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Oil & Gas Science and Technology – Rev. IFP, Vol. 65 (2010), No. 3, pp. 369-373

DOI: 10.2516/ogst/2010012

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THE CHALLENGE OF CO_2 GEOLOGICAL STORAGE

Over the last fifteen years the storage of carbon dioxide (CO_2) in deep geological formations has been considered with increasing attention as one of the major solutions to contribute to the struggle against anthropogenic climate change and ocean acidification. Predicting the part it could play during the 21st century is still a matter of discussion, and should remain so as it depends on many parameters which are poorly known. A stabilization target of concentration of greenhouse gases at 535-590 ppmv eq-CO_2 in the atmosphere (*i.e.*, 440-485 ppmv CO_2), a value which represents approximately two times its pre-industrial concentration, should be compatible with a 2.8 to 3.2°C (best estimate) warmer climate on average (IPCC Gp.III, 2007). Compared to the trend that can be extrapolated from the world economy, a stabilization target at ca. 500 ppmv CO_2 would represent a mitigation effort of 600 to 700 Gt_{CO_2} to be achieved by 2050-2060 (Pacala and Socolow, 2004). If it were assumed that the contribution of geological storage reached 10% of this amount, that would represent the challenge of injecting 60 to 70 Gt_{CO_2} in appropriate sub-surface sites over 30 to 35 years, *i.e.*, 2600 operations comparable in size to the demonstration project undertaken in 1996 at Sleipner – or 260 operations ten times larger (ca. 250 Mt_{CO_2}) already *achieved* by 2050. Some roadmaps are more intensive: for instance IEA (2009) discusses an objective of 19% for the CCS contribution to emissions reduction. Such figures show how high the stakes are for this technology.

Beyond the economic aspect of the question, which is of course vital – and not at present resolved –, an industrial perspective on this scale could materialize only if commitments are taken in many countries, not only by national institutions involved in R&D, and by private companies able to deploy the technical skill, but also and maybe more crucially by the regulating authorities at State level. The huge quantities cited above, and the need to minimize the distance between point sources of CO_2 and storage sites, give rise to an unprecedented interest for deep saline aquifers, present in most sedimentary basins. The degree of exploration of these formations, often linked to surveys undertaken by the oil industry, is extremely variable from one basin to another, and, inside a particular basin, from a given region to another. It will be frequent to address areas where the information is scarce or even non existent. It is also to be expected that prospecting efforts will concern a large variety of sedimentary basins:

- basins characterized by simple tectonics and still actively subsiding, such as the North Sea or many Tertiary basins in Southeast Asia, where the chance to find excellent reservoir properties at the adequate burial depth, 1000 to 2000 m, is fair (*e.g.*, the Utsira Sand in the North Sea);
- intra-continental basins or marginal basins of older geological age, of more complex tectonics, where the longer and often poly-phased burial and diagenetic history determined an evolution of the reservoir properties which in most cases is detrimental;
- basins located offshore, where organizing 3-D seismic surveys is relatively easy;
- but also basins located onshore, with densely populated regions, or with protected perimeters, where such surveys could be impossible, with the consequence that monitoring the CO_2 plume migration with 4-D seismic will not be possible in some areas.

PROSPECTING FOR CO_2 GEOLOGICAL STORAGE IN THE PARIS BASIN, FRANCE

In 2001-2004, the French Ministry of Industry supported a succession of yearly research projects dedicated to the geological storage of CO_2. In 2005, this effort was increased and the Ministry oriented the main research objective of the project, called PICOREF, to the evaluation of site(s) adapted to a pilot-scale storage installation, either in a depleted hydrocarbon field or in a deep saline aquifer. The south-eastern part of the Paris Basin was chosen to carry out the site screening and analysis, because preliminary rough estimates of the storage capacity were available from the European GESTCO project, and because this area offers relatively dense and high-quality petroleum data. In 2006, the public part of PICOREF funding was transferred to a dedicated program of the recently created ANR (*Agence Nationale de la Recherche*), and the activity was split into a set of five connected 3-year projects aimed at investigating a large spectrum of topics linked to CO_2 storage:
- PICOREF, on geological investigation and site characterization;
- *Intégrité*, on the continuity and sealing capacity of cap rocks;
- *Injectivité*, on reservoir management close to injection area;
- *Monitoring*, on the performance of monitoring techniques, and;
- *Carbonatation*, on long-term geochemical effects, including biogeochemistry.

The five projects were coordinated under a unique label, *Géocarbone*, and as much as possible tried to focus their work on the geological features met in the region of the Paris Basin under consideration.

We are pleased to introduce here two successive issues of Oil & Gas Science and Technology – *Revue de l'IFP*, where a large part of the work achieved by the *Géocarbone* projects is presented. The reader who would like to complete his/her information is referred to a special issue of *Chemical Geology* edited by P. Benezeth, B. Menez and C. Noiriel (2009), where articles more specifically dealing with the *Carbonatation* project were published (Benezeth *et al*., 2009).

It is out of the scope of this brief introduction to present the concepts of CO_2 geological storage. Many R&D projects have been carried out in several countries, and a huge literature is now available. Several articles and publicly accessible reports can be considered as excellent scientific reviews covering most of the relevant topics: the Canadian IEA GHG Report "*Weyburn CO_2 monitoring and storage project*" by Whittaker *et al*. (2004), the "*IPCC Special Report on Carbon Dioxide Capture and Storage*" (IPCC, 2005, mainly Chapter 5), the European Report "*Best practice for the storage of CO_2 in saline aquifers*" by Chadwick *et al*. (2007), the Australian CO2CRC Report "*Storage capacity estimation, site selection and characterisation for CO_2 storage projects*" edited by Kaldi and Gibson-Poole (2008). The topics addressed in the *Géocarbone* projects covered most of the aspects considered as important to characterize a potential storage site and to predict the storage behaviour during injection and on the longer term after injection.

In the Paris Basin the deep saline aquifers able to offer large-scale perspectives for CO_2 storage are located in carbonate formations of the Middle Jurassic (the "Dogger"), and in sandstone formations of the Triassic. The Dogger is by far the best known reservoir because it has been the main target for both petroleum E&P and geothermal energy production *(Fig. 1)*. This explains the considerable importance given to carbonate sediments by the *Géocarbone* projects. From an impressive database of almost 7000 core-sample analyses collected by the petroleum industry over 50 years, Delmas *et al*. (2010) show that the petrophysical properties of the Dogger are often quite deceiving, and depend on several features (sedimentary fabric, micro-fracturing, stylolitization) which are difficult to predict. The considerations reported above, on the expected quality of reservoirs in relatively old basins, full apply to these formations. At the site scale, understanding the permeability distribution will depend on additional characterization efforts that remain to be made, in particular to improve the connection between facies and diagenesis, and to take more well tests into account. Brosse *et al*. (2010) present a synthesis from *Géocarbone-PICOREF*, showing the main geological characteristics of the studied area at the basin scale. The scarcity of structural trapping is a prominent feature, that implies that CO_2 entrapment must be considered as a "hydrodynamic" process, as it is for instance in the Utsira Sand at Sleipner. The paper illustrates the type of data that can be available when exploring an area for site screening, the method followed to select a "sector" area, ca. 60 × 60 km, from an initially much larger regional domain, and the building of numerical 3-D "earth models", needed by the simulation work typically required before an application for storage permit.

An overview of *Géocarbone-Intégrité*, dealing with the sealing efficiency of caprocks, is presented by Fleury *et al*. (2010). A wide variety of scales and physical mechanisms must be considered. At large scale, the seismic profiles from the Saint-Martin-de-Bossenay field area were reprocessed to focus on the caprock above the Dogger formation. These data as well as well logging data show that no major discontinuity is present and that the thickness of the sealing formation based on a clay content indicator is between 30 and 100 m. Laboratory experiments performed on different facies (dominated either by carbonate or by clays) show low reactivity to CO_2. Similarly, Bemer and Lombard (2010) show that mechanical properties were not significantly modified after artificial and extreme porosity

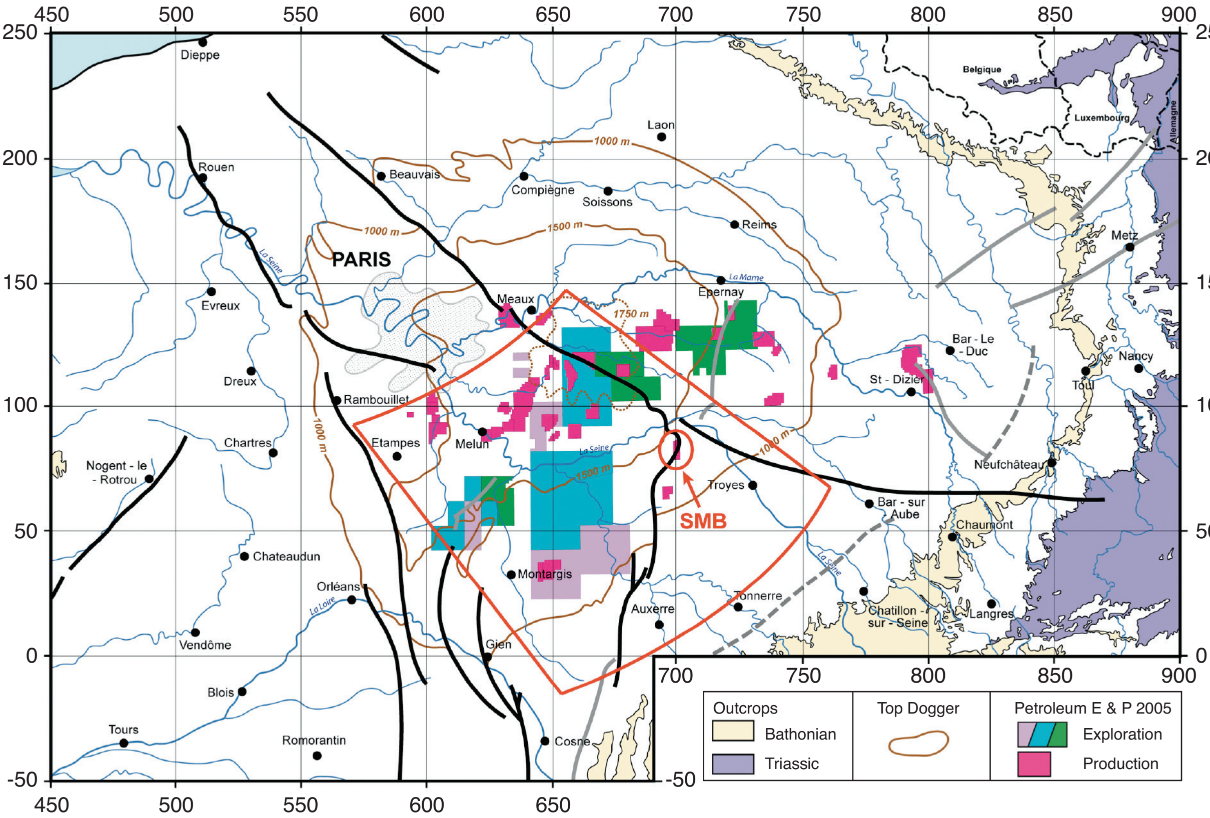

Figure 1

The part of the Paris Basin investigated by the *Géocarbone* projects is located in the southeast of Paris (orange perimeter). In this area, information on the subsurface is relatively abundant, because of past exploration efforts for petroleum (Dogger and Trias) and, in a circle of ca. 50 km radius around Paris, for geothermal heat (Dogger).

SMB: Saint-Martin-de-Bossenay - this oilfield structure could be studied because all the data were made available by the successive operators to the *Géocarbone* projects.

alteration of low permeability samples. Some general results were also obtained about the lack of modification by CO_2 of wettability, useful to determine capillary entry pressure in the laboratory using standard measurements. Carles *et al*. (2010) show the uncertainties associated with the different measurement methodologies concerning capillary entry pressure and permeability using samples from a tight interval of the *Comblanchien* formation (Dogger), dominated by mudstone facies. Berne *et al*. (2010) also measured by different methods the pore diffusivities applicable for CO_2 and ions. In the paper by Bildstein *et al*. (2010), numerical simulations are reported that predict the extent of CO_2 migration either by pure diffusion or by two phase flow in the case of capillary breakthrough. It is shown that the migration is limited vertically to less than 10 m of formation over very long periods of time. In addition, this migration produces mostly a decrease of porosity by precipitation, and, only very locally, an increase. Finally, Rohmer and Seyedi (2010) show that shear fracture reactivation criteria are not reached even for relatively high overpressure due to injection.

The objective of *Géocarbone-Injectivité* was to develop a methodology to study the complex phenomena involved in the near wellbore region during CO_2 injection. The principles, the main results of the study and some further necessary developments are summarized in Lombard *et al*. (2010). This methodology is based on experiments and simulations at the core scale, in order to understand (using physical modelling and constitutive laws) and quantify (by the calibration of simulation tools) the mechanisms involved in injectivity variations: fluid/rock interaction, transport mechanisms, geomechanical effects. These mechanisms and the associated parameters have then to be integrated in the models at the wellbore scale. Concerning fluid/rock interaction, the dissolution and precipitation phenomena linked to the acidity of the brine/CO_2 solution have been outlined and different injection scenarios have been studied. Chalbaud *et al.* (2010) present an experimental study which allowed new brine/CO_2 interfacial tension (IFT) data, necessary for CO_2 storage issues to be acquired, and a correlation with thermodynamical conditions to be proposed. Observations at the pore and core scales have also shown the possible wetting behaviour of CO_2 and the authors propose a discussion of its influence on the storage capacity of the investigated formations. The evolution of transport properties generated by the pore structure alteration of the rock near the well was also studied within *Géocarbone-Injectivité*. In the study presented in Radilla *et al.* (2010), both native samples representative of the Dogger formation and samples altered uniformly by an acid solution were characterized. The acidity resulted in a slight increase of permeability and porosity and a decrease of inertial coefficients. Both relative permeabilities and Klinkenberg effects remained unchanged. When no particle displacement takes place, the injectivity of the studied rock was not altered by the acid solution. The poroelastic properties as well as the rupture criteria (induced fracturing) have been measured on native and altered *Lavoux* and *Comblanchien* carbonate samples: the already cited Bemer and Lombard's (2010) paper outlines a clear trend of chemically induced mechanical weakening. The experimental data have been compared to the predictions obtained from phenomenological and empirical models. These results are completed by Rimmelé *et al.* (2010), who measured the evolution of mineral composition and petrophysical properties displayed by *Lavoux* carbonates and Triassic Adamswiller sandstones during transformation in a closed system in presence of CO_2 (results obtained in the framework of *Géocarbone-Carbonatation*).

Fabriol *et al.* (2010) give an overview of the results achieved in *Géocarbone-Monitoring*, and provide recommendations for site monitoring in the specific geological context of the Paris Basin – in particular, for storage hosted in the Dogger carbonates. Regarding monitoring, Becquey *et al.* (2010) simulated the application of 4-D seismics to the specific site of Saint-Martin-de-Bossenay, using existing logging data. First results indicate that injecting CO_2 will not be easily detectable and that acquisition of more data, particularly downhole seismics, will be necessary. As an alternative to active seismics, geophysical methods based on measuring changes in electrical resistivity could be an option. Bourgeois and Girard (2010) propose a new configuration called "LEMAM" (*Long Electrode Mise à la Masse*), where current is injected between two deep wells intersecting the reservoir. Their numerical simulations show that, under certain conditions, the CO_2 plume could induce modifications of the electrical potential at the surface, which are above the signal-to-noise ratio and thus measurable. Two papers deal with soil gas and fluids sampling at the surface. Battani *et al.* (2010) propose an analysis of natural CO_2 emissions at the Sainte-Marguerite site in the French Massif Central. They describe how to predict the origin, processes and evolution of a natural CO_2 leakage. Gal *et al.* (2010) developed the same techniques at the natural CO_2 reservoir of Montmiral in the French Pre-Alps. The major goals for geochemical study of both sites were to monitor natural concentrations of gas in the soil and to establish their temporal and spatial variability, which could serve as reference values for delivering CO_2 storage permits in similar geological settings. Finally, Pokryszka *et al.* (2010) present two kinds of tool which were developed in the framework of the project *Géocarbone-Monitoring*: one for early detection (pre-alert), using analysis of gas samples taken at the bottom of dedicated boreholes drilled from the surface into the intermediate caprock strata; the second to detect and quantify the gaseous flux of CO_2 from the ground to the atmosphere.

RESEARCH WORK AND FIELD PILOTS ARE NEEDED

This short overview of the contribution brought by the *Géocarbone* projects to a perspective of CO_2 geological storage in the Paris Basin illustrates the variety of topics involved, and their often complex interconnection. Industrial good practice already exists in many of the technical domains concerned, in particular petroleum E&P, natural gas storage, and exploitation of geothermal energy. But none requires so large a panel of skills. In addition, there are specific aspects in CO_2 geological storage which are still poorly covered by already existing industrial approaches, *e.g.*, the need to produce predictive simulations of phenomena that result from coupled mechanisms operating at various space and time scales, including the long term (10 000 years), and that concern sub-surface environments which cannot be described without large uncertainty.

All the above considerations, expressed as a world-scale challenge or as specific difficulties to overcome when focusing on one particular basin (the Paris Basin), show that it would not be reasonable to contemplate any industrial deployment of CCS without a strong involvement of research work associated with pilot-scale operations.

REFERENCES

Battani A., Deville E., Faure J.L., Jeandel E., Noirez S., Tocqué E., Benoît Y., Schmitz J., Parlouar D., Sarda Ph., Gal F., Le Pierres K., Brach M., Braibant G., Beny C., Pokryszka Z., Charmoille A., Bentivegna G., Pironon J., de Donato P., Garnier C., Cailteau C., Barrès O., Radilla G., Bauer A. (2010) Geochemical study of natural CO_2 emissions in the French Massif Central: How to predict origin, processes and evolution of CO_2 leakage, *Oil Gas Sci. Technol.* **65**, 4.

Becquey M., Lucet N., Huguet F. (2010) Feasibility of seismic monitoring at a potential CO_2 injection test site in the Paris Basin, *Oil Gas Sci. Technol.* **65**, 4.

Bemer E., Lombard J.M. (2010) From injectivity to integrity studies of CO_2 geological storage: chemical alteration effects on carbonates petrophysical and geomechanical properties, *Oil Gas Sci. Technol.* **65**, 3.

Benezeth P., Menez B., Noiriel C. (2009) Preface. CO_2 geological storage: Integrating geochemical, hydrodynamical, mechanical and biological processes from the pore to the reservoir scale, *Chem. Geol.* **265**, 1-2.

Berne Ph., Bachaud P., Fleury M. (2010) Diffusion properties of carbonated caprocks from the Paris Basin, *Oil Gas Sci. Technol.* **65**, 3.

Bildstein O., Kervévan C., Lagneau V., Delaplace P., Crédoz A., Audigane P., Perfetti E. Jullien M. (2010) Integrative modeling of caprock integrity in the context of CO_2 storage: evolution of transport and geochemical properties and impact on performance and safety assessment, *Oil Gas Sci. Technol.* **65**, 3.

Bourgeois B., Girard J.F. (2010) First modelling results of the EM response of a CO_2 storage in the Paris Basin, *Oil Gas Sci. Technol.* **65**, 4.

Brosse É., Badinier G., Blanchard F., Caspard E., Collin P.Y., Delmas J., Dezayes C., Dreux R., Dufournet A., Durst P., Fillacier S., Garcia D., Grataloup S., Hanot F., Hasanov V., Houel P., Kervévan C., Lansiart M., Lescanne M., Menjoz A., Monnet M., Mougin P., Nedelec B., Poutrel A., Rachez X., Renoux P., Rigollet C., Ruffier-Meray V., Saysset S., Thinon I., Thoraval A., Vidal-Gilbert S. (2010) Selection and characterization of geological sites able to host a pilot-scale CO_2 storage in the Paris Basin (*Géocarbone* PICOREF), *Oil Gas Sci. Technol.* **65**, 3.

Carles P., Bachaud P., Lasseur E., Berne P., Bretonnier P. (2010) Confining properties of carbonated Dogger caprocks (Parisian Basin) for CO_2 storage purpose, *Oil Gas Sci. Technol.* **65**, 3.

Chadwick A., Arts R., Bernstone C., May F., Thibeau S., Zweigel P. (2007) Best practice for the storage of CO_2 in saline aquifers. Observations and guidelines from the SACS and CO2STORE projects, British Geological Survey (British Geological Survey Occasional Publication, 14: http://www.bgs.ac.uk/downloads/).

Chalbaud C., Robin M., Lombard J.M., Bertin H., Egermann P. (2010) Brine/CO_2 interfacial properties and effects on CO_2 storage in deep saline aquifers, *Oil Gas Sci. Technol.* **65**, 4.

Delmas J., Brosse E., Houel P. (2010) Petrophysical properties of the Middle Jurassic carbonates in the PICOREF Sector (South Champagne, Paris Basin, France), *Oil Gas Sci. Technol.* **65**, 3.

De Gal F., Le Pierres K., Brach M., Braibant G., Beny C., Battani A., Tocqué E., Benoît Y., Jeandel E., Pokryszka Z., Charmoille A., Bentivegna G., Pironon J., Donato P., Garnier C., Cailteau C., Barrès O., Radilla G., Bauer A. (2010) Surface gas geochemistry above the natural CO_2 reservoir of Montmiral (Drôme, France), source tracking and gas exchange between soil, biosphere and atmosphere, *Oil Gas Sci. Technol.* **65**, 4.

Fabriol H., Becquey M., Huguet F., Lescanne M., Mouronval G., Pironon J., Pokryzska Z., Vu-Hoang D. (2010) The Géocarbone-Monitoring project: main results and recommendations for monitoring deep geological CO_2 storage in the Paris Basin, *Oil Gas Sci. Technol* **65**, 4.

Fleury M., Pironon J., Le Nindre Y.M., Bildstein O., Berne P., Lagneau V., Broseta D., Pichery T., Fillacier S., Lescanne M., Vidal O. (2010) Evaluating sealing efficiency of caprocks for CO_2 storage: an overview of the Géocarbone-Integrity program and results, *Oil Gas Sci. Technol.* **65**, 3.

IEA (2009) *Technology Roadmap – Carbon Capture & Storage*, (www.iea.org/papers/2009/CCS_Roadmap.pdf), 46 pp.

IPCC (2005) *IPCC Special Report on Carbon Dioxide Capture and Storage*, Intergovernmental Panel on Climate Change, Cambridge University Press, New York, USA.

IPCC (2007) *Climate Change 2007: Synthesis Report*. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, Pachauri R.K and Reisinger A. (eds), Intergovernmental Panel on Climate Change, Geneva, Switzerland, 104 pp.

Kaldi J.G., Gibson-Poole C.M., (eds) (2008) *Storage capacity estimation, site selection and characterisation for CO_2 storage projects*, CO2CRC Report N.RPT08-1001 (www.co2crc.com.au).

Lombard J.M., Azaroual M., Pironon J., Broseta D., Egermann P., Munier G., Mouronval G. (2010) CO_2 injectivity in geological storages: an overview of program and results of the Géocarbone-Injectivity Project, *Oil Gas Sci. Technol.* **65**, 4.

Pacala S., Socolow R. (2004) Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies, *Science* **305**, 5686, 968-972.

Pokryszka Z., Charmoille A., Bentivegna G. (2010) Developing methods for gaseous phase geochemical monitoring on surface and in the intermediate overburden strata of geological CO_2 storage sites, *Oil Gas Sci. Technol.* **65**, 4.

Radilla G., Kacem M., Lombard J.M., Fourar M. (2010) Transport properties of Lavoux Limestone at various stages of CO_2–like acid–rock alteration, *Oil Gas Sci. Technol.* **65**, 4.

Rimmelé G., Barlet-Gouédard V., Renard F. (2010) Evolution of the Petrophysical and Mineralogical Properties of Two Reservoir Rocks Under Thermodynamic Conditions Relevant for CO_2 Geological Storage at 3 Kilometers Depth, *Oil Gas Sci. Technol.* **65**, 4.

Rohmer J., Seyedi D.M. (2010) Coupled large scale hydromechanical modelling for caprock failure risk assessment of CO_2 storage in deep saline aquifers, *Oil Gas Sci. Technol. – Rev. IFP* **65**, 3, DOI: 10.2516/ogst/2009049.

Whittaker S., White D., Law D., Chalaturnyk R. (2004) IEA GHG Weyburn CO_2 monitoring and storage project, Summary report 2000-2004, in *GHGCT-7*, Vancouver 2004, Wilson M. and Monea M. (eds), **III**, 1-283.

Final manuscript received in April 2010
Published online in June 2010