Remediation of Baltic anoxia with pure oxygen gas:

Lessons learned from hypolimnetic oxygenation in the USA and design response to scale of the Baltic

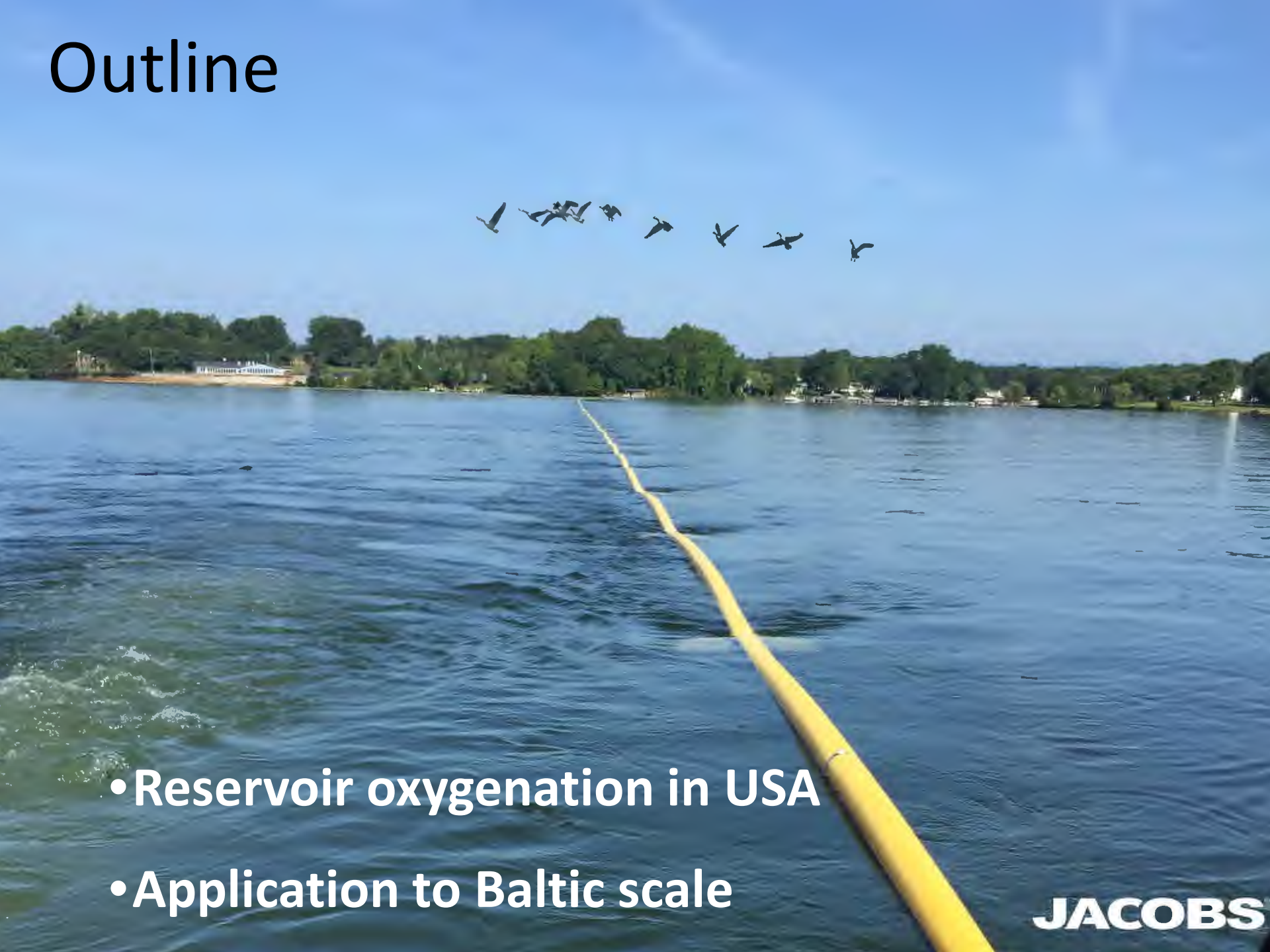
David Austin

Professional Engineer

Senior Ecologist

Jacobs Engineering Group

Outline



- Reservoir oxygenation in USA
- Application to Baltic scale

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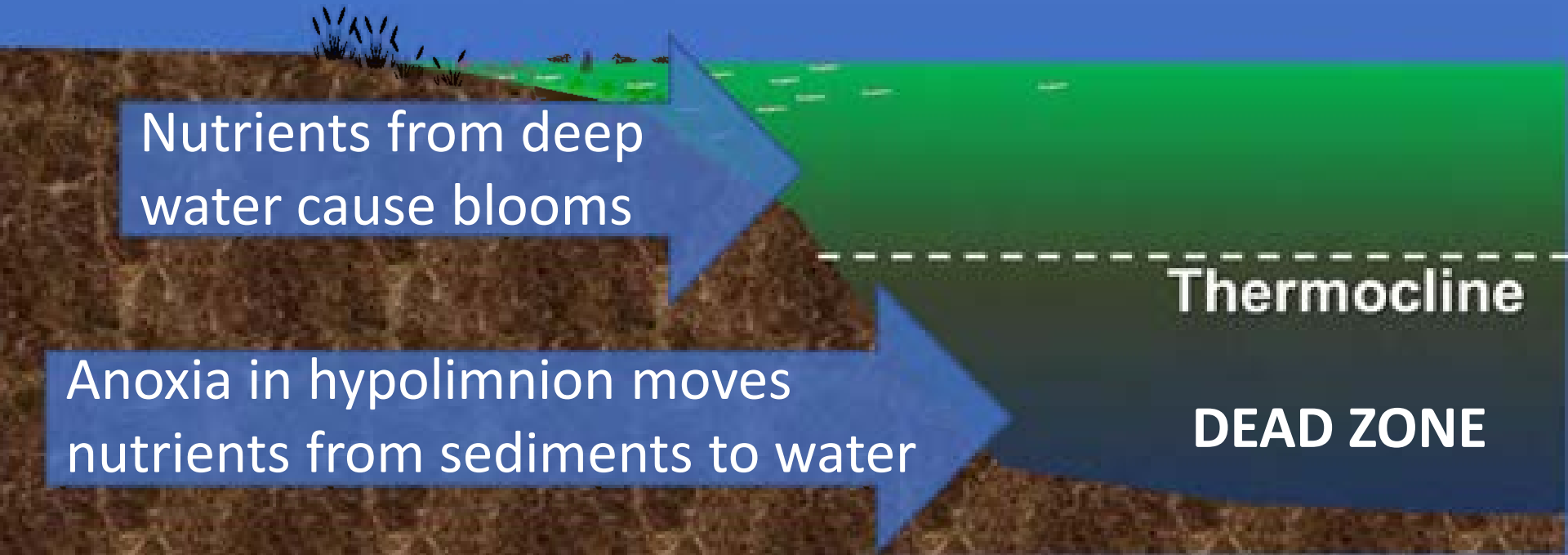
Problem: Anoxia in drinking water reservoirs is similar to Baltic

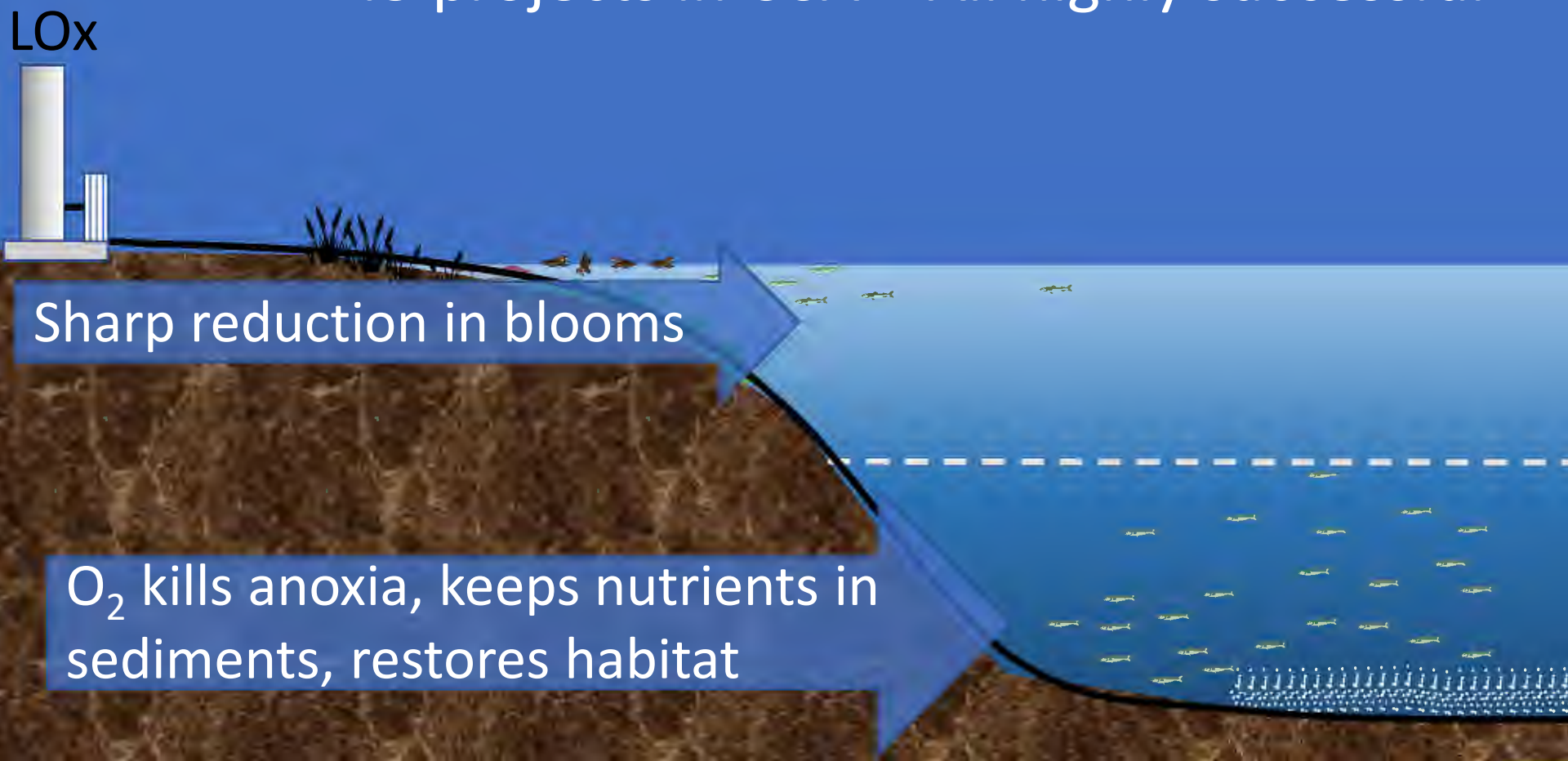
Epilimnion: warm, high DO from atmosphere & photosynthesis

Hypolimnion: cool/cold, stagnant, DO depleted by sediments

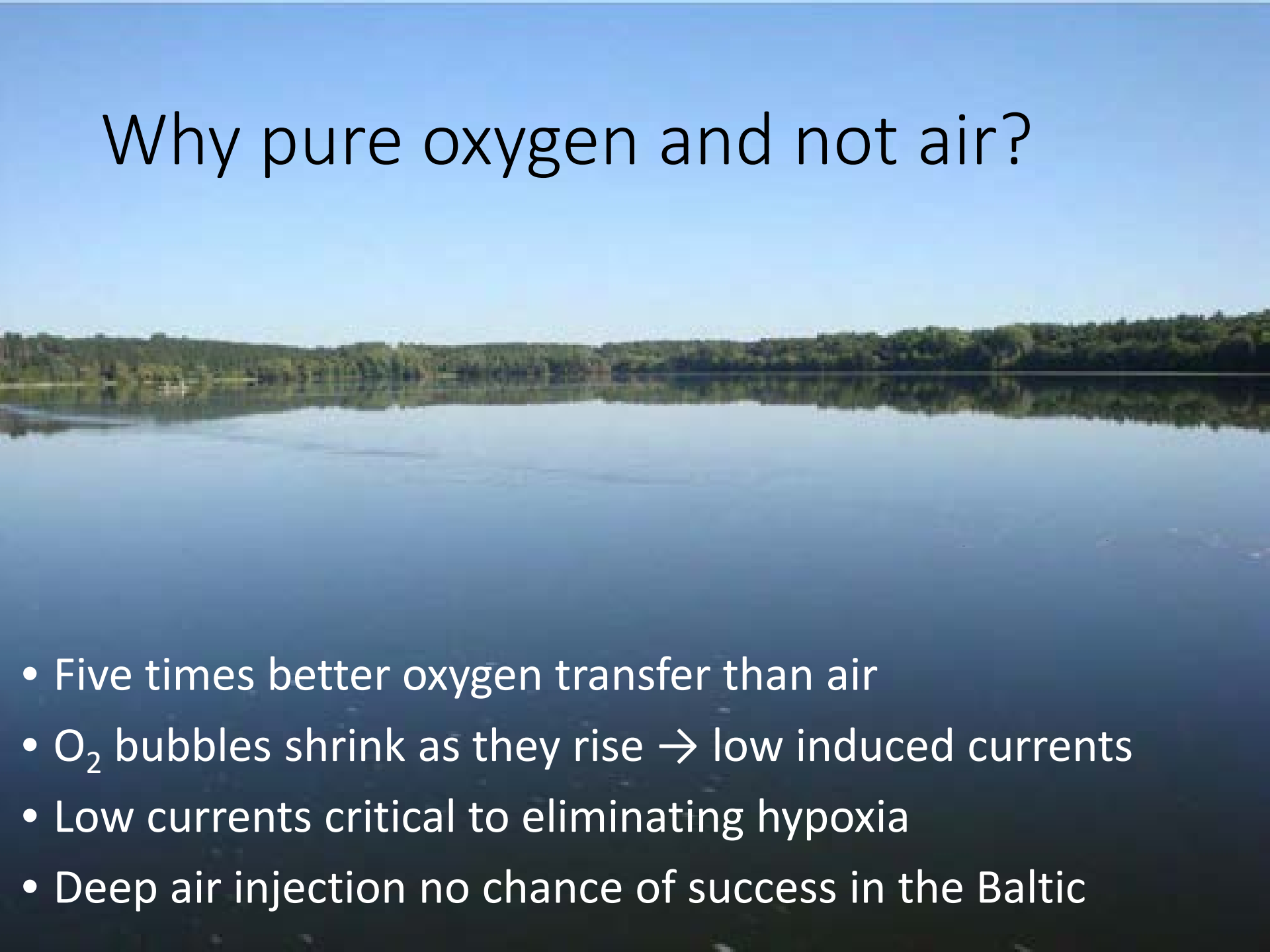


Fixing the problem

- Inject O_2 into hypolimnion (deepest part)
- 45 projects in USA – All highly successful

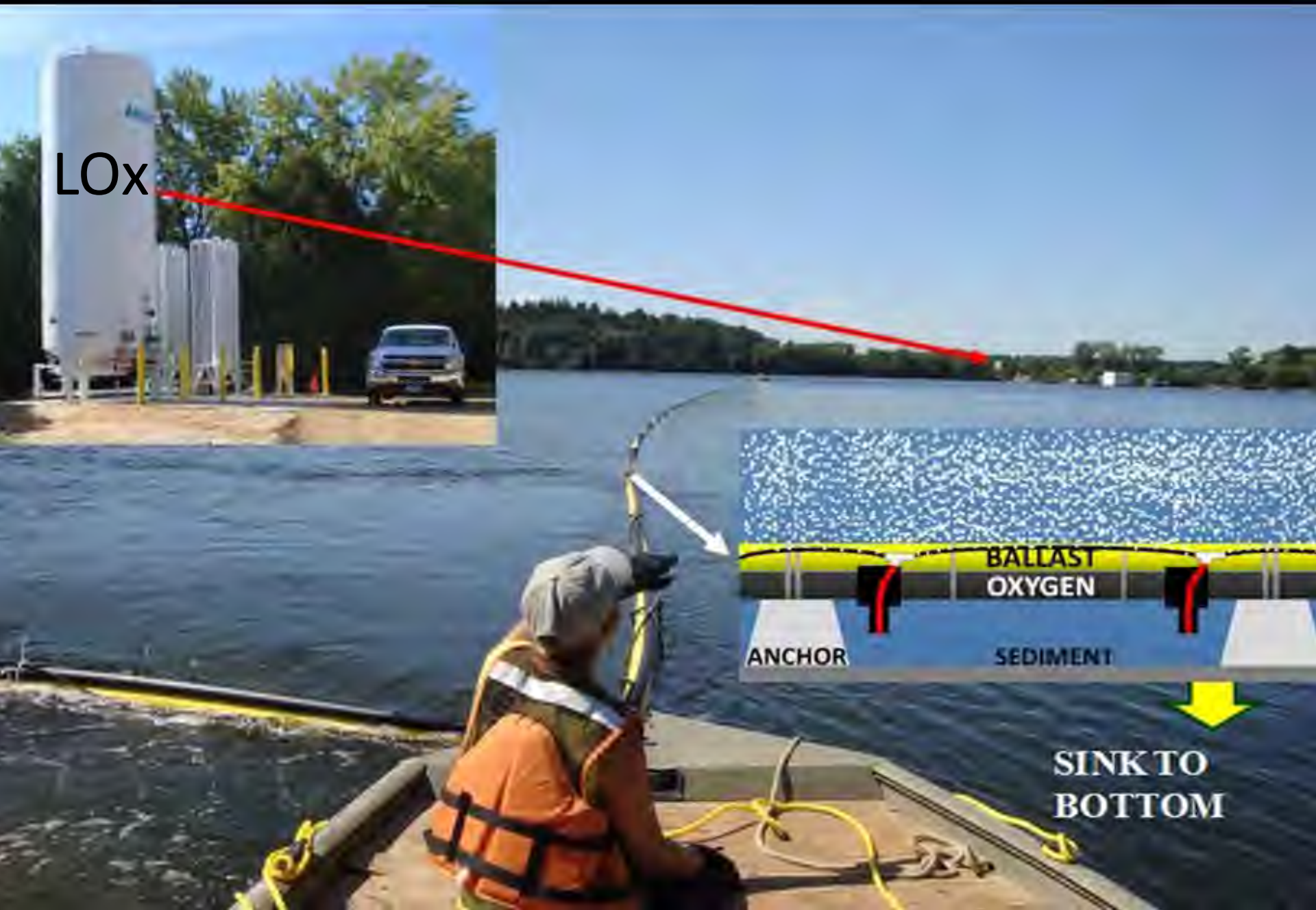


Why pure oxygen and not air?

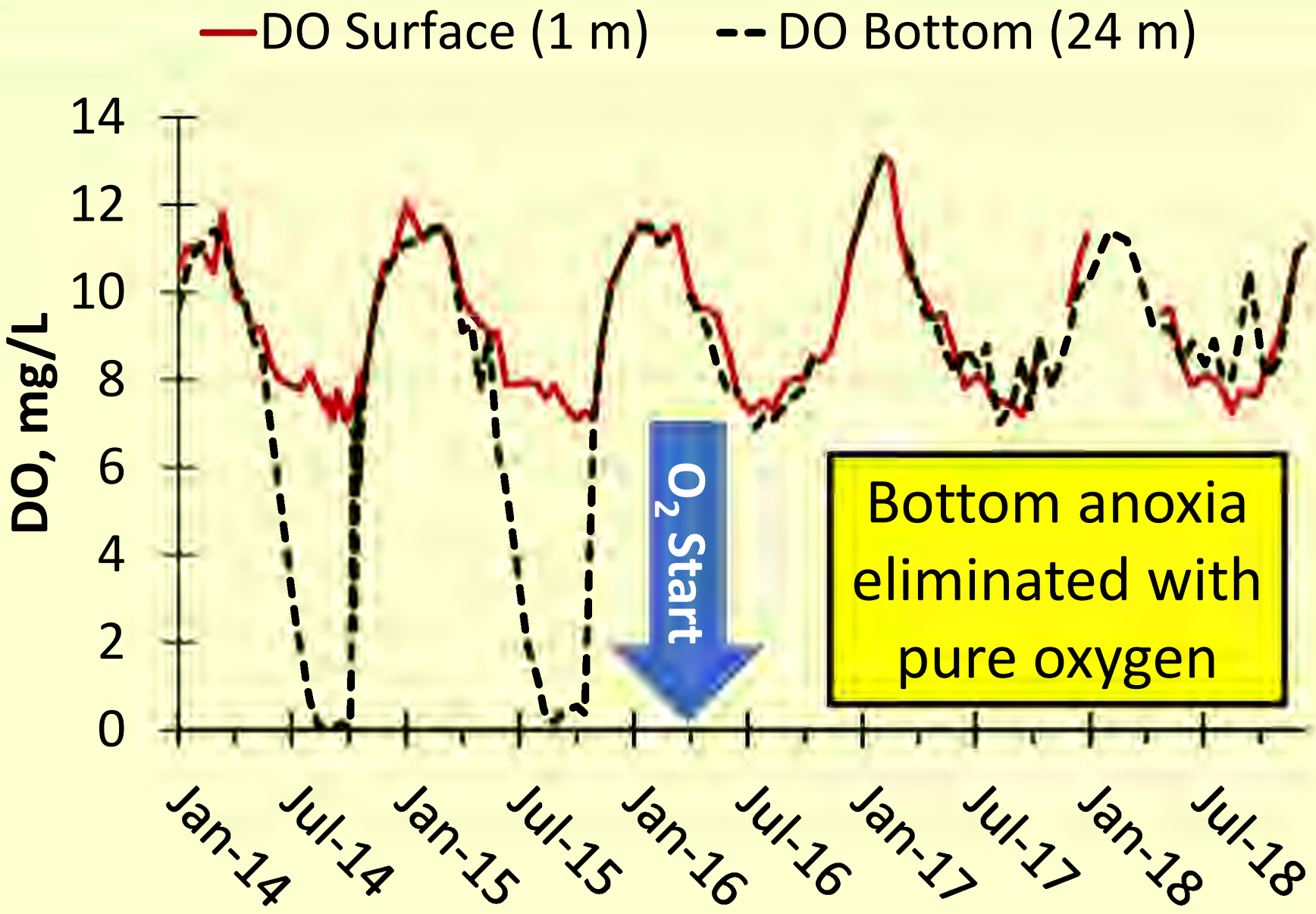


- Five times better oxygen transfer than air
- O_2 bubbles shrink as they rise → low induced currents
- Low currents critical to eliminating hypoxia
- Deep air injection no chance of success in the Baltic

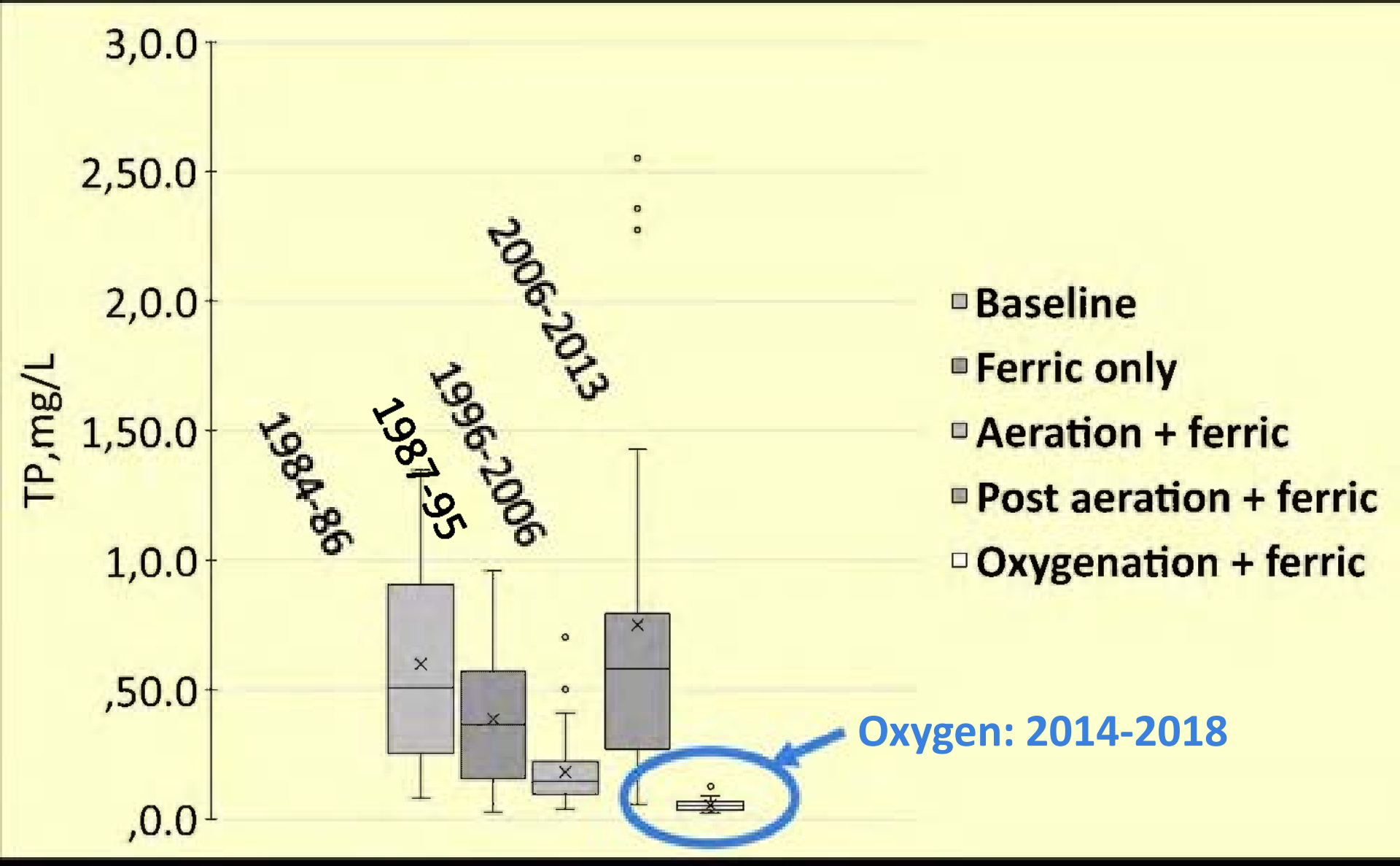
Hypolimnetic oxygenation – deep oxygen injection



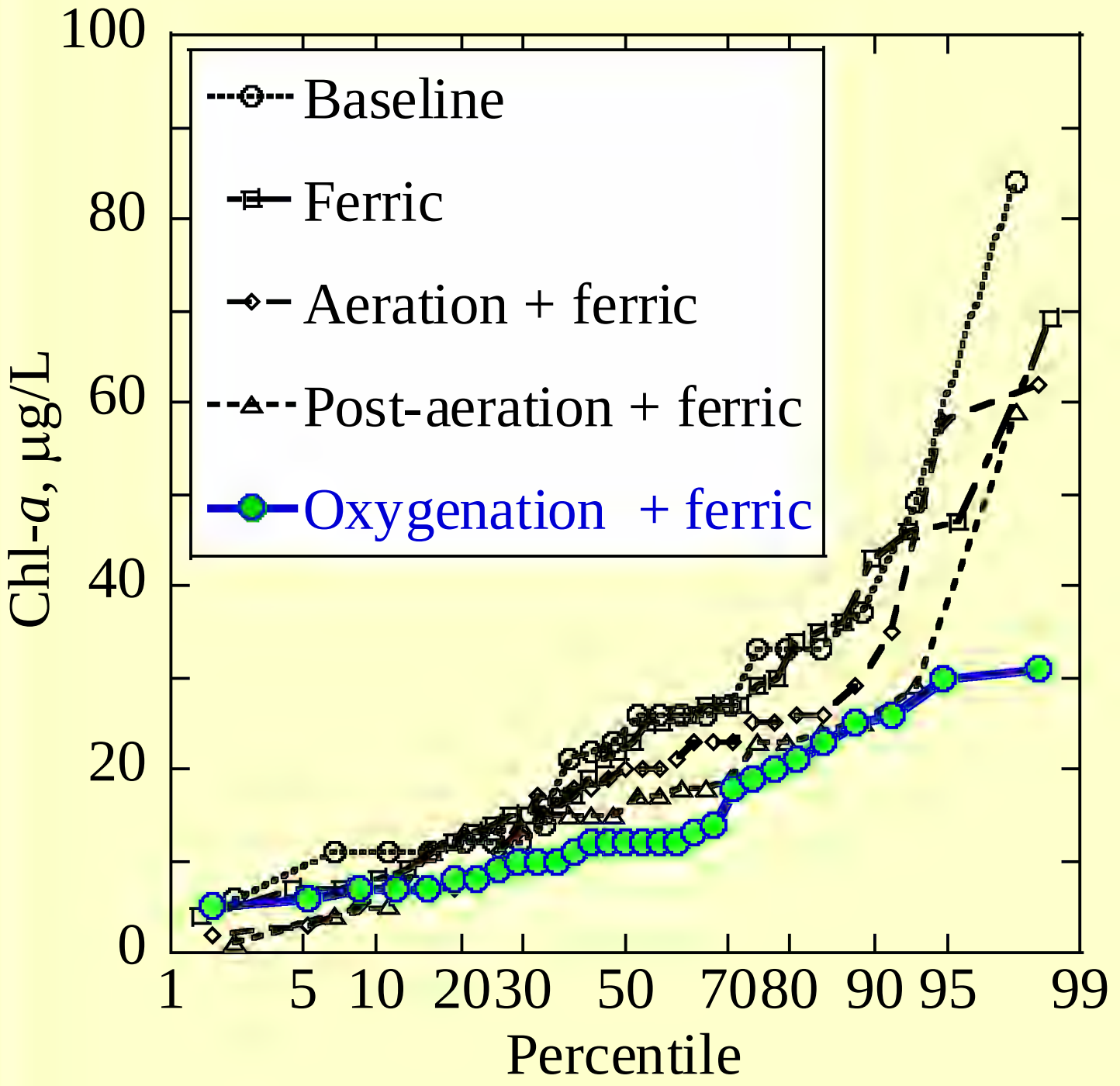
Deep oxygen injection: Aurora Reservoir, Colorado



Pleasant Lake, Minnesota: Hypolimnion Total Phosphorus



Pleasant Lake, chlorophyll-*a* (algae)

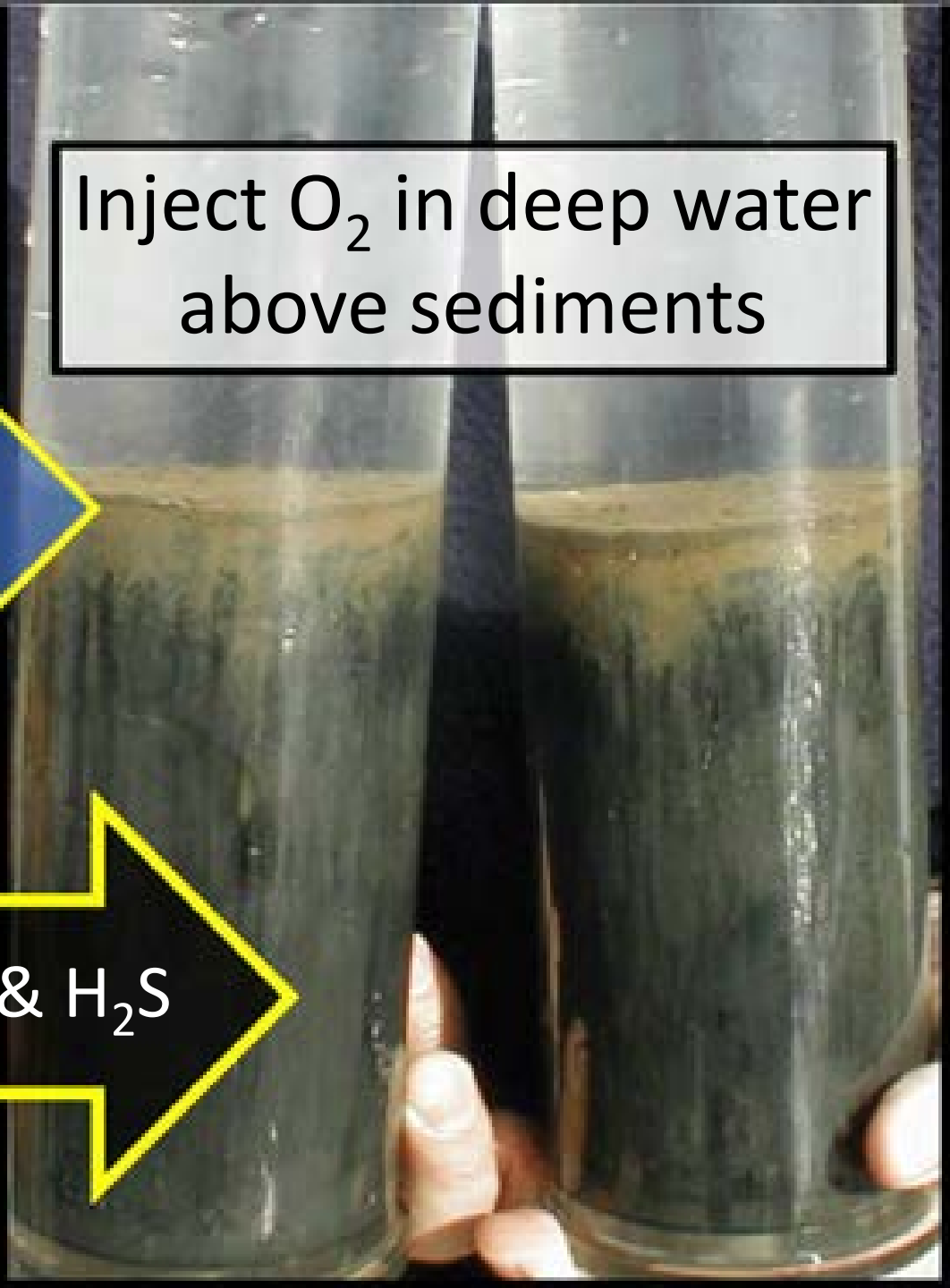


Mechanism

Inject O_2 in deep water above sediments

To create ferric iron cap

To entomb phosphorus & H_2S

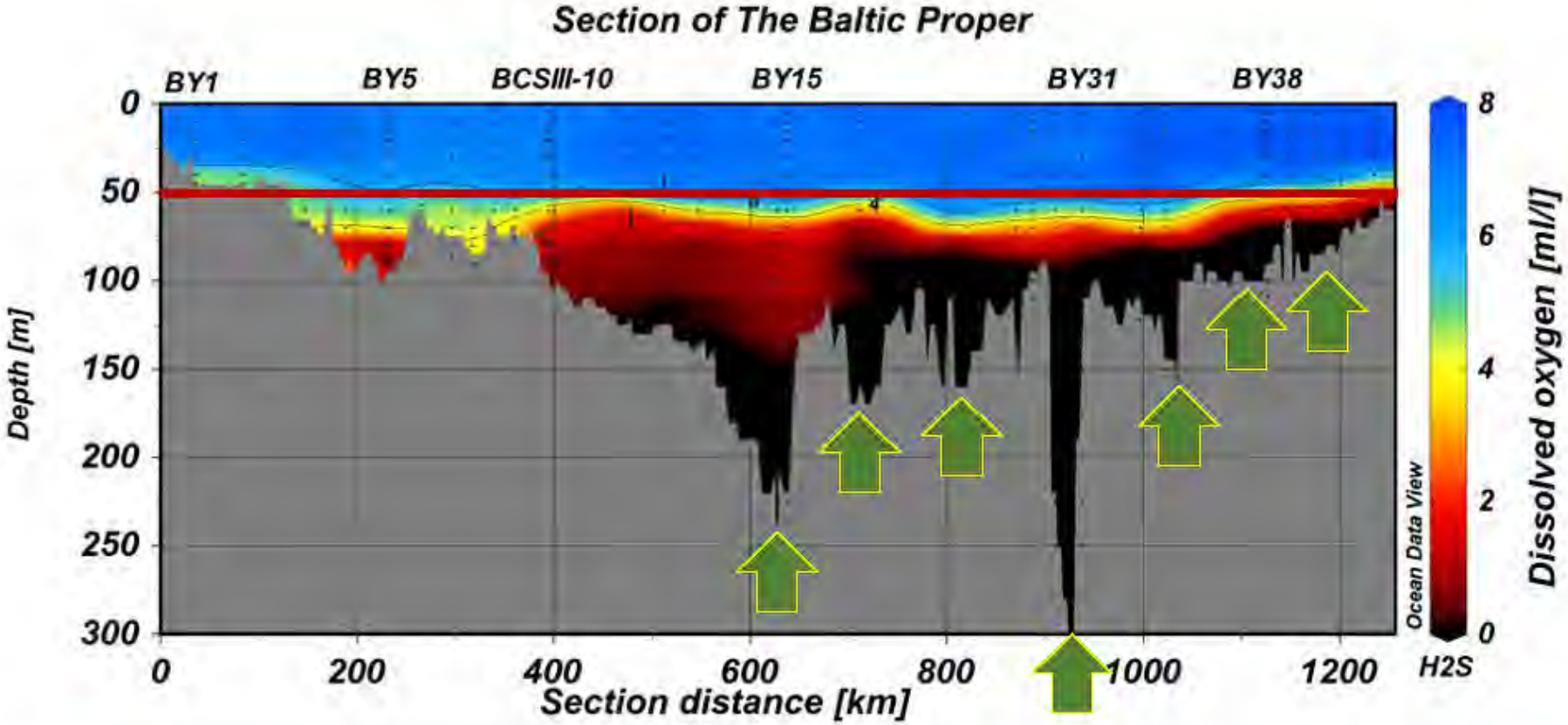


Reservoirs vs. The Baltic Sea

- **Reservoirs**: seasonal thermal stratification (epilimnion, hypolimnion)
- Baltic: seasonal stratification plus permanent saline stratification
- **Reservoirs**: hypolimnetic deep O_2 injection in the spring-fall
- Baltic: continuous deep O_2 injection in halocline (deepest sub-basins)
- **Reservoirs**: Mature O_2 injection technology at 1-10% Baltic design scale

Scaling up to the Baltic Sea

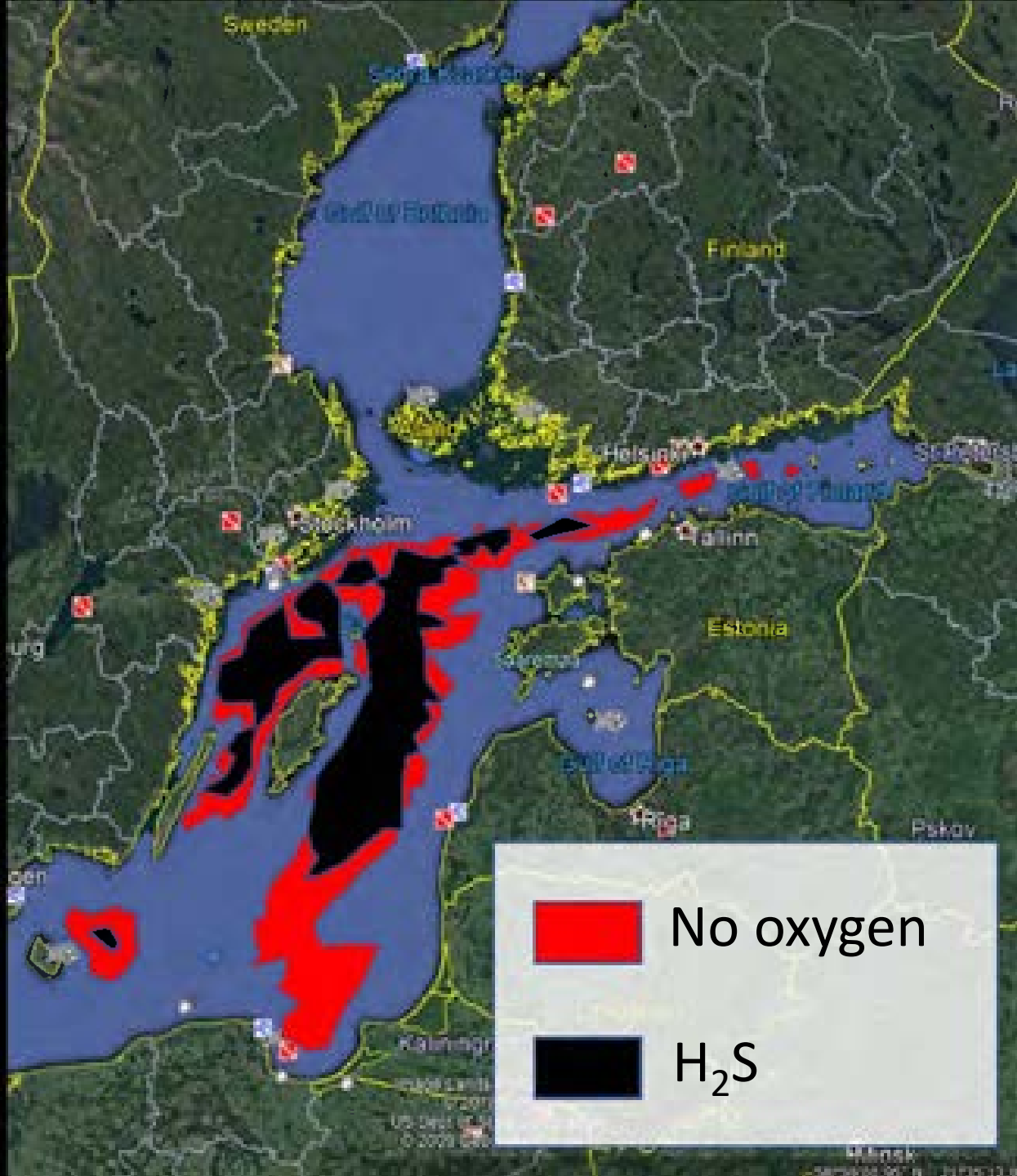
Standard engineering methods meet pressure requirements



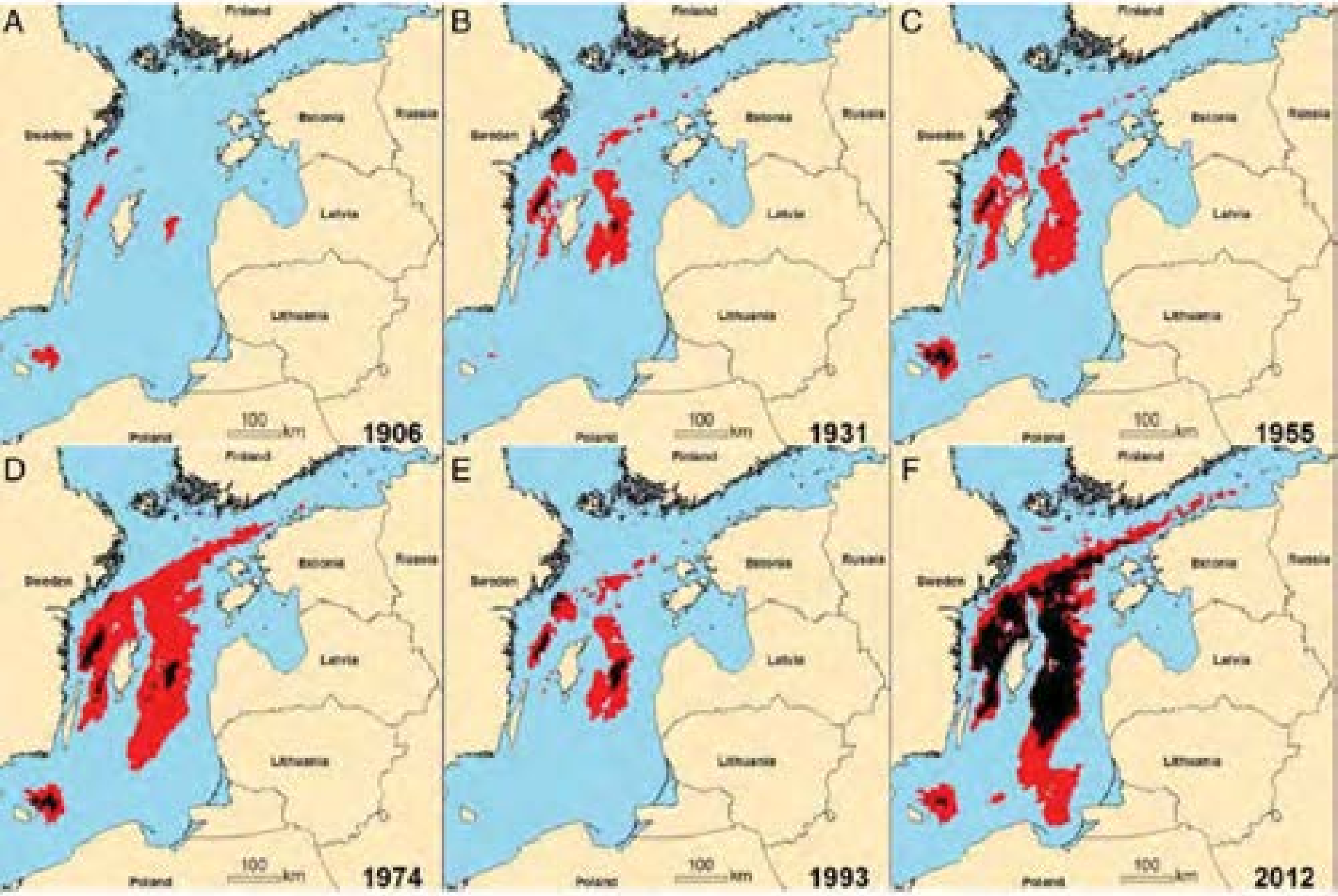
Inject pure oxygen gas in deeps

Baltic Anoxia

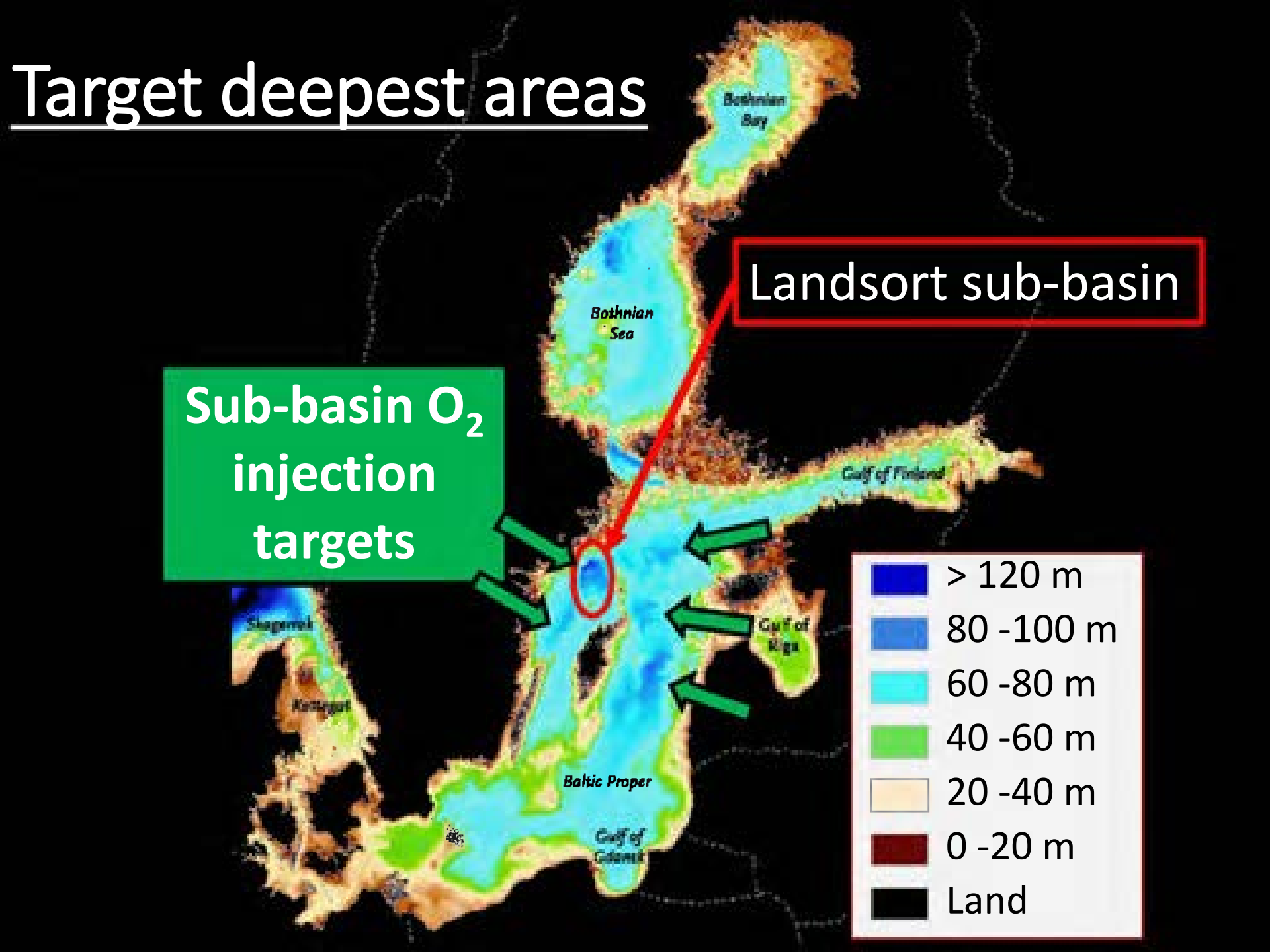
- Kill H_2S first
- Restore deep O_2



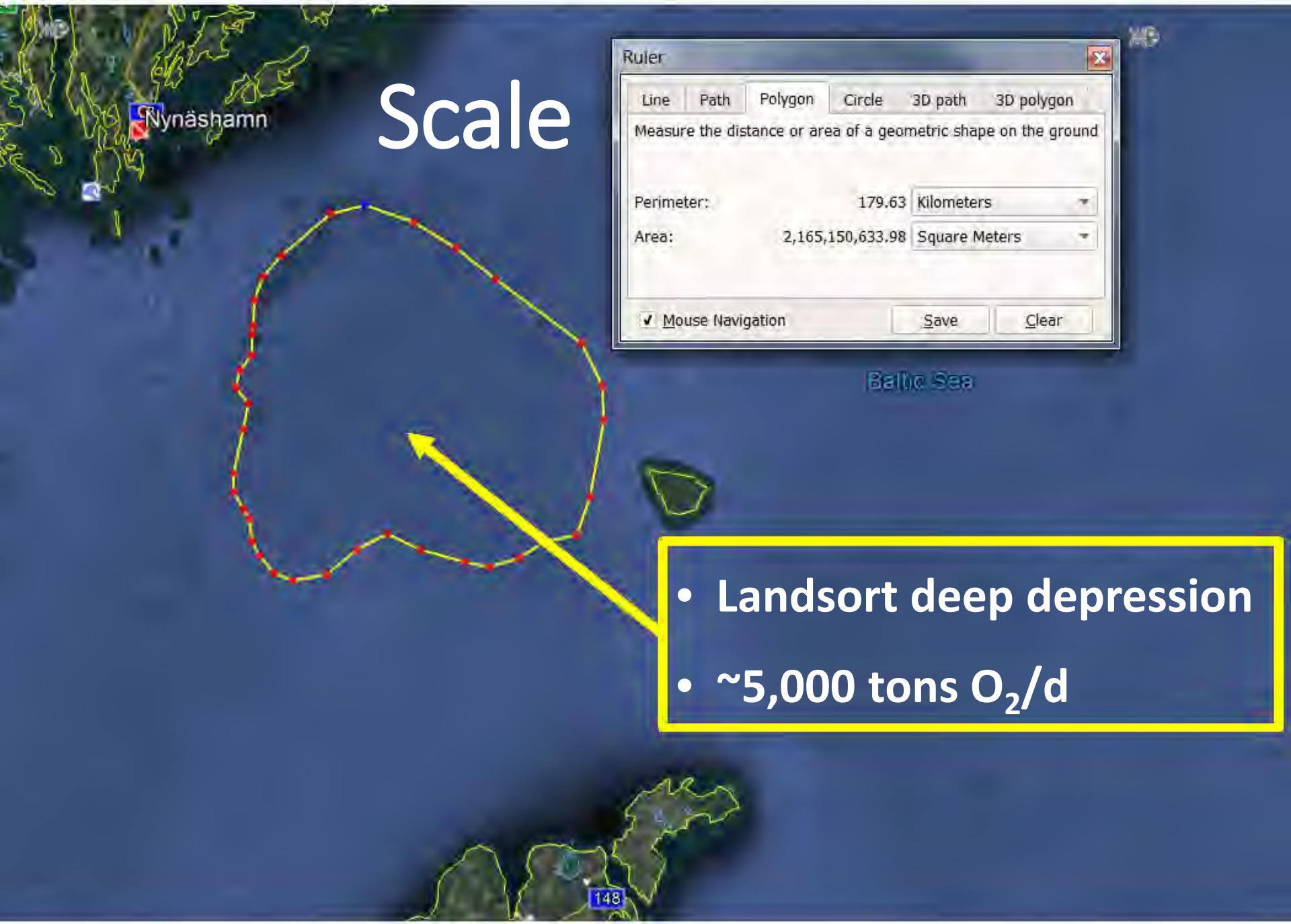
Historic anoxic progression from deeps



Target deepest areas



Scale



- **Landsort deep depression**
- **~5,000 tons O_2/d**

What does 5,000 tons O_2/d production look like?

- **Air liquefaction**
- **Fractional distillation of liquid O_2, N_2, and trace gases**

Air Liquide DBOO (€200M) for Sasol, SA

Two months supply of O_2 at 5,000 tons/d

Cryogenic fluid carrier similar to LNG carrier

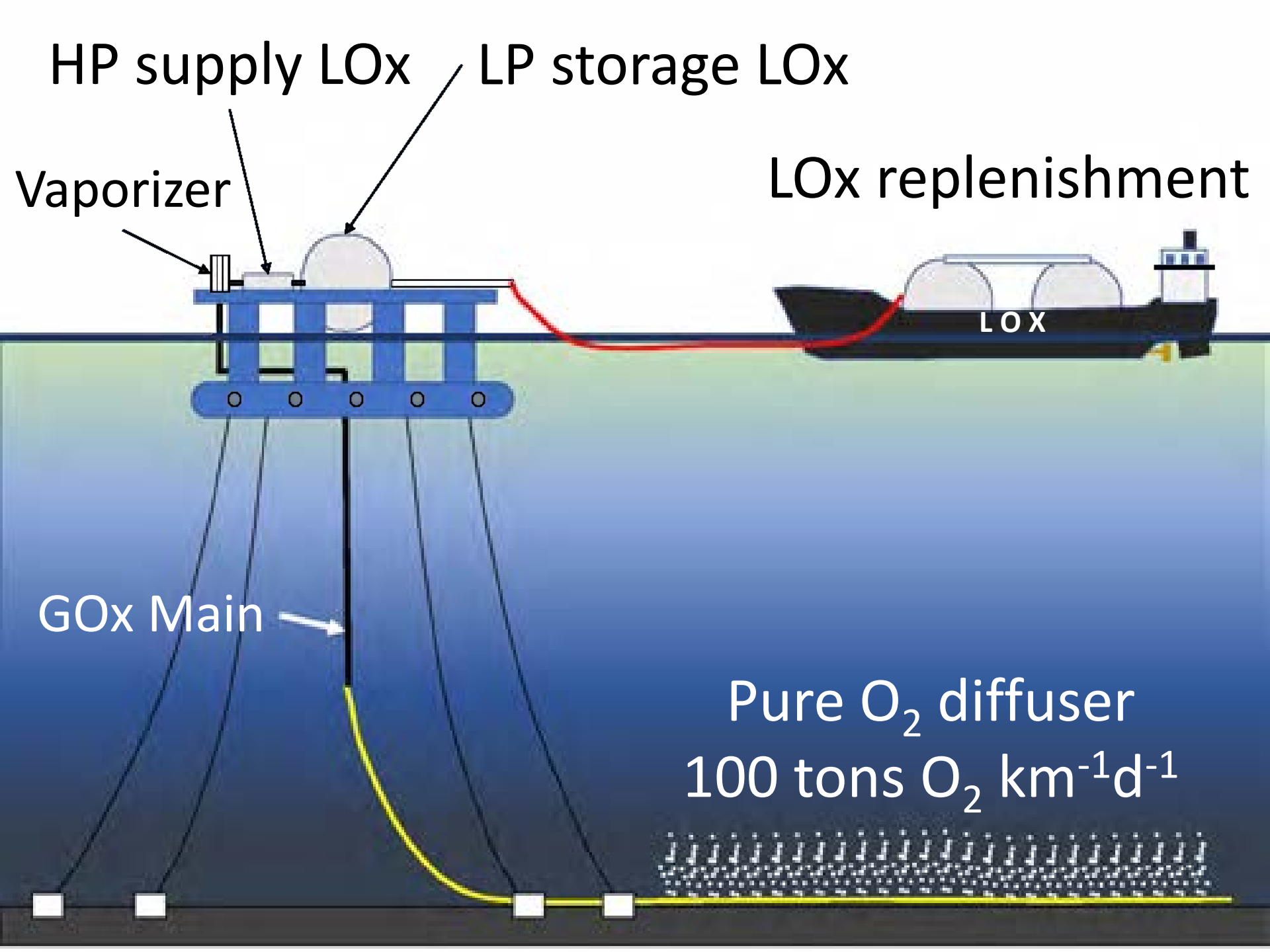
LOX carrier a bespoke design, however, not LNG conversion

Swedish expertise

Cryogenic expertise in Sweden:

- Swedegas
- Trelleborg
- Others

Pictures: Trelleborg


HP supply LOx
LP storage LOx
Vaporizer
LOx replenishment
LOX
GOx Main
Pure O_2 diffuser
100 tons O_2 $km^{-1}d^{-1}$

Infrastructure and opportunity

- Capital infrastructure of Baltic O_2
  - **Production** (land-based air liquefaction and separation)
  - **Distribution** (marine logistics)
  - **Dosing** (marine platform or land)
- Economic opportunity:

<u>Integrate LOx production with grid batteries</u>

Why Grid Batteries?
Renewable Energy Curtailment

- Curtailment: energy available ***but*** unused:
  - ✓Grid capacity limits
  - ✓**Lack of storage** to match demand & production variability
- Impact: ~€1B German curtailment payouts in 2020

Curtailed

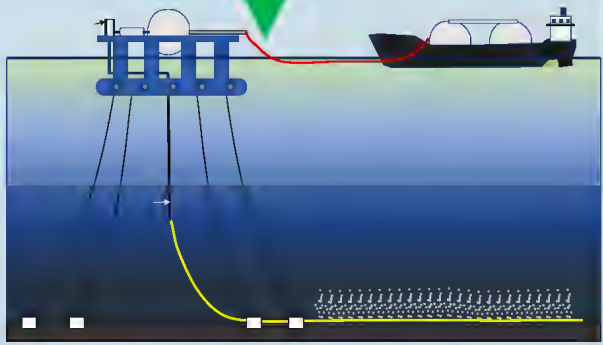
Liquid nitrogen grid battery

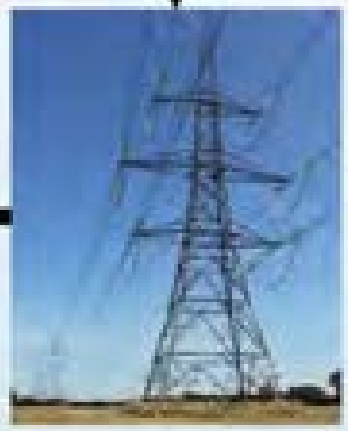
LOx

Up to 45% energy return on LOx production

Turbine generator

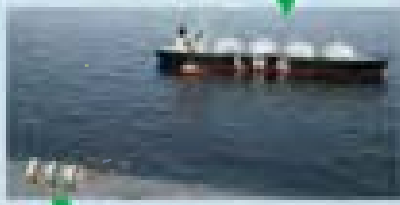
GAS ← LIQUID

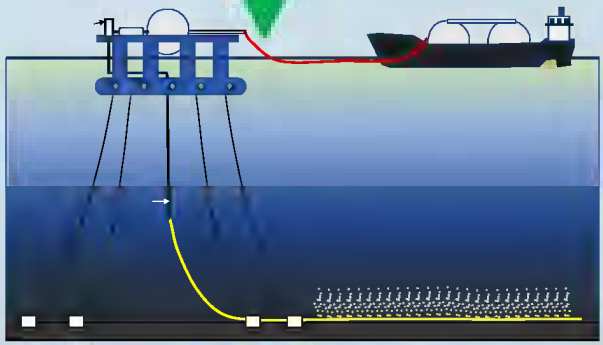




Curtailed

Electrolysis → O_2





H_2

HYDROGEN
ECONOMY
ENERGY
RECOVERY

Note:

- **Cryogenic grid batteries design-ready**
- **H_2 production currently small scale**

Conclusions

- **Technical outcome of deep oxygen injection is certain**:
  - ❑ Eliminate anoxia in Baltic deeps
  - ❑ Strongly suppress internal nutrient loading
  - ❑ Reduce magnitude, frequency, and duration of blooms
- **Scale unprecedented, but feasible and practical**:
  - ❑ Entails large program integrating mature industrial sectors, scientific community, and ecology of Baltic
  - ❑ Integration with renewable energy sector may be critical to economic viability

Some philosophy

Making is knowing and knowing is making

- Francis Bacon, 1561-1626

Those who are supposed to know but do not act simply do not yet know

- Wang Yangming, 1472-1529


Thank you.
Questions?
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