Ice Ages and Coastal Adaptations
Glaciations and isostatic rebound. Different models

Role of hydroisostasy

Pleistocene Glaciations, erosion and sediment redistribution. Input in global ocean level and regional impact on sea level changes

Relevant landscape development in time
Relative sea-level (RSL) change is the combined movement of both water and land – thus the result of:

- **Eustatic change**
- **Isostatic or tectonic change**
- **Local coastal processes**

### Eustasy

1) **Glacial-eustasy** is controlled by changes in the ocean water volume caused by glaciations and deglaciations.

2) **Tectono-eustasy** is controlled by variations in the ocean basin volume caused by sediment redistribution, changes in the volume of ocean ridge systems and hydro-isostasy.

3) **Geoidal-eustasy** is caused by variations in the earth's gravity field. Geoidal-eustasy causes changes in the distribution of ocean water. It affects the ocean level globally, but the direction and magnitude of changes differ over the globe.

### Land movements

- Tectonic changes
- Glacial isostasy
- Hydro isostasy
- Sediment isostasy

### Local coastal processes

- Local isostatic adjustment
- Intra plate stress effects
- Faulting, folding, tilting, tidal change …etc.
The Ice Age is well known to influence ocean level and shorelines globally in different way. The obvious major impact is usually assigned to the processes of growing and melting of ice sheets, linked with eustatic changes. Such changes of a shape and thickness of former ice sheets and water volumes influenced the load of Earth’s crust, generating isostatic adjustment movements in response to the loading – unloading cycles.

Problems:

Different isostatic models

Unclear glaciation scenario
Traces of extensive Gelasian glaciation?

**Russian Plain**

A. Pavlov, 1925: two extensive glaciations of Pliocene age (now Early Pleistocene). [Павлов А.П. Неогеновые и послетретичные отложения Южной и Восточной Европы. Мемуары геол. отд. о-ва любит. естеств. антропол и этногр., вып. 5, 1925.]

M. Grishenko, 1939: Early glaciation covered Voronezh district with north-south movement, as the distribution of erratics of Carboniferous limestones shows. [Грищенко М.Н. Неогеновые и четвертичные террасы бассейна Дона. БМОИП, отд. геол., т. XVII (6), 1939.]

P. Nikitin, 1957: Pliocene (now Early Pleistocene) deposits of Don river lowland contain Fennoscandian erratics. [Нikitин П.А. Плиоценовые и четвертичные флоры Воронежской области. Изд. АН СССР, 1957.]

V. Oskolkov, 1992: Tills between Pliocene beds

V. Zybakov, 2006: proglacial lake of extensive glaciation, age 2.54 – 2.4 Ma.

**North America**

G. Balco & C. W. Rovey. 2010. Absolute chronology for major Pleistocene advances of the Laurentide Ice Sheet: Geology; September 2010; v. 38; no. 9; p. 795-798

The first recorded advance of the Laurentide Ice Sheet reached 39°N, near the extreme southern limit of North American glaciation, 2.4 Ma.
Postglacial uplift

Uplift of subglacial surface by glacial isostasy
Effect of elastic lithosphere

Different isostatic models

Lithosphere rigidity $5 \times 10^{23}$ Nm (40 km)

- Rheology model of Fjeldskaar & Cathles (1991): asthenosphere with a thickness less than 150 km and viscosity less than $7.0 \times 10^{19}$ Pa s, mantle viscosity beneath the asthenosphere with viscosity $10^{21}$ Pa s, flexural rigidity of the lithosphere of $5 \times 10^{23}$ Nm (effective elastic thickness of 30-40 km).

Lithosphere rigidity $10^{25}$ Nm (100 km)
Earth parameters and models

Correction for isostatic movements is obligatory in geomorphological modeling. However, Earth parameters should be verified by known data.

Figure shows sediment load (m of rocks) above SUV peneplain and eroded below it. The map is rendered with present topography.

Figure shows isostatic response to the same load:
Left - the flexural rigidity of the lithosphere ~5x10**23 Nm (effective elastic thickness of 30-40 km)
Right - with flexural rigidity of 150 km thick lithosphere. The resulting correlation with thick lithosphere is low.
Any sea level change causes deflection of the ocean floor, hydro-isostasy, to attain isostatic equilibrium.

The hydro-isostasy is approximately 1/3 of the sea level change. But also the continents are deflected, with a mean magnitude over the continents twice the deflection of the ocean floor (the surface land area is only 29-30%)
An island moving with the sea floor will record the full sea level change, while points near the continents will record different sea level changes.
Hydro-isostasy

Ocean curves largely define the eustatic signal

130 m water increase during the last 18 000 years
80 m land uplift
40 m subsidence of ocean floor

Max 0.5 - 1mm / year

Total input
Input in present change
Local component is important to calculate deviations from the “pure” glacial isostatic adjustment. Here we show example of a model of the hydro-isostatic reaction on the final Baltic Ice Lake drop (left) and Lake Ladoga (right).
Glacial erosion and sedimentation
Combination of observations and modelling

METHODS

Regional geological and geomorphological analysis

Rate-based time-scale reconstructions

Mass-balance

Glacial erosion
Ice Age: Sedimentation

Regional compilation
Many sources used
Some apportioned into time slices

Accumulation replaces water by low-compacted sediments, with additional subsidence. Large part of deposition was concentrated on positive topographic features.

Belts of onshore accumulation are only a small part, indicating glacial erosion because of transportation of suspension material into the main peripheral sedimentary basins and on adjacent ocean slope.
Isopach maps of local regions:

Where did the material come from?

Glacial accumulation

Glacial erosion

Sediment redistribution and landscape changes

Palaeotopography
Glacial erosion is a significant, but variable factor. In particular it creates numerous overdeepenings of different scale in favorable conditions, especially in zones of ice streams with reduction of the angle of the base. In many cases glacial erosion deepened such areas hundreds meters below the drainage thresholds and “normal” non-excavated thalweg heights. Many huge enclosed basins - including the Baltic Sea - were created or strongly modified by this process. In counting the water-balance we are mostly interested in possible changing of water storage in continental parts. In relation to the ice age onset they hold additional amount of water in inner lakes and seas.
Largest zones of glacial overdeepenings from automatic landscape analysis

Distinct geological control

Zone of profound erosion partly conforms with the major boundary between basement and sedimentary cover; Graben-like structures may control ice-streams
Erosion: changes in time

Samples of rate-based time-scale reconstructions

Maximum ice extent, initial advance; erosion of soft sediments, regolith

Maximum ice extent; ice streams are of importance

Minor ice extent; ice streams are of importance

Usual developed ice extent, initial advance; erosion of soft sediments, regolith

"Active" ice sheet at degradation stage

"Passive" ice sheet

"Moderately active" ice sheet
Rate-based modeling

Involves:
• “Spider web” concentric and radial (ice stream) pattern and velocity changes, subice topography
• Erosion agents on growing and decay
• Lithology
• Abrasive changes

Separate: Iceberg scour rate
Modeling examples

Rate-base erosion assumption A-L (expansion, oscillation) (total duration ~100 000 years, low velocities and erosion speed)
Rate-base erosion assumption A (expansion) (total duration ~60,000 years)
Steps of permafrost estimations in time:

- Evaluation of the basal sub-ice temperature
- Solving the Stefan’s problem
- Correction for relevant geological features

Permafrost reduces glacial erosion
Marginal zone of maximum impact on coastal zones has more stable position along the Atlantic coast, migrating eastward due to ice sheet grow and decay, where it is also dependant on geological-geomorphological peculiarities.
Calculated isostatic response of Pleistocene-Holocene accumulation and erosion in Fennoscandia and adjacent regions
Impact of Erosion and Accumulation during the last glacial period

Redistribution Load

Rebound response today
Sediment correction for present rate of uplift is small
Remaining isostatic uplift (m) of Fennoscandia from best-fit parameters and one of the ice sheet models (A), and possible landscape changes model, accounting for future uplift, eustatic changes and sediment redistribution (B).

Negative topographic elements, previously occupied by central parts of ice sheets (Bothnian, Hudson Bay) would likely remain stable water storage with gradual shallowing up to future system of giant lakes.
Conclusions

- Glacial erosion and sedimentation significantly impact total glacial rebound, but with minor impact on present rate of uplift. Global, regional and local relevant sea-level changes in the form of sophisticated response depends on timescale and stages or cycles.

- Glacial erosion is a significant, but variable factor. It creates overdeepenings of different scale in favorable conditions. Many huge enclosed basins - including the Baltic - were created or strongly modified by this process. In relation to the ice age onset they can hold additional amount of water, even if related isostasy often reduces its volume.

- Negative topographic elements, previously occupied by central parts of ice sheets (Bothnian, Hudson Bay) would likely remain stable water storage with gradual shallowing up to future system of giant lakes.

- Hydro-isostasy impacted non-uniform relocation of coastal zone in local and regional scale. The local one is connected with water load changes of the enclosed basins. The regional influence could be subsidence of the ocean floor and subsequent uplift of continents caused by global eustatic changes.
Thank you!