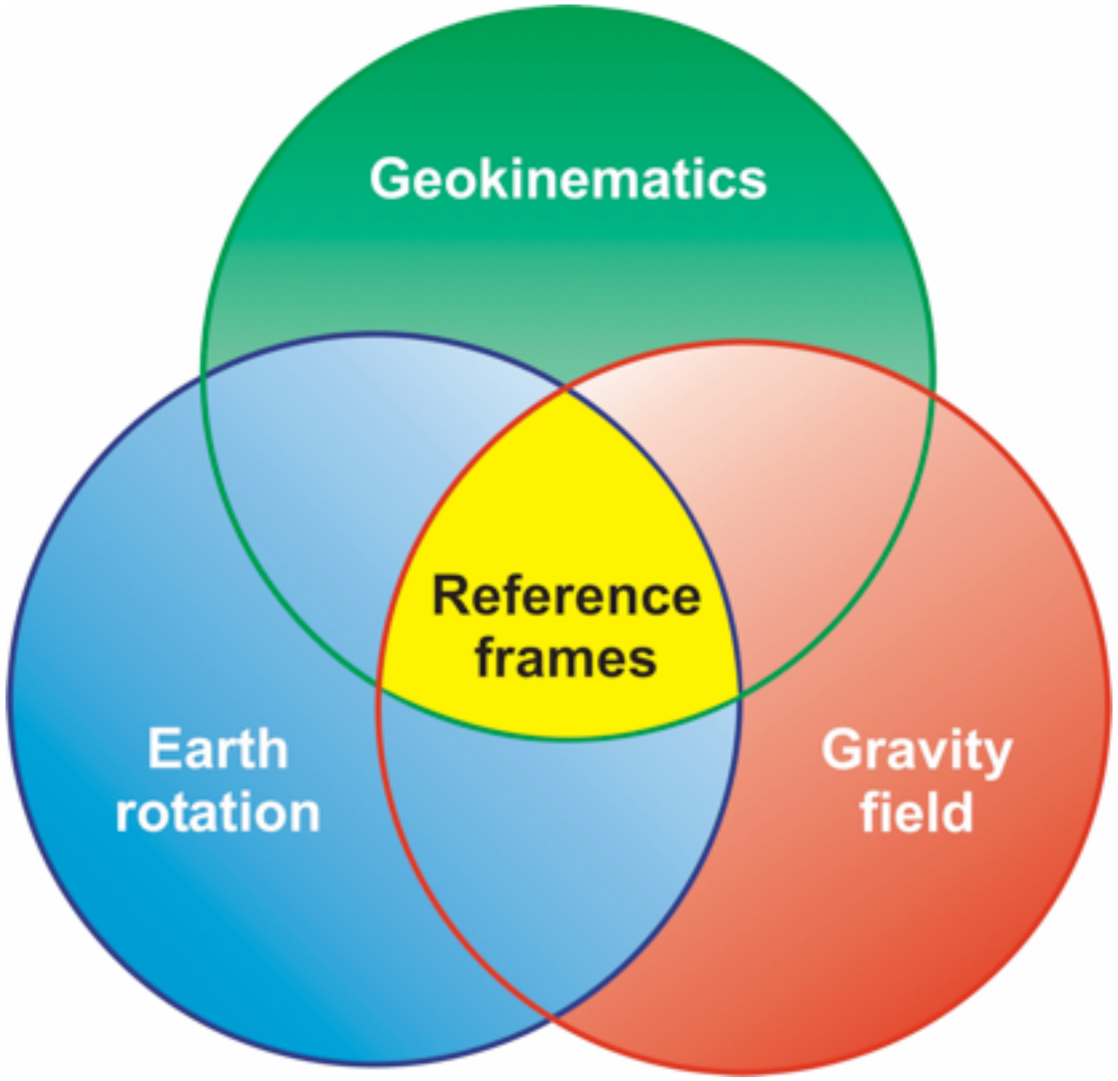
Introduction: The Three Pillars of Geodesy

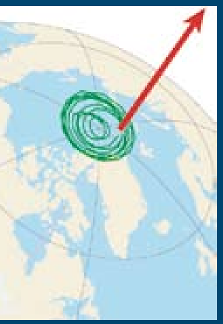
- Earth Shape (and how it changes over time)
- Earth Rotation
- Gravitational Field

In this class: We will focus on geometric aspects of Earth shape changes over time, and what they can tell us about for geophysical processes (mostly the solid Earth)



The three pillars of geodesy. *The changes in Earth's shape (geokinematic), gravity field and rotation, i.e. the "three pillars" of geodesy, provide the conceptual and observational basis for the reference frames required for Earth observation. Moreover, these "three pillars" are intrinsically linked to each other as they relate to the same unique Earth system processes. Today, the space-geodetic techniques and dedicated satellite missions are crucial in the determination and monitoring of geokinematics, Earth's rotation and the gravity field. Together, these observations provide the basis to determine the geodetic reference frames with high accuracy, spatial resolution and temporal stability.*

http://www.iag-ggos.org/about_ggos/introduction.php



L GEODETIC OBSERVING SYSTEM (GGOS)

Observing System of the International Association of Geo-
GGOS was established by IAG in July 2003. Since April
S represents IAG in the Group on Earth Observation (GEO)
s IAG's contribution to the Global Earth Observation System
(GEOSS).

ORY

tional cooperation fostered by IAG has led to the establish-
IAG Services, that provide increasingly valuable observa-
roducts not only to scientist but also for a wide range of
ic applications. Considering this development in geodesy,
ments of Earth observations, and the increasing societal
initially created GGOS as an IAG Project during the IUGG
2003 in Sapporo, Japan. After the first two years devoted to
on of the internal organizational structure of GGOS and its
with external organizations (the "Design Phase"), the Exe-
mittee of the IAG at its meetings in August 2005 in Cairns,
lecided to continue the Project. In the "Implementation
n 2005 to 2007, the GGOS Steering Committee, Executive
Science Panel, Working Groups, and Web Pages were esta-
l the Terms of Reference were revised. Finally, at the IUGG
2007 in Perugia, Italy, IAG elevated GGOS to the status of a
ent of IAG as the permanent observing system of IAG.

EANINGS OF GGOS

wo very distinct aspects, which should not be confused: the
on GGOS" consisting of components such as committees,
king groups, etc., and the "observation system GGOS" com-
infrastructure of many different instrument types, satellite
nd data and analysis centers. While GGOS as an organiza-
ablished its structure from essentially new entities and will,
xt years, add new entities where needed, the observational
re for GGOS as the system is being largely provided by the
s.

ORGANIZATION

n organization is a unifying umbrella for the IAG Services
rface between the Services and the "outside world". Inter-
GOS Committees, Science Panel and Working Groups focus
tting issues relevant for all Services. The research needed to
goals of GGOS influences the agenda of the IAG Commissi-
GGOS Working Groups. Externally, GGOS provides the links
e IAG Services and the main programs in Earth observations
cience. It constitutes a unique interface for many users to
c Services. In particular, GGOS participates on behalf of IAG
ernational programs focusing on Earth observations.

o the IAG By-Laws, GGOS "works with the IAG Services
ssions to provide the geodetic infrastructure necessary for
ing of the Earth system and global change research." This
mplies a vision and a mission for GGOS. The implicit vision
s to empower Earth science to extend our knowledge and
ing of the Earth system processes, to monitor ongoing
nd to increase our capability to predict the future behavior
n system. Likewise, the embedded mission is to facilitate
among the IAG Services and Commissions and other sta-
n the Earth science and Earth Observation communities,
scientific advice and coordination that will enable the IAG
develop products with higher accuracy and consistency
e requirements of particularly global change research, and
the accessibility of geodetic observations and products for
ge of users. The IAG Services, upon which GGOS is built,
n GGOS as a framework for communication, coordination,
fic advice necessary to develop improved or new products
sed accuracy, consistency, resolution, and stability. IAG
om GGOS as an agent to improved visibility of geodesy's
n to the Earth sciences and to society in general. The users,
ne national members of IAG, benefit from GGOS as a single
the global geodetic observation system of systems maintai-
IAG Services not only for the access to products but also to
needs. Society benefits from GGOS as a utility supporting
ce and global Earth observation systems as a basis for infor-
ns.

GGOS THE OBSERVING SYSTEM

GGOS as an observing system is built upon the existing and future infrastructure provided by the IAG Services. It aims to provide consistent observations of the spatial and temporal changes of the shape and gravitational field of the Earth, as well as the temporal variations of the Earth's rotation. In other words, it aims to deliver a global picture of the surface kinematics of our planet, including the ocean, ice cover and land surfaces. In addition, it aims to deliver estimates of mass anomalies, mass transport and mass exchange in the Earth system. Surface kinematics and mass transport together are the key to global mass balance determination, and an important contribution to the understanding of the energy budget of our planet. Moreover, the system aims to provide the observations that are needed to determine and maintain a terrestrial reference frame of higher accuracy and greater temporal stability than what is available today. By combining the "three pillars" into one observing system having utmost accuracy and operating in a well-defined and reproducible global terrestrial frame, GGOS adds to these pillars a new quality and dimension in the context of Earth system research. The observing system, in order to meet its objectives, has to combine the highest measurement precision with spatial and temporal consistency and stability that is maintained over decades.

GGOS AND ITS CHALLENGES

The observing system GGOS faces two types of scientific and technological challenges:

1. GGOS and the geodetic technologies need to meet the demanding user requirements in terms of reference frame accuracy and availability, as well as in terms of spatial and temporal resolution and accuracy of the geodetic observations. Developing an observing system capable of measuring variations in the Earth's shape, gravity field, and rotation with an accuracy and consistency of 0.1 to 1 ppb, with high spatial and temporal resolution, and increasingly low time latency, is a very demanding task. Accommodating the transition of new technologies as they evolve in parallel to maintaining an operational system is part of this challenge.

2. The Earth system is a complex system with physical, chemical and biological processes interacting on spatial scales from micrometers to global and temporal scales from seconds to billions of years. The integration of the "three pillars" into a system providing information on mass transport, surface deformations, and dynamics of the Earth therefore requires a "whole Earth'" approach harnessing the expertise of all fields of Earth science.

GGOS: AN OBSERVING SYSTEM OF LAYERED INFRASTRUCTURE

GGOS as an observing system has five major levels of instrumentation and objects that actively perform observations, are passively observed, or both. These levels are:

- Level 1: the terrestrial geodetic infrastructure;
- Level 2: the LEO satellite missions;
- Level 3: the GNSS and the Lageos-type SLR satellites;
- Level 4: the planetary missions and geodetic infrastructure on Moon and planets;
- Level 5: the extragalactic objects.

These five levels of instrumentation and objects, independent of whether they are active or passive, receivers or emitters or both, are connected by many types of observations in a rather complex way to form the integrated GGOS observing system. In this system, the major observation types at present are:

1. observations of the microwaves at the ground and at the LEO satellites emitted by GNSS satellites;
2. laser ranging to LEOs, dedicated laser ranging satellites, GNSS satellites and the Moon;
3. microwave observation of extragalactical objects (quasars) by VLBI;
4. instrumentation onboard the LEO satellites measuring accelerations, gravity gradients, satellite orientation, etc.;
5. radar and optical observations of the Earth's surface (land, ice, glaciers, sea level, ect.) from remote sensing satellites;
6. distance measurements between satellites (K-band, optical, interferometry, etc.).

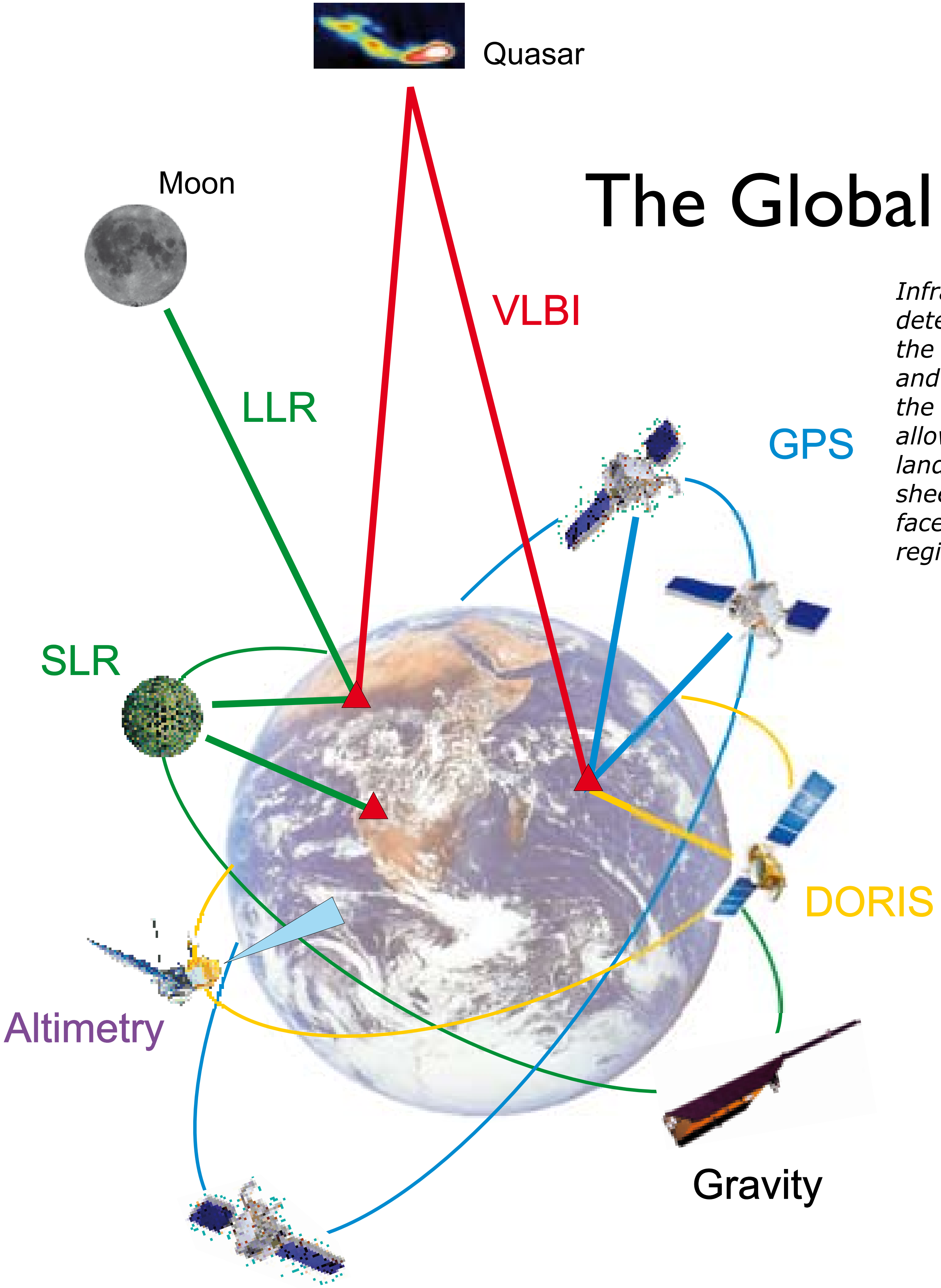
In the future, new measurement techniques will evolve and be included into the system. Different parts of the overall system are cross-linked through observations and inter-dependent. All these techniques are affected by and measure the "output" of the same unique Earth system, that is, the various geodetic fingerprints induced by mass redistribution and changes in the system's dynamics. Therefore, consistency of data processing, modeling, and conventions across the techniques and across the "three pillars"is mandatory for maximum exploitation of the full potential of the system.

THE GLOBAL GEODETIC OBSERVING SYSTEM

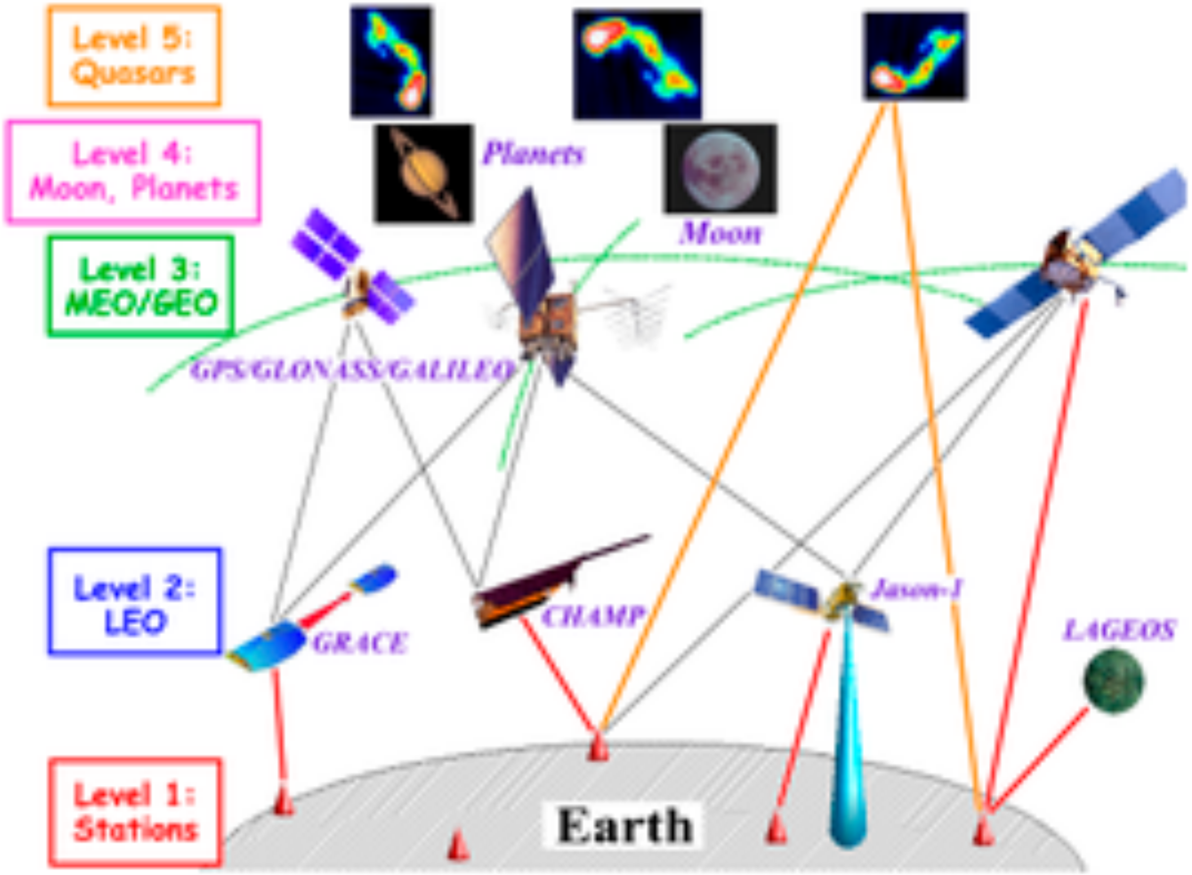
Geodesy's contribution to Earth Observation

http://www.ggos.org

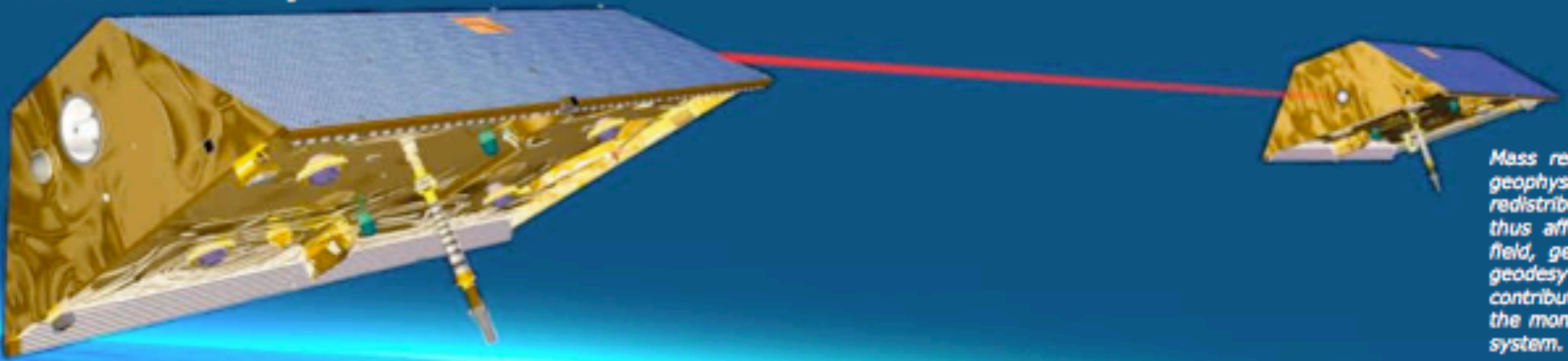
GGOS
The Global Geodetic Observing System



Infrastructure contributing to GGOS. The combined infrastructure allows the determination and maintenance of the global geodetic reference frames, and the determination of Earth's gravity field and rotation. The ground networks and navigation satellites (currently in particular GPS) are crucial for maintaining the reference frame required for high accuracy positioning. In particular, they allow the monitoring of volcanoes, earthquakes, tectonically active regions and landslide-prone areas. The Low Earth Orbit (LEO) satellites monitor sea level, ice sheets, water storage on land, atmospheric water content, high-resolution surface motion, and variations in the Earth's gravity field. The latter are caused by regional and global mass transport processes as, e.g., the hydrological cycle.



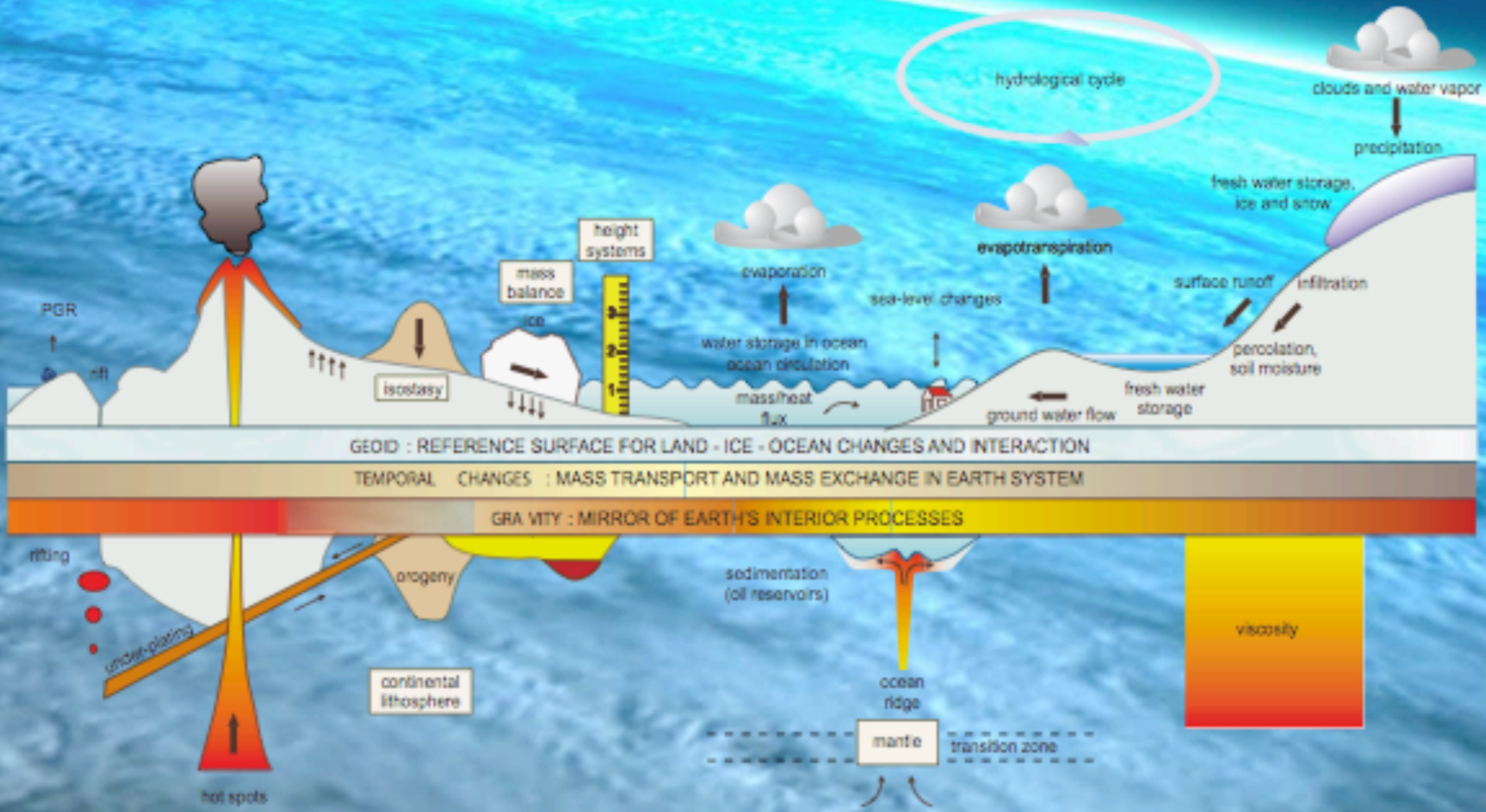
ite laser-ranging targets. The innovative sensor technologies used
se gravity field missions have already enabled a dramatic impro-
nt of the gravity field during the last decade. Gravity field models
GRACE have benefited the space geodetic analysis of the DORIS
ng data. They have been used to improve the knowledge of the
of ocean radar altimetry satellites, and for laser altimeters, the-
enhancing the geodetic contributions from other space missions.
y missions are also of central importance for altimetry, because
cise geoid is required to refer the sea surface topography to the
. The integration of all the satellite missions with the existing
-geodetic techniques for the determination of the Earth's shape
es new opportunities to determine and study the mass transport
Earth system in a globally consistent way or to derive information
anges in part of the water cycle. Analysis of the data delivered by
E yields a direct measure of mass flux with high spatial resolution
ut 500 km on the Earth's surface, and sub-monthly temporal reso-
. Combining these mass changes with advanced meteorological
is predicting water storage on land such as the Global Land Data
ilation System (GLDAS) rapidly improves the quantitative know-
of the water cycle and provides new datasets for climate change
es.



ESY'S NEW CUSTOMERS

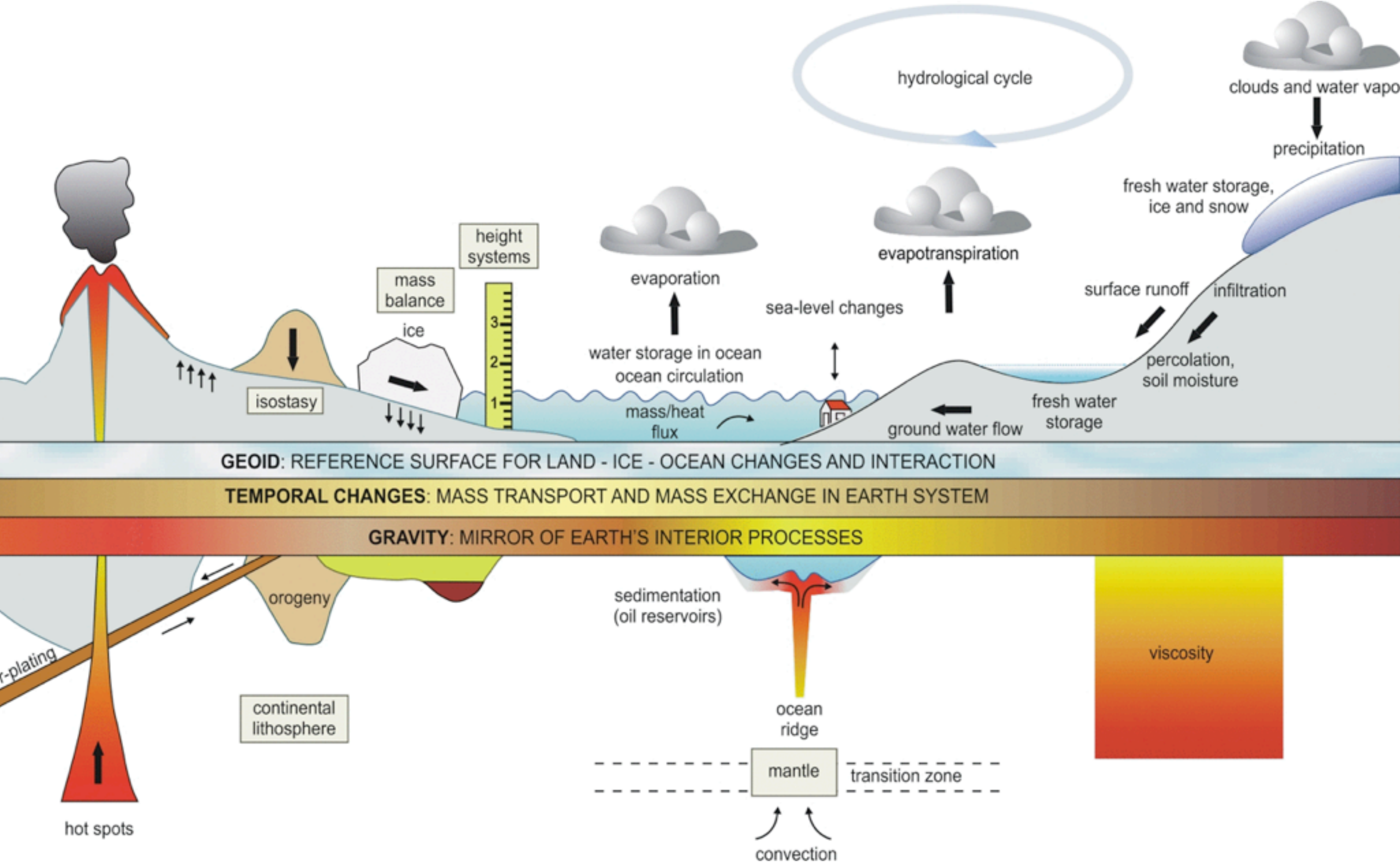
arge extent, geodesy is a "service science". In the past, the main
omers" of geodesy came from the surveying and mapping pro-
n, while today geodesy serves all Earth science, including the
ysical, oceanographic, atmospheric, and environmental science
unities. Geodesy is also indispensable for the maintenance of
activities in a modern society. Traditionally, geodesy has served
y by providing reference frames for a wide range of practical
ations from regional to global navigation on land, sea, and in air,
ruction of infrastructure, to the determination of reliable bounda-
f real estate properties. Reference frames were, however, national
ional in scope, and they were suited for the determination of coor-
s relative to a network of reference points. Thus, determination
cise point coordinates required simultaneous measurements at
al points. Today, the Global Navigation Satellite Systems (GNSS)
de access to precise point coordinates in a global reference frame
ne and anywhere on the Earth's surface with centimeter-level
acy and without requiring additional measurements on nearby
nce points.

esy has the potential to make very important contributions to the
standing of the state and dynamics of System Earth, particularly
sistent observations of the "three pillars" can be provided on
al scale with a precision at or below the 1 ppb level, and with
ient stability over decades. A prerequisite to exploiting the full
tial of geodesy for Earth observation, Earth system monitoring,
any practical applications is a sophisticated integration of all geo-
techniques (spaceborne, airborne, marine and terrestrial), proces-
nodels and geophysical background models into one system. The
ration of the "three pillars" will permit - as part of global change
rch – the assessment of surface deformation processes and the
ification of mass anomalies and mass transport inside individual
onents, and mass exchange between the components of the Earth's
m. These quantities serve as input to the study of the physics of
olid Earth, ice sheets and glaciers, hydrosphere and atmosphere.
are of particular value for the study of complex phenomena such
cial isostatic adjustment, the evolution of tectonic stress patterns,
vel rise and fall, the hydrological cycle, transport processes in the
s, and the dynamics and physics of the atmosphere (troposphere
nosphere).

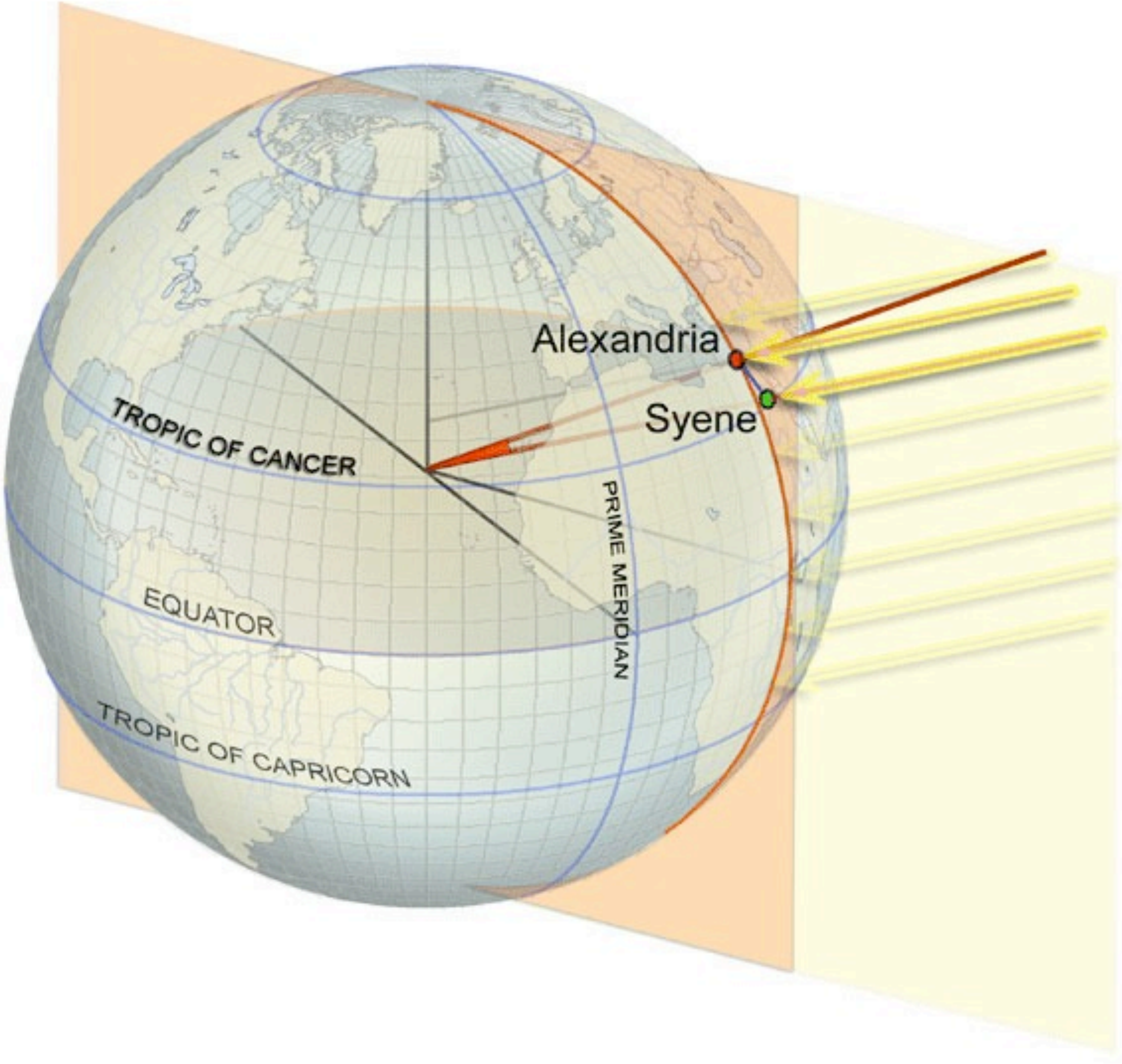


Mass redistribution in the Earth system. All geophysical processes are associated with mass redistribution and changes in the dynamics, thus affecting commonly the Earth's gravity field, geometry, and rotation. Consequently, geodesy with observations of the "three pillars" contributes to an observing system that allows the monitoring of mass transport in the Earth system.

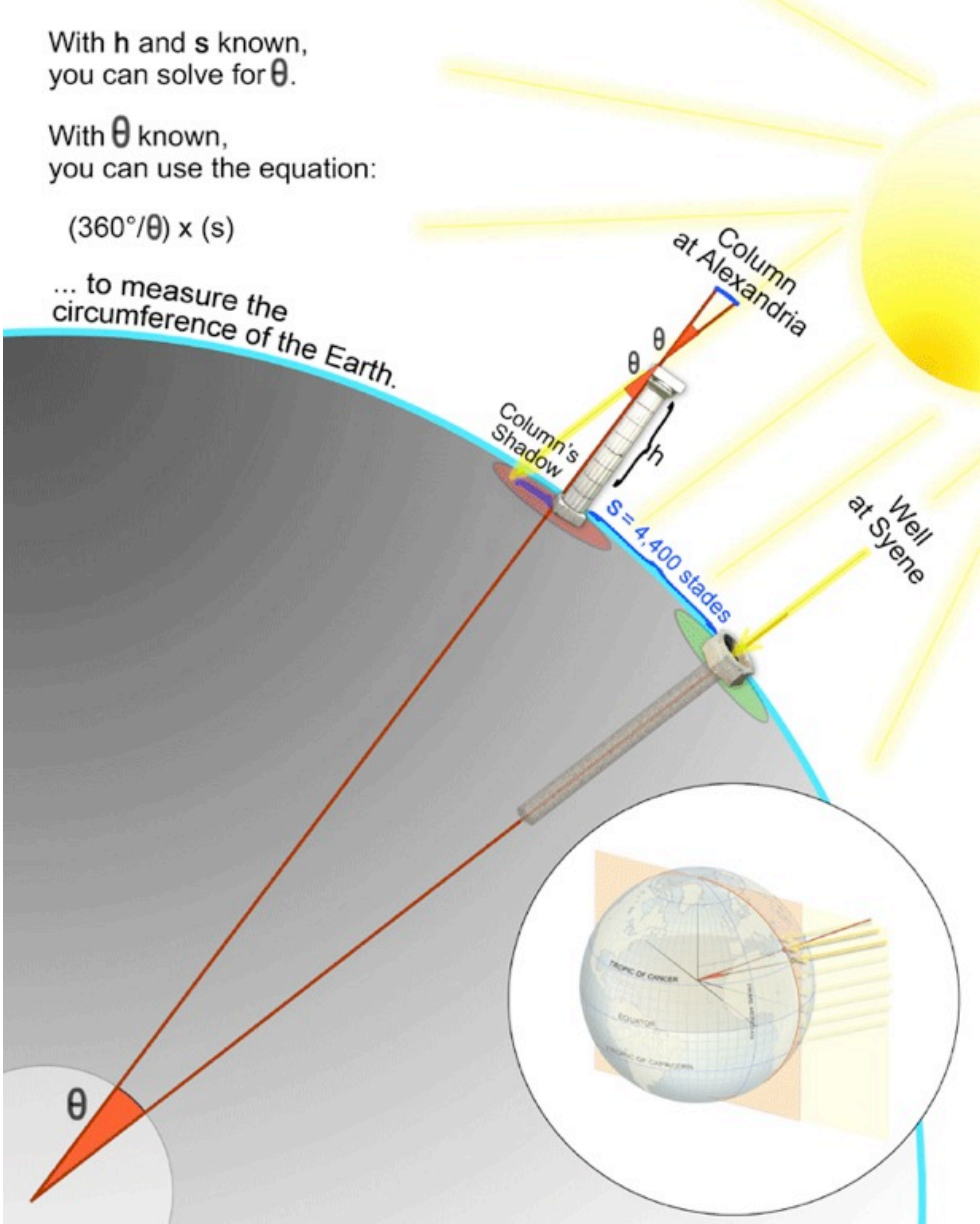
It can get a little complicated...



Eratosthenes Estimates the Size of the Earth



from: http://oceanservice.noaa.gov/education/kits/geodesy


With **h** and **s** known,
you can solve for θ.

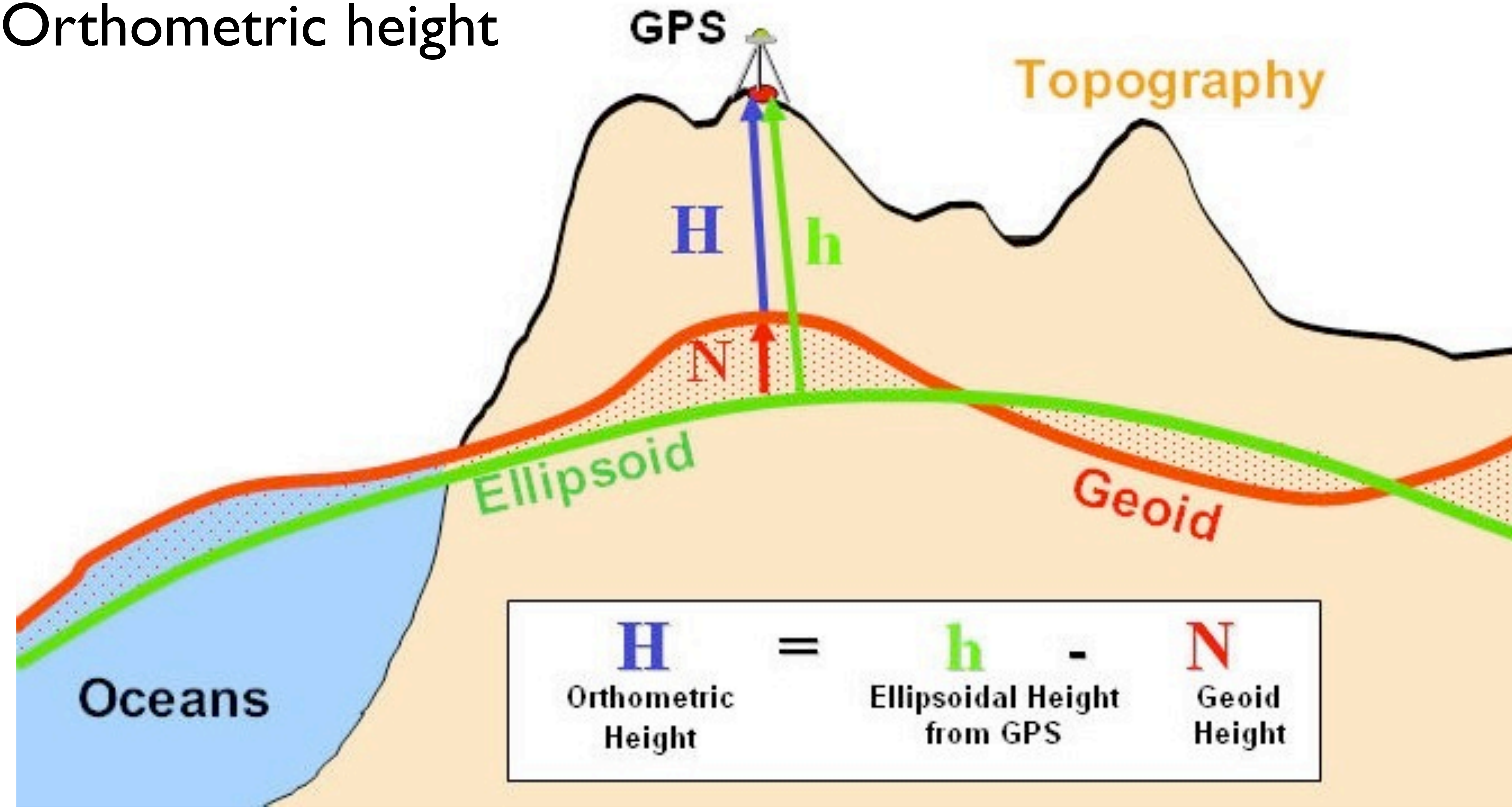
With θ known,
you can use the equation:

$(360°/\theta)$ x (s)

... to measure the circumference of the Earth.

- He got a circumference of ~40,000 km, error of near 2%.
- Lucky? Nobody really knows how big his 'stadia' were.
- Accounts of this story vary...

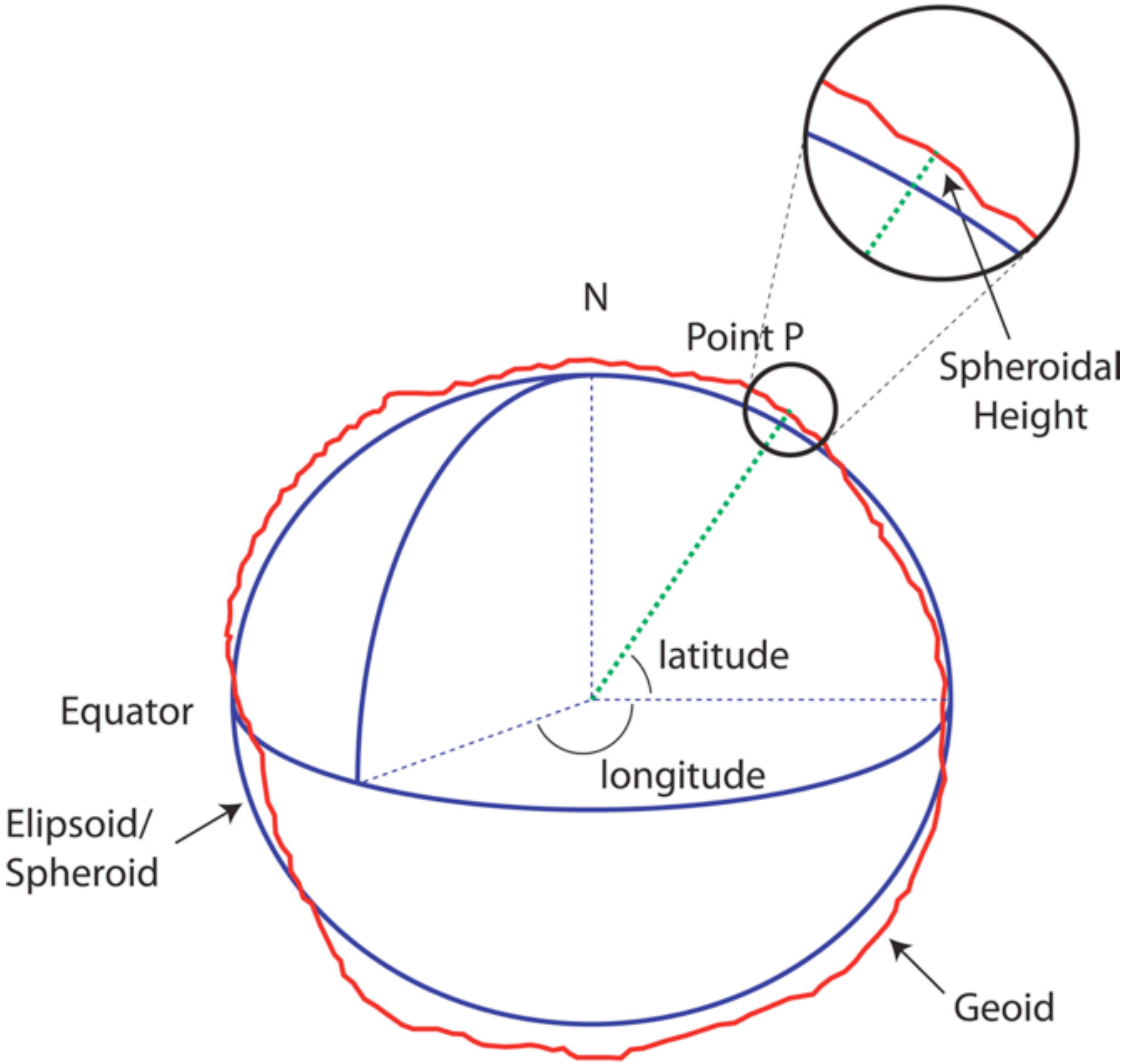
Ellipsoidal height vs. Orthometric height



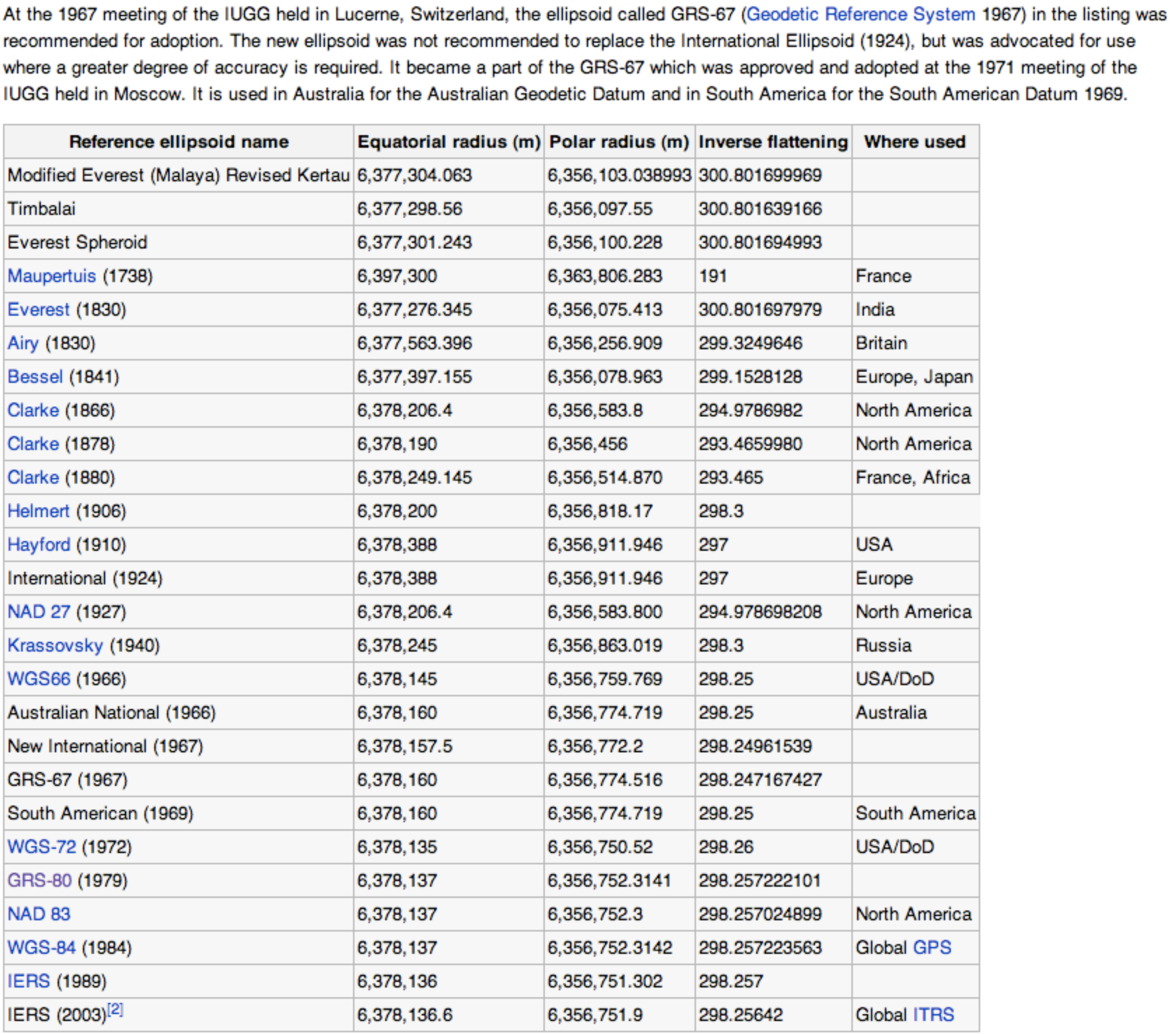
$H = h - N$

Orthometric Height = Ellipsoidal Height from GPS - Geoid Height

- What is height?
- Which direction is up?
- What is sea level?


N
Point P
Spheroidal Height
latitude
Equator
longitude
Elipsoid/ Spheroid
Geoid

Datums



At the 1967 meeting of the IUGG held in Lucerne, Switzerland, the ellipsoid called GRS-67 (Geodetic Reference System 1967) in the listing was recommended for adoption. The new ellipsoid was not recommended to replace the International Ellipsoid (1924), but was advocated for use where a greater degree of accuracy is required. It became a part of the GRS-67 which was approved and adopted at the 1971 meeting of the IUGG held in Moscow. It is used in Australia for the Australian Geodetic Datum and in South America for the South American Datum 1969.

Reference ellipsoid name	Equatorial radius (m)	Polar radius (m)	Inverse flattening	Where used
Modified Everest (Malaya) Revised Kertau	6,377,304.063	6,356,103.038993	300.801699969	
Timbalai	6,377,298.56	6,356,097.55	300.801639166	
Everest Spheroid	6,377,301.243	6,356,100.228	300.801694993	
Maupertuis (1738)	6,397,300	6,363,806.283	191	France
Everest (1830)	6,377,276.345	6,356,075.413	300.801697979	India
Airy (1830)	6,377,563.396	6,356,256.909	299.3249646	Britain
Bessel (1841)	6,377,397.155	6,356,078.963	299.1528128	Europe, Japan
Clarke (1866)	6,378,206.4	6,356,583.8	294.9786982	North America
Clarke (1878)	6,378,190	6,356,456	293.4659980	North America
Clarke (1880)	6,378,249.145	6,356,514.870	293.465	France, Africa
Helmert (1906)	6,378,200	6,356,818.17	298.3	
Hayford (1910)	6,378,388	6,356,911.946	297	USA
International (1924)	6,378,388	6,356,911.946	297	Europe
NAD 27 (1927)	6,378,206.4	6,356,583.800	294.978698208	North America
Krassovsky (1940)	6,378,245	6,356,863.019	298.3	Russia
WGS66 (1966)	6,378,145	6,356,759.769	298.25	USA/DoD
Australian National (1966)	6,378,160	6,356,774.719	298.25	Australia
New International (1967)	6,378,157.5	6,356,772.2	298.24961539	
GRS-67 (1967)	6,378,160	6,356,774.516	298.247167427	
South American (1969)	6,378,160	6,356,774.719	298.25	South America
WGS-72 (1972)	6,378,135	6,356,750.52	298.26	USA/DoD
GRS-80 (1979)	6,378,137	6,356,752.3141	298.257222101	
NAD 83	6,378,137	6,356,752.3	298.257024899	North America
WGS-84 (1984)	6,378,137	6,356,752.3142	298.257223563	Global GPS
IERS (1989)	6,378,136	6,356,751.302	298.257	
IERS (2003)[2]	6,378,136.6	6,356,751.9	298.25642	Global ITRS

The Geoid

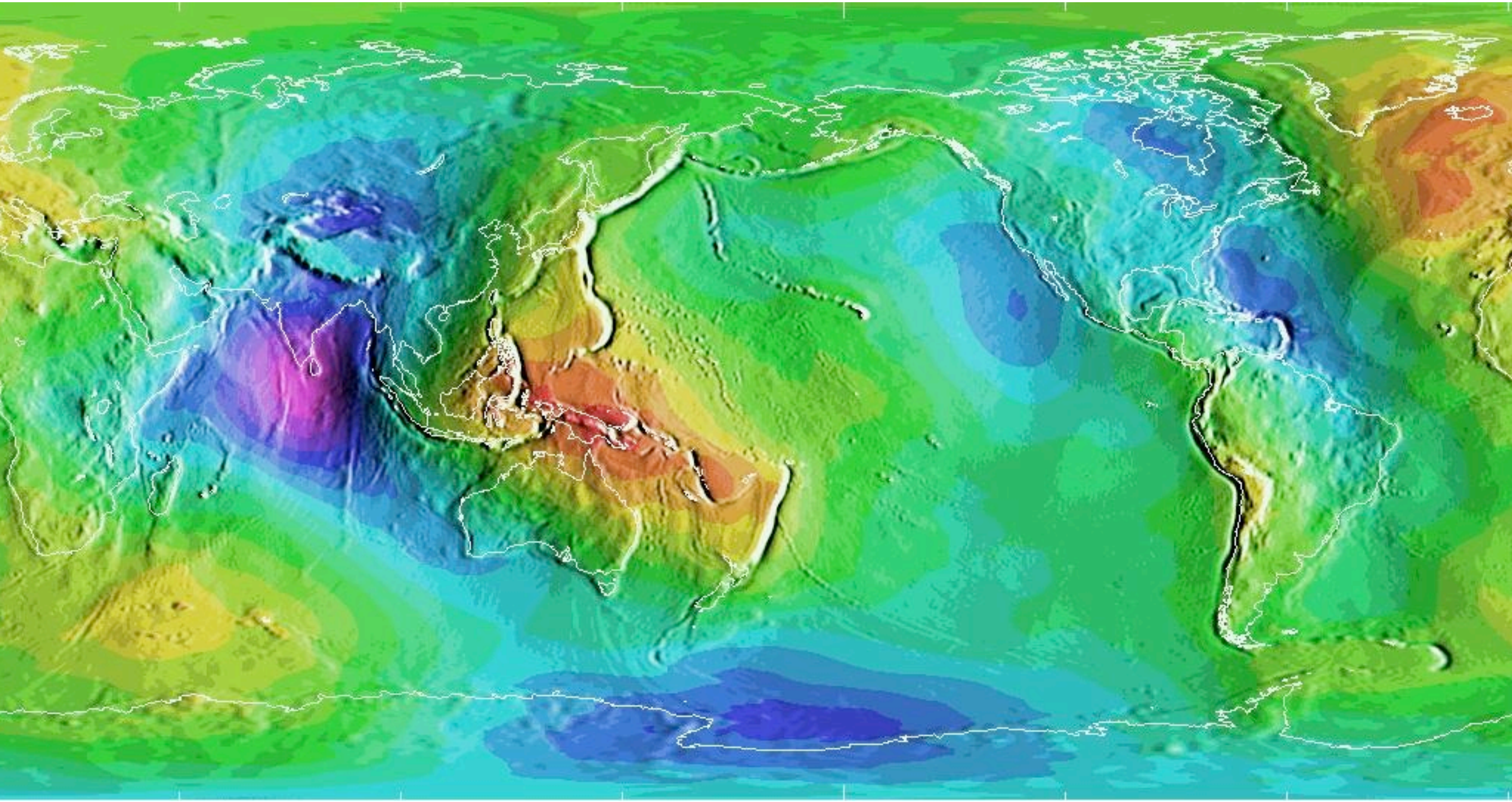
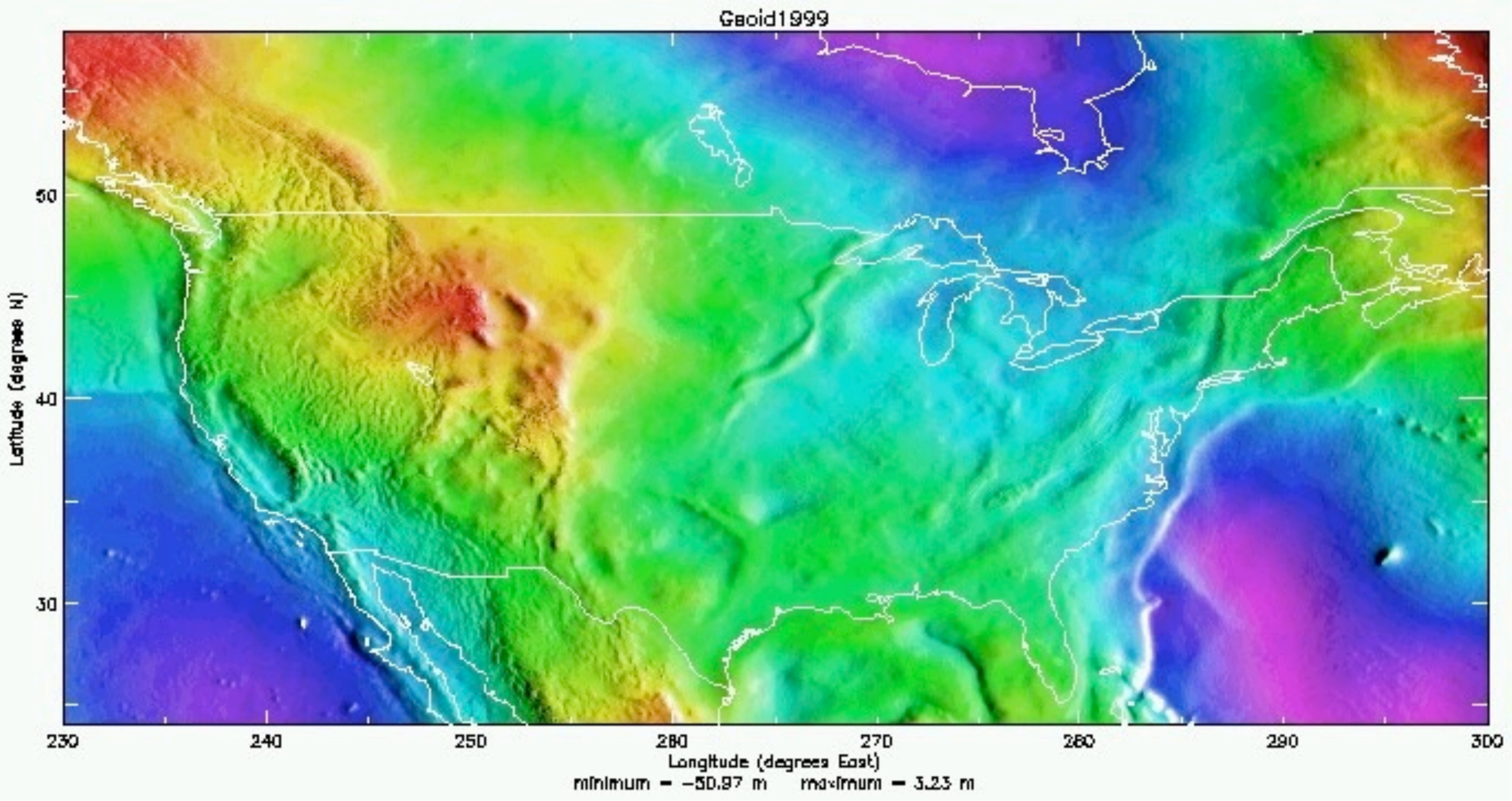


Image Name : ww15mgh; Boundaries : Lat -90N to 90N; Lon 0E to 360E;
Color Scale, Upper (Red) : 85.4 meters and higher; Color Scale, Lower (Magenta) :-107.0 meters and lower
Data Max value : 85.4 meters Data Min value :-107.0 meters Illuminated from the : East

figure taken from http://principles.ou.edu/earth_figure_gravity/geoid/index.html



***GEOID99** is a refined model of the geoid in the United States, which supersedes the previous models GEOID90, GEOID93, and GEOID96. For the conterminous United States (CONUS), GEOID99 heights range from a low of -50.97 meters (magenta) in the Atlantic Ocean to a high of 3.23 meters (red) in the Labrador Strait. However, these geoid heights are only reliable within CONUS due to the limited extents of the data used to compute it. GEOID99 models are also available for Alaska, Hawaii, and Puerto Rico & the U.S. Virgin Islands.*

See also: Smith, D. A., and D. R. Roman (2001), GEOID99 and G99SSS: 1-arc-minute geoid models for the United States, *Journal of Geodesy*, *75*, 469-490.

Vertical Land Motion (VLM) and Local Sea Level (LSL)

Local Sea Level (LSL)

- as measured by tide gauges
- relevant to coastal impacts

Geocentric Sea Level (GSL)

- sea surface height: altimeters
- relative to ITRF origin
- CM(Earth) ± 0.5 mm/yr

Vertical Land Motion (VLM)

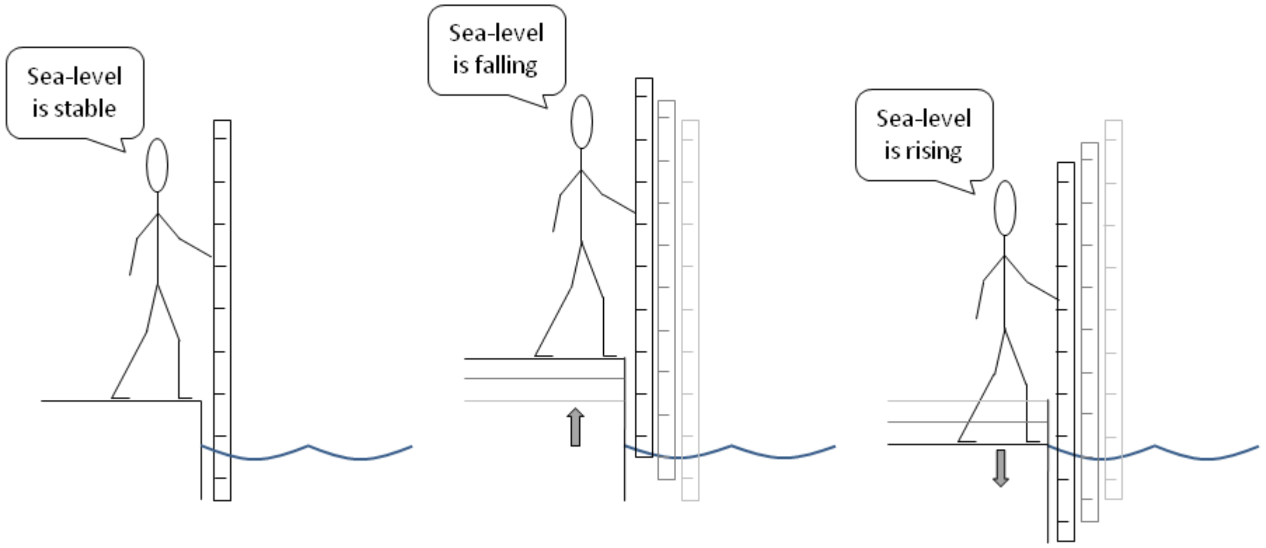
LSL = GSL - VLM

- GSL & VLM relative to ITRF

Coastal subsidence (-VLM)

- Obviously 1:1 effect on LSL

Stating the Obvious



Source: P. Whitehouse
http://www.antarcticglaciers.org/recovering-from-an-ice-age

Practical Matters

Sea level rise affects coastal areas

Piazza San Marcos, Venice Italy

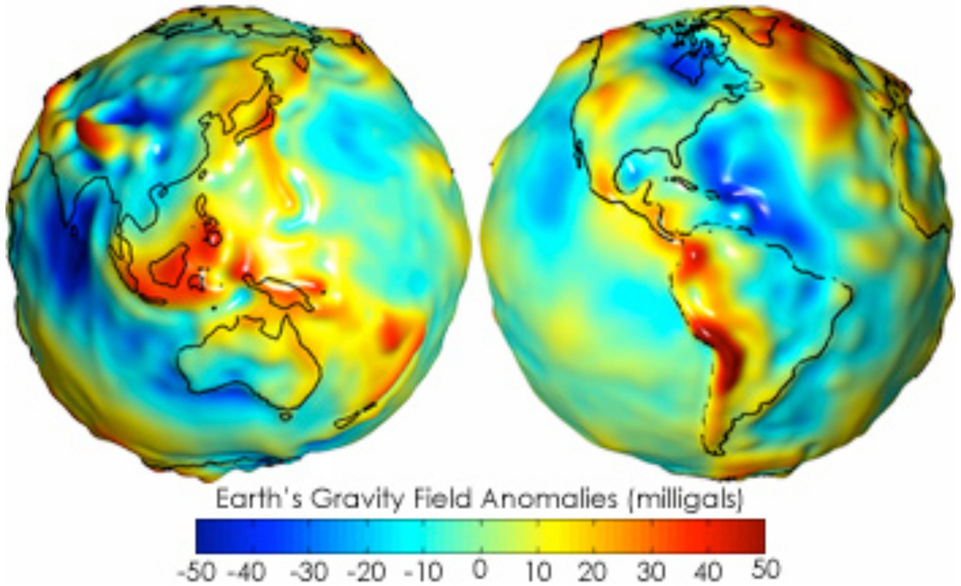
Some areas have special sensitivity


GONDOLE

The Point

- Global sea level rise ongoing at the level of ~1 mm/yr. Contributions from melting of ice and steric (temperature and salinity) of oceans.
- Regional variations owing to different mechanisms behind sea level increase
- Coastal subsidence (vertical motion of the ground) exacerbates effects of local sea level rise
- Earth shape changes at local, global levels can contribute to site specific effects.
- Venice going down at ~1 mm/yr wrt Earth Center of Mass.

Gravity anomalies



GRACE

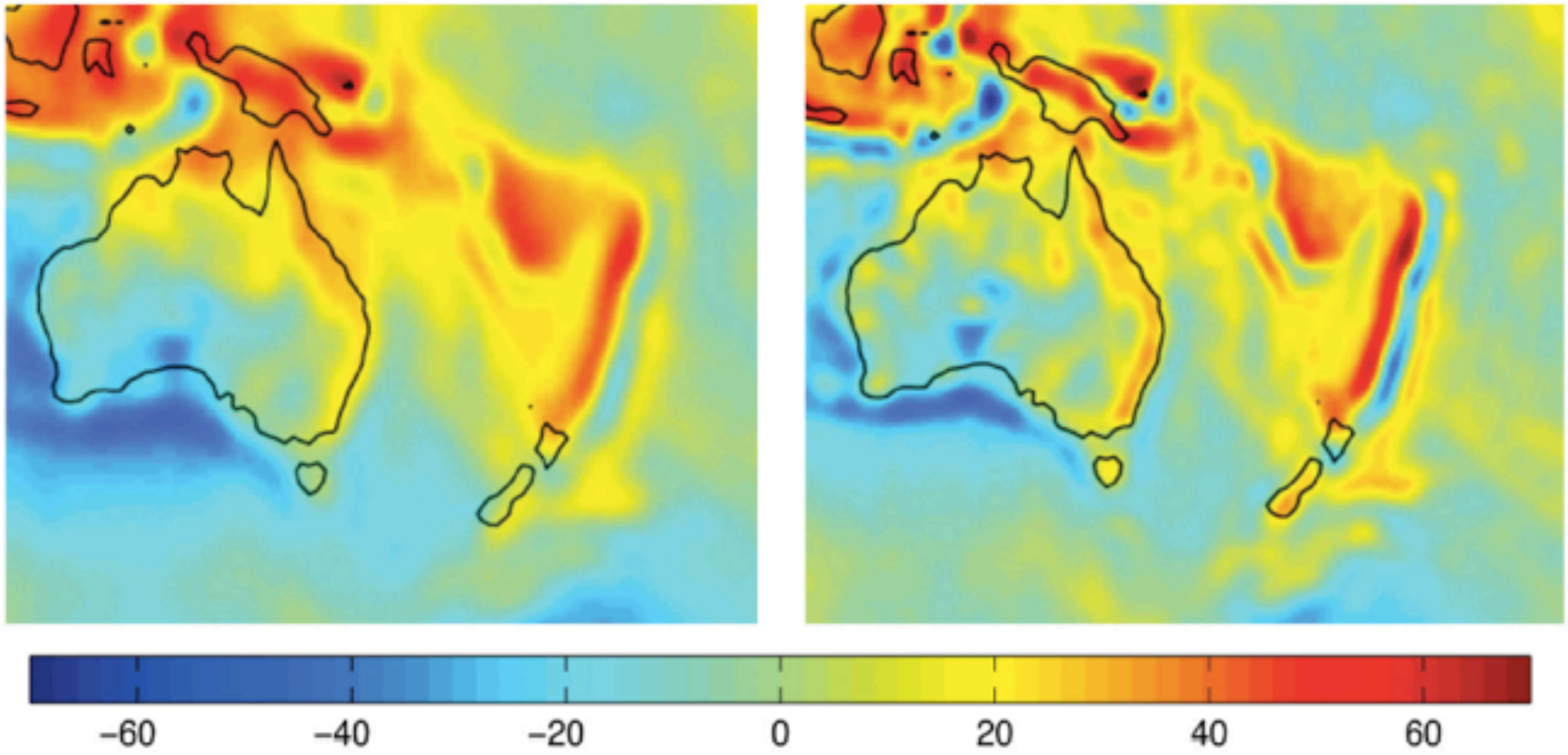
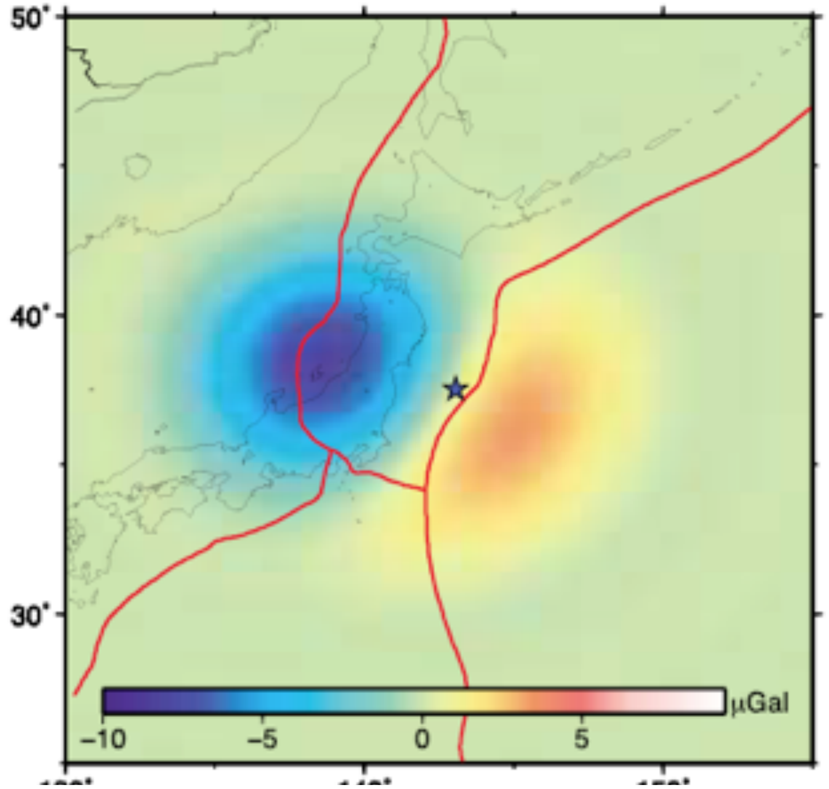


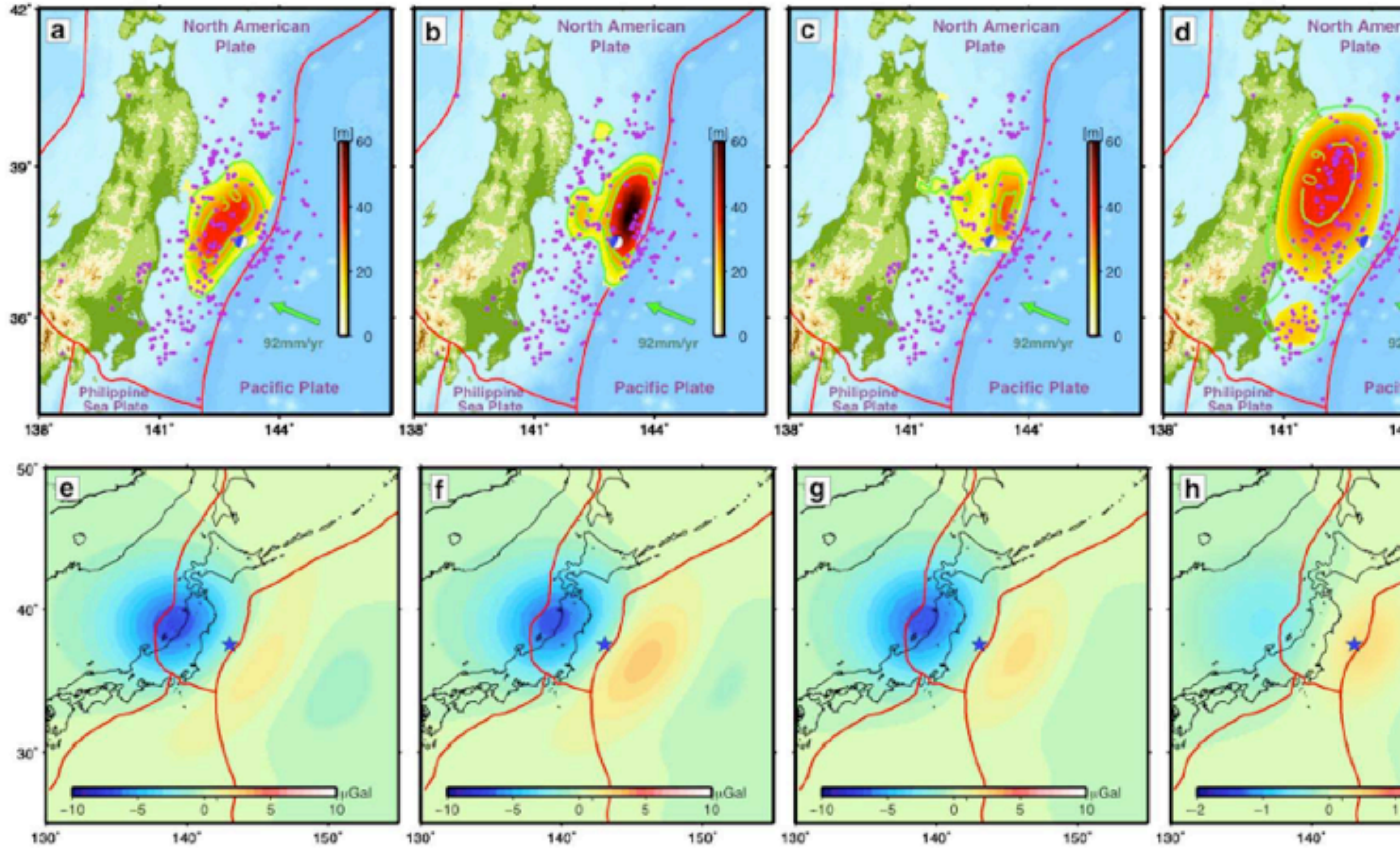
Figure 3. Improvement in resolution in gravity anomalies computed from GGM02S (right) compared to GGM01S (left) in the Tonga-Kermadec With the increased accuracy of the GGM02S model, less smoothing is required to remove artifacts and more detail is revealed. Units are mgal.

Tohoku 2011 M 9.0 Earthquake

Observed from GRACE

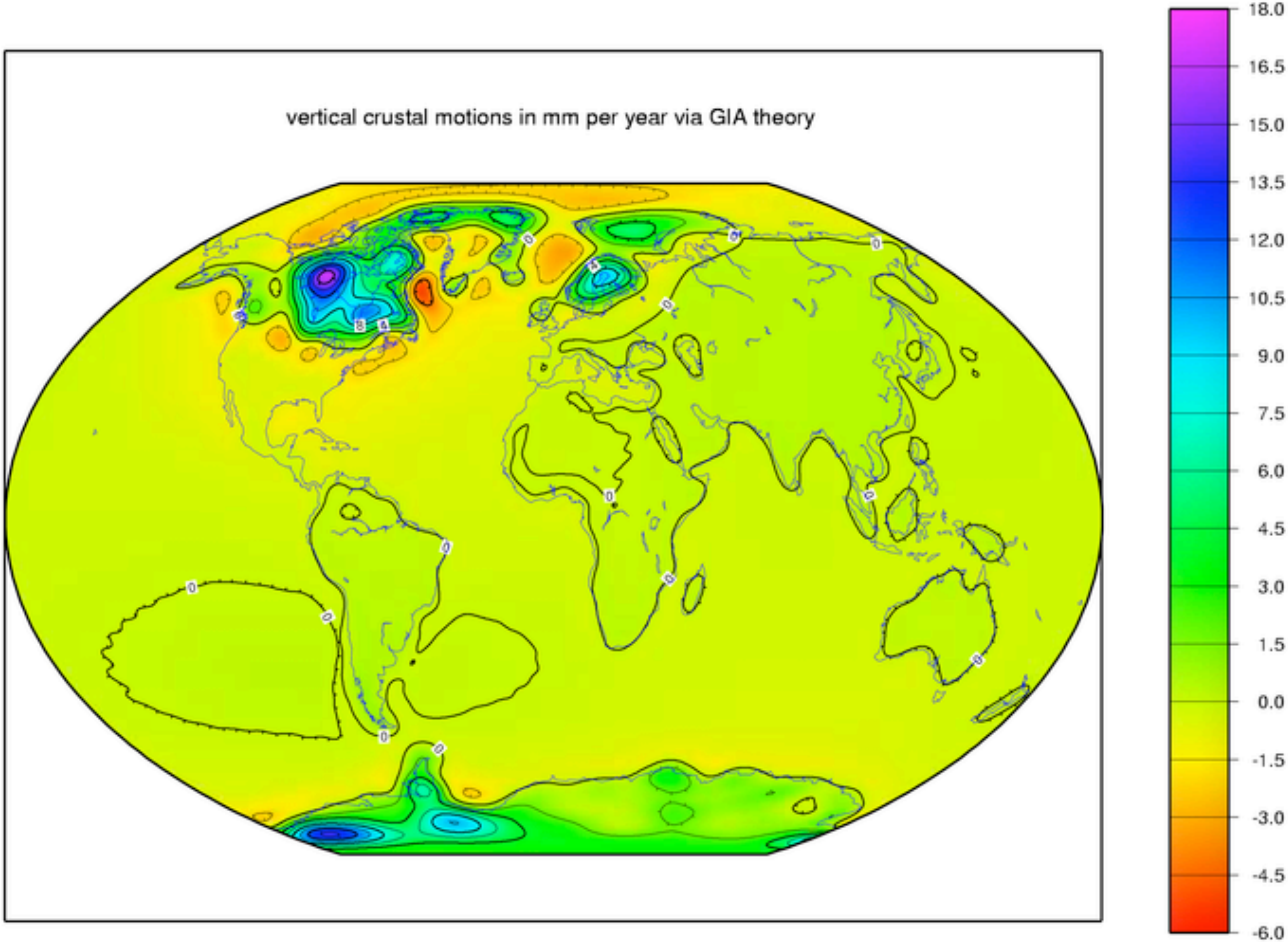


Predicted from Slip Models



How Big Are These Gravity Variations?

- In previous figure gravity varied by ~100 mgals = 0.1 gals = 0.1 cm/s^2 = .001 m/s^2
- Acceleration owing to Earth's surface gravity field is near 9.8 m/s^2
- Variation in gravity is around 1 part in 10^4 (.01%)



Paulson et al., 2007

GMT 2010 Oct 26 18:37:27 deg ord 70 Paulson GIA appx. uplift rates in mm per yr

Plate Tectonic Significance of The Gravity Field

- Equation from Coblentz et al.
- Equation from Turcotte & Schubert
- Can estimate variations in gravitational potential energy in the lithosphere
- Which can be used to estimate state of stress in the lithosphere owing to gravity forces.
- Which can be combined with plate boundary stress estimates to estimate stress on edges of the plates.

TECTONICS, VOL. 13, NO. 4, PAGES 929-945, AUGUST 1994

On the gravitational potential of the Earth's lithosphere

David D. Coblentz and Randall M. Richardson
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Michael Sandiford
Department of Geology and Geophysics, University of Adelaide, Adelaide, Australia

Gravitational Potential Energy of the Lithosphere

The gravitational potential energy per unit area of a column of material U above a given depth z is given by the integral of the vertical stress σ_{zz} from z to the surface h [e.g., *Molnar and Lyon-Caen*, 1988]

$$U = \int_z^h \sigma_{zz}(\tau)\,d\tau = g \int_z^h \int_\tau^h \rho(\tau')\,d\tau'\,d\tau \qquad (1)$$

where $\rho(z)$ is the density at depth z; h is the surface elevation; and g is the gravitational acceleration. The potential energy of the lithospheric column U_l is defined by (1) when z corresponds to the equipotential surface at which the lithosphere is compensated z_{iso}. For the purpose of this study it is useful to define the mean potential energy of the lithosphere at both the global scale $\overline{U_l^g}$ and the plate scale $\overline{U_l^p}$.

Because the lithosphere can be considered to be in isostatic equilibrium for wavelengths greater than a few hundred kilometers [*Kaula*, 1970, 1972; *Turcotte and McAdoo*, 1979; *Sandwell and Smith*, 1992], horizontal stresses can be directly related to the vertical density distribution [*Haxby and Turcotte*, 1978; *Dahlen*, 1981]

$$\overline{\sigma_{xx}} = \frac{g}{L} \int_h^L \Delta\,\rho(z)\,z\,dz \qquad (2)$$

where z is the depth; L is the lithospheric thickness; and $\overline{\sigma_{xx}}$ is the horizontal stress averaged over the thickness of the lithosphere, relative to a reference state against which the $\Delta\,\rho$ is measured. Equation (2) shows that the mean horizontal stress is related to the local dipole moment of the density distribution M

$$\overline{\sigma_{xx}} = \frac{g}{L}\,M \qquad (3)$$

Using the definition of gravitational potential energy in (1), the horizontal stress can be expressed in terms of the potential energies

$$\overline{\sigma_{xx}} = \frac{\Delta U_l}{L} \qquad (4)$$

where ΔU_l is the difference between the potential energy of the local lithospheric column U_l and the poten-

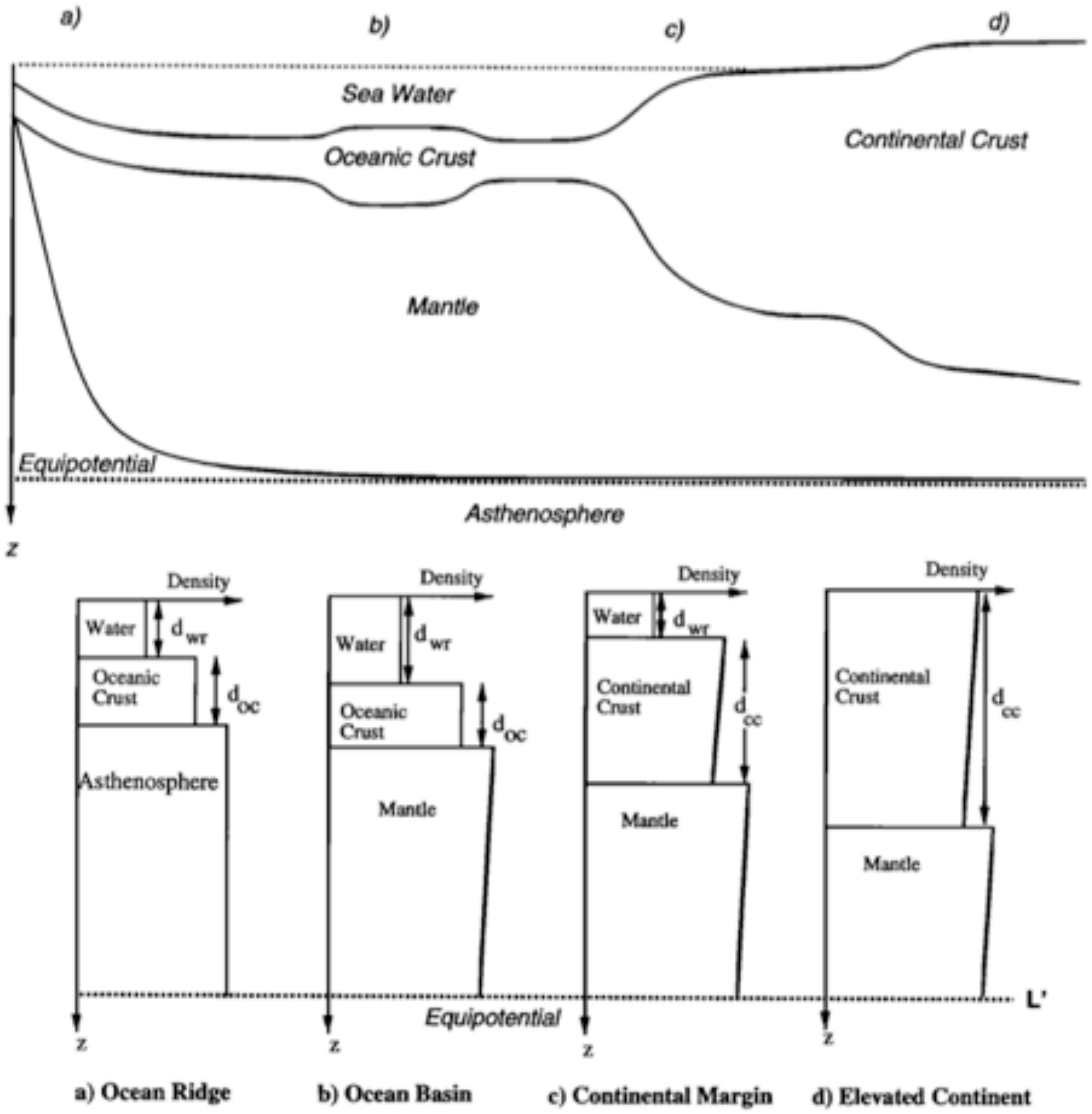


Figure 1. Schematic of the lithospheric depth-density distributions for the four lithospheric types: (a) ocean ridge, (b) oceanic basin, (c) continental margin, and (d) elevated continent. The density of the continental crust and mantle lithosphere varies as a linear function with depth. See text for details.

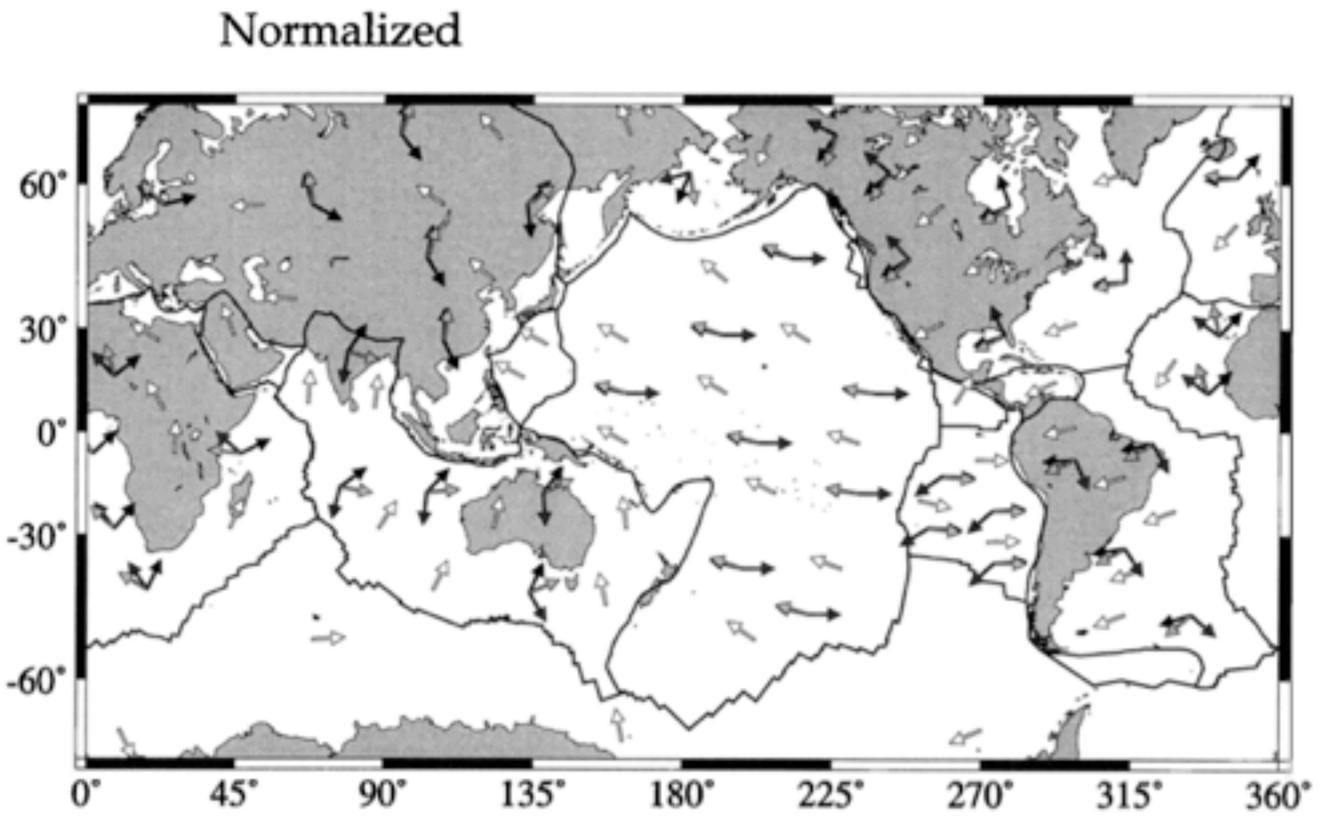
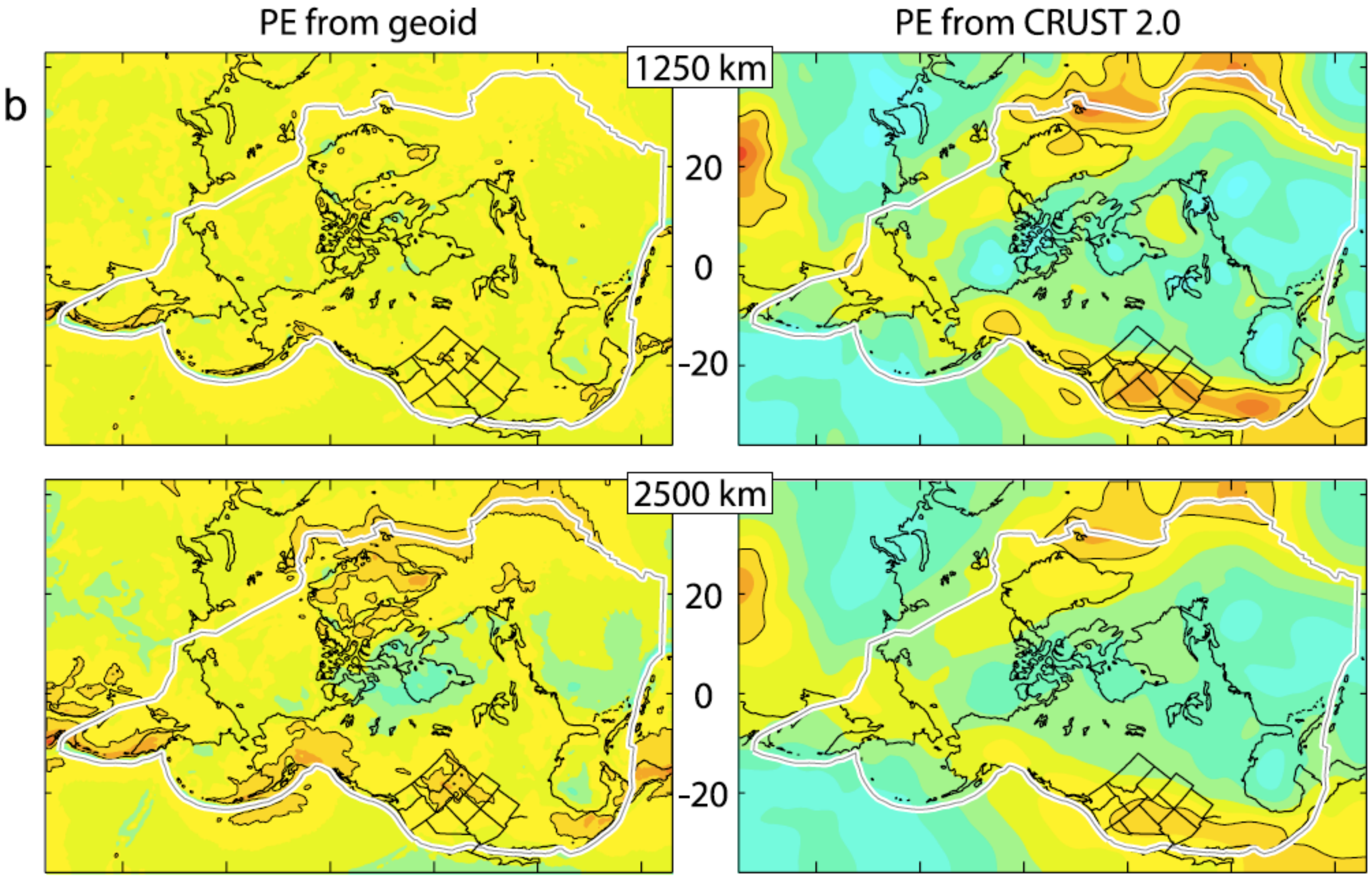


Figure 6. Comparison of ridge torque (solid arrows), topographic torque (medium gray shaded arrows), to potential energy torque (light grey shaded arrows), and absolute velocity directions (open arrows) for the sev major plates. The magnitude of the torques and velocity vectors have been normalized to unit length. Pl velocity information is from *Minster and Jordan* [1978] for the Indo-Australian plate and from NUVEL-1 [*Gr and Gordan*, 1990] for all other plates. The Pacific ridge and total torque arrows nearly coincide because the to torque acting on the plate is dominated by the ridge torque.


b
PE from geoid
PE from CRUST 2.0
1250 km
2500 km
20
0
-20
20
0
-20

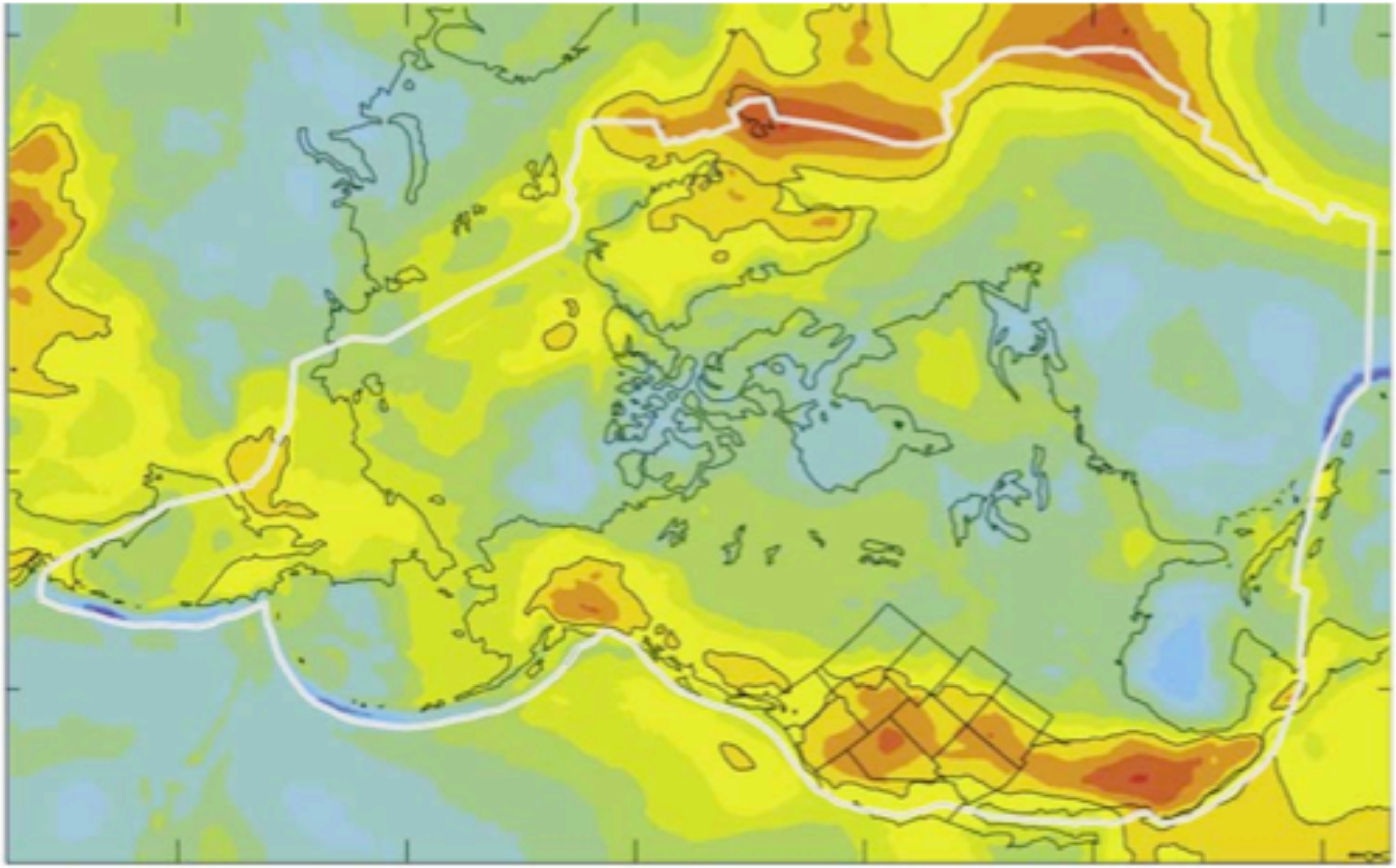
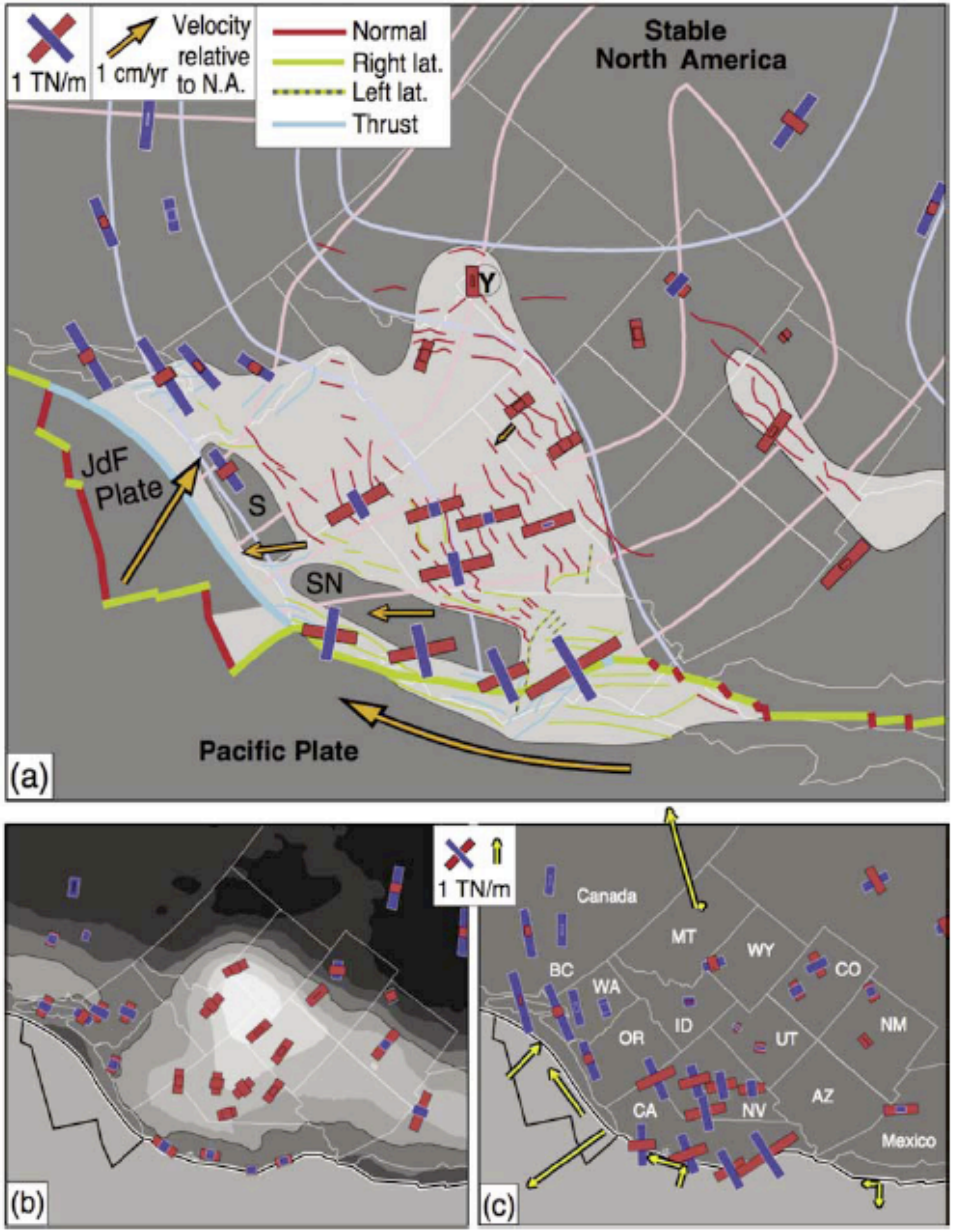


Figure 5. Estimated total gravitational potential energy relative to reference ridge (black contour) (Table A2), as discussed in Appendix A. Contour level is 1 TN/m. This is the same image as the top right plot in Figure A2.



Humphreys and Coblentz, 2007