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Understanding Continent-Ocean Sediment Transfer

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Submarine canyons are narrow but deep submarine valleys that extend for hundreds of meters. They represent the most impressive structures that shape the present morphology of passive continental margins. They can occur off the mouth of rivers: the Tagus, Zaire, Amazon, and Orinoco in the Atlantic; the Indus in the Indian Ocean; and the Var, Rhone, and Ebro in the Mediterranean. Some are at times disconnected from any stream mouth such as the Nazaré canyon, off Portugal, despite the fact that it is close to the coast. Some were connected to a river mouth during lowstands of sea level, such as the Wilmington canyon in the northwest Atlantic, or the Blackmud canyon in the northeast Atlantic.

This article discusses the morphology and recent activity of the Capbreton Canyon off the coast of France and Spain, and discusses some theories about its formation.

The margin of the Bay of Biscay is incised by numerous canyons, but Capbreton Canyon is a unique feature due to its morphology and location [*Cirac et al.*, 2001]. The canyon of Capbreton is a 300-km-long meandering submarine structure running approximately parallel to the north coast of Spain. The canyon head incises deeply into the continental shelf and is located only 250 m away from the coastline at a water depth of 30 m. Along the Spanish shelf, the south wall reaches up to 3000 m at 133 km from the canyon head [*Shepard and Dill*, 1966], making this canyon the deepest on Earth. Recent surveys [*Cirac et al.*, 2001] will help improve our understanding of the morphology.

The seismic data base used in this article includes ten seismic lines representing a total length of 60 km. The canyon is 32 km wide at

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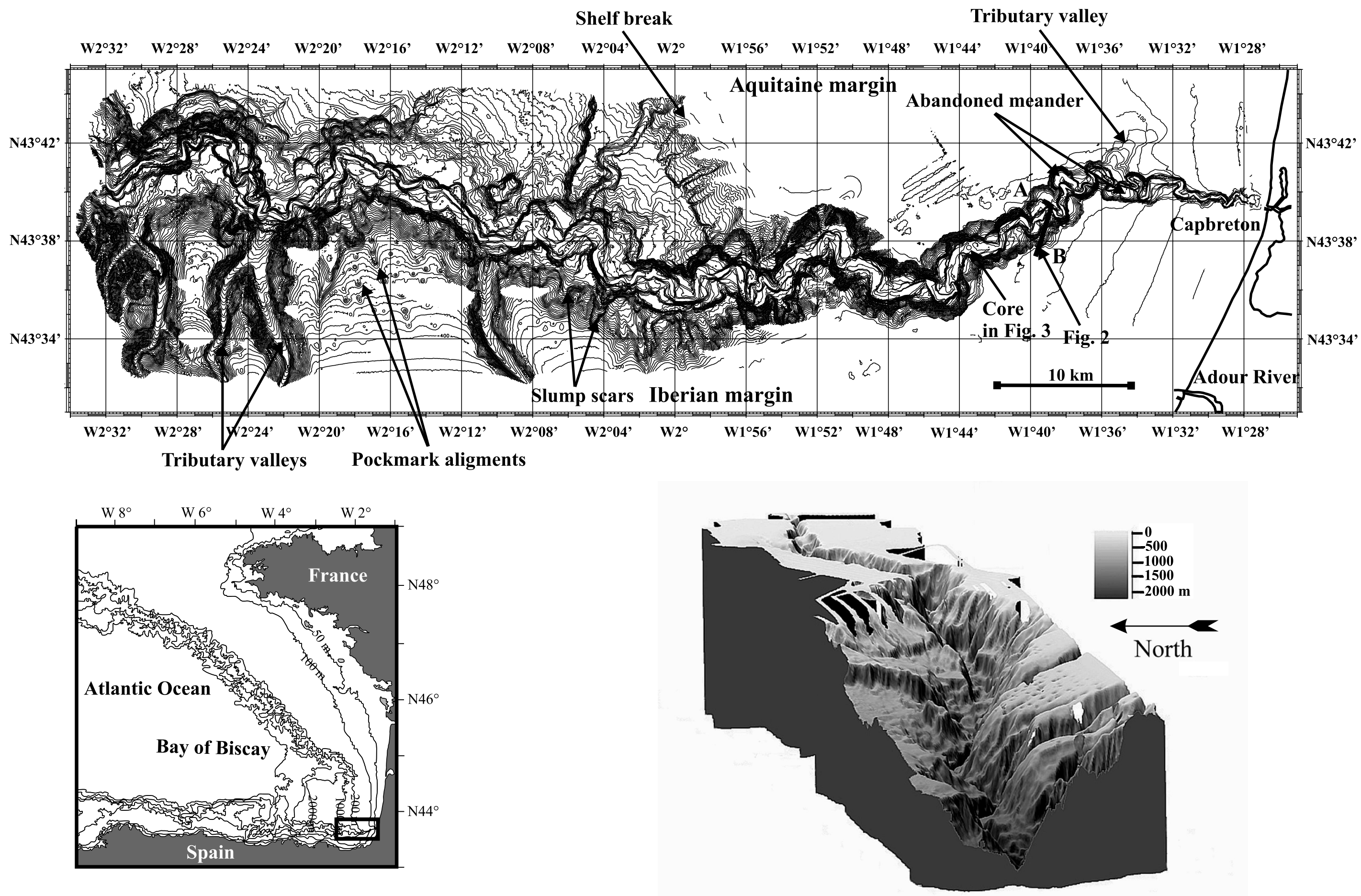

Fig. 1. The bathymorphology and the three-dimensional view of the canyon of Capbreton. Processing of EM1000 and EM300 data sets were preformed by Ifremer/Direction des Recherches Océaniques/Géosciences Marines from the Itsas 1 (1998), Itsas2 (2001), Itsas5 (2001), and Itsas6 (2002) cruises. Contours are in meters; isobaths are at 50-m intervals. Arrow on the three-dimensional view indicates north.

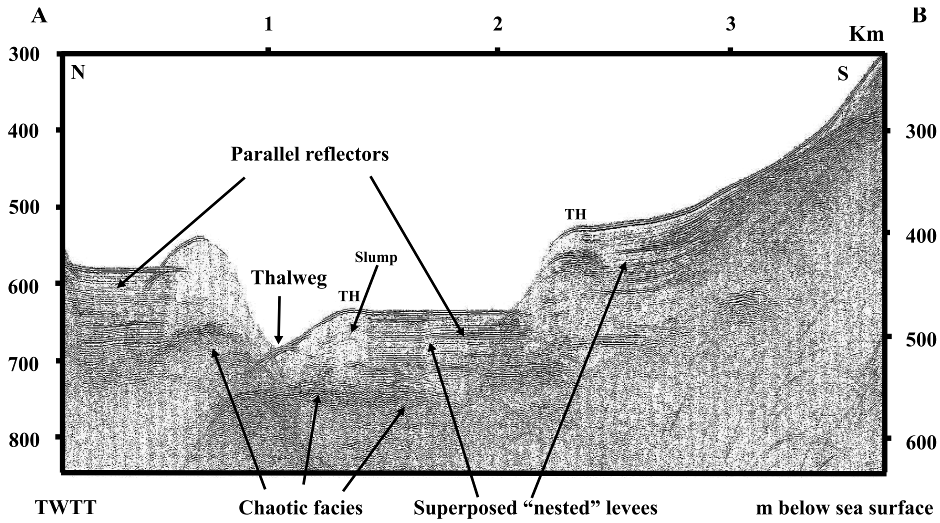

Fig. 2. This sparker seismic profile transverse to the canyon shows superposed terraces, both of which have a topographic high (TH) (See Figure 1 for location). The source used for this profile was a 12–1500 Joules SIG® sparker. The resolution of sparker seismic profiles is about 1 m with a penetration of 500 ms. Data were post-processed with the "SITHERE" software developed at IFREMER.

its widest point and has a typical V-shaped section. The average slope of the thalweg is 1.3% for the first 90 km. The canyon was directly connected with the Adour River until 1578 A.D. and was then artificially disconnected. The Adour River mouth is now located 15 km south of the canyon head. The upper part of the canyon is globally east-west, but it is comprised of several segments (Figure 1). Main directions of the segments are east-northeast-west-southwest and southeast-northwest following regional lineaments that developed during the opening of the Bay of Biscay and the Pyrenean thrust [*Boillot et al.*, 1972]. The lower part of the canyon is south-north and merges with the deep-sea fan of Cap-Ferret.

Canyon Morphology and Terraces

The canyon clearly shows active and abandoned meanders associated with terraces. Terraces are flat structures that stand up to several tens of meters above the thalweg. The bathymetric map and seismic profiles through the canyon clearly show the presence of superposed terraces, suggesting that the canyon could form by several phases of incision. All of the terraces, whatever the type, are draped by stratified facies that resulted from the spilling of the top of the turbidity currents. The finest particles transported in the top part of the turbidity current settle and form the stratified facies.

Tranier [2002] described three types of terraces. The horseshoe terraces that form when an abandoned meander of the thalweg is filled is the first, and the terraces limited by a topographic high with a relief a few meters thick bordering the terrace in the thalweg direction is the second (Figure 2). In some cases, onlap structures on the topographic high suggest this topographic high is older than the stratified facies that form the filling of the terrace. In addition, the seismic facies inside this kind of terrace are chaotic at the base and layered at the top, suggesting that these terraces are initially due to slump failures. Turbidity currents moving into the canyon spill over the initial slump deposit. This kind of terrace is confined by the canyon walls, and corresponds typically to nested levees. When no onlap is visible, the topographic high could only be the location of the highest rate of deposition by turbidity current spilling along the side of the thalweg.

The third type identified by Tranier is a flat terrace showing only the layered seismic facies. They act as a levee that forms by lateral migration of the thalweg and the associated levees. This kind of terrace is located on the convex (erosional) side of meanders. As a consequence, they could form through erosion of previous deposits, rather than through depositional processes as terraces with a topographic high.

Terraces could also be interpreted as point bars that form through lateral accretion; for example, sub-aerial fluvial systems [*Abreu et al.*, 2003]. However, dipping foresets inside terraces are infrequently observed, but could be masked by seismic hyperbols. However, the fine material usually cored in the canyon terraces suggests another method of formation.

Canyon Activity

Eleven interface gravity cores were recovered within the thalweg of the Capbreton Canyon ranging from 40 to 800 m water depth. These cores are composed of turbidites or debrites, with 75% of the sediment made of silt or coarser-grained material.

In 2000, a 33-cm-long Barnett interface gravity core was taken in the thalweg of the canyon of Capbreton at a water depth of 647 m (Figure 1). According to facies interpretation (Figure 3), it shows a succession of sedimentary facies that can be interpreted as three superimposed turbidite sequences (Figure 3) [*Mulder et al.*, 2001]. An oxidized layer that contains live benthic foraminiferal faunas indicative of a reprisal of hemipelagic deposition covers the topmost turbidite sequence. Activities of ^{234}Th (half-life = 24.1 days) in excess suggest that the most recent turbidite was deposited between 5 December 1999 and 14 January 2000. A diagenetic model based on manganese oxide distribution also agrees with this assumption [*Anschutz et al.*, 2002]. No earthquake capable of generating a slope failure in the area has been recorded during this period. There was no major flood at the mouth of the Adour River, which is the nearest river. The only natural phenomenon with the potential to trigger significant sediment motion, and finally, a turbidity current, during this period was the violent "Martin" storm that affected the Bay of Biscay on 27 December 1999.

The turbidity current could be caused by three phenomena. The first is a sediment failure due to excess pore pressure generated by the storm waves or the swell. During the December 1999 storm, waves reached 12 m in the Bay of Biscay. In that case, the shear strength of the sediment could be reduced down to failure. The second is an intensification of the coastal drift and shelf currents during the storm. A large amount of particles can then be captured at the canyon head and progressively transformed into a turbulent, unsteady flow. The third is dissipation through the canyon of the 1- to 2-m-high along-coast storm set-up through the canyon. The resulting downwelling currents may cause intensive particle erosion from the canyon head and down the canyon that generated a particle-laden bottom layer that progressively transformed into turbidity current. This recent turbidite shows that active gravity processes exist in the canyon at present. However, the calculated frequency for events similar to the 1999 turbidite, which have a periodicity of one event every decade, suggests that such events can help maintain the freshness of the canyon wall and thalweg, the mature phase of a canyon [*Farre et al.*, 1983]; but they are neither frequent nor energetic enough to explain the initial incision.

Canyon Formation

The cause of canyon formation and persistence is a key question, as canyons are the main pathways for sediments from continent to ocean. It has been proposed that most of the Mediterranean canyons began to form by sub-aerial river erosion during the drastic fall in sea level that occurred during the Messinian. For canyons located in the Atlantic Ocean, this assumption would suggest an origin during the phases of rifting and ocean opening; that is, the Cretaceous for the north Atlantic, and the Jurassic for the south Atlantic.

A second hypothesis is autocyclic origin, with processes such as sediment failure to set up an initial depression followed by retrogressive erosion to maintain, extend, and enlarge the canyon. The canyon head would move progressively landward. This process fits the numerous slump scars that are observed on

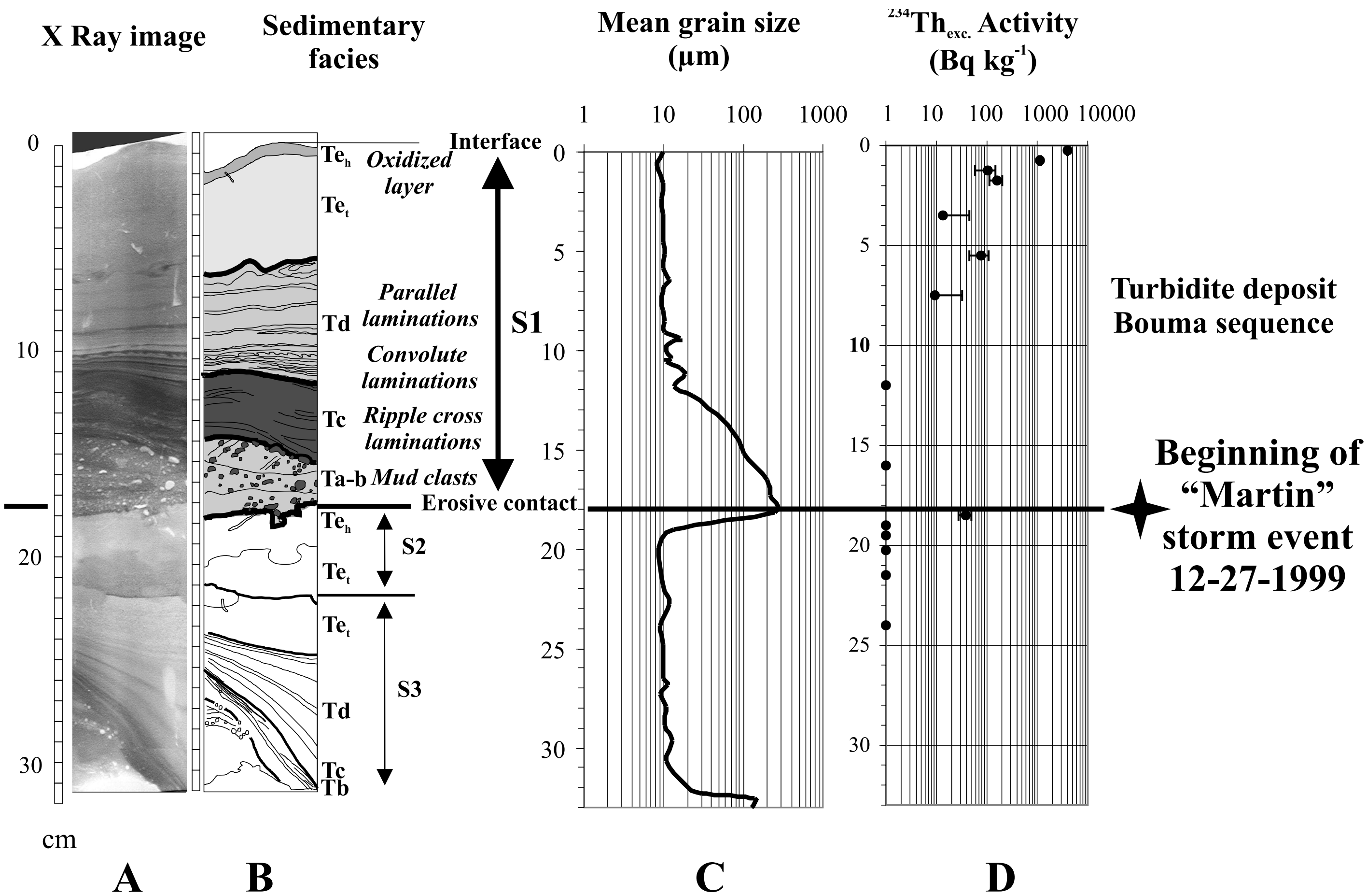

Fig. 3. Sedimentology and stratigraphy of the core. (a) X-ray image; (b) processed X-ray image (Scopix) and sedimentary facies; (c) grain size; (d) curve of corrected ^{234}Thexc. activity. Note that ^{234}Thexc. adsorbs on particles with a large specific area such as clay and fine silt. Values of ^{234}Thexc. can only be interpreted in the finest top part of the turbidite.

both sides of the canyon walls. Additional evidence supporting this hypothesis is the abundance of pockmarks lined up with the head of valleys in a landward direction on the south side (Figure 1). These pockmarks suggest upward fluid motion and deep disorganization of the sedimentary pile. They could either be the result of sediment disorganization in the direction of retrogression, or indicate weakness lineaments that direct erosion and retrogression. This would be consistent with the fact that canyons such as Capbreton follow regional, tectonic directions [*Cirac et al.*, 2001].

In some cases, both sub-aerial and submarine processes can contribute to the present canyon morphology. The major canyon of the submarine drainage basin of "La Petite Sole" in the northern part of the Bay of Biscay shows a downstream part linked to sub-aerial erosion during the synrift period, when the tributaries of the upper part were controlled by autocyclic slides during the set-up of the Neogen prograding prism [*Bourillet et al.*, 2003].

Another hypothesis suggests that canyons could be "constructed structures." In fact, they would be "bypass" areas in a globally prograding margin. They would represent the narrow areas where margins do not prograde [*Pratson et al.*, 1994] or prograde at a lesser rate. This hypothesis can be considered as valid for margins with a high sediment load, which was the case for the south part of the Bay of Biscay during the Tertiary, but not during the Holocene.

A fourth hypothesis suggests that canyons would result from intense and nearly continuous erosion by downslope eroding sediment flows [*Pratson et al.*, 1994]. Frequent in-situ measurements of a sporadic or continuous activity of particle-laden flows in canyons [*Shepard and Dill*, 1966; *Inman*, 1970] support this hypothesis. Because major canyons are usually connected to a river, the canyon head is located in an area where sediment load and sedimentation rate are very high. This suggests that canyons are formed by either very frequent, slide-induced turbulent surges, or by long-duration, hyperpycnal flows. These flows form during floods when the river flow carries sufficient suspended load. This hypothesis is consistent with the recent history of the canyon of Capbreton that was connected to the Adour River until 1578 A.D. The Adour is a small- to medium-sized river with a high capacity to trigger hyperpycnal flows, as defined by *Mulder and Syvitski* [1995]. During Quaternary ice-melting periods, the water and sediment discharge from the Adour was probably substantially higher than during the Holocene, draining the northwestern part of the Pyrenean piedmont supplied by the glaciers.

The Capbreton example shows that canyon activity is not permanent through geological time. Periods of high sediment transfer that are responsible for the incision alternate with periods of sporadic activity. During these periods of lesser activity, canyons act as bypass zones on slightly prograding margins with low sediment load, or as fill on highly prograding margins with high sediment load. Using a study on Mediterranean canyons where the canyon head is located close to the shelf break, *Baztan et al.* [2004] related periods of incision to the end of sea level fall and sea level lowstands, during which rivers are connected to canyons and periods of filling (or bypassing), to periods when river mouths are close to the canyon head, but disconnected from the river system.

In conclusion, it appears that canyons represent a negative topography that can be oriented along tectonic lineaments. The shape of a canyon results from the combination between the global margin progradation beside the canyon and the frequency, intensity, and persistence of erosional processes through the canyon. Several kinds of gravity processes contribute to canyon formation and persistence. Long-duration hyperpycnal flows might substantially contribute to the initial canyon erosion and to the formation of the meandering shape. Short-duration, slide-triggered, turbulent surges might explain the retrogressive slump scars that can be observed at canyon heads and the freshness and steepness of canyon walls.

These processes can be active on different time periods (e.g., lowstands, highstands of sea level) controlled by global tectonics or eustatism, and can be active simultaneously and depend on the regional setting. In all cases, canyons such as Capbreton represent an important pathway for sediment transfer from continent to ocean, either directly through hyperpycnal flows, or with residence time along the continental shelf through slide-induced surges.

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NASA Restructuring Draws Mixed Reactions

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Some scientists are optimistic about what they say will be new opportunities and clout that the Earth and space sciences will have under the organizational restructuring that NASA announced on 24 June, while others are concerned that these sciences may be buried bureaucratically and suffer fiscally.

Under the restructuring, which takes effect on 1 August, Goddard Space Flight Center director Alphonso Diaz will become the Science associate administrator. Associate administrator for space science Edward Weiler will become the new head of Goddard. Associate administrator for Earth Science, Ghassem Asrar, will be science deputy associate administrator and chief scientist for exploration.

The principle NASA centers focusing on science will be Goddard, the Ames Research Center, and the Jet Propulsion Laboratory. The agency's restructuring includes the establishment of three other mission directorates: for exploration systems, space operations, and aeronautics research.

NASA is also creating a strategic planning council and taking other steps to improve its decision-making process.

NASA administrator Sean O'Keefe said that the restructuring would support the re-orientation of NASA toward exploration of the Moon, Mars, and other destinations that was announced by President George W. Bush on 14 January. O'Keefe said the changes also would promote synergy across scientific disciplines.

Reaction in the Earth Sciences Community

Within the Earth sciences community, opinions varied about the impact the restructuring would have on NASA science programs.

Larry Smarr, chairman of the Earth System Science and Applications Advisory Committee (ESSAAC), and director of the California Institute for Telecommunications and Information Technology, said the restructuring is "a strong endorsement" of the Earth sciences; and that science as one of just four agency mission directorates will now receive more attention.

"If the exploration initiative sees Earth science as a prototype system for space technology around the other planets, then the Earth science mission is not just off by itself. It becomes a critical success factor for NASA's missions as a whole. That gives Earth science a much greater longevity as a funded part of NASA," Smarr said.

Charles Kennel, chair of the NASA Advisory Council, and director of the Scripps Institution, San Diego, said the idea that Earth science will not prosper within an integrated science division is belied by the fact that it had done well in the past when Earth and space science were in the same division.

However, he said the restructuring would have important interagency ramifications, because the associate administrator for Earth Science had been at the same administrative level as other key government officials associated with federal agencies with large Earth sciences components, and was able to hold direct and regular discussion with his counterparts in these other agencies. "The big loss to Earth science with the diminution of its visibility within NASA is that it won't have access at the appropriate levels of government outside NASA," he said.

Kennel said the restructuring primarily was intended to deal with fixing the agency's problem with its human space flight mission, and that any affected Earth science programs were "road kill." He added, "Because of the political softness of Earth science within the [Bush] administration, nobody stood up and said, 'No, you can't do it.'"

Rafael Bras, professor of civil and environmental engineering and Earth, atmospheric and planetary Sciences at MIT, and former ESSAAC chair, said, "I worry about the danger of the Earth sciences getting lost in the myriad of activities of a large science directorate. There will certainly be the possibility of damaging internal competition for increasingly limited resources, although theoretically the opportunity of beneficial synergism exists."

ESSAAC member Timothy Killeen, director of the National Center for Atmospheric Research (NCAR) and AGU president-elect, said that while the new agency mission is compelling and organizational changes look good, the question is how the program is managed. He said "potential distortions" with the mission could undercut NASA's long-term commitment to Earth science, and might also have an impact on some space science programs not directly related to that mission.

Killeen said that "it is a somewhat second-order derivative motivation to study the Earth [in the new mission] than it has been in the past, and that is a great concern." He said scientists should pay attention to how the plan