DEEP ROOTS OF GEOTHERMAL SYSTEMS A GEORG COLLABORATIVE PROJECT

Hjalti P. Ingólfsson[1], Knútur Árnason[2], Gudni Axelsson[2, 3], Hjalti Franzson[2], Sigrún Hreinsdóttir[3, 8], Magnús Th. Jónsson[3], Gudrún A. Sævarsdóttir[4], Gunnar Gunnarsson[5], Egill Júlíusson[6], Robert P. Podgorney[7], Freysteinn Sigmundsson[2]. Sigurður M. Gardarsson[1, 3]

[1] GEORG, Grenásvegur 9, 108 Reykjavik Iceland

[2] Iceland GeoSurvey, Grensásvegur 9, 108 Reykjavik, Iceland

[3] University of Iceland, Sæmundargata 2, 101 Reykjavík, Iceland

4 Reykjvik University, Menntavegi 1, 101 Reykjavík, Iceland

5 Orkuveita Reykjavikur, Bæjarháls 1, 110 Reykjavik, Iceland

6 Landsvirkjun, Háaleitisbraut 68, 103 Reykjavik, Iceland

7 Idaho National Laboratory, 2525 Fremont Avenue, Idaho Falls, ID 83402, United States

8 GNS, 1 Fairway Drive, Avalon 5010, New Zealand

hpi@georg.cluster.is

Keywords: Geothermal system, roots, intrusions, exploration, modelling, utilization, engineering, well design.

ABSTRACT

The nature of the heat source of volcanic geothermal systems and of the heat transfer within them is not accurately known. The heat transfer involves flow of magma, flow of fluids, heat exchange between rocks and fluids as well as thermo-elastic rock mechanics and chemical processes. Some decades ago a process termed convective downward migration (CDM) was proposed for the heat extraction and transfer mechanism. Recent modelling of silicic volcanic geothermal systems suggests a different heat transfer mechanism and much smaller shallow intrusions (dykes, sills, etc.) originating in deep magma chambers are also believed to play a primary role in the heat-source mechanism. In 2007-2008 IDDP-1 well was drilled in the Krafla geothermal field, NE Iceland. It was to be drilled to a depth of 4 to 5 km with the goal of encountering supercritical hydrothermal fluids. The well unexpectedly drilled into a high-silica rhyolite melt at approximately 2.1 km depth. IDDP-1 discharged superheated steam delivering power of about 30 MWe. This demonstrated that the deep roots of geothermal systems can be more complicated than anticipated and that huge amounts of energy can be harnessed by drilling close to (or into) magma. This experience has initiated scientific activities in Iceland towards an increased understanding of the deep roots of volcanic geothermal systems and how their energy can be tapped. On that basis the Deep Roots Geothermal (DRG) project was established. The project is managed within the Icelandic cluster cooperation of GEORG and is financially supported by GEORG, the government and main power companies of Iceland as well as the IDDP-Project. It is a comprehensive 3-year project with the overall aim to increase significantly the understanding of the relationship of water and magma in the roots of volcanoes and how heat is transferred into geothermal systems to maintain their energy as well as develop further the technology needed to harness geothermal energy at the high temperature and pressure involved.

1. INTRODUCTION

The nature of volcanic heat sources and the heat transfer to hydrothermal systems has for long been a matter of speculation. The heat transfer is likely to be a complicated process involving flow of magma, flow of fluids, heat exchange between rocks and fluids as well as thermo-elastic rock mechanics and chemical processes. In the 70’s a process termed convective downward migration (CDM) was proposed, during which a cooling front at the brittle/ductile transition migrates into the hot rock through fractures that open up due to thermo-elastic contraction of the rock (Lister, 1974; Bödvarsson, 1982). Recent modelling of silicic volcanic geothermal systems (Weis et al., 2012) suggests a different heat transfer mechanism. The simulation indicates that fluids (volatiles) from the crystallizing magma migrate upwards and produce a “plume” of very hot and ductile rocks above the intrusion. Fluids at lithostatic pressure move up the plume as fluid pulses. The heat transfer to the hydrostatic geothermal system above takes place at the brittle/ductile boundary of the plume, both by conduction (as in the CDM model) and intermittent injection of supercritical fluids into the geothermal system.

In 2007-2008 the Iceland Deep Drilling Project Well 1 (IDDP-1) was drilled in the Krafla geothermal field, NE Iceland. The well was to be drilled to a depth of 4 to 5 km with the goal of encountering supercritical hydrothermal fluids. The well unexpectedly drilled into a high-silica rhyolite melt at approximately 2.1 km depth. IDDP-1 discharged superheated steam (wellhead temperature about 450°C) delivering power of about 30 MWe. This demonstrated that the deep roots of geothermal systems can be more complicated than anticipated and that huge amounts of energy can be harnessed by drilling close to (or into) magma.

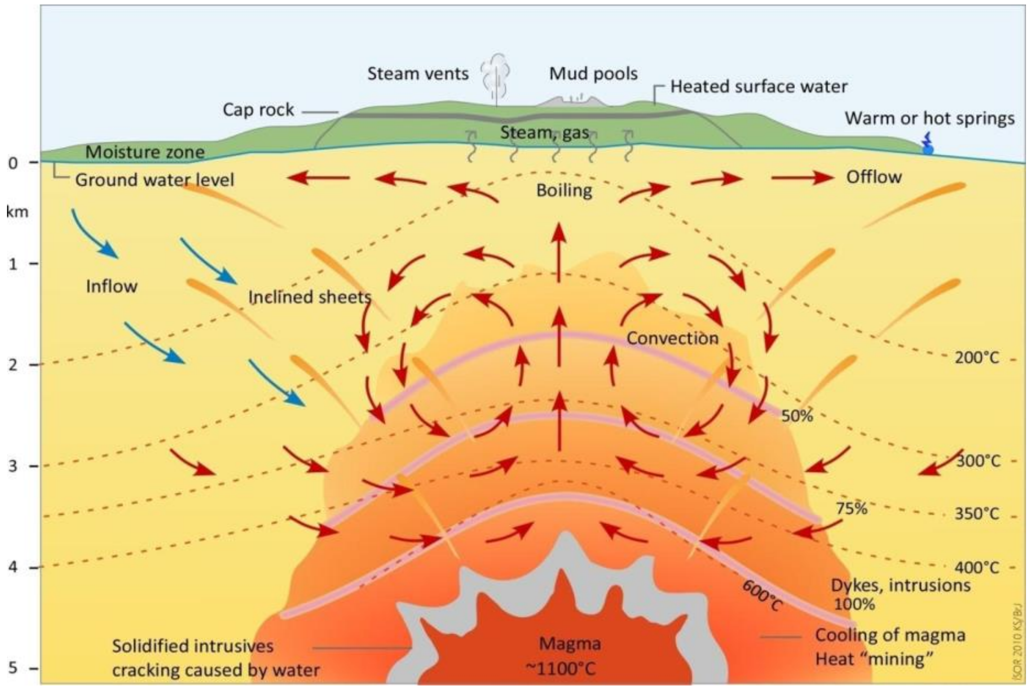

Figure 1: A sketch of the likely inner structure of an active volcanic geothermal system.

The emphasis on geothermal power production and the experience from IDDP-1 has initiated scientific activities in Iceland towards an increased understanding of the deep roots of volcanic geothermal systems and how their energy can be tapped. On that basis the Deep Roots Geothermal (DRG) project was established. The project is managed within the Icelandic cluster cooperation of GEORG and is financially supported by GEORG, Orkustofnun, Reykjavik Energy, HS Orka, Landsvirkjun and the Iceland Deep Drilling Project (IDDP). It is a comprehensive 3-year project containing the following components:

- Study of geology and structure of exposed extinct volcanic geothermal systems.
- Geophysical study of active systems by comprehensive analysis of micro-seismicity.
- Monitoring of crustal deformation and gas emission.
- Advancement of modelling physical processes in the roots of volcanic geothermal systems and advancing methods of reservoir modelling for geothermal resource management.
- Material selection and design of the components (well-heads, casings, etc.) of deep geothermal wells that can withstand the high temperatures, pressures and flow-rates.
- Design of a power process for energy utilization and material recovery of high enthalpy geothermal steam.

The aim of the project is to understand the relationship of water and magma in the roots of volcanoes and how heat is transferred into geothermal systems to maintain their energy. The state of the art technology is applied in surveying, resistivity measurements, seismic measurements, petrology and geochemistry. In addition, new simulation models will be developed. These models will be used to simulate heat transfer and operation of geothermal boreholes for high temperature steam. Furthermore, the design of wells and well heads for high temperatures is a focus of the project, as well as methods for utilizing superheated steam from greater depths.

The research work is divided in three separate, but interconnected, parts; Exploration, Modelling and Utilization, which will be described in more detail below, in separate chapters. The DRG-project has now been ongoing for two years and has resulted in interesting results already as well as highly important research tools.

The project consortium consists of a team of highly competent individuals from universities, research institutes, energy companies and engineering companies, building a strong bond between the academia and industry. The DRG project has, furthermore, synergy with, and is linked to, other international projects such as the Swiss COTHERM project, IPGT-partnership work, the ICDP Krafla Magma Drilling Project (KMDP), and EU projects; IMAGE, DEEPEGS, FUTUREVOLC and DESRUMBLE to name some.

2. PART 1 – IDENTIFICATION AND EXPLORATION

Part 1 of the DRG project is on identification and exploration of the deep roots of geothermal systems, with the aim to improve understanding of the nature of the boundary layer between magmatic intrusions and geothermal reservoirs. Part 1 is divided into three subprojects: i) What can be learned from sites where fossil roots of the geothermal system have been exposed, ii) how can the boundary layer be imaged with seismic techniques, and iii) how can crustal deformation studies complement traditional exploration methods.

The fossil roots of a geothermal system have been studied at the southern part of Hafnarfjall central volcano in West Iceland (Franzson, 1978). There one can observe relatively deeply eroded gabbro intrusion (700-1200 m) and its derivative geothermal system. The purpose is to evaluate the mechanism of heat transfer from a magma source to an overlying geothermal system. The macro geological mapping of the area has revealed a pulsating magma body with resulting up-doming, fracturing and injection of cone sheets. A tight hornfels zone forms at the southwestern and upper boundary of the intrusion suggesting a low-permeability layer separating the molten magma and the surrounding groundwater system. On the north-eastern side, however, where the gabbro contacts the highly permeable caldera pyroclastic filling, the apparent absence of hornfels implies the ready access of the groundwater system towards the magma body forming an effective heat mining process. The high-temperature system formed above the intrusion shows evidence CO_2 and sulphuric magmatic gases from the gabbro evidenced by abundance of pyrite and calcite.

The next step in the project is a more detailed mapping of the geothermal system such as aquiring fluid inclusion data on the temperature distribution and fluid composition, hydrothermal alteration mineralogy to establish the evolution of the system and an evaluation of the hornfels zone in terms of mineralogy and role in the relationship between the magma and surrounding geothermal system. The character of the hornfels will be compared with similar rocks in wells in Hellisheiði geothermal field. Future isotopic study on fluid inclusions is anticipated to evaluate in more detail the interaction of the consolidating magma and the surrounding groundwater system. Another subproject of DRG Part 1 uses seismic methods to study the roots of an active geothermal area, with the Krafla volcano and its geothermal system selected as a case study. The purpose is to study and map velocities of both S- and P-waves in and around the geothermal system in the Krafla volcano. ISOR operates an eleven station permanent seismic network in the Krafla area for Landsvirkjun. In the summer of 2014 a denser network along two profiles was operated temporarily for better location of events and to look for seismic reflections and phase conversions of seismic waves from local earthquakes. Furthermore, recorded distant earthquakes and explosions, performed within in the project, have seismic waves arriving nearly vertically (under-shooting) up through the volcano. This will give information about the seismic velocity structure in the volcano and reveal presence of magma. Recent seismic tomography studies of the Krafla volcano (Shuler et al., 2015) indicate an anomaly of low P-wave at 2-2.5 km depth in the area under the seismic profiles. This anomaly will be studied further by looking for reflections form seismic events above the anomaly. The network was operated for three months with about 90% data recovery. All the data and necessary calibration constants have been loaded into the SeisComp database and analysing software. The data are now being analyzed at Cornell University, USA. The study lines closely up with the COTHERM, which focuses on numerical modelling of volcanic geothermal systems from the magmatic heat source(s) and to the surface, and confronting estimated physical signatures (e.g. seismic wave velocities) to in situ measurements.

The third subproject of DRG Part 1 utilizes the Krísuvík geothermal area for a study of crustal deformation in geothermal areas. The project has mapped in detail repeated inflation and deflation periods at the Krísuvík geothermal area using both GPS geodesy and interferometric analysis of synthetic aperture radar images (InSAR). In early 2009 the area began inflating accompanied by high seismic activity. From late 2009 to May 2010 the region deflated again to its pre inflation level. From May 2010 until the end of 2011 the region inflated again, this time at a more rapid rate with uplift of over 7 cm measured. Deflation followed until latter half of 2015, when the area appears to have reached equilibrium. The geodetic data suggest inflation of a 4-5 km deep source beneath Sveifluháls, triggering intense seismic activity in the overlying crust due to the interaction between the plate boundary that crosses the region and the inflation source. The 2012-2015 deflation source was estimated at 3 km depth beneath Móhálsadalur. The location of the deflation source seems to coincide with a resistivity anomaly revealed by MT measurements. In order to better understand the activity repeated gravity observations were carried out, as well as studies of gas emissions. High variations in H_2O/CO_2 and H_2O/H_2S ratios have been observed. Interpretation and modelling of the data sets is in progress.

3. DRG PART 2 - NUMERICAL MODELLING OF VOLCANIC GEOTHERMAL SYSTEMS

The aim of Part 2 of the DRG project is to aid in the advancement of the methods that can be applied in the modelling of the physical processes occurring in the roots of volcanic geothermal systems, with the purpose of illuminating the overall process controlling the upwards heat transfer from the heat sources as well as improve and advance the methods that are applied in conventional geothermal reservoir modelling for geothermal resource management. The heat transfer from the roots up to shallower levels is a complicated process involving flow of magma, flow of fluids (two-phase and/or supercritical water), heat transfer as well as thermo-elastic rock mechanics and chemical processes. In conventional models of geothermal reservoir, used for assessing capacity and for management purposes during utilization, heat-sources are idealized as steady inflow of mass and energy, at relatively shallow depth, at the bottom of the models. There is, however, need to incorporate the heat sources more accurately in the models, both as specific intrusions in contact with the fluid circulation in the geothermal systems below the production reservoirs and their highly transient nature. Part 2 of the DRG project is extensively based on general conceptual models emerging from Part 1 of the DRG project.

Part 2 of DRG was split up in two parts with Part 2.1 assigned to two geothermal reservoir modelling specialists at Iceland GeoSurvey (ÍSOR) and Vatnaskil Consulting Engineers, respectively, and Part 2.2 assigned to a postdoctoral scholar based in the USA. Part 2.1 is devoted to training and application of the Hydrotherm and CSMP++ reservoir modelling software, both applicable to volcanic geothermal systems, in cooperation with the COTHERM project, guided by Dr. Thomas Driesner at ETH in Zurich, Switzerland. The first half of the 3 years intended for Part 2.1 was devoted to testing the applicability of the two software-packages to real volcano-geothermal situation, mainly through testing the software on idealized models of intrusive activity in deep permeable formations. At present this part of the project is devoted to modelling of actual conditions, e.g. in the Krafla geothermal system in NE-Iceland, in particular near the IDDP-1 well. Part 2.2 is devoted to the upgrading of industry standard reservoir modelling software intended for detailed well-by-well analysis, (which Hydrotherm and CSMP++ are not) for the modelling of the extreme physical conditions deep in volcano-geothermal systems. After initial screening of available software, the TOUGH2/iTOUGH2 package was chosen for further development. A large, and highly significant part of Part 2.2, included the development of a new supercritical equation-of-state module EOS1sc for TOUGH2/iTOUGH2. The plan is to also add an option to use temperature dependent rock properties, which allows the user to model various conditions present in magmatic geothermal reservoirs, e.g. the brittle-ductile transition. The bulk of the work planned under Part 2.2 has been completed, apart from the application of the upgraded software to real volcano-geothermal systems. Here the focus will be on the Hengill system in SW-Iceland, while the software will also be applied to the Krafla system under Part 2.1.

Several papers have been published as part of Part 2 of the DRG-project, including papers in international science-journals and in conference proceedings (Magnúsdóttir and Finsterle, 2015a and 2015b; Gunnarsson and Aradóttir, 2015). This specific project part has also enhanced synergy between different research-groups and helped avoid duplication of effort, aided in the sharing of open-source software, as well as in testing/validating of software under development.

4. DRG PART 3 - UTILIZATION OF SUPERHEATED GEOTHERMAL FLUID – ENERGY CONVERSION, CHEMISTRY AND MATERIAL CHALLENGES

An essential part of utilizing geothermal fluid from the deep roots of the geothermal system is to transfer the fluid towards the surface, utilize the energy to produce electricity, and reinject the fluid back into the earth. The main goal of this research is to develop a method to utilize efficiently the high enthalpy geothermal fluid obtained by drilling into deep geothermal systems. For efficient utilization design and reliable operations of the power plant and associated equipment, the extreme characteristics of the high enthalpy fluid have to be considered. For example, special considerations have to be made when selecting materials and designing the system which transports the fluid to the surface equipment.

The challenges within this project are extensive but for a scope which can be managed within the frame of the DRG project it has been divided into two parts. The objective of part 3.1 is to design a power process appropriate for energy utilization of high enthalpy geothermal steam taking into account thermal, chemical and material considerations. For that purpose, corrosion studies in simulated deep geothermal environment are included in part 3.1. For part 3.2 the main objectives are analyzing the mechanics of materials for deep root equipment, corrosion, erosion, thermal and mechanical stresses, failure analysis and improvements in design.

Part 3.1 is focused on the thermal process design for the utilization of heat and material resources from very high enthalpy steam. This involves thermodynamic process optimization as well as determining criteria for material selection with regard to the state of the geothermal fluid at different process stages. For this purpose, thermodynamic and geochemical fluid properties for the expected range of temperatures and pressures for the geothermal fluid were included in the analysis based on research in part 1 of DRG project as well as published data from previous research. This involves testing, data collection, and getting a good overview of the lessons learned from the IDDP-1 well as well as other projects in Iceland and throughout the world where superheated steam with unusually high enthalpy has been encountered and/or utilized. This includes a literature review for the available theoretical and empirical relations that can describe the thermodynamic properties of steam at high enthalpy and high pressure which can predict equilibrium geothermal fluid composition as function of the fluid thermodynamic conditions and chemical composition. In order to choose the optimal energy process for the power production the extreme condition of the deep geothermal fluid has to be considered. Due to chloride content in the superheated steam which will cause severe corrosion at saturation, chloride mitigation techniques need to be involved in the design of the power plant equipment. The process under consideration involves wet scrubbing combined with heat recapturing to preserve superheat. However, silica deposition will occur in the heat exchanger and it is necessary to minimize the deposition rate. Computation models verified with results from experiments will be used to predict the deposition rate for different particle properties and flow characteristics and eventually propose design. Regarding criteria for material selection, the material performance of potential materials from the IDDP-1 testing was further evaluated by conducting corrosion experiments in laboratory simulating harsh geothermal environment such as could be encountered in deep geothermal wells. The results from the testing showed that even the very high alloyed C-276 nickel alloy had considerable high CR rate after testing for 1 and 3 weeks in the simulated acidic geothermal environment as well as cracking of 625 nickel alloy after only 3 weeks of testing.

In part 3.2, the casings of the IDDP1 have been analyzed using thermal and structural nonlinear finite-element models (FEM). The load history of the casings is followed from installation and through several thermal cycles, but the well was discharged at least six times before it was quenched with cold water. The results show that changes in stiffness due to the presence of casing shoes and changes in casing thickness both have an effect on the stress and strain formations in neighboring casings. The results illustrate that during each thermal cycle, the wellbore thermal load is more severe for the production casing than for the external casings that are somewhat protected, provided that cementing in between is adequate. The nonlinear finite element method is used to construct three models of the cased well and provide a tool which can be used to assess casing failure risks by modeling various possible load scenarios that could lead to casing problems. Such modeling also provides evaluation prospects of different materials that could be used in future wells. The main conclusion of the analysis was that high stress was seen in the production casing where thickness changes of the anchor casing were located. The analysis showed that the stress in the production casing could be reduced by using a uniform thickness in the anchor casing (Kaldal et al., 2015).

A number of papers has been published in association with part 3 of the DRG project, both in international journals and conference proceedings. The project has been a platform for interdisciplinary collaboration, knowledge sharing, and understanding of the deep roots of geothermal systems.

5. CONCLUSIONS

The overall aim of this DRG project is to map realistically the road towards the understanding and ultimately the mining of the deep roots of the geothermal system using geological, geophysical, reservoir and well engineering methods. This research project is in progress, and results are gradually emerging.

The mapping of an eroded gabbro and the derivative geothermal system shows a very varied relation from a conductive transfer of heat to a direct heat mining between magma and fluid. This relation is largely dependent on the permeability of the surrounding groundwater system, where the magma-fluid interaction is proportional to permeability.

The seismic data collected under the DRG project at Krafla are of good quality and are now being analysed, looking for reflections and lateral velocity variations reviled by the undershooting. The modelling part of the DRG project has involved the application of available software to various hypothetical models, relevant for increased understanding of geothermal activity around intrusions. The new equation-of-state (EOS) for TOUGH2/iTOUGH2, developed under this part of DRG, is extremely valuable. It extends the applicability of the software, which is widely used within the geothermal industry, to much higher pressure and temperature, and consequently greater depth, than has been possible. The geothermal industry will greatly benefit from both increased understanding and improved modelling tools. Further work within the modelling part of DRG will mainly focus on further application of software to real volcano-geothermal systems. The possibility of incorporating temperature dependent rock properties in TOUGH2/ iTOUGH2 will also be addressed as well as attempts made to answer more of the research questions asked initially.

The DRG project will continue for another year (http://georg.hi.is/) and is expected to yield significant, further results. Deep roots research will also continue beyond that, most notably through the cooperative DEEPEGS project, funded by the European Union's HORIZON 2020 programme (http://deepegs.eu/).

REFERENCES

Franzson, H.: Structure and petrochemistry of the Hafnarfjall-Skarðsheiði central volcano and the surrounding basalt succession, W-Iceland. PhD thesis University of Edinburgh, (1978). 264p

Bödvarsson, G.: Terrestrial energy currents and transfer in Iceland. In G. Pálmason (editor): *Continental and Oceanic Rifts, Geodynamic Series*, **8**, Am. Geophys. Union, (1982), 271-282.

Gunnarsson, G. and Aradóttir, E.S.P.: The Deep roots of geothermal systems in volcanic areas: Boundary conditions and heat sources in reservoir modelling. *Transport in Porous Media*, (2015), 108:43–59.

Kaldal, G.S., Jónsson, M.Th., Pálsson, H., and Karlsdóttir, S.N.: Structural analysis of casings in high temperature geothermal wells in Iceland, *PROCEEDINGS*, *World Geothermal Congress 2015*, Melbourne, Australia, (2015), 11 pp.

Lister, C.R.B.: On the penetration of water into hot rock. *Geophys. J. R. Astr. Soc*., **39**, (1974), 465-509.

Magnúsdóttir, L., and Finsterle, S.: An iTOUGH2 equation-of-state module for modeling supercritical conditions in geothermal reservoirs, *Geothermics*, **57**, (2015a), 8–17.

Magnusdóttir, L., and Finsterle, S.: Extending the Applicability of the iTOUGH2 Simulator to Supercritical Conditions, *PROCEEDINGS, World Geothermal Congress 2015*, Melbourne, Australia, (2015b), 8 pp.

Gudrun Saevarsdottir, Steindor Hjartarson, Kristinn Ingason, Bjarni Palsson, William Harvey: “Utilization of Chloride Bearing High Enthalpy Geothermal Fluid”, In proceedings for World Geothermal Congress, Melbourne, April 2015

Schuler, J., T. Greenfield, R. S. White, S. W. Roecker, B. Brandsdóttir, J. M. Stock, J. Tarasewicz, H. R., Martens, and D. Pugh: Seismic imaging of the shallow crust beneath the Krafla central volcano, NE Iceland, J. Geophys. Res. Solid Earth, 120, (2015), 7156–7173.

Weis, P., Driesner, T. and Heinrich, C. A.: Porphyry-Copper Ore Shells Form at Stabile Pressure-Temperature Fronts Within Dynamic Fluid Plumes, SCIENCE, Vol. 338 (2012), 1613-1616.

Acknowledgements

This cooperative project is managed within the cluster cooperation of GEORG and is financially supported by GEORG, Orkustofnun, Reykjavik Energy, HS Orka, Landsvirkjun and the Iceland Deep Drilling Project (IDDP). The authors also acknowledge other scientists and engineers, too many to list here, who have contributed to the project.