4. Basins due to orogenic loading

Orogenic loading and lithospheric flexure: peripheral vs. retroarc foreland basin

Elastic vs. viscoelastic models

Gravity anomalies, foreland flexure, and the development of the mountain belts

Stratigraphic architecture of the foreland basins

Lithospheric strength and structural styles (thin- or thick-skinned deformation) in the fold-and-thrust belt
Orogenic loading and lithospheric flexure: peripheral vs. retroarc foreland basin

**Peripheral foreland basin**

- Foreland basins develop on continental crust in front of advancing thrust-and-fold loads along the length of subductional or collisional plate margins.

**Retroarc foreland basin**

- Roles of orogenic belts:
  1. Load the underlying lithosphere
  2. Provide sediments to the foreland basin

**Two types of foreland basins**

**A. Peripheral** foreland basins: lie on the continental crust of the subducting plate.
- Examples: Active: Taiwan, Indo-Gangetic (Hymalayan frontal thrusts), Tigris-Euphrates-Arabian Gulf basins (Zagros Mountains)
- Inactive: Molasse basins of the Alps and Pyrenees.

**B. Retroarc** foreland basin: (large scale and long life) lie on the continental crust of the overriding plate.
- Examples:
  1. Eastern foreland of the Rocky Mountains (Mesozoic to early Cenozoic)
  2. Eastern foreland of the Andes (Jurassic to Recent)
Example of peripheral foreland basin: Taiwan

Depth map of the Taiwan foreland basin (Lin & Watts, 2002)

Contour interval 0.5 km

Lin et al. (2003)
Prepared by Dr. Andrew T. Lin
Institute of Geophysics
National Central Univ. Taiwan

Lin & Watts (2002)
Flexural interactions between the Appalachian foreland basin and the Michigan and Illinois intra-cratonic basins could explain the existence of the arches and domes in the eastern US.
Example of retroarc foreland basins (Andes)

Subduction geometry and foreland basin development.

Thin-skin tectonics

Basement-involved (thick-skin) tectonics

Jordan (1995)
The geometry of the foreland basin provides some of the best evidence on the thermal and mechanical properties of the continental lithosphere.

In a cross section that is perpendicular to the strike of the foreland basin, the depths of the foreland base exponentially increase toward the orogen.

How the outermost layers of the Earth respond to loads of different duration

Appalachian foreland basins

Watts (2001)

Elastic Plate Theory

The comparison of observations (e.g. crustal structure) to calculations show that the response of the lithosphere to long-term loads is similar to what would be expected for an elastic plate that overlies an inviscid (i.e. zero viscosity) substratum.

Equations:
The general equation for the flexure of an elastic plate overlying an inviscid substratum by an applied load can be derived by first determining the response of an elastic beam of unit width subject to an external bending moment, $M_0$.

$$D \frac{d^4 y}{dx^4} + (\rho_m - \rho_{\text{infill}}) y g = 0$$

$$D = \frac{E T_e^3}{12 (1 - \nu^2)}$$

Parameters:
- $D$ = flexural rigidity
- $y$ = flexure
- $\rho_m$ = density of substratum
- $\rho_{\text{infill}}$ = density of material infilling flexure
- $E$ = Young’s modulus
- $T_e$ = elastic thickness, $\nu$ = Poisson’s ratio

Assumptions:
1. Linear elasticity
2. Plane stress
3. Cylindrical bending
4. Thin plates (i.e. plate thickness $\ll$ radius curvature)
5. Neutral surface, fixed at the half depth

Courtesy of Prof. A. B. Watts
The general equation for the deflection of an elastic beam can be solved for certain boundary conditions. Two of the most useful in geological applications are those for a continuous plate \((x \to \pm \infty, z \to 0; x = 0, \frac{dy}{dx} = 0)\) and for a broken plate (e.g. end-conditioning forces).

**Continuous plate**:

\[
y = \frac{P_b \lambda}{2 (\rho_m - \rho_{\text{infill}}) g} e^{-\lambda x} (\cos \lambda x + \sin \lambda x)
\]

\[
\lambda = \left( \frac{(\rho_m - \rho_{\text{infill}}) g}{4 D} \right)^{1/4}
\]

\(1/\lambda = \text{flexural parameter}\)

**Broken plate**:

\[
y = \frac{2 P_b \lambda}{(\rho_m - \rho_{\text{infill}}) g} e^{-\lambda x} \cos \lambda x
\]

Courtesy of Prof. A. B. Watts
Elastic vs. viscoelastic plates

(a) Elastic model \( \sigma = E\varepsilon_e \)

(C) Maxwell viscoelastic model (a+b)

Total strain: \( \varepsilon = \varepsilon_e + \varepsilon_v \)

If the system is initially unstrained – that is, \( \varepsilon = 0 \) at \( t = 0 \) – then

\[
\varepsilon_e = \frac{\sigma}{E} \quad \text{and} \quad \dot{\varepsilon}_v = \frac{d\varepsilon_v}{dt} = \frac{\varepsilon_v(t) - \varepsilon_v(0)}{t - t_0} = \frac{\varepsilon_v}{t} \quad \Rightarrow \quad \varepsilon_v = \frac{t \sigma}{\eta}
\]

\[ \therefore \varepsilon = \frac{\sigma}{E} + \frac{\sigma \cdot t}{E \eta} \]

The viscoelastic strain is made up of both and elastic and a viscous part.

Maxwell relaxation time (\( \tau \)):
The time when the elastic strain that has accumulated is equal to that of the viscous train.

\[ \tau = \frac{\eta}{E} \]

\(~ 0.1 \text{ to several c Myr or 1 to 100 Myr (Watts, 2001, p.244)})
A viscoelastic plate is initially elastic and then becomes more viscous as the age of the load increases.

Deflection of a viscoelastic plate by (a) a “wide” and (b) a “narrow” load.

Watts (2001)
Gravity anomalies and flexure of the lithosphere caused by surface loading at the edge of an orogenic belt.

The interiors of large orogenic belts are generally in a state of isostatic equilibrium (i.e., Airy isostasy), their edges show large departures (i.e., flexure).

Paper:
Stratigraphic architecture of the foreland basins

Variations in relationship between fold-thrust belt and foreland basins.

Depo-zones in an idealized foreland basin system (Horton & DeCelles, 1997)

Ricci-Lucchi (1986)

Note: The origin of the back-bulge is poorly known.
An example of a piggyback basin

Fig. 9.69. Example of a seismic transect across the edge of a foreland basin, showing blind thrusts and sediment drape over them. The main basin, filled with Pliocene sediment at the center, is an example of a satellite, or piggyback, basin. (Ricci-Lucchi 1986)
Development of a fold-thrust belt and the stratigraphy of the adjacent foreland basins (piggyback basins)

Deramond et al. (1993)

Unconformities (D1~D9) develop as imbricate thrust slices develop.

Ori et al. (1986)
The stratigraphy is made of two megasequences, each one shallowing and coarsening upwards. These two megasequences (A1+A2+A3 as well as B1+B2+B3) are separated by a major unconformity.

Allen & Allen (1990)
Episodic thrusting and unconformity development (a, b) vs. constant thrusting but varying eustasy (c, d)


Viscoelastic model
\( T_e = 67 \text{ km, } \tau = 27.5 \text{ Myr.} \)
Subsidence curves for the Rocky Mountain foreland basins

The characteristic convex-up shape, with inflexion points corresponding to thrust-loading events.
Filling up of foreland basins

Stage 1: Initial loading of outer passive margin, e.g., present day Taiwan, Timor and Papua New Guinea. Palaeocene in the Alps.
- Forebulge uplift
- Load induced flexural subsidence
- Uplift of passive margin outer shelf above wave base initiating erosion
- Sea level

Stage 2: Development of underfilled trinity as flexural profile passes over passive margin
- Increased erosion of passive margin
- Reactivation of normal faults

Stage 3: Steady state migration of the underfilled trinity over the craton i.e., rate of thrust front advance equals rate of cratonic onlap
- Retrogradational cratonic margin carbonates
- Superposition of underfilled trinity
- Delta progradation
- Forebulge unconformity

Stage 4: Transition of foreland basin from an underfilled to a filled depositional state. Siliciclastics from orogen fill the basin, smothering the underfilled stratigraphy.
- Turbidites (upper unit)
- Hemipelagic mudstones (middle unit)
- Carbonate ramp (lower unit)
- Underfilled trinity
- Basement

Crampton & Allen (1995)

Sinclair (1997)
Lithospheric strength and structural styles (thin- or thick-skinned deformation) in the fold-and-thrust belt

Watts et al. (1995) suggest that $T_e$ of the underthrust foreland lithosphere may determine whether thin-skin or thick-skin tectonics dominate the style of deformation of the thrust and fold belt.

High $T_e$ $\rightarrow$ Thin-skin

Low $T_e$ $\rightarrow$ Thick-skin (basement involved)

Note:
Others indicated that it is the dips of the subducting plate that determine the thin- or thick-skin tectonics.

High angle $\rightarrow$ Thin-skin

Low angle $\rightarrow$ Thick-skin