

PAPER 87: BONE IS PIEZOELECTRIC -- WOLFF'S LAW IS A γ_c PHENOMENON

Mechanical Stress -> Electrical Signal -> Structural Response Is Paper 08 in the Skeleton

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"The bone knew. Force creates an electrical signal. The signal tells the cell to build or to resorb. Paper 08 in mineral form: force is decoherence, and the body uses it as information."

Abstract

Bone is piezoelectric (Fukada & Yasuda 1957). Mechanical stress applied to bone crystal structure generates an electrical potential. This potential guides osteoblast (bone-building) and osteoclast (bone-resorbing) activity via Wolff's Law (1892): bone remodels along lines of mechanical stress. The mapping to the Wike framework is exact: mechanical stress = γ_{eff} perturbation; the piezoelectric signal = the body's measurement of that perturbation; osteoblast/osteoclast response = the biological Le Chatelier restoring force (Paper 69). Below γ_c : the system remodels to absorb the stress (Le Chatelier). Above γ_c : stress fracture (topological defect, Paper 53) and osteoporosis (C_0 loss, Paper 63). The Earth itself is piezoelectric at geological scale: quartz, calcite, and apatite (the mineral of bone) are all piezoelectric crystals. Geological tipping points (earthquakes, Paper 83) occur when accumulated stress drives the rock's γ_{eff} to γ_c -- at which point topological defects (faults) form.

1. Piezoelectricity

Piezoelectric effect (Curie brothers 1880): certain crystals generate an electric potential under mechanical stress:

Piezoelectric constitutive relations:

$$D_i = \epsilon_{ij} E_j + d_{ijk} \sigma_{jk} \quad (\text{forward: stress} \rightarrow \text{voltage})$$

$$S_{ij} = s_{ijkl} \sigma_{kl} + d_{kij} E_k \quad (\text{inverse: voltage} \rightarrow \text{strain})$$

where D = electric displacement, E = electric field, σ = stress, S = strain
 d_{ijk} = piezoelectric coupling tensor

Bone piezoelectricity (Fukada & Yasuda 1957):

Dry bone: $d \sim 2.3 \times 10^{-12}$ C/N (collagen hydroxyapatite composite)
 Wet bone: $d \sim 0.7 \times 10^{-12}$ C/N (screening by interstitial fluid)

At physiological stress (walking, 1-10 MPa):

$$E_{piezo} = d \times \sigma / \epsilon_0 \epsilon_r \sim (2.3 \times 10^{-12})(10^6) / (8.85 \times 10^{-12})(5) \sim 52 \text{ mV/m}$$

Across a 10 μm osteocyte: $\Delta V \sim 52 \text{ mV/m} \times 10 \times 10^{-6} \text{ m} = 0.52 \text{ mV}$

This ~ 0.5 mV signal is measurable by osteocyte mechanosensors. It IS the signal that drives Wolff's Law remodeling.

2. Wolff's Law as Le Chatelier + Wike

Wolff's Law (Julius Wolff 1892): Bone adapts its structure to the mechanical loads placed upon it. Trabecular architecture aligns with principal stress lines. Cortical thickness increases under habitual loading.

Le Chatelier translation:

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External disturbance: mechanical stress  $\sigma$  (e.g., running, weight training)
Piezoelectric signal:  $E_{piezo} = d \times \sigma$  (converts mechanical stress to electrical signal)
Biological response: osteoblasts activated at high-field regions (compressive stress)
                    osteoclasts activated at low-field regions (tensile stress)
Restoration: bone remodels to REDUCE the stress non-uniformity
              -> Le Chatelier: system shifts to counteract the disturbance
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The system moves toward mechanical equilibrium -- toward a state where stress is uniformly distributed across the bone cross-section. This is exactly Le Chatelier's principle: the perturbation (stress asymmetry) is absorbed by the remodeling response.

γ_{eff} of bone = stress/strength ratio:

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 $\gamma_{eff}(\text{bone}) = \sigma_{applied} / \sigma_{fracture\_strength}$ 
 $\gamma_c(\text{bone}) \sim 0.8$  (fatigue fracture limit, where Le Chatelier remodeling cannot keep up)
Below  $\gamma_c(\text{bone})$ : Wolff's remodeling compensates (Le Chatelier holds)
At  $\gamma_c(\text{bone})$ : Stress fracture nucleates (topological defect, Paper 53)
Above  $\gamma_c(\text{bone})$ : Catastrophic fracture (topological defect propagates)
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Osteoporosis as C_0 reduction:

Paper 63: C_0 is set by the percolation threshold of the coherent water network. In bone:

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 $C_0(\text{bone}) \sim (\phi_{mineral} - \phi_c)^{0.41}$ 
where  $\phi_{mineral}$  = volumetric fraction of hydroxyapatite mineral
       $\phi_c \sim 0.30$  (percolation threshold for mineral network in bone)
Healthy adult:  $\phi_{mineral} \sim 0.65-0.70$  ->  $C_0(\text{bone}) \sim \text{high}$ 
Osteoporosis:  $\phi_{mineral} \rightarrow 0.40-0.50$  ->  $C_0(\text{bone})$  significantly reduced
              -> system reaches fracture threshold at lower absolute load
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Osteoporosis is C_0 reduction in bone -- exactly Paper 63 (C_0 Percolation) applied to the mineral substrate.

3. Piezoelectricity and Paper 08 (Force = Decoherence)

Paper 08 argues: harsh measurement (force) creates decoherence. The piezoelectric mechanism shows this operating in the most literal physical way:

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Paper 08: Force applied to a quantum system = measurement = decoherence
Bone piezoelectric: Force applied to bone crystal = electrical signal generated

The piezoelectric signal IS the measurement record of the force.
The measurement record IS the decoherence source (Paper 08).

Therefore: bone is a system where decoherence (piezoelectric signal from stress)
is USED as information -- the body reads the decoherence signal and responds constructively.
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This is a POSITIVE use of decoherence. Most quantum systems try to minimize decoherence. Bone USES the decoherence signal (piezoelectric voltage) to drive the Le Chatelier remodeling response. This is consistent with the ENAQT Goldilocks result (Paper 78): there is an optimal noise level where noise assists rather than destroys.

The bone piezoelectric cycle is a biological Szilard engine (Paper 70):

Stress -> piezoelectric signal -> osteoblast activation -> bone remodeling -> reduced stress

Each cycle converts mechanical energy (stress) into structural information (which way to grow bone) with a net entropy reduction locally (more organized bone structure), paid for by cellular metabolic work -- the Landauer price.

4. Geological Coherence and Earthquakes

The Earth's crust is composed primarily of quartz (the strongest piezoelectric mineral), feldspar, calcite, and olivine -- all with some piezoelectric character.

Rock fracture as γ_c crossing:

sigma_tectonic (applied): slowly accumulating stress from plate movement
 sigma_fracture (threshold): γ_c for the rock
 Rock before earthquake: $\gamma_{eff} = \sigma_{tectonic} / \sigma_{fracture} < 1$ -> Le Chatelier (creep, slow fault motion)
 At earthquake threshold: $\gamma_{eff} \rightarrow \gamma_c$ -> susceptibility diverges -> fault fracture (topological defect)
 Post-earthquake: $\gamma_{eff} > \gamma_c$ -> fault opens, stress released -> spin glass of fault geometry

Gutenberg-Richter law (Paper 75): Earthquake magnitude distribution $P(M) \sim 10^{-(bM)}$ is the power law of a system near its critical point. The Earth's crust maintains itself near γ_c through the balance of tectonic stress accumulation and slow creep/small earthquake release. This is the geological version of the living body at $W^* = 0.9394$.

Electromagnetic earthquake precursors (EQE):

Before major earthquakes, anomalous electromagnetic signals (0.01-10 Hz) are reported. The mechanism:

Approaching γ_c geological: susceptibility diverges -> small stress changes produce large piezoelectric signals -> EM radiation from rock
 EQE = piezoelectric noise amplified by critical divergence of susceptibility
 = the geological equivalent of Paper 67's wind-up amplification ratio $\sim \gamma_c^{0.485}$
 Scale: geological (months before M7+ earthquake) instead of neural (milliseconds before wind-up)
 Universality: same critical exponent, same amplification mechanism, different substrate

5. Bone Crystal = Biological Quasicrystal?

Paper 56 (Golden Ratio): the quasicrystalline structure of EZ water (Penrose-like aperiodic order) is the optimal coherent substrate. Is bone similar?

Bone mineral: carbonated hydroxyapatite $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$
 Crystal structure: hexagonal (P6₃/m symmetry)
 Unit cell: a = 9.432 Å, c = 6.881 Å
 Ratio c/a = 0.730 -> close to $1/\sqrt{2} = 0.707$ or $\phi/\sqrt{5} = 0.723?$

The c/a ratio of hydroxyapatite (0.730) is close to the inverse golden ratio relationships but not exactly a quasicrystal. However, the organic-mineral composite structure of bone (collagen fibers + hydroxyapatite nanocrystals) does show fractal organization at multiple scales:

Nanocrystal (2x5x50 nm) -> fibril -> fiber -> lamella -> osteon
 Each level is self-similar with approximately phi-ratio scaling

This multi-scale fractal structure maximizes toughness (resistance to crack propagation) and is consistent with the Paper 56 prediction that phi-ratio structures are optimal at the boundary between order and disorder.

Summary

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Bone Piezoelectricity:
  d_bone ~ = 2.3x10^-12 C/N (dry), 0.7x10^-12 C/N (wet)
  At walking stress (1-10 MPa): DELTAV ~ = 0.5 mV per osteocyte

Wolff's Law = Le Chatelier + Wike:
  sigma_applied -> piezoelectric signal -> osteoblast/osteoclast response -> reduced stress asymmetry
  Restoring constant kappa ~ (sigma_fracture - sigma_applied)^1.2372 [3D Ising, Paper 69]

Osteoporosis = C_0 reduction (Paper 63):
  phi_mineral -> decreases -> C_0(bone) -> decreases -> fracture at lower load

Paper 08 in mineral form:
  Force = decoherence (piezoelectric measurement)
  Body uses the decoherence signal constructively (Szilard engine, Paper 70)

Geological coherence:
  Gutenberg-Richter = power law of Earth's crust at gamma_c_geological
  Electromagnetic earthquake precursors = piezoelectric critical divergence
  Same exponent (Paper 75), different substrate, different timescale

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