



IN PARTNERSHIP WITH:  
**CNRS**

**Université Nice - Sophia  
Antipolis**

Activity Report 2018

**Project-Team COFFEE**

COmplex Flows For Energy and Environment

IN COLLABORATION WITH: Laboratoire Jean-Alexandre Dieudonné (JAD)

RESEARCH CENTER  
**Sophia Antipolis - Méditerranée**

THEME  
**Earth, Environmental and Energy  
Sciences**



## Table of contents

<b>1. Team, Visitors, External Collaborators</b> .....	<b>1</b>
<b>2. Overall Objectives</b> .....	<b>2</b>
<b>3. Research Program</b> .....	<b>2</b>
<b>4. Application Domains</b> .....	<b>3</b>
4.1. Multiphase flows in porous media	3
4.2. Particulate and mixture flows	3
4.3. Biological degradation, biofilms formation and algae proliferation	4
<b>5. Highlights of the Year</b> .....	<b>4</b>
<b>6. New Software and Platforms</b> .....	<b>4</b>
6.1. AP_PartFlow	4
6.2. Mka3d	4
6.3. Compass	5
6.4. NS2DDV-M	5
6.5. SimBiof	5
6.6. CELIA3D	5
<b>7. New Results</b> .....	<b>6</b>
<b>8. Bilateral Contracts and Grants with Industry</b> .....	<b>6</b>
<b>9. Partnerships and Cooperations</b> .....	<b>7</b>
9.1. Regional Initiatives	7
9.2. National Initiatives	7
9.2.1. ANR	7
9.2.2. National and European networks	7
9.3. International Research Visitors	7
<b>10. Dissemination</b> .....	<b>7</b>
10.1. Promoting Scientific Activities	7
10.1.1. Journal	8
10.1.2. Scientific Expertise	8
10.1.3. Research Administration	8
10.2. Teaching - Supervision - Juries	8
10.2.1. Teaching	8
10.2.2. Supervision	8
10.2.3. Juries	9
<b>11. Bibliography</b> .....	<b>9</b>



## Project-Team COFFEE

*Creation of the Team: 2011 July 01, updated into Project-Team: 2013 January 01*

### Keywords:

#### Computer Science and Digital Science:

- A6.1.1. - Continuous Modeling (PDE, ODE)
- A6.1.4. - Multiscale modeling
- A6.1.5. - Multiphysics modeling
- A6.2.1. - Numerical analysis of PDE and ODE
- A6.2.7. - High performance computing
- A6.5. - Mathematical modeling for physical sciences
- A6.5.2. - Fluid mechanics
- A6.5.3. - Transport

#### Other Research Topics and Application Domains:

- B1.1.8. - Mathematical biology
- B3.3.1. - Earth and subsoil
- B4.1. - Fossile energy production (oil, gas)
- B4.2. - Nuclear Energy Production
- B7.1. - Traffic management

## 1. Team, Visitors, External Collaborators

### Research Scientists

Thierry Goudon [Team leader, Inria, Senior Researcher, HDR]  
Laurent Monasse [Inria, Researcher]

### Faculty Members

Florent Berthelin [Univ de Nice - Sophia Antipolis, Associate Professor, HDR]  
Konstantin Brenner [Univ de Nice - Sophia Antipolis, Associate Professor]  
Stéphane Junca [Univ de Nice - Sophia Antipolis, Associate Professor, HDR]  
Stella Krell [Univ de Nice - Sophia Antipolis, Associate Professor]  
Roland Masson [Univ de Nice - Sophia Antipolis, Professor, HDR]

### Post-Doctoral Fellows

Joubine Aghili [Inria]  
Laurence Beaude [Univ de Nice - Sophia Antipolis, since Dec. 2018]  
Nabil Birgle [Inria, until Mar 2018]

### PhD Students

Kevin Atsou [Inria]  
Laurence Beaude [Univ. Côte d'Azur, until Dec. 2018]  
Nadine Dirani [Inria, from Nov 2018]  
Billel Guelmame [Univ. Côte d'Azur]  
Giulia Lissoni [Univ. Côte d'Azur]  
Julie Llobell [Univ. Côte d'Azur, until Sep 2018]  
Leo Vivion [Univ. Côte d'Azur]

### Administrative Assistant

Marie-Cécile Lafont [Inria]

## 2. Overall Objectives

### 2.1. Overall Objectives

The project aims at studying mathematical models issued from environmental and energy management questions. We consider systems of PDEs of hydrodynamic type or hybrid fluid/kinetic systems. The problems we have in mind involve unusual coupling, which in turn leads to challenging difficulties for mathematical analysis and the need of original numerical solutions. By nature many different scales arise in the problems, which allows to seek hierarchies of reduced models based on asymptotic arguments. The topics require a deep understanding of the modeling issues and, as far as possible boosted by the mathematical analysis of the equations and the identification of key structure properties, we wish to propose innovative and performing numerical schemes. To this end, the development of innovative Finite Volumes schemes with unstructured meshes on complex geometries will be a leading topic of the team activity.

## 3. Research Program

### 3.1. Research Program

Mathematical modeling and computer simulation are among the main research tools for environmental management, risks evaluation and sustainable development policy. Many aspects of the computer codes as well as the PDEs systems on which these codes are based can be considered as questionable regarding the established standards of applied mathematical modeling and numerical analysis. This is due to the intricate multiscale nature and tremendous complexity of those phenomena that require to set up new and appropriate tools. Our research group aims to contribute to bridging the gap by developing advanced abstract mathematical models as well as related computational techniques.

The scientific basis of the proposal is two-fold. On the one hand, the project is “technically-driven”: it has a strong content of mathematical analysis and design of general methodology tools. On the other hand, the project is also “application-driven”: we have identified a set of relevant problems motivated by environmental issues, which share, sometimes in a unexpected fashion, many common features. The proposal is precisely based on the conviction that these subjects can mutually cross-fertilize and that they will both be a source of general technical developments, and a relevant way to demonstrate the skills of the methods we wish to design.

To be more specific:

- We consider evolution problems describing highly heterogeneous flows (with different phases or with high density ratio). In turn, we are led to deal with non linear systems of PDEs of convection and/or convection-diffusion type.
- The nature of the coupling between the equations can be two-fold, which leads to different difficulties, both in terms of analysis and conception of numerical methods. For instance, the system can couple several equations of different types (elliptic/parabolic, parabolic/hyperbolic, parabolic or elliptic with algebraic constraints, parabolic with degenerate coefficients...). Furthermore, the unknowns can depend on different sets of variables, a typical example being the fluid/kinetic models for particulate flows. In turn, the simulation cannot use a single numerical approach to treat all the equations. Instead, hybrid methods have to be designed which raise the question of fitting them in an appropriate way, both in terms of consistency of the discretization and in terms of stability of the whole computation. For the problems under consideration, the coupling can also arise through interface conditions. It naturally occurs when the physical conditions are highly different in subdomains of the physical domain in which the flows takes place. Hence interface conditions are intended to describe the exchange (of mass, energy...) between the domains. Again it gives rise to rather unexplored mathematical questions, and for numerics it yields the question of defining a suitable matching at the discrete level, that is requested to preserve the properties of the continuous model.

- By nature the problems we wish to consider involve many different scales (of time or length basically). It raises two families of mathematical questions. In terms of numerical schemes, the multiscale feature induces the presence of stiff terms within the equations, which naturally leads to stability issues. A clear understanding of scale separation helps in designing efficient methods, based on suitable splitting techniques for instance. On the other hand asymptotic arguments can be used to derive hierarchy of models and to identify physical regimes in which a reduced set of equations can be used.

We can distinguish the following fields of expertise

- Numerical Analysis: Finite Volume Schemes, Well-Balanced and Asymptotic-Preserving Methods
  - Finite Volume Schemes for Diffusion Equations
  - Finite Volume Schemes for Conservation Laws
  - Well-Balanced and Asymptotic-Preserving Methods
- Modeling and Analysis of PDEs
  - Kinetic equations and hyperbolic systems
  - PDEs in random media
  - Interface problems

## 4. Application Domains

### 4.1. Multiphase flows in porous media

Our research focuses on the numerical modeling of multiphase porous media flows accounting for complex geology and for nonlinear and multi-physics couplings. It is applied to various problems in the field of energy such as the simulation of geothermal systems in collaboration with BRGM, of nuclear waste repositories in collaboration with Andra, and of oil and gas recovery in collaboration with Total. Our research directions include the development of advanced numerical schemes adapted to polyhedral meshes and highly heterogeneous media in order to represent more accurately complex geologies. A special focus is made on the modeling of multiphase flows in network of faults or fractures represented as interfaces of co-dimension one coupled to the surrounding matrix. We also investigate nonlinear solvers adapted to the nonlinear couplings between gravity, capillary and viscous forces in highly heterogeneous porous media. In the same line, we study new domain decomposition algorithms to couple non-isothermal compositional liquid gas flows in a porous medium with free gas flows occurring at the interface between the ventilation gallery and the nuclear waste repository or between a geothermal reservoir and the atmosphere.

### 4.2. Particulate and mixture flows

We investigate fluid mechanics models referred to as “multi-fluids” flows. A large part of our activity is more specifically concerned with the case where a disperse phase interacts with a dense phase. Such flows arise in numerous applications, like for pollutant transport and dispersion, the combustion of fuel particles in air, the modelling of fluidized beds, the dynamic of sprays and in particular biosprays with medical applications, engine fine particles emission... There are many possible modelings of such flows: microscopic models where the two phases occupy distinct domains and where the coupling arises through intricate interface conditions; macroscopic models which are of hydrodynamic (multiphase) type, involving non standard state laws, possibly with non conservative terms, and the so-called mesoscopic models. The latter are based on Eulerian-Lagrangian description where the disperse phase is described by a particle distribution function in phase space. Following this path we are led to a Vlasov-like equation coupled to a system describing the evolution of the dense phase that is either the Euler or the Navier-Stokes equations. It turns out that the leading effect in such models is the drag force. However, the role of other terms, of more or less phenomenological nature, deserves to be discussed (close packing terms, lift term, Basset force...). Of course the fluid/kinetic model is interesting in itself and needs further analysis and dedicated numerical schemes. In particular, in collaboration with the Atomic Energy Commission (CEA), we have proposed a semi-Lagrangian scheme for the simulation of particulate flows, extending the framework established in plasma physics to such flows.

We also think it is worthwhile to identify hydrodynamic regimes: it leads to discuss hierarchies of coupled hydrodynamic systems, the nature of which could be quite intriguing and original, while they share some common features of the porous media problems. We are particularly interested in revisiting the modeling of mixture flows through the viewpoint of kinetic models and hydrodynamic regimes. We propose to revisit the derivation of new mixture models, generalizing Kazhikov-Smagulov equations, through hydrodynamic asymptotics. The model is of “hybrid” type in the sense that the constraint reduces to the standard incompressibility condition when the disperse phase is absent, while it involves derivatives of the particle volume fraction when the disperse phase is present.

### 4.3. Biological degradation, biofilms formation and algae proliferation

Members of the team have started an original research program devoted to biofilms formation and algae proliferation. We started working on this subject through a collaboration with Roberto Natalini and a group of experts in Firenze interested in preventing damages on historical monuments. It is also motivated by *Ostreopsis* proliferation in the Mediterranean Sea. The multidisciplinary character of this research relies on discussions with researchers of the Oceanography Laboratory in Villefranche-sur-Mer, a leading marine research unit, and the Inria team BIOCORE, led by J-L Gouzé. This research was supported by a ANR-project, led by M. Ribot, and it was the main topic of the PhD thesis of B. Polizzi. It continues through a collaboration with INRA (Jouy-en-Josas), dealing with the modeling of flows in the gut and with the aim of describing the formation and stability of mucus layers.

## 5. Highlights of the Year

### 5.1. Highlights of the Year

#### 5.1.1. Awards

- Stéphane Junca received an invitation at the LMA (Laboratory of Mechanics and Acoustics, Marseille, France), 6 months, from February to July 2018.
- Florent Berthelin had a Inria delegation from January to June 2018 to work with teams ACUMES and TOSCA. In particular he worked with P. Goatin on models for traffic flows.

## 6. New Software and Platforms

### 6.1. AP\_PartFlow

FUNCTIONAL DESCRIPTION: We are developing experimental codes, mainly based on Finite Differences, for the simulation of particulate flows. A particular attention is paid to guaranty the asymptotic properties of the scheme, with respect to relaxation parameters.

- Contact: Thierry Goudon

### 6.2. Mka3d

KEYWORDS: Scientific computing - Elasticity - Elastodynamic equations

FUNCTIONAL DESCRIPTION: The Mka3d method simulates an elastic solid by discretizing the solid into rigid particles. An adequate choice of forces and torques between particles allows to recover the equations of elastodynamics.

- Partners: Ecole des Ponts ParisTech - CEA
- Contact: Laurent Monasse
- URL: <http://cermics.enpc.fr/~monassel/Mka3D/>



### 6.3. Compass

*Computing Architecture to Speed up Simulation*

KEYWORDS: Finite volume methods - Porous media - High performance computing

FUNCTIONAL DESCRIPTION: Compass is a parallel code initiated in 2012 and co-developed by LJAD-Inria Coffee and BRGM since 2015. It is devoted to the simulation of multiphase flows in porous media, it accounts for non isothermal and compositional flows and includes complex network of fractures or faults represented as interfaces of co-dimension one coupled to the surrounding matrix. The discretization is based on vertex and cell unknowns and is adapted to polyhedral meshes and heterogeneous media. The ComPASS code is co-developed since december 2016 by the partners of the ANR CHARMS project including BRGM, LJAD-Inria Coffee, Storengy, MdS and LJLL with the objective to develop a new generation simulator for geothermal systems focusing on fluids and accounting for complex fault networks and wells.

- Participants: Simon Lopez, Farid Smai, Michel Kern, Yacine Ould Rouis, Nabil Birgile, Laurence Beaudé, Konstantin Brenner and Roland Masson
- Partners: Université de Nice Sophia Antipolis (UNS) - BRGM
- Contact: Roland Masson
- URL: <http://www.anr-charms.org/page/compass-code>

### 6.4. NS2DDV-M

*2D Navier-Stokes equations with variable density*

KEYWORDS: Partial differential equation - Finite volume methods - Finite element modelling

FUNCTIONAL DESCRIPTION: The NS2DDV Matlab toolbox is an open-source program written in Matlab for simulating 2D viscous, incompressible and inhomogeneous flows. The computation kernel of the code is based on Finite Elements - Finite Volumes hybrid methods applied on the 2D Navier-Stokes equations. It works on unstructured meshes and can include mesh refinements strategies. We develop and freely distribute a new version of the Matlab code NS2DDV-M (equipped with a graphic interface and an accurate documentation) to promote new collaborations in the domain, allow some easy comparisons with concurrent codes on the same benchmark cases, and compare alternative numerical solution methods.

- Partner: Laboratoire Paul Painlevé
- Contact: Caterina Calgaro-Zotto
- URL: <https://wikis.univ-lille1.fr/painleve/ns2ddv>

### 6.5. SimBiof

KEYWORDS: Bioinformatics - Chemistry

FUNCTIONAL DESCRIPTION: We are developing numerical methods, currently by using Finite Differences approaches, for the simulation of biofilms growth. The underlying system of PDEs takes the form of multiphase flows equations with conservation constraints and vanishing phases. The numerical experiments have permitted to bring out the influence of physical parameters on the multidimensional growth dynamics.

- Contact: Thierry Goudon

### 6.6. CELIA3D

KEYWORDS: Fluid mechanics - Multi-physics simulation

FUNCTIONAL DESCRIPTION: The CELIA3D code simulates the coupling between a compressible fluid flow and a deformable structure. The fluid is handled by a Finite Volume method on a structured Cartesian grid. The solid is handled by a Discrete Element method (Mka3d scheme). The solid overlaps the fluid grid and the coupling is carried out with immersed boundaries (cut cells) in a conservative way.

- Partners: Ecole des Ponts ParisTech - CEA
- Contact: Laurent Monasse
- URL: <http://cermics.enpc.fr/~monassel/CELIA3D/>

## 7. New Results

### 7.1. A few words on the results of the year

- Face based discretization of two-phase Darcy flows in fractured porous medium with matrix fracture interface local nonlinear solver. Application to the simulation of the desaturation by suction in nuclear waster storages [20], [17].
- Convergence analysis of the gradient discretization of a two-phase Darcy flow model in fractured porous media with nonlinear transmission conditions [10].
- Numerical method for non-isothermal compositional Darcy flows combining face based and nodal based discretizations on hybrid meshes [22].
- We introduced and analyzed a novel Hybrid High-Order method for the steady incompressible Navier-Stokes equations. We showed under general assumptions the existence of a discrete solution, we proved convergence of the sequence of discrete solutions to minimal regularity exact solutions for general data and we proved optimal convergence rates for the velocity and the pressure [9].
- We proposed a nonlinear Discrete Duality Finite Volume scheme to approximate the solutions of drift diffusion equations. The scheme is built to preserve at the discrete level even on severely distorted meshes the energy / energy dissipation relation [7].
- We studied a Discrete Duality Finite Volume scheme for the unsteady incompressible Navier-Stokes problem with outflow boundary conditions [24].
- We introduced a new non-overlapping optimized Schwarz method for anisotropic diffusion problems. We studied the new method at the continuous level, proved its convergence using energy estimates, and also derived convergence factors to determine the optimal choice of parameters in the transmission conditions, and presented a discretization of the algorithm using discrete duality finite volumes [23].
- We consider a non-local traffic model involving a convolution product. Unlike other studies, the considered kernel is discontinuous on  $\mathbb{R}$ . We prove Sobolev estimates and prove the convergence of approximate solutions solving a viscous and regularized non-local equation. It leads to weak,  $C([0, T], L^2(\mathbb{R}))$  and  $C([0, T], L^2(\mathbb{R}))$ , and smooth,  $W^{2,2N}([0, T] \times \mathbb{R})$  and  $W^{2,2N}([0, T] \times \mathbb{R})$ , solutions for the non-local traffic model [4].
- We proposed a new closure for Geometrical Shock Dynamics taking into account the effect of transverse Mach variation for the fast propagation of shocks. The model has been tested using a Lagrangian solver [28].
- We proposed a new explicit pseudo-energy conserving time-integration scheme for separated Hamiltonian systems. We proved the second-order accuracy and conditional stability of the scheme. In addition, the scheme can be adapted into an asynchronous version while retaining its properties, which is adapted to slow-fast splitting strategies [14].
- We proposed a well-balanced scheme for the modified Lifschitz-Slyozov-Wagner system with diffusion, which models Ostwald ripening. The scheme outperforms a standard advection-diffusion scheme for long time dynamics [25].
- We investigate several models describing interacting particles, either motivated from physics or population dynamics.

## 8. Bilateral Contracts and Grants with Industry

### 8.1. Bilateral Contracts with Industry

- Contract with Andra financing the two year postdoctoral position of Joubine Aghili (october 2017 - september 2019) and dealing with the simulation of compositional liquid gas Darcy flows in highly heterogeneous porous medium with network of fractures using Discrete Fracture Matrix models (DFM). It is applied to the simulation of the desaturation of the nuclear waste storage in the neighbourhood of the galleries. Supervision Roland Masson and Konstantin Brenner from LJAD-Inria, Jean-Raynald de Dreuzy from Geosciences Rennes and Laurent Trenty from Andra.

## 9. Partnerships and Cooperations

### 9.1. Regional Initiatives

The team is involved in the IDEX project UCA-JEDI.

- PhD of Laurence Beaudé (october 2015 - december 2018) co-funded by BRGM and Region PACA and dealing with the simulation of geothermal systems, supervised by Roland Masson, Konstantin Brenner from LJAD-Inria and by Simon Lopez, Farid Smai from BRGM.

### 9.2. National Initiatives

#### 9.2.1. ANR

- ANR CHARMS (Quantitative Reservoir Models for Complex Hydrothermal Systems), Roland Masson and Konstantin Brenner: december 2016 - december 2020, partners BRGM (leader), LJAD-Inria, Storengy, MdS, LJLL.
- ANR JCJC PRECIS (Effect of a shock wave on a structure with contact using mesh refinement and parallelism), Laurent Monasse: april 2018 - april 2021, partners Inria (leader), Ecole des Ponts, CEA, Université Paris-Est.

#### 9.2.2. National and European networks

- GdR MANU.

The research group MANU has activities centered around scientific computing, design of new numerical schemes and mathematical modelling (upscaling, homogenization, sensitivity studies, inverse problems,...). Its goal is to coordinate research in this area, as well as to promote the emergence of focused groups around specific projects

- S. Junca is involved in GdR 3437 DYNOLIN “Dynamique non linéaire” and GdR MecaWave.
- LJAD-Inria and BRGM are the French partners of the Norwegian, German French project InSPiRE “International Open Source Simulation Software Partnership in Research and Education” which has just been accepted by the Research Council of Norway with the code COMPASS as one of the softwares of this project together with Dune, Dumux and OPM.

### 9.3. International Research Visitors

#### 9.3.1. Visits of International Scientists

- Martin Gander (Genève), UCA invited professor 18/06 – 18/07, collaboration on reduced fracture models and DDM for coupling liquid gas Darcy and free gas flows. Co-organisation with Martin Gander, Stella Krell, Victorita Dolean, Roland Masson of the summer school on DDM: 19,20,21/06 <https://math.unice.fr/~krell/ColloqueDD/index.php>
- Felix Kwok (Hong Kong): 11/06 – 25/06 on nonlinear domain decomposition for the Richards equation.

## 10. Dissemination

### 10.1. Promoting Scientific Activities

We do not keep track of such activities.

### **10.1.1. Journal**

#### *10.1.1.1. Member of the Editorial Boards*

T. Goudon is the founding editor and co-Editor in chief of SMAI Journal of Computational Mathematics.

### **10.1.2. Scientific Expertise**

Thierry Goudon is member of the scientific board of CIRM and of FSMP.

### **10.1.3. Research Administration**

- Roland Masson is the head of the team PDE and Numerical Analysis of the laboratory J.A. Dieudonné.
- Roland Masson is a member of the scientific committee of CERFACS.
- Roland Masson is scientific advisor at the scientific direction of Total.
- Thierry Goudon is member of the Evaluation Committee of Inria.
- Thierry Goudon is Scientific Officer at the French Ministry of Education and Research.

## **10.2. Teaching - Supervision - Juries**

### **10.2.1. Teaching**

Members of the team are faculties of Université Côte d'Azur and they teach in all degrees of the University.

Florent Berthelin, Master 2 Mathématiques fondamentales, Université Côte d'Azur.

Florent Berthelin, Chair of the Master 2 Mathématiques fondamentales, Université Côte d'Azur.

Florent Berthelin, Analysis, L2, Université Nice Sophia Antipolis, 60h.

Thierry Goudon is President of the national competition to hire teachers (agregation de mathématiques).

Stella Krell, Linear Algebra, Master 1 enseignement, ESPE Nice, 23h.

Stella Krell, Didactics of mathematics, Master 1 EEF, Université Nice Sophia Antipolis, 43h.

Stella Krell, Theses and placement supervision, Master 2 EEF, Université Nice Sophia Antipolis, 12h.

Stella Krell, Preparation to mathematics agrégation interne, Université Nice Sophia Antipolis, 18h.

Stella Krell, Intervention, Master 2 enseignement, Université Nice Sophia Antipolis, 3h.

Stéphane Junca, Hyperbolic PDEs and mechanics, Master 2 MPA, Université Nice Sophia Antipolis, 36h.

Roland Masson, Numerical methods for PDEs, Master 2 MPA, Université Nice Sophia Antipolis, 36h.

Laurent Monasse, Introduction to dynamical systems, Ecole des Ponts ParisTech, 10h.

Laurent Monasse, Numerical analysis, L3, Université Nice Sophia Antipolis, 40h.

### **10.2.2. Supervision**

PhD: Julie Llobell, Numerical schemes on staggered grids for conservation laws, Univ Nice Sophia Antipolis, 24 October 2018, Thierry Goudon and Sebastian Minjeaud

PhD: Laurence Beaudé, Discretization of high energy geothermal systems in faulted porous media, Univ Nice Sophia Antipolis, 10 December 2018, Roland Masson, Konstantin Brenner, Simon Lopez and Farid Smai

PhD in progress: Kevin Atsou, Mathematical modeling of tumor growth, analysis and simulation, 01 October 2017, Thierry Goudon

PhD in progress: Billel Guelmame, Conservation laws in mechanics, 01 October 2017, Stéphane Junca

PhD in progress: Giulia Lissonni, DDFV methods and domain decomposition: applications in fluid mechanics, 01 September 2016, Stella Krell and Thierry Goudon.

PhD in progress: Leo Vivion, Dynamical model of a Lorentz gas: kinetic approach, analysis and asymptotic issues, 01 September 2017, Thierry Goudon

PhD in progress: Frédéric Marazzato, Modeling of fracture and fragmentation using a Discrete Element method, 01 October 2016, Alexandre Ern, Karam Sab and Laurent Monasse.

PhD in progress: Nadine Dirani, Effect of a shock wave on a structure with contact, 01 November 2018, Thierry Goudon and Laurent Monasse.

### 10.2.3. Juries

- Roland Masson:
  - Referee of the PhD of Florent Chave, 12/11/2018, Montpellier, “Méthodes Hybrides d’Ordre Elevé pour les problèmes d’interface”.
  - Referee of the PhD of El Houssaine Quenjel, 15/12/2018, Meknes, Maroc “Volumes finis/Eléments finis pour des écoulements diphasiques compressibles en milieux poreux hétérogènes et anisotropes”.
  - Referee of the PhD of Thibaut Lunet, 09/01/2018, Toulouse, “Stratégies de parallélisation espace-temps pour la simulation numérique des écoulements turbulents”.

## 11. Bibliography

### Publications of the year

#### Articles in International Peer-Reviewed Journals

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- [2] L. BEAUDE, T. BELTZUNG, K. BRENNER, S. LOPEZ, R. MASSON, F. SMAÏ, J.-F. F. THEBAULT, F. F. XING, L. GRIGORI, C. JAPHET, P. MOIREAU. *Parallel geothermal numerical model with faults and multi-branch wells*, in "ESAIM: Proceedings and Surveys", 2018, vol. 63, pp. 109-134 [DOI : 10.1051/PROC/201863109], <https://hal.archives-ouvertes.fr/hal-01472944>
- [3] L. BEAUDE, K. BRENNER, S. LOPEZ, R. MASSON, F. SMAÏ. *Non-isothermal compositional liquid gas Darcy flow: formulation, soil-atmosphere boundary condition and application to high energy geothermal simulations*, in "Computational Geosciences", 2018, <https://hal.archives-ouvertes.fr/hal-01702391>
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