Seismic Reflections II

Beyond the Flat-Layer Model

ESS 314 Geophysics · University of Washington

Week 3, Lecture 9 · April 22, 2026

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By the end of this lecture…

[LO-9.1] *Derive* the dipping-layer travel-time equation; compute up-dip and down-dip apparent velocities; recover true velocity and dip

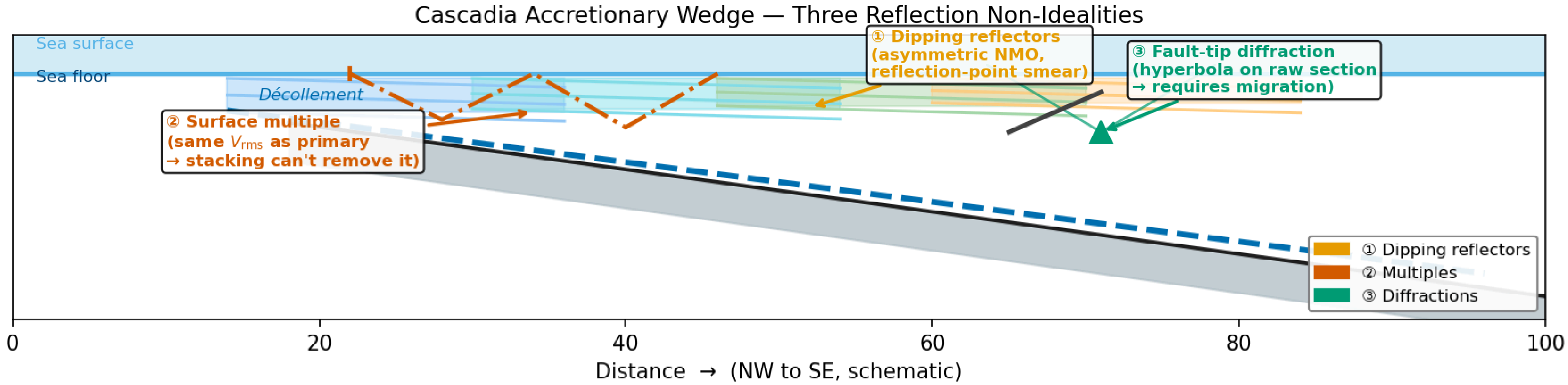
[LO-9.2] *Identify* multiple types; predict long-path multiple TWTT and NMO velocity; explain why stacking cannot remove it

[LO-9.3] *State* the diffraction equation; describe what migration accomplishes

[LO-9.4] *Apply* Shuey approximation $R(\theta) \approx R(0)+G\sin^2\theta$; classify AVO Classes I–IV

[LO-9.5] *Evaluate* DL denoising claims; identify two failure modes

Why the Flat-Layer Model Fails: Cascadia



Each non-ideality requires a distinct correction: DMO for ①, SRME for ②, migration for ③.

Five Assumptions That Fail

In Lecture 8, the CMP stacking pipeline assumed:

1. **Reflectors are horizontal** — no linear term in $t^2(x)$
2. **Only primary reflections** — every event is a single bounce
3. **Continuous interfaces** — no point scatterers
4. **Noise-free wavefield** — no ground roll or surface waves
5. **Only travel times matter** — amplitude constant with offset

This lecture relaxes each assumption in turn:

> **Why it matters** → **What breaks** → **The math** → **How to fix it**

① Dipping Reflectors: Geometry

For perpendicular depth h, dip δ, velocity V_1:

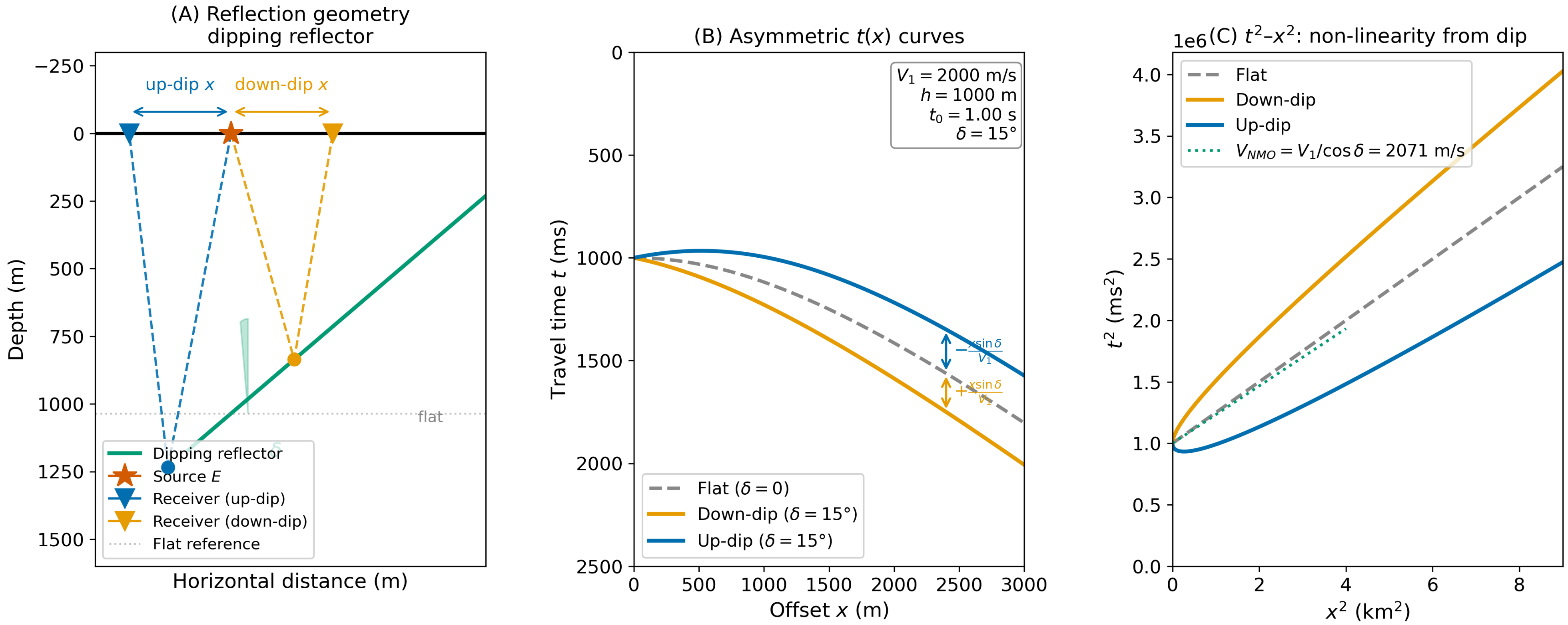
$$t_d(x) = \frac{1}{V_1}\sqrt{x^2 + 4hx\sin\delta + 4h^2} \quad \text{(down-dip)}$$

$$t_u(x) = \frac{1}{V_1}\sqrt{x^2 - 4hx\sin\delta + 4h^2} \quad \text{(up-dip)}$$

Both have $t(0) = t_0 = 2h/V_1$ — **same zero-offset time**.

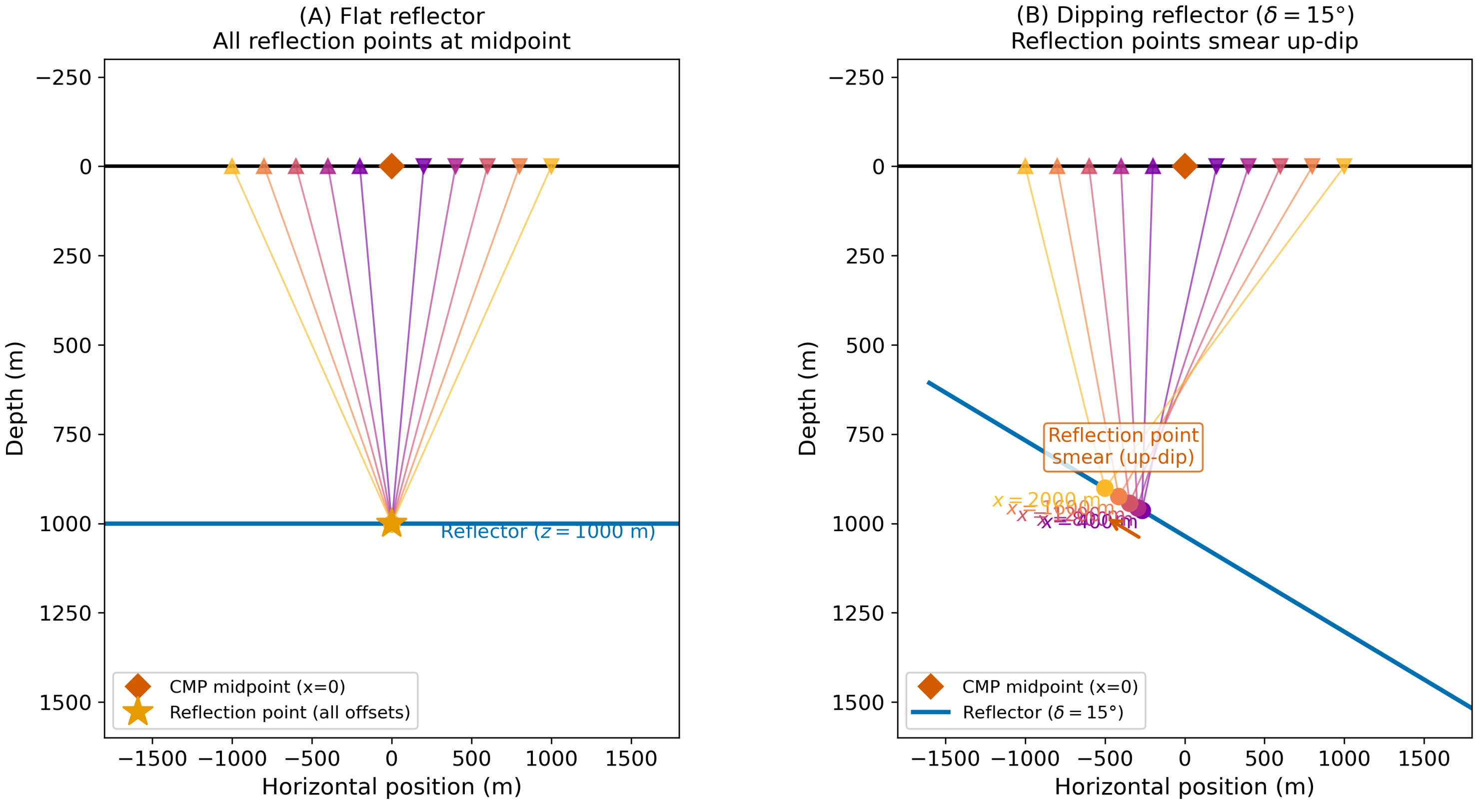
> Key: a **linear term** $\pm\,(2t_0\sin\delta/V_1)\cdot x$ appears in t^2 — the mathematical signature of dip

① Dipping Layer: Asymmetric Curves



Down-dip: MORE moveout (slower apparent V). Up-dip: LESS moveout (faster apparent V). All share the same t_0.

① CMP Reflection-Point Smear



For dipping reflectors, stacking without ***DMO correction*** *blurs the subsurface image. DMO repositions reflection points before NMO stacking.*

① NMO Velocity and Dip Recovery

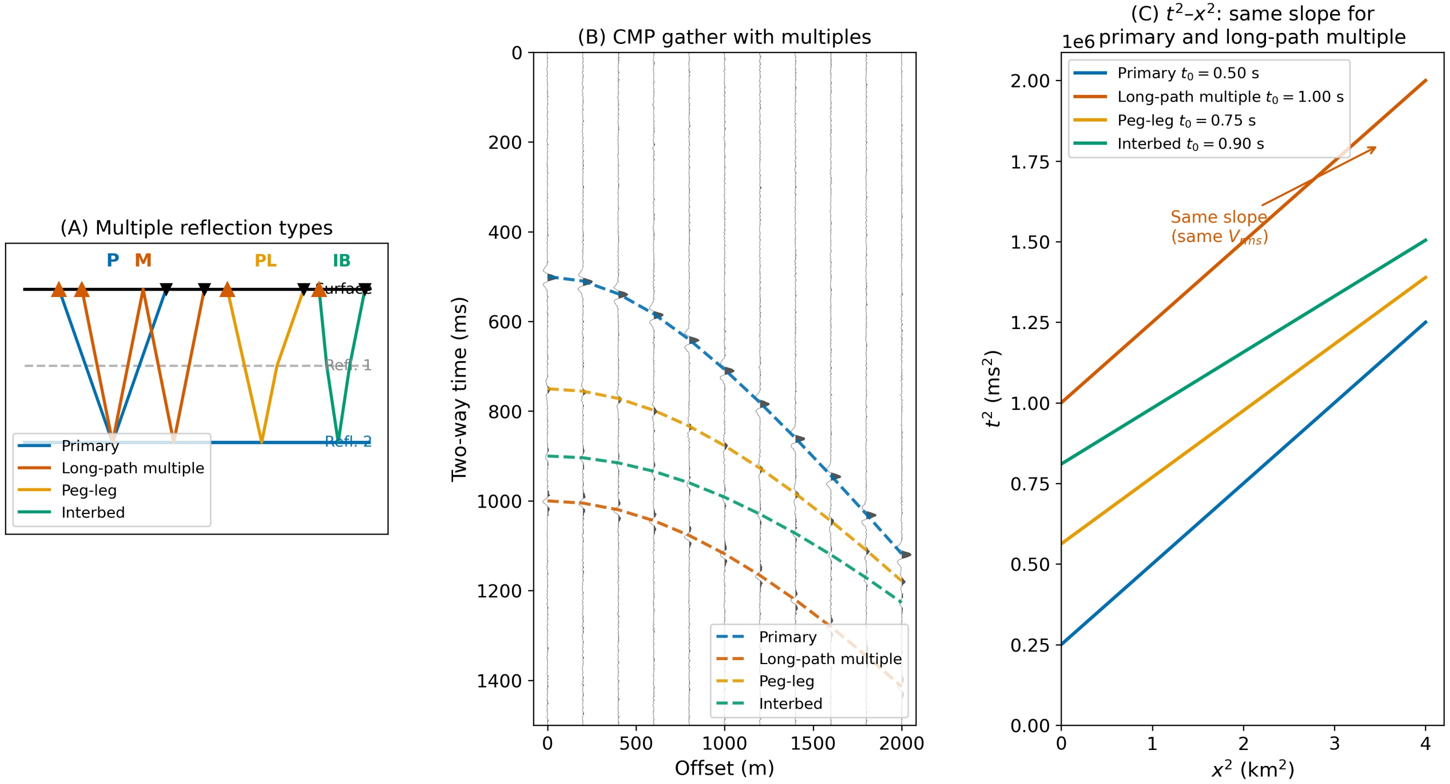
Taylor expansion of $t_d(x)$ at small x gives:

$$V_{\text{NMO,dip}} = \frac{V_1}{\cos\delta} \qquad (> V_1 \text{ for any } \delta > 0)$$

Recover V_1 and δ from two-survey apparent velocities V_d, V_u:

$$V_1 = \frac{2V_dV_u}{V_d + V_u} \qquad \sin\delta = \frac{V_u - V_d}{V_u + V_d}$$

② Multiple Reflections



② The Multiple Suppression Problem

Long-path surface multiple TWTT:

$$t_{\mathrm{mult}}^2(x) = (2t_0)^2 + \frac{x^2}{V_{\mathrm{rms}}^2}$$

Same NMO velocity as the primary → NMO correction flattens BOTH simultaneously.

Stacking cannot suppress the multiple.

Suppression methods:

- **SRME** (surface-related multiple elimination): autocorrelation-based prediction and subtraction
- **DL in τ-p domain**: CNN trained to separate primaries from multiples by slope

③ Diffractions: Huygens Principle

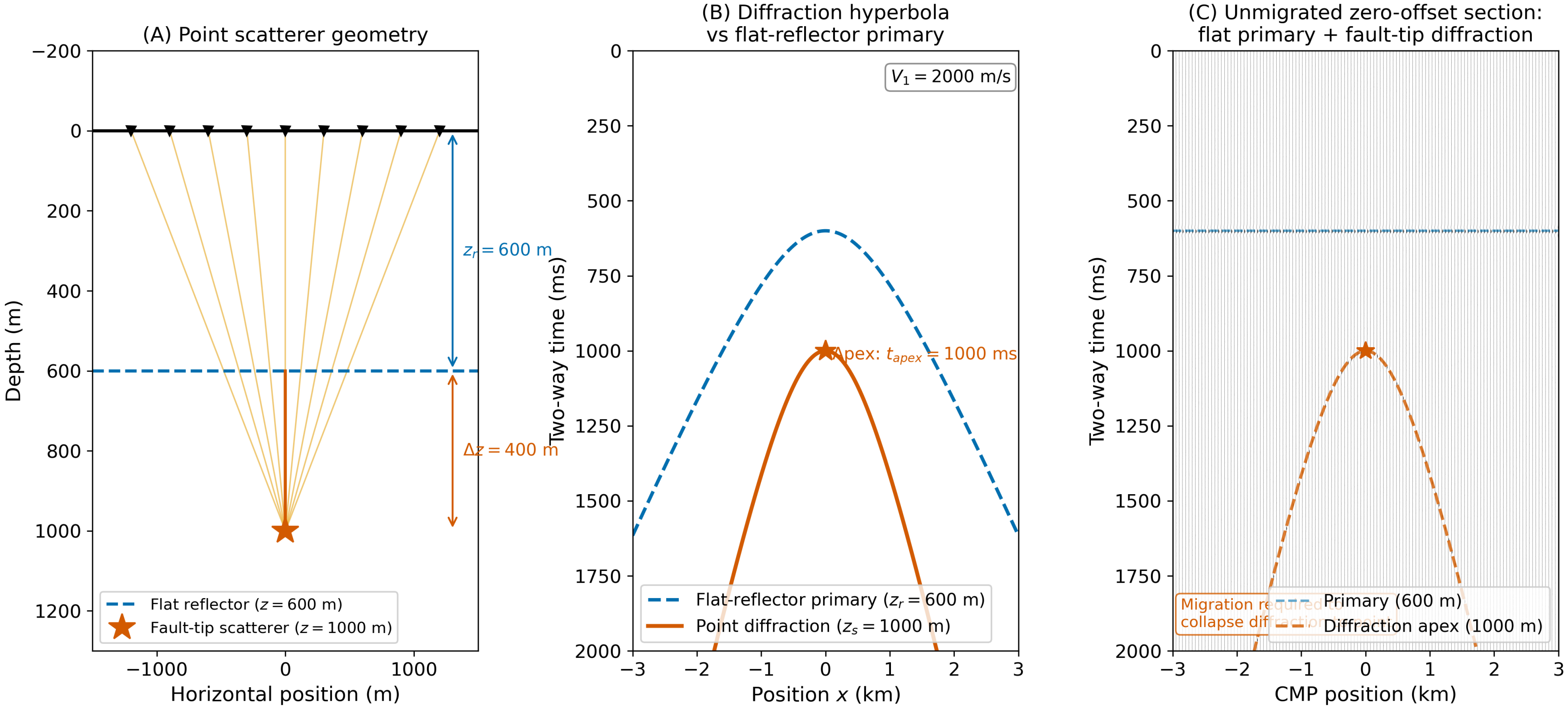
Any sharp edge (fault tip, channel boundary, unconformity) acts as a **secondary point source** of spherical waves.

$$t_{\text{diff}}(x) = \frac{2}{V_1}\sqrt{(x - x_s)^2 + z_s^2}$$

Key properties vs primary reflections:

- **Uniform amplitude** across all offsets (isotropic emission)
- Energy from a **single point**, not a planar interface
- Migration collapses it to the point (x_s, z_s)

③ Diffractions in the Seismic Section



Bowtie patterns (synclines) and diffraction tails (fault tips) are unmigrated artefacts. Migration (Lecture 10) collapses them.

④ Shot Gather Noise and f–k Filtering

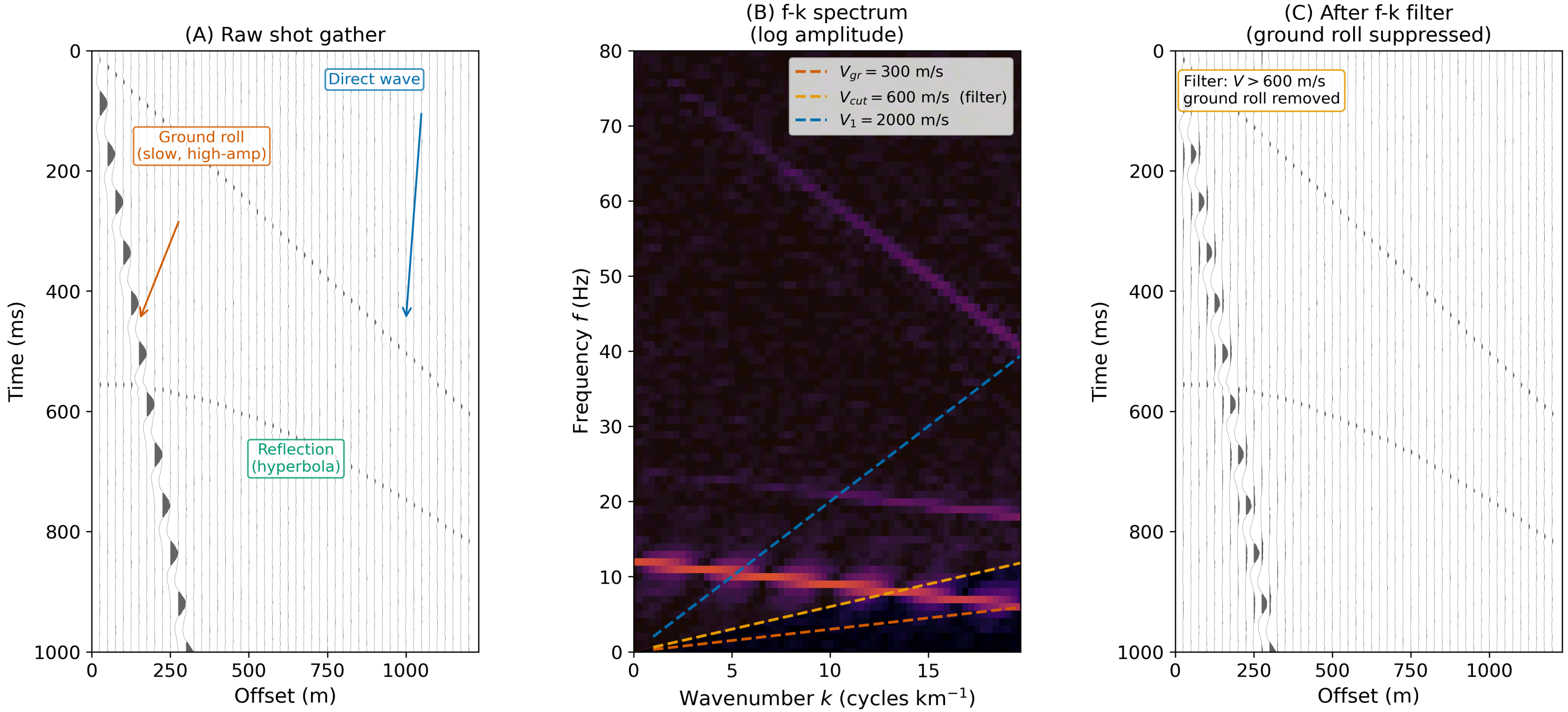
Coherent noise in raw shot gathers:

- Ground roll: $V \approx 300$ m/s, $f \approx 5$–20 Hz — **high amplitude**
- Direct wave: $V \approx V_1$, linear, easily muted
- Air blast: $V \approx 340$ m/s

f–k filter: reject all $|k| > f/V_\mathrm{cutoff}$, preserving $V > V_\mathrm{cutoff}$

> Velocity cone: $|k| \leq f / V_\mathrm{cutoff}$ in f–k space defines the slope threshold separating slow noise from faster reflections.

④ f–k Ground Roll Suppression



(A) Raw shot gather

(B) f-k spectrum (log amplitude)

(C) After f-k filter (ground roll suppressed)

Ground roll occupies the slow fan (high $|k|$ per Hz). Rejecting it preserves reflections ($V > 600$ m/s).

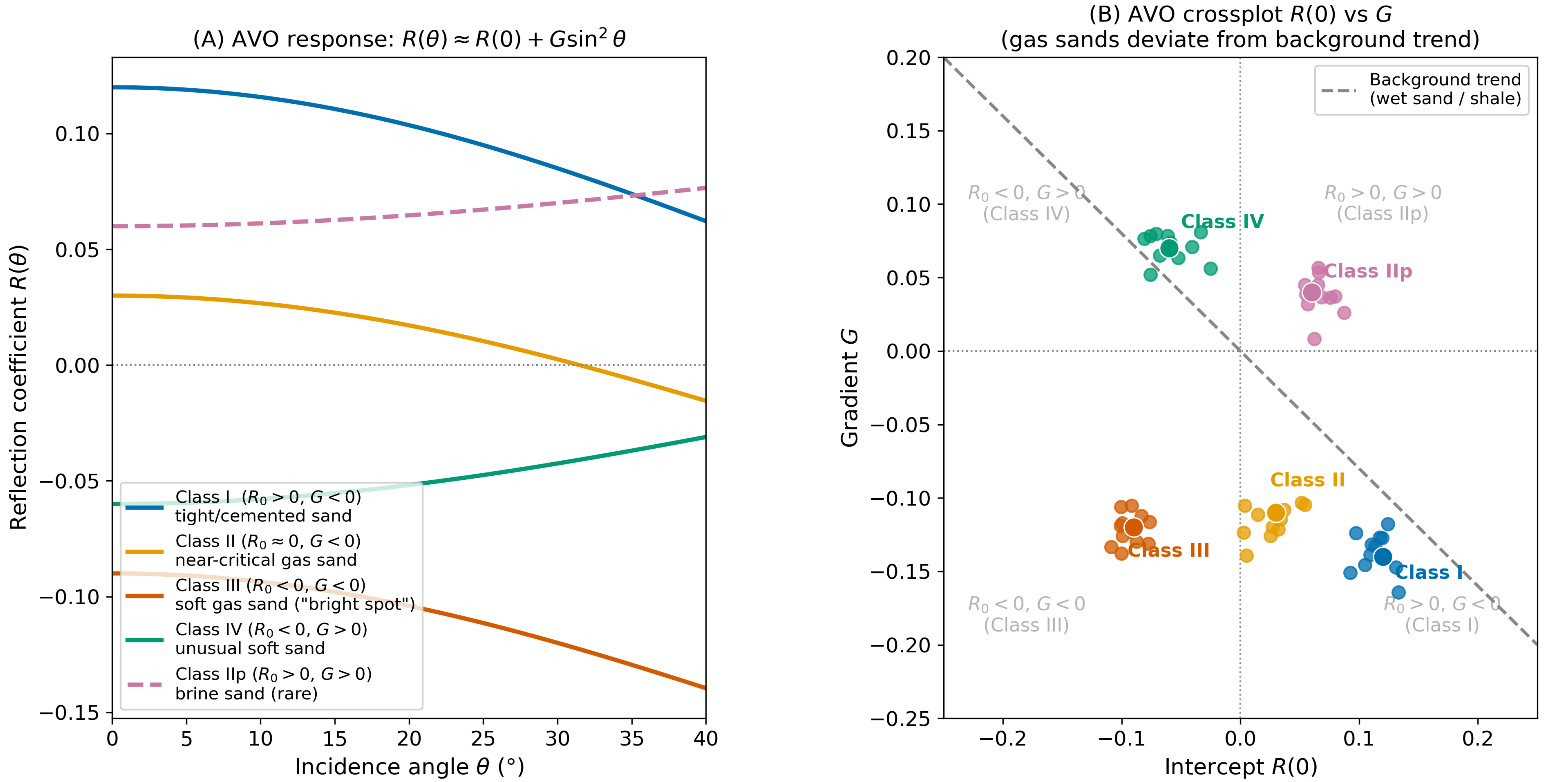
⑤ AVO: Zoeppritz + Shuey

At oblique incidence θ_i, energy partitions into reflected P, S, transmitted P, S (Zoeppritz equations). Shuey (1985) linearisation:

$$R(\theta_i) \approx \underbrace{R(0)}_{\text{intercept}} + \underbrace{G}_{\text{gradient}} \sin^2\theta_i$$

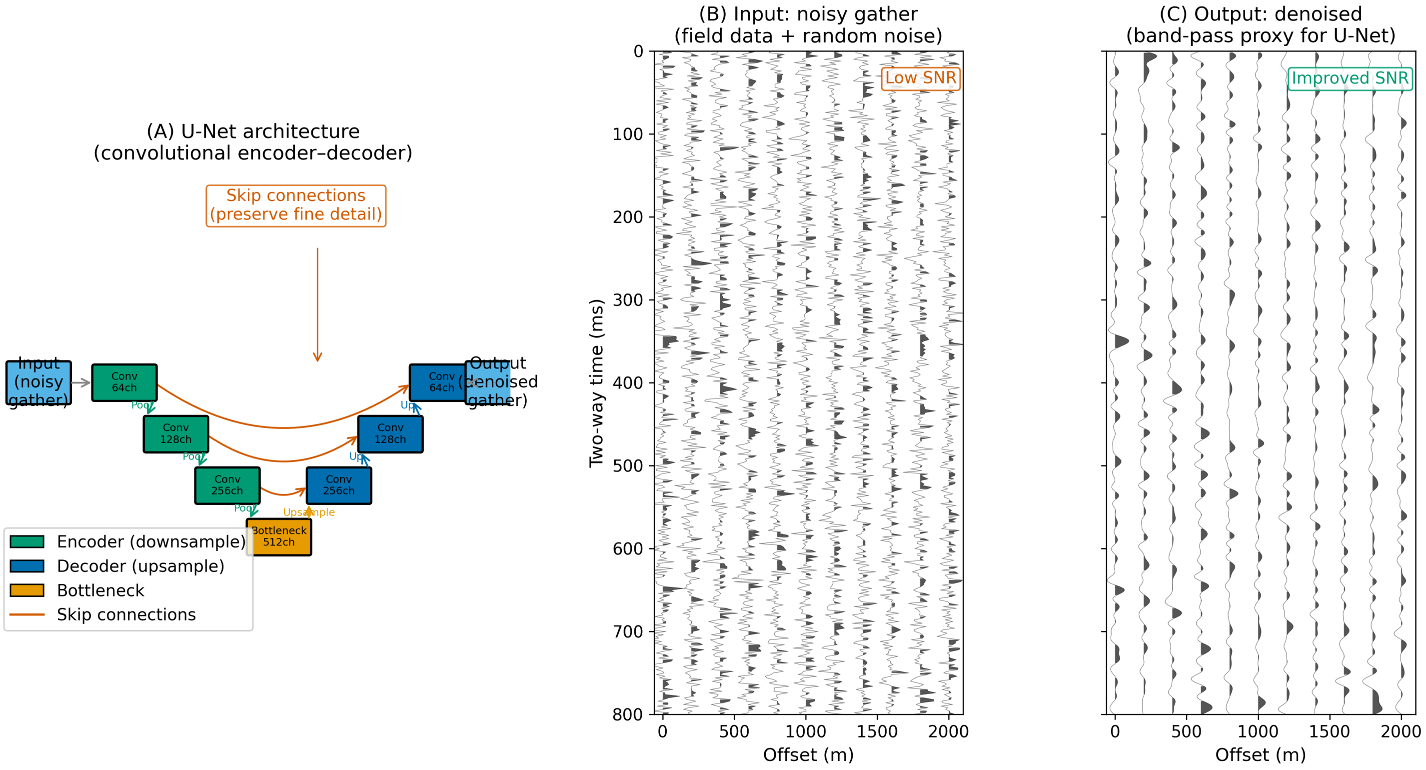
- $R(0) = (Z_2 - Z_1)/(Z_2 + Z_1)$ — normal-incidence reflectivity
- G = AVO gradient, sensitive to $\Delta(V_P/V_S)$ — **fluid content**
- Gas substitution lowers V_P, leaves V_S unchanged → large $|G|$

⑤ AVO Classes I–IV



Gas sands (Class III): ***negative*** $R(0)$ ***and*** G *— amplitude brightens with offset. The* $R(0)$–G *crossplot separates gas from brine-saturated sands.*

DL Denoising: U-Net Architecture



Skip connections preserve fine spatial detail. Supervised training requires paired noisy/clean data — unavailable for field data; self-supervised methods train on the noisy data alone.

DL Failure Modes — Critical Evaluation

1. **Domain shift**: network trained on synthetic gathers fails on field data where noise is non-stationary and geologically correlated
2. **Physics inconsistency**: denoised output may violate AVO, polarity, or reciprocity — creating spurious bright spots
3. **Interpretability gap**: cannot determine whether amplitude anomaly is a true DHI or a network artifact

False bright spots from DL denoising have been documented in published case studies.

Worked Example: Dipping Layer

$h = 800$ m, $V_1 = 2000$ m/s, $\delta = 10^\circ$

Quantity	Formula	Result
t_0	$2h/V_1$	**0.80 s**
V_{NMO}	$V_1/\cos\delta$	**2031 m/s**
$t_d(2400\,\mathrm{m})$	Exact dip eq.	**1.553 s**
$t_u(2400\,\mathrm{m})$	Exact dip eq.	**1.322 s**

Check: $\sin\delta = (2421 - 1704)/(2421 + 1704) = 0.174 \approx \sin 10^\circ$ ✓

Concept Check

1. A flat-layer NMO correction is applied to a dipping reflector ($\delta = 12^\circ$). Is the corrected gather over- or under-corrected? Quantify the velocity error.
2. A long-path multiple arrives at $t_0 = 1.4$ s with $V_{\text{rms}} = 2400$ m/s. What is the parent primary TWTT? Compute the reflector depth.
3. What distinguishes a diffraction hyperbola from a primary reflection? Name two geological features in the Cascadia wedge that commonly produce diffractions.
4. A sand–shale interface has $R(0) = -0.08$ and $G = -0.10$. What AVO class is this? Is the sand likely gas- or brine-saturated?