NEWSLETTER GEOBRASIL
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- **NATURE**

SEISMIC REFLECTION IMAGING OF TWO MEGATHRUST SHEAR ZONES IN THE NORTHERN CASCADIA SUBDUCTION ZONE

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At convergent continental margins, the relative motion between the subducting oceanic plate and the overriding continent is usually accommodated by movement along a single, thin interface known as a megathrust. Great thrust earthquakes occur on the shallow part of this interface where the two plates are locked together. Earthquakes of lower magnitude occur within the underlying oceanic plate, and have been linked to geochemical dehydration reactions caused by the plate's descent. Here I present deep seismic reflection data from the northern Cascadia subduction zone that show that the inter-plate boundary is up to 16 km thick and comprises two megathrust shear zones that bound a >5-km-thick, 110-km-wide region of imbricated crustal rocks. Earthquakes within the subducting plate occur predominantly in two geographic bands where the dip of the plate is inferred to increase as it is forced around the edges of the imbricated inter-plate boundary zone. This implies that seismicity in the subducting slab is controlled primarily by deformation in the upper part of the plate. Slip on the shallower megathrust shear zone, which may occur by aseismic slow slip, will transport crustal rocks into the upper mantle above the subducting oceanic plate and may, in part, provide an explanation for the unusually low seismic wave speeds that are observed there.
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- **SCIENCE**

GEOCHEMISTRY: Enhanced: What Biogenic Minerals Tell Us
Danielle Fortin
Science 12 March 2004; 303(5664): p. 1618-1619
http://www.sciencemag.org/cgi/content/summary/303/5664/1618?ct

Microbial Polysaccharides Template Assembly of Nanocrystal Fibers
Clara S. Chan, Gelsomina De Stasio, Susan A. Welch, Marco Girasole, Bradley H. Frazer, Maria V. Nesterova, Sirine Fakra, and Jillian F. Banfield
Science 12 March 2004; 303(5664): p. 1656-1658
http://www.sciencemag.org/cgi/content/abstract/303/5664/1656?ct

POLAR RESEARCH: Plucky Scientists Plucked From Jaws of Death
Theres Redeby
Science 12 March 2004; 303(5664): p. 1591
http://www.sciencemag.org/cgi/content/summary/303/5664/1591?ct

GEOLOGY: Cold Snaps in the Cretaceous
Brooks Hanson
Science 12 March 2004; 303(5664): p. 1585c
http://www.sciencemag.org/cgi/content/summary/303/5664/1585c?ct

EARTH SCIENCE: Old and Crusty
Linda Rowan
Science 12 March 2004; 303(5664): p. 1585a
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Axel Hohn
J. Environ. Qual. 1 March 2004; 33(2): p. 795
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Bermudagrass Management in the Southern Piedmont, USA: IX. Trace Elements in Soil with Broiler Litter Application
A. J. Franzluebbers, S. R. Wilkinson, and J. A. Stuedemann
J. Environ. Qual. 1 March 2004; 33(2): p. 778-784
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Optimizing Phosphorus Characterization in Animal Manures by Solution Phosphorus-31 Nuclear Magnetic Resonance Spectroscopy
Benjamin L. Turner
J. Environ. Qual. 1 March 2004; 33(2): p. 757-766
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Chemical Composition of Organic Matter in Extremely Acid, Lignite-Containing Lake Sediments Impacted by Fly Ash Contamination
A. Chabbi and C. Rumpel
J. Environ. Qual. 1 March 2004; 33(2): p. 628-636
http://jeq.scijournals.org/cgi/content/abstract/33/2/628?ct

Measured Concentrations of Herbicides and Model Predictions of Atrazine Fate in the Patuxent River Estuary
Laura L. McConnell, Jennifer A. Harman-Fetcho, and James D. Hagy, III
J. Environ. Qual. 1 March 2004; 33(2): p. 594-604
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Fate of Colloidal-Particulate Elemental Selenium in Aquatic Systems
Yiqiang Zhang, Zahir A. Zahir, and William T. Frankenberger, Jr.
J. Environ. Qual. 1 March 2004; 33(2): p. 559-564
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Validation of the In Vitro Gastrointestinal (IVG) Method to Estimate Relative Bioavailable Lead in Contaminated Soils

J. L. Schroder, N. T. Basta, S. W. Casteel, T. J. Evans, M. E. Payton, and J. Si
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Time and Moisture Effects on Total and Bioavailable Copper in Soil Water Extracts
Andreas Tom-Petersen, Hans Christian Bruun Hansen, and Ole Nybroe
J. Environ. Qual. 1 March 2004; 33(2): p. 505-512
http://jeq.scijournals.org/cgi/content/abstract/33/2/505?ct

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S. J. Rodvang, D. M. Mikalson, and M. C. Ryan
J. Environ. Qual. 1 March 2004; 33(2): p. 476-487
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Asbestos and the Pleura: A Review
David W. Cugell and David W. Kamp
Chest 1 March 2004; 125(3): p. 1103-1117
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Microbial Diversity and Heterogeneity in Sandy Subsurface Soils
Jizhong Zhou, Beicheng Xia, Heshu Huang, Anthony V. Palumbo, and James M. Tiedje
Appl. Environ. Microbiol. 1 March 2004; 70(3): p. 1723-1734
http://aem.asm.org/cgi/content/abstract/70/3/1723?ct

Application of a Vital Fluorescent Staining Method for Simultaneous, Near-Real-Time Concentration Monitoring of Two Bacterial Strains in an Atlantic Coastal Plain Aquifer in Oyster, Virginia Mark E. Fuller, Brian J. Mailloux, Sheryl H. Streger, James A. Hall,
Pengfei Zhang, William P. Kovacik, Simon Vainberg, William P. Johnson, Tullis C. Onstott, and Mary F. DeFlaun
Appl. Environ. Microbiol. 1 March 2004; 70(3): p. 1680-1687
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Wood-Destroying Soft Rot Fungi in the Historic Expedition Huts of Antarctica
Robert A. Blanchette, Benjamin W. Held, Joel A. Jurgens, Douglas L. McNew, Thomas C. Harrington, Shona M. Duncan, and Roberta L. Farrell
Appl. Environ. Microbiol. 1 March 2004; 70(3): p. 1328-1335
http://aem.asm.org/cgi/content/abstract/70/3/1328?ct

Phage Community Dynamics in Hot Springs
Mya Breitbart, Linda Wegley, Steven Leeds, Tom Schoenfeld, and Forest Rohwer
Appl. Environ. Microbiol. 1 March 2004; 70(3): p. 1633-1640
http://aem.asm.org/cgi/content/abstract/70/3/1633?ct

Direct Observation of Microbial Inhibition of Calcite Dissolution
Andreas Luttge and Pamela G. Conrad
Appl. Environ. Microbiol. 1 March 2004; 70(3): p. 1627-1632
http://aem.asm.org/cgi/content/abstract/70/3/1627?ct

- **EARTH PAGES**

Anthropology and geoarchaeology

Kennewick Man may not be re-interred

Seven and a half years after the discovery of a 9300-year old human skeleton in Columbia River alluvium in Washington state, USA, researchers may finally be able to study the remains. So-called Kennewick Man caused a storm when first unearthed, for his skull was very different from that of any other early American colonist. Indeed, partial studies suggested close resemblance to Europeans. Four Native American tribes in the Pacific Northwest claimed the skeleton for reburial, under the Native American Graves Protection and Repatriation Act. The move was not entirely connected with respect for sacred rites. Evidence that the area might have been first colonised by people who were not related to the tribes living there just before European occupation in the 19th century could undermine claims for mineral and other land rights by native people. On 4 February 2004 a San Francisco court ruled that the remains were so different from any North American indigenous people, that the claimants had no rights over them. Studies of a skull cast of Kennewick Man since he was placed under lock and key now suggest a possible origin from Asian hunter-gatherers similar to the Ainu people of modern Japan. However, modern techniques of genetic analysis and isotopic studies of tooth enamel that could settle the issue of origin and relatedness require the original material. Interestingly, a spear point is lodged in the pelvis, so, like the famous Ice Man of the Italian-Austrian Alps, Kennewick Man may have been the victim of either a deadly dispute or ritual killing.

Climate change and palaeoclimatology

Influence of continental weathering on climate boosted

Since the resurrection of Chamberlin’s idea that the rate of chemical weathering of continental crust helps regulate atmospheric CO_2 by Maureen Raymo, the hypothesis has not yet been supported by convincing geochemical evidence. There is such a lag between changes in ocean chemistry and evidence for global climate change, that correlations are flimsy. The need is for a proxy for weathering of the land surface that resides in seawater for a geologically very short period. Such an element is osmium (Os), which passes from river water through the oceans to sea-floor sediments in about 25 thousand years, so changes in its abundance in sediments ought to match the pace of any climatic shifts. In principle, there are two main sources for elements in seawater, from sea-floor hydrothermal alteration of oceanic crust, and from continental weathering. The first can be considered to be more or less constant, except on time scales of tens of million years. Continental weathering is a response to climate change, and keeps pace with it. Researchers at the UK Open University and the University of Köln in Germany analysed samples for osmium and carbon isotopes through a sequence of Jurassic mudstones on the NE coast of England (Cohen, A.S. *et al*. 2004. Osmium isotope evidence for the regulation of atmospheric CO_2 by continental weathering. *Geology*, v. **32**, p. 157-160). The carbon isotopes show a sudden drop in d^{13}C within a very hydrocarbon-rich unit famous for it contribution of jet (oil-rich lignite) to Victorian funereal jewellery. This negative excursion is recognisable world-wide at around 180 Ma. The most likely explanation is a monstrous blurt of methane from destabilised gas hydrate on the Jurassic sea floor (see *Methane hydrate - more evidence for the ‘greenhouse’ time bomb*, August 2000 issue of *EPN*). The Jet Rock of the Whitby coast therefore preserves a nice example of sudden climatic change, and by the end of its deposition carbon isotopes returned to Jurassic background values. Methane, a powerful “greenhouse” gas, is rapidly oxidised to CO_2 in the atmosphere, so reducing its initial warming effect, but climate would have been hotter for some time afterwards until the excess CO_2 was drawn down somehow. Interestingly, the Jet Rock also shows a sudden leap in the abundance of ^{187}Os, reflected in the ^{187}Os/^{186}Os ratio of the samples, and an upward step in the value of the ^{87}Sr/^{86}Sr ratio – one of the fastest rises known. The latter is generally assigned to an increase in continental weathering, since continental crust contains more radiogenic ^{87}Sr than does oceanic crust. The implication of the osmium-isotopic shift is odd; it requires an increase in the rate of continental weathering by 4 to 8 times that in the preceding period. That is a vast change, even if it only lasted for a short period, but it tallies with what is known about the temperature dependence of the dissolved loads of rivers in more recent times. If the osmium isotope excursion truly reflects massive continental weathering, then it is possible to calculate the drawdown of the excess CO_2 in the atmosphere from a commensurate flux of calcium and magnesium ions from the continents, that would eventually form marine carbonates. The authors estimate a mere 37-123 ka to get rid of it. Yet continent-derived radiogenic ^{87}Sr remained high for much longer, and the authors’ arguments become tricky. One interesting aside is that, unlike today, more groundwater found its way to the oceans than surface run-off during the Jurassic, perhaps 6 times more. It is easy to look on weathering as what happens at the interface between rocks and the weather; the land surface. Not so. A great deal of chemistry that releases soluble ions goes on in the subsurface, above and below the water table. It is by no means as simple as reactions between carbonic acid in rainwater and silicate minerals. Weathering is the product of hydrogen ions’ (whatever their source) effects on silicates. Bacteria are extremely important actors in modifying pH below the surface, for example the sulphate-sulphide reducers, and the oxidative dissolution of sulphides produces sulphuric acid. Even more interesting for the chemistry of groundwater is the curious role of iron hydroxide. Under oxidising conditions it adsorbs many elements from solution, including platinum-group elements, such as osmium. Should conditions become reducing, dissolution of goethite skins on sedimentary grains releases the accumulated elements. A warming trend almost inevitably results in increased precipitation, and rising water tables. It also should boost biological productivity on land and an increase in the amount of buried organic matter, which create reducing conditions in groundwater.

Economic and applied geology

Onshore gas hydrate reserves close to recovery

The Mackenzie delta in Arctic Canada has been an area of conventional hydrocarbon exploration for decades. In 1972 methane-ice mixtures in the permanently frozen ground were discovered in one well at a depth of about a kilometre during exploratory drilling. They are rich, with up to 90% of the pore spaces in alluvial gravels being full of the white gas hydrate. Being associated with conventional gas at greater depths, there is a good chance that combined production could make the considerable reserves economic. On their own, gas hydrates are not yet economic, even onshore, since they would need heating to break down the peculiar compound, and natural gas prices are currently at a low level. Economics also depend on a conventional gas pipeline being extended to the area Tests and computer simulations suggest that production of deeper conventional gas can lower the pressure on the gas hydrate inducing it to break down and add to the flow from a well. In maybe 10 to 20 years production could begin. The likely origin of the Canadian reserves and those in the North Slope of Alaska is from methane leaking from deeper reserves to “freeze” in the colder conditions at shallow depths.

Arctic North America could eventually produce up to one sixth of current US natural gas consumption from onshore gas hydrate. Of course, vastly greater gas-hydrate potential exists offshore - between 10 000 to 42 000 trillion cubic metres (tcm) world-wide, compared with 370 tcm of estimated conventional gas reserves. Methane (CH_4) burns to produce less carbon dioxide per unit of heat energy than more carbonic natural gas, so is a means of easing “greenhouse” gas emissions. Potentially it could be feedstock for CO_2-free hydrogen production. Pressures on the economy of Japan, which has very few natural energy resources, have prompted Japanese researchers to begin exploratory offshore drilling into the Nankai trough offshore of SE Japan, where there are potentially rich reserves of gas hydrate in sands. This may produce commercially in 10 to 15 years. The thorniest problem with many gas hydrate deposits is that they are in “tight”, fine-grained sediments.

Source: Kerr, R.A. 2004. Gas hydrate resource: smaller but sooner. *Science*, v. **303**, p. 946-947

Geochemistry, mineralogy, petrology and volcanology

A “Whoops” moment for geochemists?

A great deal of effort and innumerable theses and papers have gone into modelling the derivation of magmas from their parent rocks, especially the mantle, over the last three decades. Most is based on the division of trace elements into “compatible” and “incompatible”, the first being those which tend to remain in minerals that make up the residuum during magmagenesis, and the second those that favour melts. Most incompatible elements have large ionic radii. The modelling centres on the degree to which elements remain in solids, the appropriate parameter being an element’s mineral-melt partition coefficient (K_D). Partition coefficients are usually deduced from an element’s abundance in phenocrysts that are in contact (and supposed equilibrium) with an igneous rock’s groundmass material, which is assumed to have formed from magma, and its concentration in that once liquid phase. Models for partial melting and fractional crystallisation, plus several variants, all involve K_Ds, for olivines, pyroxenes, feldspars, garnet, amphiboles and so on. For the generation of basaltic magmas, the first step is partial melting in the mantle itself, for which direct estimation of K_Ds is not possible. Instead they are assumed from mineral-melt chemistries in crustal igneous rocks, with some allowance for elevated temperatures and pressures and other conditions. Each mineral has its own distinctive suite of K_Ds for many elements, and the chemistry of an igneous rock has often been traced back to which suite of minerals was present in a residue, i.e. the source rock itself, as well as the degree to which one or other process proceeded. The 19 February 2004 issue of *Nature* included an ominous article (Hiraga, T, *et al*. 2004. Grain boundaries as reservoirs of incompatible elements in the Earth’s mantle. *Nature*, v. **427**, p. 699-703).

The study by geochemists at the University of Minnesota and Oak Ridge National Laboratory, USA, concentrated only on the mineral olivine, and a few elements present at trace levels in it. Their experiments simulated equilibrium conditions under mantle conditions. Results showed that incompatible elements in olivine, such as Ca and Al, tend to concentrate mainly at boundaries between grains where they are readily available to any melt that starts to form, rather than uniformly throughout the mineral grain. The finer the grain size of the rock, the greater the area of grain boundaries, and so the more incompatible elements tend to be concentrated at them The tendency is predictable on thermodynamic grounds, but has only been studied previously in alloys and other artificial materials. Geochemists have generally regarded grain boundaries as places where impurities in rocks gather. If the same rock is analysed with and without the crushed powder having been washed in acid, different trace element concentrations result. This has been attributed to secondary effects, such as the passage of hydrothermal fluids or groundwater. Since K_Ds that are used widely involve concentrations in whole mineral grains, the basis of geochemical modelling might be compromised. Melting begins at grain boundaries, so the low degrees involved in generating basalts could be biased by the effect. Moreover, vapour phases moving through the mantle (supercritical water and CO_2), will follow grain boundaries too, and so may easily pick up and transport incompatible elements. Their entry into the crust carrying mantle-derived incompatible elements, such as rare-earths, strontium and lead, would lead to metasomatic effects that could play havoc with interpretations of isotopic data based on these elements. Carbonatites, probably formed from mantle-derived carbonic fluids, are enriched in many incompatible elements. Similarly worrying data, such as estimates of the incompatible element partitioning into carbonic fluids, have emerged in the past, but so far have been notable only for the silence with which most geochemists greeted them.

Planetary, extraterrestrial geology, and meteoritics

The creators of worlds

Inverting Robert Oppenheimer's memory of the line in the Bhagavad Gita, "I am become Death, the destroyers of worlds", during his Road-to-Damascus moment when the first atomic weapon was tested, may seem an odd headline for an article on geochemistry. But geochemists sometimes do give the air of being on the verge of solving the "Big Question". Alex Halliday of ETH in Zurich is one of them (Halliday, A.N. 2004, Mixing, volatile loss and compositional change during impact-driven accretion of the Earth. *Nature*, v. **427**, p. 505-509). It is now well accepted that Earth's early evolution was one of repeated big impacts during planetary accretion. It probably culminated in a collision with a Mars-sized planet that not only created the Moon from the debris splattered from both bodies, but set the Earth's chemistry for all subsequent time; a sort of geochemists' Year Zero. When that happened and what ensued has all manner of connotations (see *Geoscience consensus challenged* in *EPN* for January 2004). Halliday reviews evidence from several isotopic systems (Pb, Xe, Sr, W) that are reckoned to be appropriate "fingerprints" for the environments in which planets accreted. His treatment takes the data as a whole, rather than separated into one or another isotopic system. He begins with the assumption in most accretion models that metallic cores form continuously and in equilibrium with the silicate outer mantle of rocky planets. That is important in using W isotopes to model the "when", since tungsten is likely to enter iron-rich metal rather than silicates (see *Mantle and core do not mix* in *EPN* February 2004). In fact estimates for the time taken for the Earth to gather 2/3 of its mass based on W isotopes (~11 Ma) are a lot faster than those based on other isotopes (between 15 to 40Ma). Halliday's explanation is the seemingly sound one that when big things form from smaller ones (whatever contributed to core and mantle), the chances of them mixing and reaching equilibrium, before they definitively separate into the inner and outer Earth, are not good. Reviewing the somewhat bewildering permissiveness of isotopic data from Earth and Moon that bear on "Year Zero" he concludes that the massive loss of xenon (and other "volatile" elements) that characterises Earth, by comparison with what is known about the Solar System's pre-planetary composition, was 50 to 80 Ma after the "start of the Solar System". The Moon has provided insufficient data for its age of formation to be tied down isotopically. Although its Hf-W age might be >44 Ma relative to the Earth's beginning, there again, perhaps >54 Ma, and it may have formed even later. Eventually we reach modelling (read "speculation"?) that takes us to the putative composition of the culprit for Year Zero, "Theia" (a Titan and the product of incestuous liaison between Uranus and his mother Gaia).

What seems odd to me is that some of the parent isotopes for those used in fingerprinting (e.g. ^{182}Hf for ^{182}W, and plutonium for a Xe isotope) can only form in supernovae events, and are so short-lived that the balance between their formation and their influence on partitioning of their daughters in planets is pretty delicate in terms of timing. Indeed all radioactive isotopes, and every element with greater atomic mass than iron, in the Solar System have this origin, because it is impossible for a star the size of the Sun to form them. Massive stars that become supernovas are common enough, and when they "go off" and what blend of heavy elements they produce depend on how big they were and when they formed. Interstellar material is surely a mix of debris from a number of such events of different ages, and new stars and planetary systems form from that. Maybe they are triggered by nearby supernovas, but that also contributes to the isotopic mix that has evolved since a galaxy formed. Just suppose that the mix for the Solar System was heterogeneous, with differently aged uranium, thorium, rubidium, hafnium and other elements heavier than can be formed inside small stars like the Sun, and must have formed in big ones that eventually blasted their products into interstellar space. If the Earth accreted as an open, non-equilibrated system, then what of the Solar System itself? Bit early to say, really….

Tectonics

Quantifying motions inside continents

If you are a member of the Geological Society of America you will either have heard or read the 2003 Address of its President (Burchfiel, B.C. 2004. New technology; new geological challenges. *GSA Today*, v. **14**, p. 4-10). If not, get the February 2004 issue of *GSA Today*, if only for the wonderful illustrations in Burchfiel's paper. His topic is how the use of ever-increasing precision of satellite global positioning (GPS) has revolutionised continental neotectonics, since it began to be used by geoscientists in the late-1980s. The illustrations have a backdrop of what I suspect to be the 90m resolution Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM), and show the fine topographic detail that stems very much from active tectonic movements. Superimposed on them are estimates of the speed at which points on the surface are moving and the directions of motion, gathered using GPS technology. Measured in mm per year, these velocities stem from the most precise positional measurements, with the degradation built into the GPS satellite signals for US military reasons (turned off in 2001) removed using differential processing. They are averages representing motions over the last 17 years or so. The most dramatic example covers the Tibetan Plateau and areas to the east of it, based on extensive work by Chinese scientists.. In general it shows a sort of clockwise swirling away of expelled crust east of the Eastern Himalayan Syntaxis (the "big bend" at the eastern termination of the Himalaya) in the ranges through which the headwaters of the Irrawaddy, Salween and Mekong rivers flow, rather than the eastward expulsion towards the China Sea first postulated by Tapponier in the early 1980s. Field studies suggest that this kind of motion has been going on for at least the last 4-6 Ma. Another conflict with expectation lies in the area of the Longmen Shan mountains and the huge Sichuan Basin of western China. A simple model of crust being expelled from the zone of the India-Asia collision suggests that Tibetan crust would be moving eastwards here to throw up the steep front of the Longmen Shan above the Sichuan Basin. There is in fact very little sideways movement at the surface. Explaining this requires deep crust from Tibet moving in a ductile manner far below, thereby "inflating" the Longmen Shan where entirely different kinds of crust are juxtaposed.. Many of the motions in East Asia can only be explained in terms of differential movements at different levels in the lithosphere, and the influence of subduction systems, such as the Indo-Burman and West Pacific, as well as the long-suspected expulsion of over-thickened crust in Tibet due to increased gravitational potential there.

- **JEM**

CONTENTS LIST for JEM, 2004, vol. 06, issue 03:

NEWS ARTICLES
News
Legislation
Environmental quality
Chemical hazards
Public and occupational health
Research activities
Publications
http://xlink.rsc.org/?DOI=b401997k

FULL PAPERS

On-site simultaneous determination of anions and cations in drainage water using a flow injection-capillary electrophoresis system with contactless conductivity detection, Pavel Kubá, Miriam Reinhardt, Beat Müller, Peter C. Hauser
http://xlink.rsc.org/?DOI=b316422e

Chemical (polycyclic aromatic hydrocarbon and heavy metal) levels in contaminated stormwater and sediments from a motorway dry detention pond drainage system, Ragunathan Kamalakkannan, Vic Zettel, Alex Goubatchev, Karen Stead-Dexter, Neil I. Ward
http://xlink.rsc.org/?DOI=b309384k

Pesticides in rainwater in Flanders, Belgium: results from the monitoring program 1997-2001, D. Quaghebeur, B. De Smet, E. De Wulf, W. Steurbaut
http://xlink.rsc.org/?DOI=b312558k

Mobilization of aluminium and deposition on fish gills during sea salt episodes - catchment liming as countermeasure, Hans-Christian Teien, William J. F. Standring, Brit Salbu, Marilyn Marskar,

Frode Kroglund, Atle Hindar
http://xlink.rsc.org/?DOI=b314708h

Concentrations of polychlorinated dibenzo-p-dioxins, dibenzofurans, non-ortho polychlorinated biphenyls, and mono-ortho polychlorinated biphenyls in Japanese flounder, with reference to the relationship between body length and concentration, Yutaka Okumura, Yoh Yamashita, Satoshi Isagawa
http://xlink.rsc.org/?DOI=b311911d

Polycyclic aromatic hydrocarbon (PAH) concentration and composition determined in farmed blue mussels (Mytilus edulis) in a sea loch pre- and post-closure of an aluminium smelter, A. D. McIntosh, C. F. Moffat, G. Packer, L. Webster
http://xlink.rsc.org/?DOI=b311189j

The polycyclic aromatic hydrocarbon and geochemical biomarker composition of sediments from sea lochs on the west coast of Scotland, L. Webster, R. J. Fryer, C. Megginson, E. J. Dalgarno, A. D. McIntosh, C. F. Moffat
http://xlink.rsc.org/?DOI=b314870j

Polycyclic aromatic hydrocarbons in sediments and mussels of Corral Bay, south central Chile, Hernán Palma-Fleming, Adalberto J. Asencio P., Elena Gutierrez
http://xlink.rsc.org/?DOI=b307018b

Two high-speed, portable GC systems designed for the measurement of non-methane hydrocarbons and PAN: Results from the Jungfraujoch High Altitude Observatory, L. K. Whalley, A. C. Lewis, J. B. McQuaid, R. M. Purvis, J. D. Lee, K. Stemmler, C. Zellweger, P. Ridgeon
http://xlink.rsc.org/?DOI=b310022g

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Contents
Lithology and Mineral Resources

Vol. 39, No. 2, 2004
Simultaneous English language translation of the journal is available from MAIK “Nauka / Interperiodica” (Russia).

Distributed worldwide by Kluwer Academic/Plenum Publishers. *Lithology and Mineral Resources* ISSN 0024-4902.

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