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Presentation of the Dana Medal of the Mineralogical Society of America for 2016 to Patrick Cordier

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It is with great pleasure and with enthusiasm, I propose Patrick Cordier for MSA Dana medal. The former President and Vice-President of the Société Française de Minéralogie et de Cristallographie and co-author of the book for the general public on mineralogy *Ce que disent les minéraux* ("What do the minerals say"), he is one of the few people that capture the essence of modern mineralogical research allied to concepts coming from materials science and physics. A physicist by training and now professor of physics at the University of Lille, he embarked on the route to become one of the world's leading mineralogists by studying the plastic deformation of quartz and his Ph.D. in 1989.

What could be simpler than to understand the plasticity of mineral with the composition of SiO_2? Indeed, in reality it was a very difficult task, a subject rich in experimental folk law and dubious observations, the young researcher developed a methodology based on rigorous experimental protocol, quantitative state-of-the-art transmission electron microscopy (TEM) characterization of defect densities and their crystallography, and pertinent theoretical analysis of the results. This first adventure into the field of mineralogical research produced several well-documented publications using mechanical experiments, heat treatment, infrared spectroscopy, electron spin resonance (ESR), and, of course, TEM. The major results from this early period were the first and, I believe even today, the only determination of the equilibrium concentration of the hydro-garnet defect in quartz and the development of new vision of the importance of hydro-garnet defect (4H in Si site) (identified by ESR) in the hydrolytic weakening of quartz facilitating the easy glide of dislocations. In the following years, Patrick expanded his activities to include the characterization of shocked minerals from meteorite impacts and interstellar material. The collaborative work on Comet 81P/Wild 2, published in two *Science* papers in 2006, remains one of his most cited publications. Patrick's growing reputation attracted young researchers to join his group and indeed even offers of research in other areas, such as optical fibers, work that is also highly cited. He finally decided to leave the work on optic fibers to others and to divided his research group into parts; first the deformation of minerals at mantle and core conditions led by himself and second the behavior of minerals in impact and interstellar conditions led by Hugues Leroux, the unifying research instrument of the group being the TEM. The development of TEM methods for the characterization has been an important continuing theme in his research. During his thesis, he used the then new weak beam dark field method to characterize the width of dislocations and detect their dissociation. The development the large angle convergent beam electron diffraction (LACBED) method for dislocation characterization has been important for low symmetry minerals. This method provides superposed images from the direct image and diffraction pattern, which combine to produce a very efficient method of characterizing dislocations in radiation sensitive minerals such as quartz and other minerals recovered from high-pressure experiments. More recently Patrick has been active in the promotion of the precession electron diffraction (PED) for the characterization of twins in quartz and coesite. The PED allows small differences in diffraction pattern intensity to be measured permitting the correct interpretation of small differences in structure factor.

Patrick recognized very early that the deformation machines that an individual research group could operate would be inadequate to explore the plastic deformation of minerals over the vast range of pressure and temperature of the Earth's interior. As a young professor, he developed a long and sustained collaboration with the Bayerisches Geoinstitut, which had been labeled as European high-pressure research center. A series of collaborations with this institute allowed the development of multi-anvil deformation assembly (Cordier and Rubie 2001) that would be the cornerstone for subsequent experiments on mantle minerals at in-situ conditions.

The work that followed explored the deformation of key mantle minerals (garnet, majorite, olivine, diopside, wadselyite, $MgSiO_3$ perovskite, coesite, K-lingunite) almost all characterized by detailed TEM analysis of the dislocation slip systems. Many of these studies being a first, for example $MgSiO_3$ perovskite, in this case perovskite recovered from the multi-anvil press was too radiation sensitive for TEM and Patrick collaborated with experts in X-ray diffraction characterization of dislocations to reach his scientific objective. Patrick recognized the limitations of the "micro-structure only" approach he had developed with the multi-anvil press, he encouraged the development of the D-DIA with group member Paul Raterron and several of their joint publications on the effect of pressure on deformation of olivine and diopside have had important impact the new understanding of role of pressure on the plasticity of the upper mantle.

From the very beginning Patrick was a specialist in the imaging and characterizing dislocations by TEM. Dislocations are essential to our understanding of mineral properties such as mechanisms of plastic deformation, crystal preferred orientation (CPO), dislocation (pipe) diffusion, and crystal growth. Although there is wealth of information on the dislocation structures in pure metals, the same is not true of minerals because of the more complex chemistry, lower crystal symmetry, and the covalent nature of the bonding that depends on both bond length and angle resulting more diverse topological possibilities. It is into this new field of the nature of the dislocation core structure and implications for dislocation glide and plasticity that Patrick has pushed his recent research effort. During glide-controlled plastic-

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ity, the dislocation mobility is facilitated by changes in the core structure imposed by the periodic crystal lattice to overcome the Peierls energy barrier. Initial steps in this field used the generalized stacking fault model; this approach using ab initio quantum mechanics to determine energies, which provided a new way of looking at dislocation cores and their energy as a function of line direction in the glide plane. Patrick created an improved model using the Peierls-Nabarro (PN) model to estimate the Peierls stresses for dislocation slip at any given pressure. The PN approach allows the prediction of the dislocation core structure that can spread in the glide plane, and hence can be validated in the rare cases where there is high-resolution transmission electron microscopy (HRTEM) image of the dislocation core. Such a case was recently found for [001](110) dislocation in $SrTiO_3$ cubic perovskite, where it was shown that the essential elements of the core structure were reproduced by the PN model. The initial project on forsterite showed that core structure of the **a**[100] and **c**[001] Burgers vector dislocations behaved differently with increasing pressure, mechanical resistance to slip for **a**[100] Burgers increases with pressure, where as the **c**[001] resistance does not increase significantly. The theoretical results accord well with experimental observations using the D-DIA, which observed easy **a**-slip at low pressure that becomes more resistant at high pressures and finally becomes more resistant than **c**-slip at the highest pressures. The power of atomic modeling was wonderfully illustrated in Carrez et al. (2007), where the slip systems of the unquenchable Post-Perovskite $MgSiO_3$ phase were predicted at lower mantle pressures. An improved Nabarro-Herring-Gerkin dislocation model using finite-element approach allows the study of core structures that spread out of the glide plane in a 3D pattern, as occurs in wadsleyite, where ½<111>{101} and [100](010) are the easy slip systems at high pressure with dissociated dislocations as observed by TEM. An exciting new development is the possibility to explicitly take into account temperature by introducing a quantitative model for the kink-pair nucleation on the dislocation lines. Initial attempts using well-known thermal data for MgO shows remarkable agreements between experiment and theory. The search for a multi-scale understanding of dislocation did not stop at single dislocations, the interaction between gliding dislocation so critical to predict stress-strain behavior has been modeled in new ground breaking research, still in its infancy, but holds much promise to the extrapolation to larger scales. The incredible development of atomic modeling of dislocation cores by Patrick Cordier and his research group in the last six years has put our understanding of plasticity of minerals on firmer physical basis, with the prospective of a more scientific extrapolation of fundamental variables, such as flow stress and strain rate to the times scales, pressures, and temperatures of the deep Earth.

It is important to mention the continuing attention that Patrick has paid to the application of his observations, experimental results, or theoretical calculations concerning dislocations in minerals to problems concerning a wide audience in Earth sciences. Although much of his work is of a very fundamental nature, he has tried to put his results in the context of a multi-scale methodology. For example much the work on the characterization of slip systems at the single-crystal level, either via TEM or atomic modeling has been using in visco-plastic self-consistent (VPSC) polycrystalline modeling of CPO development and calculated seismic anisotropic properties that can be discussed in the light of geophysical observations. An example of this approach is where the presence of the **c**-direction slip in olivine at the pressures corresponding 250 to 400 km depth provides an alternative explanation to the reduction of anisotropy in the region due to crystal plasticity, previously postulated to be caused by diffusion creep. The resulting paper is Patrick's most cited geodynamics contribution. He has also explored other aspects of multi-scale methodology, such as two-phase behavior in D″ layer. The complete chain of scales has recently been explored from dislocation core to geodynamics.

Olivine does not have enough dislocation slip system to accommodate the general strain needed for strain compatibility across grain boundaries. This classical problem, defined by Von Mises yield criterion, has been known for a long time. Patrick and colleagues study a defect called disclination and showed that these defects could be detected by EBSD in experimentally deformed olivine and made atomic scale modeling to show disclinations could provided rotational deformation for strain compatibility, providing the missing link to the olivine plasticity paradox.

Finally these recent developments using the hierarchical multi-scale method have been recognized by the award of a five-year European Research Council (ERC) Advance grant, Europe's highest academic funding award, to extend this method to minerals of more complex structure, such as perovskite (see http://umet.univ-lille1.fr/Projets/RheoMan/).

In summary, the contribution of Patrick Cordier to our understanding of the physics of dislocations in minerals has been highlighted by the following publications.

(1) Development and application of state-of-the-art TEM methods [weak beam, large angle convergent beam electron diffraction (LACBED) and precession electron diffraction (PED)]. His expertise with these methods has allowed him to characterize twins and dislocations in naturally and experimentally deformed minerals at an unsurpassed level.
(2) Developed the multi-anvil press into a deformation machine.
(3) Based on a wealth of observations he has contributed to our knowledge of the slip systems of all major mantle minerals deformed at in situ mantle conditions.
(4) Identified the dislocation core as the fundamental element controlling the glide process and put in motion a coherent research program based on atomic modelling to determine the critical stress for dislocation motion.
(5) Devised a multi-scale approach based on the atomic to the geodynamic scale.
(6) Developed the concept and proved the validity of the hierarchical multi-scale method with MgO to produce a new rheological paradigm for the deep Earth, capable of predicting the temperature, pressure, and strain rate dependence.
(7) Detected the missing deformation defect in olivine called a "disclinations" that allows olivine deform with strain compatability at grain boundaries despite olivine having

only four dislocation slip systems.

(8) Recent results presented at AGU Fall Meeting 2015 provide a new development stimulated by his ERC award is possibility of creep regime in the lower mantle controlled by pure dislocation climb, a mechanism that will provide new rheology.

I think it is very fitting for the Dana medal to be awarded to Patrick Cordier for his unique research contributions to observation, theory, and application of dislocations in minerals to the hierarchical multi-scale understanding of the plastic deformation and a new rheology for the deep Earth. I am sure that James D. Dana would have approved of the new applications of mineralogy by Patrick Cordier to what he would have called "mountain building."

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