lists the dynamic subsidence rates of the 17 Ma surface at selected horizontal locations. It is noted that these values do not account for subsidence caused by the sediment compaction.

Key constraints determined from previous studies and the seismic section to build the simulation model for Stage I from 17 to 12.5 Ma were (1) rapid subsidence over the entire Uleung Basin in response to the initial back-arc opening; (2) basin filling geometry (Fig. 4) showing significantly thicker deposits in the central region (~2 s in two-way travel time) and the southern margin (~1.5 s in
two-way travel time) than those in the northern portion of the area; (3) constant 1500 m of the paleo-water depth; (4) a very low depositional angle in the deep-water regime (Table 1); and (5) a series of the down-lapping sedimentary units migrating northward (Fig. 4). As a result of these constraints, the reconstructed subsidence (Table 2) of Stage I generally has the highest rates in the central region with an asymmetric decrease toward both margins of the basin. The final parameters for the sediment supply (Fig. 5) gradually increase with time, leading to the continuously elongated down-lapping units northward seen on the seismic section (Fig. 6(A) and (B)).

Key constraints on Stage II from 12.5 to 6.5 Ma were (1) uplift of the southern margin of the basin by the back-arc closing; (2) the shallow water depth (~100 m) at the top of the anticlinal fold in the vicinity of the Dolgorae-I at around 10 Ma (Chough and Barg, 1987; Yoon et al., 1997; Park, 1998); (3) thick deposits (~1.5 s in two-way travel time) in the northern sector (Fig. 4); and (4) the oblique progradational units that gradually migrated outward over the deformed shelf sequence (uplifted and folded), to be followed by a transition from sigmoid progradational to aggradational units (Fig. 4). Thus the uplift rates of the model (Table 2) in this stage were high enough to raise the southern margin with lower rates northward that were sufficient to create the necessary space for the thick deposits found here. In the early part of Stage II (12.5–10.3 Ma), the final parameter set of Fig. 5 shows a change in the rate of sediment supply from very low to high. This enables the simulation model to change of the character of the oblique progradational units over the shallow region of the thrust and fold sequence to the sigmoid progradational patterns (Fig. 6(C)). The initial low sediment supply captures the trap of terrigenous sediment behind the thrust zone at the beginning of the tectonic uplift of 12 Ma as reported in Chough et al. (1997) and Park (1998), and the following high sediment supply reflects the active subaerial erosion over the thrust zone as reported in Park (1998). To model the transition from aggradational units to sigmoid progradational units (Fig. 6(D)) the rate of uplift within the simulation was diminished so as to enable the raising of relative sea level at around 9 Ma.

Key constraints to the sedimentary fill of Stage III from 6 Ma to the present were (1) termination of compressional tectonic movement; (2) subsidence produced by the local normal faulting at a relatively low rate (Chough and Barg, 1987); (3) the end of the subaerial erosion coinciding with the restarting of tectonic subsidence at 6.5 Ma (Chough et al., 1997); and (4) generation of packages of the retrogradational (6.5–3.8 Ma) and progradational to aggradational (3.8 to present) units (Fig. 4). The subsidence

### Table 2

Final input parameters for the vertical tectonic movement at selected locations

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>1</th>
<th>50</th>
<th>60</th>
<th>75</th>
<th>80</th>
<th>85</th>
<th>90</th>
<th>98</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (Ma)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Fig. 5. Reconstructed geohistory of changes in rates of sediment supply in study area.

Subsidence rate (m/ka) (+: uplift, -: subside).
and sediment supply rates were stable and low for this time period, and thus the given sea-level change in this model played a major role. This accounted for the stratal patterns listed above (Fig. 6(E) and (F)).

4. Discussion

The evolution of the gross sedimentary geometries exhibited in the cross section of the Ulleung Basin suggests that these were the product of tectonic events that forced an increase in the sediment supply. The “in-phase” relationship between tectonic movement and its positive effects on the basin sedimentation enabled the thickening of the sedimentary body and the basin fill to expand basinward rapidly. In contrast, the “out-of-phase” relationship between tectonic movement and rates of sedimentation first affected basin sedimentation negatively so that the size of the basin fill was stable and the shelf front (or shoreface) retreated landward, but then gradually changed to effective sedimentary fill. In addition, tectonic movement significantly deformed, by thrusts and folds, the pre-existing basin physiography at various localities. Topographic variation by the tectonic deformation in the Ulleung Basin also exerted a critical influence on the character of the sediment fill and the stacking stratal patterns it exhibits.

4.1. In-phase and out-of-phase responses of sediment supply to tectonic movements

From 17 to 12.5 Ma (Stage I) the relative sea level rose rapidly across the basin. The in-phase response of the sediment supply to active tectonic movement meant that sediment accumulation kept pace with relative sea level, maintaining a constant bathymetry (1500-m-water depth in the southern basin) and gradually covering the farther northern basin floor (Fig. 6(B)). Sediment liberation from upland source area is in general a response to tectonic uplift.
However, as the results of sediment flux to the adjunct hanging-wall basin from an uplifting block by fault slip in numerical experiments of Ellis et al. (1999) and Allen and Densmore (2000), there is a delayed response time of 0.1–1 Ma that indicates that the upland sediment-source area first absorbs the effect of perturbations in the tectonic activity. In this Stage I, instead of uplift, the tectonic subsidence caused high rates of sedimentation in the depocenter and without the delayed response time, suggesting that local reorganization of the sediment route by the tectonic forcing rapidly trapped more sediment over the subsidence maximum.

In Stage II the regional deformation was in the form of thrusts and folds that started at 12.5 Ma along the southern margin (Fig. 6(C)). The sediment supply related to this tectonic uplift did not increase rapidly; rather it showed an out-of-phase response that was delayed roughly 2 Ma before adjusting sediment delivery. The response time was longer than that which Ellis et al. (1999) and Allen and Densmore (2000) suggested. However, this tectonic activity (from 12.5 to 10.3 Ma) initiated a series of southern thrusts and folds that trapped and cut off the terrigenous sediment source behind them, causing additional time to deliver the eroded sediment to the basin floor of the study area (Fig. 7). Then continuous tectonic uplift from 10.3 to 9 Ma caused high rates of subaerial erosion and the sediment supply began to increase, generating a strong regressive pulse in the shelf system (Fig. 7). This high sediment supply continued for roughly 2 Ma to the end of this stage at 6.5 Ma, even though the uplift stopped around 9 Ma. The shelf front migrated continuously basinward tens of kilometers during this period.

4.2. Topographic control on stratigraphy

The migration of the shelf front actively continued from 10.3 to 9 Ma until the front reached the northern limb of the anticlinal fold near the Dolgorae-I well at around 9 Ma. Interestingly, this regressive pulse suddenly diminished, even though the sediment supply kept responding to the tectonic uplift (Fig. 6(D) and Fig. 7). The modeled stratigraphy indicates that potential space, which had to be filled in order to cause regression, increased significantly because the sediment front reached the large open area of accommodation beyond the anticlinal fold. The topographic change (in time and space), was due to not only the successive local uplift but also to the migration of the shelf front to the deeper basin, forcing sediment

![Fig. 7. Modeled stratigraphic section of northern 30 km of Dolgorae-I well. See Fig. 6(F) for this location. (A) The Haq et al. (1987) eustatic curve (applied as a given condition). Changes in (B) sediment supply and (C) tectonic movement (S(-): subsidence, U(+): uplift) were derived from stratigraphic inversion, in which processes were constrained with data from stratigraphic column of exploration well. The gray boxes indicate time lags between sediment supply response and tectonic activity in Stage II.](image-url)
to bypass over the shelf slope and halting the shelf front advance. This caused the development of two separate sedimentary layers: one on the continental shelf and the other over the deeper basin floor (Fig. 6(D)). Seismic facies analysis (Lee et al., 2001) suggests that in the middle Late Miocene a large quantity of sediment supplied from the southern sources bypassed the shelf front to the deeper basin floor. This was reflected as the products of gravity slides, debris flows, and high-density turbidity currents that were concentrated at a shelf front that had been steepened by the anticlinal fold and local tectonic uplift. Conventionally the mechanism invoked to deliver terrigenous sediment to a deep-water basin has been a sea-level fall below the shelf edge (Posamentier and Vail, 1988; Van Wagoner et al., 1990). However, the reconstructed stratigraphy of the Ulleung Basin implies that at least here, the sediment was efficiently transported to deeper basin floor by the effect of a change in basin physiography. The mechanism reflected by a change in basin physiography has also been observed in physical experiments (Mohr et al., 2004).

Sediments slowly onlapped over the shelf slope and then two sedimentary units were inter-layered with each other, forming a complex discontinuity over the continental slope (Fig. 7). Valley incision occurred and produced unconformities while the shelf front was steep and a eustatic lowstand occurred at the latest stage of the compressional event (Chough and Lee, 1992; Cheong et al., 1999). These unconformities were conveniently preserved beneath the subsequent eustatic highstand from 6.5 to 3.8 Ma (Fig. 6(E)).

4.3. Eustatic control on stratigraphy

During Stage III, when the sediment supply and subsidence rates remained low and were nearly constant, short-term eustatic fluctuation captured major variation in the stratal architecture. Sea level was relatively high from 6.5 to 3.8 Ma, and caused more accommodation over the continental shelf while preventing the shelf front from prograding further basinward (Fig. 7). High frequency sea-level fluctuations during the past 3.8 Ma functioned effectively as a eustatic sediment pump, delivering sediments basinward. The delivered sediment and lowered gradient of the shelf front gave rise to the development of progradational and aggradational units in this period (Fig. 7).

During Stages I and II the paleobathymetric data indicate that relative base level was controlled by the strong tectonic subsidence (Stage I, maximum subsidence = 1 m/ka) and tectonic uplift (Stage II, maximum uplift = 0.3 m/ka). Even though short-term rate of eustatic change has a same order of magnitude as these strong tectonic signals, the amplitude of this change was very small relative to the paleobathymetry of 1500 m (Stage I) and high frequency of this sea-level change was likely averaged out by the long-term tectonic event (Stage II). Thus, based on the analysis of the simulation generated for Stages I and II, eustatic control on stratal development was concealed by the tectonic signal.

4.4. Source of error by extensional basin setting

SEDPAK only models vertical tectonic movement (i.e., vertical subsidence, uplift, and faulting), and does not accurately model slope deformation or the thinning (or thickening) of deposits that may be the response to either extensional or compressional tectonic settings. This lateral deformation may be important in sequence development, yet the effects of these settings have only recently been investigated using numerical approaches and remain poorly understood (e.g., Hardy and Gawthorpe, 1998; Csato and Kendall, 2002). The southern margin of the Ulleung Basin experienced significant changes in lateral crustal deformation during the back-arc opening and subsequent closure during the Tertiary. Incorporating lateral distortion into SEDPAK and other simulations would allow for better insight of evolving stratigraphy under these conditions.

5. Conclusions

Major variations in sediment supply in the Ulleung Basin coincided with changes in the direction and rate of tectonic movement. The combination of sediment supply and tectonics governed the development of the stratigraphic architecture in the early part of the basin evolution (Stages I and II). The reconstructed controlling parameter set supports the existence of: (1) a strong tectonic driver (i.e., the rapid subsidence of the Early and Middle Miocene) that immediately caused an in-phase high sediment input, while generating a significant pulse of the basin growth (i.e., shelf-front migration basinward). The basin evolution in Stage I delineated the downlap
In addition to tectonic movement and sediment supply, basin physiography played a critical role in developing the stratigraphic architecture. The rate of creation of accommodation at the migrating shelf depocenter. Here the paleobathymetry was one order of magnitude larger than eustatic fluctuation base-level change) led to sediment being transported actively to the deep basin floor in Stage III, working as a major control on the stratigraphic configuration. However, the effects of a eustatic control in Stage I was filtered by the depth of the prograding shelf toe at 9 Ma initiated bypass of the supplied sediment to the deep basin floor by gravity or turbidity flows.

Eustatic sediment pump (i.e., high-frequency base-level change) led to sediment being transported actively to the deep basin floor in Stage III, working as a major control on the stratigraphic configuration. However, the effects of a eustatic control in Stage I was filtered by the depth of the basin depocenter. Here the paleobathymetry was one order of magnitude larger than eustatic fluctuation and was kept constant by a strong tectonic signal. Short-term fluctuation in the eustatic movement during Stage II was blurring by the relatively long-term tectonic forcing.

Acknowledgments

We would like to thank Heeman Cheong, Sik Huh, Michael Kelberer, Tetsuji Muto, and Chris Paola for thoughtful inputs and stimulating discussions. This study was supported by the Korea Energy Management Corporation (2000-R-TI03-P-02) to D.C.

References


