[3]DPRI, Kyoto Univ., Gokasho, Uji 611-0011, Japan

[4]AIST, Central7, 1-1-1, Higashi, Tsukuba 305-8567, Japan

[5]Niigata Univ., 8050, Ninomachi, Igarashi, Niigata 950-2181

[6]Tokyo Univ., 7-3-1, Hongo, Bunkyo 113-0032, Japan

[7]JAMSTEC, 2-15, Natsushima-cho, Yokosuka 237-0061, Japan

The Hyogo-ken Nanbu earthquake (1995.1, MJMA=7.2) activated the Nojima fault in the northern part of Awaji Island, southwest Japan and a surface rupture appeared more than 10km long. After the earthquake, the Hirabayashi NIED borehole was drilled penetrating through the fault zone to a depth of 1838m from a point about 302m SE from the surface trace of the Nojima fault. In the borehole, physical well logging was done from 251m depth down to the bottom. At the same time, cores were collected from 1000m depth with an almost 100% recovery rate and remarkable fractured zones containing cataclastic rocks were confirmed at three depths, around 1140m, 1300m and 1800m. Gamma ray logging survey indicates that the intensity of natural gamma ray changes abruptly within the interval of intrusive rocks. Matching values of depths at the boundaries between intrusive rocks and host rocks, the calibration equation was obtained between "core depth" and "logging depth"; "core depth" is measured by adding up lengths of drilling pipes and "logging depth" is measured by the total length of the cable taken down a logging tool. Results of well logging show that, in the depth interval of host rocks , normal resistivity is from several hundreds to several thousands ohm m, micro resistivity is several tens ohm m, P wave velocity is 5 - 6km/sec, density is about 2.6g/cm3 and neutron porosity is several %. On the other hand, in the depth interval of the fracture zone, those properties decrease down to several tens ohm m, several ohm m, 2 - 4km/sec, 1.5 - 2.0g/cm3 and increase up to several tens %, respectively. Investigating correlations between physical properties measured by well logging in the Hirabayashi NIED borehole, three fracture zones are characterized. In fracture zones, neutron porosity is beyond 10%, P wave velocity is less than 5 km/sec. The decreasing rate of density is higher and the logarithm of normal resistivity increases more gently with the increase of neutron porosity than in the depth interval of host rocks. The correlation between neutron porosity and P wave velocity is not clear and normal resistivity does not obey the Archie's relation in the fracture zones. The fracture zone at a depth of 1800m indicates some different characters from other two fracture zones; P wave velocity, density and neutron porosity appear to change gently contrasting to a remarkable decrease of normal resistivity.

T22C MCC: 3005 Tuesday 1340h

Role of Large Strike-Slip Faults in Tectonics of the Tibetan Plateau II

(joint with G)

Presiding: **B Ritts,** Utah State University**; S A Graham,** Stanford University

T22C-01 1340h INVITED

400My of Deformation Along Tibet Active Strike Slip Faults

Nick O Arnaud (33-0-467143729; Nicolas.Arnaud@dstu.univ-montp2.fr)

CNRS Lab. Dyn. Lithosphere, ISTEEM-UMII, Bat.22, Univ. Montpellier II Place Eu. Bataillon, Montpellier 34095, France, Metropolitan

While it is widely accepted that strike slip faults in Tibet accommodate a significant part of the tertiary convergence between India and Asia, the true Cenozoic magnitude of the offset is still largely debated. Direct dating of Cenozoic piercing points is the most powerful tool to assess the total offset, but their use is not always possible. Therefore one gets to use older markers although this leads to significant results ONLY at the supreme condition that pre-Cenozoic movement of those markers be accurately known. The Kunlun and Altyn Tagh faults for example form a prominent example of Tibetan presently active fault, but they also constitute geological frontiers between blocks of different geological histories accreted at various times since early Paleozoic. One may thus question how much of the visible offset is indeed Cenozoic. Although deformation facies agree with recent kinematics, multi-geochronological approach indicates a series of events from 280-230 Ma to 120±10 Ma. The former may be linked either with suturing of the Qiantang and Kunlun blocks farther to the south, or collision further to the north or east in the Qilian Shan and Bei Shan ranges, while the latter range appears to be growing in importance with ongoing work but is still largely unexplained. Oblique subductions of collision to the north of the Qilian Shan are adequate candidates. Argon loss suggests that deformation was associated to a 250-300°C thermal pulse that lasted 5 to 20 Ma after the onset of movement (Arnaud et al., 2003). Unroofing on all faults occurred much later, around 25 Ma ago when sudden cooling suggests a component of normal faulting (Mock et al., 1999). Strong inheritage was also found along the Ghoza active fault, in central western Tibet. Of course the fact that some of the deformation is much older than the Cretaceous and shares compatible deformation criteria with the present-day deformation leads to false appreciation of the pure Cenozoic offset, potentially concluding to an over or underestimation of the true Tertiary deformation. However these earlier deformation zones can also be used as transcrustal markers to evaluate Cenozoic offset, suggesting for example for the Altyn Tagh fault a minimum offset of 400 km, in agreement with other estimations of post-Jurassic offset (Meyer et al., 1998, Sobel et al., 2001, Ritts et al., 2000). The key to a clear assessment of tertiary movements along the strike slip faults and their true importance in building of the Plateau is thus the very detailed dating of recent, usually cold and/or badly equilibrated, deformation facies. This is complicated by the very nature of the deformed rocks, usually far from the geochronologist standards ! High resolution in situ dating from high to low temperatures with very careful study of the deformation is thus a prerequisite, as well as a complete study of the regional geological history. This is the case for ongoing studies along the Karakorum fault where a continuous deformation from 20 Ma to the present can be characterized with details through time. Arnaud, N., Tapponnier, P., Roger, F., Brunel, M., Schärer, U., Wen, C., and Xu, Z., 2003, J Geophys Res-Solid Earth, v. 108. Meyer, B., Tapponnier, P., Bourjot, L., Métivier, F., Gaudemer, Y., Peltzer, G., Guo Shunmin, and Zhitai, C., 1998, Geophys. J. Int., v. 135, p. 1-47. Mock, C., Arnaud, N.O., and Cantagrel, J., Marie, 1999, Earth and Planetary Science Letters, v. 171, p. pp.107-122. Ritts, B.D., and Biffi, U., 2000, Geological Society of America Bulletin, v. 112, p. pp.61-74. Sobel, E.R., Arnaud, N., Jolivet, M., Ritts, B.D., and Brunel, M., 2001, GSA special publication v. 194, p. 247-267.

T22C-02 1355h INVITED

A reality check on the timing of initiation, geological offsets, slip rates and geodetic rates on the Karakoram strike-slip fault.

Michael P. Searle[1] (44 1865 272000; mikes@earth.ox.ac.uk)

Richard J. Phillips[1] (44 1865 272000; richardp@earth.ox.ac.uk)

[1]dept. Earth Sciences Oxford University, Parks Rd, Oxford OX1 3PR

Total geological offset of 1000 km along the dextral Karakoram fault (Peltzer & Tapponnier 1989) were based on incorrect correlation of granite belts from the Pamir to S. Tibet and active slip rates of 30mm/yr-1 were based on an assumption of the age of offset post-glacial features (10 ± 2 ka; Liu et al. 1992). Detailed mapping and U-Pb and 40Ar/39Ar geochronology has confirmed that total dextral offsets are less than 120 km, the timing of initiation of the fault must have been younger than 15 Ma and that exhumation of sheared leucogranites and migmatites occurred between 15-11 Ma (Searle et al., 1997; Dunlap et al., 1998). We stress that: 1. All Tibetan fault slip rates published prior to 1996 are invalid as no precise timing constraints on the post-glacial Quaternary features were used. The common assumption was that all glacial features were formed 10 ± 2 ka, without any absolute dating. The glacial and fluvial features used to constrain offsets could have been awry by a factor of 3 or 4 (from 3.5 Ma - 20,000 ka). 2. Recent slip rates derived from cosmogenic isotope dating of offset Quaternary features should be treated with immense caution because during the continual recycling process of glacial moraine or alluvial fan burial, exposure and re-deposition, it cannot be known precisely which phase of exhumation is being dated. 3. Long-term geological slip rates on offset granites, precisely constrained by U-Pb geochronology remain the best estimates of timing of initiation, total finite offset and slip rates on Tibetan strike-slip faults. 4. The Karakoram fault is unlikely to be a lithospheric scale fault, because (a) temperatures beneath the southern part of the Tibetan plateau and beneath the faults are high enough to induce melting (>700°C at only 20 km depth), and (b) the lower crust beneath these faults must be underplated cold, old granulite facies crust of the Indian shield. 5. There appears to be a distinct lack of seismicity located along the Karakoram fault today. GPS data suggest that right-lateral slip parallel to the Karakoram fault occurred at 3.4 ± 5 mm/yr (Gaur 2002). If this figure is meaningful, then the slip today must be taken up mainly by aseismic creep, which suggests high temperatures occur at shallow depths along the fault, consistent with continuous but sporadic, and very young high-temperature metamorphism and anatexis in the southern Karakoram (Fraser et al. 2001). References cited: Dunlap, W.J., Weinberg, R.F. & Searle, M.P. 1998. J. Geol. Soc. London, 155, 903-12. Fraser, J.E., Searle, M.P., Parrish, R.R. & Noble, S.R. 2001. Bull. Geol. Soc. America, 113, 1443-55. Gaur, V. 2002. Abstract, 17th Himalaya-Karakoram-Tibet Workshop, Sikkim. Peltzer, G., Tapponnier, P. 1988. J. Geophysical Research, 93, 15058-117. Searle, M.P., Weinberg, R.F. & Dunlap, W.J. 1998. In: Continental Transpressional and Transtensional Tectonics. Geol. Soc. London Spec. Pub. 135, 307-26.

T22C-03 1410h

Detrital zircon provenance analysis of Oligocene sandstone in the eastern Xorkol basin and its implications for the magnitude of displacement along the eastern Altyn Tagh fault

Yongjun Yue[1] (yongjun@pangea.stanford.edu)

Stephan A Graham[1] (graham@pangea.stanford.edu)

Bradley D Ritts[2] (ritts@cc.usu.edu)

Joseph L Wooden[3] (jwooden@usgs.gov)

[1]Geological and Environmental Sciences, Stanford University, 450 Serra Mall, Stanford 94305-2115

[2]Department of Geology, Utah State University, 4505 Old Main Hill, Logan 84322-4505

[3]U.S. Geological Survey, 345 Middlefield Road, Menlo Park 94025

Oligocene strata in the eastern Xorkol basin north of the Altyn Tagh fault (ATF) consist of interbedded pebble to cobble conglomerate and red mudstone deposited in a braided fluvial environment. Ubiquitous imbrication in the conglomerate beds yields paleocurrent measurements indicative of north to northwest-directed paleoflow, suggesting sediment derivation from the southern side of the ATF. Clast types include slate, phyllite, limestone, dolomite, metavolcanic rocks and metasandstone, indicating a low-grade metamorphic source terrane with few granitic intrusions. In order to better characterize the source of Oligocene detritus, a sandstone sample was collected in the uppermost Oligocene strata for SHRIMP detrital zircon age dating. Most of the zircon grains are zoned in structure and pink in color with few fractures. Thirty spot analyses yield a characteristic age distribution for the sandstone. Except for 5 analyses which give discordant ages between 650 Ma and 830 Ma, 19 analyses are clustered around 917 Ma with a standard deviation of 42 Ma, and the other 6 analyses lie between 1100 Ma and 1700 Ma. The zircon grains have a mean Th/U ratio of 0.42 with standard deviation of 0.19, typical for zircons of magmatic origin. The resulting zircon age distribution puts important constraints on the source of the Oligocene detritus in the eastern Xorkol basin. The lack of Paleozoic zircon ages eliminates the main part of the central Qilian Shan, the southern Qilian Shan and Qaidam basin as possible sources because they contain widespead Paleozoic plutons. It also eliminates the Ordovician and Silurian volcaniclastic rocks of the northern Qilian Shan as a possible source inasmuch as their detrital zircons, shed from a synchronous magmatic arc in the central Qilian Shan, are predominantly early Paleozoic in age. Therefore, the only possible sources are Cambrian and Neoproterozoic strata in the southern part of the northern Qilian Shan and the northernmost part of the central Qilian Shan, where the Neoproterozoic strata contain zircon grains whose U/Pb ages are concordant at 930 Ma and zircon grains whose ages range between 1000 and 1600 Ma. An Oligocene piercing point is thus deduced by realigning this possible source and the Xorkol basin, consistent with 350-400 km of left-lateral offset along the eastern segment of the ATF. Determination of the magnitude of displacement along the eastern ATF is critical for understanding the nature of this fault and its role in the formation of the Tibet Plateau. Because the areally small northern part of the northern Qilian Shan beyond our piercing point is unlikely to accommodate a significant portion of the 350-400 km of left-lateral offset along the ATF, northeastward extrusion must have existed to assist in accommodating this offset, indicating that the ATF was an extrusion boundary, at least in the early Neogene. On the other hand, the 350-400 km of left-lateral offset is smaller than the offset along the western segment of the ATF. This decrease in offset indicates that the ATF is also a boundary across which slip was transferred into crustal shortening of the Qilian Shan and the Qaidam basin.

T22C-04 1425h

Gaoligong and Chong Shan Shear Zones, Yunnan, and Accommodation of the Northward Movement of India Relative to Indochina During the Mid-Cenozoic

Sinan O Akciz[1] (akciz@mit.edu)

Clark B. Burchfiel[1] (bcburch@mit.edu)

James L Crowley[1] (jlcrowle@MIT.EDU)

Yin Jiyun[2] (chenlzh@public.km.yn.cn)

Chen Liangzhong[2] (chenlzh@public.km.yn.cn)

[1]EAPS, MIT, 77 Massachusetts Ave., Cambridge, MA 02139

[2]Yunnan Institute of Geological Sciences, No. 131 Baita Road, Kunming 111004, China

Since the collision between Eurasia and India at ca. 45 Ma, there has been 2000-3500 km of convergence between India and Asia. How and where the indentation was accommodated in the region east of the India indenter are still subject to speculation, due to lack of geological investigations carried out in the region. Our field studies show that a significant part of the post-collisional northward indentation of India into Asia has been absorbed by the previously undocumented Gaoligong Shan (GSSZ) and Chong Shan (CSSZ) shear zones, in addition to the left-lateral displacement along the better-known Ailao Shan shear zone that lies farther NE in Yunnan, China. Penetrative ductile deformation marked by steep foliation and subhorizontal lineation affects all rock types within both shear zones and kinematic indicators show right-lateral and left-lateral shear along the GSSZ and CSSZ, respectively. U/Pb ages on several monazite grains and grain fractions from mylonitic to non-mylonitic leucogranites within the shear zone range from ca. 80-18 Ma. The youngest ages come from undeformed leucogranites cross-cutting the foliation, which indicate that right-lateral movement ended before ca. 18 Ma, when right-lateral shear between India-Sibumasu switched to the Sagaing fault zone in Burma. High-temperature sinistral strike-slip shearing along the CSSZ was active at ca. 28 Ma and terminated before ca.17 Ma, based on U/Pb ages of monazite grains from deformed and foliation cross-cutting leucogranites. These new geochronological data suggest that both the GSSZ and CCSSZ are not belts of Precambrian metamorphic rocks as previously suggested, but are important Cenozoic shear zones that are contemporaneous with the left-lateral Ailao Shan shear zone. The documentation of these structures also indicate that crustal fragments in SE Asia did not extrude to the southeast as a single block, but rather extruded as at least two crustal fragments with considerable internal deformation, bounded by three large-scale intra-continental shear zones.

T22C-05 1440h INVITED

GPS Measurements from the Southern Tibetan Plateau: Tests of Plate-like or Continuous Deformation

R. Bendick[3,4] (44-1223-337192; bendick@esc.cam.ac.uk); S. Jade[1] (sridevi@cmmacs.ernet.in); B. Bhatt[2] (bhatt@cmmacs.ernet.in); V. Gaur[1] (gaur@cmmacs.ernet.in); P. Molnar[4] (molnar@cires.colorado.edu); M. Anand[1] (anand@cmmacs.ernet.in); D. Kumar[1] (kumar@ecmmacs.ernet.in)

[1]CSIR, CMMACS, Bangalore 5650037, India

[2]Indian Institute of Astrophysics, none, Bangalore 560034, India

[3]COMET, Bullard Laboratories Madingley Road, Cambridge CB3 0EZ, United Kingdom

[4]CIRES, CB 399 University of Colorado, Boulder, CO 80309-0399, United States

Observations of relative motion in a geodetic network in Ladakh, India, and across southern Tibet indicate slow shear on the Karakorum fault, rapid east-west extension across the whole of southern Tibet, and constant arc-normal convergence between India and southern Tibet along the Himalayan arc. Measurements of ten campaign-style and six permanent sites with GPS precise geodesy provide bounds on the style and rate of surface deformation in the Tibet-Himalaya region. Divergence between sites at Leh, Ladakh, India and Shiquanhe, western Tibet as well as slow relative motion among sites within the Ladakh network limit right-lateral slip parallel to the Karakorum fault to only 3-5 mm/yr (1 σ). This low rate concurs with a recent estimate of 3-4 mm/yr for late Holocene time, but disagrees with the much higher rate of 30-35 mm/yr that has been used to argue for plate-like behavior of the Tibetan Plateau. Convergence between the Indian subcontinent and Ladakh at 15.5 $\pm$ 1.7 mm/yr at N42 $^\circ$ E $\pm$ 3° (1 σ) differs little from estimates of convergence across the central segment of the Himalaya. Finally, lengthening of the baseline between Leh, Ladakh and Lhasa (in southeastern Tibet) at 17.8 $\pm$ 1 mm/yr is consistent with an extrapolation of rates of east-west extension of the Tibetan Plateau based both on shorter GPS baselines and on diverging slip vectors of earthquakes in the Himalaya and suggests no significant acceleration associated with the Karakorum fault.

T22C-06 1455h

InSAR observations of conjugate strike-slip faulting in West Central Tibet

Michael Taylor[1] (mtaylor@ess.ucla.edu)

Gilles Peltzer[1,2] (peltzer@ess.ucla.edu)

An Yin[1] (yin@ess.ucla.edu)

[1]Earth and Space Sciences, UCLA 3806 Geology Bldg., Los Angeles, CA 90095-1567, United States

[2]Jet Propulsion Laboratory, Caltech, Pasadena, CA 91109, United States

A combination of Landsat7 image interpretation and repeat-pass synthetic aperture radar interferometry (InSAR) characterizes the fault geometry and kinematics of the Bue Co conjugate strike-slip fault system in west central Tibet (33°N, 82°E). The conjugate strike-slip fault system is centered along the E-trending Bangong-Nujiang suture zone, and is comprised of the NE-striking left-slip Bue Co fault to the north and NW-striking right-slip Lamu Co fault to the south. Preliminary interferograms were constructed using radar image pairs spanning 6 to 7 years from descending passes of the ERS European Space Agency satellites. Maps of the surface displacement field along the radar line of sight show a concentration of strain along the Lamu Co fault, consistent with right-lateral slip. These results agree with slip constraints from geologic observations. Within the detection limit of InSAR, we do not observe a significant strain gradient along the opposing Bue Co fault, which is consistent with basic fracture mechanics. This result of a single active fault that comprises a conjugate strike-slip fault system is similar to InSAR observations along the Dong Co conjugate fault system 300 km to the east (32°N, 86°E). We suggest that conjugate strike-slip structures are characteristic of central Tibet, and that they are consistent with a constrictional strain field of regional extent.

T22C-07 1510h

Geodetic slip rates for the major strike-slip faults in the eastern Tibet

Qi Wang[1] (whgps@public.wh.hb.cn)

Jeffrey T. Freymueller[2] (jeff@giseis.alaska.edu)

[1]Institute of Seismology, China Seismological Bureau, Wuhan 430071, China

[2]Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775, United States

Several active fault systems in the northern and eastern Tibet control, to a large extent, the pattern of active deformation due to the India-Asia collision. Recent GPS geodetic measurements in the region suggest rates of strike-slip motion ranging from several mm/yr to 1 cm/yr on these major faults. Here we report a detailed description of fault slip rates and their variation for the Haiyuan, eastern Kunlun, Xianshuihe-Xiaojiang and Red River faults, using data from hundreds of GPS sites. Many of these sites are part of the Chinese national GPS network, surveyed mostly in 1999 and 2001. The geodetic slip rate estimates for these faults suggest that while active faulting on the major fault systems plays an important role in accommodating eastward crustal movement of Tibetan Plateau, internal deformation and rotation of tectonic blocks bounded by these major faults absorb a significant amount of the eastward lateral extrusion of Tibetan crust.

T22C-08 1525h

Northeastwards decrease in the late Pleistocene-Holocene slip-rate and propagation of the Altyn Tagh fault (China).

Anne-Sophie Meriaux[1] (925-422-3110; meriaux1@llnl.gov); Frederick J Ryerson[1] (ryerson1@llnl.gov); Paul Tapponnier[2] (tappon@ipgp.jussieu.fr); Jerome Van der Woerd[3] (Jerome.Vanderwoerd@eost.u-strasbg.fr); Robert C Finkel[4] (finkel1@llnl.gov); Xiwei Xu[4]; Zhiqin Xu[5]

[1]IGPP, Lawrence Livermore National Laboratory, PO BOX 808, L-206, Livermore, Ca 94550', United States

[2]Tectonique, IGPP, 4 place Jussieu, Paris Cedex 75252, France

[3]IPGS-EOST, 5 Rue rene Descartes, Strasbourg 67084, France

[4]Seismological Bureau, 63 Fuxing Ave, Beijing 100036, China

[5]Ministry of Land and Resources, Baiwanzhuand Rd, Beijing 100037, China

Measured, long-term ($>$ 100 Ka) slip-rates appear to decrease northeastwards along the Altyn Tagh Fault. Our recent results imply that the rate is fastest near Tura, on the central segment of the fault (85 $-$ 89°E). Here, offsets of fluvial terrace risers and abandoned channels ($\approx$ 420 m) and glacial features ($\approx$ 3.5 km) are constrained by both radiocarbon and cosmogenic dating (^{10}Be and ^{26}Al) and yield a slip rate of $\approx$30 mm/yr. Farther East, north of Huatougou, at the transition between a push-up mountain and a pull-apart basin, cosmogenic dating of offset terrace risers on the most active trace of the fault system yields a well-constrained rate of 18 mm/yr. Yet farther East, near Aksay, on the north Altyn Tagh fault (NATF), at three sites where extensive radiocarbon and surface exposure dating were performed, the slip-rate is 20 $\pm$ 3 mm/yr, with a lower bound of 13 $\pm$ 2 mm/yr. At 95°E, eastern of the main Subei junction, the rate found at Lou Zhao Wan on the NATF, is only on order of 15 mm/yr with a minimum of 12.5 mm/yr. Finally, near Shibao Cheng (96°E) the slip rate of 4$\pm$2 mm/yr has been obtained west of the junction with the Qilian Shan Front (Meyer *et al.*, 1996). Thus, long-term morphochronologic measurements over a length of $\approx$ 1000 km indicate a systematic eastward decrease, from 30 mm/yr to 4 mm/yr, of the left-lateral slip-rate along the fault. This behavior is in contrast to that on the Kunlun Fault where the morphochronologic rate over a similar length of the fault appears to have remained constant over the last 45 Ka (Van der Woerd *et al*, 2000). At a more detailed level, the ATF slip rate appears to display a stepwise decrease at the junctions with branching, sub-perpendicular, active thrusts south of the fault. We relate this pattern to the eastward propagation of the fault, still in progress, whose present kinematics remains linked to the formation, in the last 10 Ma, of thrusts that young to the northeast. This propagation process has been a vital element in the building of the NE corner of the Tibet plateau (Meyer *et al*, 1998).

T22D MCC: 3007 Tuesday 1340h

New Views of the Structure and Composition of the Deep Earth IV

(joint with GP, S, V, MR, DI)

Presiding: **D L Farber,** Lawrence Livermore National Laboratory**; J Badro,** University Paris VI - Institut de Physique du Globe

T22D-01 1340h

The Effect of Pressure on Diffusion of Au, Pd, and Re in Fe-Ni Alloys

Heather C. Watson[1] (518-276-8827; watsoh@rpi.edu)

Yingwei Fei[2] (y.fei@gl.ciw.edu)

Bruce Watson[1] (watsoe@rpi.edu)

[1]Rensselaer Polytechnic Institute, Department of Earth and Environmental Sciences 110 Eighth St., Troy, NY 12180, United States

[2]Geophysical Laboratory, Carnegie Institution of Washington 5251 Broad Branch Rd, NW, Washington, DC 20015, United States

It is understood that the core of the earth consists predominantly of an iron-nickel alloy. Diffusion is commonly considered to be a rate limiting step in many processes such as crystal growth as well as element partitioning. It follows that understanding the diffusive behaviour of trace siderophile elements in Fe-Ni alloys could help constrain models of core formation, time and length scales of communication between the inner and the outer core of the earth, and crystallization of the inner core. We measured the effect of pressure on the diffusivity of several siderophile elements (Au, Pd, Re) in solid 90:10 iron-nickel alloy using a multi-anvil pressure device. The elements investigated can be considered to be broadly representative of many siderophile elements. Diffusion couple experiments were conducted at pressures ranging from 5 to 25 GPa, and temperatures ranging from 1200° C to 1600° C. Alloys for the diffusion couples were presynthesized by compacting and heating mixtures of pure metal powders in a piston-cylinder device at 1GPa and 1400° C for 60 hours. The diffusion couples were made by juxtaposing a disk of pure 90%Fe 10%Ni alloy with another disk of a similar alloy doped with up to 2% of the diffusant of interest. The duration of the experiments ranged from 12-120 hours. Diffusion profiles in all experimental products were measured by elctrom microprobe analysis. It was found that there is a substantial decrease in diffusivity with the application of pressure for all three elements, and the magnitude of this decrease appears to be similar for all three elements. The relative diffusivities consistently span

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